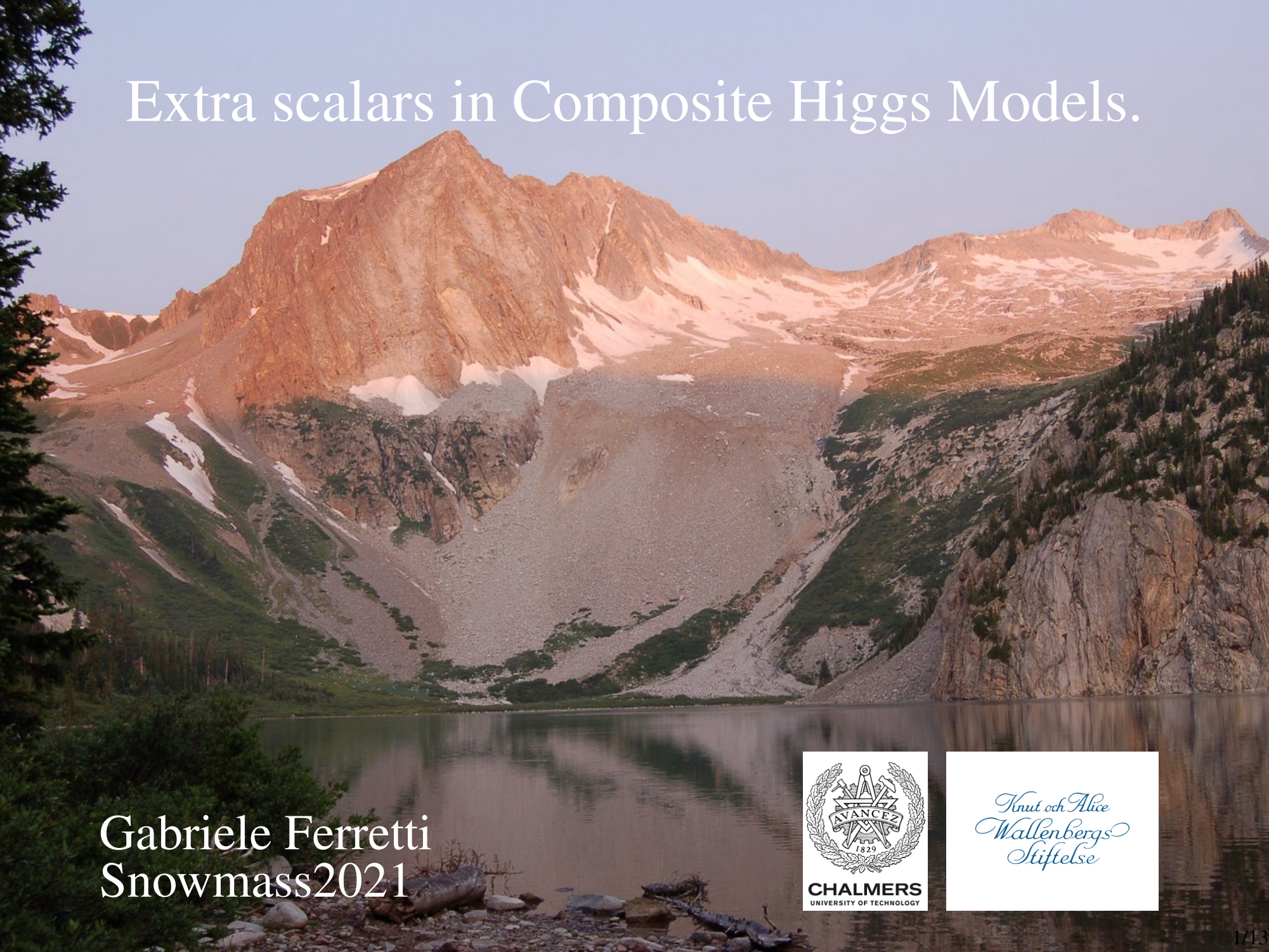
Extra scalars in Composite Higgs Models.



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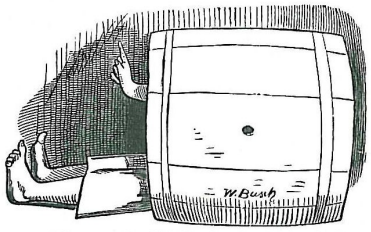
Snowmass2021

- A (still developing) proposal from a constellation of people with similar interests:
  Diogo Buarque Franzosi, Giacomo Cacciapaglia, Aldo Deandrea, Gabriele Ferretti, Thomas Flacke, Benjamin Fuks, Luca Panizzi, Werner Porod...

- Some references at the end (Mostly shameless propaganda, not an attempt to give proper credit!)

- Overlap with many other ideas in **EF09**, **EF08**, **TF08**...



Main point:

All composite Higgs models except the minimal one (MCHM) have additional scalars (ϕ) realized as pseudo Nambu-Goldstone bosons (pNGB), just like the Higgs itself.

Observe that, in strongly coupled gauge theories, the most easily realized symmetry breaking patterns are *not* of the minimal type $SO(5)/SO(4)$.

Thus, *conditionally to some sort of composite Higgs scenario being true, the existence of additional light scalars is generic*.

$\star$ An interesting (and less studied) class of models is one where dimension 3 interactions with the *gauge potentials*, typical of the Higgs boson(s): ($k\frac{m_V^2}{v}\times$)

$$\phi_0\, Z_\mu\, Z^\mu, \quad \phi_0\, W^+_\mu\, W^{-\mu}, \quad \phi_+\, Z_\mu\, W^{-\mu}, \quad \phi_{++}\, W^-_\mu\, W^{-\mu}$$

do not arise (for $\phi \neq h$), or are strongly suppressed.

(This because the neutral component of the multiplet does not get a v.e.v. for various reasons.)

The absence of these couplings makes this class of models qualitatively different. For instance, the neutral scalars easily evade all LEP bounds.

$\star$ There are still dimension 5 interactions now involving vector boson *field strengths*. For neutral ϕ: ($k\frac{gg'}{\Lambda}\times$)

$$\phi G^a_{\mu\nu}\overset{(\sim)}{G}{}^{a\mu\nu}, \quad \phi F_{\mu\nu}\overset{(\sim)}{F}{}^{\mu\nu}, \quad \phi F_{\mu\nu}\overset{(\sim)}{Z}{}^{\mu\nu}, \quad \phi Z_{\mu\nu}\overset{(\sim)}{Z}{}^{\mu\nu}, \quad \phi W^+_{\mu\nu}\overset{(\sim)}{W}{}^{-\mu\nu}$$

All computable, given a model, via ABJ anomaly of hyperfermions or simply loops of SM fermions like the Higgs. There are models in which ϕ turns out to be glue-phobic ~~ϕGG~~ or photo-phobic ~~ϕFF~~ or both.

$\star$ More exotic possibilities for charged/colored objects:

$$\phi_+ W^-_{\mu\nu}\overset{(\sim)}{F}{}^{\mu\nu}, \quad \phi_+ W^-_{\mu\nu}\overset{(\sim)}{Z}{}^{\mu\nu}, \quad \phi_{++} W^-_{\mu\nu}\overset{(\sim)}{W}{}^{-\mu\nu},$$

$$d^{abc}\phi^a G^b_{\mu\nu}\overset{(\sim)}{G}{}^{c\mu\nu}, \quad \phi^a G^a_{\mu\nu}\overset{(\sim)}{F}{}^{\mu\nu}, \quad \phi^a G^a_{\mu\nu}\overset{(\sim)}{Z}{}^{\mu\nu}, \quad \phi^a_+ G^a_{\mu\nu}\overset{(\sim)}{W}{}^{-\mu\nu}$$

$\star$ Interactions with SM fermions are more model dependent

$$\sum \frac{k_\psi m_\psi}{v}\, \phi\, \bar{\psi}(\gamma^5)\psi'$$

They are strongly constrained by flavor, particularly in the I and II generation. There are also models in which ϕ is fermio-phobic.

$\star$ Finally, the most relevant double ϕ interactions comes from the dimension 4 (non-linear) kinetic term "$(D\phi)^2$"

$$c_1\, g\, \phi\, \partial_\mu \phi' V^\mu + c_2\, g^2\, \phi\, \phi' V_\mu V'^\mu$$

c_1, c_2 are computable in terms of the quantum numbers and the symmetry breaking pattern. There are models in which they are absent for some of the ϕs.

$\star$ The *mass* of these objects depends on the details of their symmetry breaking potential:

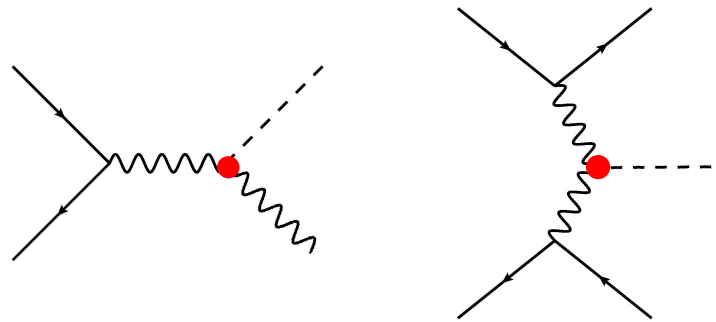
A universal *positive* contribution arises from gauge loops, similar to the pion electromagnetic mass splitting $m^2 \approx \frac{g^2}{16\pi^2}\Lambda^2$.

- Neutral pNGBs. Could be quite light, but also very weakly coupled. One can take $m \gtrsim 10$ GeV to avoid bounds from hadronic resonances, but they could also be lighter.
- Electrically charged pNGBs. Heavier, but still they could have $m \lesssim 1$ TeV.
- Colored pNGBs. They can get a large mass $m \gtrsim 1$ TeV.

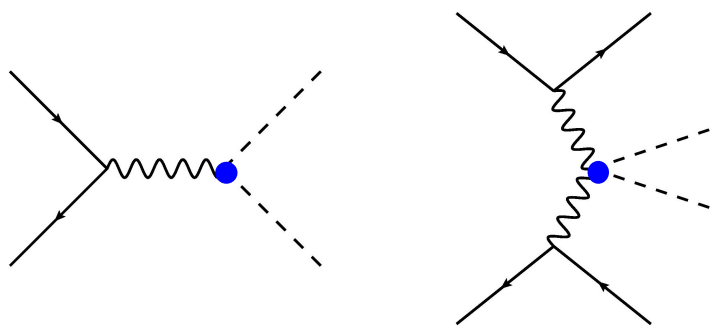
There are composite Higgs constructions for all of these.
Note that *the stronger they couple, the heavier they are*.

$\star$ The most elusive ones: glue-phobic, neutral pNGBs

The single production modes are: associated production and VBF both via the dimension 5 operators •

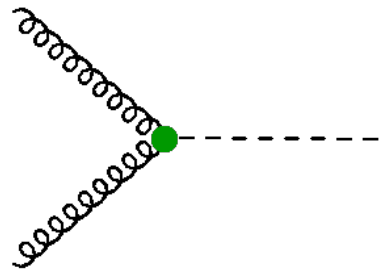


Pair production is instead driven by the dimension 4 operators •

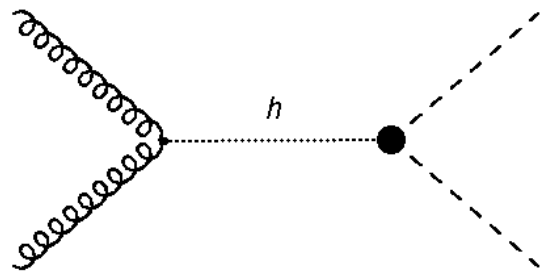


All viable at both lepton and hadron colliders. Small cross-sections.

$\star$ If ϕGG is present, at hadron colliders there is, of course, also a gluon fusion mode $\bullet$.



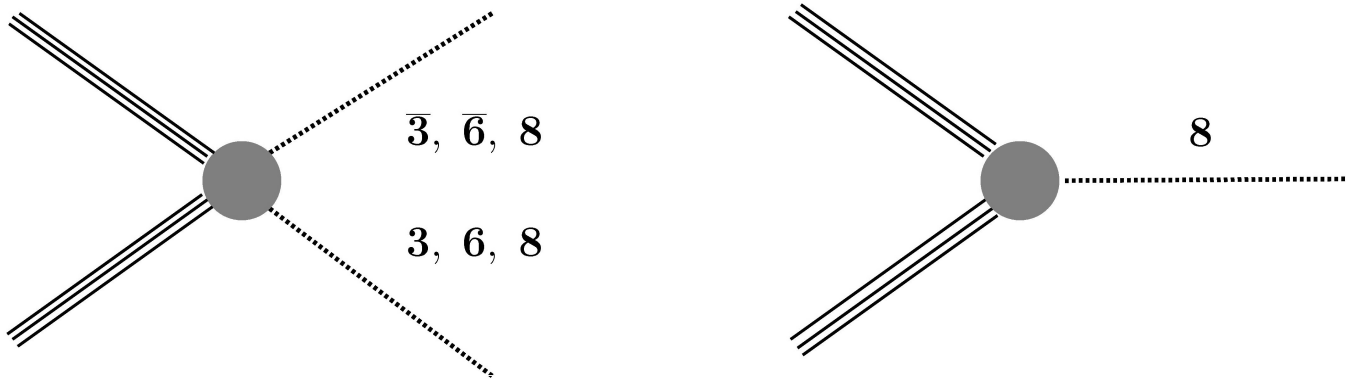
$\star$ There is also the possibility of Higgs mediated pair production via $h\phi\phi$ $\bullet$, where the Higgs can even be (a bit) off-shell.



$\star$ Depending on the ϕ decay modes, there are still regions in the $\sigma \times$ BR vs m_ϕ plane that can be targeted at the HL-LHC.

$\star$ Charged or colored objects have model independent pair production cross-sections and are, of course, more constrained.

For instance, there are models of partial compositeness where colored triplets, sextets, octets arise naturally together with top partners.



Triplets and sextets can have Baryon number violating couplings of relevance for $n - \bar{n}$ oscillations.

$\star$ Charged pNGBs can also have interesting signatures. For instance a Doubly charged scalar arises in some models, analogous to the one in the Georgi-Machacek model.

If fermio-phobic, it would give rise to signatures such as $\phi^{++} \to W^+ W^+$ which are less studied than the usual di-lepton channels.

$\star$ Lastly, since many partial compositeness models with top-partners come hand-in-hand with some additional pNGBs, one should reassess the searches of VLQs in the light of possible decays in addition to the usual triad $T \to t\,Z,\ t\,h,\ b\,W$.

Some of these exotic decays $T/X \to t/b\,\phi$ might even be the most promising discovery channel in some regions of parameter space.

Conclusions

- I presented a *smörgåsbord* of possible scenarios arising in models with extra pNGBs.
- They are quite generic and might leave us some chance of seeing on-shell new physics at HL-LHC or a lepton collider.
- Many connected lines of investigation: Long-lived particles, Dark matter candidates, EWPT, Z line shape, Higgs BSM decays, $n - \bar{n}$ oscillations, VLQ exotic decays...
- We are a chatty bunch. If you have questions, comments, interest, drop any of us a line!

THANK YOU!

Some (clickable) references

- A paper similar in spirit, with more details, couplings etc... 1604.06467.
- Composite Higgs constructions yielding additional pNGBs: 1311.6562, 1312.5330, 1404.7137, 1506.00623, 1703.06903.
- pNGB phenomenolgy: 1507.02283, 1610.06591, 1610.07354, 1902.06890, 2002.01474, 2004.09825, 2005.13578.
- Exotic VLQ decays: 1907.05894, 1907.05929, 1908.07524.