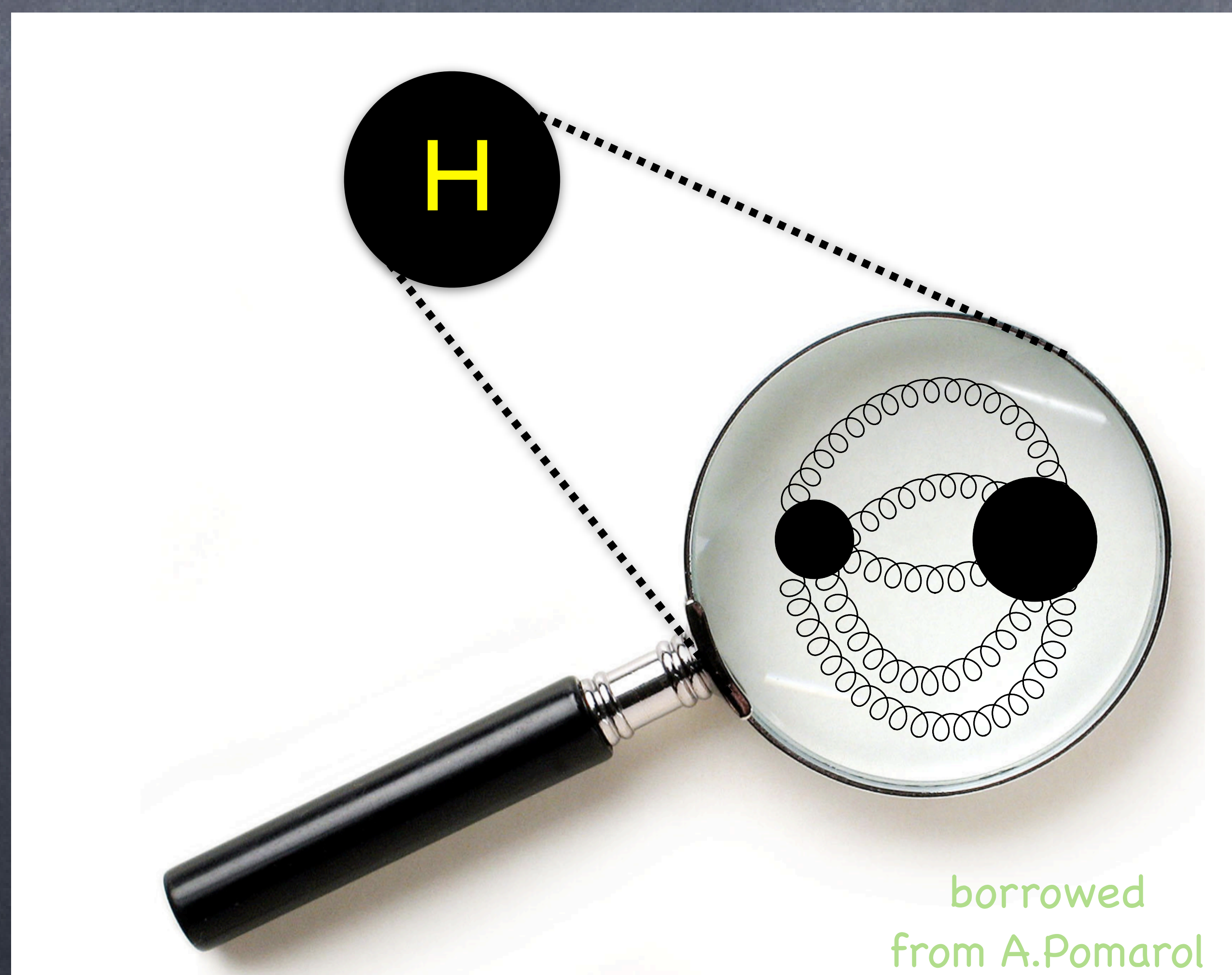
Adam Falkowski

Composite Higgs Review

Higgs Couplings @ SLAC, 11 November 2016



drawing heavily from reviews
Contino 1005.4269
Panico, Wulzer 1506.01961
and slides of A. Pomarol, A, Wulzer, L. Da Rold

Higgs as we know it

ATLAS+CMS
1606.02266

$$m_H = 125.09 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.})\ \text{GeV},$$

- Higgs mass is known to a good precision
- From theoretical point of view, scalars should have masses close to the cutoff scale of the QFT, unless a symmetry protects the relation m << Λ
- Theoretical prejudice suggests that we should see new states near mh, providing the cutoff to the SM and implementing a new symmetry

Final Run-1 and Preliminary Run-2 results

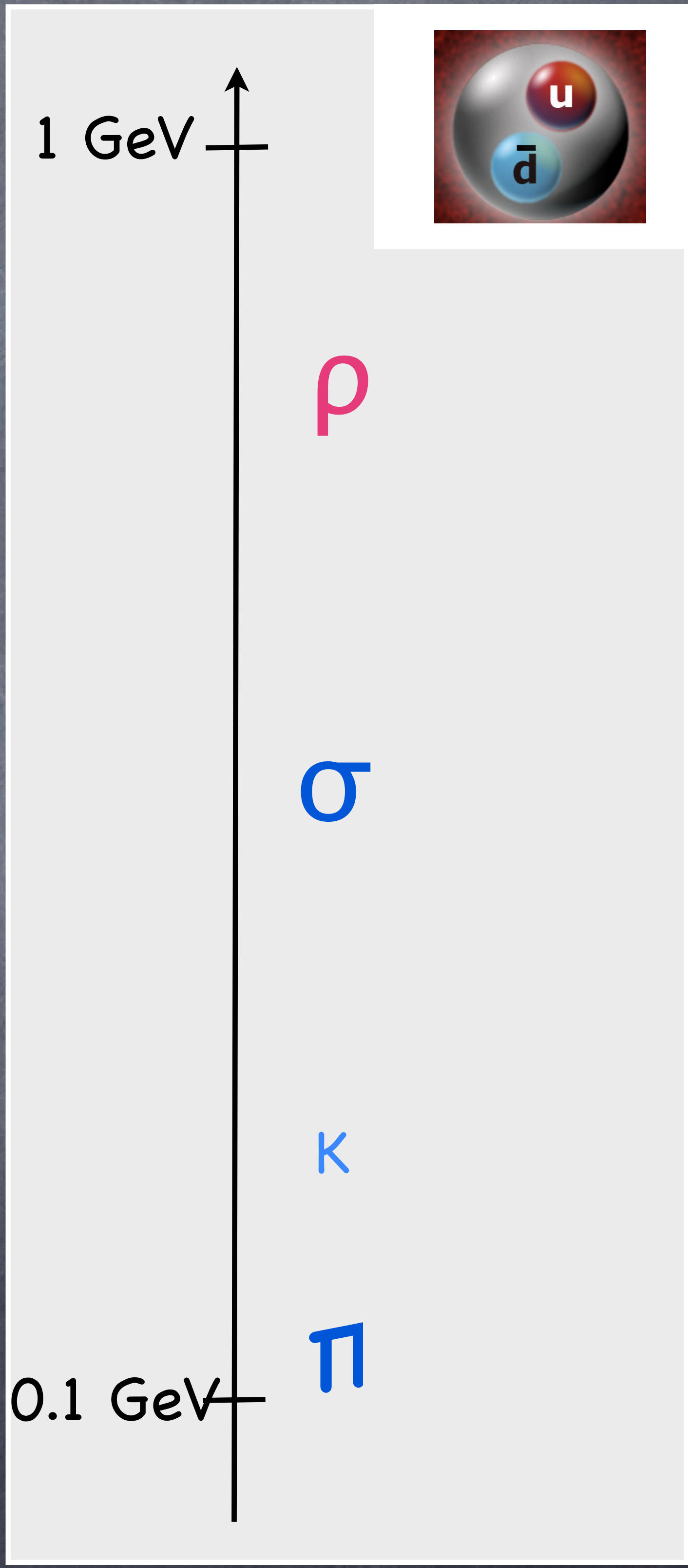
Channel	Production	Run-1	ATLAS Run-2	CMS Run-2
$\gamma\gamma$	ggh	$1.10^{+0.23}_{-0.22}$	$0.62^{+0.30}_{-0.29}$ [4]	$0.77^{+0.25}_{-0.23}$ [5]
	VBF	$1.3^{+0.5}_{-0.5}$	$2.25^{+0.75}_{-0.75}$ [4]	$1.61^{+0.90}_{-0.80}$ [5]
	Wh	$0.5^{+1.3}_{-1.2}$	-	-
	Zh	$0.5^{+3.0}_{-2.5}$	-	-
	Vh	-	$0.30^{+1.21}_{-1.12}$ [4]	-
	$t\bar{t}h$	$2.2^{+1.6}_{-1.3}$	$-0.22^{+1.26}_{-0.99}$ [4]	$1.9^{+1.5}_{-1.2}$ [5]
$Z\gamma$	incl.	$1.4^{+3.3}_{-3.2}$	-	-
ZZ^*	ggh	$1.13^{+0.34}_{-0.31}$	$1.34^{+0.39}_{-0.33}$ [4]	$0.96^{+0.40}_{-0.33}$ [6]
	VBF	$0.1^{+1.1}_{-0.6}$	$3.8^{+2.8}_{-2.2}$ [4]	$0.67^{+1.61}_{-0.67}$ [6]
WW^*	ggh	$0.84^{+0.17}_{-0.17}$	-	-
	VBF	$1.2^{+0.4}_{-0.4}$	$1.7^{+1.2}_{-0.9}$	-
	Wh	$1.6^{+1.2}_{-1.0}$	$3.2^{+4.4}_{-4.2}$	-
	Zh	$5.9^{+2.6}_{-2.2}$	-	-
	$t\bar{t}h$	$5.0^{+1.8}_{-1.7}$	-	-
	incl.	-	-	0.3 ± 0.5 [7]
$\tau^+\tau^-$	ggh	$1.0^{+0.6}_{-0.6}$	-	-
	VBF	$1.3^{+0.4}_{-0.4}$	-	-
	Wh	$-1.4^{+1.4}_{-1.4}$	-	-
	Zh	$2.2^{+2.2}_{-1.8}$	-	-
	$t\bar{t}h$	$-1.9^{+3.7}_{-3.3}$	-	-
$b\bar{b}$	VBF	-	$-3.9^{+2.8}_{-2.9}$ [8]	$-3.7^{+2.4}_{-2.5}$ [9]
	Wh	$1.0^{+0.5}_{-0.5}$	-	-
	Zh	$0.4^{+0.4}_{-0.4}$	-	-
	Vh	-	$0.21^{+0.51}_{-0.50}$ [10]	-
	$t\bar{t}h$	$1.15^{+0.99}_{-0.94}$	$2.1^{+1.0}_{-0.9}$ [11]	$-0.19^{+0.80}_{-0.81}$
$\mu^+\mu^-$	incl.	$0.1^{+2.5}_{-2.5}$	$-0.8^{+2.2}_{-2.2}$ [13]	-
multi-ℓ	cats.	-	$2.5^{+1.3}_{-1.1}$ [14]	$2.3^{+0.9}_{-0.8}$ [15]

Composite Scalars in QCD

- Spectrum of low-energy QCD contains scalars with m~GeV << M_Planck without any hierarchy problem. That's because they are composite states, and quantum correction to their masses are naturally cut off at 1 GeV.

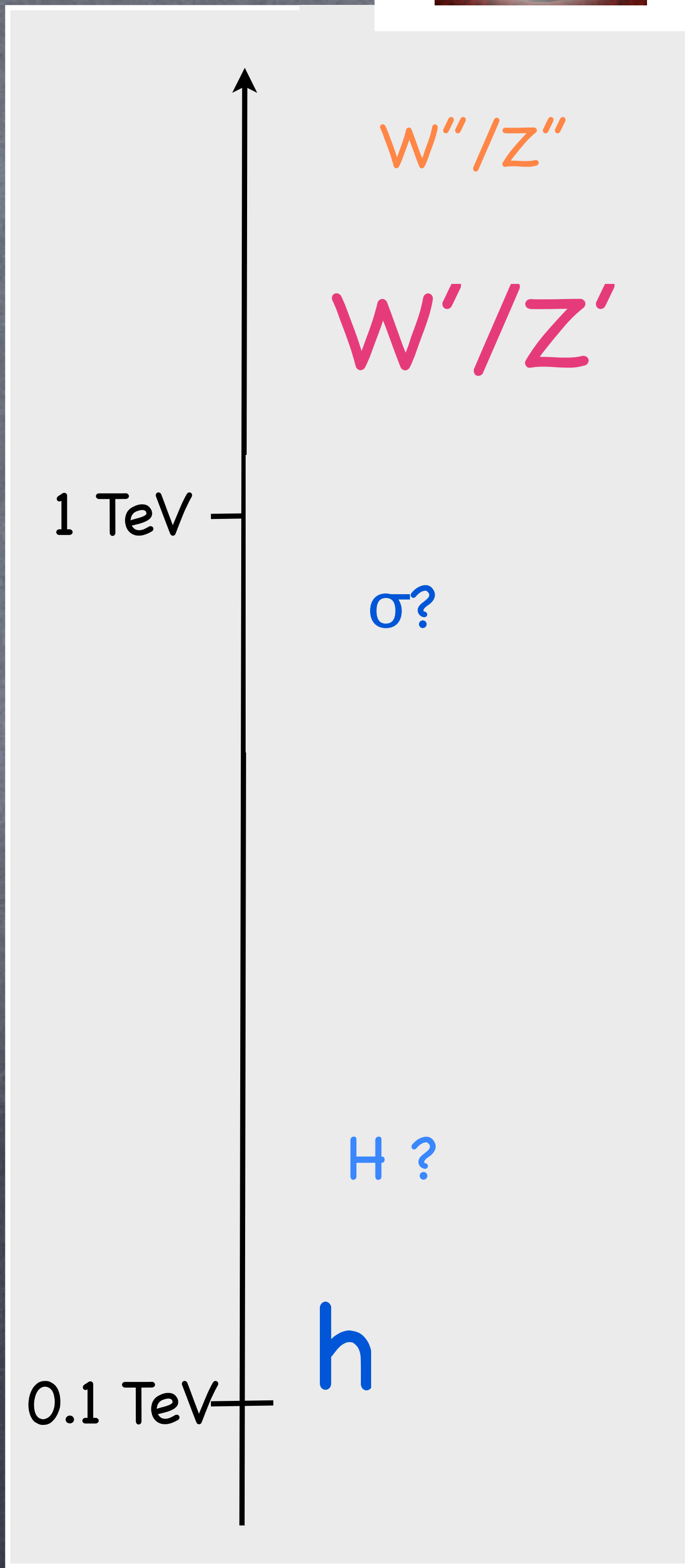
- Moreover, it contains pions and kaons who are (pseudo-)scalar with m<< 1 GeV. That's because they are pseudo-Goldstone bosons of approximate SU(3)xSU(3) symmetry of QCD rotating left- and right-handed light quarks, which is then spontaneously broken to SU(3) by vacuum condensate

- Technically, pions are protected by shift symmetry $\pi \to \pi + \alpha$ in the effective Lagrangian below 1 GeV



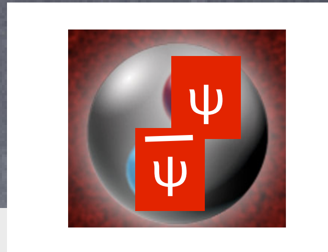
Composite Higgs

- This or similar structure can be carried over to a strongly interacting gauge sector confining near the TeV scale
- σ-like scalars are not attractive candidates for the 125 GeV Higgs, as the latter should be narrow and much lighter than cut-off
- Therefore, the 125 GeV Higgs should be pion-like, that is it should be a pseudo-Goldstone boson
- Optionally, depending on the global symmetry of the strongly interacting sector, there may be additional light pGB scalars (kaon-like) forming an extended Higgs sector
- Near the TeV scale there should be a tower of spin-1 and other resonances



Composite (PGB) Higgs

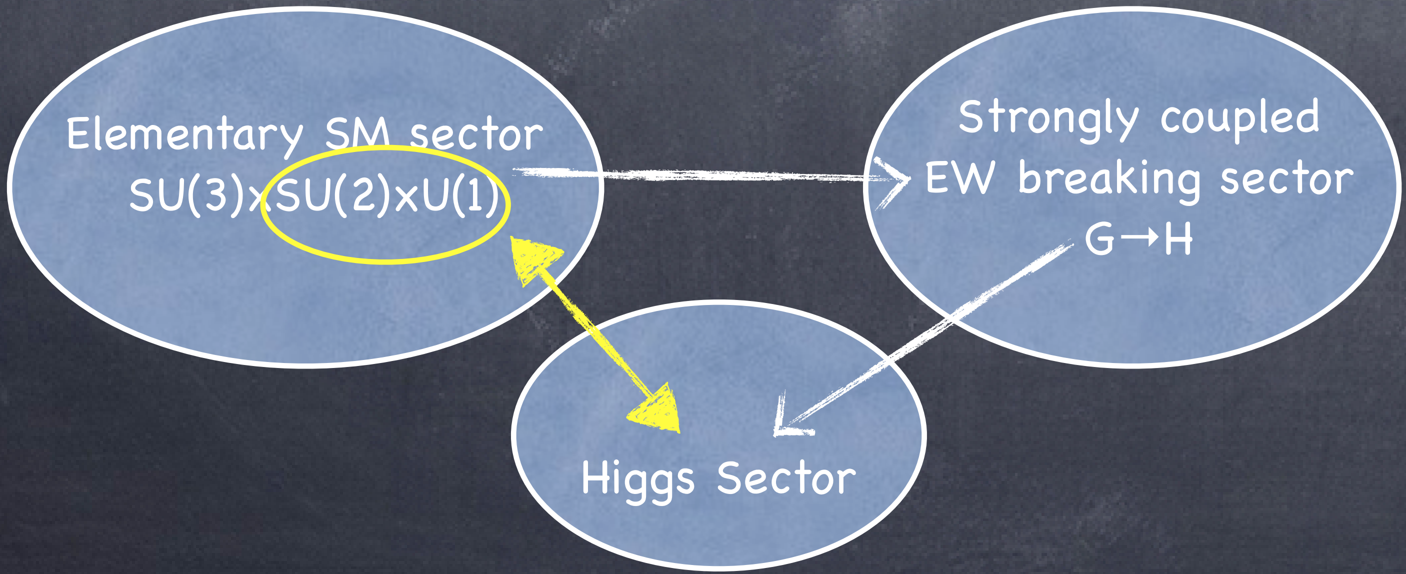
Kaplan, Georgi
Phys. Lett. B136 (1984)

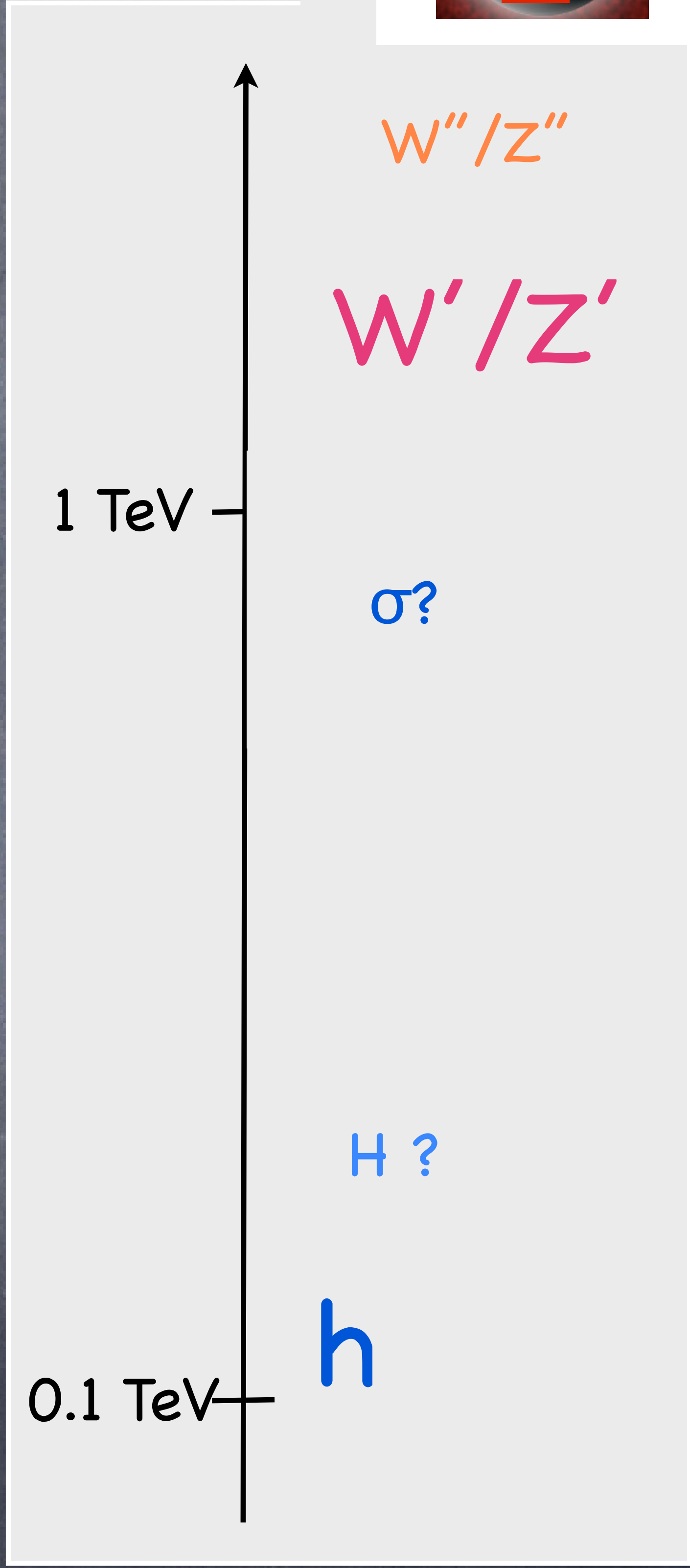


- Composite Higgs scenario assumes the existence of a strongly coupled sector charged under the SM local symmetry. Furthermore, the strong sector has a global symmetry that is larger than the SM gauge group

- Spontaneous breaking of that global symmetry gives rise to a set of Goldstone boson, some of which are identified with the SM Higgs doublet

- The global symmetry is softly broken by couplings to SM, allowing the Higgs to acquire mass (becoming a pseudo-Goldstone boson) but still protecting the Higgs mass from quadratically divergent loop corrections





Agashe et al
hep-ph/041289

Minimal Composite Higgs

SO(5)/SO(4) goldstone bosons

Broken SO(5) generators

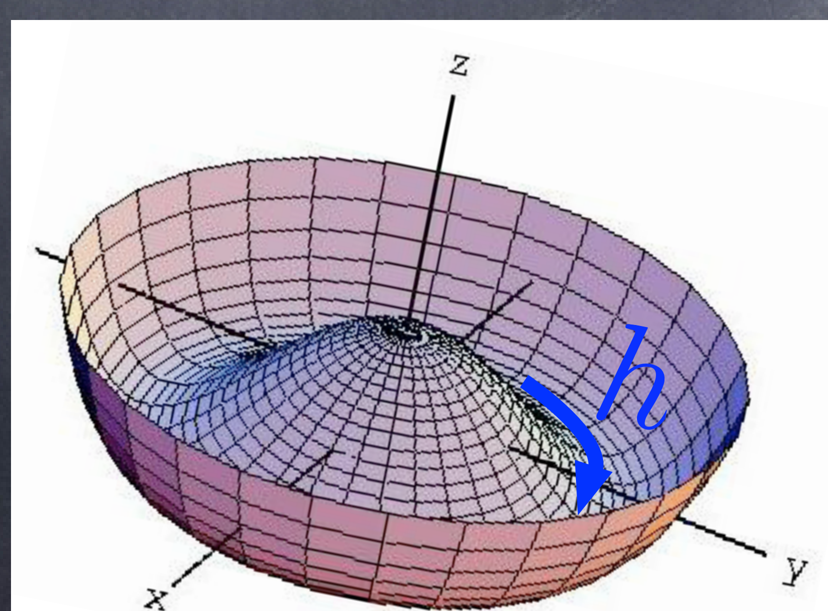
$$\Sigma(x) = (0,0,0,0,1) \,.\, \exp\left(\frac{-i\sqrt{2}T^a h^a}{f}\right)$$

Decay constant

- Model with pGB Higgs arising from strongly interacting sector where SO(5) global symmetry is spontaneously broken to SO(4)
- SO(5)=10 generators, SO(4)=6 generators, thus 4 Goldstone boson corresponding to 1 Higgs doublet (minimal Higgs sector)
- Higgs can be thought of as an angular variable along the valley of unbroken SO(4), while the radial direction corresponds to heavy excitations which are integrated out in effective description

$$\Sigma(x) = \begin{pmatrix} 0 \\ 0 \\ 0 \\ \sin\left(\frac{\hat{v}+h}{f}\right) \\ \cos\left(\frac{\hat{v}+h}{f}\right) \end{pmatrix}$$

Our Higgs boson



$$\mathcal{L} \supset \frac{1}{2} f^2 \partial_\mu \Sigma^T \partial_\mu \Sigma$$

Minimal Composite Higgs

Contino
1005.4269

- SM SU(2)LxU(1)Y local symmetry can be embedded into unbroken SO(4)=SU(2)LxSU(2)R subgroup
- To correctly realize hypercharge extend global symmetry to SO(5)xU(1)

$$(P_T)_{\mu\nu} \equiv \eta_{\mu\nu} - \frac{q_\mu q_\nu}{q^2}$$

Form factors

$$\mathcal{L} = \frac{1}{2}(P_T)^{\mu\nu}\left[\Pi_0^X(q^2)\, X_\mu X_\nu + \Pi_0(q^2)\,\mathrm{Tr}(A_\mu A_\nu) + \Pi_1(q^2)\,\Sigma A_\mu A_\nu \Sigma^t\right]$$

U(1) vector

SO(5) vector

Lowest order Lagrangian for EW gauge bosons

$$\mathcal{L} \supset \frac{f^2}{8}\sin^2\left(\frac{\hat{v}+h}{f}\right)\left[W_\mu^1 W_\mu^1 + W_\mu^2 W_\mu^2 + W_\mu^3 W_\mu^3 - 2W_\mu^3 B_\mu + B_\mu B_\mu\right]$$
$$+\frac{1}{2}\left(\eta_{\mu\nu}q^2 - q_\mu q_\nu\right)\left(\Pi_0'(0)(W_\mu^1 W_\nu^1 + W_\mu^2 W_\nu^2 + W_\mu^3 W_\nu^3) + [\Pi_0'(0) + \Pi_0^{X\prime}(0)]B_\mu B_\nu\right)$$
$$+\ldots$$

Identify:

$$v = f\sin\left(\frac{\hat{v}}{f}\right)$$

$$\frac{1}{g_L^2} = \Pi_0'(0), \qquad \frac{1}{g_Y^2} = \Pi_0'(0) + \Pi_0^{X\prime}(0)$$

Composite Higgs couplings to EW gauge bosons is always reduced!

$$\mathcal{L} \supset \sqrt{1 - \frac{v^2}{f^2}}\,\frac{h}{v}\left(2m_W^2 W_\mu^+ W_\mu^- + m_Z^2 Z_\mu Z_\mu\right)$$

Non-Minimal Composite Higgs

Mrazek et al
1105.5403

Examples of cosets with custodial symmetry

G	H	N_G	NGBs rep.$[H]$ = rep.$[\mathrm{SU}(2)\times\mathrm{SU}(2)]$
SO(5)	SO(4)	4	$\mathbf{4} = (\mathbf{2},\mathbf{2})$
SO(6)	SO(5)	5	$\mathbf{5} = (\mathbf{1},\mathbf{1}) + (\mathbf{2},\mathbf{2})$
SO(6)	SO(4) × SO(2)	8	$\mathbf{4_{+2}} + \mathbf{\bar{4}_{-2}} = 2\times(\mathbf{2},\mathbf{2})$
SO(7)	SO(6)	6	$\mathbf{6} = 2\times(\mathbf{1},\mathbf{1}) + (\mathbf{2},\mathbf{2})$
SO(7)	G_2	7	$\mathbf{7} = (\mathbf{1},\mathbf{3}) + (\mathbf{2},\mathbf{2})$
SO(7)	SO(5) × SO(2)	10	$\mathbf{10_0} = (\mathbf{3},\mathbf{1}) + (\mathbf{1},\mathbf{3}) + (\mathbf{2},\mathbf{2})$
SO(7)	$[\mathrm{SO}(3)]^3$	12	$(\mathbf{2},\mathbf{2},\mathbf{3}) = 3\times(\mathbf{2},\mathbf{2})$
Sp(6)	Sp(4) × SU(2)	8	$(\mathbf{4},\mathbf{2}) = 2\times(\mathbf{2},\mathbf{2}), (\mathbf{2},\mathbf{2}) + 2\times(\mathbf{2},\mathbf{1})$
SU(5)	SU(4) × U(1)	8	$\mathbf{4}_{-5} + \mathbf{\bar{4}_{+5}} = 2\times(\mathbf{2},\mathbf{2})$
SU(5)	SO(5)	14	$\mathbf{14} = (\mathbf{3},\mathbf{3}) + (\mathbf{2},\mathbf{2}) + (\mathbf{1},\mathbf{1})$

just doublet

doublet+singlet

2 doublets

- Many other coset structure possible, giving rise to extended Higgs sector
- Some of those may be more minimal than the minimal one, once realized in terms of fundamental degrees of freedom of the strong sector

D. Kaplan
Nucl.Phys. B365 (1991)

Coupling to fermions

Panico, Wulzer
1506.01961

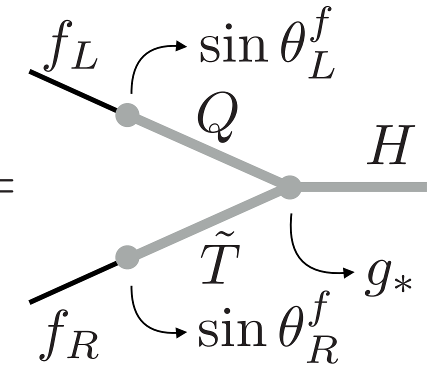
Partial compositeness:

elementary fermions mix with chiral composite operators which have mass terms after EW breaking

$$\mathcal{L}^f_{\text{int}} = \lambda_R \bar{t}_R \mathcal{O}_L + \lambda_L \bar{q}_L \mathcal{O}_R$$

Elementary Composite

$$y_t =$$



$$= g_* \cdot \sin\theta_L^f \cdot \sin\theta_R^f$$

Physics depends on representation O

$$\mathcal{L}^f_{\text{int}} = \lambda_R \overline{T}^I_R \mathcal{O}^I_L + \lambda_L \overline{Q}^I_L \mathcal{O}^I_R$$

E.g. for SO(5) one can choose fundamental rep.

$$Q_L = \frac{1}{\sqrt{2}}\{-i\,b_L,\ -b_L,\ -i\,t_L,\ t_L,\ 0\}$$

$$T_R = \{0,\ 0,\ 0,\ 0,\ t_R\}$$

$$\mathcal{L}_{\text{strong}} \supset (\Sigma^T O_L)(\Sigma^T O_R)$$

Different choices lead to different Higgs couplings strength to fermions

$\mathcal{Q}_L \setminus \mathcal{Q}_R$	**1**	**5**	**10**	**14**
5	$1/2$	$3/2$	$1/2$	$\frac{5}{2}\,\frac{1-\frac{24}{25}\frac{y_1}{y_4}}{1-\frac{4}{5}\frac{y_1}{y_4}}$
10	$\times$	$1/2$	$3/2$	$3/2$
14	$3/2$	$\frac{9}{2}\,\frac{1-\frac{10}{9}\frac{y_1}{y_4}}{1-2\frac{y_1}{y_4}}$	$3/2$	$\frac{11}{2}\,\frac{1-\frac{64}{55}\frac{y_1}{y_4}-\frac{6}{11}\frac{y_9}{y_4}}{1-\frac{8}{5}\frac{y_1}{y_4}}$

borrowed from A. Wulzer slides

$$\xi \equiv \frac{v^2}{f^2}$$

Montull et al
1308.0559

$$\text{MCHM}_{\mathbf{5}\oplus\mathbf{5}} \longrightarrow k_F = \frac{1-2\xi}{\sqrt{1-\xi}}$$

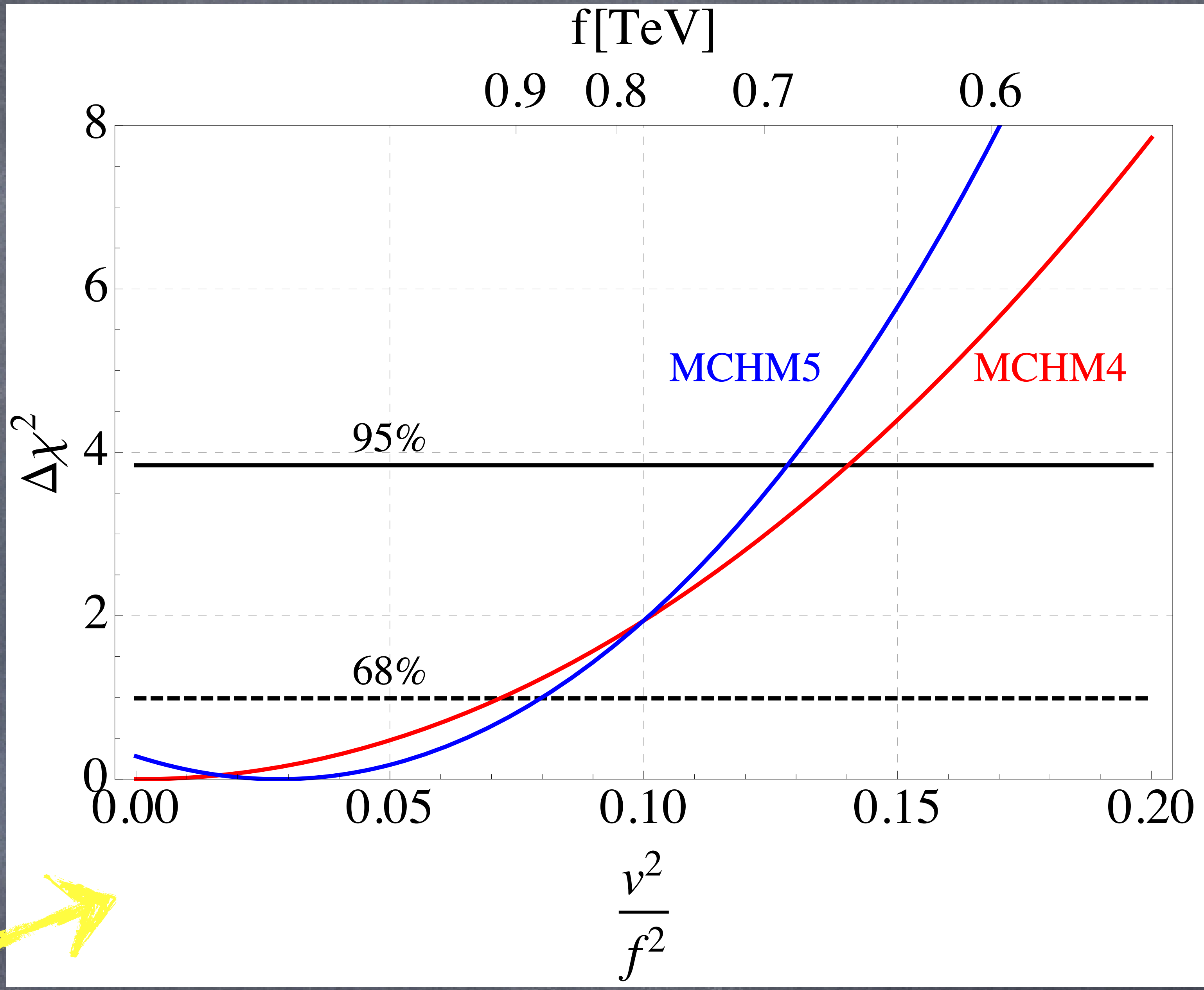
$$\text{MCHM}_{\mathbf{4}\oplus\mathbf{4}} \longrightarrow k_F = \sqrt{1-\xi}$$

$$\text{MCHM}_{\mathbf{14}\oplus\mathbf{1}} \longrightarrow k_F = \frac{1-2\xi}{\sqrt{1-\xi}}$$

Current constraints

- Precise bound on global symmetry breaking scale depends a bit on realization of fermion sector
- However typical bound is in the 700 GeV ballpark

Channel	Production	Run-1	ATLAS Run-2	CMS Run-2
$\gamma\gamma$	ggh	$1.10^{+0.23}_{-0.22}$	$0.62^{+0.30}_{-0.29}$ [4]	$0.77^{+0.25}_{-0.23}$ [5]
	VBF	$1.3^{+0.5}_{-0.5}$	$2.25^{+0.75}_{-0.75}$ [4]	$1.61^{+0.90}_{-0.80}$ [5]
	Wh	$0.5^{+1.3}_{-1.2}$	-	-
	Zh	$0.5^{+3.0}_{-2.5}$	-	-
	Vh	-	$0.30^{+1.21}_{-1.12}$ [4]	-
	$t\bar{t}h$	$2.2^{+1.6}_{-1.3}$	$-0.22^{+1.26}_{-0.99}$ [4]	$1.9^{+1.5}_{-1.2}$ [5]
$Z\gamma$	incl.	$1.4^{+3.3}_{-3.2}$	-	-
ZZ^*	ggh	$1.13^{+0.34}_{-0.31}$	$1.34^{+0.39}_{-0.33}$ [4]	$0.96^{+0.40}_{-0.33}$ [6]
	VBF	$0.1^{+1.1}_{-0.6}$	$3.8^{+2.8}_{-2.2}$ [4]	$0.67^{+1.61}_{-0.67}$ [6]
WW^*	ggh	$0.84^{+0.17}_{-0.17}$	-	-
	VBF	$1.2^{+0.4}_{-0.4}$	$1.7^{+1.2}_{-0.9}$	-
	Wh	$1.6^{+1.2}_{-1.0}$	$3.2^{+4.4}_{-4.2}$	-
	Zh	$5.9^{+2.6}_{-2.2}$	-	-
	$t\bar{t}h$	$5.0^{+1.8}_{-1.7}$	-	-
	incl.	-	-	0.3 ± 0.5 [7]
$\tau^+\tau^-$	ggh	$1.0^{+0.6}_{-0.6}$	-	-
	VBF	$1.3^{+0.4}_{-0.4}$	-	-
	Wh	$-1.4^{+1.4}_{-1.4}$	-	-
	Zh	$2.2^{+2.2}_{-1.8}$	-	-
	$t\bar{t}h$	$-1.9^{+3.7}_{-3.3}$	-	-
$b\bar{b}$	VBF	-	$-3.9^{+2.8}_{-2.9}$ [8]	$-3.7^{+2.4}_{-2.5}$ [9]
	Wh	$1.0^{+0.5}_{-0.5}$	-	-
	Zh	$0.4^{+0.4}_{-0.4}$	-	-
	Vh	-	$0.21^{+0.51}_{-0.50}$ [10]	-
	$t\bar{t}h$	$1.15^{+0.99}_{-0.94}$	$2.1^{+1.0}_{-0.9}$ [11]	$-0.19^{+0.80}_{-0.81}$
$\mu^+\mu^-$	incl.	$0.1^{+2.5}_{-2.5}$	$-0.8^{+2.2}_{-2.2}$ [13]	-
multi-ℓ	cats.	-	$2.5^{+1.3}_{-1.1}$ [14]	$2.3^{+0.9}_{-0.8}$ [15]



LHCHXSWG
1610.07922

Digression: general EFT Higgs constraints

$$
\begin{aligned}
\mathcal{L}_{\rm hvv} = \frac{h}{v}[& 2(1+\delta c_w) m_W^2 W_\mu^+ W_\mu^- + (1+\delta c_z) m_Z^2 Z_\mu Z_\mu \\
& + c_{ww} \frac{g_L^2}{2} W_{\mu\nu}^+ W_{\mu\nu}^- + \tilde{c}_{ww} \frac{g_L^2}{2} W_{\mu\nu}^+ \tilde{W}_{\mu\nu}^- + c_{w\Box} g_L^2 \left(W_\mu^- \partial_\nu W_{\mu\nu}^+ + \text{h.c.} \right) \\
& + c_{gg} \frac{g_s^2}{4} G_{\mu\nu}^a G_{\mu\nu}^a + c_{\gamma\gamma} \frac{e^2}{4} A_{\mu\nu} A_{\mu\nu} + c_{z\gamma} \frac{e g_L}{2 c_\theta} Z_{\mu\nu} A_{\mu\nu} + c_{zz} \frac{g_L^2}{4 c_\theta^2} Z_{\mu\nu} Z_{\mu\nu} \\
& + c_{z\Box} g_L^2 Z_\mu \partial_\nu Z_{\mu\nu} + c_{\gamma\Box} g_L g_Y Z_\mu \partial_\nu A_{\mu\nu} \\
& + \tilde{c}_{gg} \frac{g_s^2}{4} G_{\mu\nu}^a \tilde{G}_{\mu\nu}^a + \tilde{c}_{\gamma\gamma} \frac{e^2}{4} A_{\mu\nu} \tilde{A}_{\mu\nu} + \tilde{c}_{z\gamma} \frac{e g_L}{2 c_\theta} Z_{\mu\nu} \tilde{A}_{\mu\nu} + \tilde{c}_{zz} \frac{g_L^2}{4 c_\theta^2} Z_{\mu\nu} \tilde{Z}_{\mu\nu}]
\end{aligned}
$$

$$
\mathcal{L}_{\rm hff} = -\frac{h}{v} \sum_{f=u,d,e} m_f f^c (I + \delta y_f e^{i\phi_f}) f + \text{h.c.}
$$

$$
\begin{aligned}
\delta c_w &= \delta c_z + 4\delta m, \\
c_{ww} &= c_{zz} + 2 s_\theta^2 c_{z\gamma} + s_\theta^4 c_{\gamma\gamma}, \\
\tilde{c}_{ww} &= \tilde{c}_{zz} + 2 s_\theta^2 \tilde{c}_{z\gamma} + s_\theta^4 \tilde{c}_{\gamma\gamma}, \\
c_{w\Box} &= \frac{1}{g_L^2 - g_Y^2} \left[g_L^2 c_{z\Box} + g_Y^2 c_{zz} - e^2 s_\theta^2 c_{\gamma\gamma} - (g_L^2 - g_Y^2) s_\theta^2 c_{z\gamma} \right], \\
c_{\gamma\Box} &= \frac{1}{g_L^2 - g_Y^2} \left[2 g_L^2 c_{z\Box} + (g_L^2 + g_Y^2) c_{zz} - e^2 c_{\gamma\gamma} - (g_L^2 - g_Y^2) c_{z\gamma} \right]
\end{aligned}
$$

relative correction
to W mass

- In SM EFT, assuming MFV, there are 9 independent linear combinations of CP-even dimension-6 operators which affect single Higgs couplings to matter at leading order but don't affect electroweak precision observables

- These combinations can be labeled by the Higgs boson couplings in the effective Lagrangian to which each one contributes

- The current Higgs data already allow one to place non-trivial constraints on these 9 combinations of dimension-6 operators

Digression: general EFT Higgs constraints

$$
\begin{aligned}
\mathcal{L}_{\rm hvv} = \frac{h}{v}[& 2(1+\delta c_w) m_W^2 W_\mu^+ W_\mu^- + (1+\delta c_z) m_Z^2 Z_\mu Z_\mu \\
& + c_{ww} \frac{g_L^2}{2} W_{\mu\nu}^+ W_{\mu\nu}^- + \tilde{c}_{ww} \frac{g_L^2}{2} W_{\mu\nu}^+ \tilde{W}_{\mu\nu}^- + c_{w\Box} g_L^2 \left(W_\mu^- \partial_\nu W_{\mu\nu}^+ + \text{h.c.} \right) \\
& + c_{gg} \frac{g_s^2}{4} G_{\mu\nu}^a G_{\mu\nu}^a + c_{\gamma\gamma} \frac{e^2}{4} A_{\mu\nu} A_{\mu\nu} + c_{z\gamma} \frac{e g_L}{2 c_\theta} Z_{\mu\nu} A_{\mu\nu} + c_{zz} \frac{g_L^2}{4 c_\theta^2} Z_{\mu\nu} Z_{\mu\nu} \\
& + c_{z\Box} g_L^2 Z_\mu \partial_\nu Z_{\mu\nu} + c_{\gamma\Box} g_L g_Y Z_\mu \partial_\nu A_{\mu\nu} \\
& + \tilde{c}_{gg} \frac{g_s^2}{4} G_{\mu\nu}^a \tilde{G}_{\mu\nu}^a + \tilde{c}_{\gamma\gamma} \frac{e^2}{4} A_{\mu\nu} \tilde{A}_{\mu\nu} + \tilde{c}_{z\gamma} \frac{e g_L}{2 c_\theta} Z_{\mu\nu} \tilde{A}_{\mu\nu} + \tilde{c}_{zz} \frac{g_L^2}{4 c_\theta^2} Z_{\mu\nu} \tilde{Z}_{\mu\nu}]
\end{aligned}
$$

$$
\mathcal{L}_{\rm hff} = -\frac{h}{v} \sum_{f=u,d,e} m_f f^c (I + \delta y_f e^{i\phi_f}) f + \text{h.c.}
$$

	Higgs Run1&2
δc_z	-0.13 ± 0.11
c_{zz}	-0.56 ± 0.33
$c_{z\Box}$	0.21 ± 0.12
$c_{\gamma\gamma}$	0.0072 ± 0.0073
$c_{z\gamma}$	-0.015 ± 0.074
c_{gg}	-0.0040 ± 0.0009
δy_u	0.17 ± 0.13
δy_d	-0.51 ± 0.18
δy_e	-0.13 ± 0.13

Channel	Production	Run-1	ATLAS Run-2	CMS Run-2
$\gamma\gamma$	ggh	$1.10^{+0.23}_{-0.22}$	$0.62^{+0.30}_{-0.29}$ [4]	$0.77^{+0.25}_{-0.23}$ [5]
	VBF	$1.3^{+0.5}_{-0.5}$	$2.25^{+0.75}_{-0.75}$ [4]	$1.61^{+0.90}_{-0.80}$ [5]
	Wh	$0.5^{+1.3}_{-1.2}$	-	-
	Zh	$0.5^{+3.0}_{-2.5}$	-	-
	Vh	-	$0.30^{+1.21}_{-1.12}$ [4]	-
	$t\bar{t}h$	$2.2^{+1.6}_{-1.3}$	$-0.22^{+1.26}_{-0.99}$ [4]	$1.9^{+1.5}_{-1.2}$ [5]
$Z\gamma$	incl.	$1.4^{+3.3}_{-3.2}$	-	-
ZZ^*	ggh	$1.13^{+0.34}_{-0.31}$	$1.34^{+0.39}_{-0.33}$ [4]	$0.96^{+0.40}_{-0.33}$ [6]
	VBF	$0.1^{+1.1}_{-0.6}$	$3.8^{+2.8}_{-2.2}$ [4]	$0.67^{+1.61}_{-0.67}$ [6]
WW^*	ggh	$0.84^{+0.17}_{-0.17}$	-	-
	VBF	$1.2^{+0.4}_{-0.4}$	$1.7^{+1.2}_{-0.9}$	-
	Wh	$1.6^{+1.2}_{-1.0}$	$3.2^{+4.4}_{-4.2}$	-
	Zh	$5.9^{+2.6}_{-2.2}$	-	-
	$t\bar{t}h$	$5.0^{+1.8}_{-1.7}$	-	-
	incl.	-	-	0.3 ± 0.5 [7]
$\tau^+\tau^-$	ggh	$1.0^{+0.6}_{-0.6}$	-	-
	VBF	$1.3^{+0.4}_{-0.4}$	-	-
	Wh	$-1.4^{+1.4}_{-1.4}$	-	-
	Zh	$2.2^{+2.2}_{-1.8}$	-	-
	$t\bar{t}h$	$-1.9^{+3.7}_{-3.3}$	-	-
$b\bar{b}$	VBF	-	$-3.9^{+2.8}_{-2.9}$ [8]	$-3.7^{+2.4}_{-2.5}$ [9]
	Wh	$1.0^{+0.5}_{-0.5}$	-	-
	Zh	$0.4^{+0.4}_{-0.4}$	-	-
	Vh	-	$0.21^{+0.51}_{-0.50}$ [10]	-
	$t\bar{t}h$	$1.15^{+0.99}_{-0.94}$	$2.1^{+1.0}_{-0.9}$ [11]	$-0.19^{+0.80}_{-0.81}$
$\mu^+\mu^-$	incl.	$0.1^{+2.5}_{-2.5}$	$-0.8^{+2.2}_{-2.2}$ [13]	-
multi-ℓ	cats.	-	$2.5^{+1.3}_{-1.1}$ [14]	$2.3^{+0.9}_{-0.8}$ [15]

- Some tension in the global fit due to the deficit in the bb decay mode
- Decrease in bb needs to be compensated by negative contributions to Higgs-gluon couplings, to avoid overshooting γγ, WW, and ZZ channels

EFT for composite Higgs

Giudice et al
hep-ph/0703164

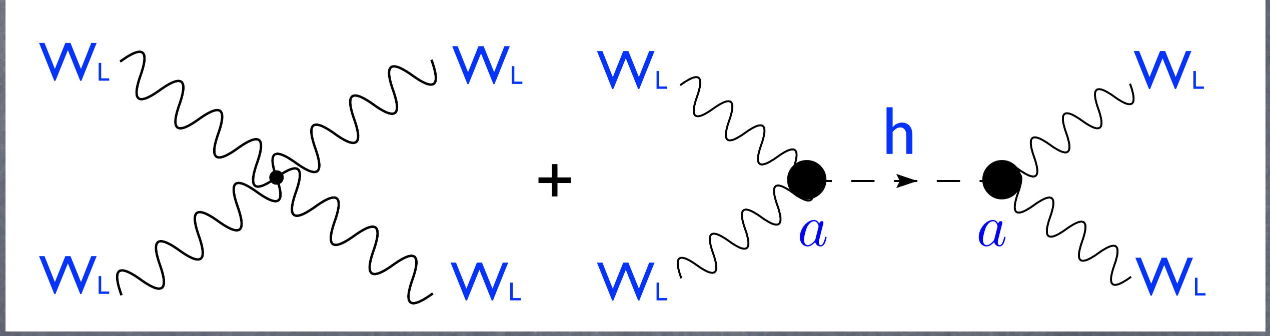
SILH power counting rules for EFT dimension-6 operators

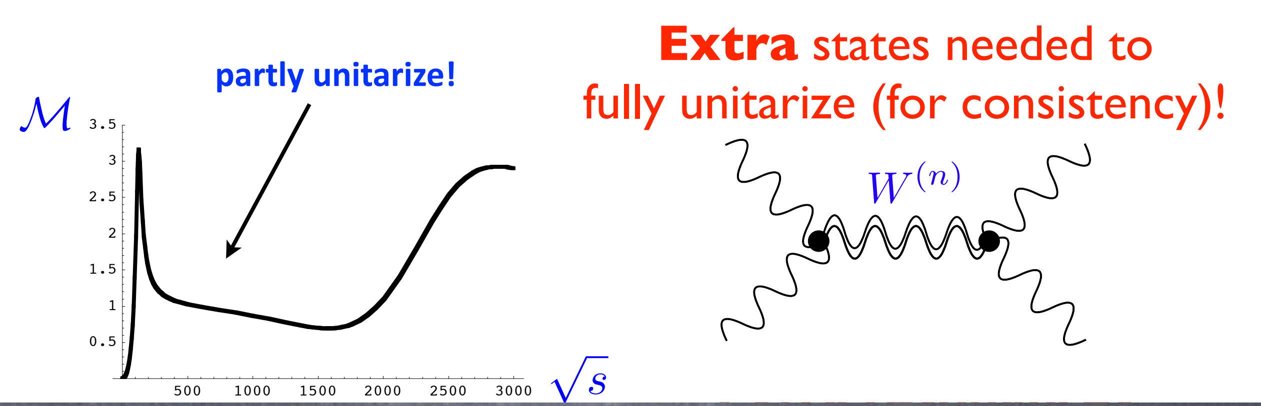
$$\mathcal{L}_{\rm SILH} = \frac{c_H}{2f^2}\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) + \frac{c_T}{2f^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right)$$
$$-\frac{c_6\lambda}{f^2}\left(H^\dagger H\right)^3 + \left(\frac{c_y y_f}{f^2} H^\dagger H \bar{f}_L H f_R + \text{h.c.}\right)$$
$$+\frac{ic_W g}{2m_\rho^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)\left(D^\nu W_{\mu\nu}\right)^i + \frac{ic_B g'}{2m_\rho^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(\partial^\nu B_{\mu\nu}\right)$$
$$+\frac{ic_{HW} g}{16\pi^2 f^2}(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} + \frac{ic_{HB} g'}{16\pi^2 f^2}(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$
$$+\frac{c_\gamma g'^2}{16\pi^2 f^2}\frac{g^2}{g_\rho^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{c_g g_S^2}{16\pi^2 f^2}\frac{y_t^2}{g_\rho^2} H^\dagger H G^a_{\mu\nu} G^{a\mu\nu}.$$

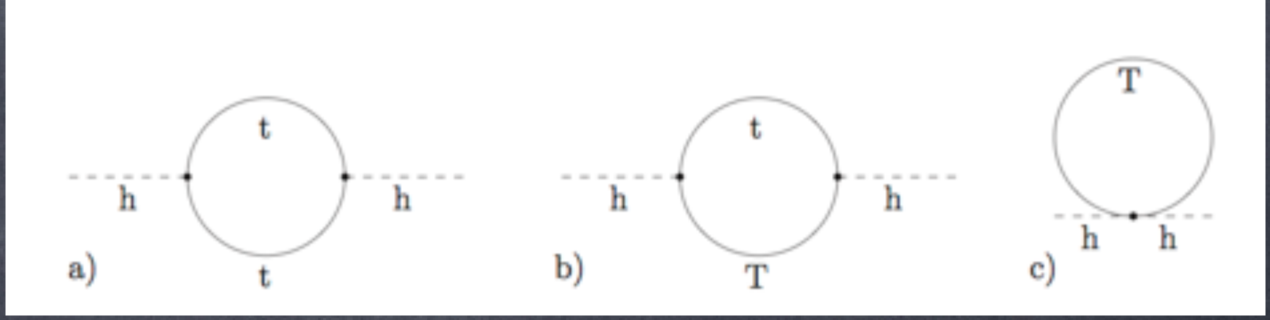
- Dominant effects yield rescaling of Higgs couplings to WW/ZZ/ff
- Contributions to Higgs contact interactions suppressed by additional small parameter yt^2/g*^2 due to shift symmetry

Composite Higgs Predictions

- Couplings of the Higgs boson modified by amounts of order v^2/f^2
- New vector resonances at the scale M*= g* f to unitarize VV amplitudes
- Corrections to electroweak precision observables from new resonances and modified Higgs couplings
- Assuming naturalness: f should be close to v, resonances should not be too heavy, and there should also be top partners near TeV
- Optional: fermionic partners to lighter quarks, extra scalars in Higgs sectors, 750 GeV resonances, etc.



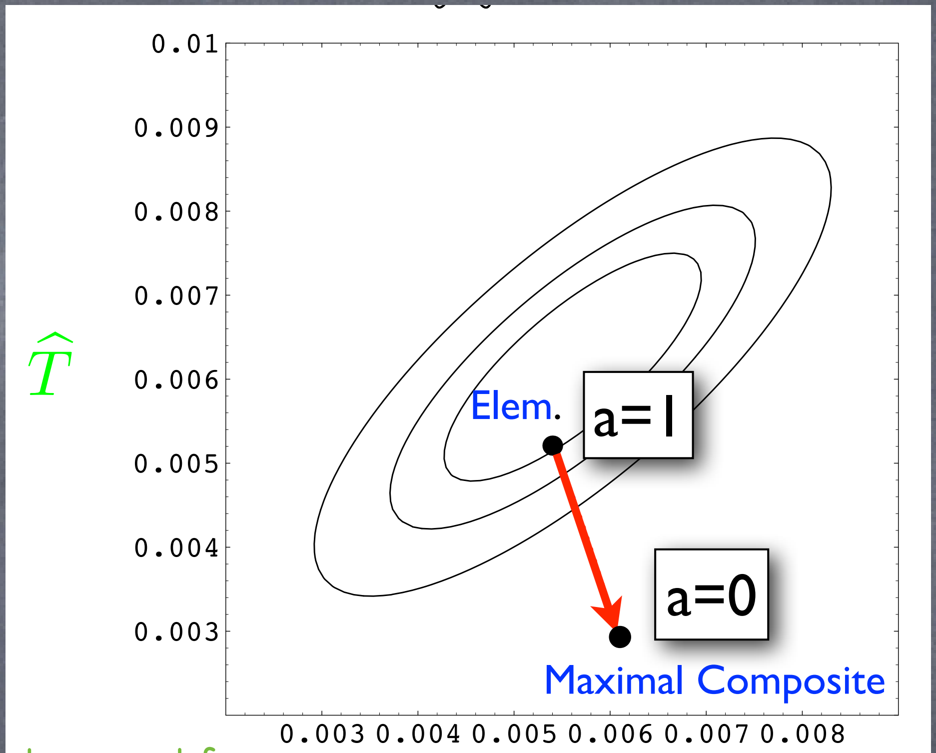




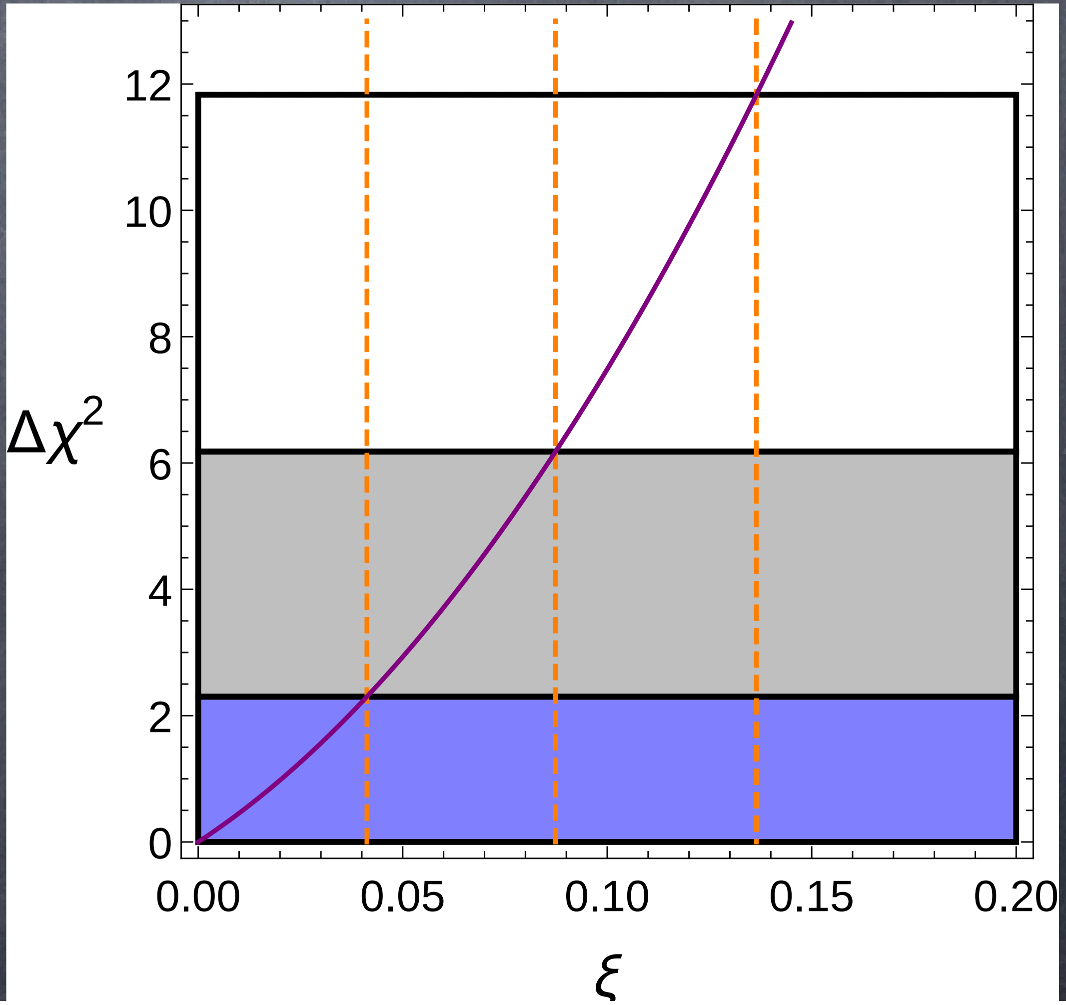
from Perelstein, hep-ph/0512128

Electroweak Precision Constraints

- New resonances give a positive contribution to S parameter
- Moreover, modifications of Higgs couplings effectively yield positive contribution to S and negative contribution to T
- Finally, there can be a new large contribution to Zbb vertex
- Constraints on symmetry breaking scale f are generically somewhat stronger than from LHC Higgs data, although they are much more model dependent



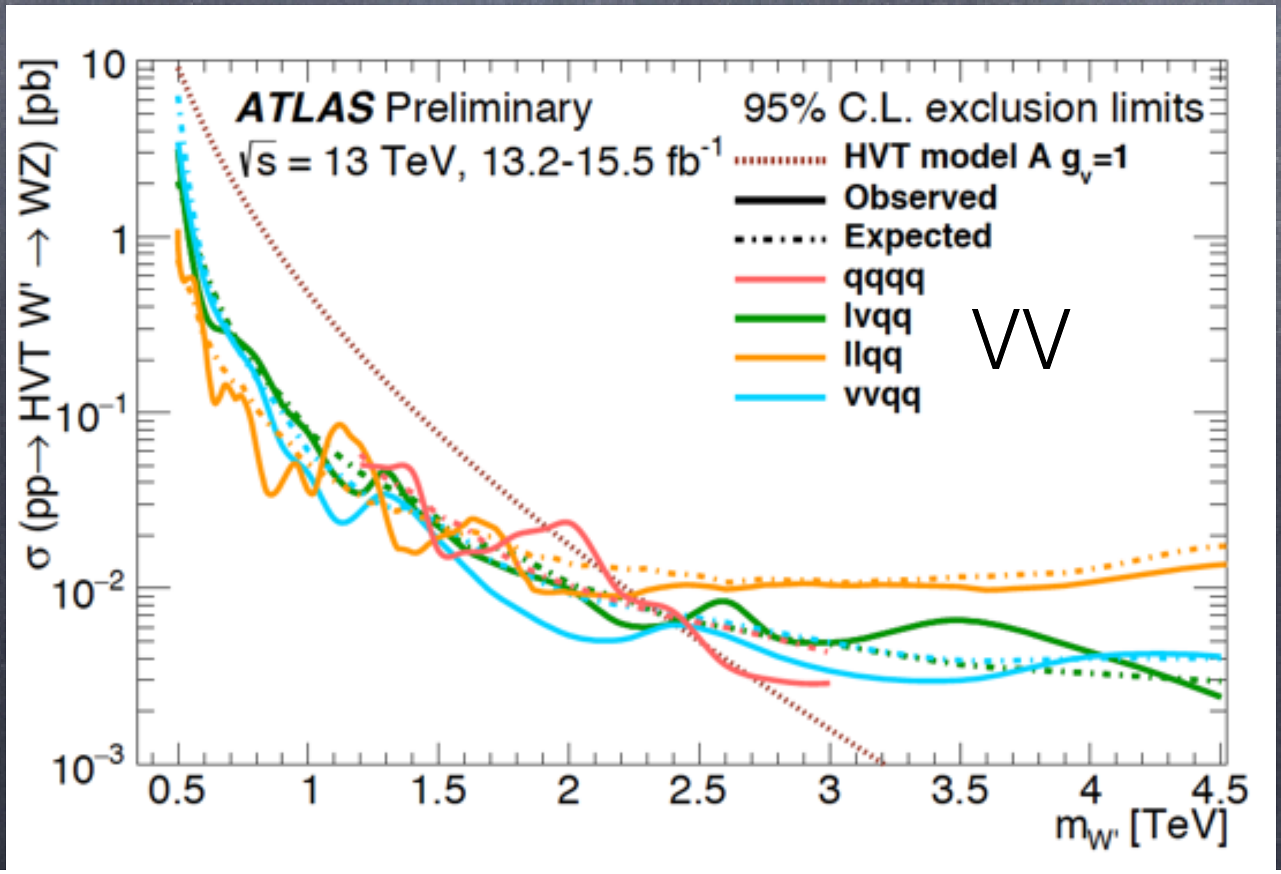
borrowed from A. Pomarol



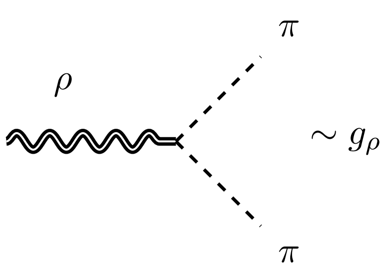
Ghosh et al 1511.08235

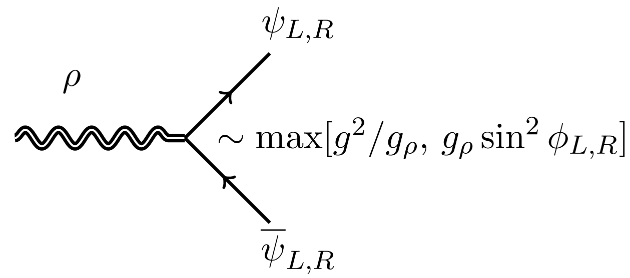
Direct Search for Vector Resonances

- Heavy vector resonances W' and Z' coupled most strongly to the heaviest SM particles. One should search for resonances in the t-tbar, and W+W-, WZ, and Wh invariant mass spectrum
- Couplings to quarks and to lepton is more model dependent. Some wiggle room to control production cross section. Depending on parameters dilepton signatures may be the leading ones.
- Current limits typically around 2-3 TeV, but can be evaded by tweaking parameters



Direct Search for Vector Resonances





	$VV,\, Vh$	$\bar{q}_L\gamma^\mu q_L$	$\bar{u}_R\gamma^\mu u_R$	$\bar{d}_R\gamma^\mu d_R$	$\bar{\ell}_L\gamma^\mu \ell_L$	$\bar{e}_R\gamma^\mu e_R$
$\rho^{0,\pm}$	g_ρ	$-\frac{g^2}{g_\rho}(1 - a_L \frac{g_\rho^2}{g^2} s^2_{L,q})\tau^a$	–	–	$-\frac{g^2}{g_\rho}\tau^a$	–
ρ^0_B	g_ρ	$-\frac{1}{6}\frac{g'^2}{g_\rho}(1 + 3a_L \frac{g_\rho^2}{g'^2} s^2_{L,q})$	$-\frac{2}{3}\frac{g'^2}{g_\rho}$	$\frac{1}{3}\frac{g'^2}{g_\rho}$	$\frac{1}{2}\frac{g'^2}{g_\rho}$	$\frac{g'^2}{g_\rho}$
$\rho^\pm_C$	g_ρ	–	–	–	–	–

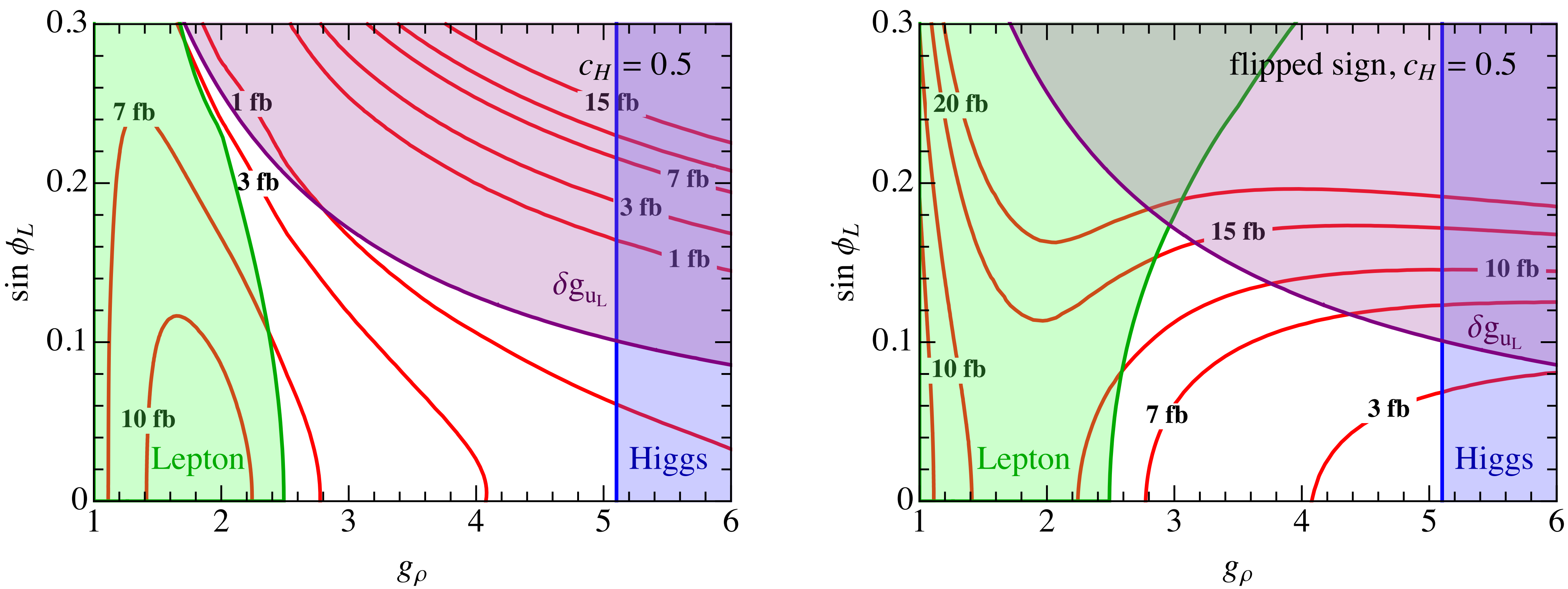
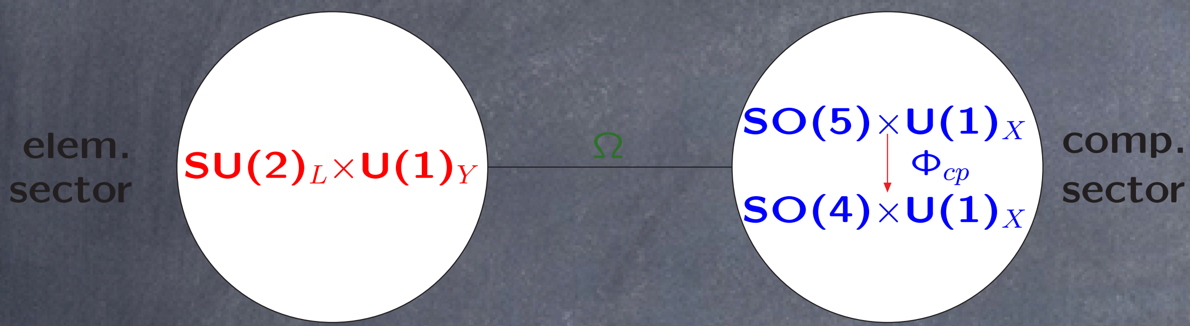


Figure 5. "Composite quarks (standard composite Higgs)." Diboson rate contours for $m_\rho = 2$ TeV and $c_H = 1/2$ with $a_L = 1$ (left) and $a_L = -1$ (right). The y-axis varies the degree of left compositeness of the (u_L, d_L) and (c_L, s_L) multiplets. The compositeness of the (t_L, b_L) multiplet is fixed at $\sin\phi^t_L = 0.4$.

Low et al
1507.07557

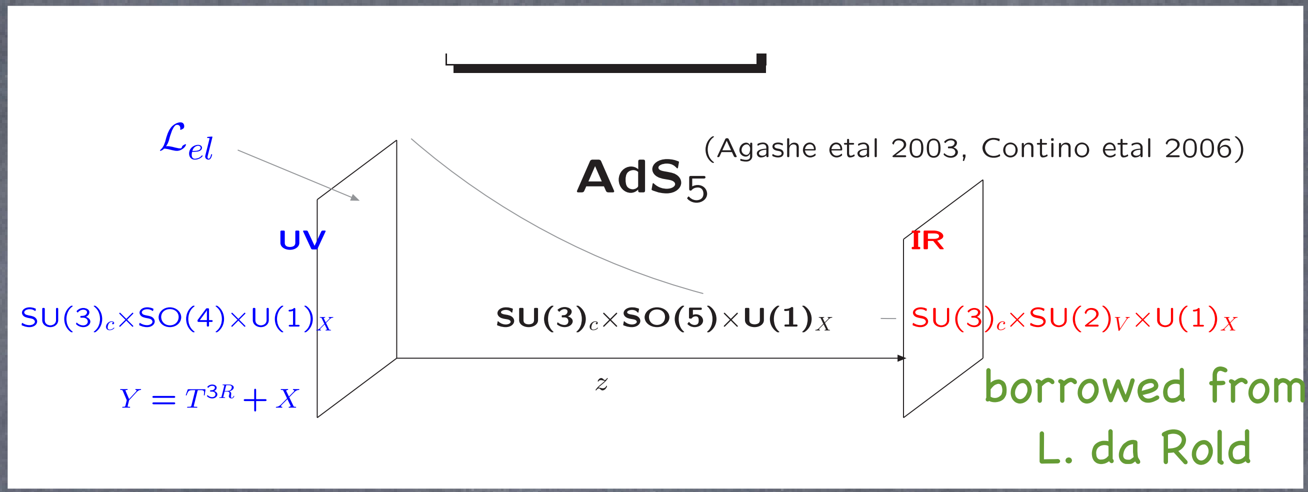
Related scenarios

Little Higgs/2-site model



Limit of CH where extra gauge bosons are weakly coupled and cutoff pushed higher

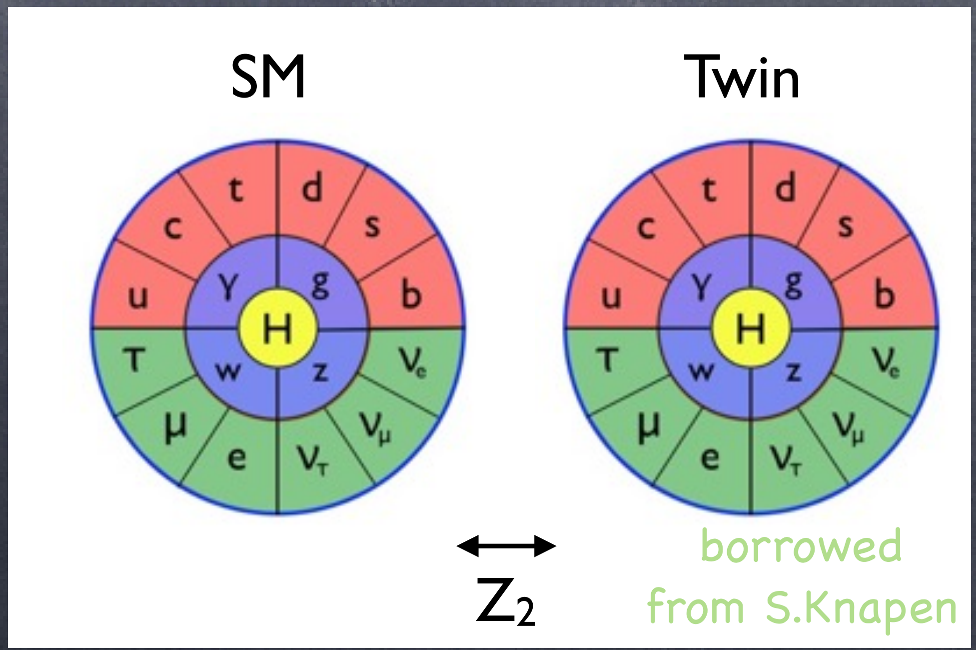
RS gauge-Higgs



Holographic version of large N composite Higgs where form factors are calculable

$\boxed{\text{CH}}$

Twin Higgs



Variant of CH where global symmetry arises accidentally from discrete symmetry, and strong sector charged under new SU(3) color

Summary

- Compositeness is a very natural framework to explain origin scalar particles, including the SM Higgs doublet
- The lightness of the Higgs boson wrt to the fundamental scale can be quantitatively understood, though fine-tuning seems inevitable at this point
- Precision measurements in the Higgs sector are a key to constraining the scale of Higgs compositeness