Heavy axions emerging from composite Higgs models

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Outline

Introduction

The strong CP problem

$$\mathcal{L}_{QCD} \supset \theta \frac{g_s}{32\pi^2} G\tilde{G} \qquad |\theta| \leq 10^{-10}$$

$$\underbrace{\text{why is } \theta \text{ so small?}}_{\downarrow}$$

Peccei, Quinn, Wilczek, Weinberg ('70s)
promote θ to a dynamical field
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The hierarchy problem

$$\mathcal{L}_H \supset m_H^2 |H|^2 \qquad \Delta m_H^2 \approx \Lambda_{NP}^2$$

$$\underbrace{\text{Why is } m_H^2 \ll \Lambda_{NP}^2}$$

$\downarrow$

Composite Higgs Models
The Higgs is a pseudo-Nambu-Goldstone-Boson
(pNGB) and its mass is protected by symmetry

What and why?

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- Tackle multiple problems simultaneously: strong CP problem, hierarchy problem
- Good learning opportunity for me

Model Setup

Gauge group and breaking pattern

$$\mathcal{G}_{HC} \times SU(2N_{GC}+3) \times SU(2)_L \times U(1)_{Y'}$$

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$$f_{GC} \downarrow \langle \Phi \rangle , \langle \Xi \rangle$$
$$\mathcal{G}_{HC} \times Sp(2N_{GC}) \times \quad SU(3)_C \quad \times SU(2)_L \times U(1)_Y$$

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$$f_{GC} \downarrow \langle \Phi \rangle , \langle \Xi \rangle$$

$$\underbrace{\mathcal{G}_{HC}}_{\substack{\chi \quad \omega \\ G_F}} \times \underbrace{Sp(2N_{GC})}_{\substack{\psi \\ SU(12)}} \times \underbrace{SU(3)_C}_{\substack{q \\ SU(3)_L \times SU(3)_R}} \times SU(2)_L \times U(1)_Y$$

The hypercolor gauge group

Constraints

Requirements	Constraints
○ $G_F/H_F \supset$ Higgs, axion	$\rightarrow$ $SU(4)/Sp(4)$ composite Higgs model

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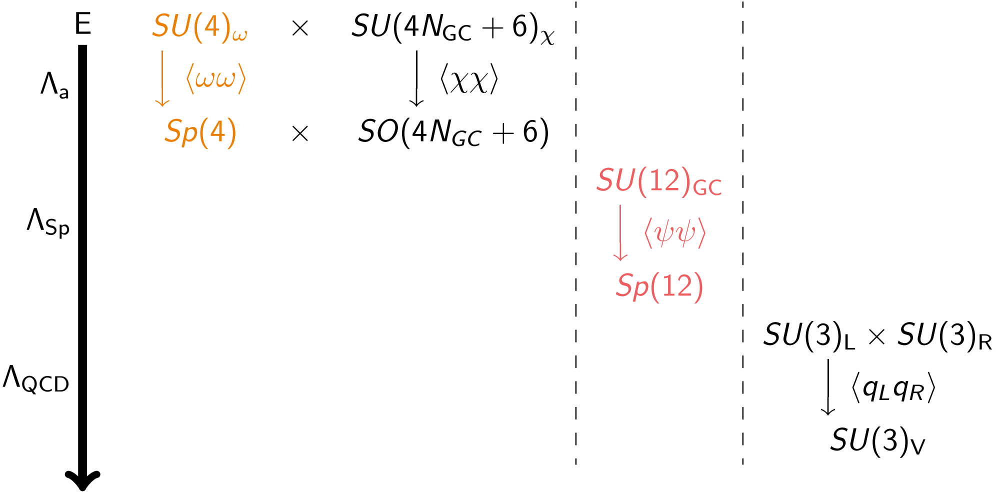
$$SO(11)_{\mathrm{HC}}, SO(13)_{\mathrm{HC}}$$
$$3 \leq N_{\mathrm{GC}} \leq 6$$

The different global symmetries



The meson resonances

	$SU(4)$	$Sp(4)$	names
$\langle\omega\omega\rangle$	$\mathbf{6}$	$\mathbf{1}$	σ_ω
		$\mathbf{5}$	π_ω
	$SU(4N_{GC}+6)$	$SO(4N_{GC}+6)$	names
$\langle\chi\chi\rangle$	$\supset \mathbf{1}$	$\mathbf{1}$	σ_χ
	$SU(12)$	$Sp(12)$	names
$\psi\psi$	$\mathbf{66}$	$\mathbf{1}$	σ_ψ
		$\mathbf{65}$	π_ψ

$$Sp(4) \supset SU(2)_L \times SU(2)_R$$

$$\pi_\omega \to \underbrace{(\mathbf{2},\mathbf{2})}_{\tilde{h}} \oplus \underbrace{(\mathbf{1},\mathbf{1})}_{\eta}$$

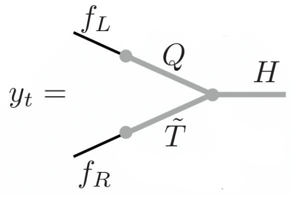
Additional Higgs-like pions contained in π_ψ.

Addition singlets like $\sigma_\chi, \sigma_\omega$.

Partial Compositeness

Linear couplings between SM and HC fermions

$$\mathcal{L}_{int} \sim q\mathcal{O}_{lin}, \quad \mathcal{O}_{lin} = \left(\omega^T P_f\, \omega\, \chi\right)$$



We need to study the **baryonic** resonances

Baryon	$SU(4) \times SU(4N_{GC}+6)$
$\omega\omega\chi$	$(\mathbf{4} \times \mathbf{4}, \Box) \to (\mathbf{6} \oplus \mathbf{10}, \Box)$
$\overline{\omega\omega}\chi$	$(\bar{\mathbf{4}} \times \bar{\mathbf{4}}, \Box) \to (\mathbf{6} \oplus \overline{\mathbf{10}}, \Box)$
$\overline{\omega}\omega\overline{\chi}$	$(\bar{\mathbf{4}} \times \mathbf{4}, \overline{\Box}) \to (\mathbf{1} \oplus \mathbf{15}, \overline{\Box})$

$\rightarrow$ **not enough partners for all three generations**

The chiral approach

- Dynamics of the Goldstone bosons: broken generators and Σ-matrix
- Explicit breaking sources: gauge fields and Yukawa interactions

  $\rightarrow$ we assign them transformation properties under the global symmetries

We systematically write a Lagrangian by putting all terms that respect the full symmetry of the model, for example

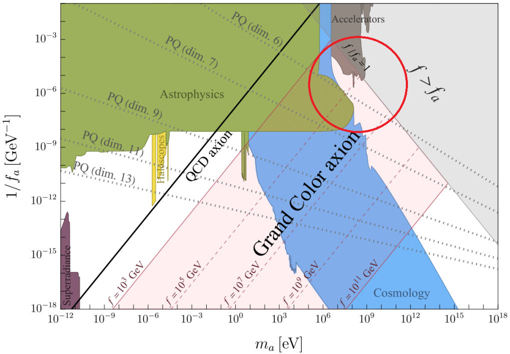
$$\mathcal{L}_{kin} = \frac{f_a^2}{8} \text{Tr}\left[(D_\mu \Sigma_{EW})^\dagger (D_\mu \Sigma_{EW}) \right] \qquad V_{gauge} = C_g g^2 f_a^4 \text{Tr}\left[S_g \Sigma S_g^T \Sigma^\dagger \right]$$

(Partial) conclusions

From symmetry reasons, the potential of η reads

$$\frac{c_{ud}}{N} f_{\mathrm{Sp}}^4 \,\mathrm{Tr}\left[Y_u \Sigma_L Y_d^T \Sigma_R\right] + h.c.$$

$$m_\eta^2 \approx 2\frac{c_{ud}}{N} y_u y_d \frac{f_{\mathrm{Sp}}^4}{f_a^2}$$



[Valenti et al. 2206.04077]

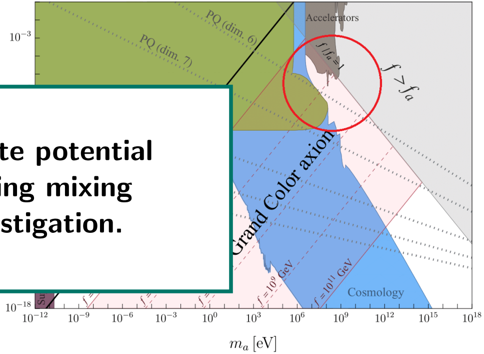
(Partial) conclusions

From symmetry reasons, the potential of η reads

$$\frac{c_{ud}}{N} f_{\mathrm{Sp}}^4 \,\mathrm{Tr}\left[Y_u \Sigma \right.$$

$$m_\eta^2 \approx 2\frac{c_u}{N}$$

Study of the complete potential and masses, including mixing effects, under investigation.



[Valenti et al. 2206.04077]

Internship

Topic

3-month internship before the start of the master's thesis to get acquainted with EFT and in particular HEFT in the context of singlet scalar extension, 2HDM and MCHM

Purpose

Collaboration with a research group of CMS:

- Identify theoretical limits on the Wilson's coefficients
- Understand an apparent mismatch between different EFT parametrization for 2HDM

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  - hierarchy problem

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- A lot can be learned from both the fundamental approach and the EFT one

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  - strong CP problem
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Thanks for the attention!

Main references

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The field content

	$SO(N_{HC})$	$Sp(2N_{GC})$	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
$Q_L = \begin{pmatrix} q_L \\ \psi_q \end{pmatrix}$	$\mathbf{1}$	$\mathbf{1}$	$\square$	$\mathbf{2}$	$\frac{1}{6}$
	$\mathbf{1}$	$\square$	$\mathbf{1}$	$\mathbf{2}$	0
$U_R = \begin{pmatrix} u_R \\ \psi_u \end{pmatrix}$	$\mathbf{1}$	$\mathbf{1}$	$\square$	$\mathbf{1}$	$-\frac{2}{3}$
	$\mathbf{1}$	$\square$	$\mathbf{1}$	$\mathbf{1}$	$-\frac{1}{2}$
$D_R = \begin{pmatrix} d_R \\ \psi_d \end{pmatrix}$	$\mathbf{1}$	$\mathbf{1}$	$\square$	$\mathbf{1}$	$\frac{1}{3}$
	$\mathbf{1}$	$\square$	$\mathbf{1}$	$\mathbf{1}$	$\frac{1}{2}$

The HC gauge group

$$\beta^0_{HC} = \frac{11}{3} C_2(\mathbf{Ad}) - \frac{2}{3} \sum_i N_{R_i} T(R_i)$$

$$\beta^1_{HC} = \frac{34}{3} C_2^2(\mathbf{Ad}) - \frac{10}{3} C_2(\mathbf{Ad}) \sum_i N_{R_i} T(R_i) - 2 \sum_i C_2(R_i) N_{R_i} T(R_i)$$

$$\alpha_c = \frac{\pi}{3 \max_i [C_2(R_i)]} \qquad \alpha^* = -4\pi \frac{\beta_0}{\beta_1}$$

$$\underbrace{\beta_0 > 0 \qquad \alpha^* > \alpha_c}$$

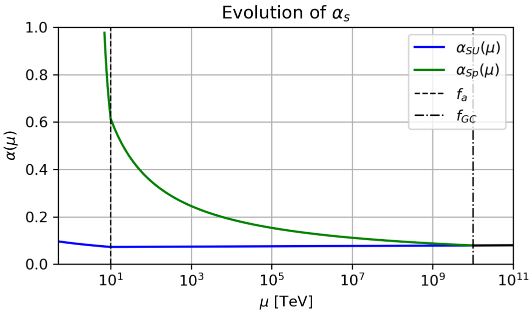
$$\downarrow$$

$$SO(11)_{HC} \to N_{GC} \leq 3$$

$$Sp(4)_{HC} \to N_{GC} \leq 2$$

The hypercolor gauge group

Asymptotic freedom



$m_a^2 f_a^2 = \Lambda_{\mathrm{QCD}}^4 + \Lambda_{\mathrm{Sp}}^4 \qquad \Lambda_{\mathrm{Sp}} \gg \Lambda_{\mathrm{QCD}}$

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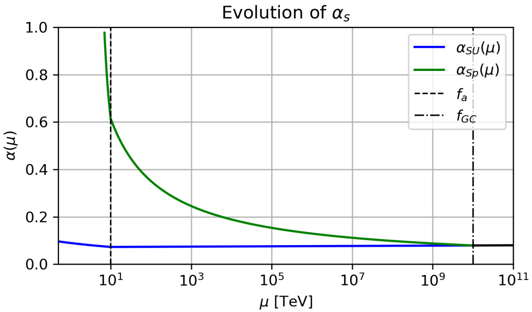

Including all constraints from before

$\downarrow$

$SO(11)_{\mathrm{HC}}, SO(13)_{\mathrm{HC}}$

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$\mathcal{G}_{HC}$	ω	χ	G_F/H_F
$Sp(2N_{HC})$	$4 \times \mathbf{F}$	$(4N_{GC}+6) \times \mathbf{A}_2$	$\dfrac{SU(4) \times SU(4N_{GC}+6) \times U(1)}{Sp(4) \times SO(4N_{GC}+6)}$
$SO(N_{HC})$	$4 \times \mathbf{Spin}$	$(4N_{GC}+6) \times \mathbf{F}$	

The chiral approach

Taking the EW coset as an example:

$$\Sigma_0 = \begin{pmatrix} i\sigma_2 & 0 \\ 0 & -i\sigma_2 \end{pmatrix}$$

$$\Sigma_{ew} = U\,[\Pi]\,\Sigma_0, \quad \Sigma \to g\Sigma g^T, \quad g \in SU(4).$$

$$U[\Pi] = exp\left\{\frac{2\sqrt{2}i}{f_a}\Pi\right\}, \quad \Pi = \sum_u \pi_i X_i$$

$$\mathcal{L}_{kin} = \frac{f_a^2}{8} Tr\left[(D_\mu \Sigma_{ew})^\dagger (D_\mu \Sigma_{ew})\right]$$

Kinetic term

$$\mathcal{L}_{kin} = \frac{1}{2}\left(\partial_\mu \tilde{h}\right)^2 + \frac{1}{2}\left(\partial_\mu \eta\right)^2 + \frac{1}{2}\frac{(\tilde{h}\partial_\mu \tilde{h} + \eta\partial_\mu\eta)^2}{1-\tilde{h}^2-\eta^2}$$

$$+ \frac{g_w^2}{4}\tilde{h}^2\left[W_\mu^+ W^{-\mu} + \frac{1}{2\cos\theta_W^2} Z_\mu Z^\mu\right]$$

Partial Compositeness

Due to the lack of enough top partners for all three generations, we are forced to choose a mixed scenario for the mass mechanism

$$\mathcal{L}_{mix}[\Lambda_{UV}] = \frac{\lambda_{Q_3}}{\Lambda_{UV}^{\gamma_{Q_3}}}\overline{Q}_3^{\alpha}\mathcal{O}_{Q_3}^{\alpha} + \frac{\lambda_{U_3}}{\Lambda_{UV}^{\gamma_{U_3}}}\overline{U}_3\mathcal{O}_{U_3} + \frac{\lambda_{D_3}}{\Lambda_{UV}^{\gamma_{D_3}}}\overline{D}_3\mathcal{O}_{D_3} + \\ + \sum_{i,j=1}^{3}\frac{\lambda_U^{ij}}{\Lambda_{UV}^{n}}\left(Q_i U_j^c\right)_{\alpha}^{\dagger}\mathcal{O}_{bil}^{U,\alpha} + \frac{\lambda_D^{ij}}{\Lambda_{UV}^{n}}\left(Q_i D_j^c\right)_{\alpha}^{\dagger}\mathcal{O}_{D,bil}^{\alpha} + h.c.$$

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$$\mathcal{L}_{yuk} = \sum_{i,j=1}^{3} Y_u^{ij} \left(q^i u^j + \psi_q^i \psi_u^j\right) \tilde{h} + \sum_{i,j=1}^{3} Y_d^{ij} \left(q^i d^j + \psi_q^i \psi_d^j\right) \tilde{h} + h.c.$$

Yukawa interaction

$$\mathcal{L}_{int}[\Lambda_{GC}] = \frac{\lambda_{q_L^3}}{\Lambda_{GC}^{\gamma_{q_3}}} \overline{q}^{3,\alpha} \mathcal{O}_q^\alpha + \frac{\lambda_{t_R}}{\Lambda_{GC}^{\gamma_t}} \overline{t}_R \mathcal{O}_{t_R} + \frac{\lambda_{b_R}}{\Lambda_{GC}^{\gamma_b}} \overline{b}_R \mathcal{O}_{b_R} + \frac{\lambda_{\psi_q^3}}{\Lambda_{GC}^{\gamma_{\psi_q}}} \overline{\psi_q^{3,\alpha}} \mathcal{O}_{\psi_q^3}^\alpha + \frac{\lambda_{\psi_u^3}}{\Lambda_{GC}^{\gamma_{\psi_u}}} \overline{\psi_u^3} \mathcal{O}_{\psi_u^3} + \frac{\lambda_{\psi_d^3}}{\Lambda_{GC}^{\gamma_{\psi_d}}} \overline{\psi_d^3} \mathcal{O}_{\psi_d^3}$$

$$\lambda_f\left(\Lambda_{HC}\right) \approx \lambda_f\left(\Lambda_{GC}\right)\left(\Lambda_{GC}/\Lambda_{HC}\right)^{\gamma_f}$$

pNGBs potential

EW coset $\langle\omega\omega\rangle$

- Gauge contribution

$$V_{gauge} = C_g g^2 f_a^4 \,\mathrm{Tr}\left[S_g \Sigma S_g^T \Sigma^\dagger\right]$$

- Top contribution

$$V_{top} = C_y \frac{\lambda_{t_L}\lambda_{t_R} f_a}{4\pi} \left(\overline{t_L} t_R\right) \mathrm{Tr}\left[P_Q^1 \Sigma^\dagger P_t \Sigma^\dagger\right]$$

- Other quarks

$$V_{quarks} = -C_q f_a^4 y^2 \sum_{\alpha=1}^{2} |\mathrm{Tr}\left[\Sigma P_\alpha^u\right]|^2$$

$\Longrightarrow$ $\tilde{h}$ gets a potential
η does not!

pNGBs potential

EW coset $\langle \omega\omega \rangle$

Gauge and top contribution

- Leading corrections for $\tilde{h}$
- $\tilde{h}$ develops a vev

Other quarks

- subleading contribution to the $\tilde{h}$ potential
- η could acquire a vev

pNGBs potential

GC coset $\langle\psi\psi\rangle$

Gauge contribution

- 51 pNGBs are charged

  $\rightarrow\ m_\Pi^2 \sim g^2 f_{Sp}^2$
- 14 pNGBs are neutral

Yukawa contribution

- Charged pNGBs

  $\rightarrow\ m_\Pi^2 \sim y_u^2 f_{Sp}^2$
- Neutral pNGBs

  $\rightarrow\ m_{\Pi_0}^2 \sim y_u y_d f_{Sp}^2$

Spurion analysis

$$V_{gauge} = C_g f_a^4 \left(\mathrm{Tr}\left[S_W^A \Sigma (S_W^A)^T \Sigma^\dagger \right] + \mathrm{Tr}\left[S_B \Sigma (S_B)^T \Sigma^\dagger \right] \right). \quad (1)$$

$$V_{top} = -\frac{C_{tS,1} f_a^4}{16\pi^2} \left(\lambda_{t_L}^4 \,\mathrm{Tr}\left[P_Q^\alpha \Sigma^\dagger P_Q^\beta \Sigma^\dagger \right] \mathrm{Tr}\left[\Sigma P_{Q\alpha}^\dagger \Sigma P_{Q\beta}^\dagger \right] + \lambda_{t_R}^4 \left[P_t \Sigma^\dagger P_t \Sigma^\dagger \right] \mathrm{Tr}\left[\Sigma P_t^\dagger \Sigma P_t^\dagger \right] + \lambda_{t_R}^2 \lambda_{t_L}^2 \,\mathrm{Tr}\left[P_Q^\alpha \Sigma^\dagger P_t \Sigma^\dagger \right] \mathrm{Tr}\left[\Sigma P_{Q\alpha}^\dagger \Sigma P_t \right] \right). \quad (2)$$

$$V_{quarks} = -C_q f_a^4 \left(y_u^2 \sum_{\alpha=1}^{2} |\mathrm{Tr}\left[\Sigma P_\alpha^u \right]|^2 + y_d^2 \sum_{\alpha=1}^{2} |\mathrm{Tr}\left[\Sigma P_\alpha^d \right]|^2 \right). \quad (3)$$

GC pion mixing

$$\mathcal{L}_{yuk} \supset y_u^{33} \underbrace{\psi_q^3 \psi_u^3}_{\Lambda_{Sp}^2 \Pi} \tilde{h} + h.c$$

$$V \supset \begin{pmatrix} \tilde{h} & \Pi \end{pmatrix} \begin{pmatrix} \mu_{\tilde{h}}^2 & y_u^{33} \Lambda_{Sp}^2 \\ y_u^{33} \Lambda_{Sp}^2 & m_\Pi^2 \end{pmatrix} \begin{pmatrix} \tilde{h} \\ \Pi \end{pmatrix}$$

We need to suppress the yukawas for the GC fermions, otherwise a big mixing between $\tilde{h}$ and Π occurs

$\rightarrow$ we assume a different anomalous dimension for the SM and GC top-partners

The axion mass

The mixing between the η and the neutral pions Π_0 can be described in term of a different symmetry breaking pattern contained in $SU(12)/Sp(12)$. The potential and the axion mass read

$$\frac{c_{ud}}{N} f^4 \,\mathrm{Tr}\left[Y_u \Sigma_L Y_d^T \Sigma_R\right] + h.c.$$

$$m_a^2 \approx 2\frac{c_{ud}}{N} y_u y_d \frac{f_{Sp}^4}{f_a^2}$$

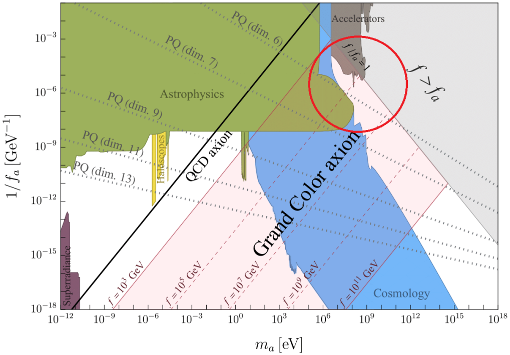

Figure: A.Valenti et al. [3]

Operators

$$\mathcal{L} \supset c_1 \Lambda_{Sp}^3 \,\mathrm{Tr}\left[\Sigma M + M^\dagger \Sigma^\dagger\right] + c_2 \Lambda_{Sp}^2 \,\mathrm{Tr}\left[\Sigma M\right] \mathrm{Tr}\left[M^\dagger \Sigma^\dagger\right] +$$
$$c_3 \Lambda_{Sp}^2 \left\{\mathrm{Tr}\left[\Sigma M\right]^2 + h.c\right\} + c_4 \Lambda_{Sp}^2 \left\{\mathrm{Tr}\left[\Sigma M \Sigma M\right] + h.c.\right\}.$$

Fermion masses

$$C_y \frac{\lambda_{t_L} \lambda_{t_R} f_a}{4\pi} \left(\overline{t_L} t_R\right) \mathrm{Tr}\left[P_Q^1 \Sigma^\dagger P_t \Sigma^\dagger\right] = \frac{C_y^t \lambda_{Q_3} \lambda_{U_3}}{4\pi} \left(\sqrt{1 - \frac{H^2 + \eta^2}{f_a^2}} + i \frac{\eta}{f_a}\right) \bar{t}_L t_R$$

$$C_y \frac{\lambda_{b_L} \lambda_{b_R} f_a}{4\pi} \left(\overline{b_L} b_R\right) \mathrm{Tr}\left[P_Q^2 \Sigma^\dagger P_b \Sigma^\dagger\right] = \frac{C_y^b \lambda_{Q_3} \lambda_{D_3}}{4\pi} \left(\sqrt{1 - \frac{H^2 + \eta^2}{f_a^2}} + i \frac{\eta}{f_a}\right) \bar{b}_L b_R$$

$$\mathcal{L}_{yuk} = \sum_{i,j=1}^{3} Y_u^{ij} \left(q^i u^j + \psi_q^i \psi_u^j\right) \tilde{h} + \sum_{i,j=1}^{3} Y_d^{ij} \left(q^i d^j + \psi_q^i \psi_d^j\right) \tilde{h} + h.c.$$

$$k_\lambda = 1 - \frac{3Z_6^2 v^2}{2\lambda_{SM} m_H^2}$$

$$k_t = 1 - \frac{Z_6 v^2}{tan(\beta) m_H^2}$$

$$Z_6 \approx -\frac{m_H^2 cos(\beta - \alpha)}{v^2} \approx \mathcal{O}(1) \qquad cos^2(\beta - \alpha) = \mathcal{O}\left(\frac{v^4}{m_s^4}\right)$$

$k_\lambda,\ k_t \to 1$ for $m_H^2 \gg v^2$.