Pseudoscalar pair production via off-shell Higgs in composite Higgs models

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Outline

1. Introduction and signal definition
2. Simulation setup and fake and matched photons
3. Analysis
4. Other production mechanisms
5. Conclusion

1 - Introduction and signal definition

- Technicolor (TC): 4D confining gauge theory G_{HC} with fermionic matter $\rightarrow$ dynamical EW symmetry breaking (hierarchy problem) Weinberg 76, Susskind 79

$$\langle\psi\psi\rangle \sim f^3 \rightarrow f = v$$

- Composite Higgs (CH): Vacuum misalignment, Higgs as a pseudo-Goldstone boson (pNGB) (Little-hierarchy problem and doublet nature of Higgs) Georgi, Kaplan 84

$$v = f \sin\theta$$

- Partial Compositeness (PC): top mass from mixing with composite top partner Kaplan 91 and large anomalous dimension from Walking dynamics Holdom 81
- Fundamental CH: all these ingredients in a 4D fermionic gauge theory Ferretti, Karateev 1312.5330.
  Example with 2 rep. of G_{HC}: EW ψ, and QCD-charged χ.

Let us think about a pessimist (but motivated) scenario for phenomenology...

Barnard, Gherghetta, Ray 13, Ferretti, Karateev 13, Ferretti 16

	Sp(4)	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	SU(4)	SU(6)
$\binom{\psi_1}{\psi_2}$	$\square$	**1**	**2**	0	**4**	**1**
$\psi_{3,4}$	$\square$	**1**	**1**	$\pm 1/2$		**1**
$\chi_{1,2,3}$	$\square$	**3**	**1**	X	**1**	**6**
$\chi_{4,5,6}$	$\square$	$\bar{\mathbf{3}}$	**1**	$-X$	**1**	

- $f \gtrsim 1.2\,\text{TeV}$, $\sin\theta \lesssim 0.2$.
- SM modified interaction $\mathcal{O}(\sin\theta)^*$ $\rightarrow$ hard precision Higgs and top physics.
- Color coset pNGBs from SU(6)/SO(6). $\pi_c = 8_0, 6_{-2X}, \bar{6}_{2X}$ of $SU(3)_c \times U(1)$ refs in Thomas' talk.
  $m^2_{\pi_c} \sim \mathcal{O}(g_s^2 f^2, m_\chi f) \gtrsim 2\,\text{TeV}$ (unknown m_χ, $g_s \gg g$)
- Non-pNGB resonances (top partner, vector,...) too heavy $m_{\rho,T,\ldots} \gtrsim 10\,\text{TeV}$
- Abelian pNGB (a), from anomaly-free U(1). Not much power beyond $f > 1\,\text{TeV}$ Cacciapaglia, Ferretti, Flacke, Serôdio 19

*Indirect EWPO $\sin\theta \lesssim 0.2$ (cancellations might relax DBF, Cacciapaglia, Deandrea 18). Direct Higgs measurement $\sin\theta \lesssim 0.4$.

The η state

Let us go on with our motivated pessimism...

- We are left with EW coset pNGBs from SU(4)/Sp(4), π. Only one extra pNGB besides the Higgs doublet: the singlet η.
- Coupling to SM gauge bosons dictated by WZW anomaly $\to$ very small and **photophobic!**
- Tree-level couplings to SM fermions vanish, due to an approximate Z_2 symmetry $\eta \to -\eta$
  - Embeddings $SU(4) \to SU(2)_L \times SU(2)_R$ ($\sim$ dominant top partner)
    $\mathbf{1} \to (\mathbf{1},\mathbf{1})$, $\mathbf{6} \to 2\times(\mathbf{1},\mathbf{1})+(\mathbf{2},\mathbf{2})$, $\mathbf{15} \to (\mathbf{1},\mathbf{1})+2\times(\mathbf{2},\mathbf{2})+(\mathbf{3},\mathbf{1})+(\mathbf{1},\mathbf{3})$

$$\mathcal{O}_{\mathbf{6},\mathbf{1}} = \mathrm{Tr}\,(Q_{L\mathbf{6}} U^*) t^c_{R\mathbf{1}},$$
$$\mathcal{O}_{\mathbf{6},\mathbf{15}} = \mathrm{Tr}\,(Q_{L\mathbf{6}} U^* t^c_{R\mathbf{15}}) \ \text{(with } T^3_R = 0),$$
$$\mathcal{O}_{\mathbf{6},\mathbf{6}} = c\,\mathrm{Tr}\,(Q_{L\mathbf{6}} U^*)\mathrm{Tr}\,(t^c_{R\mathbf{6}} U^*) + c'\,\mathrm{Tr}\,(Q_{L\mathbf{6}} U^* t^c_{R\mathbf{6}} U^*) \ \text{(with } \alpha_R = 0),$$
$$\mathcal{O}_{\mathbf{15},\mathbf{6}} = \mathrm{Tr}\,(Q_{L\mathbf{15}} t^c_{R\mathbf{6}} U^*).$$

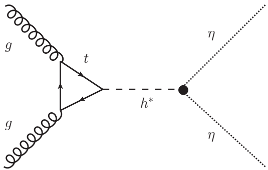
  - Bilinear fermion masses with hyperquark masses respecting Sp(4) (1502.04718)

* The η state with these characteristics is a common feature in other realizations too.

Signal definition - η-pair production via offshell Higgs

- We might still have a chance at the LHC!
- For $m_\eta > m_h/2$ the main production is*

$$pp \to h^* \to \eta\eta$$



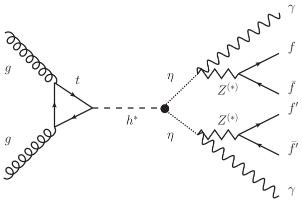
- η extremelly narrow ($eV \lesssim \Gamma_\eta \lesssim keV$) $\to$ on-shell Higgs can't compete.
- Interactions (photo- and fermio-phobic) - λ_η not suppressed by v/f!!

$$\mathcal{L}_\eta = -\frac{1}{2}\lambda_\eta \frac{m_h^2}{v} h\eta^2 + \frac{\kappa}{16\pi^2 v}\,\eta\left(\frac{g^2 - g'^2}{2} Z_{\mu\nu}\tilde{Z}^{\mu\nu} + gg' F_{\mu\nu}\widetilde{Z}^{\mu\nu} + g^2 W^+_{\mu\nu}\widetilde{W}^{-\mu\nu}\right)$$

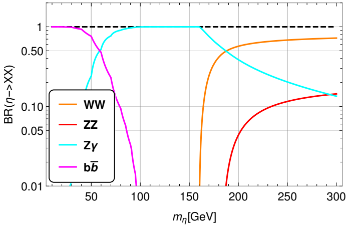
*Eventually overcome by other mechanisms, discussed later.

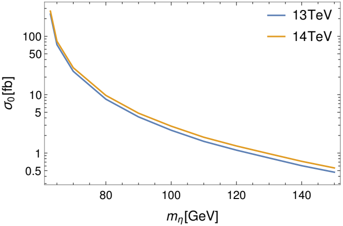
For $m_\eta < m_h/2$, bounds from BR and exoctic Higgs decay.

$$pp \to h^* \to \eta\eta \to Z^{(*)}\gamma Z^{(*)}\gamma \to f\bar{f}f'\bar{f}'\gamma\gamma$$



$$\sigma = \lambda^2\sigma_0 BR(\eta \to Z^{(*)}\gamma)^2 BR(Z^{(*)} \to f\bar{f})BR(Z^{(*)} \to f'\bar{f}'), \quad \lambda = \lambda_\eta \kappa_t$$





* Fermionic decay channels are generated via loops of gauge bosons $\sim$ 2-loop suppression, Bauer, Neubert, Thamm, 17, Craig, Hook, Kasko, 18

2 - Simulation setup and fake and matched photons

- MadGraph_aMC@NLO with + Pythia8 + Delphes (+ flat K-factor)
- Signal:
  - UFO model including the top triangle. $K = 2.05$.
  - (Semi-)leptonic decays: $f\bar{f} = \ell^+\ell^-$, $f'\bar{f'} = \ell'^+\ell'^-$, $\tau^+\tau^-$, jj, $\nu\bar{\nu}$ and $b\bar{b}$
- Background, $\sigma_{13}[pb]$(NLO QCD K-factor, (MG 1405.0301))

$$pp \to X + n_\gamma \gamma + \text{ jets}$$

Leptons \ Photons	2γ	1γ	0γ	K_{14}
$\ell^+\ell^-\ell'^+\ell'^-$ (4ℓ)	$1.17 \times 10^{-2}(1.36)$	$1.09 \times 10^{0}(1.34)$	$5.53 \times 10^{1}(1.29)$	1.10
$\ell^+\ell^-\ell'^+\nu$ (3ℓ)	$1.17 \times 10^{-2}(2.88)$	$7.94 \times 10^{0}(2.24)$	$5.08 \times 10^{2}(1.62)$	1.09
$\ell^+\ell^-$ (2ℓ)	$1.27 \times 10^{-1}(1.50)$	$2.71 \times 10^{1}(1.46)$		1.08
$\ell^+\ell^-\nu\bar{\nu}$	$1.95 \times 10^{-1}(1.36)$	$4.04 \times 10^{1}(1.34)$	$3.68 \times 10^{3}(1.29)$	1.11
$\tau^+\tau^-$	$5.67 \times 10^{1}(1.50)$	$1.30 \times 10^{4}(1.46)$		1.08
$t_{lep}\bar{t}_{lep}$	$4.86 \times 10^{-1}(1.34)$	$1.05 \times 10^{2}(1.45))$	$1.98 \times 10^{4}(1.47)$	1.18
Generation Cuts:	$p_T(j) > 20$ GeV $\Delta R(j,\gamma) > 0.4$ $\lvert\eta(\gamma)\rvert < 2.5$	$p_T(\ell) > 10$ GeV $\Delta R(\ell^+,\ell^-) > 0.4$	$p_T(\gamma) > 10$ GeV $\Delta R(\ell,\gamma) > 0.4$	

Merging photon multiplicities

Matching Procedure:

- Reconstructed photons originated from partons, which are isolated ($\Delta R = 0.4$) and hard ($p_T > 10\,\text{GeV}$) are called **matched***
- If $\#$ matched photons $>$ $\#$ generated photons $\rightarrow$ discard event
- For the highest multiplicity sample keep all events

Other type of photons:

- Misidentified electron (γ_e)
- Hadronic photons (γ_h)
- Multi-particle origin (γ_m): $e^- \rightarrow \gamma e^-$ and $\gamma \rightarrow e^+ e^-$

* matching different photon from generated and missing the generated is extremmelly inlike!

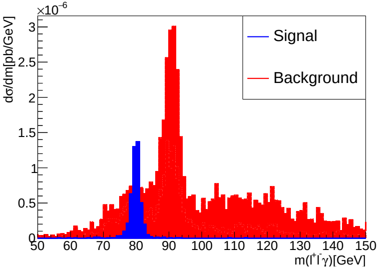
3 - Analysis

Goal: optimize sensitivity (significance) for HL-LHC (3/ab, $\sqrt{s} = 14\,\text{TeV}$)

$$\text{Same flavour opposite sign (SFOS)} \equiv \ell^+\ell^-$$

$$\geq 1 \text{ SFOS}, \quad \geq 2 \text{ photons}, \quad \geq 3 \text{ leptons}^*$$

$$|m(\ell^+\ell^-\gamma) - m_\eta| \leq 2\,\text{GeV}$$

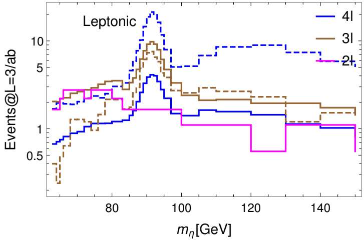


* aiming at fully-leptonic decay

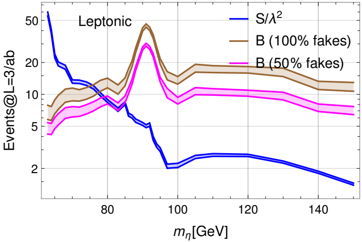
Results

Background components

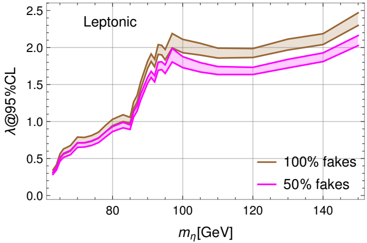
(Dashed: 1γ. Solid: 2γ.)

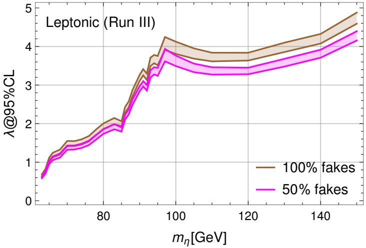


Signal (S) & Backg. (B) total



Bounds on λ_η





Effect of fake photons and matching

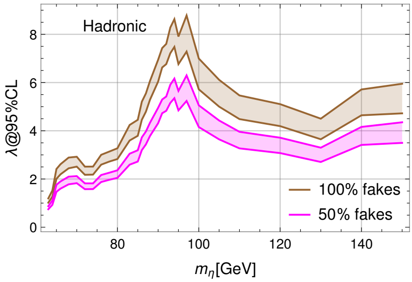
Rates in % (after selection ≥ 1 SFOS and ≥ 3 leptons)

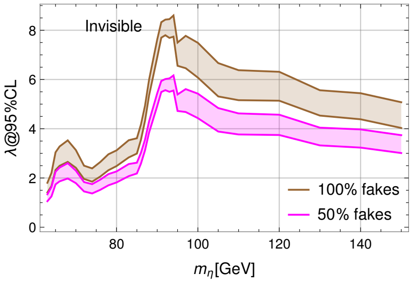
	ME (n_γ)	reconstructed	matched	electron	multi-part.	hadronic
4ℓ	0	=1	4.04*	4.92	0.687	0.365
		≥ 2	0.0525*	2.98×10^{-4}	~ 0	5.96×10^{-4}
	1	=1	65.6	5.01	0.768	0.340
		≥ 2	2.99*	9.60×10^{-3}	~ 0	1.01×10^{-3}
	2	=1	39.1	4.98	0.684	0.367
		≥ 2	47.4	0.0171	~ 0	~ 0
3ℓ	0	=1	1.38*	7.77×10^{-3}	0.0146	0.343
		≥ 2	0.0117*	4.86×10^{-4}	~ 0	~ 0
	1	=1	66.9	0.191	0.0854	0.322
		≥ 2	0.851*	1.34×10^{-3}	~ 0	1.34×10^{-3}
	2	=1	39.0	0.269	0.140	0.313
		≥ 2	47.3	0.0108	~ 0	~ 0
2ℓ	1	=1	2.04	0.571	0.214	0.286
		≥ 2	~ 0*	~ 0	~ 0	~ 0
	2	=1	66.2	0.552	~ 0	0.276
		≥ 2	1.44	~ 0	~ 0	~ 0

- Despite the small cross section reduction from matching, photons from $Z \to \ell^+\ell^-\gamma$ tend to mimic better the signal photon. Effect after all cuts can reach $\sim 90\%$.
- 2ℓ needs also a fake electron (many coming from a ME photon) $\to$ reason for low ME=rec γ rates.

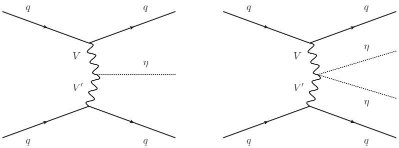
Other decay channels

- Invisible $\ell^+\ell^-\nu\bar{\nu}$ and Hadronic channels $\ell^+\ell^- jj$ are very dirt and hard
- Instead of ≥ 3 leptons, require
  - Hadronic: $m(jj\gamma) > m_\eta - 20\,\text{GeV}$
  - Invisible: $p_T(E_T^{\text{miss}}\gamma) > 40\,\text{GeV}$





4 - Other production mechanisms

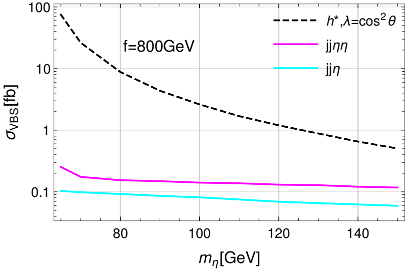


- Double-η production via kinetic term (VBF, 2η-strahlung).

$$\mathcal{L} \supset \frac{f^2}{8} D_\mu U D^\mu U^\dagger \supset \left(M_W^2 W^{+,\mu} W_\mu^- + \frac{M_Z^2}{2} Z^\mu Z_\mu \right) \left(1 + \frac{2\cos\theta}{v} h - \frac{\sin^2\theta}{v^2} \eta^2 \right)$$

- Single-η via WZW anomalous interaction (VBF, η-strahlung)

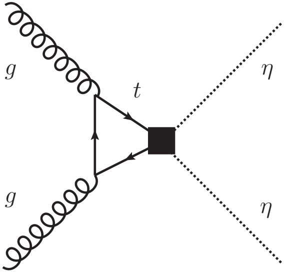
$pp \to jj\eta\eta,\ jj\eta$
$\kappa = 2c_\theta s_\theta$
$p_T(j) > 10\,\text{GeV},\ \Delta R(jj) > 0.4$



- Although $\eta - t - \bar{t}$ vanishes, $\eta^2 t\bar{t}$ is always present,

$$\mathcal{L} \supset -m_t \left(1 + \frac{h}{v}\kappa_t - \frac{h^2}{f^2}\kappa_{th^2} - \frac{\eta^2}{f^2}\kappa_{t\eta^2}\right)\bar{t}t$$

Q_L	t_R	κ_t	κ_{th^2}	$\kappa_{t\eta^2}$	λ_η	comments
6	**1**	$\cos\theta$	$1/2$	$1/2$	$\cos\theta$	
6	**15**	$\cos\theta$	$1/2$	$1/2$	$\cos\theta$	$T_R^3 = 0$ of $(\mathbf{1}, \mathbf{3})$
6	**6**	$\cos(2\theta)/\cos\theta$	2	1	$\cos\theta$	$\alpha_R = 0$
15	**6**	$\cos\theta$	$1/2$	$1/2$	$\cos\theta$	



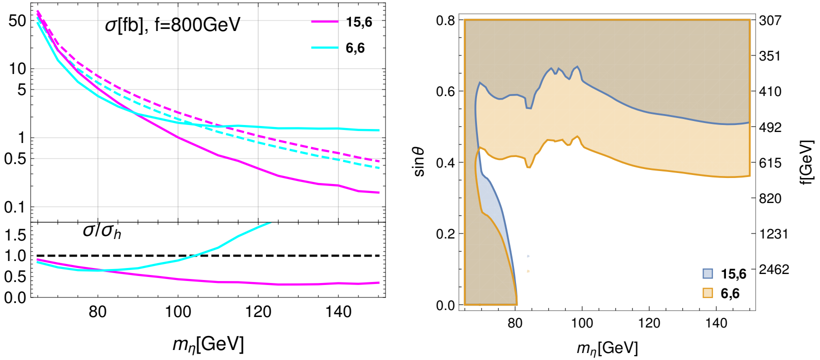


Figure: *Left:* Total η pair production cross section at 14 TeV LHC for Q_L, t_R^c in the **15, 6** (cyan) and **6, 6** (magenta) including the coherent sum of contact and off-shell Higgs contributions in solid lines, and only the off-shell Higgs in dashed lines. *Right:* Excluded region in $(m_\eta, \sin\theta)$ space for the same choice of spurions, using the leptonic selection.

Analysis of the potential: η mass and λ_η

Potential dominated by leading dimension operators from:

- Hyperfermion mass

$$V_m = B_m f^4 \,\mathrm{Tr}\,(\epsilon_0 U) + \mathrm{h.c.}$$

- EW gauge boson loops,

$$V_g = B_g f^4 \,\mathrm{Tr}\, \left(g^2 T_L^A U T_L^{AT} U^\dagger + g'^2 T_R^3 U T_R^{3T} U^\dagger \right).$$

- One of the spurions that generates top mass,

$$Q_{L\mathbf{6}},\ t^c_{R\mathbf{1}}: \quad V_t = -B_t f^4 y_Q^2 \mathrm{Tr}\,(S^{\mathbf{6}}_{q_L^a} U^*)\mathrm{Tr}\,(S^{\mathbf{6}}_{q_L^a} U^*)^*$$

$$Q_{L\mathbf{6}},\ t^c_{R\mathbf{15}}: \quad V_t = -B_t f^4 \left(y_Q^2 \mathrm{Tr}\,(S^{\mathbf{6}}_{q_L^a} U^*)\mathrm{Tr}\,(S^{\mathbf{6}}_{q_L^a} U^*)^* + y_t^2 \mathrm{Tr}\,(S^{\mathbf{15}}_{t_R} U S^{\mathbf{15}*}_{t_R} U^*) \right)$$

$$Q_{L\mathbf{6}},\ t^c_{R\mathbf{6}}: \quad V_t = -B_t f^4 \left(y_Q^2 \mathrm{Tr}\,(S^{\mathbf{6}}_{q_L^a} U^*)\mathrm{Tr}\,(S^{\mathbf{6}}_{q_L^a} U^*)^* + y_t^2 \mathrm{Tr}\,(S^{\mathbf{6}}_{t_R} U^*)\mathrm{Tr}\,(S^{\mathbf{6}}_{t_R} U^*)^* \right) |_{\alpha_R=}$$

$$Q_{L\mathbf{15}},\ t^c_{R\mathbf{6}}: \quad V_t = -B_t f^4 \left(y_Q^2 \mathrm{Tr}\,(S^{\mathbf{15}}_{q_L^a} U S^{\mathbf{15}*}_{q_L^a} U^*) + y_t^2 \mathrm{Tr}\,(S^{\mathbf{6}}_{t_R} U^*)\mathrm{Tr}\,(S^{\mathbf{6}}_{t_R} U^*)^* \right),$$

- In all cases we find

$$\lambda_\eta = \cos\theta$$

- And the mass

$$Q_{L\mathbf{6}},\ t^c_{R\mathbf{1}}: \quad \frac{m_\eta^2}{f^2} = \frac{m_h^2}{v^2}$$

$$Q_{L\mathbf{6}},\ t^c_{R\mathbf{15}}: \quad \frac{m_\eta^2}{f^2} = \frac{m_h^2}{v^2}$$

$$Q_{L\mathbf{6}},\ t^c_{R\mathbf{6}}: \quad \frac{m_\eta^2}{f^2} = \frac{m_h^2}{v^2} + 8y_t^2 B_t$$

$$Q_{L\mathbf{15}},\ t^c_{R\mathbf{6}}: \quad \frac{m_\eta^2}{f^2} = \frac{m_h^2}{v^2} + 8y_t^2 B_t \cos 2\alpha_R\,.$$

- The only scenarios allowing a light η are $Q_{L\mathbf{6}},\ t^c_{R\mathbf{6}}$ and $Q_{L\mathbf{15}},\ t^c_{R\mathbf{6}}$.
- For large f a fine cancellation between the 2 terms is necessary $\rightarrow$ manifestation of fine tuning issue.

5 - Conclusion

- Off-shell Higgs production of η dominates for low m_η and large f.
- We can exclude $\lambda_\eta \sim 1$ (CH value) up to $m_\eta \approx 85\,\text{GeV}$ at HL-LHC
- Fake photons (and matching) play an important role in the study
- We developed a machinery to do photon matching (might be useful for other phenomenological studies)

Embedding (backup)

- $SU(4) \to SU(2)_L \times SU(2)_R$

  $$\mathbf{1} \to (\mathbf{1},\mathbf{1}), \quad \mathbf{6} \to 2\times(\mathbf{1},\mathbf{1}) + (\mathbf{2},\mathbf{2}), \quad \mathbf{15} \to (\mathbf{1},\mathbf{1}) + 2\times(\mathbf{2},\mathbf{2}) + (\mathbf{3},\mathbf{1}) + (\mathbf{1},\mathbf{3}),$$

- $Q_{L\mathbf{n}} = t_L S^{\mathbf{n}}_{t_L} + b_L S^{\mathbf{n}}_{b_L} \equiv q^a_L S^{\mathbf{n}}_{q^a_L}$ and $t^c_{R\mathbf{n}} = t^c_R S^{\mathbf{n}}_{t_R}$
- Case of multiple possibilities, $S^{\mathbf{6}}_{t_R} = \sin\alpha_R S^{I\mathbf{6}}_{t_R} + \cos\alpha_R S^{II\mathbf{6}}_{t_R}$, where $S^{I\mathbf{6}}_{t_R}$ and $S^{II\mathbf{6}}_{t_R}$ are the singlets of $SU(2)_L \times SU(2)_R$ and $Sp(4)$ respectively. In the same way $S^{\mathbf{15}}_{q^a_L} = \sin\alpha_L S^{I\mathbf{15}}_{q^a_L} + \cos\alpha_L S^{II\mathbf{15}}_{q^a_L}$.