Models of Composite Higgs Bosons

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some useful references on composite Higgs boson models:

Cacciapaglia, Deandrea, Gaur, Harada, Okada, JHEP 11, 055 (2018) [arXiv:1806:01024]

Csaba, Grojean, Terning, Rev. Mod. Phys. 88, 045001 (2016) [arXiv:1512.00468]

Bellazzini, Csaki, Serra, EPJC 74, 2766 (2014) [arXiv: 1401.2457]

De Simone, Matsedonskyi, Rattazzi, Wulzer, JHEP 04, 004 (2013) [arXiv:1211.5663]

Outline of this talk:

“Naturalness” (thanks to Peter Onyisi)

Top-down structure of Composite Higgs models

Bottom-up structure of Composite Higgs models

Heavy resonances associated with Composite Higgs

Composite Higgs and precision measurements

Composite Higgs and the 10-50 TeV mass scale

“Naturalness”

What is the real question here ? We know that the Higgs boson spontaneously breaks electroweak symmetry, but we have no idea why. The SM does not predict EW symmetry breaking, it only gives a phenomenology of this situation.

If we want to answer the why question, we need alter the Higgs boson sector of the SM in some way. This will have implications for our understanding of the quark and lepton mass spectrum, CP violation, neutrinos, unification, dark matter – in short, everything !

There are three classes of explanation for EWSB.

1. It is an accident. Just live with it.

2. There is a mechanism that connects this problem to that of quantum gravity and the cosmological constant. (see, e.g. Dvali, arXiv:1908.05984). String theory ideas about the “swampland” fall into this class.

3. There is a mechanism based on flat-space QFT. The Higgs potential is given by a Feynman diagram (or similar) calculation. That is, the explanation is “mechanical”. But this necessarily involves new particles and forces beyond the SM that couple to the Higgs sector.

The minimal SUSY model contains a beautiful explanation. Integrating out the stop-Higgsino sector generates a negative mass term for the Higgs. However, the “sweet spot” for this idea has gluinos below 2 TeV.

This is a general problem for perturbative solutions to the problem of generating the Higgs potential. We typically expect

$$\mu^2 \sim -3 \frac{y_t^2}{(4\pi)^2} M^2$$

where M is the mass of the particle integrated out. There are many types of models where the sign is negative, as required. However, the estimate gives

$$M \sim 750 \text{ GeV}$$

So why do we not see these particles at the LHC ?

This is the “little hierarchy problem”. It is a feature of all current mechanical models of EWSB.

We hope that there is an explanation that uses some unknown principle of strong-coupling physics. There is a lot of room for new ideas.

Strong-coupling potentially brings additional problems. A strongly-coupled Higgs sector will potentially contribute large corrections to precision electroweak observables, W nonlinear couplings, top quark interactions.

The strongest general constraint is

$$S < 0.14$$

which, in models, pushes the strong-interaction scale above 3 TeV.

Top-down structure of Composite Higgs models

To make the Higgs boson much lighter than the strong interaction scale, an attractive idea is to consider them as Goldstone bosons associated with a strong-interaction symmetry breaking.

This idea goes back to 1982 papers of Buchmuller, Love, Peccei, and Yanagida.

We can imagine explicitly breaking the symmetries of the strong-interaction theory systematically to generate small masses and, eventually, the Higgs potential.

schema of the “Littlest Higgs” model
(Arkani-Hamed, Cohen, Katz, Nelson)

strong interactions at $\Lambda \sim 20\ \mathrm{TeV}$

top partners, some scalars at

$$M \sim \Big(\frac{g^2}{(4\pi)^2}\Big)^{1/2}\Lambda \sim 1\ \mathrm{TeV}$$

Higgs potential at

$$\mu \sim -\Big(\frac{y_t^2}{(4\pi)^2}\Big)^{1/2} M \sim 100\ \mathrm{GeV}$$

Light scalars (pseudo-Goldstone bosons) often appear in strongly interacting gauge theories, even in QCD. Light fermions are harder to arrange, but they are known to appear in some supersymmetric gauge theories.

Another idea: In a 5-dimension model, gauge fields are

$$A_M^A = (A_\mu^A, A_5^A)$$

A_5^A is a multiplet of scalars that has zero mass in leading order. This can contain the Higgs scalars.

Massless fermions will be accompanied by massive Kaluza-Klein partners. The massless fermions can be chiral, but their massive partners are vectorlike.

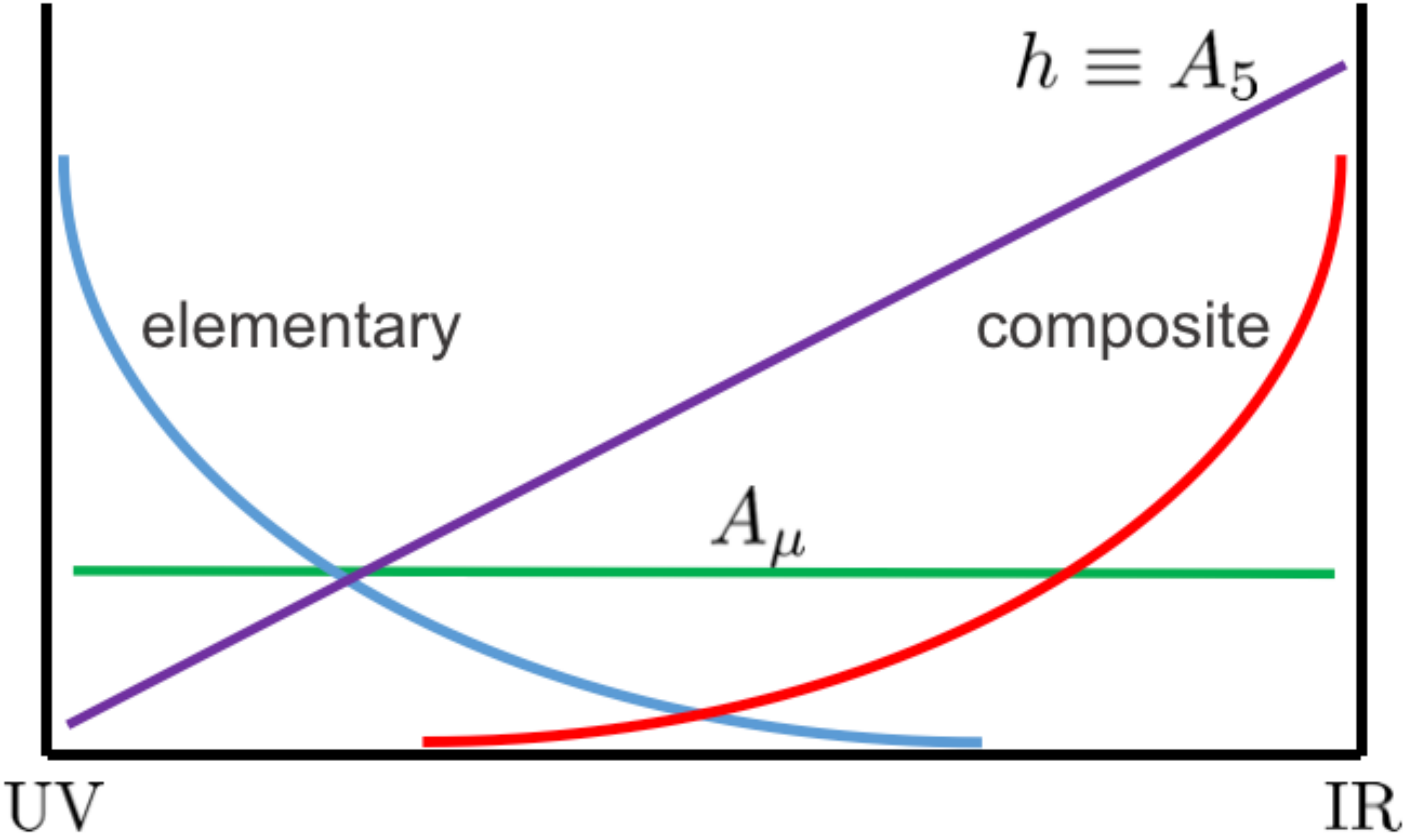
Vectorlike fermions do not get their mass from the Higgs mechanism. Then they evade the restrictions on 4th generation fermions and can be as massive as one wishes.

A particular attractive choice for the 5-d geometry is a slice of anti-de Sitter space (Randall-Sundrum geometry)

$$ds^2 = \frac{1}{(kz)^2}(dx^\mu dx_\mu - dz^2)$$

Each depth in the 5th dimension represents a different length scale, from TeV to …

The boundaries of the 5-d region can be considered the “IR brane”, with TeV dynamics, and “UV brane”, with dynamics at a higher scale.   The the Higgs generates mass preferentially for wavefunctions localized near the IR brane.


$h \equiv A_5$
elementary
composite
A_μ
UV
IR

There are two important concepts that are intuitive in this framework:

AdS/CFT duality: The 5-dimensional theory that can be studied in perturbation theory can be a representation of a 4-dimensional strongly coupled theory.

strong interaction resonances ⟷ Kaluza-Klein resonances

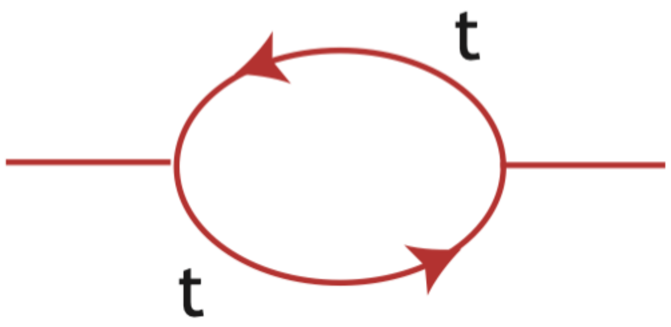
This duality is exact in some supersymmetric models.

Top partial compositeness: To the extent that the top quark obtains a large mass from the Higgs sector, the top quark must be strongly coupled to the Higgs sector. The top quark will be close to the IR, thus, partially composite.

Bottom-up structure of Composite Higgs models

Whatever the structure of the theory at high energy, there are constraints that much be addressed at TeV energies.

A Higgs boson that couples to the top quark has the mass correction



which is UV quadratically divergent. In a theory that allows one to calculate the Higgs potential, this divergence must be cancelled by another UV divergent diagram involving top quark partners. If the partners are very heavy, a fine-tuning is required. This is the “little hierarchy” again.

In the SM, it is always possible to change variables so that the couplings of the Higgs boson are flavor-diagonal. This is not true if the Higgs sector is extended. There will be flavor anomalies unless there is a GIM-type cancellation mechanism.

The top partners must be unstable and probably must decay promptly. This also might imply flavor-mixings forbidden in the SM.

Color triplet top quark partners have large production cross sections at the LHC and are now strongly constrained.

However, there is no reason why the top partners cannot be color-singlet. Scenarios of this type are called "neutral naturalness". Such partners would have suppressed pair production cross sections. They could decay to, e.g.,

$$E \to \tau^- \nu \qquad N \to hZ$$

observable but not the easiest signatures at the LHC.

Models such as Twin Higgs and Folded SUSY have neutral naturalness without strong Higgs interactions. In these models, the 1-loop UV divergence is cancelled, but the mechanism fails at higher loops. Probably this mechanism requires a composite-Higgs completion to work correctly.

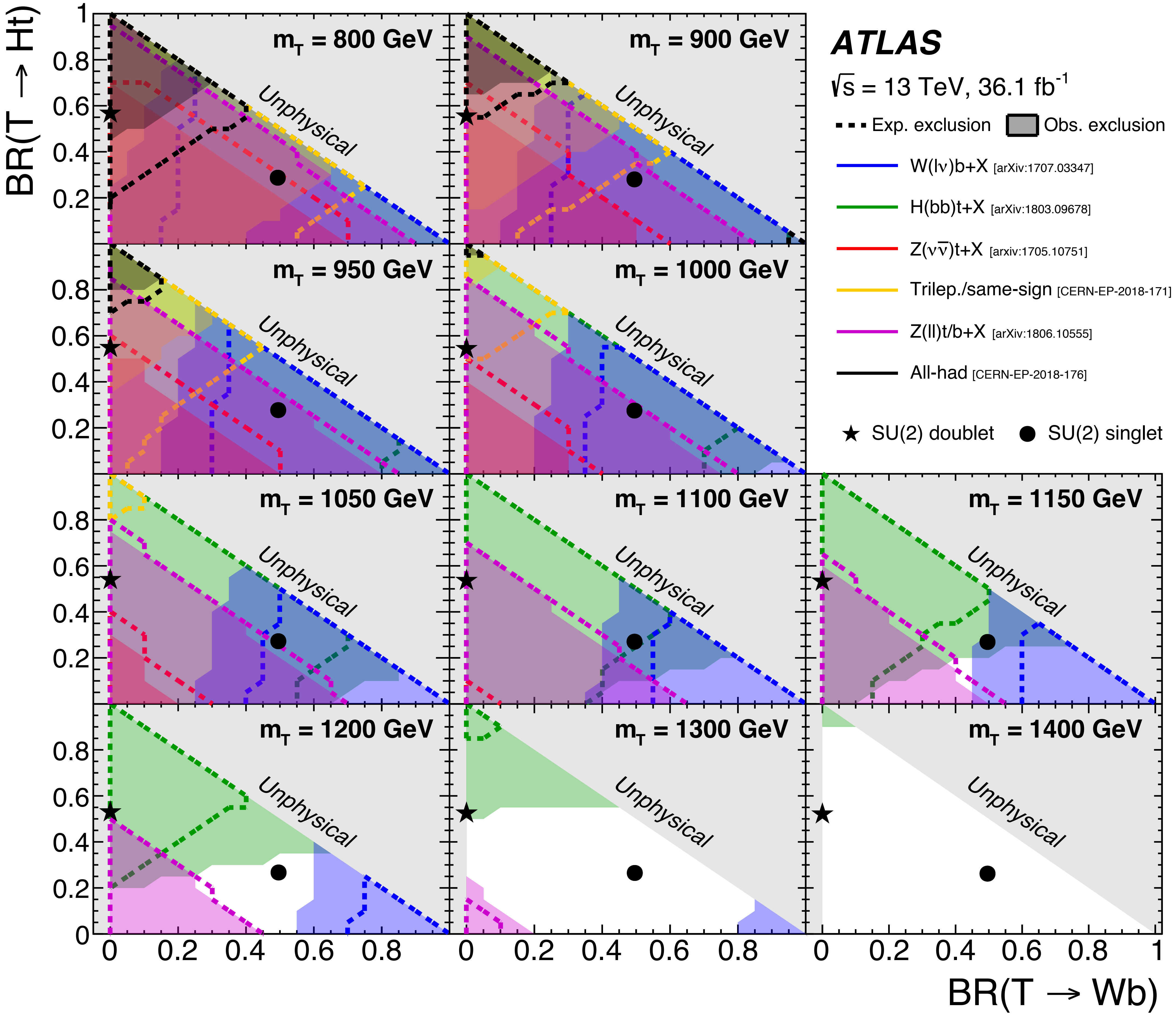
Heavy resonances associated with Composite Higgs

From both the top-down and the bottom-up point of view, composite Higgs models must contain new particles beyond the SM. These would probably be seen as resonances in heavy particle channels:

$$(Wt)\ ,\ (Zh)\ ,\ (t\bar{t})\ ,\ \text{etc.}$$

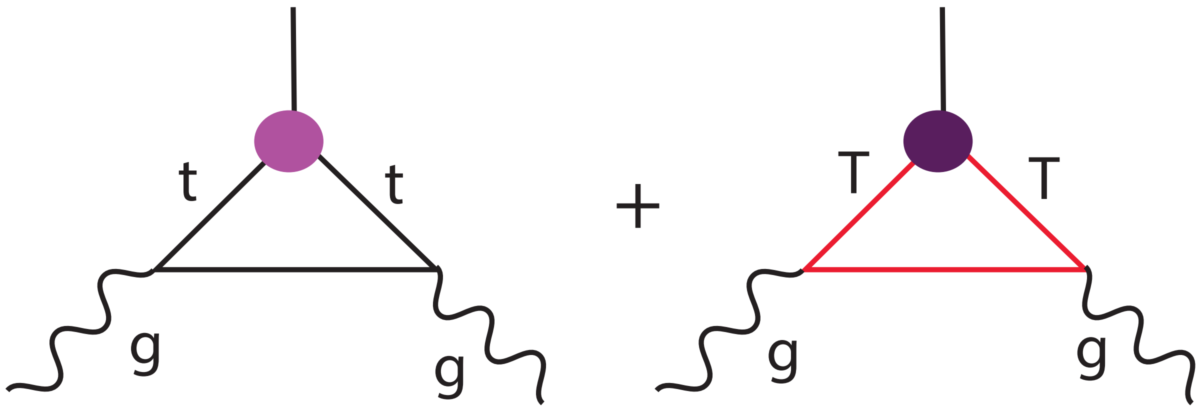
Both Little Higgs and RS models contain both fermionic and bosonic heavy resonances.

Giacomo Cacciapaglia will discuss the systematic searches for these states at the LHC.


ATLAS
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
Exp. exclusion
Obs. exclusion
W(lν)b+X [arXiv:1707.03347]
H(bb)t+X [arXiv:1803.09678]
Z(νν̄)t+X [arxiv:1705.10751]
Trilep./same-sign [CERN-EP-2018-171]
Z(ll)t/b+X [arXiv:1806.10555]
All-had [CERN-EP-2018-176]
★ SU(2) doublet
● SU(2) singlet
m_T = 800 GeV
m_T = 900 GeV
m_T = 950 GeV
m_T = 1000 GeV
m_T = 1050 GeV
m_T = 1100 GeV
m_T = 1150 GeV
m_T = 1200 GeV
m_T = 1300 GeV
m_T = 1400 GeV
Unphysical
BR(T → Ht)
BR(T → Wb)
0
0.2
0.4
0.6
0.8
1

Composite Higgs and precision measurements

Top partial compositeness implies that the htt coupling will be modified by a form factor. The hgg coupling will receive two distinct new effects,



leading to a shifted and also q^2- dependent coupling. To sort out the various components, it will be important to measure

the htt coupling
the hgg coupling on mass shell
the hgg coupling at high Higgs p_T $\quad (|q^2| \gg m_t^2)$

Top partial compositeness also implies corrections to the top quark electroweak form factors and contact interactions. These can be measured systematically to high precision in

$$e^+e^- \to t\bar{t}$$

Typically t_R is more composite than (t_L, b_L). This can be tested using polarized beams.

Also, b_R may be partially composite. The experimental constraints are actually not very strong. The process

$$e^+e^- \to b\bar{b}$$

at 250 GeV might already be interesting as test of composite Higgs models.

Composite Higgs and the 10-50 TeV mass scale

Finally, it is important to note that the structure I have described for top-down composite Higgs models has a central role for physics at 10-50 TeV parton CM energy.

There are other reasons to want experiments at 10-50 TeV:

Dirac gauginos can be heavier than 10 TeV

Solutions to flavor anomalies may require 10 TeV leptoquarks.

If an s-channel vector resonance is discovered (say, at 5 TeV), we will need to go to many times that energy to test whether it is a Kaluza-Klein recurrence.

But if the Higgs is composite, this strongly motivates new strong interactions above 10 TeV. Then we will need to invent a way to reach that energy with accelerators.

This is beyond the limit of any current accelerator technology. It takes decades to develop new accelerator technologies, so we need to start thinking about this today.

pp collider:

FCC-hh can pair-produce some 10 TeV particles. But is the energy of FCC-hh high enough ?

The cost of FCC-hh at current prices for the (still in prototype) 16 T magnets is > 10 x LHC. The official CDR cost is 4 x LHC.

Doubling the energy of FCC-hh would require high-Tc superconducting magnets produced at industrial scale.

μμ collider:

A muon collider in the LHC tunnel is an attractive option. Can we put enough muons into a small phase space to achieve the required luminosity, of order $10^{36}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$?

The backgrounds from muon decay in the incoming beams are enormous. Can we design a detector to do useful physics ?

e+e-/γγ linear collider:

Plasma wakefield and dielectric accelerators can achieve multi-GeV/m. But the problem of combining 1 m stages into a 10 km linac is unsolved. The efficiency of converting line power to beam power is a major issue.

If one or more of these technologies is the future of the Energy Frontier, Snowmass should call for a long-term effort to solve these problems (and more of us should participate).

We should also be thinking about what the most relevant measurements are, and whether it will be possible to make them. Composite Higgs models give a concrete setting in which to think about this.

Conclusions: (in my humble opinion)

The why problem of Electroweak Symmetry Breaking is still the most important problem in particle physics.

SUSY and similar models of EWSB no longer have pride of place. We need to seriously investigate the idea that the Higgs boson is composite, with new strong interactions at 10-50 TeV.

There are many possibilities both for model-building for composite Higgs and for experimental signatures. In particular, particle searches and precision measurements on t, b, h can provide complementary (and needed) information. It is important to treat these models and measurements holistically at Snowmass.

Ultimately, composite Higgs models require new strong interactions at the 10-50 TeV scale. To understand these new fundamental interactions, we will have to go there. We must begin thinking now about the technologies that will make it possible.