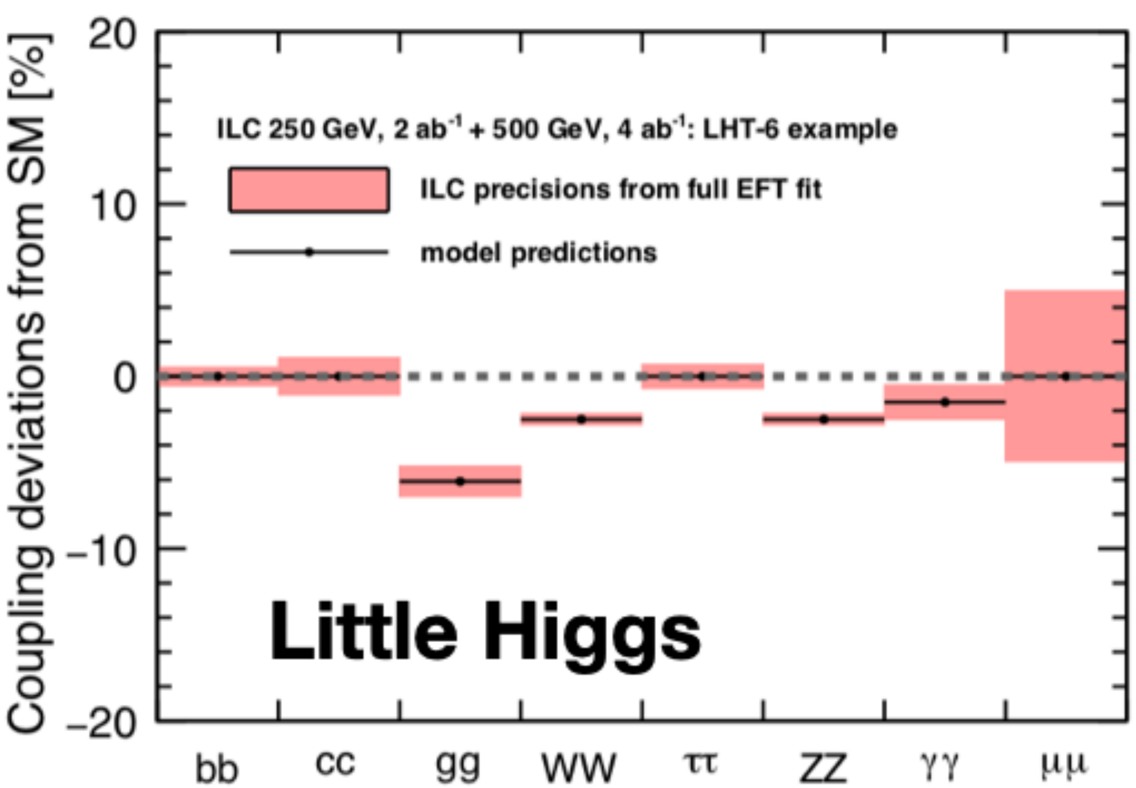
About the case for precision Higgs measurement



M. E. Peskin

ECFA Higgs workshop
April 2022

The case for precision measurements of the Higgs boson properties is strong.

However, as yet, this case is not made sharply. Many elements are too technical for a presentation to the public and even to our scientific colleagues.

An important goal of the ECFA study must be to improve the statement of the case for an e+e- Higgs factory. Separate versions should be addressed to the HEP community, to scientists outside our field, and to governments and the public.

In this talk, I would like to give an outline of this case, noting points that need further development.

1. Centrality of Higgs boson
2. Implications of Higgs as an Effective Field Theory
3. Burden of discovery using precision
4. Mass reach of Higgs precision
5. Higgs and flavor / Higgs portal
6. Higgs Inverse Problem

In the ILC Report to Snowmass (arXiv:2203.07622), we made our best attempt to state this case for an audience of particle physicists (and the US P5 panel).

See especially Chapter 13-14. This section, like most of the physics discussion in this paper, applies to all proposed Higgs factories.

We would appreciate your critiques and feedback.

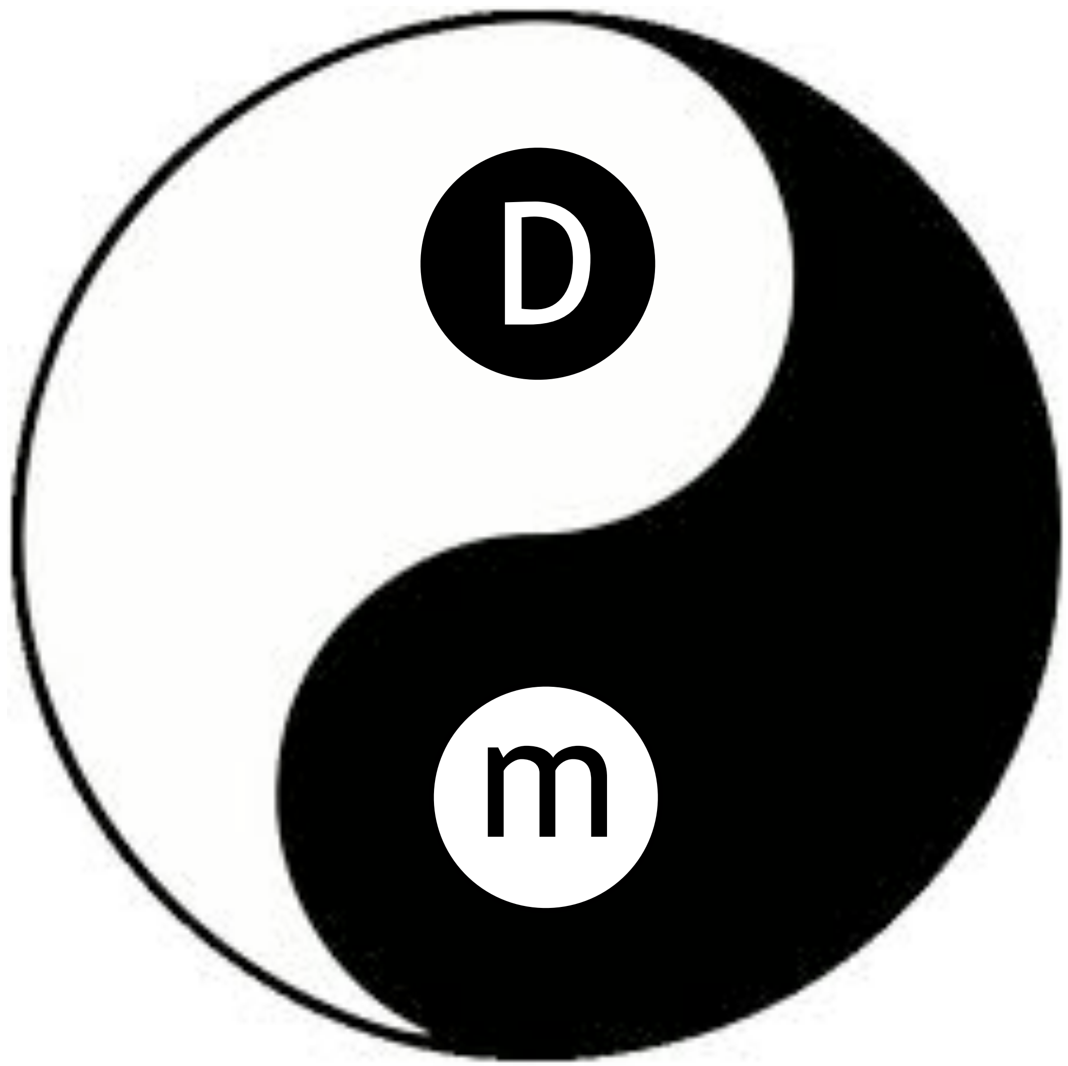
We would also appreciate it if you would endorse this report. Please visit:

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

Centrality of the Higgs Boson:

40 years ago, at Lepton-Photon 1981, Lev Okun introduced this metaphor for the Standard Model Lagrangian, and, by extension, for all of our knowledge of particle physics:

Gauge side



Higgs side

Gauge side / Higgs side

Maxwell's equations

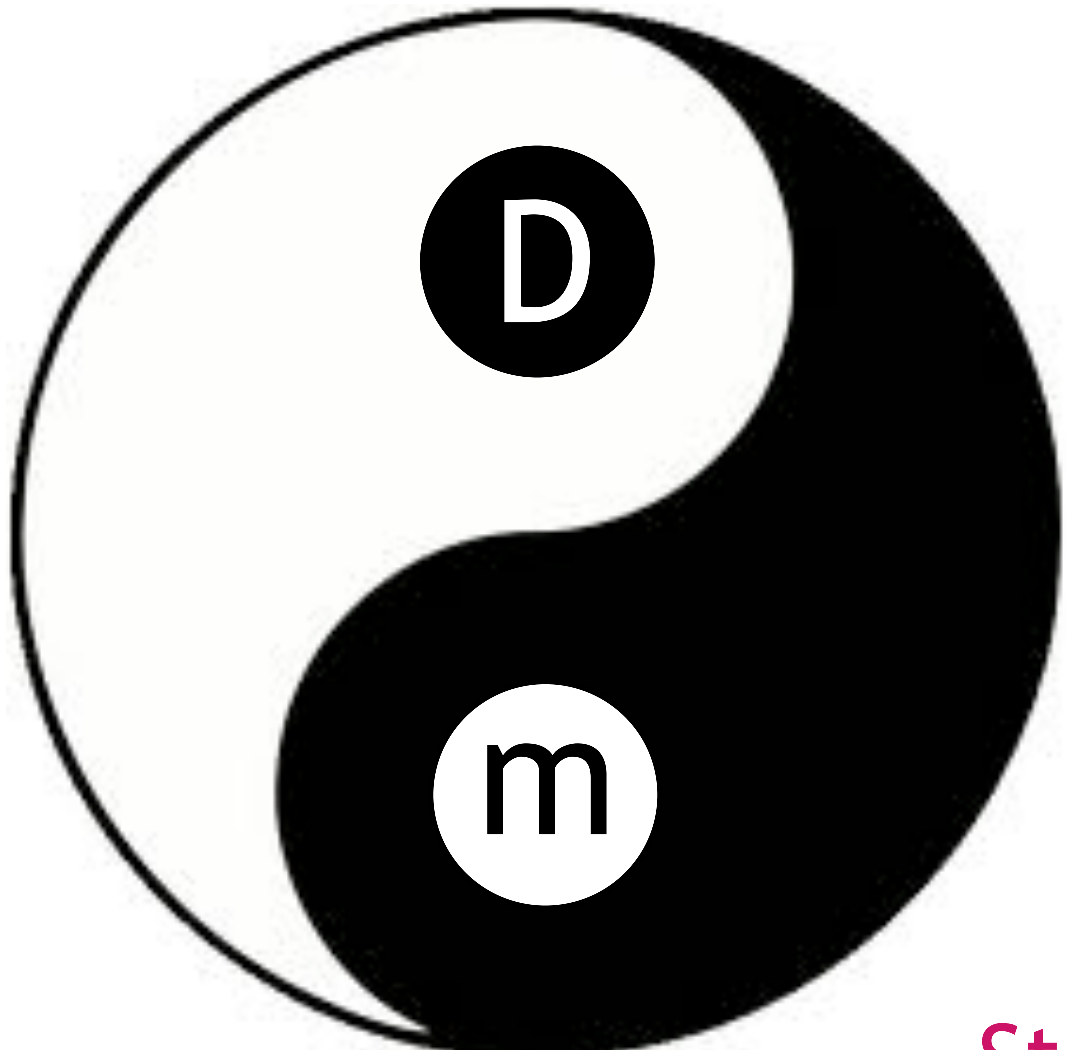
Quantum numbers

Parity violation

W, Z boson

Proton structure

Asymptotic freedom



W, Z masses

Quark masses and mixings

Neutrino masses

CP violation

L, B violation

Dark energy

Standard Model all-powerful

Standard Model impotent

Dark matter? It depends on the model.
WIMP dark matter is firmly on the Higgs side.

Every model of neutrino mass, quark mixings, CP violation, baryogenesis begins with a specific assumption about the nature of the Higgs boson.

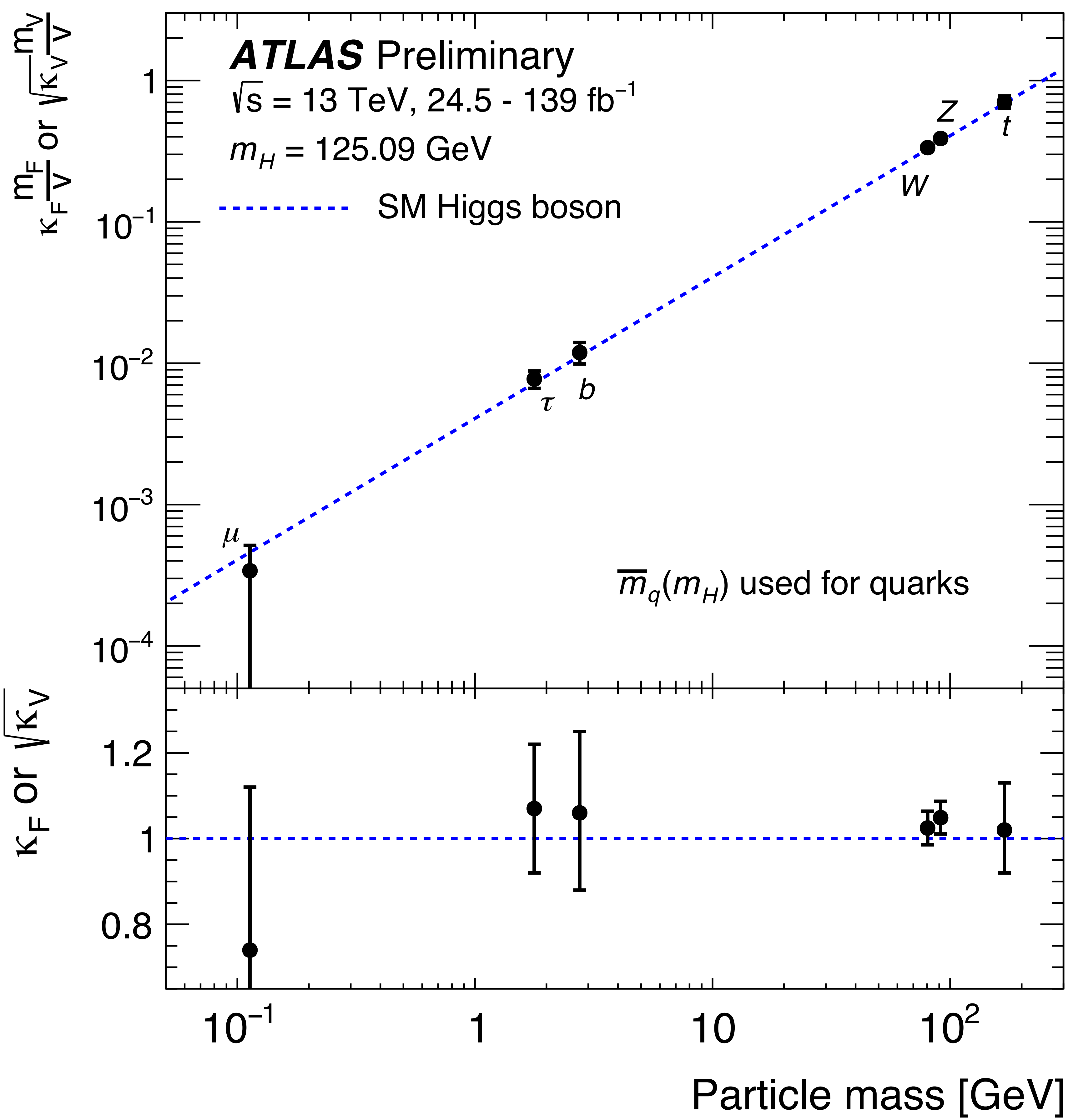
Typically, models assume that the Higgs boson is an elementary scalar with no a priori constraints on its couplings.

We cannot make progress on any of the “Higgs side” questions until we understand the principles that cause the Higgs boson to act as it does.

Implications of Higgs as an Effective Field Theory:

A question often asked is: Why do we need to explore the Higgs boson with higher precision ? Doesn't LHC do extremely well already?

Another: What is the target precision for a Higgs factory? Is it only that we should advance beyond LHC ?



Haven't we already proved that Higgs is the origin of mass ?

The answer depends on your model of SU(2)xU(1) breaking.

Consider: SU(2)xU(1) is broken by an expectation value for an effective Higgs scalar doublet.   There is new physics beyond the SM, but the new particles lie at a higher mass scale M .

In that case, the most general effective Lagrangian describing particle physics at the Higgs scale is:

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_j \frac{c_j}{M^2} \mathcal{O}_j + \cdots$$

i.e., Standard Model Effective Field Theory (SMEFT).

In this model, new physics corrections to Higgs boson couplings are of the order of

$$v^2/M^2 \qquad\qquad v = 246 \text{ GeV}$$

that is, well below 10% for $M \sim 2 \text{ TeV}$.

In this model, we would not have expected to see any deviation from the Standard Model in the current LHC data set. In fact, today, we are not even in the game.

Once we reach sensitivity to v^2/M^2 effects, the corrections can be of any form.

Burden of discovery using precision:

The study of precision Higgs measurements is not about making the error bars smaller.

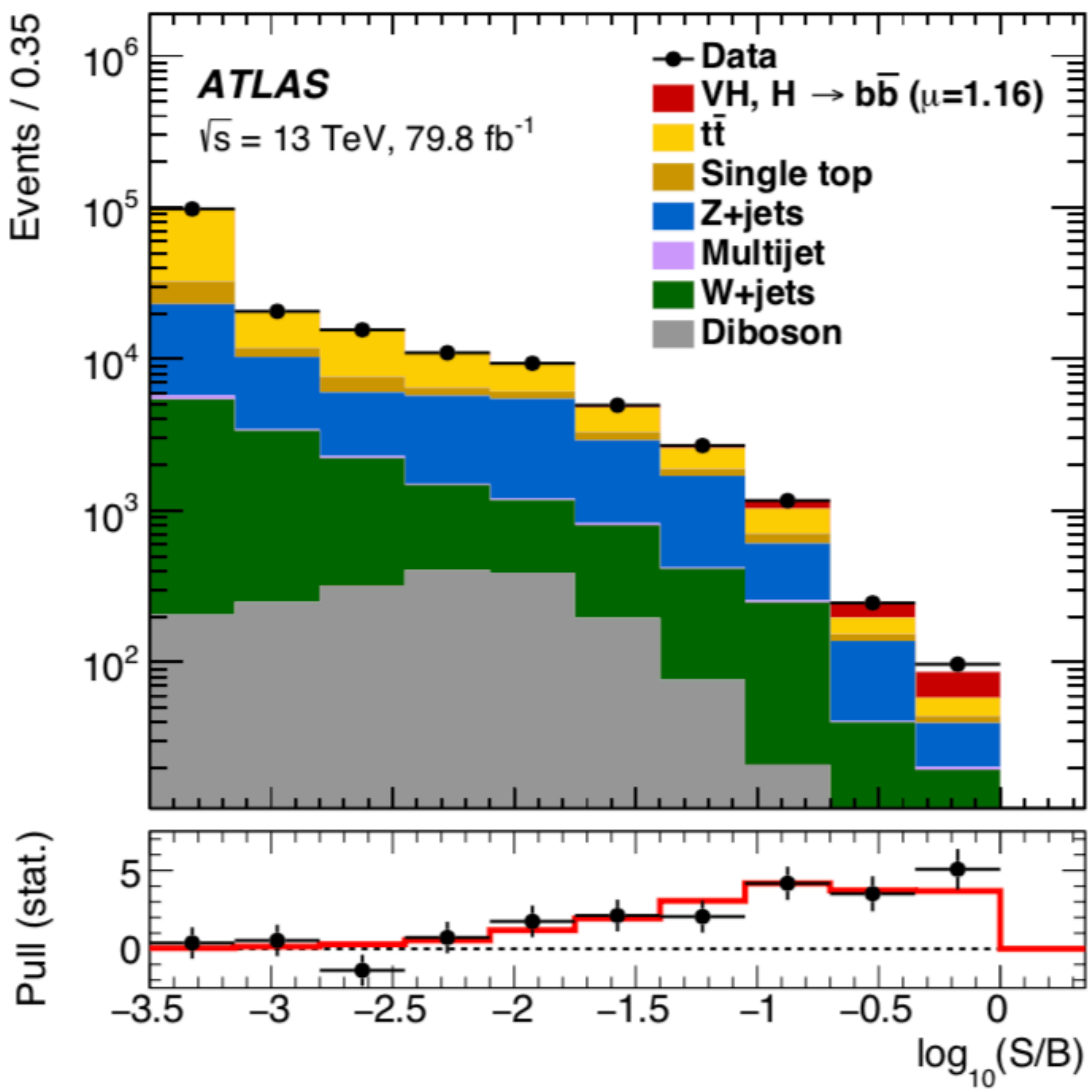
It is about discovering that the Standard Model is violated, and proving this to a skeptical audience.

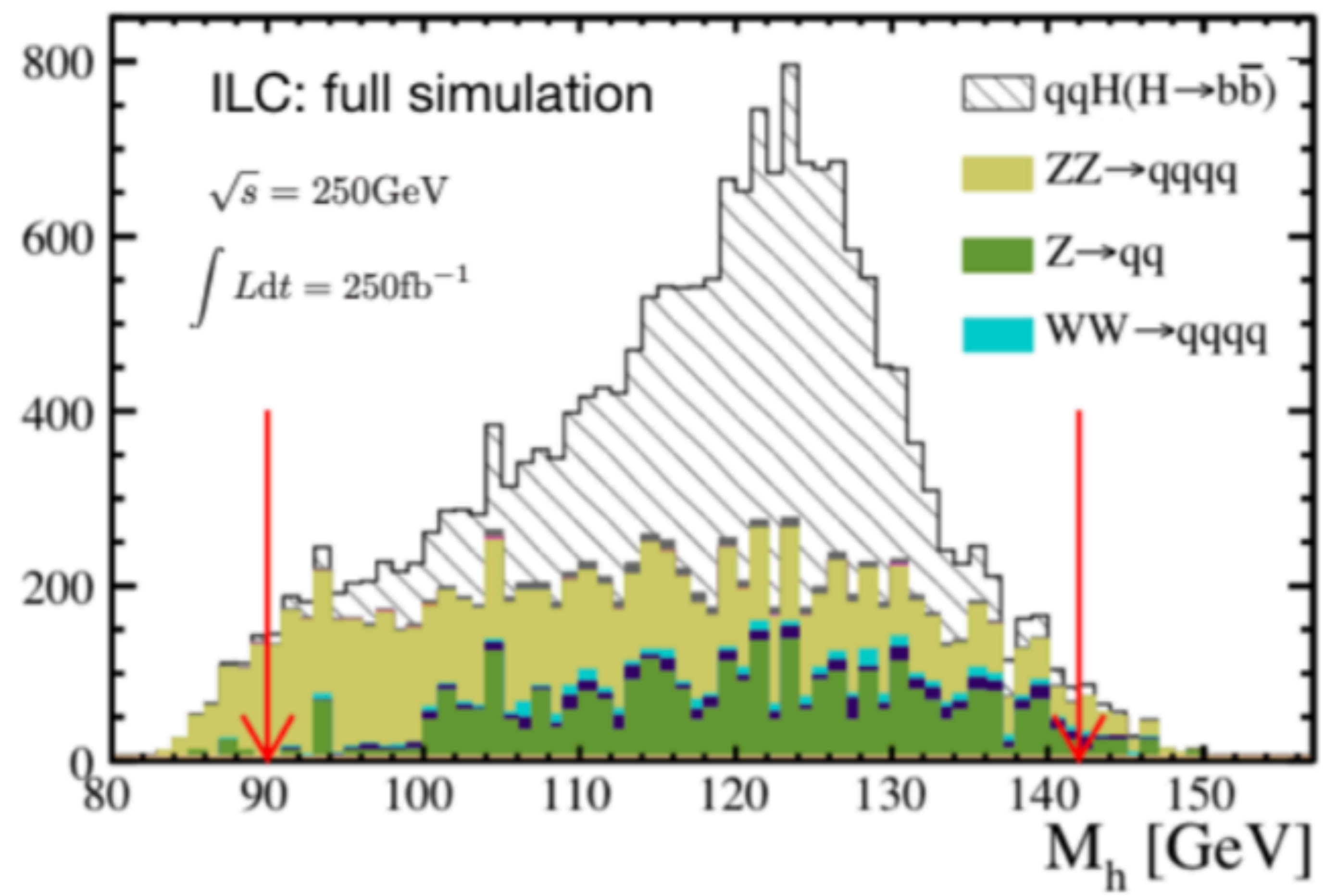
There is tremendous advantage in being in a situation in which the dominant uncertainties are statistical, and these are continuously improvable.

e+e- colliders offer two different production mechanisms

$$e^+e^- \to ZH \qquad W^*W^* \to H$$

allowing internal checks as well as increased statistics.





(1/8 of the ILC data set at 250 GeV)

Mass reach of Higgs precision:

It seems easy to rate Higgs precision studies vs. the direct search reach of LHC. However, this is actually quite subtle.

The size of Higgs coupling corrections is always v^2/M^2, but the coefficient depends on whether the corrections are tree-level or loop-level. The comparison to LHC depends on whether the particles involved are strongly interacting or electroweak.

Often, the models with new particles accessible to LHC are different from the models with large Higgs coupling corrections.   Then LHC searches and Higgs coupling measurements are complementary rather than competitive.

case of minimal supersymmetry:

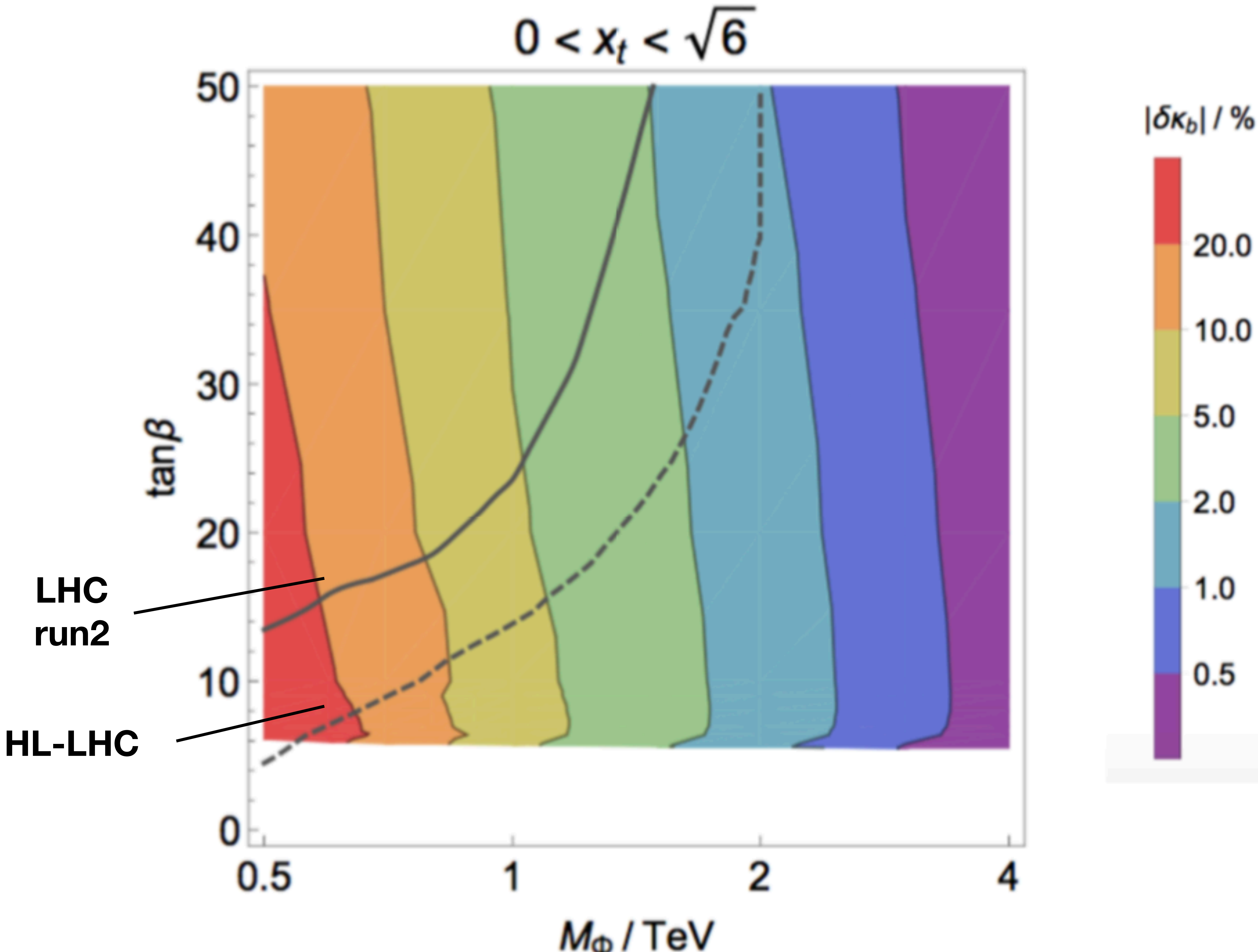
there are at least three distinct mechanisms for generating large Higgs coupling corrections:

tree-level mixing as in 2-Higgs-doublet models

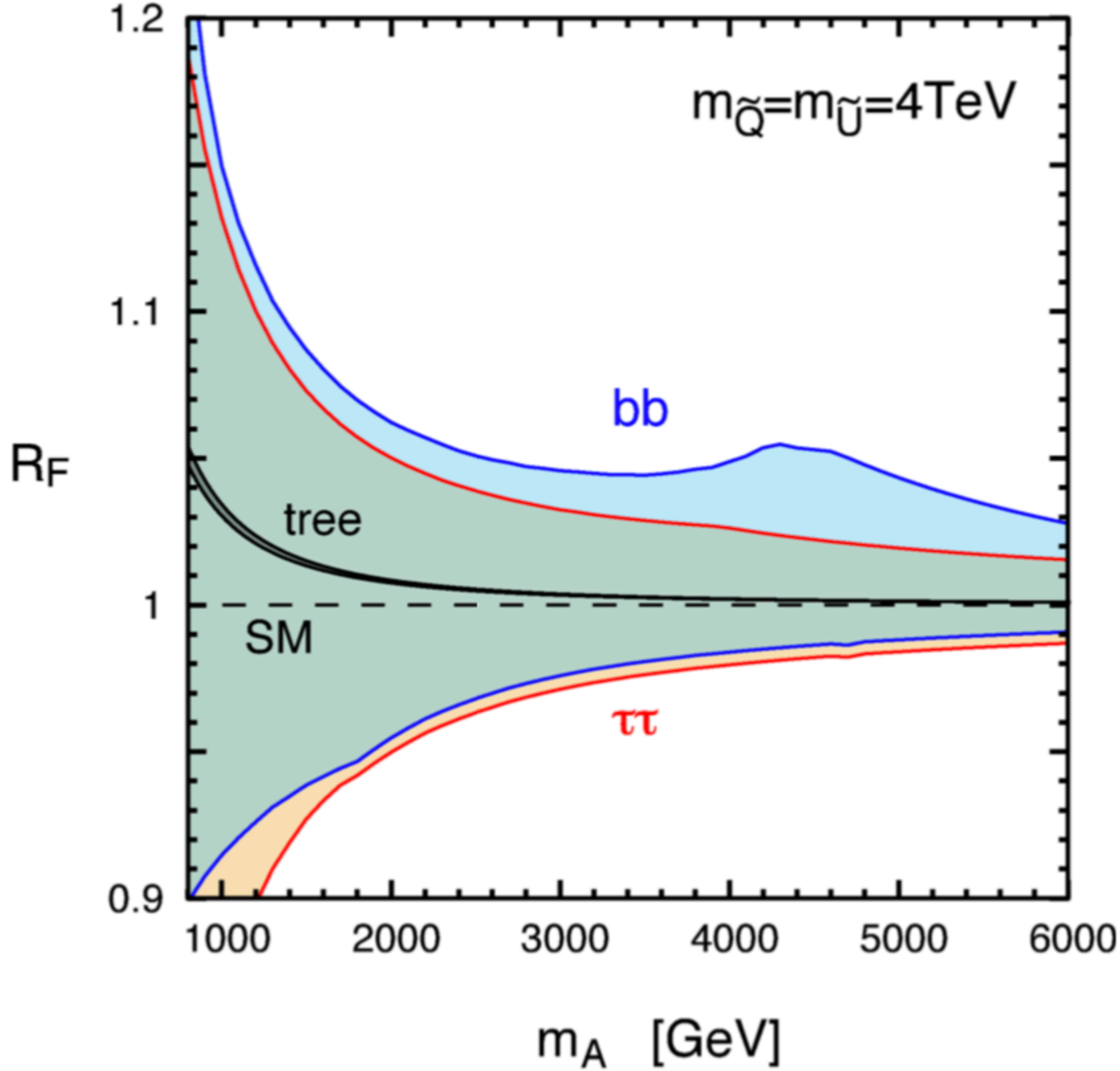
loop corrections to the hbb vertex from a large A term

loop corrections to the hgg vertex from light top squarks

The full story is not yet understood systematically.



Wells and Zhang 2017



Endo, Moroi, Nojiri 2015

Higgs and flavor:

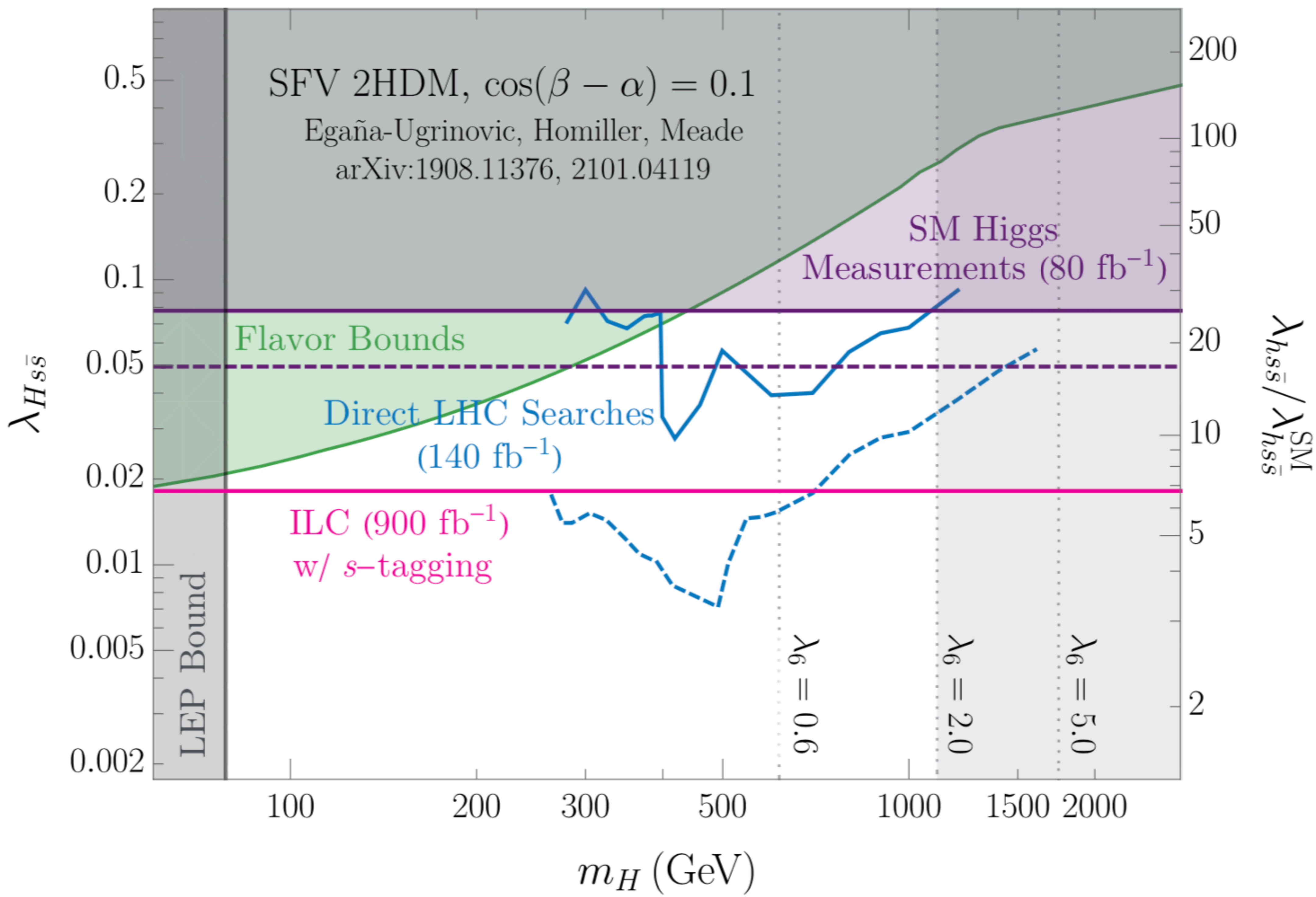
Models of SU(2)xU(1) breaking have historically been structured to avoid flavor-mixing as much as possible.

However, the large mass hierarchies in the fermion mass spectrum are generated by the Higgs sector. Shouldn't we look for clues in the Higgs couplings ?

This implies special interest in the 2nd generation Higgs couplings, the couplings to μ, c, s .

An attractive idea is that there is a separate Higgs for each generation. These appear mixed in the single effective Higgs, with the dominant contribution being that of the 3rd generation.

Recently, Altmannshofer and Gori and Egana-Ugrinovic, Homiller, and Meade have explored this idea in flavor-dependent 2-Higgs doublet models. The absolute sizes of Higgs couplings to the 2nd generation are small, and so it is possible to have significant anomalies consistent with all flavor constraints.



Basso, et al. 2022

In the Standard Model, we can redefine the fields so that off-diagonal Higgs couplings such as

$$H \to \tau\mu \qquad H \to bs$$

are forbidden. When we reach the dimension-6 coefficients in SMEFT, this freedom is already used up. Thus, we might expect these flavor-violating Higgs decays to appear at the level

$$BR \sim 10^{-3} - 10^{-4}$$

A Higgs factory can also observe states in a dark sector through the "Higgs portal", down to branching ratios of about 10^{-4}. This may be a unique way to access these states. The LHC is obtaining strong bounds on certain Higgs exotic decays, especially those with muons, but an e+e- collider will be needed for modes with hadronic final states, e.g.

$$H \to b\bar{b} + \text{missing}$$

$$H \to \text{dark jets}$$

Higgs Inverse Problem:

I have already emphasized that Higgs boson couplings may contain corrections of size few % due to new physics. These corrections can be of arbitrary form.

This implies that the Higgs coupling corrections will form a pattern. This pattern is different for different BSM model and potentially provides clues to new physics beyond the reach of LHC.

Some simple observations about the largest effects are

2-Higgs-doublet models → b, τ couplings

3rd generation chiral mixing → b couplings

Higgs singlet, Higgs as Goldstone → W, Z couplings

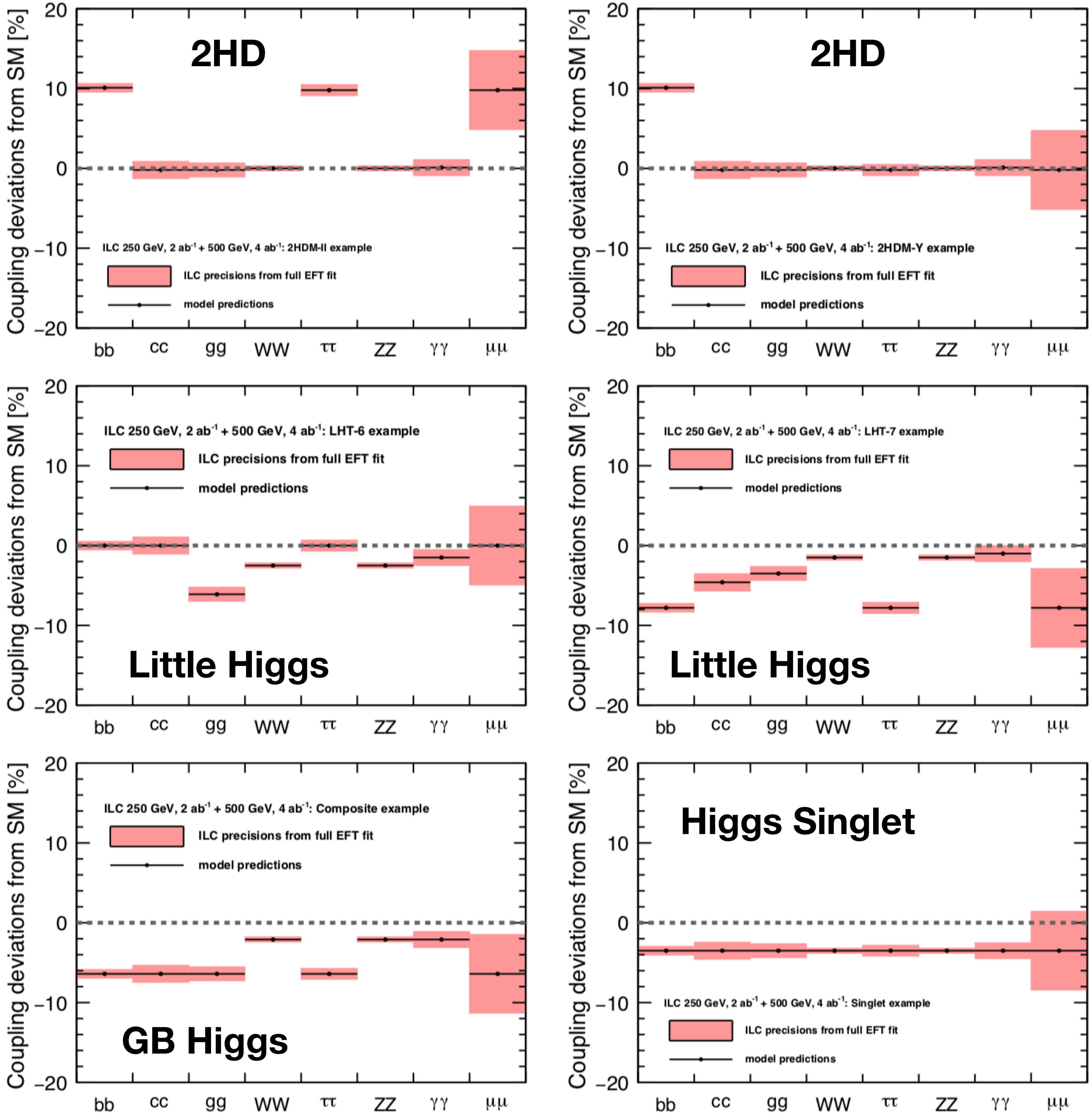
heavy vectorlike quarks → g, t couplings

In Barklow et al., arXiv:1708.08912 , we collected a number of specific models with large Higgs coupling deviations due to new particles out of reach of HL-LHC.

Here is a composite:

Uncertainties shown are those expected for the ILC at 500 GeV.

It is beyond hope to survey all of BSM model space, but it would be good to understand more generally how to translate a Higgs deviation pattern to guidance on models.



Barklow, et al.

The case for an e+e- Higgs factory is strong today, but it can be made stronger with concerted effort, especially in the relation between models and their impact on the Higgs properties.

I hope that we can also think about how to translate the technical aspects of this case into mottos that usefully guide our scientific colleagues and the general public.