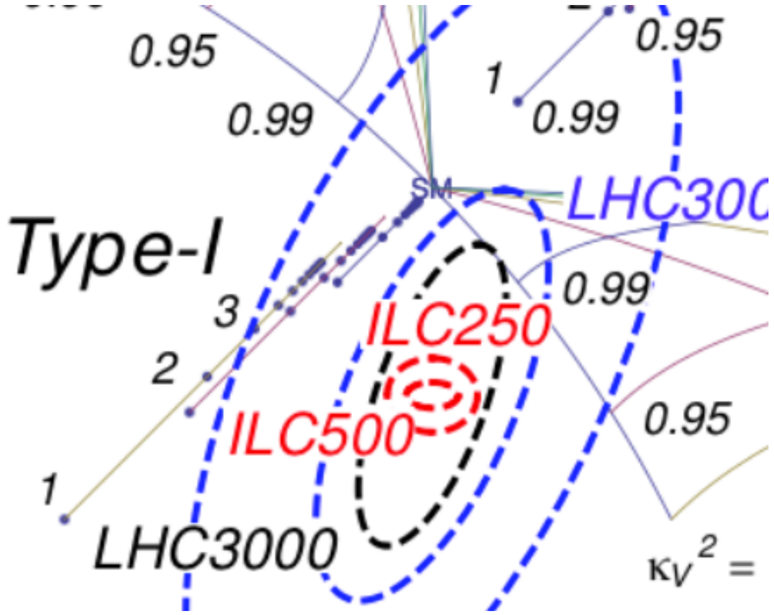
The Higgs Inverse Problem



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Like Hitoshi Murayama in the previous lecture, I am excited for the prospects of the International Linear Collider in Japan.

Hitoshi explained:

What can the ILC do for HPNP theorists ?

In this lecture, I will discuss:

What can HPNP theorists do for the ILC ?

There is an issue that needs much better understanding from the theory community.

This is the "Higgs Inverse Problem" .

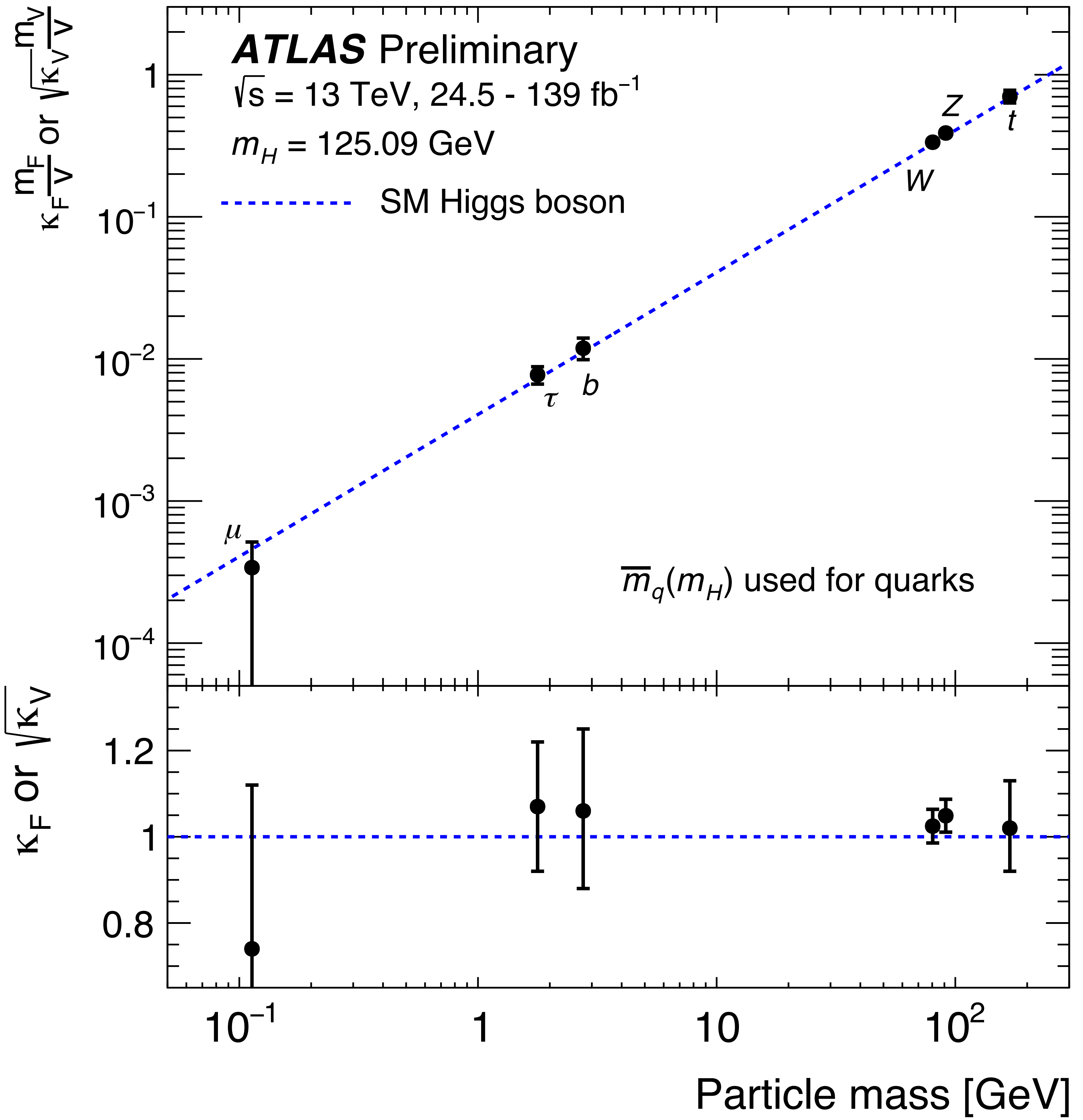
Better understanding of this problem will generally improve our global picture of physics beyond the SM, and it will also sharpen the physics case for the ILC.

To begin, a little introduction:

Since the discovery of the 125 GeV Higgs boson in 2012, the LHC experiments have made tremendous progress in confirming the basic features of this particle. In 2012, one could make a checklist of qualitative properties of the Higgs boson that could be verified experimentally:

- ✔ $J^{PC} = 0^{++}$
- ✔ production by gg
- ✔ production by VBF
- ✔ assoc. production with W, Z
- ✔ decay to $b\bar{b}$
- ✔ decay to $\tau^+\tau^-$
- ✔ decay to W^+W^-
- ✔ decay to ZZ
- ✔ decay to $\gamma\gamma$
- ✔ coupling to $t\bar{t}$

Now these tests of the SM Higgs properties have become quantitative. Here is the ATLAS comparison of the proportionality of Higgs couplings to particle masses:



What more have we to learn about the Higgs boson ?

In fact, the study of the 125 GeV Higgs boson has hardly begun.

All of the results above are explained by the following, much weaker, hypothesis:

Aside from the 125 GeV Higgs boson, there are no other new particles at masses < M ~ 1 TeV.

It is a mystery why this should be so. This is called the "little hierarchy problem". However, all solutions to the gauge hierarchy problem allow this parameter region, and some can actually explain why it is natural.

The statement is the result of Haber's decoupling theorem:

Given the hypothesis above, all corrections to the SM predictions for Higgs boson couplings due to new physics are parametrically of order

$$v^2/M^2$$

The proof is easy: Integrate out all particles of mass ~ M. This yields the SMEFT effective Lagrangian

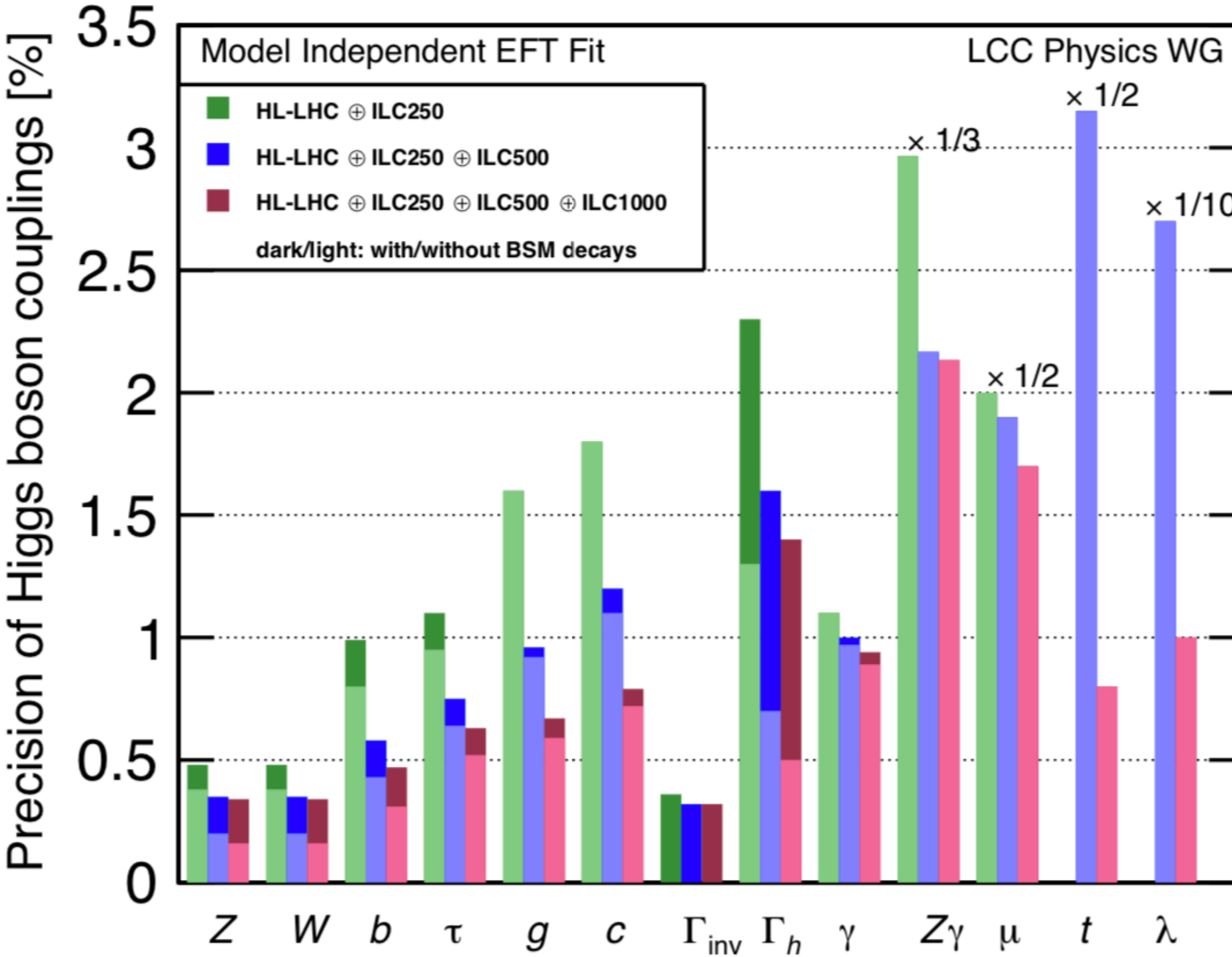
$$\mathcal{L} = \mathcal{L}_4 + \sum_i \frac{c_i}{M^2}\mathcal{O}_i + \sum_j \frac{d_j}{M^4}\mathcal{O}_j + \cdots$$

where the $\mathcal{O}_i$ are of dimension 6, etc. $\mathcal{L}_4$ is the most general dimension-4 Lagrangian with SU(3)xSU(2)xU(1) symmetry — but this is just the Standard Model.

So, at the current level of accuracy in Higgs couplings, we do not know whether there is 1 Higgs, multiple Higgses, or multiple new particles coupling to the Higgs — as long as the new particles are sufficiently heavy.

To discriminate these models with high significance by measuring the Higgs couplings, we need to make measurements of better than 1% precision.

This is the program of “Higgs factory” e+e- collider such as ILC.



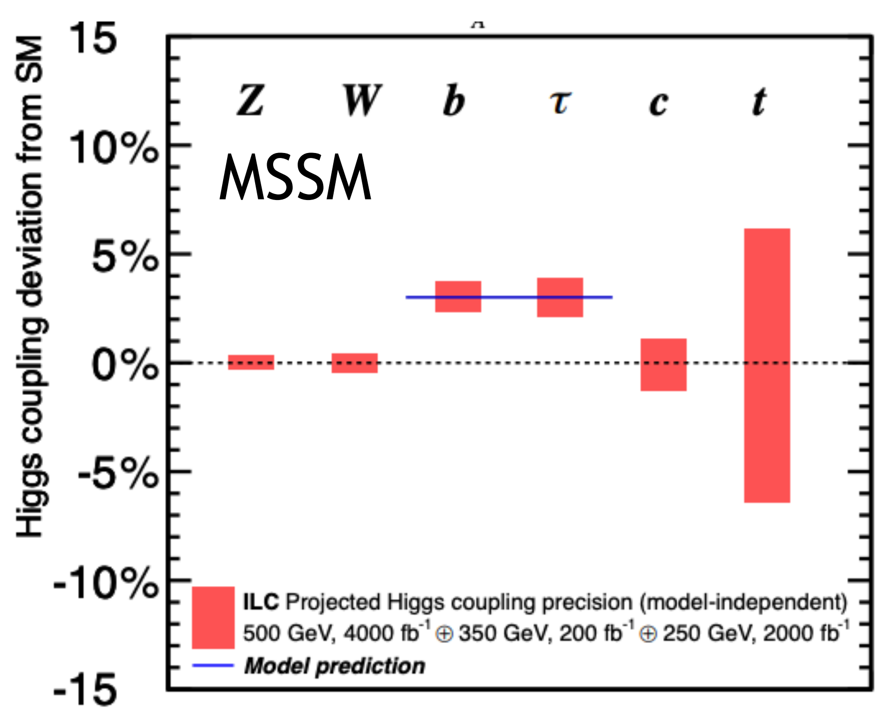
arXiv:1908.11299

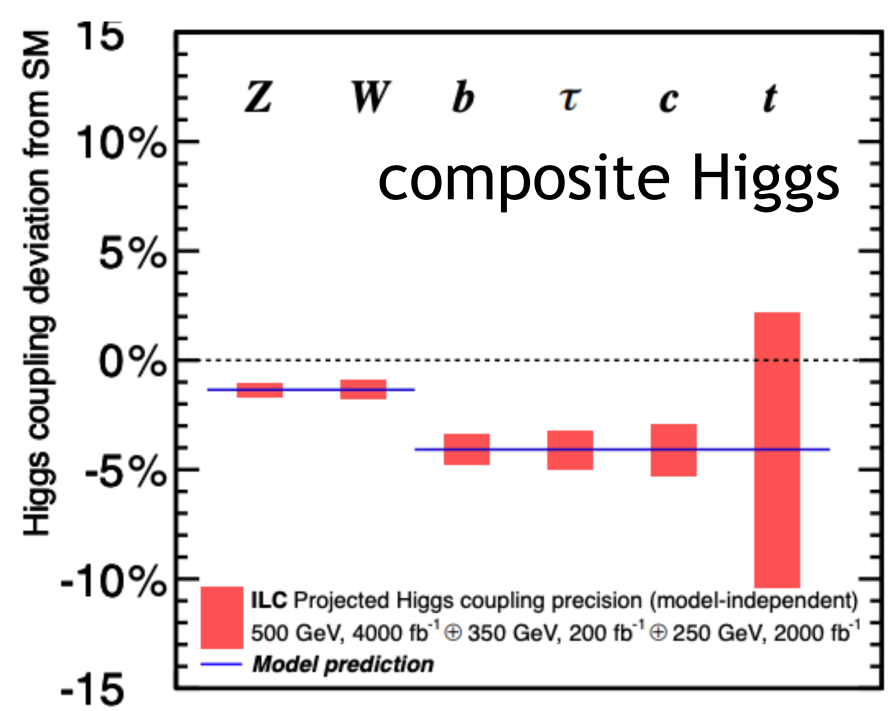
An important feature of this story is that — when the parameters of the SM are fixed — the SM predictions are fixed for all Higgs decay modes.

In the SM, there are 10 decay modes with BR's > 10^{-4} :

$$b\bar{b},\ W^+W^-,\ gg,\ \tau^+\tau^-,\ c\bar{c},\ ZZ,\ \gamma\gamma,\ \gamma Z,\ \mu^+\mu^-,\ s\bar{s}$$

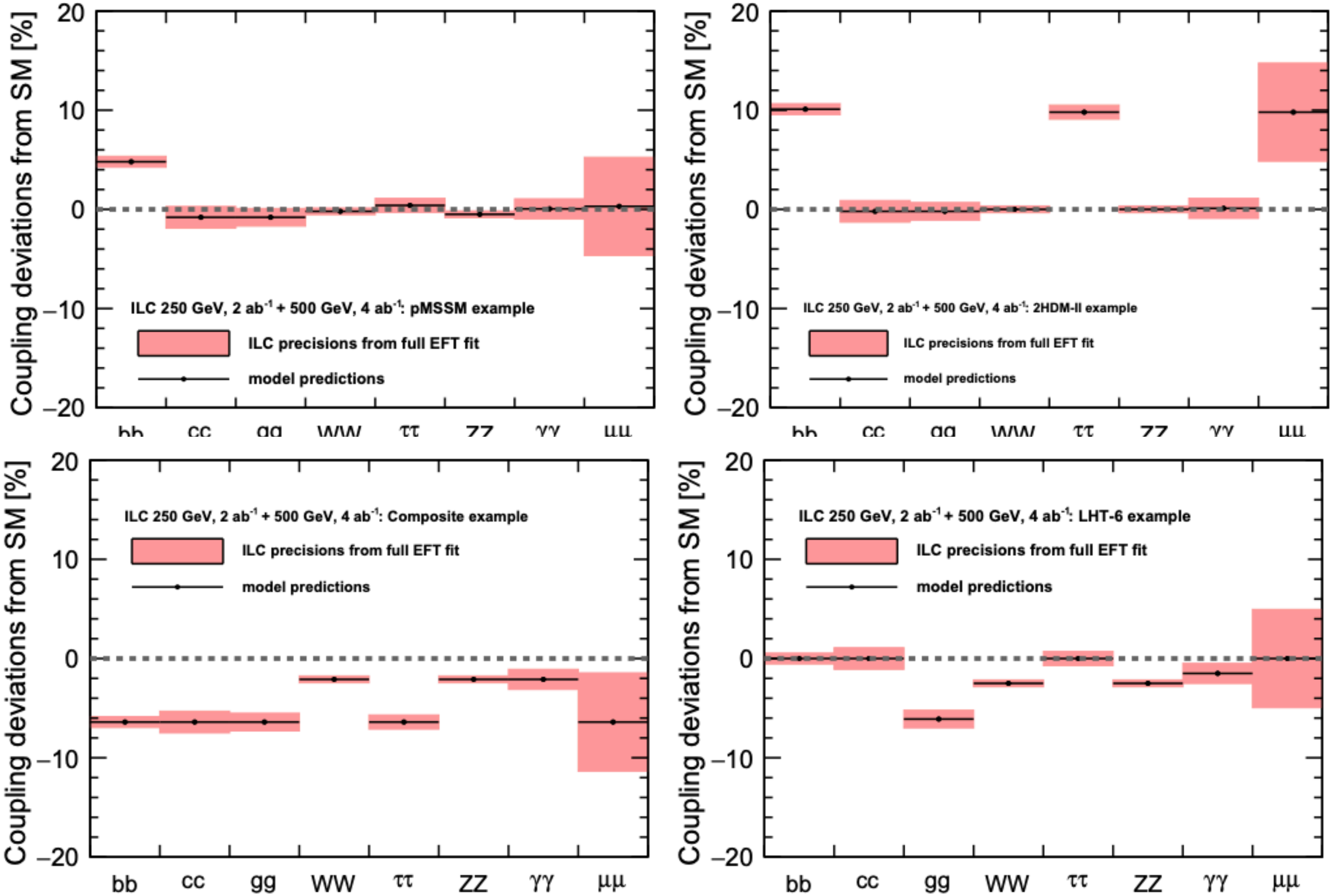
Across the space of new physics models, the corrections to these various couplings have a different pattern for each model. This is an idea with a long pedigree. It is illustrated in this figure from arXiv:1506.05992, which we obtained from Prof. Kanemura:





Here are more contrasting models, from arXiv:1708.08912

SUSY model | 2 Higgs doublet model



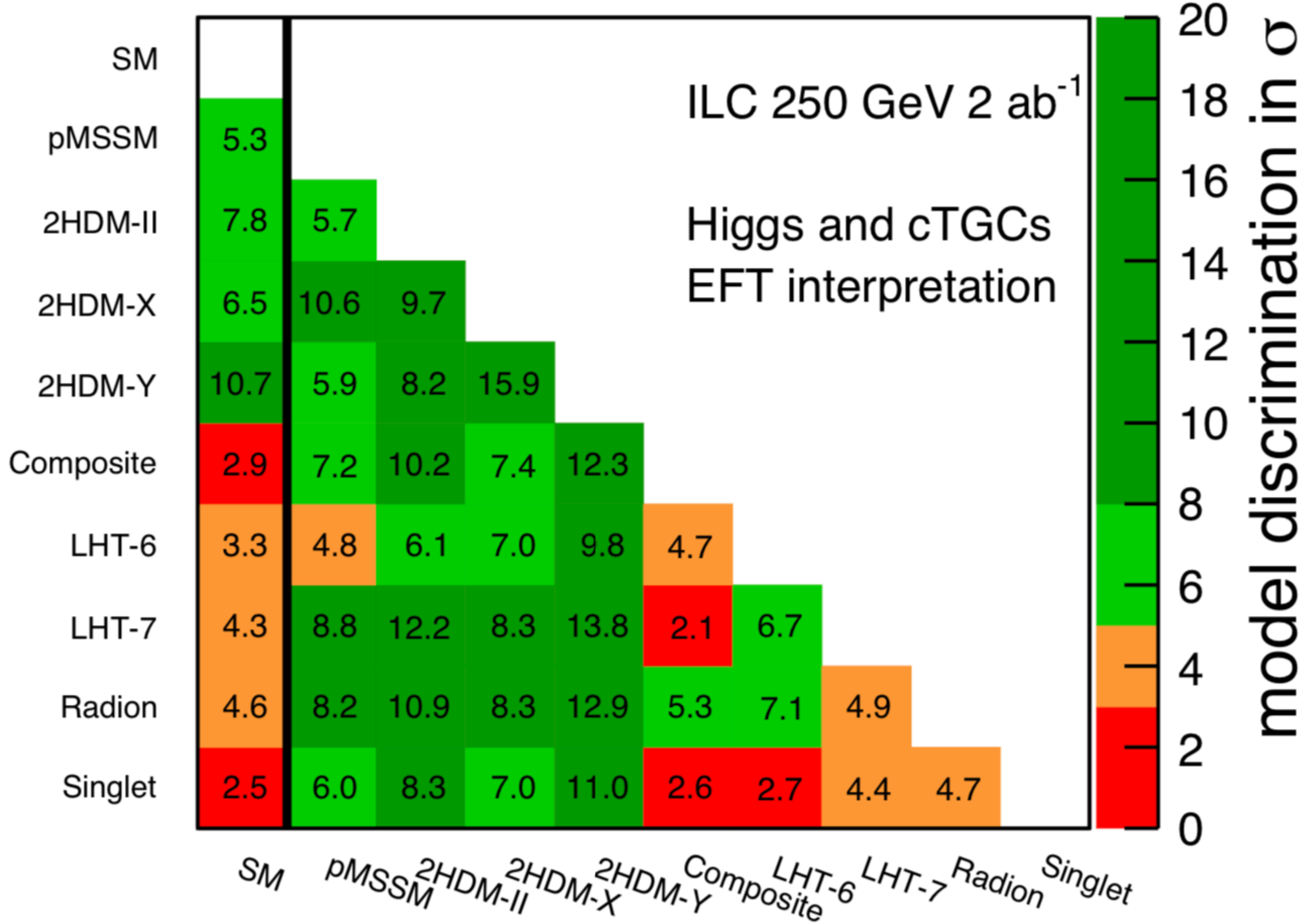
composite Higgs model | Little Higgs model

In arXiv:1708.08912, the ILC Physics Working Group carried out an interesting exercise.   We collected a group of 9 new physics models that would not be excluded by LHC but would give significant corrections to the Higgs boson couplings. Note that these were specific “representative” models, not parameter regions. We then asked,

(1) could the ILC distinguish these models from the SM ?

(2) could the ILC distinguish these models from one another ?

Here are the results displayed graphically:



ILC 250 GeV 2 ab^{-1}
Higgs and cTGCs
EFT interpretation
model discrimination in σ
SM
pMSSM
2HDM-II
2HDM-X
2HDM-Y
Composite
LHT-6
LHT-7
Radion
Singlet
5.3
7.8 5.7
6.5 10.6 9.7
10.7 5.9 8.2 15.9
2.9 7.2 10.2 7.4 12.3
3.3 4.8 6.1 7.0 9.8 4.7
4.3 8.8 12.2 8.3 13.8 2.1 6.7
4.6 8.2 10.9 8.3 12.9 5.3 7.1 4.9
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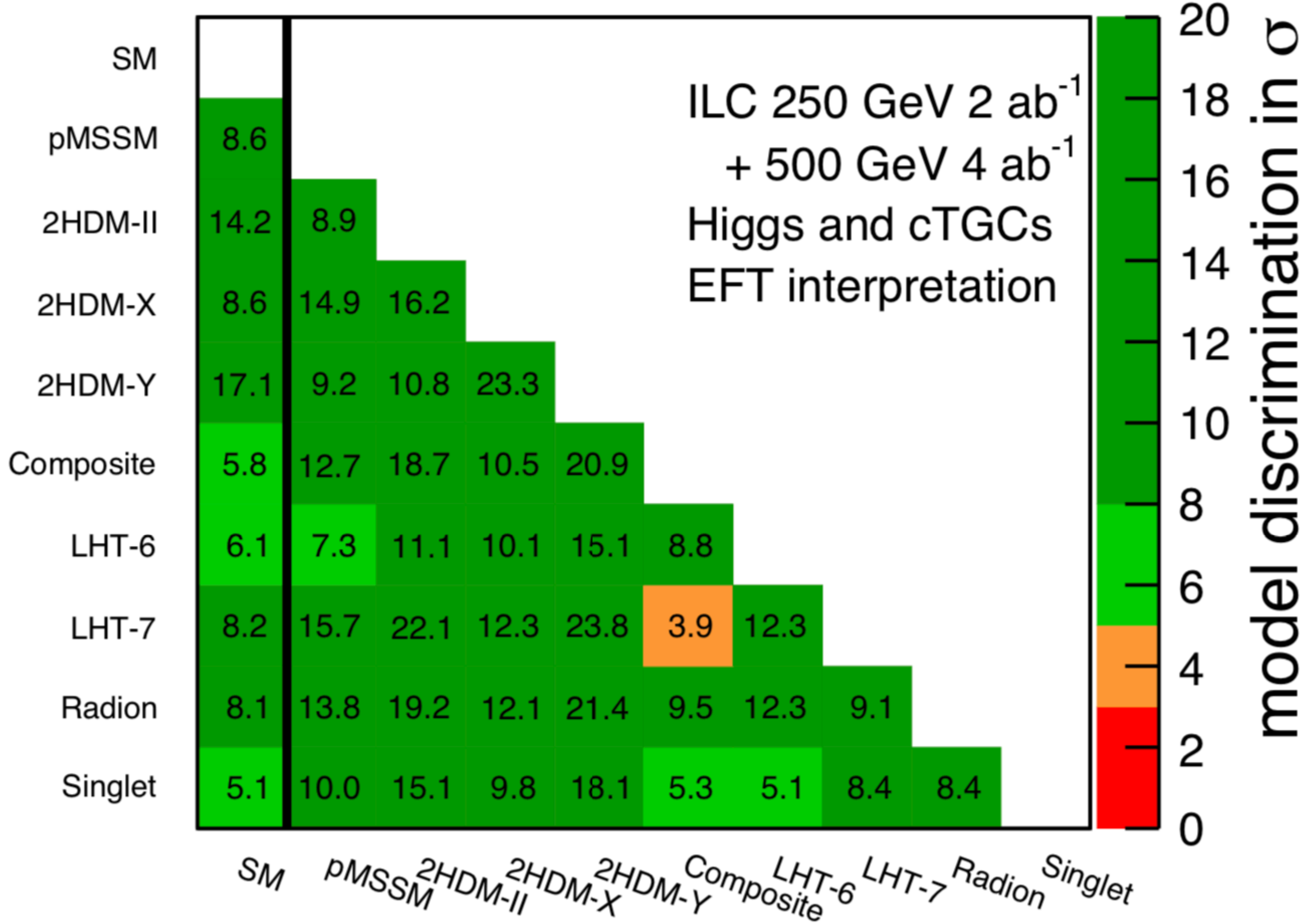
0 2 4 6 8 10 12 14 16 18 20


ILC 250 GeV 2 ab^{-1}
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8.4
8.4

At this level, this is just a game, but it would be good to turn this into a better understanding of the program of measuring Higgs couplings.

This suggests studying the "Higgs Inverse Problem":

Given a measured pattern of deviations from the SM in Higgs boson couplings, to what extent can we determine the underlying new physics model ?

Typically, talks at HPNP go the other way. But doing those calculations gives insight needed to answer this question.

There are good physics reasons for some of the differences in the patterns of Higgs couplings.

I like to say that each particular Higgs coupling has its own personality.

The easiest way to approach this is to look at different types of effects that can be seen in deviations of the Higgs couplings from the SM predictions.

Universal modifications:

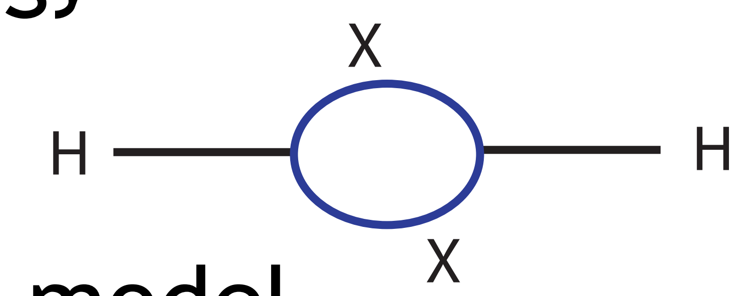
These have a simple pattern: The fractional change is the same for all decay modes.

Examples are:

Mixing of the Higgs with a singlet scalar field

Corrections to the Higgs self-energy from a new sector

$$\mathcal{L} = Z(g_X)^{-1} |\partial_\mu H|^2 + \cdots$$



Composite Higgs; nonlinear sigma model

$$\mathcal{L} = |\partial_\mu H|^2 + \frac{|H^\dagger \partial_\mu H|^2}{(1 - |H|^2/f_\pi^2)} + \cdots$$

Generation-independent modifications

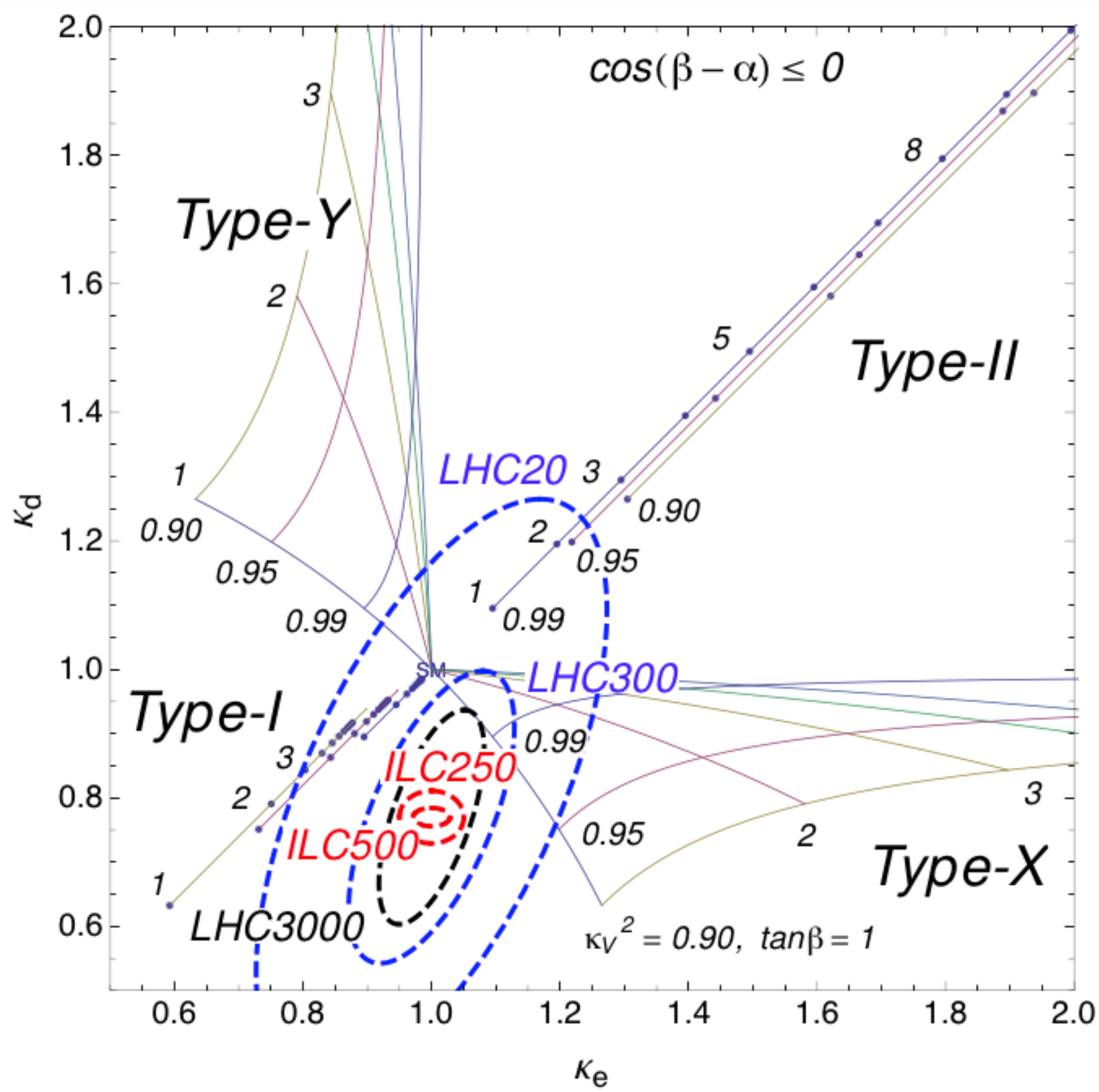
A familiar example is the tree-level 2-Higgs-doublet model, where we have (Type II)

$$g(d\overline{d}) = -\frac{\sin\alpha}{\cos\beta}\frac{m_d}{v} \qquad g(u\overline{u}) = \frac{\cos\alpha}{\sin\beta}\ \frac{m_u}{v}$$

In models with decoupling

$$-\frac{\sin\alpha}{\cos\beta} = 1 + \mathcal{O}(\frac{m_Z^2}{m_A^2})$$

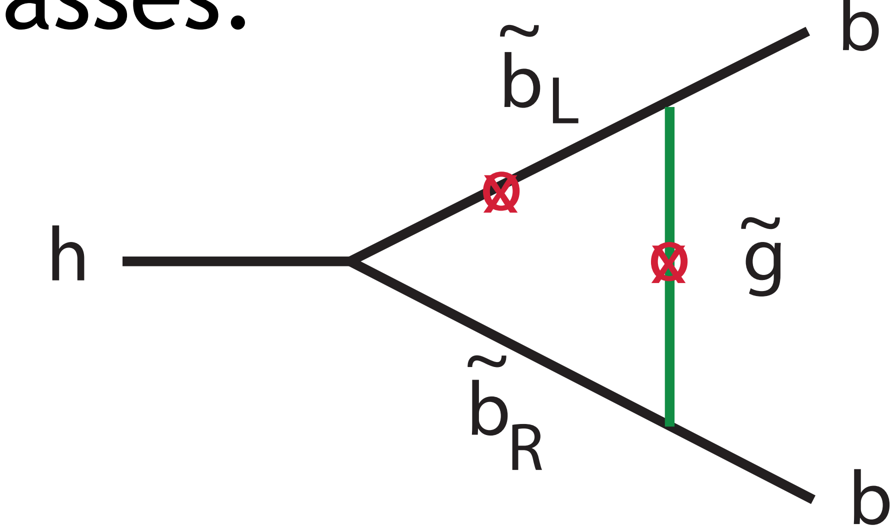
$$\frac{g(hVV)}{g(hVV)|_{SM}} = \sin(\beta-\alpha) = 1 + \mathcal{O}(\frac{m_Z^4}{m_A^4})$$



Kanemura, Tsumura, Yagyu, Yokoya

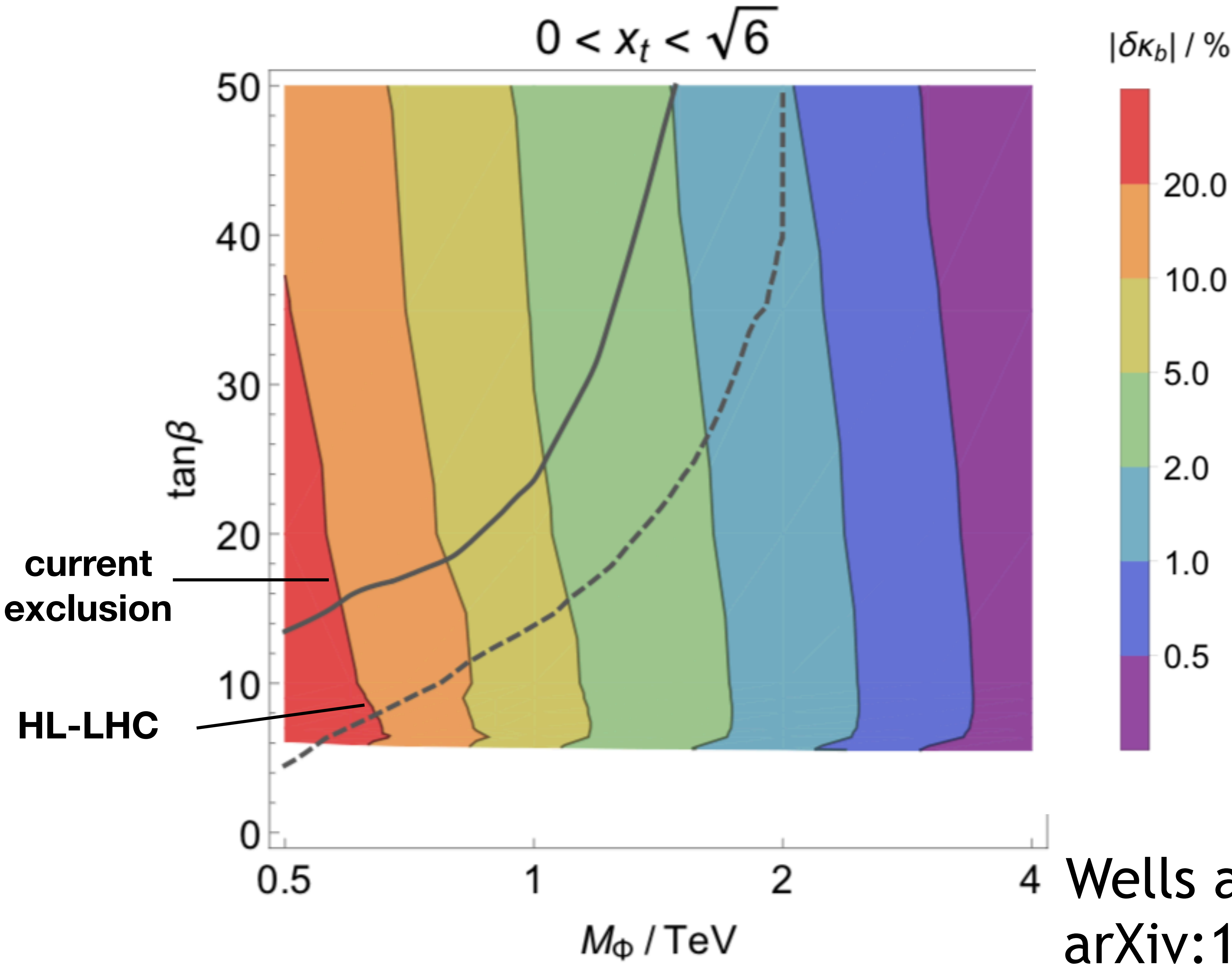
In SUSY models, this particular effect is seen in both b and τ couplings — and not in W, Z couplings, which provide an important reference.

However this picture can be modified by loop effects. In particular, the following effect can be substantial for large b masses:



Warning: Many SUSY codes are not accurate for squark masses ~ 5 TeV. Sven Heinemeyer will discuss this point.

worked example: grand-unified SUSY

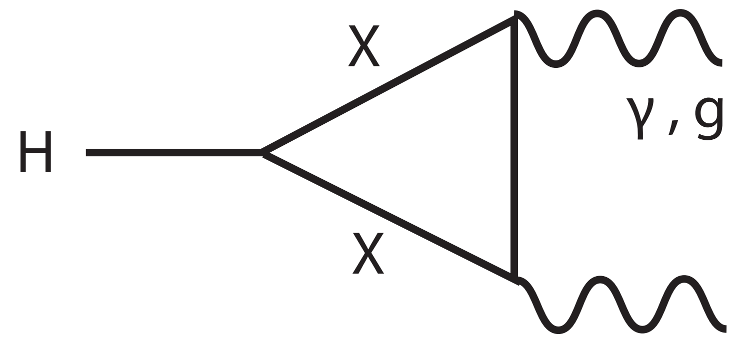


$(\kappa_b - 1)$ in %

Wells and Zhang, arXiv:1711.04774

Gauge-sector loop effects

Since the Higgs couplings to γ, g are generated only by loops, these loops can contain any heavy particles with the appropriate quantum numbers.c



Note that vectorlike fermions obtain only a small part of their mass $(\mathcal{O}(v^2/M^2))$ from SU(2)xU(1) breaking, thus satisfying decoupling.

Composite Higgs models, which require vectorlike top quark partners, generally show anomalies in hgg.

Mixing of the Higgs with the dilaton or radion produces these effects at the level of the trace anomaly.

Generation-dependent modifications

Bjorken (and many others): Why not have a separate Higgs boson for each generation ? In general, the lightest Higgs boson will have components of all of these more fundamental bosons.

Stefania Gori will discuss model-building strategies for generation-dependent Higgs couplings tomorrow.

We should be aware of the possibility of large fractional deviations in the Higgs couplings of the 2nd generation. Hopefully, we can fully explore this (c, s, μ) at ILC.

Flavor-violating couplings

In the SM, it is automatic that Higgs boson couplings are flavor-diagonal.

In models of an extended Higgs sector, this is no longer true. In particular, in any theory with generation-dependent modifications of the Higgs couplings, flavor violation in Higgs decay is expected.

Decoupling implies that the rates are $\mathcal{O}(v^4/M^4) \sim 10^{-3}$, so this prediction is not tested yet. Information on

$$h \to b\bar{s} \qquad h \to \tau + \mu^-$$

can enter the global understanding of Higgs boson couplings.

Just now, the Snowmass 2022 study of the future of particle physics is going on in the US.

For that study, it would be good to have a much sharper quantitative discussion of of the path from the Higgs coupling pattern to BSM models.

This is the purview of the Snowmass working group EF02: Higgs as a Portal to New Physics — Patrick Meade and Isobel Ojalvo, conveners.

We plan to discuss this subject in the

https://agenda.linearcollider.org/event/9135/

I welcome all of you to contribute (and to sign the report by registering at this site)!

The editors of the Theory sections are

Nathaniel Craig, Mihoko Nojiri, Maxim Perelstein, and me

Please contact us to submit material or to get involved.

The precision study of the Higgs boson can tell us that there is new physics beyond the Standard Model,

but it also can tell us much about the nature of the new physics beyond the Standard Model.

Please help us in bringing this story to a higher level of insight and refinement.