Composite Higgs Models: From Underlying Dynamics to LHC Signatures (and back)

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H. Cai, T. Flacke, M. Lespinasse [arXiv:1512.04508]
A. Belyaev, G. Cacciapaglia, H. Cai, T. Flacke, H. Serodio, A. Parolini [arXiv:1512.07242]

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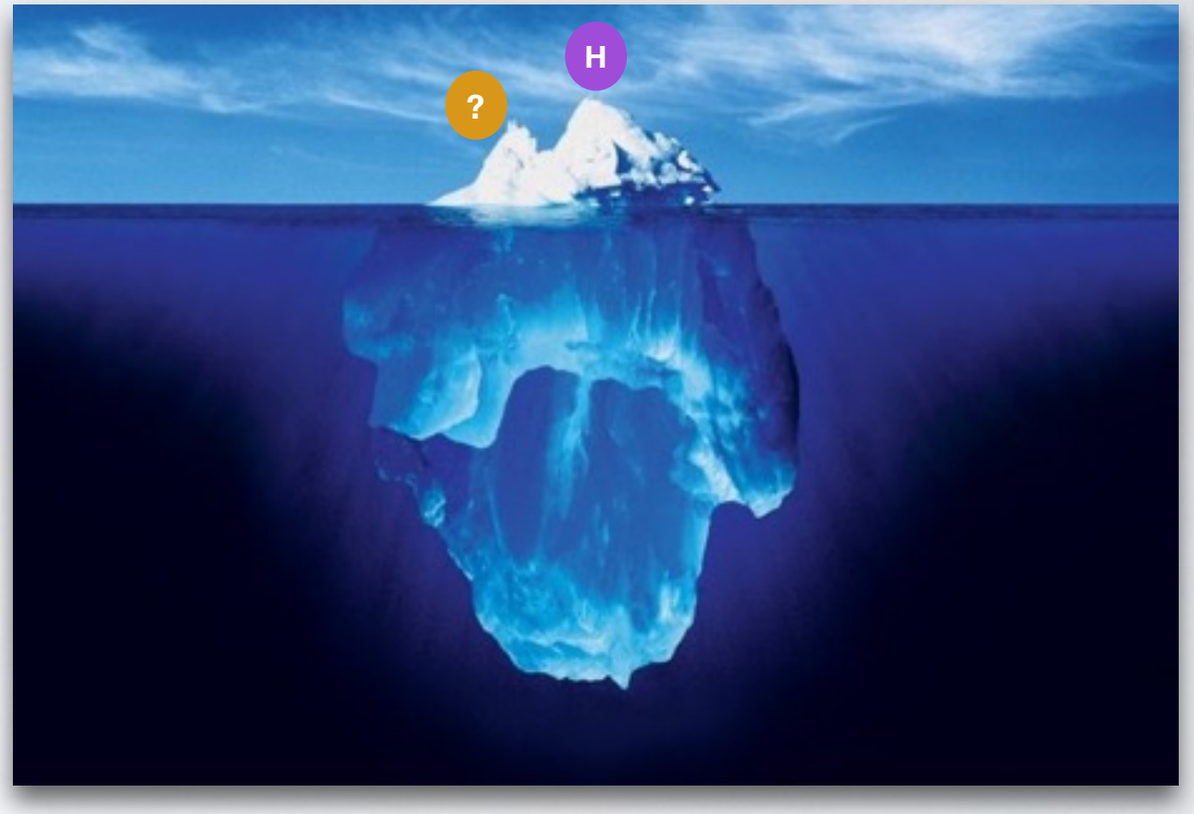
Outline

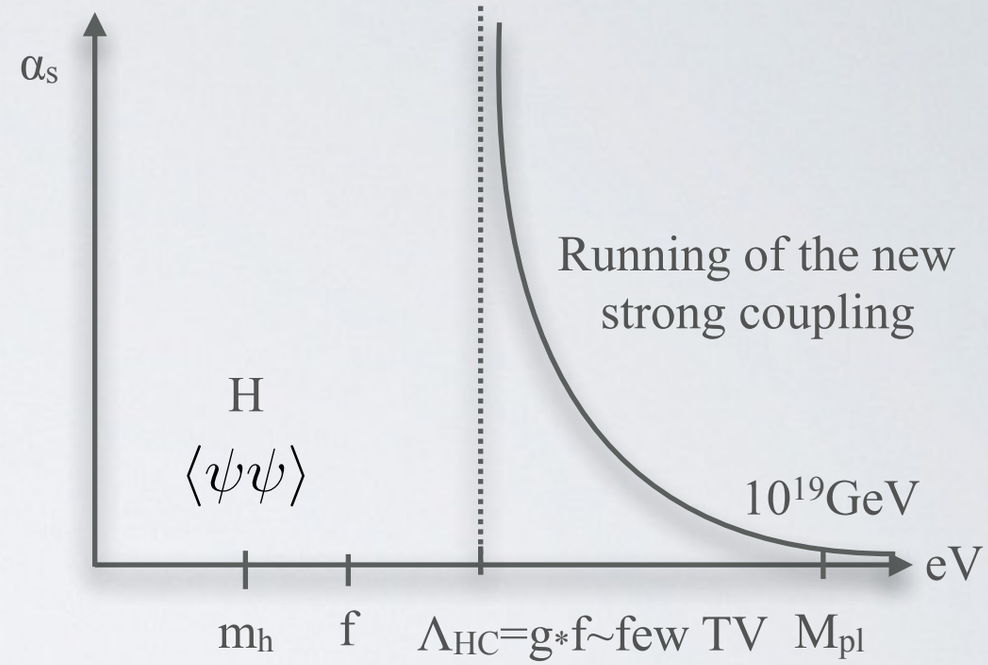
- Motivation & Overview
- Recent activities
  (IPNL group, Korea group, joint)
- One example: Composite models and di-boson signatures at LHC
- Conclusions



Motivation

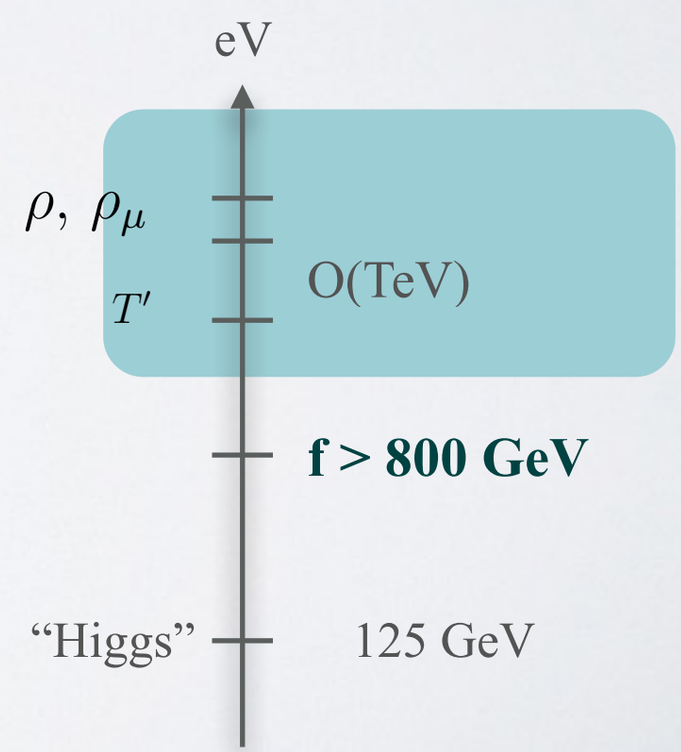
An alternative solution to the hierarchy problem:

- 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 prize 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 addressed in our programme in the last ~2 years

- What should the underlying field content of the UV theory be?
  What are field content and global symmetries in the confined phase?
  [JHEP1603,211, PLB755(2016),328, JHEP1511,201, arXiv:1512.04508, arXiv:1512.07242]
- How are quark masses generated? (How) can top-partners be light?
  [PRD93(2016),071701]
- How can problems with FCNCs be avoided? [JHEP1506,085]
- Frameworks / tools / optimized search strategies (and bounds for)
  - vector resonances [arXiv:1605.01363]
  - top- (or other quark-) partners [JHEP1412,080, PRD92(2015),011701, JHEP1507,086, JHEP1509,012, JHEP1509,022, JHEP1507,086, JHEP1604,014, arXiv:1604.07421]
  - other composite resonances [JHEP1511,201, arXiv:1512.04508, arXiv:1512.07242, PRL115(2015),171802]
  - modified Higgs couplings or signatures [JHEP1504,082, PRD93(2016),035026]

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

Ferretti etal. [JHEP 1403, 077, arXiv:1604.06467] classified candidate models which:

- 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).

Full list of 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]

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 ψ, χ), 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]

Effective description of the genuine pNGB SM singlet

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

- The mass m_a must result from *explicit* breaking of the U(1) symmetries (e.g. through mass terms for the underlying ψ, χ).

  $m_a \ll \Lambda_{HC}$ 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 ψ, χ.

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 to the di-photon excess

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

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

$$\begin{aligned} \sigma(pp \to a \to gg) &\lesssim 3\,\text{pb} && \text{ATLAS [PRD 91 (2015), 5], CMS [PAS-EXO-14-005]} \\ \sigma(pp \to a \to WW) &\lesssim 40\,\text{fb} && \text{ATLAS [arXiv:1509.00389]} \\ \sigma(pp \to a \to ZZ) &\lesssim 12\,\text{fb} && \text{ATLAS [1507.05930]} \\ \sigma(pp \to a \to Z\gamma) &\lesssim 4\,\text{fb} && \text{ATLAS [PLB 738 (2014), 428]} \end{aligned}$$

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

$$R_{gg} \lesssim 1400 - 2800,\ R_{WW} \lesssim 19 - 38,\ R_{ZZ} \lesssim 6 - 12,\ R_{Z\gamma} \lesssim 2 - 4.$$

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_a
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_a 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 (and 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.
- The last two years of the IPNL-Korea U. collaboration have been very productive and established a deep research connection between the institutes, with many ongoing and planned works for the future.