Phenomenological viability of the NLHT

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In collaboration with **José I. Illana**

- **New Littlest Higgs model with T-parity (NLHT)**
- **Constraining the NLHT parameter space**
- **Conclusions**

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JHEP 11 (2022), 055 [2209.06195 [hep-ph]]

1. NLHT

Motivation and symmetries

- Little Higgs models: solution to the *little* HP at the TeV scale
  - ❑ Higgs is the GB of an spontaneously broken global group G at the scale f: CCWZ formalism
  - ❑ Gauge and Yukawa interactions break the global symmetries *collectively*: collective symmetry breaking
  - ❑ No quadratic divergences to the Higgs mass
  - ❑ To avoid constrains from EWPD: *T-parity*
- Interesting model: LHT $\mathrm{SU}(5) \xrightarrow[f]{\Sigma_0} \mathrm{SO}(5)$
- LHT non-gauge invariant in fermionic sector [2103.17078 [hep-ph]]

- Solution: **NLHT** **(minimal gauge invariant extension)**
- Global group and SSB:

$$\mathrm{SU}(5) \times [\mathrm{SU}(2) \times \mathrm{U}(1)]^2 \xrightarrow[f]{\Sigma_0,\widehat{\Sigma}_0} \mathrm{SO}(5) \times [\mathrm{SU}(2) \times \mathrm{U}(1)]$$

with $\widehat{\Sigma}_0 = \Sigma_0$

- ❑ $14 + 4$ GB parametrized à la CCWZ

$$\Pi = \pi^a X^a, \quad \{X^a\} = 14\ \mathrm{SU}(5)\ \text{brk. gen.}$$
$$\xi = e^{i\frac{\Pi}{f}} \xrightarrow{G} V\xi U^\dagger = U\xi\Sigma_0 V^T \Sigma_0 \qquad V \in \mathrm{SU}(5)$$
$$\Sigma = \xi\Sigma_0\xi^T \xrightarrow{G} V\Sigma V^T \qquad U \in \mathrm{SO}(5)$$

$$\widehat{\Pi} = \widehat{\pi}^a \widehat{X}^a, \quad \left\{\widehat{X}^a\right\} = 4\ [\mathrm{SU}(2) \times \mathrm{U}(1)]^2\ \text{brk. gen.}$$
$$\widehat{\xi} = e^{i\frac{\widehat{\Pi}}{f}} \xrightarrow{G} \widehat{V}\widehat{\xi}\widehat{U}^\dagger = \widehat{U}\widehat{\xi}\Sigma_0 \widehat{V}^T \Sigma_0 \qquad \widehat{V} \in [\mathrm{SU}(2) \times \mathrm{U}(1)]^2$$
$$\widehat{\Sigma} = \widehat{\xi}\Sigma_0\widehat{\xi}^T \xrightarrow{G} \widehat{V}\widehat{\Sigma}\widehat{V}^T \qquad \widehat{U} \in [\mathrm{SU}(2) \times \mathrm{U}(1)]$$

1. NLHT

Symmetries

- Gauge group and SSB

$$[\mathrm{SU}(2)\times\mathrm{U}(1)]_1\times[\mathrm{SU}(2)\times\mathrm{U}(1)]_2 \xrightarrow[f]{\Sigma_0,\widehat{\Sigma}_0} \mathrm{SU}(2)_L\times\mathrm{U}(1)_Y$$

❑ 8 gauge fields (same as in LHT)

$(\gamma, W^\pm, Z)$ massless
$(A_H, W_H^\pm, Z_H)$ massive $\sim f$

❑ GB:

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

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

❑ A combination of $(\omega^\pm, \widehat{\omega}^\pm)$, $(\omega^0, \widehat{\omega}^0)$, $(\eta, \widehat{\eta})$ eaten by $W_H^\pm, Z_H, A_H$

- SM SSB:

$$\mathrm{SU}(2)_L\times\mathrm{U}(1)_Y \xrightarrow[v]{\langle H\rangle} \mathrm{U}(1)_Q$$

❑ $\pi^\pm, \pi^0$ eaten by $W^\pm, Z$. Masses $\sim v$. γ massless

- Physical scalar fields

❑ $h, \phi^{\pm\pm}, \phi^\pm, \phi^0, \phi^P$ usual ones

❑ Remaining comb. of $(\omega^\pm, \widehat{\omega}^\pm)$, $(\omega^0, \widehat{\omega}^0)$, $(\eta, \widehat{\eta})$

❑ Total: 11 physical scalar fields

1. NLHT

T-parity

- Conflicts with EWPD ⟶ T-parity
- Gauge sector:

❑
$$\underset{g_1,\, g_1'}{[\mathrm{SU}(2)\times \mathrm{U}(1)]_1} \overset{\mathrm{T}}{\longleftrightarrow} \underset{g_2,\, g_2'}{[\mathrm{SU}(2)\times \mathrm{U}(1)]_2}$$
$$g_1 = g_2 = \sqrt{2}g, \quad g_1' = g_2' = \sqrt{2}g'$$

❑ $\gamma, W^{\pm}, Z \to$ T-even gauge bosons

$A_H, W_H^{\pm}, Z_H \to$ T-odd gauge bosons

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

- Scalar sector:

❑ Introduce $\Omega \in Z\left[G_g\right]$

❑
$$\Pi \overset{T}{\to} -\Omega\Pi\Omega$$
$$\xi \overset{T}{\to} \Omega\xi^{\dagger}\Omega, \quad \Sigma \overset{T}{\to} \widetilde{\Sigma} = \Omega\Sigma_0\Sigma^{\dagger}\Sigma_0\Omega$$

$$\widehat{\Pi} \overset{T}{\to} -\widehat{\Pi}$$
$$\widehat{\xi} \overset{T}{\to} \widehat{\xi}^{\dagger}, \quad \widehat{\Sigma} \overset{T}{\to} \Sigma_0\widehat{\Sigma}^{\dagger}\Sigma_0$$

❑ $H \to$ T-even scalar fields

$\eta,\ \omega,\ \Phi,\ \hat{\eta},\ \hat{\omega} \to$ T-odd scalar fields

$$\mathcal{L}_S = \frac{f^2}{8}\mathrm{tr}\left[(D^{\mu}\Sigma)^{\dagger}D_{\mu}\Sigma\right] + \frac{f^2}{8}\mathrm{tr}\left[\left(D^{\mu}\widehat{\Sigma}\right)^{\dagger}D_{\mu}\widehat{\Sigma}\right] \supset \text{gauge boson masses}$$

1. NLHT — Fermions

- Fermions: leptons (similar for quarks)

  - Quintuplets

SU(5) $\Psi_1[5^*] = \begin{pmatrix} -i\sigma^2 l_{1L} \\ i\chi_{1L} \\ -i\sigma^2 \tilde{l}^c_{1L} \end{pmatrix}$, SU(5) $\Psi_2[5] = \begin{pmatrix} -i\sigma^2 \tilde{l}^c_{2L} \\ i\chi_{2L} \\ -i\sigma^2 l_{2L} \end{pmatrix}$

SO(5) $\Psi_R[5] = \begin{pmatrix} -i\sigma^2 (\tilde{l}^c_-)_R \\ i(\chi_+)_R \\ -i\sigma^2 l_{HR} \end{pmatrix}$, $[SU(2)\times U(1)]$ $\widehat{\Psi}_R = \begin{pmatrix} -i\sigma^2 (\tilde{l}^c_+)_R \\ i(\chi_-)_R \\ 0_2 \end{pmatrix}$

  - Transformation properties

❖ Under G :

$$\Psi_1 \xrightarrow{G} V^*\Psi_1, \quad \Psi_2 \xrightarrow{G} V\Psi_2$$
$$\Psi_R \xrightarrow{G} U\Psi_R, \quad \widehat{\Psi}_R \xrightarrow{G} \widehat{U}\widehat{\Psi}_R$$

❖ Under T-parity:

$$\Psi_1 \xrightarrow{T} \Omega\Sigma_0\Psi_2 \quad \Psi_R \xrightarrow{T} \Omega\Psi_R, \quad \widehat{\Psi}_R \xrightarrow{T} -\Omega\widehat{\Psi}_R$$

realization compatible with gauge invariance

- T-even:

$$l_L = \frac{l_{1L}-l_{2L}}{\sqrt{2}} = (\nu_L, \ell_L)^T$$
$$(\chi_+)_L = \frac{\chi_{1L}+\chi_{2L}}{\sqrt{2}}, \quad (\chi_+)_R$$
$$(\tilde{l}^c_+)_L = \frac{\tilde{l}^c_{1L}-\tilde{l}^c_{2L}}{\sqrt{2}} = \left((\tilde{\nu}^c_+)_L, (\tilde{\ell}^c_+)_L\right)^T$$
$$(\tilde{l}^c_+)_R = \left((\tilde{\nu}^c_+)_R, (\tilde{\ell}^c_+)_R\right)^T$$

- T-odd:

$$l_{HL} = \frac{l_{1L}+l_{2L}}{\sqrt{2}} = (\nu_{HL}, \ell_{HL})^T$$
$$l_{HR} = (\nu_{HR}, \ell_{HR})^T$$
$$(\chi_-)_L = \frac{\chi_{1L}-\chi_{2L}}{\sqrt{2}}, \quad (\chi_-)_R$$
$$(\tilde{l}^c_-)_L = \frac{\tilde{l}^c_{1L}+\tilde{l}^c_{2L}}{\sqrt{2}} = \left((\tilde{\nu}^c_-)_L, (\tilde{\ell}^c_-)_L\right)^T$$
$$(\tilde{l}^c_-)_R = \left((\tilde{\nu}^c_-)_R, (\tilde{\ell}^c_-)_R\right)^T$$

1. NLHT **Fermions**

- Heavy leptons masses (similar for quarks)

  - l_H, (χ_+) and $(\tilde{l}^c_-)$ get a mass $\sim \kappa f$ from

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

Remark 1: SU(5) invariant.
No κ contributions alone to the Higgs mass

  - (χ_-) and $(\tilde{l}^c_+)$ get a mass $\sim \hat{\kappa} f$ from

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

Remark 2: New Yukawa coupling $\hat{\kappa}$

Remark 3: No Higgs in $\hat{\xi}$.
No $\hat{\kappa}$ contributions alone to the Higgs mass

- Top quark sector

$$\mathcal{L}_{Y_t} = -i\frac{\lambda_1}{4} f \epsilon_{ijk}\epsilon_{xy} \left[\left(\overline{Q^t_1}\right)_i \Sigma_{jx}\Sigma_{ky} + \left(\overline{Q^t_2}\Sigma_0\Omega\right)_i \tilde{\Sigma}_{jx}\tilde{\Sigma}_{ky} \right] t_R - \frac{\lambda_2 f}{\sqrt{2}} \left(\overline{T}_{1L}\hat{X}T_{1R} + \overline{T}_{2L}\hat{X}^* T_{2R} \right) + \text{h.c.}, \quad \hat{X} = \hat{\Sigma}_{33}^{-1/2}$$

- Kinetic term and gauge interactions for fermions

  - LH fermions

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

  - RH fermions (CCWZ)

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

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

1. NLHT

Masses

- Gauge fields

$$M_W = \frac{gv}{2}$$
$$M_Z = M_W / c_W$$
$$M_{W_H} = M_{Z_H} = \sqrt{2} g f$$
$$M_{A_H} = \sqrt{\frac{2}{5}} g' f$$

Remark: heavy gauge fields $\sqrt{2}$ heavier than in LHT

- Top sector

$$m_t = \frac{1}{\sqrt{2}} \frac{\lambda_1 \lambda_2}{\sqrt{\lambda_1^2 + \lambda_2^2}} v$$
$$M_{T_+} = \sqrt{\frac{\lambda_1^2 + \lambda_2^2}{2}} f$$
$$M_{T_-} = \frac{\lambda_2}{\sqrt{2}} f$$
$$M_{T_+} > M_{T_-}$$

- Light scalar fields (only log. div.)

$$M_h^2 = \frac{f^2}{8\pi^2} \log \Lambda^2 \left(3\lambda_1^2 \lambda_2^2 - 6g^4 - \frac{2}{5} g'^4 - 12 T_\kappa \right)$$
$$T_\kappa = \mathrm{tr}\left(\kappa_l \kappa_l^\dagger \widehat{\kappa}_l \widehat{\kappa}_l^\dagger \right) + 3\mathrm{tr}\left(\kappa_q \kappa_q^\dagger \widehat{\kappa}_q \widehat{\kappa}_q^\dagger \right)$$

CSB

$$M_{\widehat{\eta}}^2 = \frac{72}{5} M_h^2 \frac{T_\kappa}{3\lambda_1^2 \lambda_2^2 - 6g^4 - \frac{2}{5} g'^4 - 12 T_\kappa}$$
$$M_{\widehat{\omega}}^2 = 8 M_h^2 \frac{g^4 + T_\kappa}{3\lambda_1^2 \lambda_2^2 - 6g^4 - \frac{2}{5} g'^4 - 12 T_\kappa}$$

- Heavy leptons

$$m_{l_H} = m_{\chi_+} = m_{\widetilde{l}^c_-} = \sqrt{2} \kappa_l f$$
$$m_{\chi_-} = m_{\widetilde{l}^c_+} = \sqrt{2} \widehat{\kappa}_l f$$

- Heavy quarks

$$m_{q_H} = m_{\chi^q_+} = m_{\widetilde{q}^c_-} = \sqrt{2} \kappa_q f$$
$$m_{\chi^q_-} = m_{\widetilde{q}^c_+} = \sqrt{2} \widehat{\kappa}_q f$$

- Heavy scalar fields (quad. div.)

$$M_\Phi = \sqrt{2} \frac{f}{v} M_h$$

- Higgs quartic coupling

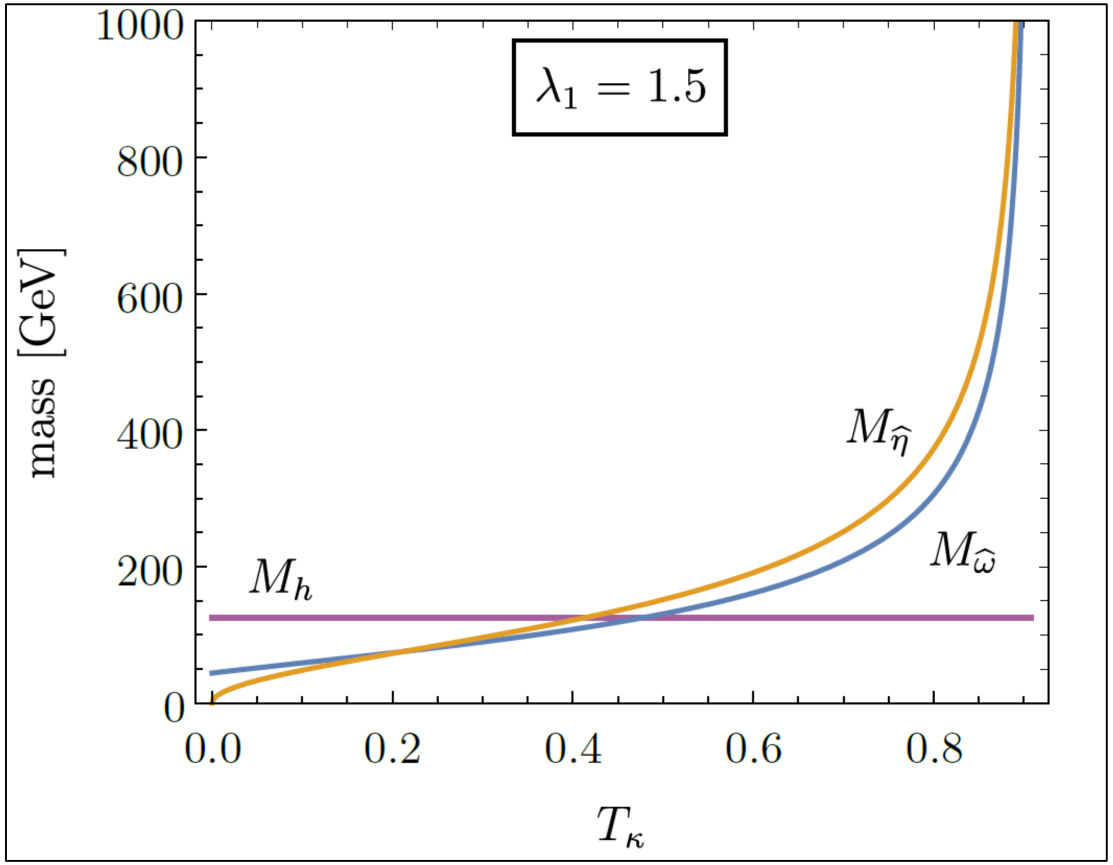
$$\lambda = \frac{1}{16\pi^2} \frac{\Lambda^2}{f^2} \left(g^2 + g'^2 + 3\lambda_1^2 \right)$$

Relates λ_1 and Λ.

1. NLHT

Masses

- Role of T_κ on new GB masses



- ❑ Masses strictly increasing with T_κ.
- ❑ No quad. div. ⟶ New scalars are naturally light. Mass upper bound of 1 TeV.
- ❑ There is a value of T_κ such that

$$M_{\hat\eta} > M_{\hat\omega} \to T_\kappa > \frac{5}{4}g^4$$

Parameter space

- Allowed λ_1 values

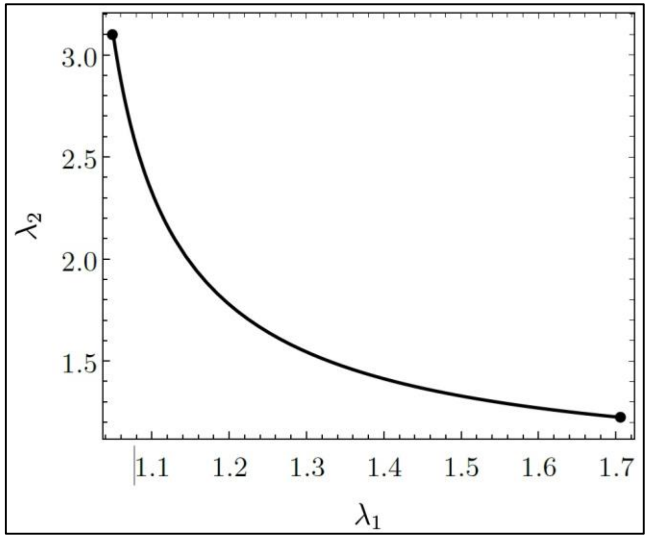
  - Yukawa couplings λ_1 and λ_2 related through m_t

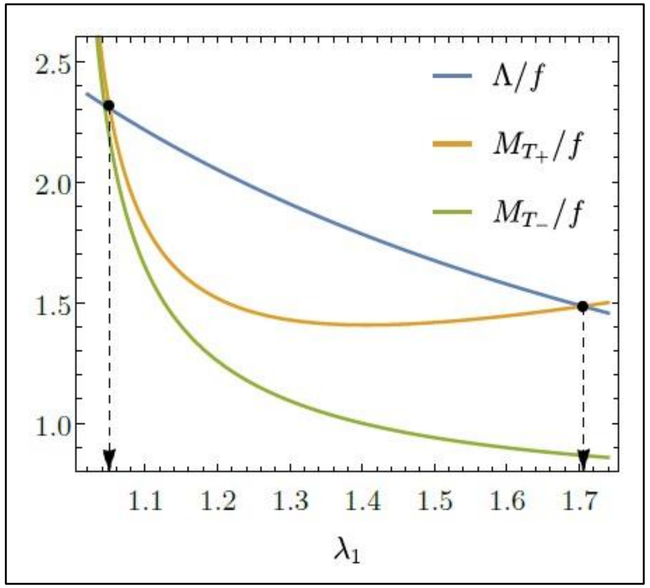
$$\frac{1}{\lambda_1^2} + \frac{1}{\lambda_2^2} = \left(\frac{v}{\sqrt{2}m_t}\right)^2$$

  - The T-even (heavier) top partner mass must remain below Λ

$$\frac{M_{T_+}}{f} < \frac{\Lambda}{f}$$

$$\lambda_1 \in [1.05, 1.71]\,, \quad \frac{\Lambda}{f} \in [1.49, 2.32] < 4\pi$$





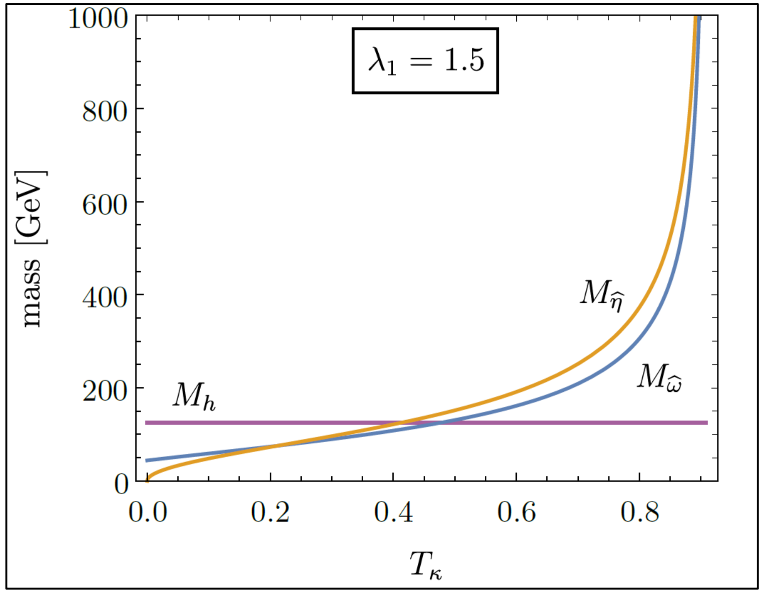
2. Pheno **Parameter space**

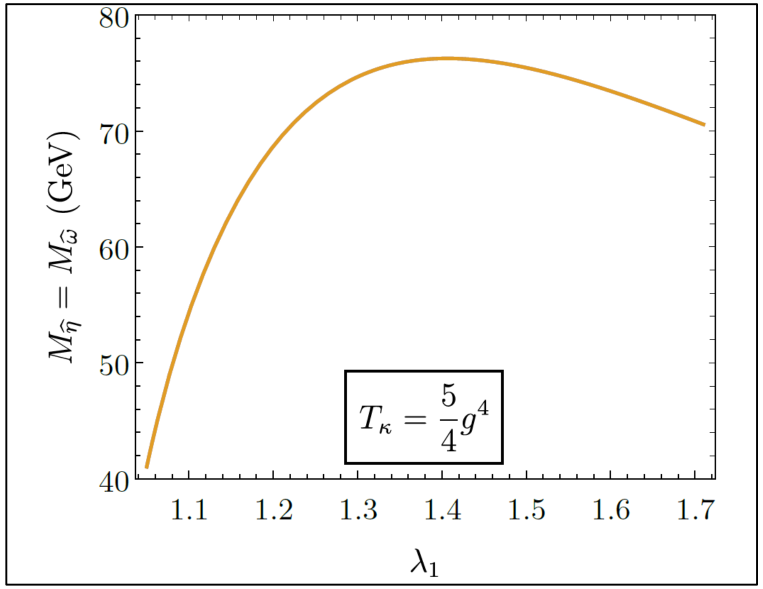
- EWPD on vector-like quarks: Top partners
  - ❑ LHC bounds: Vector-like quarks heavier than 2 TeV
  - ❑ On the T-odd (lightest) top quark partner:

$$M_{T\_} > 2\,\text{TeV} \Rightarrow f > 0.9\,\text{TeV}$$

- Dark matter candidate (WIMP)
  - ❑ LTP is stable and a DM candidate.
  - ❑ Light T-odd particles: $\widehat{\eta}$ and A_H
  - ❑ Vector DM less constrained: A_H DM
  - ❑ $f > 0.9$ TeV implies $M_{A_H} \gtrsim 200$ GeV and mass hierarchy

$$200\,\text{GeV} < M_{A_H} < M_{\widehat{\omega}} < M_{\widehat{\eta}}$$





Parameter space

- DM relic density: Co-annihilators

  - LHT case:

    - For $M_{A_H} \gtrsim 150$ GeV co-annihilations needed to reproduce the current DM relic density

    - T-odd quarks and leptons share masses nearly mass degenerate with A_H

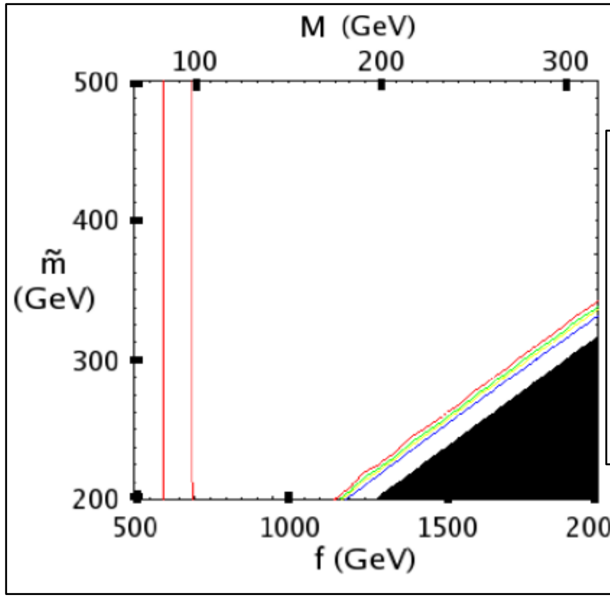
  - NLHT case:

    - T-odd quarks too heavy due to EWPD ($m \gtrsim 2$ TeV)

    - Leptons less constrained: T-odd leptons co-annihilators

    - Simplification 1: diagonal and degenerate Yukawas

$$\widehat{\kappa}_{li} = \kappa_{li} \equiv \kappa_l \qquad \widehat{\kappa}_{qi} = \kappa_{qi} \equiv \kappa_q \quad \Rightarrow \quad T_\kappa = 3\kappa_l^4 + 9\kappa_q^4$$



[Birkedal *et al.*, 2006]

- Simplification 2: No new GB contributions to co-annihilations:

Lighter $\widehat{\omega}$: $M_{\widehat{\omega}} > M_{A_H} + M_h$

Together with $M_{\widehat{\eta}} < 1$ TeV (natural mass)

→ lower and upper bounds for T_κ

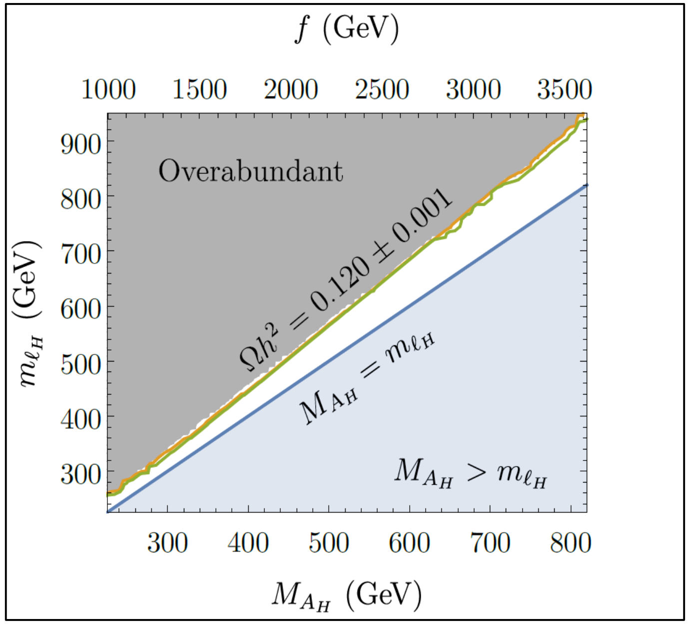
2. Pheno **Simplified model**

- **Fixing the heavy leptons Yukawa coupling**
  - ❑ A_H and T-odd leptons contribute to DM relic density
  - ❑ Using micrOMEGAs (freeze-out) and $\Omega h^2 \approx 0.12$ gives the relation

$$m_{\ell_H} \approx 1.16 M_{A_H}$$

  - ❑ Using $m_{\ell_H} = \sqrt{2}\kappa_l f$ and $M_{A_H} = \sqrt{\frac{2}{5}} g' f$:

$$\kappa_l \approx 0.185$$



- **EWPD on vector-like quarks: rest of heavy quarks**
  - ❑ LHC bounds on VL quarks $m > 2$ TeV
  - ❑ Lower bound on κ_q:

$$\kappa_q > \frac{\sqrt{2}}{f\ [\text{TeV}]}$$

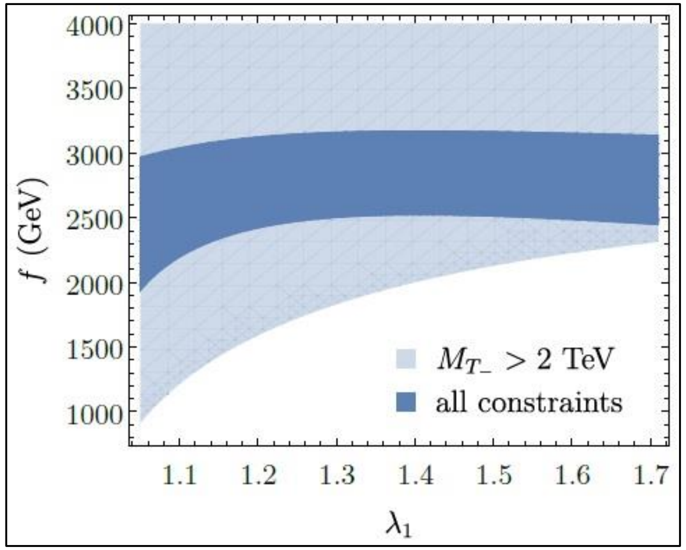
2. Pheno

Simplified model

- Allowed region in $\lambda_1 - f$ plane

$$f \in [2.0, 3.1]\ \text{TeV}, \quad \lambda_1 \in [1.05, 1.71]$$

Remark: not all values of λ_1 are available for a given f.



$$M_{A_H} \in [450, 680]\ \text{GeV}$$
$$M_{Z_H} = M_{W_H} \in [1.9, 2.8]\ \text{TeV}$$
$$M_\Phi \in [1.5, 2.2]\ \text{TeV}$$

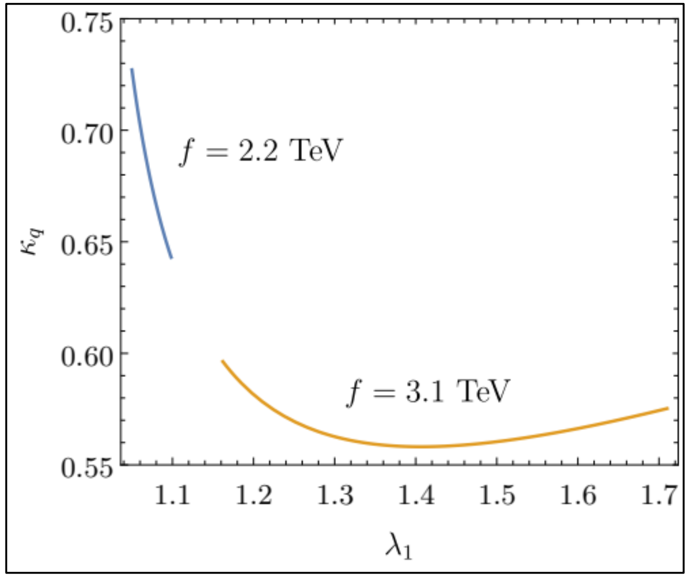
$$M_{T_+} \in [2.8, 6.9]\ \text{TeV}$$
$$M_{T_-} \in [2.0, 6.9]\ \text{TeV}$$

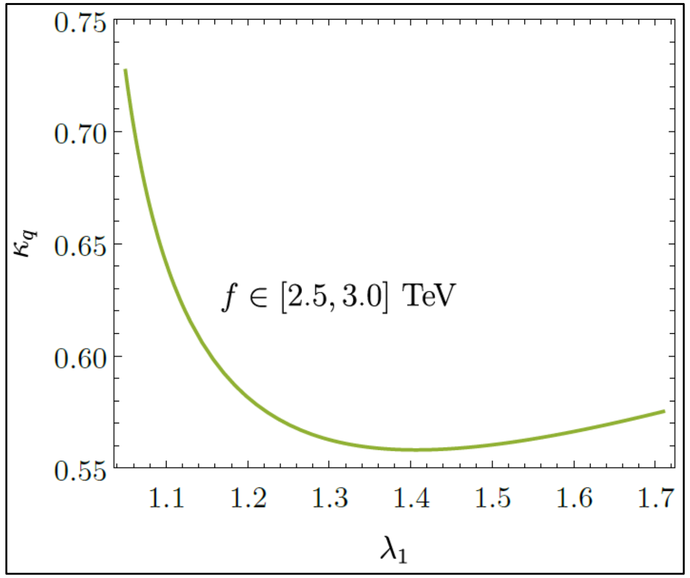
$$\kappa_l \text{ fixed} \Rightarrow m_{\ell_H, \tilde{l}^c_+} \in [530, 800]\ \text{GeV}$$

- Correlations

❑ The Yukawa couplings λ_1 and κ_q get correlated

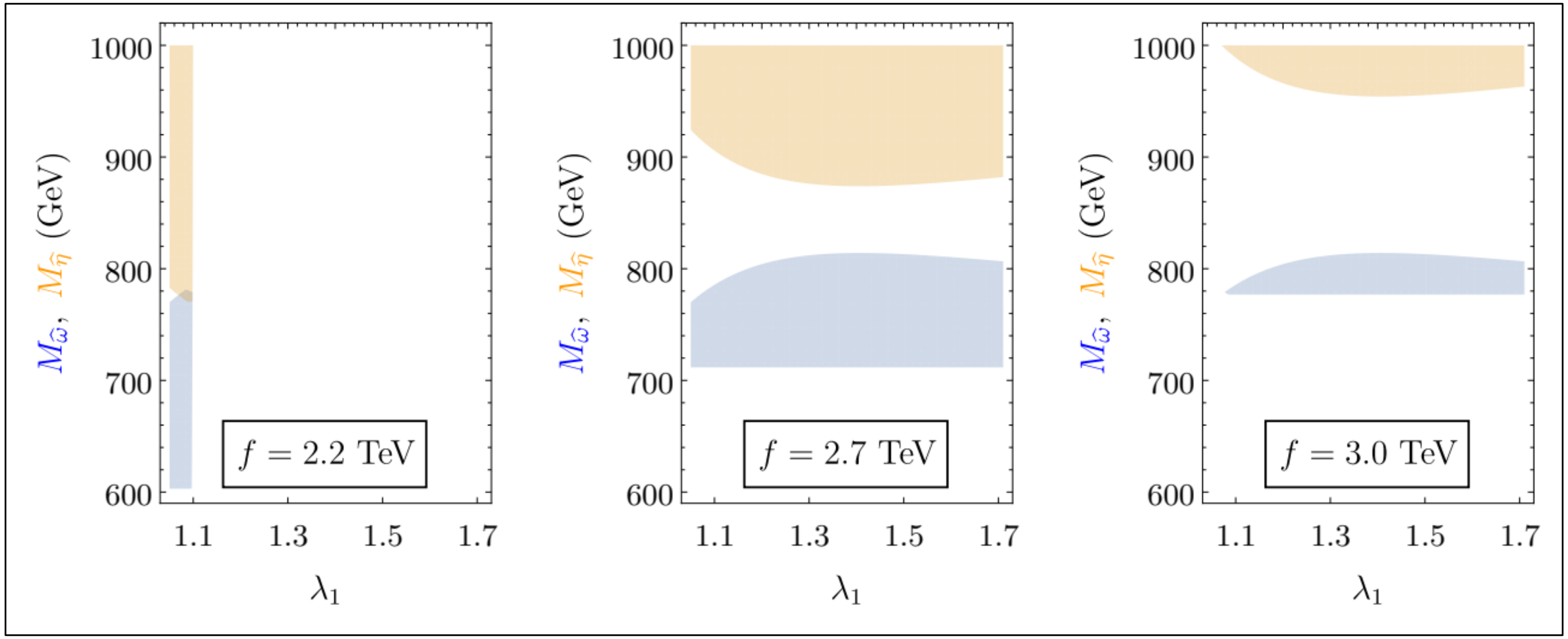
$$m_{q_H} \in [2.0, 3.2]\ \text{TeV}$$





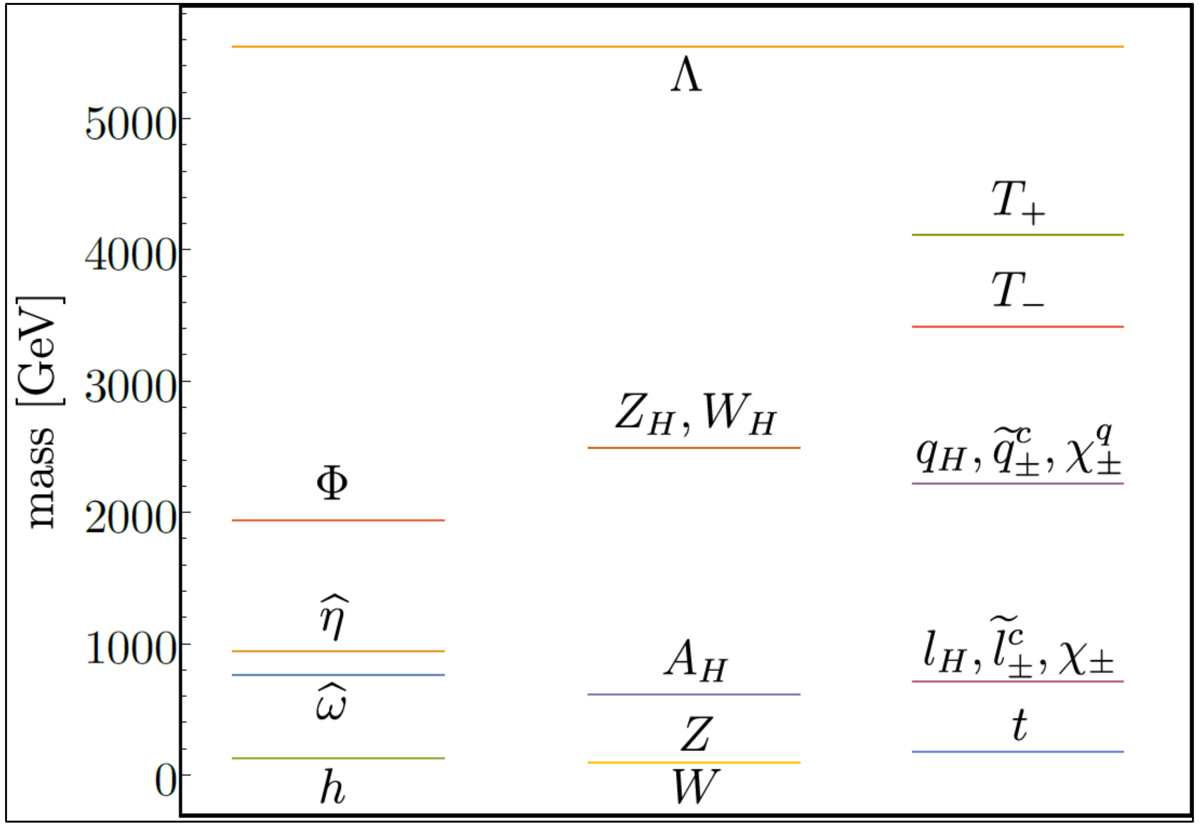
2. Pheno

Simplified model



$$M_{\hat\omega} \in [600, 800] \text{ GeV}$$
$$M_{\hat\eta} \in [800, 1000] \text{ GeV}$$

2. Pheno **Simplified model**



Typical spectrum for $f = 2.7$ TeV and $\lambda_1 = 1.2$

Conclusions

- Little Higgs models offer a solution to the HP at the TeV scale
- The LHT $SU(5)/SO(5)$ is not gauge invariant in the fermionic sector
- We construct a New and gauge invariant LHT (NLHT) enlarging minimally the global symmetry group to

$$SU(5) \times [SU(2) \times U(1)]^2 \xrightarrow[f]{\Sigma_0, \widehat{\Sigma}_0} SO(5) \times [SU(2) \times U(1)]$$

The gauge group is $[SU(2) \times U(1)]^2 \xrightarrow[f]{\Sigma_0, \widehat{\Sigma}_0} SU(2)_L \times U(1)_Y$ (same as in LHT)

- ❑ New particles
  - ❖ 4 extra light T-odd scalar fields: singlet and real triplet
  - ❖ Extra (χ_-) and $(\tilde{l}^c_+)$ with masses $\sim \hat{\kappa} f$

- Assuming:
  - ❑ No mass exceeds the cutoff scale
  - ❑ Current lower bounds on VL quarks
  - ❑ Simplified model with mass degenerate heavy fermions compatible with the usual A_H as DM
- We found:
  - ❑ $f \in [2,3]$ TeV
  - ❑ Yukawa couplings κ_q and λ_1 get correlated
  - ❑ Yukawa coupling κ_l fixed
  - ❑ Particle spectrum bounded from above and below
- The NLHT is viable

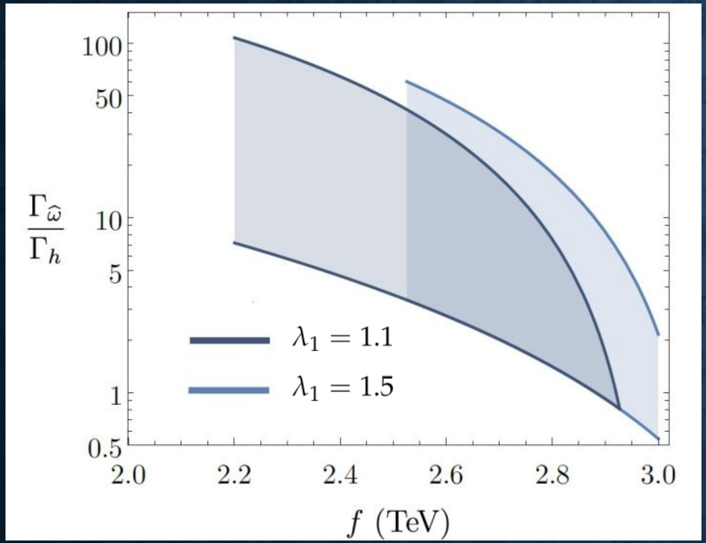
THANKS FOR YOUR ATTENTION

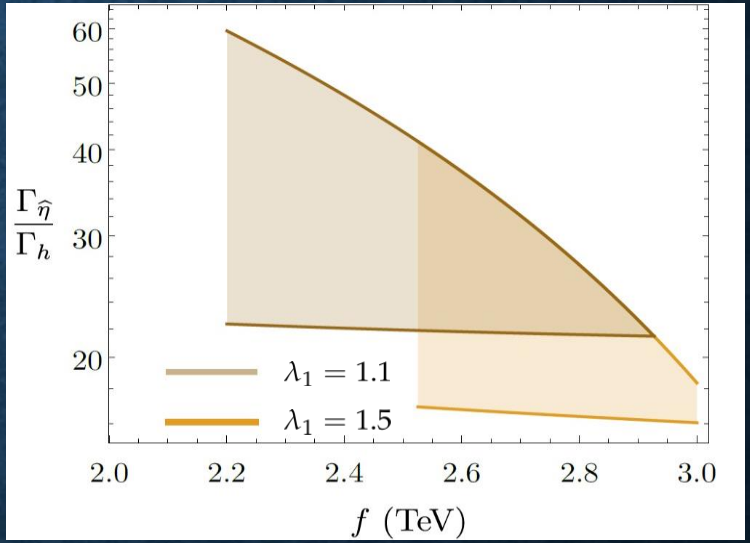
Backup

C. New scalar fields lifetime and production

JHEP 11 (2022), 055.

- $\widehat{\omega}$ and $\widehat{\eta}$ decay into LH SM lepton and a RH T-odd mirror lepton
- Width and lifetime comparable with that of the Higgs





- Production:
  - ❑ Pair produced with a T-odd heavy particle
  - ❑ Produced by EW interaction

} Not sizeable production rates

B. Higgs mass in the LHT

- Gauge and top sector contributions are understood

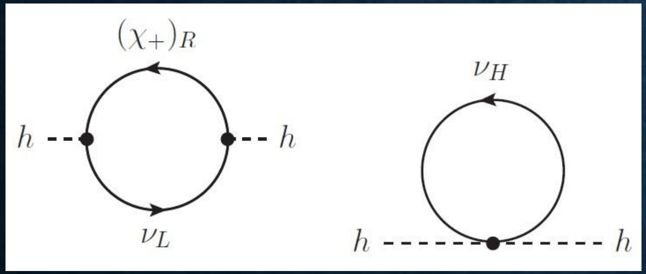
$$\mu^2 = \frac{f^2}{16\pi^2}\log\Lambda^2\left(6g^4 + \frac{2}{5}g'^4 - 3\lambda_1^2\lambda_2^2\right)$$

- Heavy fermion sector break the global $SU(5)$

$$\mathcal{L}_{Y_H}^{(a)} = -\kappa_l f\left(\overline{\Psi}_2\xi + \overline{\Psi}_1\Sigma_0\xi^\dagger\right)\Psi_R + \text{h.c.}$$
$$\mathcal{L}_{Y_H}^{(b)} = -\kappa_l f\left(\overline{\Psi}_2\xi + \overline{\Psi}_1\Sigma_0\Omega\xi^\dagger\Omega\right)\Psi_R + \text{h.c.}$$

Contributions proportional to κ_l ?

a) T-even



$$\delta\mu^2 = \frac{1}{8\pi^2}\kappa_l^2\left[M_\chi^2 - \left(\sqrt{2}\kappa_l f\right)^2\right]\log\Lambda^2$$

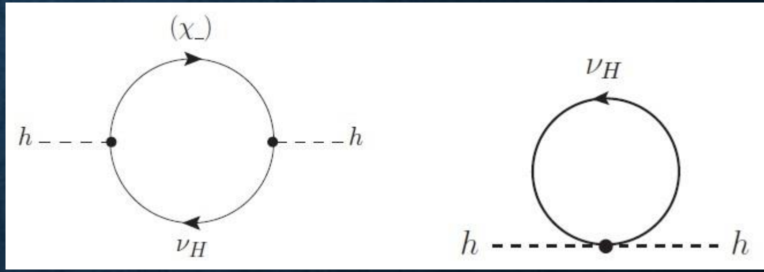
$$\delta\mu^2 = 0 \iff M_\chi = \sqrt{2}\kappa_l f$$

No quadratic divergences if $(\chi_\pm)_R$ lives in Ψ_R.

$(\chi_\pm)_R$ not optional.

T-even case independent of κ_l

b) T-odd



$$\delta\mu^2 = \frac{1}{8\pi^2}\kappa_l^2 M_\chi^2\log\Lambda^2 \neq 0$$

D. Top sector in the LHT

- Top quark sector → CSB → top partners

❑ Fields

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

❑ Transformation properties

$$Q_1^t \xrightarrow{G} V^* Q_1^t, \quad Q_2^t \xrightarrow{G} V Q_2^t, \quad Q_1^t \xrightarrow{T} \Omega\Sigma_0 Q_2^t, \quad T_{1R} \xrightarrow{T} T_{2R}$$

T-even:

$$\mathcal{T}_L = \frac{\mathcal{T}_{1L}-\mathcal{T}_{2L}}{\sqrt{2}} = (t_L, b_L)^T, \quad t_R$$

$$(T_+)_{L,R} = \frac{(T_1)_{L,R}+(T_2)_{L,R}}{\sqrt{2}}$$

T-odd:

$$\mathcal{T}_{HL} = \frac{\mathcal{T}_{1L}+\mathcal{T}_{2L}}{\sqrt{2}} = (t_{HL}, b_{HL})^T$$

$$(T_-)_{L,R} = \frac{(T_1)_{L,R}-(T_2)_{L,R}}{\sqrt{2}}$$

❑ Yukawa Lagrangian

SU(3) invariant: no Higgs mass contribution

$$\mathcal{L}_{Y_t} = -i\frac{\lambda_1}{4} f \epsilon_{ijk}\epsilon_{xy}\left[\left(\overline{Q_1^t}\right)_i \Sigma_{jx}\Sigma_{ky} + \left(\overline{Q_2^t}\Sigma_0\Omega\right)_i \widetilde{\Sigma}_{jx}\widetilde{\Sigma}_{ky}\right] t_R - \frac{\lambda_2 f}{\sqrt{2}}\left(\overline{T}_{1L} T_{1R} + \overline{T}_{2L} T_{2R}\right) + \text{h.c.}$$

non SU(3) invariant but no Higgs couplings

E. Higgs mass dependence on T_κ in NLHT

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- $\mathcal{L}_{Y_H}$ SU(5) invariant $\longrightarrow$ no κ contribution to m_h

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

- $\mathcal{L}_{\widehat{Y}_H}$ no Higgs couplings $\longrightarrow$ no $\widehat{\kappa}$ contribution to m_h

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

Sectors communicate through Ψ_1, Ψ_2 $\longrightarrow$ CSB $\longrightarrow$ $m_h^2 \sim \kappa^2 \widehat{\kappa}^2 \log \Lambda^2$

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- Fermion masses and mixings (new features)

❑ Charged leptons (similar for down-type quarks):

Field	Mass
$\ell_L \to V_L^{\ell}\ell_L,\quad \ell_R \to V_R^{\ell}\ell_R$	$\frac{\lambda_l v}{\sqrt{2}} = V_L^{\ell} m_\ell V_R^{\ell\dagger}$
$\ell_{HL} \to V_L^{l_H}\ell_{HL},\quad \ell_{HR} \to V_R^{l_H}\ell_{HR}$	$\sqrt{2}\kappa_l f = V_L^{l_H} m_{\ell_H} V_R^{l_H\dagger}$
$(\tilde{\ell}^c_-)_L \to V_L^{l_H}(\tilde{\ell}^c_-)_L,\quad (\tilde{\ell}^c_-)_R \to V_R^{l_H}(\tilde{\ell}^c_-)_R$	$\sqrt{2}\kappa_l f = V_L^{l_H} m_{\ell_H} V_R^{l_H\dagger}$
$(\tilde{\ell}^c_+)_L \to V_L^{\tilde{l}^c_+}(\tilde{\ell}^c_+)_L,\quad (\tilde{\ell}^c_+)_R \to V_R^{\tilde{l}^c_+}(\tilde{\ell}^c_+)_R$	$\sqrt{2}\hat{\kappa}_l f = V_L^{\tilde{l}^c_+} m_{\tilde{l}^c_+} V_R^{\tilde{l}^c_+\dagger}$

❑ Neutral leptons at LO (similar for up-type quarks)

Field	Mass
$\nu_L \to V_L^{\ell}\ell_L$	0
$\nu_{HL} \to V_L^{l_H}\nu_{HL},\quad \nu_{HR} \to V_R^{l_H}\nu_{HR}$	$\sqrt{2}\kappa_l f = V_L^{l_H} m_{\ell_H} V_R^{l_H\dagger}$
$(\tilde{\nu}^c_-)_L \to V_L^{l_H}(\tilde{\nu}^c_-)_L,\quad (\tilde{\nu}^c_-)_R \to V_R^{l_H}(\tilde{\nu}^c_-)_R$	$\sqrt{2}\kappa_l f = V_L^{l_H} m_{\ell_H} V_R^{l_H\dagger}$
$(\chi_+)_L \to V_L^{l_H}(\chi_+)_L,\quad (\chi_+)_R \to V_R^{l_H}(\chi_+)_R$	$\sqrt{2}\kappa_l f = V_L^{l_H} m_{\ell_H} V_R^{l_H\dagger}$
$(\chi_-)_L \to V_L^{\tilde{l}^c_+}(\chi_-)_L,\quad (\chi_-)_R \to V_R^{\tilde{l}^c_+}(\chi_-)_R$	$\sqrt{2}\hat{\kappa}_l f = V_L^{\tilde{l}^c_+} m_{\tilde{l}^c_+} V_R^{\tilde{l}^c_+\dagger}$
$(\tilde{\nu}^c_+)_L \to V_L^{\tilde{l}^c_+}(\tilde{\ell}^c_+)_L,\quad (\tilde{\nu}^c_+)_R \to V_R^{\tilde{l}^c_+}(\tilde{\nu}^c_+)_R$	$\sqrt{2}\hat{\kappa}_l f = V_L^{\tilde{l}^c_+} m_{\tilde{l}^c_+} V_R^{\tilde{l}^c_+\dagger}$

❑ Misalignment matrices

Between κ_l and λ_l: usual one

$$V = V_L^{l_H\dagger} V_L^{\ell}$$

Between κ_l and $\hat{\kappa}_l$: new one

$$\hat{W} = V_L^{\tilde{l}^c_+\dagger} V_L^{l_H}$$

Old ones:

$$W = \tilde{V}_L^{\dagger} V_L^{l_H} = \mathbb{1}$$

$$Z = V_R^{\chi\dagger} V_R^{l_H} = \mathbb{1}$$