Technically Natural Higgs Boson from Planck Scale

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Based on M. Rosenlyst,
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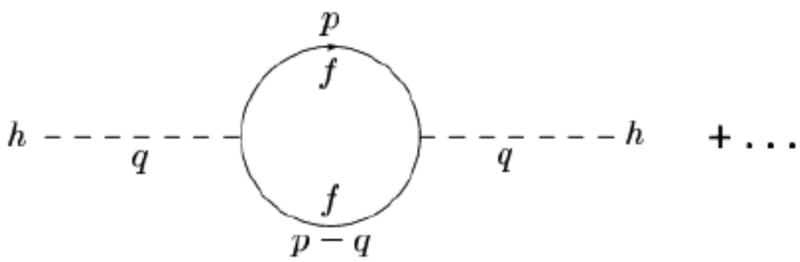
The Electroweak (EW) Hierarchy Problem

- Loop corrections to the Higgs mass:

$$m_h^2 = m_{h0}^2 + \delta m_{h0}^2 = m_{h0}^2 + 2.57 \cdot 10^{-2} \Lambda^2 + \ldots,$$

  - m_h : The physical mass of the Higgs boson
  - m_{h0} : The bare mass of the Higgs boson
  - Λ : The cut-off scale above new physics happens



- Fine-tuning of the bare mass of the Higgs boson for e.g. Λ equals Planck scale:

$$m_{h0}^2 = m_h^2 - k\Lambda_{\text{Planck}}^2 + \ldots$$
$$\approx (125\ \text{GeV})^2 - (2 \cdot 10^{18}\ \text{GeV})^2.$$

The Composite Higgs Framework

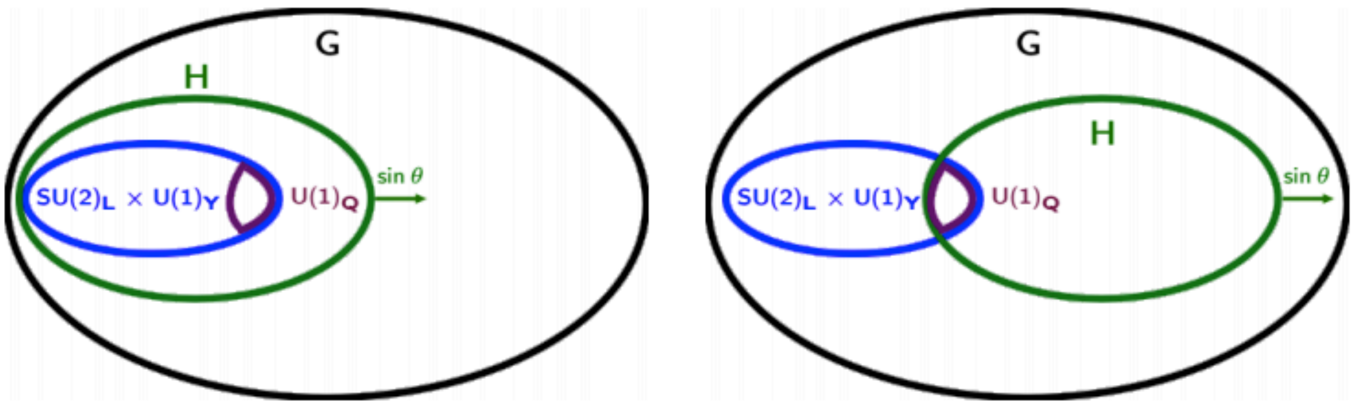
- New strong hypercolor (HC) interactions: (E. Farhi and L. Susskind (1981))

$$G_{HC} \times SU(3)_C \times SU(2)_L \times U(1)_Y$$

- The SM Higgs is replaced by a composite Higgs, consisting of new strongly interacting fermions (hyper-fermions)

- Chiral symmetry breaking: $G \to H$

EW unbroken vacuum Σ_{CH} $(\sin\theta = 0)$ Technicolor vacuum Σ_{TC} $(\sin\theta = 1)$



Composite Higgs vacuum: $\Sigma_0 = \cos\theta\Sigma_{CH} + \sin\theta\Sigma_{TC}$

- Generating dynamically the EWSB, and therefore EW gauge boson masses and a natural light pNGB Higgs.

Fermion Mass Generation Approaches

- i) Extended Technicolor (ETC): $f\,f\,\Psi\,\Psi$
  (S. Dimopoulos and L. Susskind (1979))
- ii) Partial Compositeness (PC): $f\,\Psi\,\Psi\,\Psi$
  (D. B. Kaplan (1991))
- iii) Fundamental Partial Compositeness (FPC): $f\,\Psi\,S$
  (F. Sannino et al. (2016))
- iv) Partially Composite Higgs (PCH): $\Psi\Psi H$ and $\overline{f}\,f\,H$
  (J. Galloway et al. (2017) and A. Agugliaro et al. (2017))

f : SM fermions

Ψ : New strongly interacting fermions

S : HC-charged scalars

H : Elementary Higgs doublet

New Problems

- i) Extended Technicolor (ETC): $f\,f\,\Psi\,\Psi$

$$m_f \sim \left(\frac{\Lambda_{\rm HC}}{\Lambda_f}\right)^2 v_{\rm EW}$$

Dangerous flavour changing neutral currents (FCNCs)

- ii) Partial Compositeness (PC): $f\,\Psi\,\Psi\,\Psi$

$$m_f(\Lambda_f) \simeq m_f(\Lambda_{\rm HC}) \left(\frac{\Lambda_f}{\Lambda_{\rm HC}}\right)^{-\gamma_m}$$

Complicated UV Complete theories

- iii) Fundamental Partial Compositeness (FPC): $f\,\Psi\,S$

$$m_f \sim \left(\frac{\Lambda_{\rm HC}}{M_{S_f}}\right)^2 v_{\rm EW}$$

Reintroduction of hierarchy problem

New Problems

- iv) Partially Composite Higgs (PCH):
  - The neutral states of the Higgs doublets:

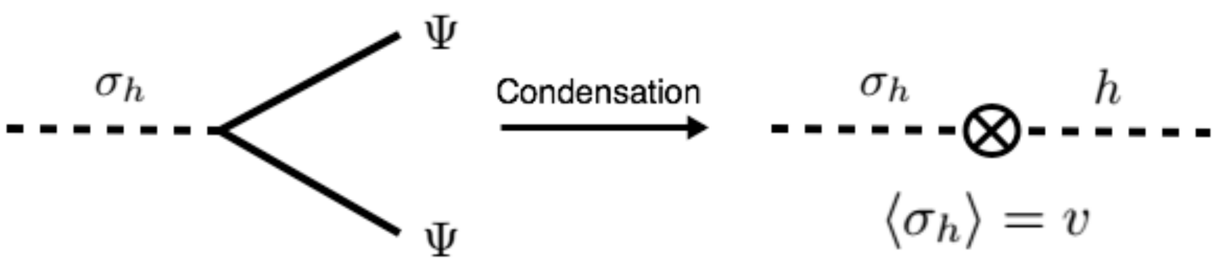
    σ_h : Elementary Higgs
    h : Composite Higgs

  - The composite h achieves a VEV from the composite dynamics:

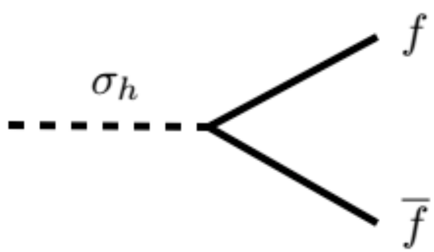
$$\langle h \rangle = f \sin\theta$$

f : The pNGB decay constant
θ : The vacuum misalignment angle

  - This VEV can be transferred to the elementary Higgs via the Yukawas:



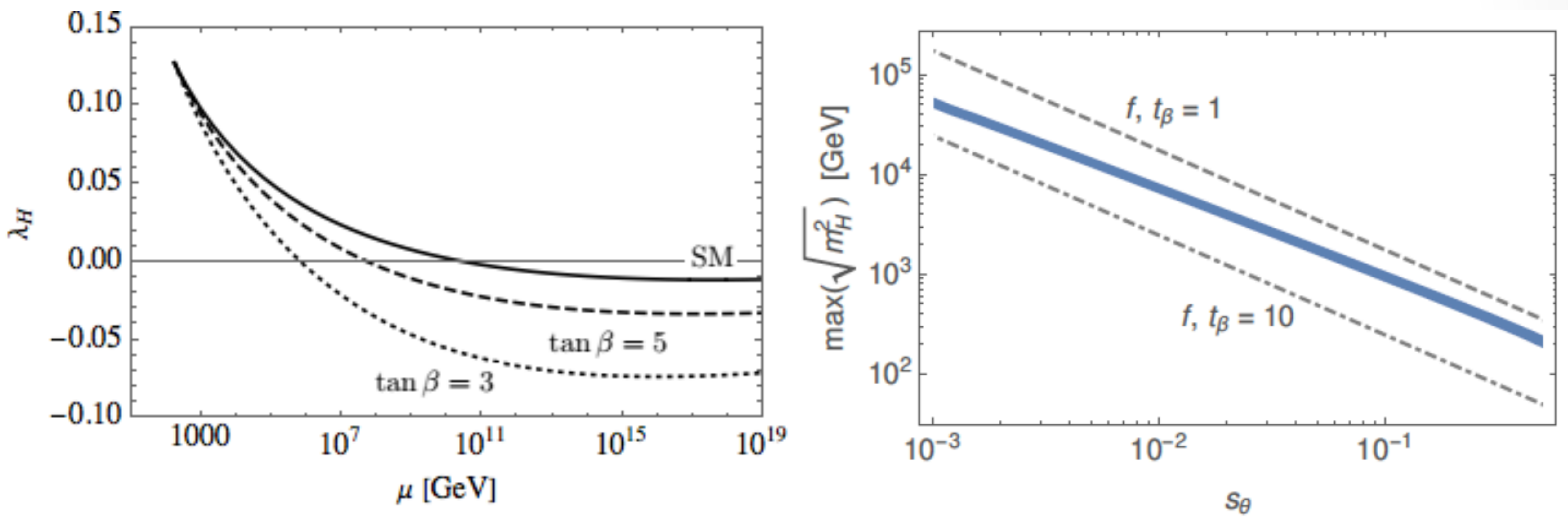
  - Via Yukawas, SM fermions obtain their masses:



New Problems

- PROBLEM: The stability of the Higgs vacuum:

$$y_t = y_t^{\rm SM} / \sin\beta \qquad \tan\beta = \frac{v}{f\sin\theta}$$



(M. Rosenlyst et al. JHEP 01 (2018) 051)

- For alleviating the EW hierarchy problem, we need a large mass parameter m_H, but this requires unnatural small $\sin\theta$.

The Novel Mechanism

- A large compositeness scale alleviates the problems from the various fermion mass generation approaches!

$$\Lambda_{\rm HC} \sim \frac{4\pi v_{\rm EW}}{\sin\theta} \sim m_{\rm Planck}$$

- Large compositeness scale ==> small $\sin\theta \sim 3\times 10^{-16}$
  ==> unnatural cancellation between the Higgs potential contributions

- A small $\sin\theta$ can be technically natural in models based on vacuum misalignment with an associated global $\mathbb{Z}_2$ symmetry.

- We need a minimum of one $\mathbb{Z}_2$ -odd Higgs doublet.

- A small vacuum misalignment, $\theta \ll 1$, is achieved in the direction of the neutral CP-even component of this doublet.

- According to 't Hooft's naturalness principle, $\theta \ll 1$ is technically natural due to the restoration of the global $\mathbb{Z}_2$ symmetry when $\theta = 0$.
  (G. 't Hooft (1980))

A Concrete Model Example

- This mechanism may be realized in
  - Composite Higgs (CH)
  - Partially Composite Higgs (PCH)
  - Little Higgs
  - Holographic extra dimensions
  - Twin Higgs
  - Elementary Goldstone Higgs

- We consider this mechanism in the PCH models.

- We note following minimal cosets with a Higgs candidate and custodial symmetry:
  - SU(4)/Sp(4), SU(5)/SO(5), SU(6)/Sp(6), SU(6)/SO(6) and $SU(4)^2/SU(4)$

- A $\mathbb{Z}_2$ symmetry is present in the three latter cases.

- For concreteness, we consider the minimal coset SU(6)/Sp(6), predicting one composite $\mathbb{Z}_2$ -odd Higgs doublet.

A Concrete Model Example

- Adding six Weyl fermions:

$$\Psi \equiv (\psi^1, \psi^2, \psi^3, \psi^4, \psi^5, \psi^6)^T$$

- A conserved $\mathbb{Z}_2$ symmetry for $\theta = 0$:

$$P = \mathrm{Diag}(1\,,1\,,1\,,1\,,-1\,,-1)$$

	G_{HC}	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$\mathbb{Z}_2$
$\Psi_1 \equiv (\psi_1, \psi_2)^T$	$\square$	$\mathbf{1}$	$\square$	0	+1
ψ_3	$\square$	$\mathbf{1}$	$\mathbf{1}$	−1/2	+1
ψ_4	$\square$	$\mathbf{1}$	$\mathbf{1}$	+1/2	+1
$\Psi_2 \equiv (\psi_5, \psi_6)^T$	$\square$	$\mathbf{1}$	$\square$	0	−1
H	$\mathbf{1}$	$\mathbf{1}$	$\square$	+1/2	−1

- Assuming that the elementary Higgs doublet, H, transforms $\mathbb{Z}_2$ -odd.

- The UV complete Lagrangian:

$$\begin{aligned}\mathcal{L}_{\rm PCH} =& \Psi^\dagger i\gamma^\mu D_\mu \Psi + D_\mu H^\dagger D^\mu H \\ & - m_H^2 H^\dagger H - \lambda_H (H^\dagger H)^2 - \left(\frac{1}{2}\Psi^T M \Psi \right. \\ & \left. + y_U H_\alpha (\Psi^T P^\alpha \Psi) + y_D \widetilde{H}_\alpha (\Psi^T \widetilde{P}^\alpha \Psi) + \text{h.c.}\right)\end{aligned}$$

$$\begin{aligned}\mathcal{L}_{\rm Y} = &- y_t^{ij} \bar{q}_{L,i} H u_{R,j} - y_b^{ij} \bar{q}_{L,i} \widetilde{H} d_{R,j} \\ &- y_e^{ij} \bar{l}_{L,i} \widetilde{H} e_{R,j} + \text{h.c.}\,.\end{aligned}$$

- Explicit masses of hyper-fermions: $M = \begin{pmatrix} m_1 i\sigma_2 & 0 & 0 \\ 0 & m_2 i\sigma_2 & 0 \\ 0 & 0 & -m_3 i\sigma_2 \end{pmatrix}$

A Concrete Model Example

- Upon condensation: $\mathrm{SU}(6) \to \mathrm{Sp}(6)$

$$\Sigma(x) = \exp\left[\frac{2\sqrt{2}i}{f}\pi_a(x)X_a\right]E_{\rm CH}$$

$$E_{\rm CH} = \begin{pmatrix} +i\sigma_2 & 0 & 0 \\ 0 & -i\sigma_2 c_\theta & -\mathbb{1}_2 s_\theta \\ 0 & +\mathbb{1}_2 s_\theta & +i\sigma_2 c_\theta \end{pmatrix}$$

G_0/H_0	$\mathbb{Z}_2$–odd pNGBs	$\mathbb{Z}_2$–even pNGBs
$\Phi_{\rm even} = (2, 1/2)_+$ $\eta' = (1, 0)_+$	$\Phi_{\rm odd} = (2, 1/2)_-$ $\Delta = (3, 0)_-$ $\varphi^0 = (1, 0)_-$	$\eta = (1, 0)_+$

- The effective Higgs potential:

$$V^0_{\rm eff} = m_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 - 4\pi f^3 Z\left(\frac{1}{2}{\rm Tr}[M\Sigma] - y_U H_\alpha {\rm Tr}[P^\alpha\Sigma] - y_D \widetilde{H}_\alpha {\rm Tr}[\widetilde{P}^\alpha \Sigma] + {\rm h.c.}\right)$$

$$V^{\rm 1-loop}_{\rm gauge} = C_g f^4 \left(\sum_{i=1}^{3} g_L^2 {\rm Tr}[T_L^i \Sigma T_L^{iT} \Sigma^\dagger] + g_Y^2 {\rm Tr}[T_R^3 \Sigma T_R^{3T}\Sigma^\dagger]\right)$$

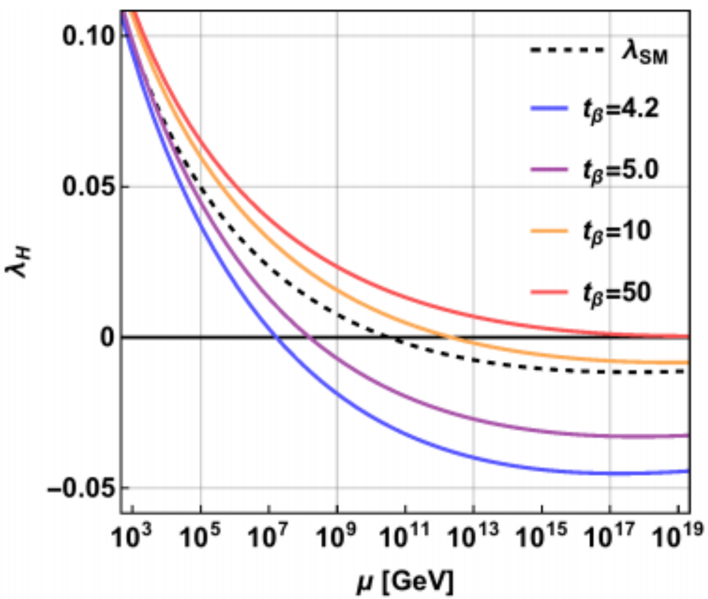
- Minimizing the potential: $m_2 + m_3 = -\dfrac{c_\theta m_\lambda^2 t_\beta^2}{8\pi Z f}$, $\quad y_U + y_D = \dfrac{t_\beta m_\lambda^2}{4\sqrt{2}\pi Z f^2}$

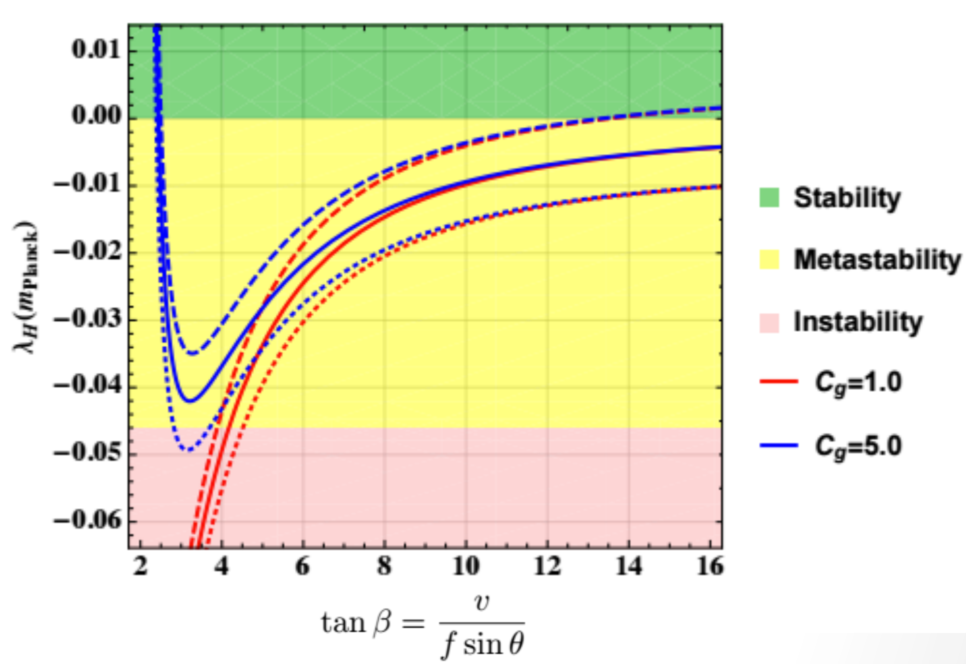
$$m_\lambda^2 \equiv m_H^2 + \lambda_H v^2$$

Vacuum Stability Analysis

- Numerical calculations of the RG running of the quartic coupling λ_H for

$$\Lambda_{\rm HC} \sim 4\pi f = m_{\rm Planck} \qquad m_H = f \approx 1 \times 10^{18}\ \text{GeV}$$

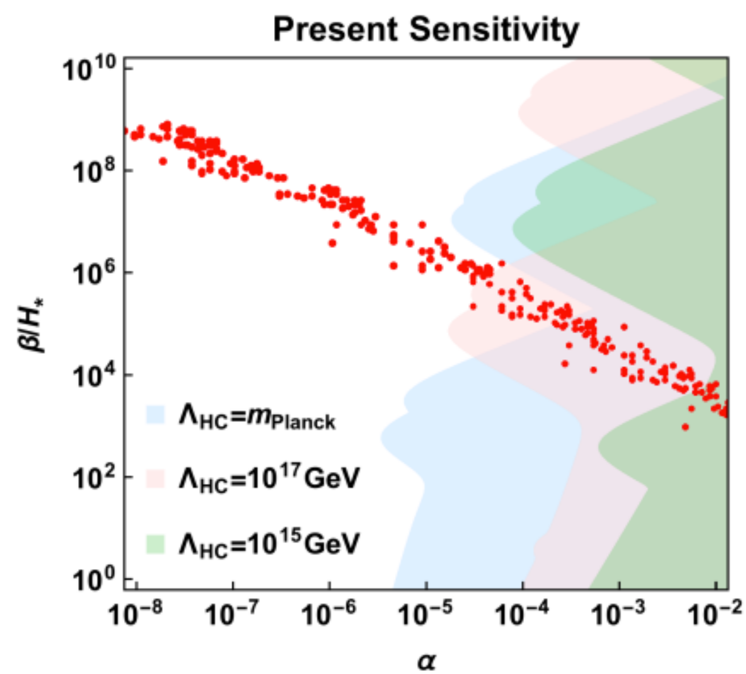


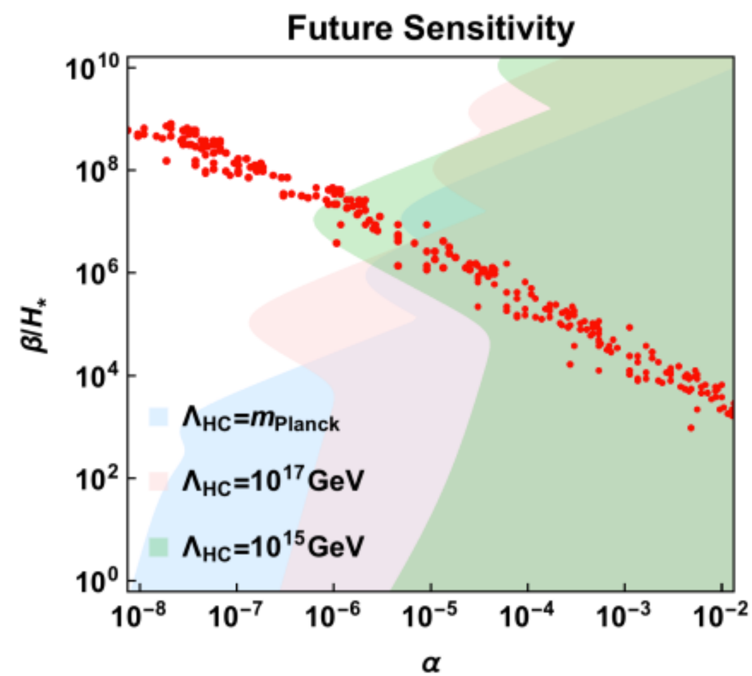


- For large enough $\tan\beta$, the Higgs vacuum is metastable or even stable.

Constraints from Gravitational Waves

- A analysis of gravitational waves (GWs) leading to successful strong first-order EW phase transitions (red points)
- The present and future exclusions in the parameter space of α and β/H^* are depicted for various $\Lambda_{\rm HC} \sim 4\pi f$.
- Set by GW experiments with ultra-high-frequency GWs from graviton to photon conversion (A. Ejlli et al. (2019))



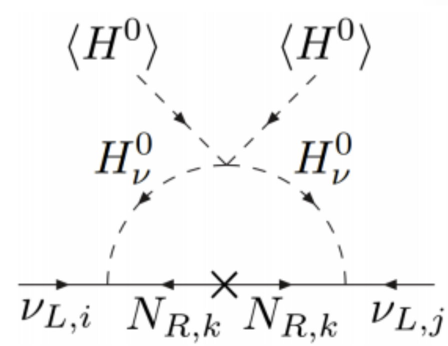


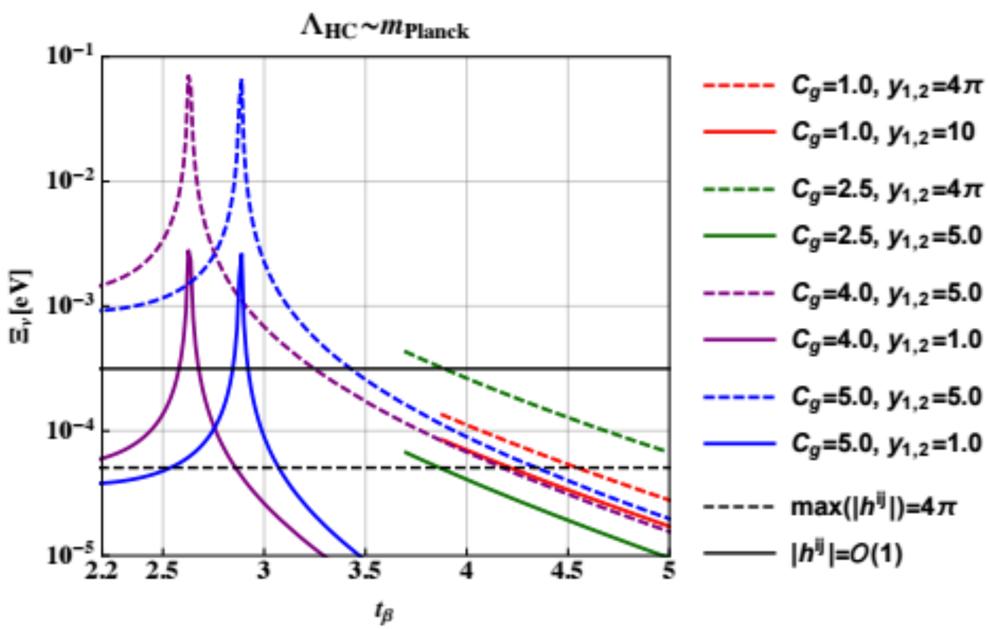
Loop-Induced Neutrino Masses

- The neutrino masses may be naturally generated via loops of a second Higgs doublet, transforming even under the $\mathbb{Z}_2$ symmetry:

$$H_\nu = \frac{1}{\sqrt{2}}\begin{pmatrix} \sigma_R - i\sigma_I \\ -(\pi_\nu^2 + i\pi_\nu^1) \end{pmatrix} \qquad \mathcal{L}_Y \supset -h^{ij}\bar{l}_{L,i} H_\nu N_{R,j} + \text{h.c.}$$

$$m_\nu^{ij} = \sum_{k=1}^{3} \frac{h^{ik}h^{jk}}{(4\pi)^2} M_k \left[\frac{m_R^2}{m_R^2 - M_k^2} \ln\left(\frac{m_R^2}{M_k^2}\right) - \frac{m_I^2}{m_I^2 - M_k^2} \ln\left(\frac{m_I^2}{M_k^2}\right) \right]$$
$$\equiv \sum_{k=1}^{3} h^{ik}h^{jk}\Xi_{\nu,k} \, ,$$





$$h^{ij} = \begin{pmatrix} 1.19 & 1.71 & 0.32 \\ 0 & 3.65 & 4.36 \\ 0 & 0 & 4.82 \end{pmatrix}$$

Close to the Planck Scale

- All the dimensionful fundamental parameters are approximately $\mathcal{O}(10^{18})$ GeV :
  - The compositeness scale: $\Lambda_{\rm HC} \sim 4\pi f = m_{\rm Planck}$
  - The pNGB decay constant: $f \approx 1 \times 10^{18}$ GeV
  - The explicit masses of the hyper-fermions: $6m_1 = 3m_{2,3} = f$
  - The right-handed neutrino masses: $M_{1,2,3} = f$
  - The mass parameters of the elementary Higgs doublets (H and H_ν): $m_H = m_{H_\nu} = f$

Summary

I have presented:

- A concrete UV complete Partially Composite Higgs model with compositeness scale up to the Planck scale assisted by a novel mechanism
- This mechanism is based on softly breaking a global $\mathbb{Z}_2$ symmetry by technically natural small vacuum misalignment ($\theta \ll 1$)
- Dynamically triggering the electroweak symmetry breaking and the SM fermion mass generation
- All the dimensionful fundamental parameters are $\sim \mathcal{O}(10^{18})$ GeV
- The vacuum stability has been investigated
- The parameter space can already be searched by gravitational waves from a confinement-induced phase transition
- The mass and mixing of the neutrinos may be naturally generated via loops of a second $\mathbb{Z}_2$ -even Higgs doublet

Future Work

- By extending the elementary scalar content to a two-index antisymmetric SU(6) scalar multiplet, the explicit masses of the fermions may be generated, like in

  T. Alanne et al. Phys. Rev. D 96, 095012 (2017)

- The Higgs doublet candidate is a mixture between an elementary and composite Higgs, where the lightest mass eigenstate is identified with the 125 GeV Higgs while the heavier has a mass of $\mathcal{O}(10^{18})$ GeV . Maybe interesting for

  - Inflation
  - Dark energy (quintessence)
  - Scale invariant UV theory
  - Gravity theories
  - Axion physics

- There are general expectations that all global symmetries are explicitly broken by gravitational effects. The studies of such violations in this model are left for future work.

  R. Kallosh et al. Phys. Rev. D 52, 912 (1995)