Singlets in Composite Higgs Models in the light of LHC di-boson searches

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based on:

G. Cacciapaglia, H. Cai, A. Deandrea, T. Flacke, S.J. Lee, A. Parolini [JHEP 1511 (2015) 201]

H. Cai, T. Flacke, M. Lespinasse [arXiv:1512.04508]

A. Belyaev, G. Cacciapaglia, H. Cai, T. Flacke, H. Serodio, A. Parolini [arXiv:1512.07242, PRD 94, xxx]

A. Belyaev, G. Cacciapaglia, H. Cai, G. Ferretti, T. Flacke, H. Serodio, A. Parolini [in preparation]

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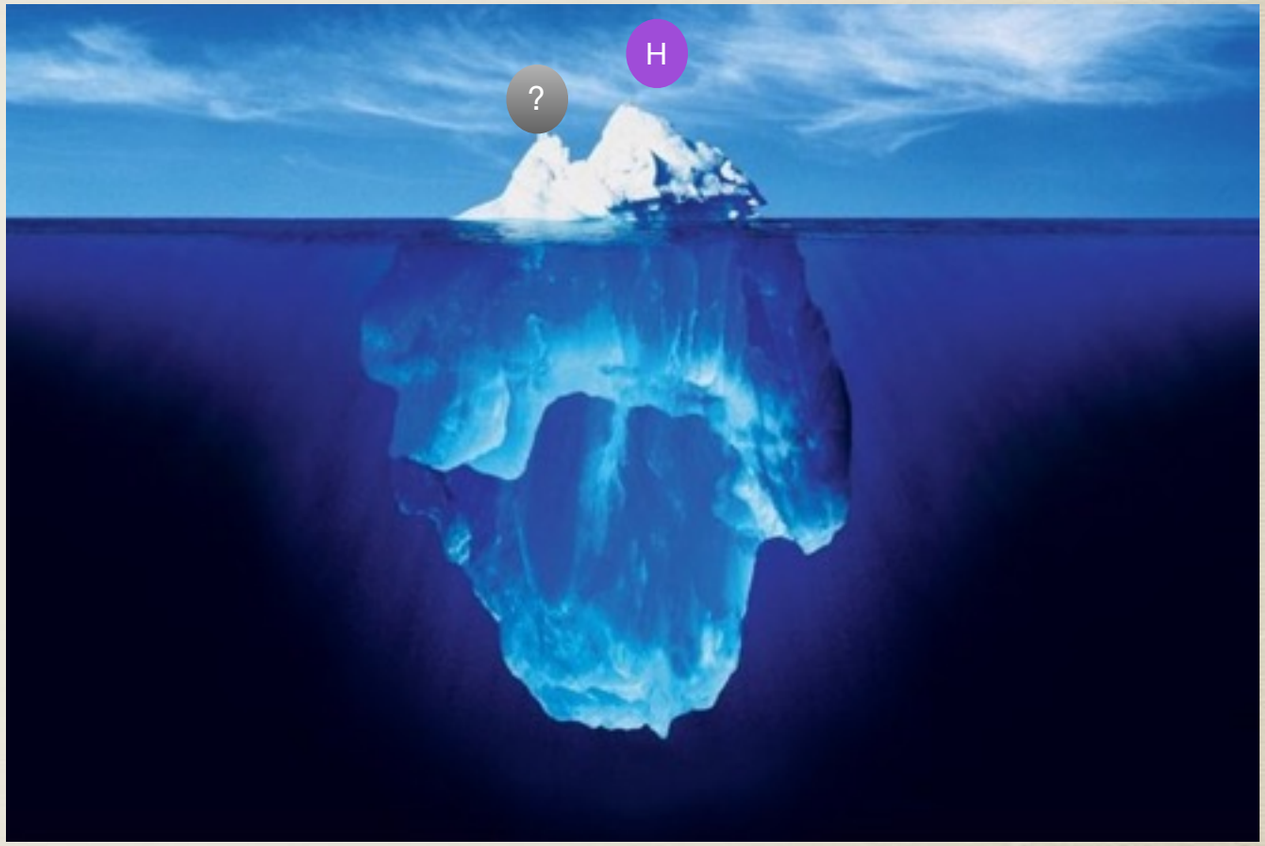
Outline

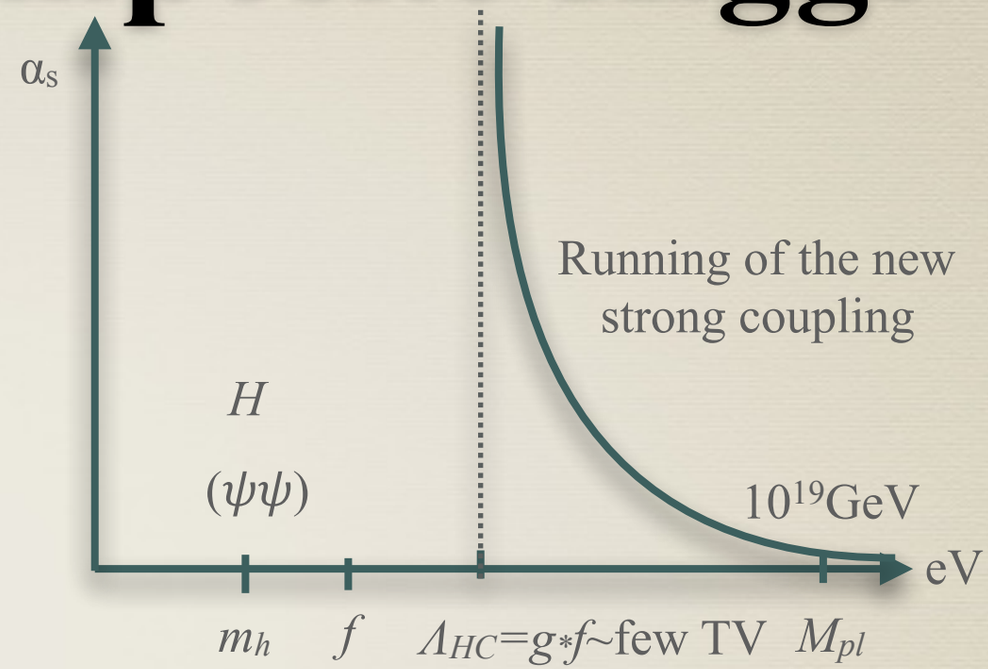
- Motivation & Overview
- Towards UV embeddings of composite Higgs models
- Colored light states in CHM UV embeddings
- Di-boson signatures as a common feature of CHM UV embeddings
- Conclusions



Motivation for a composite Higgs

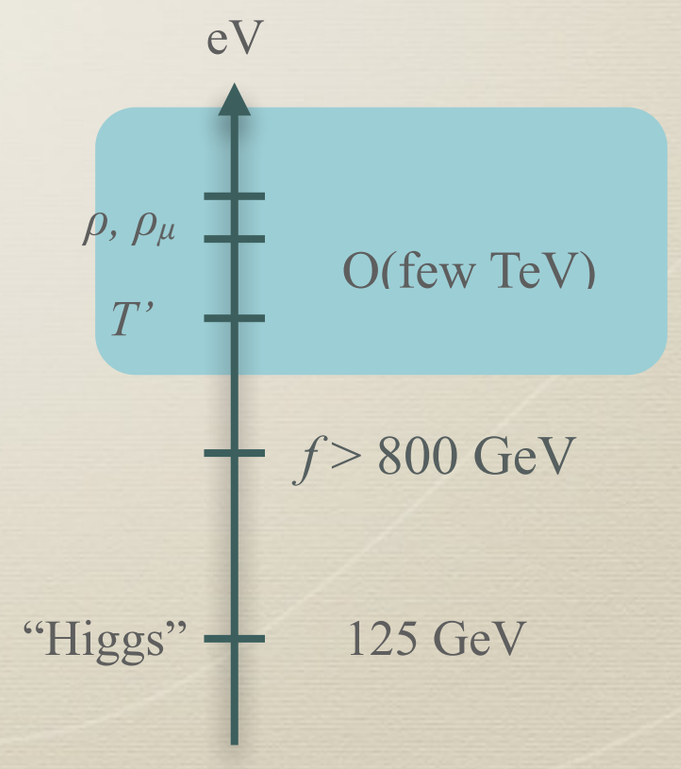
An alternative solution to the hierarchy problem:

- Generate a scale $\Lambda_{HC} << M_{pl}$ through a new confining gauge group.
- Interpret the Higgs as a pseudo-Nambu-Goldstone boson (pNGB) of a spontaneously broken global symmetry of the new strong sector.
  Kaplan, Georgi [1984]



The price to pay:

- From the generic setup, one expects additional resonances (vectors, vector-like fermions, scalars) around Λ_{HC} (and additional light pNGBs?).
- The non-linear realization of the Higgs yields deviations of the Higgs couplings from their SM values.
- …and many model-building questions …



Some questions in composite Higgs models

- What are suitable underlying UV theories?
- What are field content and global symmetries in the confined phase?
- How are quark masses generated?
- (How) can top-partners be light?
- How can problems with FCNCs be avoided?
- What are bounds from electroweak precision measurements?
- What are the ``best'' LHC search channels, optimized search strategies and tools, and what are the bounds and indication for
  - vector resonances
  - top- (or other quark-) partners
  - other composite resonances
  - modified Higgs couplings or signatures?

Composite Higgs Models: Towards an underlying model and its low-energy phenomenology

Ferretti etal. [JHEP 1403, 077, arXiv:1604.06467] classified candidate models which:
c.f. also Gherghetta etal (2014), Vecchi (2015) for early related works on individual models

- contain no elementary scalars (to not re-introduce a hierarchy problem),
- have a simple hyper-color group,
- have a Higgs candidate amongst the pNGBs of the bound states,
- have a top-partner amongst its bound states (for top mass via partial compositeness),
- satisfy further "standard" consistency conditions (asymptotic freedom, no anomalies),

The resulting models have several common features:

- All models require two types of hyper-quarks ψ, χ . The Higgs is realized as a $\psi\psi$ bound state. Top partners are realized as $\psi\psi\chi$ or $\psi\chi\chi$ bound states.
- None of the models has the minimal EW coset *SO(5)/SO(4)*. The smallest EW cosets are instead *SU(4)/Sp(4)*, *SU(5)/SO(5)*, or *SU(4)xSU(4)/SU(4)*.

BUT: There are two more common features of all models.

1. All models contain colored pNGBs. In particular, all models contain a pNGB transforming as an octet of $SU(3)_c$.
   [c.f. JHEP1511,201 for a first study on the phenomenology and bounds on colored pNGBs in CH UV embeddings.]
2. All models contain two spontaneously broken U(1) symmetries (global phases of χ, ψ), which are singlets under the Standard Model group. One linear combination (η') is anomalous under the hyper color group (and hence expected to be heavy). The orthogonal combination (a) is an SM singlet which couples to the SM only through the Wess-Zumino-Witten anomaly.
   Hence, a pNGB with (calculable and fixed) WZW couplings is a genuine prediction of the UV completions under consideration.
   [arXiv:1512.07242]

Example: SU(4)/Sp(4) coset based on GHC = Sp(2Nc) and colored pNGBs

[JHEP1511,201]

Field content of the microscopic fundamental theory and its charges w.r.t. the gauge group $Sp(2N)\times SU(3)\times SU(2)\times U(1)$, and the global symmetries $SU(4)\times SU(6)\times U(1)$:

	$Sp(2N_c)$	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$SU(4)$	$SU(6)$	$U(1)$
ψ_1 ψ_2	$\square$	**1**	**2**	0	**4**	**1**	$-3(N_c-1)q_\chi$
ψ_3	$\square$	**1**	**1**	$1/2$			
ψ_4	$\square$	**1**	**1**	$-1/2$			
χ_1 χ_2 χ_3	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	**3**	**1**	$2/3$	**1**	**6**	q_χ
χ_4 χ_5 χ_6	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	$\bar{\mathbf{3}}$	**1**	$-2/3$			

Bound states of the model:

	spin	SU(4)×SU(6)	Sp(4)×SO(6)	names
$\psi\psi$	0	$(\mathbf{6},\mathbf{1})$	$(\mathbf{1},\mathbf{1})$ $(\mathbf{5},\mathbf{1})$	σ π
$\chi\chi$	0	$(\mathbf{1},\mathbf{21})$	$(\mathbf{1},\mathbf{1})$ $(\mathbf{1},\mathbf{20})$	σ_c π_c
$\chi\psi\psi$	1/2	$(\mathbf{6},\mathbf{6})$	$(\mathbf{1},\mathbf{6})$ $(\mathbf{5},\mathbf{6})$	ψ_1^1 ψ_1^5
$\chi\overline{\psi}\overline{\psi}$	1/2	$(\mathbf{6},\mathbf{6})$	$(\mathbf{1},\mathbf{6})$ $(\mathbf{5},\mathbf{6})$	ψ_2^1 ψ_2^5
$\psi\overline{\chi}\overline{\psi}$	1/2	$(\mathbf{1},\overline{\mathbf{6}})$	$(\mathbf{1},\mathbf{6})$	ψ_3
$\psi\overline{\chi}\overline{\psi}$	1/2	$(\mathbf{15},\overline{\mathbf{6}})$	$(\mathbf{5},\mathbf{6})$ $(\mathbf{10},\mathbf{6})$	ψ_4^5 ψ_4^{10}
$\overline{\psi}\sigma^\mu\psi$	1	$(\mathbf{15},\mathbf{1})$	$(\mathbf{5},\mathbf{1})$ $(\mathbf{10},\mathbf{1})$	a ρ
$\overline{\chi}\sigma^\mu\chi$	1	$(\mathbf{1},\mathbf{35})$	$(\mathbf{1},\mathbf{20})$ $(\mathbf{1},\mathbf{15})$	a_c ρ_c

contains $SU(2)_L \times SU(2)_R$ bidoublet *"H"*

form a and η' SM singlets

20 colored pNGB:
$(8,1,1)_0 \oplus (6,1,1)_{4/3} \oplus (\overline{6},1,1)_{-4/3}$

contain $(3,2,2)_{2/3}$ fermions: t_L-partners

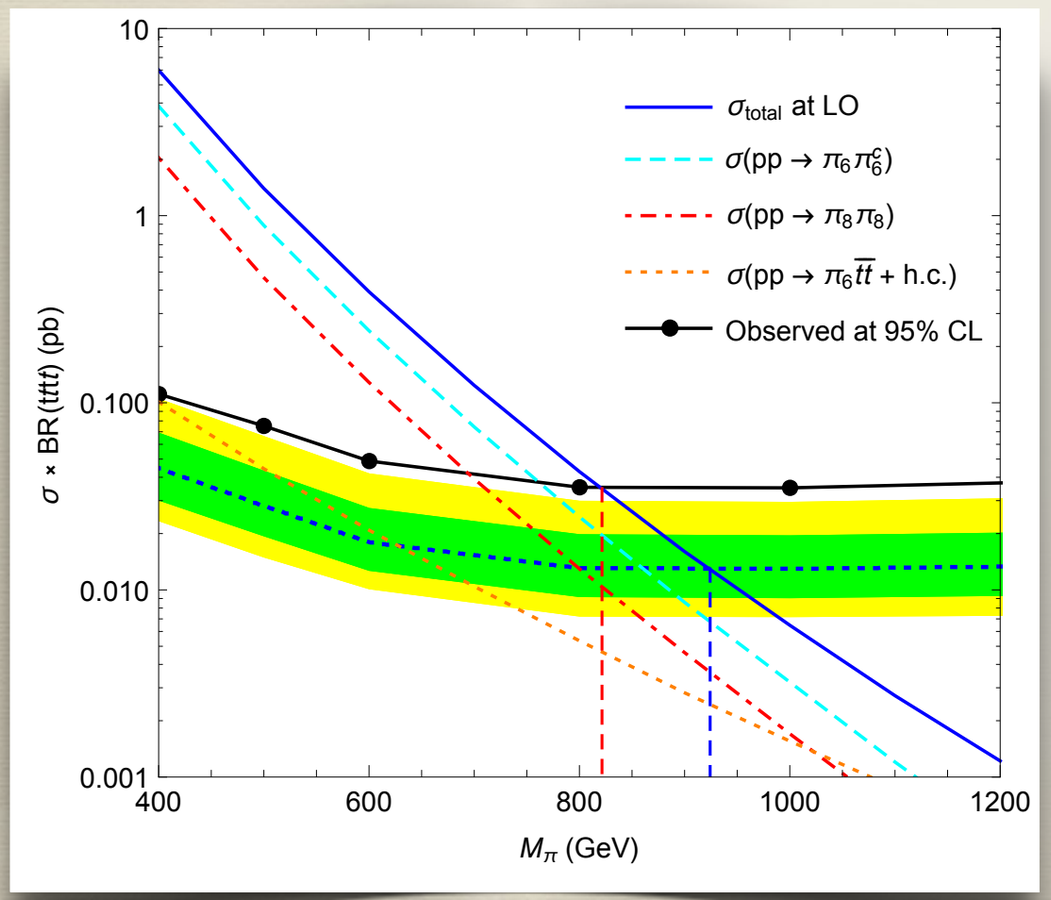
contain $(3,1,X)_{2/3}$ fermions: t_R-partners

Phenomenology of colored PNGBs

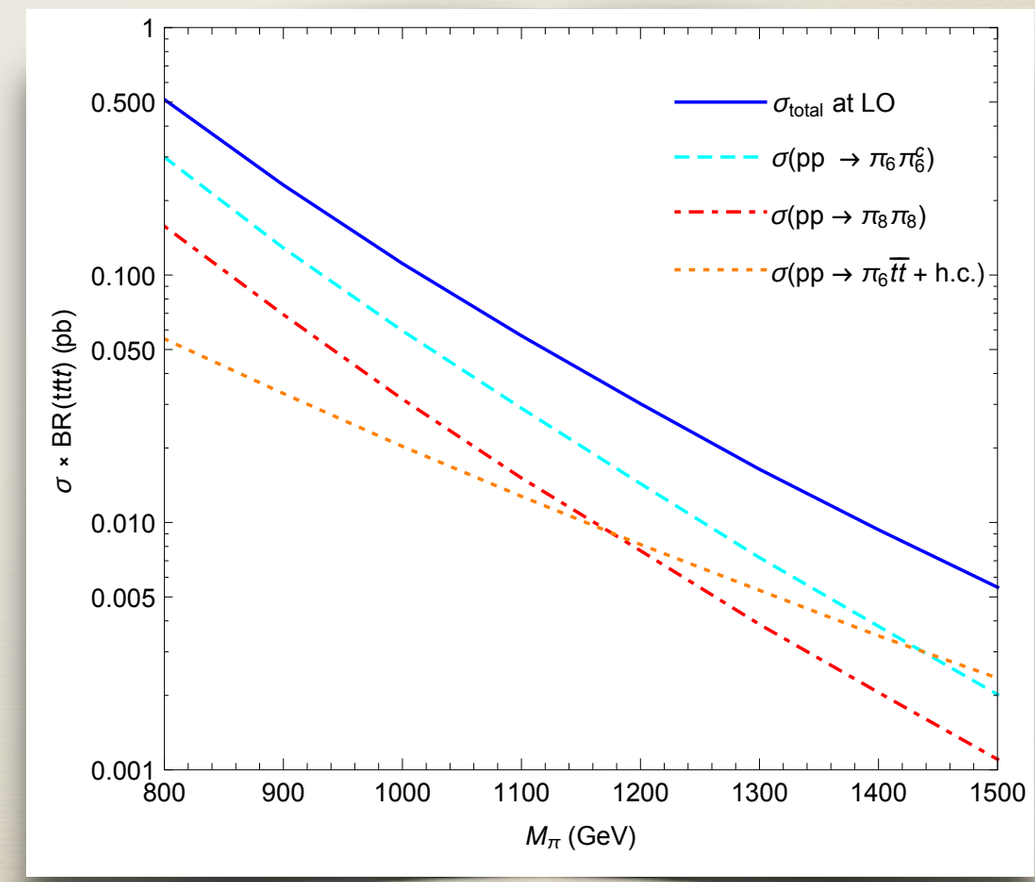
Effective Lagrangian:

$$\mathcal{L}_{eff} = |D_\mu \pi_6|^2 - m_{\pi_6}^2 |\pi_6|^2 + \frac{1}{2}(D_\mu \pi_8)^2 - \frac{1}{2} m_{\pi_8}^2 (\pi_8)^2 - V_{\text{scalar}}(\pi_6, \pi_8)$$
$$+ a_R\ \pi_6 t_R^c t_R^c + a_L\ \pi_6^c t_L t_L + b\ \pi_8 t_R^c t_L + h.c.,$$

Bounds from 8TeV 4t SSDL search:



Production cross section at 13 TeV:



For a more detailed discussion c.f. [JHEP1511,201]

The more general case:
Full list of "minimal" CHM UV embeddings

G_{HC}	ψ	χ	EW	Colour	X
$Sp(2N_c)$, $2 \leq N_c \leq 18$	**F**	**A**	$\frac{SU(4)}{Sp(4)}$	$\frac{SU(6)}{SO(6)}$	$2/3$
$SO(11)$, $SO(13)$	**Spin**	**F**			$2/3$
$Sp(2N_c)$, $N_c \geq 2$	**A**	**F**	$\frac{SU(5)}{SO(5)}$	$\frac{SU(6)}{Sp(6)}$	$1/3$
$Sp(2N_c)$, $N_c \geq 6$	**Adj**	**F**			$1/3$
$SO(11)$, $SO(13)$	**F**	**Spin**			$1/3$
$SO(7)$, $SO(9)$	**Spin**	**F**	$\frac{SU(5)}{SO(5)}$	$\frac{SU(6)}{SO(6)}$	$2/3$
$SO(7)$, $SO(9)$	**F**	**Spin**			$1/3$
$SO(N_c)$, $N_c \geq 15$	**Adj**	**F**			$1/3$
$SO(N_c)$, $N_c \geq 55$	**S**	**F**			$1/3$
$SU(4)$	**A**	**F**	$\frac{SU(5)}{SO(5)}$	$\frac{SU(3)^2}{SU(3)}$	$1/3$
$SO(10)$, $SO(14)$	**F**	**Spin**			$1/3$
$SU(4)$	**F**	**A**	$\frac{SU(4)^2}{SU(4)}$	$\frac{SU(6)}{SO(6)}$	$2/3$
$SO(10)$	**Spin**	**F**			$2/3$
$SU(7)$	**F**	$\mathbf{A}_3$	$\frac{SU(4)^2}{SU(4)}$	$\frac{SU(3)^2}{SU(3)}$	$1/12$
$SU(N_c)$, $N_c \geq 5$	**F**	**A**			$2/3$
$SU(N_c)$, $N_c \geq 5$	**F**	**S**			$2/3$
$SU(N_c)$, $N_c \geq 5$	**A**	**F**			$1/12$
$SU(N_c)$, $N_c \geq 8$	**S**	**F**			$1/12$

The complete list of theories. The HC representations are: **F**: fundamental, **S**: 2-index symmetric, **A**: 2-index anti-symmetric, $\mathbf{A}_3$: 3 index anti-symmetric, **Adj**: adjoint, **Spin**: spinorial of SO. The last column contains the $U(1)_X$ charge assignment. [arXiv:1512.07242]

Note: The bound state particle content is model-dependent, but *all* models contain an SM singlet pNGB.

Effective Lagrangian:

$$\mathcal{L} = \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{m_a^2}{2} a^2 + \frac{g_i^2}{32\pi^2}\frac{\kappa_i}{f_a}\, a\, \epsilon^{\mu\nu\alpha\beta} G^i_{\mu\nu} G^i_{\alpha\beta}$$

- The mass m_a must result from *explicit* breaking of the U(1) symmetries (e.g. through mass terms for the underlying χ, ψ). $m_a \ll \Lambda_{HC}$ is technically natural.
- f_a results from chiral symmetry breaking. One would expect $f_a \sim f \sim O(\mathrm{TeV})$.
- The WZW coefficients κ_i are fully determined by the quantum numbers of χ, ψ.

Phenomenology

- a is produced in gluon fusion.
- a decays to $gg, WW, ZZ, Z\gamma, \gamma\gamma$ with fully determined branching ratios.
- The resonance is narrow.

CH underlying dynamics predicts di-boson signatures
An application: the di-photon excess

(For a similar analysis for the di-boson excess, c.f. [arXiv: 1512.04508])

Assume for the moment that the 750 GeV di-photon excess is real, and the di-photon rate is 5 - 10 fb.

ATLAS and CMS determined bounds on other di-boson channels at 8 and 13 TeV. The strongest bounds at 750 GeV are (mostly from 8 TeV data):

$\sigma_8(pp \to a \to gg)$	$\lesssim$	3 pb	ATLAS [PRD 91, 5], CMS [PAS-EXO-14-005]
$\sigma_8(pp \to a \to WW)$	$\lesssim$	40 fb	ATLAS [JHEP 1601, 032]
$\sigma_8(pp \to a \to ZZ)$	$\lesssim$	12 fb	ATLAS [EPJ C76,1, 45], CMS [JHEP 1408, 174]
$\sigma_8(pp \to a \to Z\gamma)$	$\lesssim$	6 fb	ATLAS [PLB 738, 428], CMS PAS HIG-14-031
$\sigma_{13}(pp \to a \to gg)$	$\lesssim$	3 pb	ATLAS-CONF-2016-030

Relating those to the di-photon cross section at 13 TeV yields bounds on the decay widths ratios $R_{XY} \equiv Br(a \to XY)/Br(a \to \gamma\gamma)$

$$R_{gg} \lesssim 300\ (600),\ R_{WW} \lesssim 19\ (38),\ R_{ZZ} \lesssim 6\ (12),\ R_{Z\gamma} \lesssim 3\,(6)$$

for a 10 (5) fb di-photon signal.

Under the assumption that the di-photon resonance is real: which models are not yet excluded by current LHC run I and run II di-boson searches?

		R_{WW}	R_{ZZ}	$R_{Z\gamma}$	R_{gg}	Γ_{tot}	f_σ
SU(7)	(**F**, **A$_3$**)	9.5	3.0	0.8	140	0.4	2900
~~SU(5)~~	~~(**A**, **F**)~~	~~10~~	~~3.2~~	~~0.9~~	~~**1300**~~	~~3.2~~	~~830~~
SO(11)	(**Spin**, **F**)	4.4	0.5	**3.5**	**500**	0.8	2330
SO(13)	(**Spin**, **F**)	2.6	0.2	2.6	**400**	1.0	4000
~~SU(4)~~	~~(**A**, **F**)~~	~~**23**~~	~~**6.6**~~	~~**3.4**~~	~~**960**~~	~~1.7~~	~~680~~
SO(7)	(**F**, **Spin**)	**20**	5.7	2.7	**600**	1.5	1300
SO(9)	(**F**, **Spin**)	16	4.8	2.0	300	0.8	2200
SO(10)	(**F**, **Spin**)	15	4.6	1.8	227	0.6	2500
SO(11)	(**F**, **Spin**)	15	4.3	1.7	180	0.4	2900
SO(13)	(**F**, **Spin**)	13	4.1	1.5	120	0.3	3500
SO(14)	(**F**, **Spin**)	13	4.0	1.4	99	0.2	3800

List of models that can explain the di-photon excess of 10 fb (5 fb) and are compatible with present "di-boson" searches. $R_{XX} \equiv \sigma_{XX}/\sigma_{\gamma\gamma}$.The models are grouped according to the Higgs coset: $SU(4)^2/SU(4)$ for the top block, $SU(4)/Sp(4)$ for the second block, and $SU(5)/SO(5)$ for the bottom one. Values for Γ_{tot} and f_σ are given in GeV. [arXiv:1512.07242]

Conclusions

- Composite Higgs Models provide a viable solution to the hierarchy problem but — being strongly coupled theories — they still provide many challenges and room for exploration.
- EFT descriptions of composite Higgs models are only part of the story. UV embeddings need to be studied in more detail, and they will lead to novel (as well as already well-known) BSM LHC signatures.
- We showed that di-boson signatures are predicted in a large class of CH UV embeddings. The models are highly predictive because the branching ratios of different di-boson channels are fully determined by the quantum numbers of the underlying fermion field content.
- Another feature common to all models we considered are potentially light colored scalar resonances.

Backup

Results for Wess-Zumino-Witten coefficients

G_{HC} anomaly free $U(1)$ combination: $q_\psi = N_\chi T_\chi,\ q_\chi = -N_\psi T_\psi,$
(T_x: Dynkin indices of the HC reps., N_x: fermion multiplicities.)

WZW coefficients of the $U(1)_\psi$ and $U(1)_\chi$ associated "Goldstones":

$$\begin{aligned}
&\kappa_W = \kappa_B = d_\psi, && \text{for} \quad SU(4)/Sp(4),\\
&\kappa_W = \kappa_B = 2d_\psi, && \text{for} \quad SU(5)/SO(5) \text{ and } SU(4)^2/SU(4),\\
&\begin{aligned}\kappa_g &= 2d_\chi,\\ \kappa_B &= 12X^2 d_\chi,\end{aligned} && \text{for} \quad \text{all color cosets},
\end{aligned}$$

where d_x is the dimension of the rep..

WZW coefficient of the G_{HC} anomaly-free combination: $\kappa_i = q_\psi \kappa_i^\psi + q_\chi \kappa_i^\chi$.