Physics Beyond the Standard Model

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1 Unexpectancy

Neutrino masses, flavour, dark matter, the strong-CP problem, the matter-antimatter asymmetry, unification, quantum gravity... There is no shortage of profound open questions in fundamental physics. I see no reason why some physics playing a role in these puzzles should show up at the HL-LHC. I see no reason why it shouldn't. The reason is that there is no fundamental energy scale associated with these phenomena. If one injects additional *assumptions* concerning, for example, the magnitudes of couplings involved or the number of fundamental space-time dimensions then one can argue for a specific energy scale (neutrino masses, unification) or by *appealing to some particular dynamics* that selects an energy scale (dark matter thermal freeze-out, electroweak baryogenesis) then we may be able to point in a certain direction. However, the nature of the assumptions should always be kept in mind, and minds should be kept open.

Before entertaining the possibility that new physics might come along and answer some lingering question, there is always the possibility that it won't. After all, no one can answer Isidor Rabi yet. When we throw all connections to open problems out the window we open Pandora's box of BSM signatures and have only few theoretical guides. Any signature should be 'possible', in the sense that a plausible microscopic theory could, at least in principle, be found. Furthermore, there is no reason for parameters in such a theory to be chosen to arbitrarily special values, giving yet another guide. Beyond that it's anybody's guess. I'll start by venturing two.

1.1 Who's ordering that?

Why not circle back to the unexpected muons of 1936? Do they get their mass from the Higgs? Presumably yes, but physics is an experimental science and we want to know for sure. At 13 TeV the Higgs production cross section for gluon fusion is 49 pb. Each experiment has had about 140 fb^{-1} delivered, thus each has been delivered around 7 million Higgs bosons. On the other hand, the Higgs branching ratio into muons is $\approx 2 \times 10^{-4}$. Thus each experiment has, in principle, been delivered over 1 thousand Higgs bosons which have decayed to muons. Were there no background we could reasonably expect a $\sim 1.5\%$ accuracy on the Higgs coupling to muons. Unfortunately there is a significant background and so best present errors are at the $\sim 21\%$ level [7,8]. Still, this is pretty good. We're headed towards the 5σ 'discovery' threshold for this coupling.

How about HL-LHC? Well, this is a relatively clean channel and so we would expect systematics to be well under control. In this case a naïve luminosity rescaling would suggest an improvement to the level of 5% should be achievable.[1] Indeed, this is confirmed by the estimate in [8]. So a presently SM-like Higgs coupling to muons could still evolve into a $\gtrsim 4\sigma$ discrepancy at the HL-LHC. Thanks to the cleanliness of this channel there is plenty of room for new surprises at high-lumi!

Could one have a plausible scenario in which this arises? The best way to answer this question lies, as always, in effective field theory (EFT). See App. (A) for a crash course. We can capture muon-specific modifications of the Higgs Yukawa coupling through the

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[1] I haven't included the roughly 3 pb growth in the production cross section between 13 and 13.6 TeV.

usual Yukawa coupling and an additional, gauge-invariant, contribution coming from as-yet-unknown new microscopic physics

$$\mathcal{L}_\mu = \left(1 + \frac{|H^2|}{\Lambda^2}\right) \lambda H L_\mu E^c_\mu \ \ , \tag{1.1}$$

where Λ is the field scale associated with the microscopic new physics. In the UV theory Λ is linked to the mass of the new states responsible for generating this extra interaction through some coupling $g_\star$ which can only be determined by going to high energies and directly discovering these particles, of mass $M \sim g_\star \Lambda$. As explained in App. (A) it is erroneous to consider Λ itself as a mass scale.

In any case, in this theory the Higgs Yukawa coupling to muons is modified by an amount

$$\delta c_{h\mu\mu} = \frac{v^2}{\Lambda^2} \tag{1.2}$$

where $v = 246$ GeV is the Higgs vacuum expectation value (vev). So, if $\Lambda \approx 1.1$ TeV in natural units a 5% deviation in the Higgs coupling could arise. However, to get a 5σ deviation would require $\Lambda \approx 500$ GeV and so the new responsible states shouldn't be too far away, presumably with mass $M \lesssim 4\pi\Lambda \lesssim 6$ TeV.

So, in summary, there is plenty of room for more 'Who ordered that?' surprises at the HL-LHC, with immediate consequences concerning the energy scale at which the culprit new particles should show up.[2]

1.2 The Higgs Self-Coupling?

Another observable worth discussing is the Higgs self-coupling, measured through Higgs pair production at the LHC, accounting for the fact that this arises predominantly in gluon fusion through two diagrams,[3] one of which involves the Higgs self-coupling. Presently the central value for the Higgs self-coupling measurement is a little high, however the uncertainties are at the level of around 190% [9]. In words: We haven't even started to measure it yet!

The naïve luminosity rescaling would suggest that at HL-LHC one might then hope to measure it with an accuracy of $\sim 40\%$. Indeed, this isn't too far off, with estimates for the future suggesting a precision of $\sim 50\%$ [10]. For the sake of argument let's play the game of supposing the central value of $\lambda_{h^3}/\lambda_{h^3}^{\rm SM} \approx 3$ [9] persists all the way to the end of HL-LHC. This would be a 4σ discrepancy! Again, plenty of room for surprises left in the data to be collected...

It's important to ask, however, if it is even possible to have a microscopic theory behind the Higgs sector of the SM which would modify the Higgs couplings to ZZ, WW etc by amounts smaller than, say, 10% to agree with present Higgs coupling measurements, yet with a modification of the Higgs self-coupling at the 200% level? Can this really be possible without some fine-tuning of parameters to suppress the Higgs single-coupling deviations?

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[2] An astute student would, at this point, ask me why the same λ should multiply both terms in the Lagrangian.

[3] Draw them!

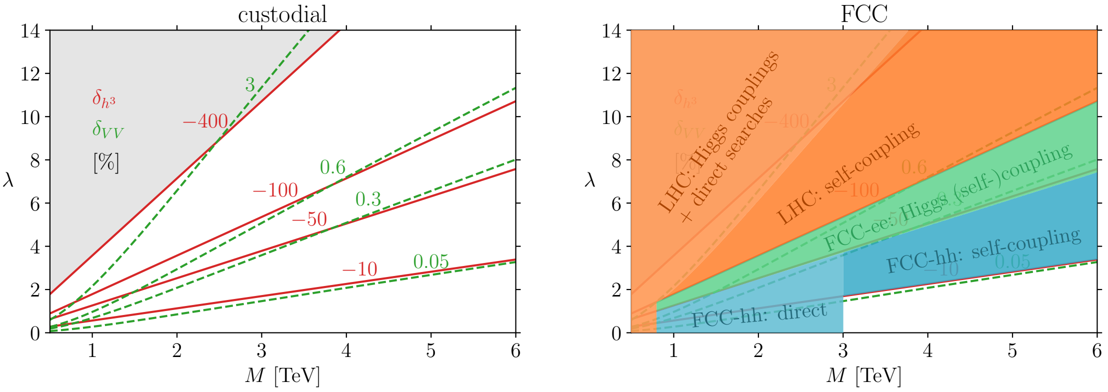

Figure 1: Vector and self-coupling modifications in the custodial quadruplet model and accompanying search prospects. Left: Single-Higgs coupling and self-coupling deviations. Top right: Regions probed, at the two-sigma level, by different types of future measurements at the LHC and FCC.

It turns out that this is, indeed, possible. In [11] a model (the 'custodial quadruplet') was studied in which the ratio of coupling modifications satisfies[4]

$$-\frac{\delta_{hVV}}{\delta_{h^3}} = 3\left(\frac{m_h}{4\pi v}\right)^2 + \left(\frac{m_h}{M}\right)^2 \approx \frac{1}{200} + \frac{1}{580}\left(\frac{3\ \text{TeV}}{M}\right)^2 . \tag{1.3}$$

So we see that a microscopic 'UV' scenario with no fine-tuning of parameters can give self-coupling modifications 200 times greater than the hZZ or hWW modifications! In the context of this model one could have a 200% modification of the Higgs self-coupling with only 1% modifications of these other couplings. This means the self-coupling measurements could be the *leading* source of evidence for new physics at the HL-LHC. This is depicted in fig. 1.

In summary, it is indeed possible that some BSM new physics surprise could show up in measurements of the Higgs self-coupling at the HL-LHC. Is it likely? This is impossible to say. The 'custodial quadruplet' model is far from the usual canon of BSM scenarios and it's hard to argue there is any special motivation for it. On the other hand, we have to be clear eyed and aware of our preconceptions. Everything is on the table at this stage.

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[4] I promise this isn't just shameless self-promotion. If you want to know more about this model I would be happy to discuss.