Minimally Extended SILH

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DESY, 2016

Motivation

- The first signals of new heavy resonances can typically be explained by a variety of explicit models, including many Composite H+S (CHS) models

- The important quantitative and qualitative features of CHS UV completions can be derived without a detailed study of each particular model

- Describe a set of motivated models with PNGB/generic, CP even/odd composite singlet within the same framework

- Construct a predictive EFT reflecting the structural features of the underlying dynamics

Framework

Assumptions:

- new resonance S has a spin 0
- S is an EW singlet
- S is the second lightest composite state
- S is a part of a new strong sector which
  - produces PNGB Higgs
  - Goldstone sym breaking and top mass from partial compositeness
  - rest of SM fields are elementary

Dimensional Analysis

- EFT for SM + S, characterised by two unknown parameters

$m_\rho \sim g_\rho f$	cutoff, typical mass of composite states (>1TeV)
$g_\rho \sim 1 - 4\pi$	typical coupling of composite states
$\xi = v^2/f^2$	EW tuning $\xi \lesssim 0.2$

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- Power Counting

from length and $\hbar$ counting we get:

$$m_\rho^2 f^2 \left[\frac{S}{f}\right]^{\#_S} \left[\frac{H}{f}\right]^{\#_H} \left[\frac{y_q\, \bar{q}q}{m_\rho^2 f}\right]^{\#_{\bar{q}q}} \left[\frac{gA}{m_\rho}\right]^{\#_A} \left[\frac{p}{m_\rho}\right]^{\#_p}$$

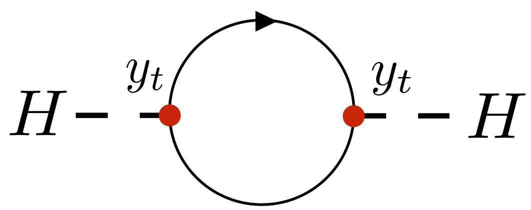
generic composite states

SM coupling to the strong sector controlled by Yukawas and gauge couplings

PNGB selection rules

- Goldstone symmetry can require a presence of symmetry breaking sources

$$\frac{N_c\, y_t^2}{(4\pi)^2}$$



PNGB Higgs or S potential

Pion mass splitting in QCD

mass hierarchy in PNGB S case:

$$m_h^2 : M^2 : m_\rho^2 \ \sim \ \frac{N_c y_t^2}{(4\pi)^2}\xi : \frac{N_c y_t^2}{(4\pi)^2} : 1$$

PNGB with Anomalies

‣shift symmetry breaking by anomalies

- coupling to SM gauge bosons $$\frac{N_f g_X^2}{(4\pi)^2}\frac{S}{f}X_{\mu\nu}\tilde{X}^{\mu\nu}$$

- mass from the anomaly associated to strong sector gauge bosons $$m_\eta \sim \frac{N_f}{N} m_\rho \qquad g_\rho = \frac{4\pi}{\sqrt{N}}$$

$$N_f \frac{g_\rho^2}{(4\pi)^2}$$ with respect to generic power counting

UV selection rules

- "loop" suppression in large-N theories for non-PNGB S

quarks and gluons at $N\frac{g_S^2}{16\pi^2} \sim 1$ $\Rightarrow$ composite mesons $g_\rho = \frac{4\pi}{\sqrt{N}}$ $m_\rho \neq f(N)$

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parametrically large effects of the selection rules may be visible even with not too large scale separation

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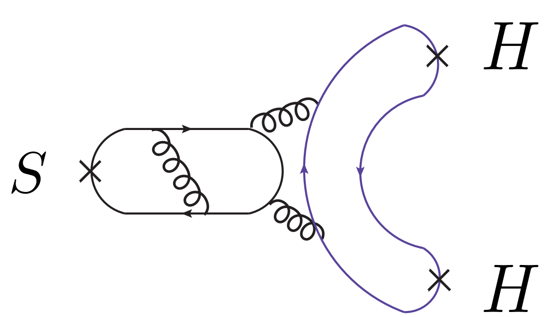
$$\frac{g_\rho^2}{(4\pi)^2}$$



$\sim 1/N$

Zweig rule in QCD, e.g. for $\phi \to \pi\pi\pi$

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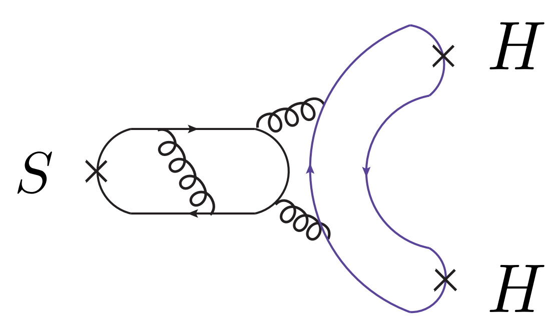

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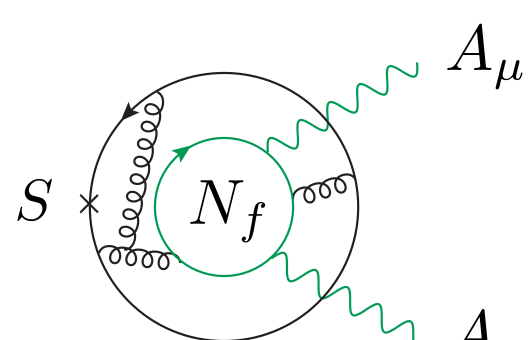

$\sim N_f/N$

not relevant in QCD because $N_f \sim N_c$

UV selection rules

- "loop" suppression in N-site models

SM | $e^{H/f}$ | $m_\rho \quad g_\rho$

tree-level int.out. of heavy composite states automatically leads to generic power counting for the operators generated at tree level

E.g. the operator $SF_{\mu\nu}F^{\mu\nu}$ appears only at one-loop level

$$\left[\frac{g_\rho}{4\pi}\right]^2 \left[\frac{g}{g_\rho}\right]^2 \frac{S}{f} F_{\mu\nu}F^{\mu\nu}$$

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$N_f \dfrac{g_\rho^2}{(4\pi)^2}$ - same loop factor with respect to $\left[\dfrac{g}{g_\rho}\right]^2 \dfrac{S}{f} F_{\mu\nu}F^{\mu\nu}$ as in large-N

Automatic implementation of Minimal Coupling, suppressing the operators

$SX_{\mu\nu}X^{\mu\nu}$ $\quad |H|^2 G_{\mu\nu}G^{\mu\nu},\ |H|^2\gamma_{\mu\nu}\gamma^{\mu\nu}$ $\quad (D_\mu H)^\dagger \sigma^i (D_\nu H) W^{i\mu\nu},\ (D_\mu H)^\dagger (D_\nu H) B^{\mu\nu}$

Power Counting Rule

$$m_\rho^2 f^2 \left[\frac{N_c y_t^2}{(4\pi)^2}\right]^{\#_{\not{L}}} \left[\frac{N_f g_\rho^2}{(4\pi)^2}\right]^{\#_L} \left[\frac{y_q \bar{q} q}{m_\rho^2 f}\right]^{\#_{\bar{q}q}} \left[\frac{g_A A}{m_\rho}\right]^{\#_A} \left[\frac{S}{f}\right]^{\#_S} \left[\frac{H}{f}\right]^{\#_H} \left[\frac{\partial_\mu}{m_\rho}\right]^{\#_\partial}$$

- shift breaking by top loops
- MC, 1/N, or anomaly shift breaking “loop” suppression
- reconstruct SM fermion Yukawa couplings

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counter-example from SILH:

kinetic term of the goldstone fields $U = \exp[i\chi/f]$ contains

$\mathrm{Tr}[D_\mu U (D^\mu U)^\dagger] \quad \rightarrow \quad$ c1 $|H|^2 |D_\mu H|^2$ + c2 $\partial_\mu |H|^2 \partial^\mu |H|^2$

order-1, shift preserving   order-1, shift breaking, correlated

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order-1, shift preserving   order-1, shift breaking, correlated

- Using field redefinitions (equations of motion) and integration by parts we will try to reduce the full set of operators to the minimal one, without introducing the power counting breaking

Constructing the Basis of Operators

- Generic S, operators with 2 derivatives, H and S

$$\mathcal{O}_1 = \tfrac{1}{f}|D_\mu H|^2 S \qquad \mathcal{O}_2 = \tfrac{i}{f}(H^\dagger D_\mu H)\partial^\mu S + \text{h.c.} \qquad \mathcal{O}_3 = \tfrac{1}{f}\partial_\mu |H|^2 \partial^\mu S$$

$$\mathcal{O}_4 = \tfrac{1}{f}(H^\dagger \Box H)S + \text{h.c.} \qquad \mathcal{O}_5 = \tfrac{1}{f}|H|^2 \Box S \qquad \mathcal{O}_6 = \tfrac{1}{f}\Box |H|^2 S$$

• H shift symmetry preserving $\mathcal{O}_1$ can be expressed as two <u>correlated</u> shift breaking operators

$$\mathcal{O}_1 = \frac{1}{2}\left(\mathcal{O}_5 - \mathcal{O}_4\right)$$

• the coefficients of $\mathcal{O}_{4,5}$ now break the power counting

• both can be eliminated by H and S e.o.m., generating e.g.

$$\sim \frac{M^2}{f} S|H|^2$$

Constructing the Basis of Operators

- PNGB S, operators with H and S without derivatives $S^n|H|^{2m}$

• applying S or H e.o.m. we generate unsuppressed shift symmetry breaking

$$\frac{y_t^2}{16\pi^2}\frac{m_\rho^2}{f}S|H|^2 \;\rightarrow\; \frac{1}{f}SH^\dagger\Box H \;\;\text{or}\;\; \frac{1}{f}\Box S|H|^2$$

• because of the generic form of e.o.m.

$$\frac{y_t^2}{(4\pi)^2}S^m|H|^n + \Box S + \cdots = 0$$

Constructing the Basis of Operators

- resulting basis

- CP odd S

$S X^2 \quad S^{2,4} \quad S\bar{q}Hq \quad S^2|H|^2$

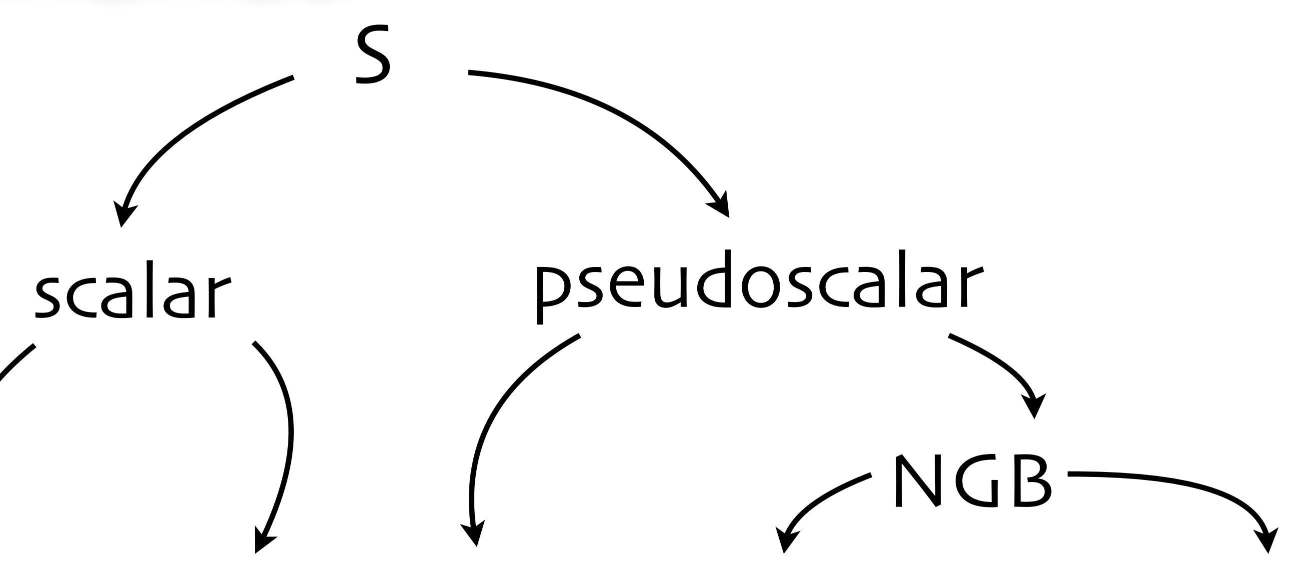
- CP even generic S

$S X^2 \quad S^{2,4} \quad S\bar{q}Hq \quad S^{3,5} \quad S|D_\mu H|^2 \quad S|H|^2 \quad S^3|H|^2 \quad S|H|^4$

- CP even PNGB S

$S X^2 \quad S^{2,4} \quad S\bar{q}Hq \quad S^2|H|^2 \quad S^{3,5} \quad S|H|^2 \quad S^3|H|^2 \quad S|H|^4$

Scenarios



	generic	NGB	generic	p.c.	anom.
$k_X\, SX^2$	$\frac{g_X^2}{g_\rho^2}\frac{1}{f}$	$\frac{3y_t^2}{(4\pi)^2}\frac{g_X^2}{g_\rho^2}\frac{1}{f}$	$\frac{g_X^2}{g_\rho^2}\frac{1}{f}$	$\frac{3y_t^2}{(4\pi)^2}\frac{g_X^2}{g_\rho^2}\frac{1}{f}$	$\frac{N_f^{(X)} g_X^2}{(4\pi)^2}\frac{1}{f}$
$k_q\, S\bar{q}Hq$	$y_q\frac{1}{f}$	$y_q\frac{1}{f}$	$iy_q\frac{1}{f}$	$iy_q\frac{1}{f}$	—
$k_H\, S\lvert D_\mu H\rvert^2$	$\frac{1}{f}$	—	—	—	—
$k_{H1}\, S\lvert H\rvert^2\ ,\ k_{H2}\, S\lvert H\rvert^4/f^2\ ,\ k_{H3}\, S^3\lvert H\rvert^2/f^2$	$\frac{3y_t^2}{(4\pi)^2}\frac{m_\rho^2}{f}$	$\frac{3y_t^2}{(4\pi)^2}\frac{m_\rho^2}{f}$	—	—	—
$k_{H4}\, S^2\lvert H\rvert^2$	—	$\frac{3y_t^2}{(4\pi)^2}\frac{m_\rho^2}{f^2}$	$\frac{3y_t^2}{(4\pi)^2}\frac{m_\rho^2}{f^2}$	$\frac{3y_t^2}{(4\pi)^2}\frac{m_\rho^2}{f^2}$	$\frac{\tilde{N}_f g_\rho^2}{(4\pi)^2}\frac{3y_t^2}{(4\pi)^2}\frac{m_\rho^2}{f^2}$
$k_M\, S^2\ ,\ k_4\, S^4/f^2$	m_ρ^2	$\frac{3y_t^2}{(4\pi)^2}m_\rho^2$	m_ρ^2	$\frac{3y_t^2}{(4\pi)^2}m_\rho^2$	$\frac{\tilde{N}_f g_\rho^2}{(4\pi)^2}m_\rho^2$
$k_3\, S^3\ ,\ k_5\, S^5/f^2$	$\frac{m_\rho^2}{f}$	$\frac{3y_t^2}{(4\pi)^2}\frac{m_\rho^2}{f}$	—	—	—

* "Generic" cases allow for additional "loop" suppression

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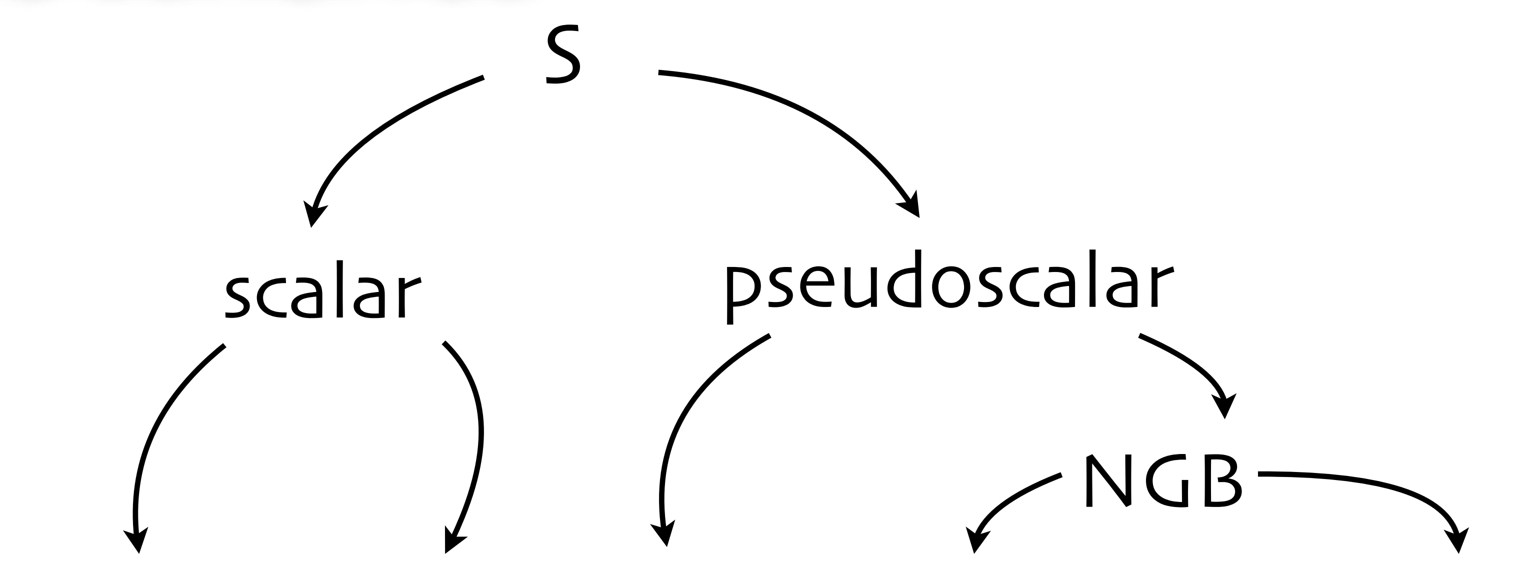

	generic	NGB	generic	p.c.	anom.
$k_X\, SX^2$	$\frac{g_X^2}{g_\rho^2}\,\frac{1}{f}$	$y_t^2/16\pi^2$	$\frac{g_X^2}{g_\rho^2}\,\frac{1}{f}$	$y_t^2/16\pi^2$	$N_f\, g_\rho^2/16\pi^2$
$k_q\, S\bar{q}Hq$	$y_q\frac{1}{f}$	$y_q\frac{1}{f}$	$iy_q\frac{1}{f}$	$iy_q\frac{1}{f}$	—
$k_H\, S\|D_\mu H\|^2$	$\frac{1}{f}$	—	—	—	—
$k_{H1}\, S\|H\|^2\ ,\ k_{H2}\, S\|H\|^4/f^2\ ,\ k_{H3}\, S^3\|H\|^2/f^2$	$y_t^2/16\pi^2$	$y_t^2/16\pi^2$	—	—	—
$k_{H4}\, S^2\|H\|^2$	—	$y_t^2/16\pi$	$y_t^2/16\pi^2$	$y_t^2/16\pi^2$	$N_f\, g_\rho^2/16\pi^2$
$k_M\, S^2\ ,\ k_4\, S^4/f^2$	m_ρ^2	$y_t^2/16\pi^2$	m_ρ^2	$y_t^2/16\pi^2$	$N_f\, g_\rho^2/16\pi^2$
$k_3\, S^3\ ,\ k_5\, S^5/f^2$	$\frac{m_\rho^2}{f}$	$y_t^2/16\pi^2$	—	—	—

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Higgs Physics

- Generic CH effects lead to $\xi \lesssim 0.2$

- Higgs-scalar S mixing affects Higgs phenomenology. We concentrate on the effects which can be dominated by S and supersede the SILH effects

		effect of scalar S		compositeness
		generic	PNGB	effects [+MC]
$\mathcal{O}_g$	$\frac{g_S^2}{v^2}\lvert H\rvert^2 G_{\mu\nu}G^{\mu\nu}$	$k_g k_{H1}\frac{3y_t^2}{(4\pi)^2}\frac{1}{g_\rho^2}\frac{m_\rho^2}{M^2}\xi$	$k_g k_{H1}\frac{9y_t^4}{(4\pi)^4}\frac{1}{g_\rho^2}\frac{m_\rho^2}{M^2}\xi$	$c_g\frac{3y_t^2}{(4\pi)^2}\frac{1}{g_\rho^2}\xi$
$\mathcal{O}_\gamma$	$\frac{g'^2}{v^2}\lvert H\rvert^2 B_{\mu\nu}B^{\mu\nu}$	$(k_W+k_B)k_{H1}\frac{3y_t^2}{(4\pi)^2}\frac{1}{g_\rho^2}\frac{m_\rho^2}{M^2}\xi$	$(k_W+k_B)k_{H1}\frac{9y_t^4}{(4\pi)^4}\frac{1}{g_\rho^2}\frac{m_\rho^2}{M^2}\xi$	$c_\gamma\frac{3y_t^2}{(4\pi)^2}\frac{1}{g_\rho^2}\xi$
$\mathcal{O}_W$	$\frac{ig}{2v^2}(H^\dagger\sigma^i\overleftrightarrow{D}_\mu H)(D_\nu W^{\mu\nu})^i$	$4k_W k_{H1}\frac{3y_t^2}{(4\pi)^2}\frac{1}{g_\rho^2}\frac{m_\rho^2}{M^2}\xi$	$4k_W k_{H1}\frac{9y_t^4}{(4\pi)^4}\frac{1}{g_\rho^2}\frac{m_\rho^2}{M^2}\xi$	$c_W\frac{1}{g_\rho^2}\xi$
$\mathcal{O}_B$	$\frac{ig'}{2v^2}(H^\dagger\overleftrightarrow{D}_\mu H)(\partial_\nu B^{\mu\nu})$	$-4k_W k_{H1}\frac{3y_t^2}{(4\pi)^2}\frac{1}{g_\rho^2}\frac{m_\rho^2}{M^2}\xi$	$-4k_W k_{H1}\frac{9y_t^4}{(4\pi)^4}\frac{1}{g_\rho^2}\frac{m_\rho^2}{M^2}\xi$	$c_B\frac{1}{g_\rho^2}\xi$
$\mathcal{O}_{HW}$	$\frac{ig}{v^2}(D_\mu H)^\dagger\sigma^i(D_\nu H)W^{i\mu\nu}$	$-4k_W k_{H1}\frac{3y_t^2}{(4\pi)^2}\frac{1}{g_\rho^2}\frac{m_\rho^2}{M^2}\xi$	$-4k_W k_{H1}\frac{9y_t^4}{(4\pi)^4}\frac{1}{g_\rho^2}\frac{m_\rho^2}{M^2}\xi$	$c_{HW}\frac{1}{g_\rho^2}\xi\left[\frac{g_\rho^2}{(4\pi)^2}\right]$
$\mathcal{O}_{HB}$	$\frac{ig'}{v^2}(D_\mu H)^\dagger(D_\nu H)B^{\mu\nu}$	$4k_W k_{H1}\frac{3y_t^2}{(4\pi)^2}\frac{1}{g_\rho^2}\frac{m_\rho^2}{M^2}\xi$	$4k_W k_{H1}\frac{9y_t^4}{(4\pi)^4}\frac{1}{g_\rho^2}\frac{m_\rho^2}{M^2}\xi$	$c_{HB}\frac{1}{g_\rho^2}\xi\left[\frac{g_\rho^2}{(4\pi)^2}\right]$
$\mathcal{O}_q$	$\frac{1}{v^2}\bar{q}Hq\lvert H\rvert^2$	$y_q k_{H1}\left(k_q-\frac{k_H}{2}\right)\frac{3y_t^2}{(4\pi)^2}\frac{m_\rho^2}{M^2}\xi$	$y_q k_{H1}k_q\frac{3y_t^2}{(4\pi)^2}\frac{m_\rho^2}{M^2}\xi$	$c_q y_q\xi$
$\mathcal{O}_H$	$\frac{1}{2v^2}\partial_\mu\lvert H\rvert^2\partial^\mu\lvert H\rvert^2$	$k_{H1}\left(k_{H1}\frac{3y_t^2}{(4\pi)^2}\frac{m_\rho^2}{M^2}-k_H\right)\frac{3y_t^2}{(4\pi)^2}\frac{m_\rho^2}{M^2}\xi$	$k_{H1}^2\frac{9y_t^4}{(4\pi)^4}\frac{m_\rho^4}{M^4}\xi$	$c_H\xi$

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- effect of generic S on $h \to gg$

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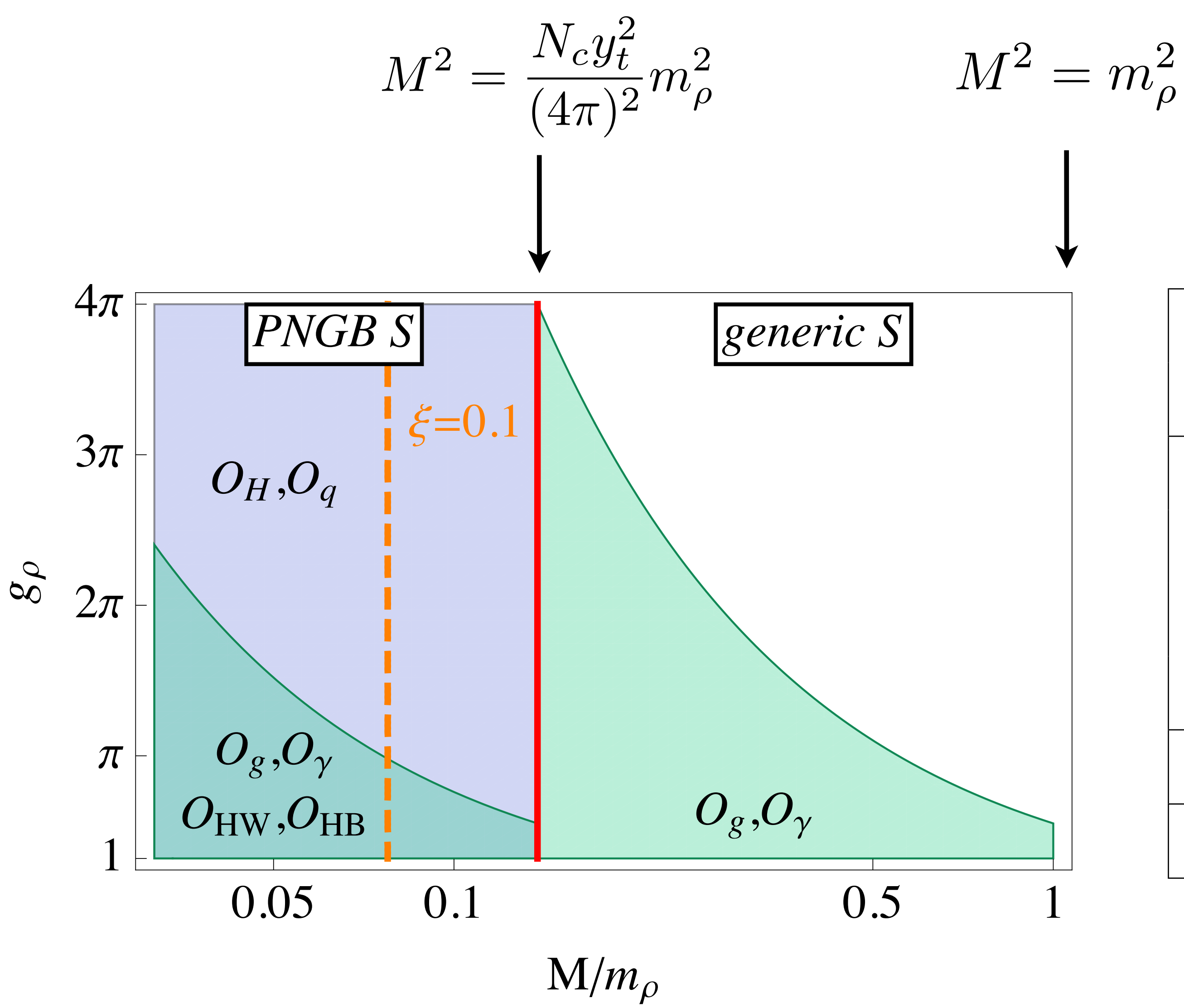
$\mathcal{O}_H$	$\frac{1}{2v^2}\partial_\mu\|H\|^2\partial^\mu\|H\|^2$	$k_{H1}\left(k_{H1}\frac{3y_t^2}{(4\pi)^2}\frac{m_\rho^2}{M^2} - k_H\right)\frac{3y_t^2}{(4\pi)^2}\frac{m_\rho^2}{M^2}\xi$	$k_{H1}^2 \frac{9y_t^4}{(4\pi)^4}\frac{m_\rho^4}{M^4}\xi$	$c_H\xi$

- $\mathcal{O}_g$ is dominated by effects of the generic S if $M < m_\rho$ i.e. in all the regime of validity
- SM top loop contribution to $h \to gg$ is modified by order ξ due to the Higgs compositeness effects in the operators $\mathcal{O}_q$ and $\mathcal{O}_H$
- S effect becomes dominant for $M^2/m_\rho^2 \lesssim 3y_t^2/g_\rho^2$

Higgs Physics

SILH gives estimates for the "generic" compositeness effects, hence S effects becomes enhanced when its parameters deviate from the power counting



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$\mathcal{O}_{HW}$	$\frac{ig}{v^2}(D_\mu H)^\dagger \sigma^i (D_\nu H) W^{i\mu\nu}$
$\mathcal{O}_{HB}$	$\frac{ig'}{v^2}(D_\mu H)^\dagger (D_\nu H) B^{\mu\nu}$
$\mathcal{O}_q$	$\frac{1}{v^2}\bar{q}Hq\|H\|^2$
$\mathcal{O}_H$	$\frac{1}{2v^2}\partial_\mu \|H\|^2 \partial^\mu \|H\|^2$

Summary

- We provided a simple description of a new composite scalar accompanying the composite Higgs, extending the SILH* framework

- We derived the relations between the patterns of S and H couplings and the structure of the underlying theory

- The proposed strategy can be extended to higher order operators, theories with extra symmetries, light S scenarios

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Thank you!