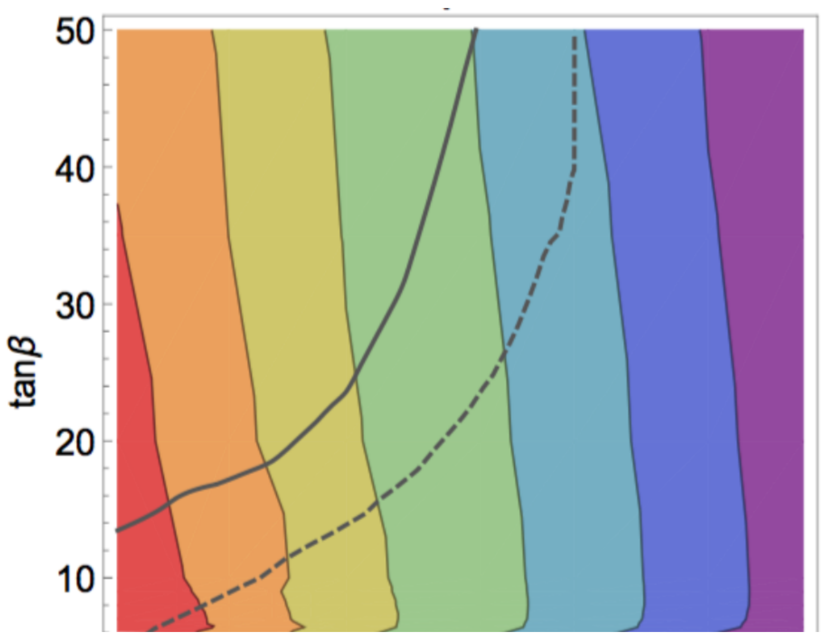
Physics of the Higgs Boson at High Precision



M. E. Peskin
LPC Topic of the Week
September 2018

The Standard Model does an amazing job of accounting for a wide variety of phenomena observed in elementary particle physics:

$$m_\pi^2 \ll m_\rho^2$$

$$K^+ \to \mu^+ \nu \text{ but } K^0 \not\to \mu^+ \mu^-$$

$$\sigma(e^+ e^- \to \text{hadrons}) \approx \text{ naive quark model value}$$

$$m_W / m_Z = \cos\theta_w$$

$$A_\tau = 15\% \ , \ A_b = 95\% \text{ at the } Z^0$$

$$BR(t \to W_0^+ b) \approx 70\%$$

The Standard Model accounts quantitatively for the hadron mass spectrum, the properties of B meson decays — including CP violation — and the most complex quark-gluon-W-Z reactions observed at the LHC.

Simply by adding a neutrino mass term (possibly a conventional one with right-handed neutrinos), it can account for neutrino flavor mixing.

But, despite this, the Standard Model is manifestly incomplete. There are important qualitative questions about particle physics that it is totally unable to answer:

The Standard Model:

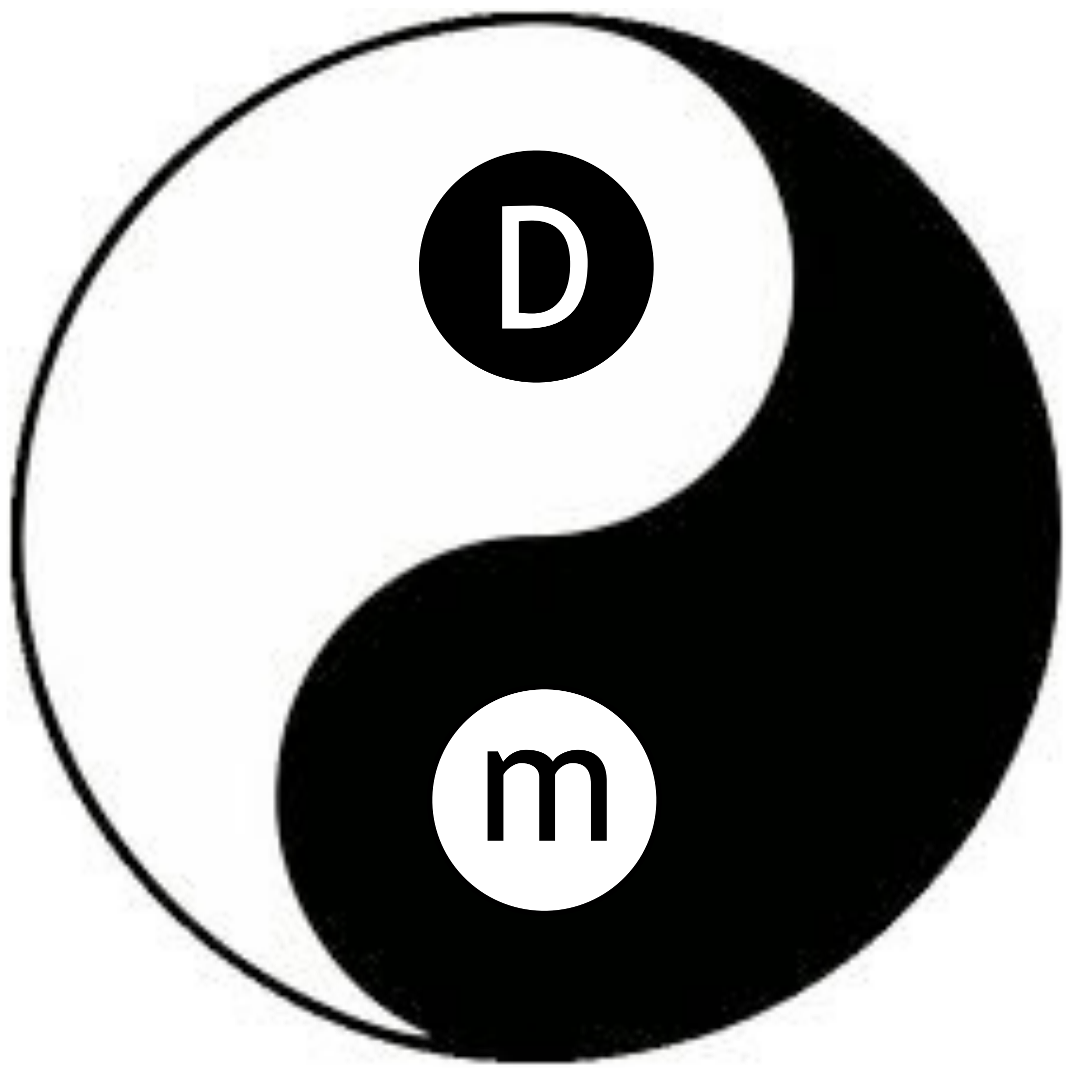
cannot predict electroweak symmetry breaking
cannot predict the spectrum of quark and lepton masses
cannot predict the cosmic matter/antimatter asymmetry
cannot predict the existence of dark matter

What is the difference between the phenomena that the Standard Model can predict and those that the Standard Model cannot predict ?

In 1981, I attended a talk by the late great Russian theorist Lev Okun. The subject of the talk was

"What is the problem #1 [of particle physics] ?"

Okun gave as the answer to this question the following figure:



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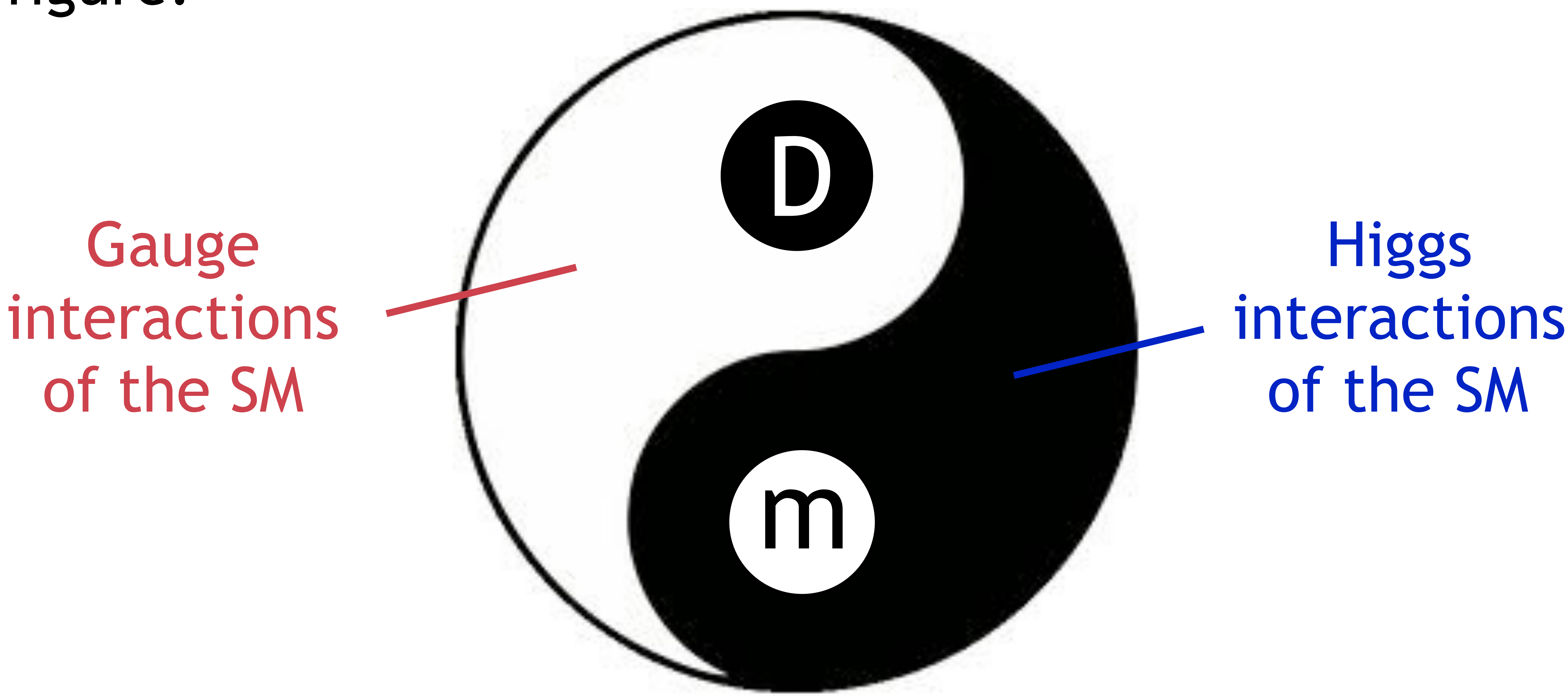


All of the dramatic successes of the SM come from the gauge interactions of SU(3)xSU(2)xU(1).

All of the ugly adjustible constants that need to be fit from experiment (including the sign of μ^2) come from the interactions of the Higgs field.

An opinion that you have heard very frequently in your education is that it is urgent for us to find evidence of new physics beyond the Standard Model.

Actually, since even before Okun's talk, particle physicists have been searching for signs of new physics. These searches have taken many forms:

direct particle searches at LEP, Tevatron, and LHC
searches for precision effects on Z and W
searches for BSM mechanisms of CP violation
direct and indirect searches for dark matter

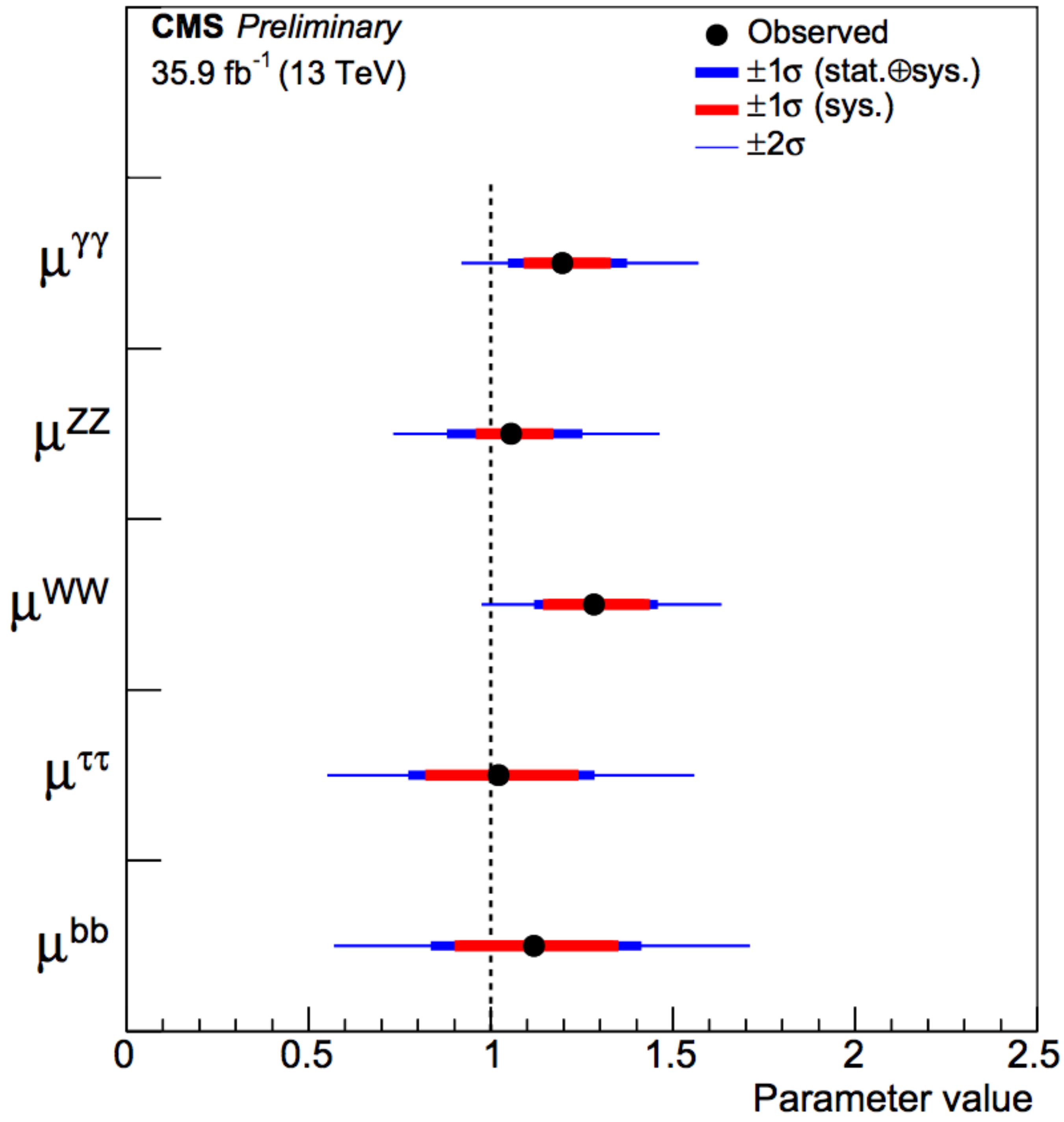
In all cases, a large parameter space of possibilities has been excluded. Now the limits of these techniques with current facilities are in sight.

But there is still one technique that has not be exploited yet. This is to make a detailed examination of the Higgs Boson itself.

Nigel Locker (quoted in Physics Today):

“You would be nuts not to study the heck out of the Higgs.”

Wait ! It took a long time to find the Higgs Boson, but now we have discovered it at the LHC and measured its couplings. Isn't it SM-like ?



Yes, but, this does not mean that the true nature of the Higgs boson has been clarified.

It is a property of the SM that, under very general assumptions, the Higgs Boson must be SM-like to a first approximation.

Decoupling theorem (Howard Haber):

If the Higgs boson has a mass at the electroweak scale and the mass of the lightest new physics particle is M, then the corrections to the Higgs properties due to new physics are of order m_h^2/M^2

For M ~ 1 TeV, this implies few-% corrections only.

Proof of the theorem:

The SM is the most general renormalizable QFT with SU(2)xU(1) gauge symmetry and the known particle content.

If new fields are heavy, we can integrate them out of the Lagrangian. The main effect of this is to shift the parameters of the SM. Any other effects are described by adding operators of higher dimension to the SM Lagrangian.

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{M^2} \sum_i \tilde{c}_i \mathcal{O}_{6i} + \frac{1}{M^4} \sum_i \tilde{d}_i \mathcal{O}_{8i} + \cdots$$

Actually, despite the good agreement between the LHC data and the SM description of the Higgs boson, we still know very little about the basics of the Higgs field.

We do not know yet whether there is one Higgs, many Higgses, composite Higgses, etc. There might be a "Higgs sector" that contains many new particles. In the SM, there are multiple quarks and leptons. Why not multiplet HIggs fields?

All of this is hidden from us by the Decoupling Theorem.

The Decoupling Theorem does have a nice corollary.

Since the SM is the most general dimension-4 Lagrangian, once the parameters of the SM are determined by experiment, the SM gives definite predictions for the Higgs boson properties.

Lepage, Mackenzie, and I have argued that lattice QCD will determine the crucial input parameters

$$m_b, m_c, \alpha_s$$

to compute Higgs couplings with accuracies at the part per mil level.

So, BSM cannot hide if we can measure the Higgs couplings with sufficient accuracy.

In the theoretical literature, there are many examples of models that give small but nontrivial modifications of the Higgs Boson properties.

In a model with two Higgs doublets, the physical states are mixtures of the two fields

mixing angle $\begin{array}{ll} \alpha : & h^0, H^0 \\ \beta : & \pi^0, A^0 \quad \pi^\pm, H^\pm \end{array}$ $\tan\beta = v_u/v_d$

Then the coupling modifications are

$$g(b\bar{b}) = -\frac{\sin\alpha}{\cos\beta}\frac{m_b}{v} \qquad g(c\bar{c}) = \frac{\cos\alpha}{\sin\beta}\frac{m_c}{v}$$

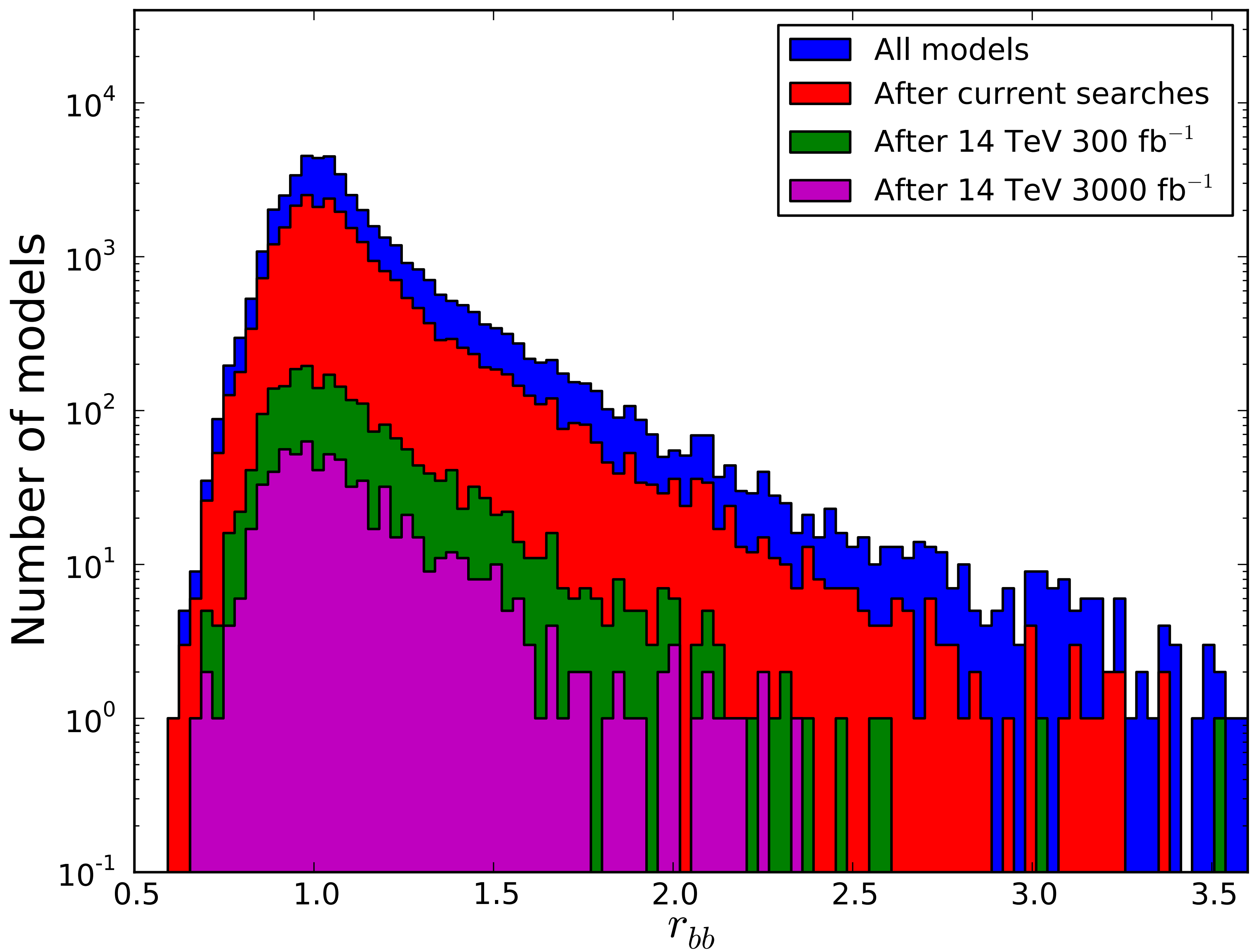
In full models such as SUSY, the two angles are not independent. In fact, typically,

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

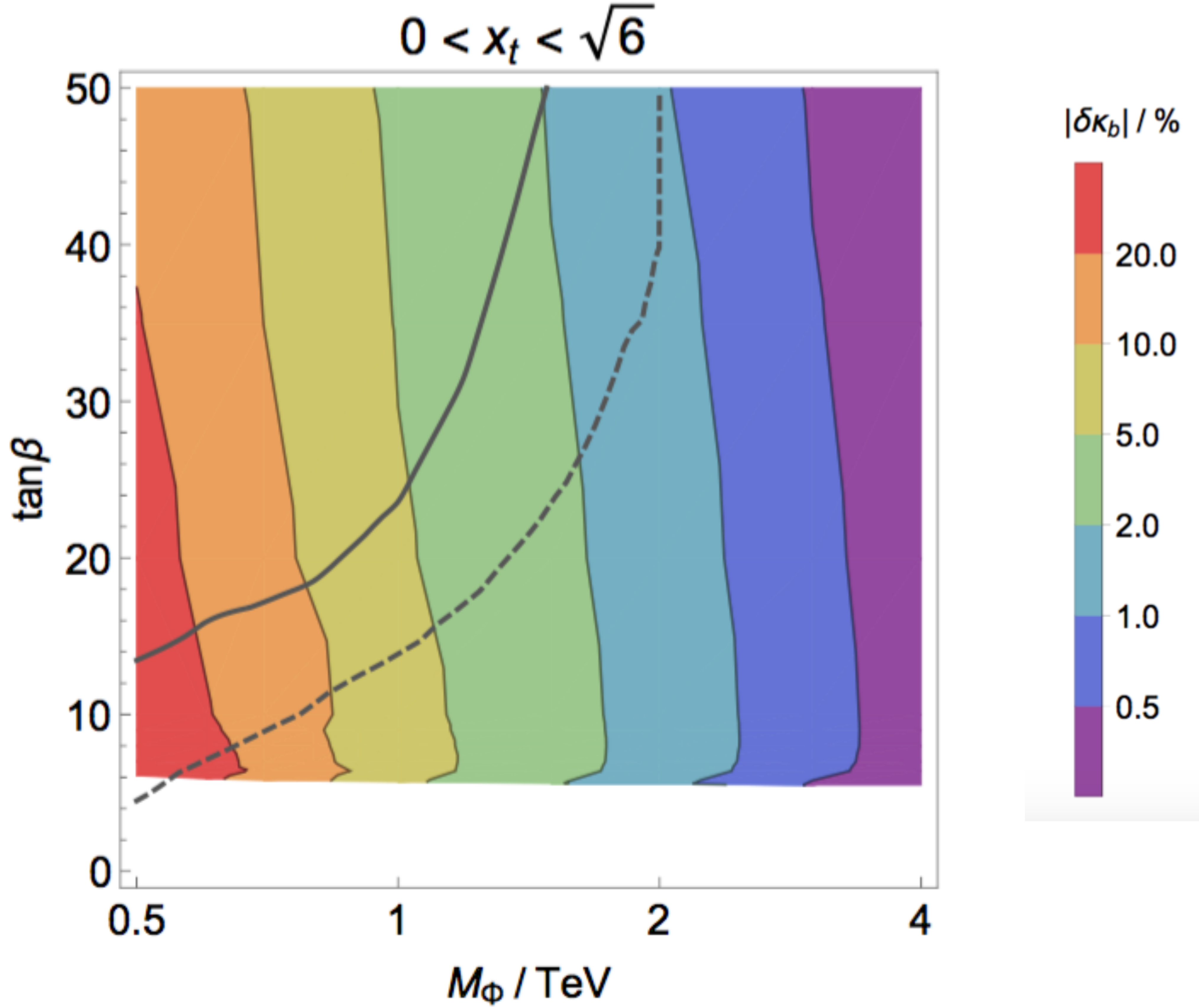
so that

$$\frac{g_{hbb}}{g_{hbb}|_{SM}} = \frac{g_{h\tau\tau}}{g_{h\tau\tau}|_{SM}} \approx 1 + 6\% \left(\frac{500 \text{ GeV}}{m_A}\right)^2$$

In supersymmetric models, there can also be large radiative corrections from b-squark loops, even if the squarks are at 4-5 TeV.



Cahill-Rowley, Hewett, Ismail, Rizzo



Wells and Zhang : models with b-τ unification

An important point visible in both analyses is that direct particle searches and searches for Higgs anomalies probe the space of BSM models from different directions.

The point is not somehow to beat LHC but rather to explore for new physics through a different window.

The coupling of the Higgs boson to vector bosons is simple in the SM:

$$g(hVV) = \frac{2m_V^2}{v}$$

Corrections to this from models with an extended Higgs sector are usually small, since it is the lightest Higgs that has the largest vacuum expectation value. In SUSY,

$$g(hVV) = 1 + \mathcal{O}(\frac{m_Z^4}{m_A^4})$$

Still, the hWW and hZZ coupling can obtain corrections from a number of sources outside the SM.

Mixing of the Higgs with a singlet gives corrections

$$g(hVV) \sim \cos\phi \sim (1 - \phi^2/2)$$

These might be most visible in the hVV couplings. Similarly, field strength renormalization of the Higgs can give few % - level corrections.

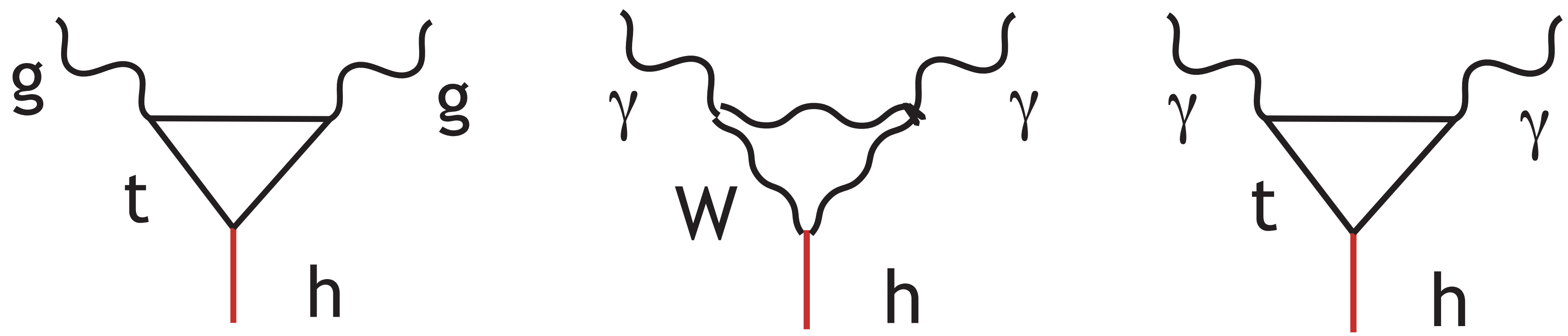
If the Higgs is a composite Goldstone boson, these couplings are corrected by

$$g(hVV) \sim (1 - v^2/f^2)^{1/2} \sim \text{few } \%$$

The decays

$$h \to gg \ , \ h \to \gamma\gamma \ , \ h \to \gamma Z^0$$

proceed through loop diagrams.



The loops are dominated by heavy particles that the Higgs boson cannot decay to directly.

However, again, decoupling puts a restriction:

Only the heavy particles of the SM, that is, t, W, Z, get 100% of their mass from the Higgs. For BSM particles such as $\widetilde{t}$ or T, the contribution to these loops is proportional to the fraction of their mass that comes from the Higgs vev.

Then, for example, a vectorlike T quark contributes

$$g(hgg)/SM = 1 + 2.9\% \Big(\frac{1\ \mathrm{TeV}}{m_T}\Big)^2$$

$$g(h\gamma\gamma)/SM = 1 - 0.8\% \Big(\frac{1\ \mathrm{TeV}}{m_T}\Big)^2$$

A complete model will have several new heavy states, and mixing of these with the SM top quark. For example, for the “Littlest Higgs” model

$$g(hgg)/SM = 1 - (5 - 9\%)$$

$$g(h\gamma\gamma)/SM = 1 - (5 - 6\%)$$

A pattern emerges. At the few - % level each Higgs coupling has its own personality and is corrected from the SM prediction by different types of new physics. Generally, we have:

fermion couplings - multiple Higgs doublets

gauge boson couplings - Higgs singlets, composite Higgs

$\gamma\gamma$, gg couplings - heavy top quark partners

tt coupling - top quark compositeness

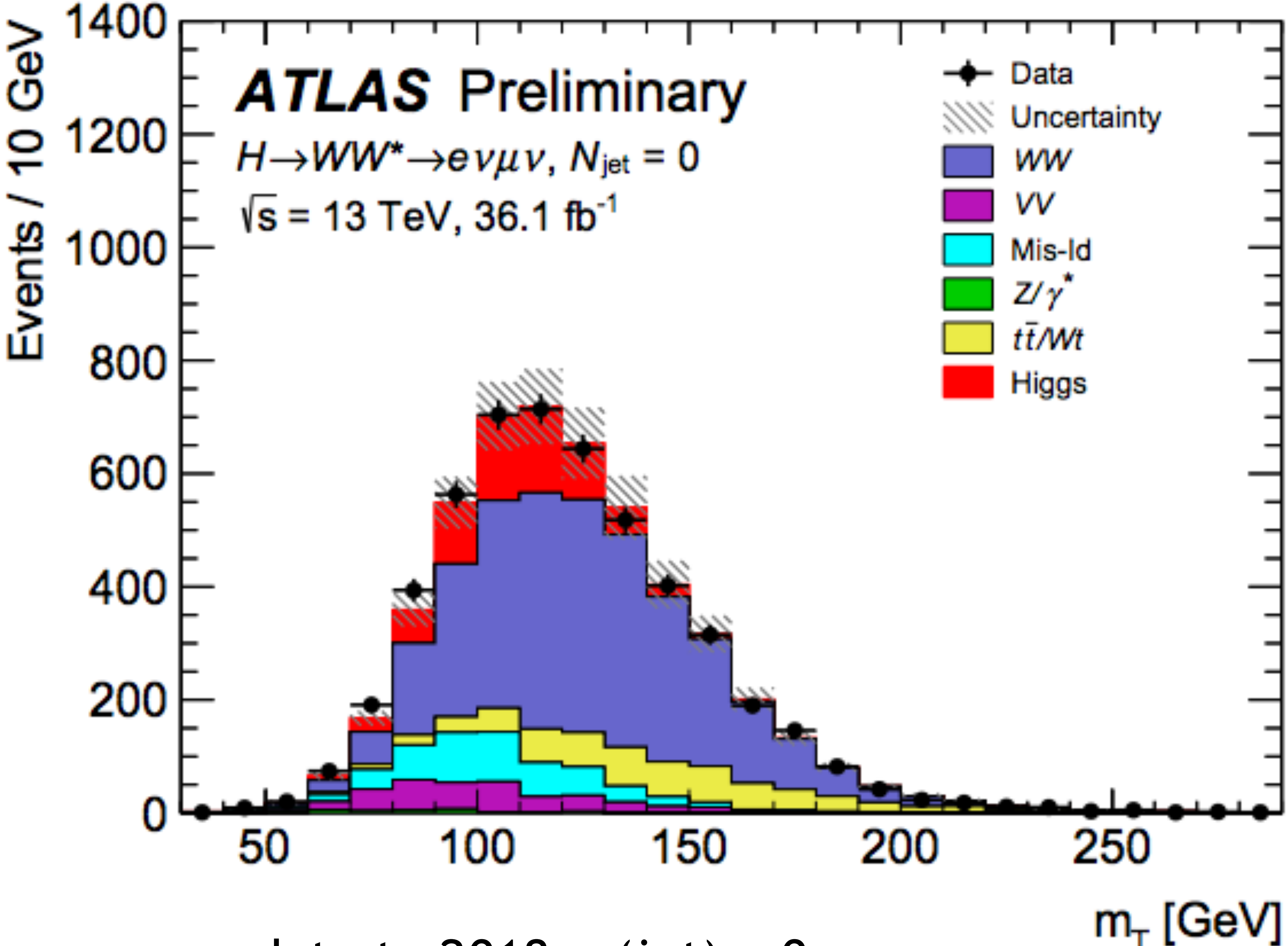
hhh coupling (large deviations) - baryogenesis

Can we actually measure Higgs couplings to the accuracy needed to test these predictions?

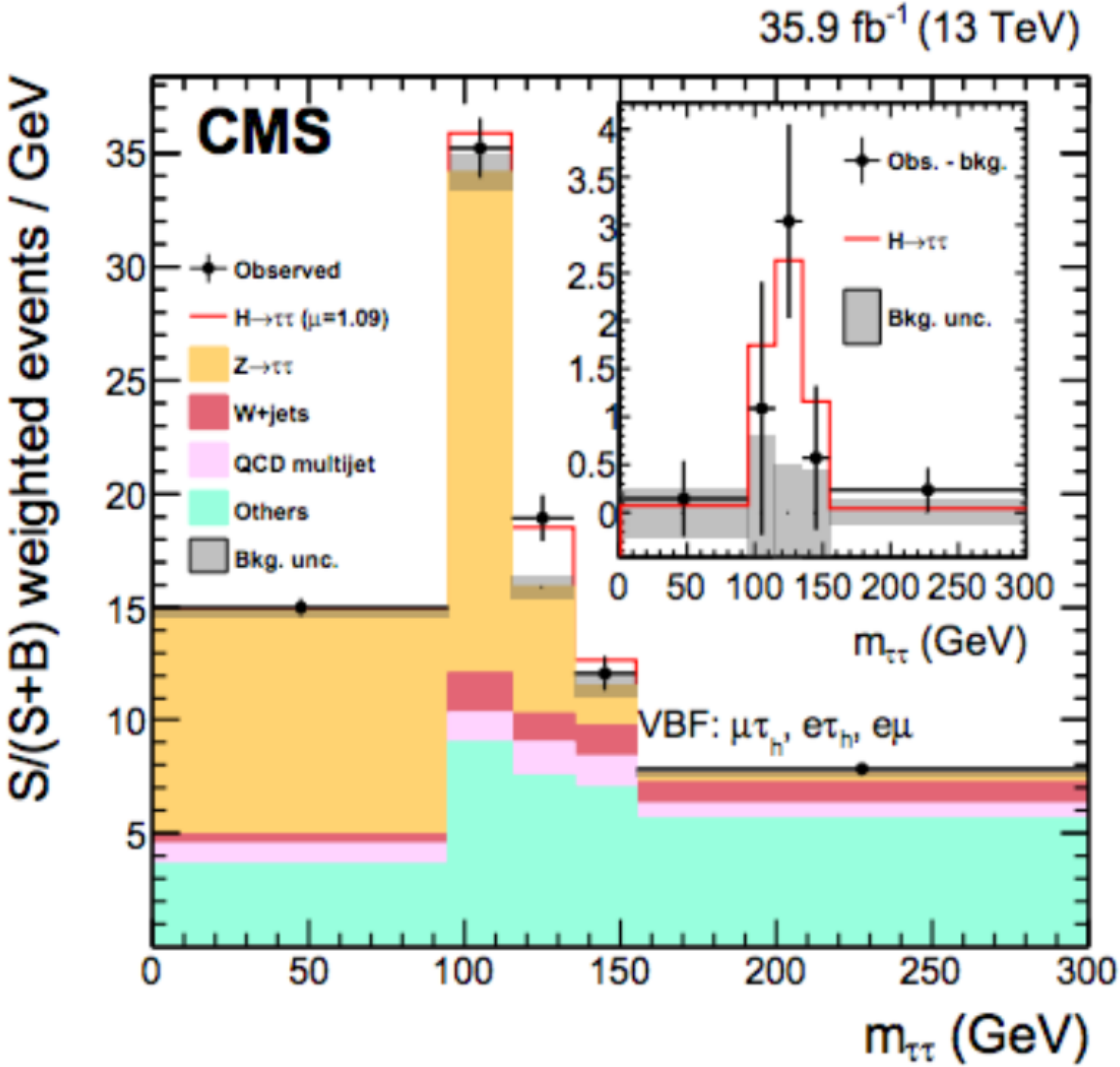
1% measurement accuracy or better is required.

This is a challenge for measurements at hadron colliders.

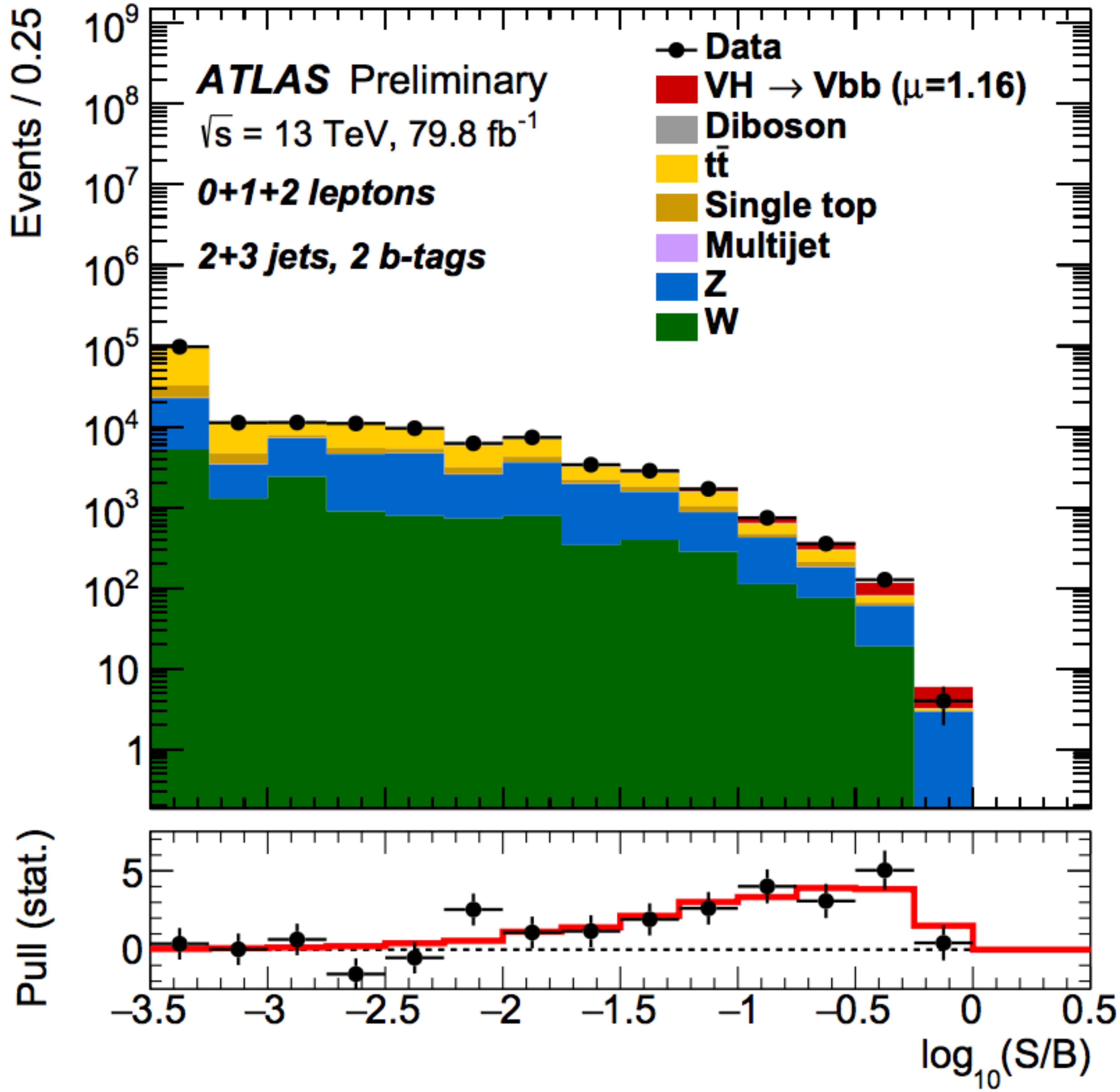
At the LHC — except for rare, fully reconstructable channels such as $\gamma\gamma$, 4 lepton — Higgs events are not characteristic. We start with samples that are 10% Higgs, 90% background. Then we apply severe selections and machine-learning classifiers to suppress these background events.



update to 2018, n(jet) = 0



35.9 fb-1 (13 TeV)
CMS
S/(S+B) weighted events / GeV
Observed
H→ττ (μ=1.09)
Z→ττ
W+jets
QCD multijet
Others
Bkg. unc.
Obs. - bkg.
H→ττ
Bkg. unc.
mττ (GeV)
VBF: μτh, eτh, eμ
mττ (GeV)



ATLAS July 2018

Can we achieve a 1% modeling error in the estimation of the residual background ?

1% error = 5% error on the relevant Higgs coupling

5% x 3σ = not in the game

Keep in mind that the burden of proof is high. The object is not to improve the error bars. It is to demonstrate with high confidence that the Standard Model is violated.

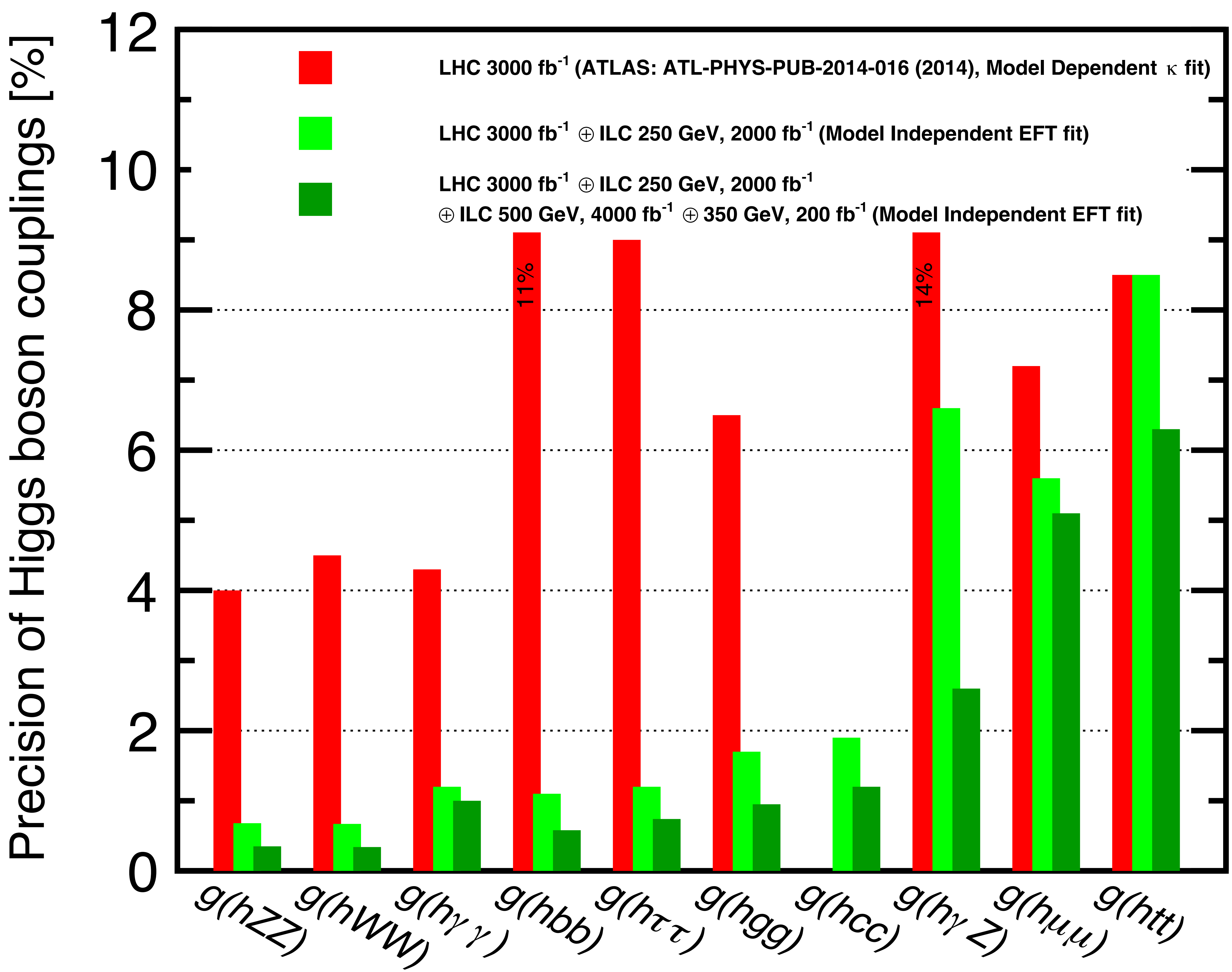
A different experimental technique is needed.   It should be one in which Higgs events are readily identified and dominate their backgrounds after simple selections.

This is actually the situation in e+e- production of Higgs bosons. With projected event samples, the errors on Higgs couplings are statistics-limited (systematic errors on σ x BR ~ 0.1%) and thus improvable if anomalies are discovered.

Here are the expectations for the accuracy of Higgs coupling determinations at the International Linear Collider proposed for construction in Japan.

The expectations for other proposed future e+e- colliders CLIC (at CERN), CEPC (in China), and FCC-ee (at CERN) are similar.

I will explain and defend these estimates tomorrow.



arXiv:1710.07621

To explain the power of these measurements, we proposed the following exercise: Collect a sample of models such that the new particles are too heavy to be discovered at the (HL-)LHC (but with nontrivial modification of the Higgs couplings). Look up the Higgs coupling deviations in the literature. Can these accuracies discover BSM physics?

the models:

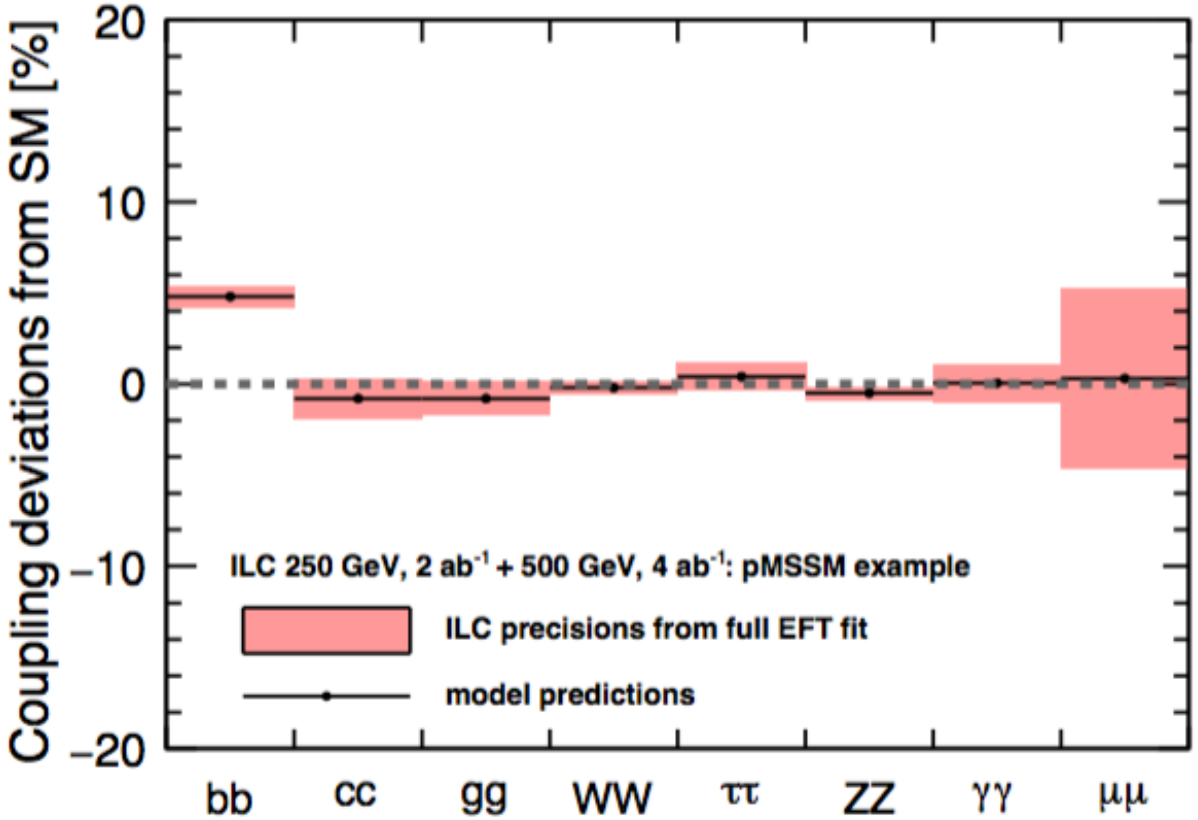
1. PMSSM model with b squarks at 3.4 TeV.
2. Type II Higgs-doublet model with H at 600 GeV
3. Type X 2-Higgs-doublet model with H at 450 GeV
4. Type Y 2-Higgs-doublet model with H at 600 GeV
5. MCHM5 Composite Higgs model, with f = 1.2 TeV
6. Little Higgs model w. T-parity, f = 0.8 TeV
7. Little Higgs model w. T-parity, f = 1 TeV, extension for light quark Yukawa couplings
8. Higgs-radion mixing model, radion at 500 GeV
9. Higgs singlet mixing model, singlet at 2.8 TeV

(Your additional suggestions would be appreciated.)

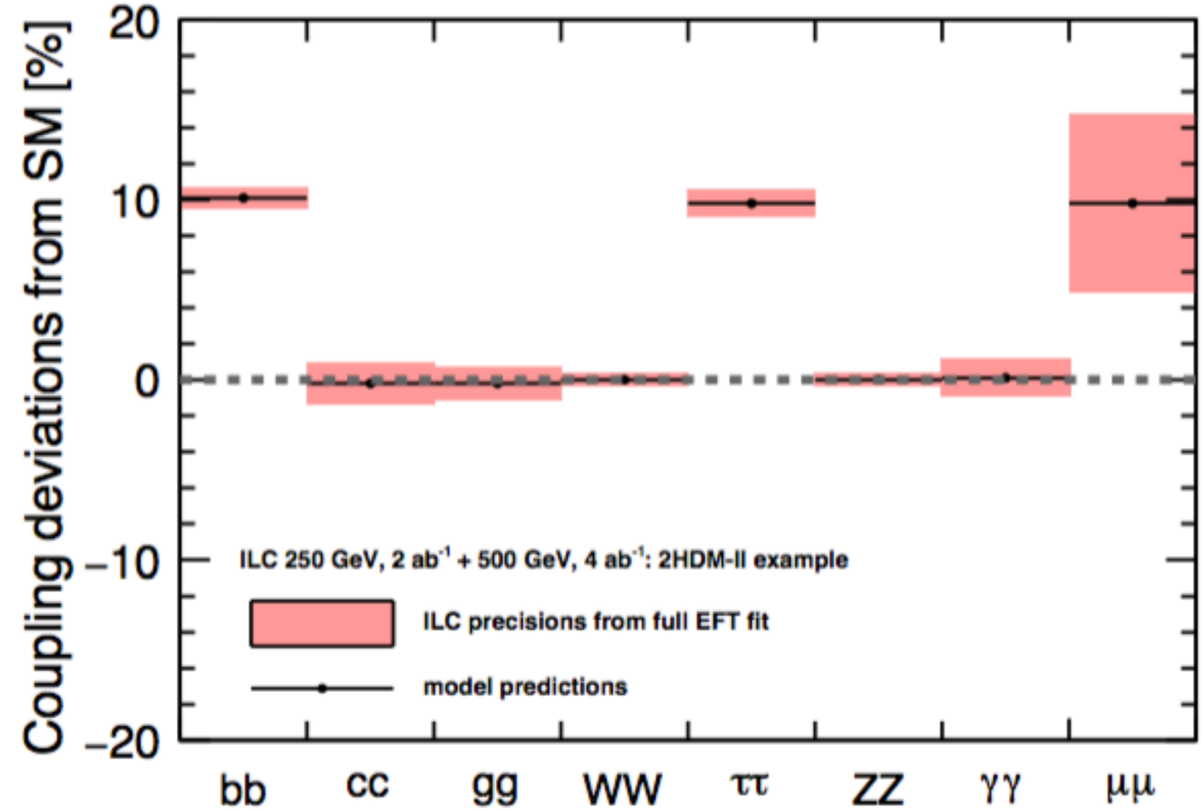
their coupling deviations:

	Model	$b\bar{b}$	$c\bar{c}$	gg	WW	$\tau\tau$	ZZ	$\gamma\gamma$	$\mu\mu$
1	MSSM [35]	+4.8	-0.8	- 0.8	-0.2	+0.4	-0.5	+0.1	+0.3
2	Type II 2HD [37]	+10.1	-0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
3	Type X 2HD [37]	-0.2	-0.2	-0.2	0.0	+7.8	0.0	0.0	+7.8
4	Type Y 2HD [37]	+10.1	-0.2	-0.2	0.0	-0.2	0.0	0.1	-0.2
5	Composite Higgs [39]	-6.4	-6.4	-6.4	-2.1	-6.4	-2.1	-2.1	-6.4
6	Little Higgs w. T-parity [40]	0.0	0.0	-6.1	-2.5	0.0	-2.5	-1.5	0.0
7	Little Higgs w. T-parity [41]	-7.8	-4.6	-3.5	-1.5	-7.8	-1.5	-1.0	-7.8
8	Higgs-Radion [42]	-1.5	- 1.5	+10.	-1.5	-1.5	-1.5	-1.0	-1.5
9	Higgs Singlet [43]	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5

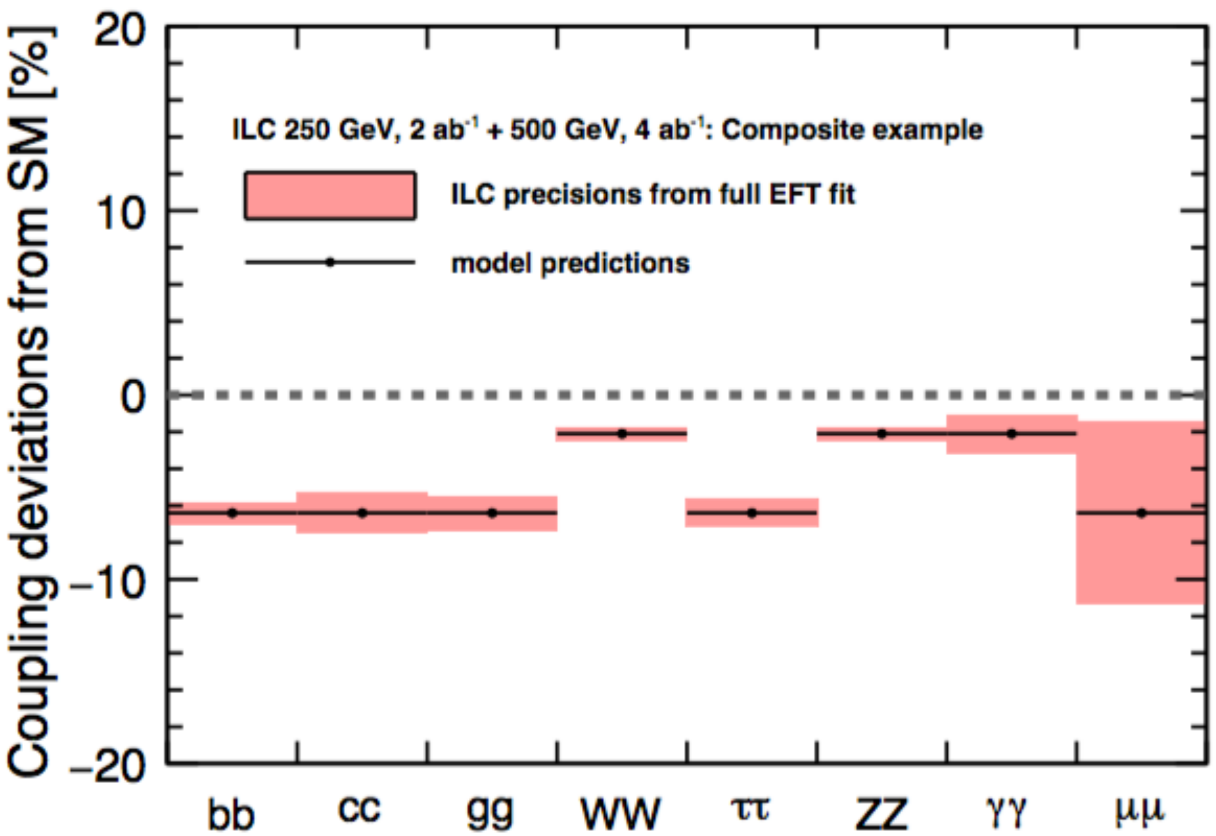
heavy SUSY



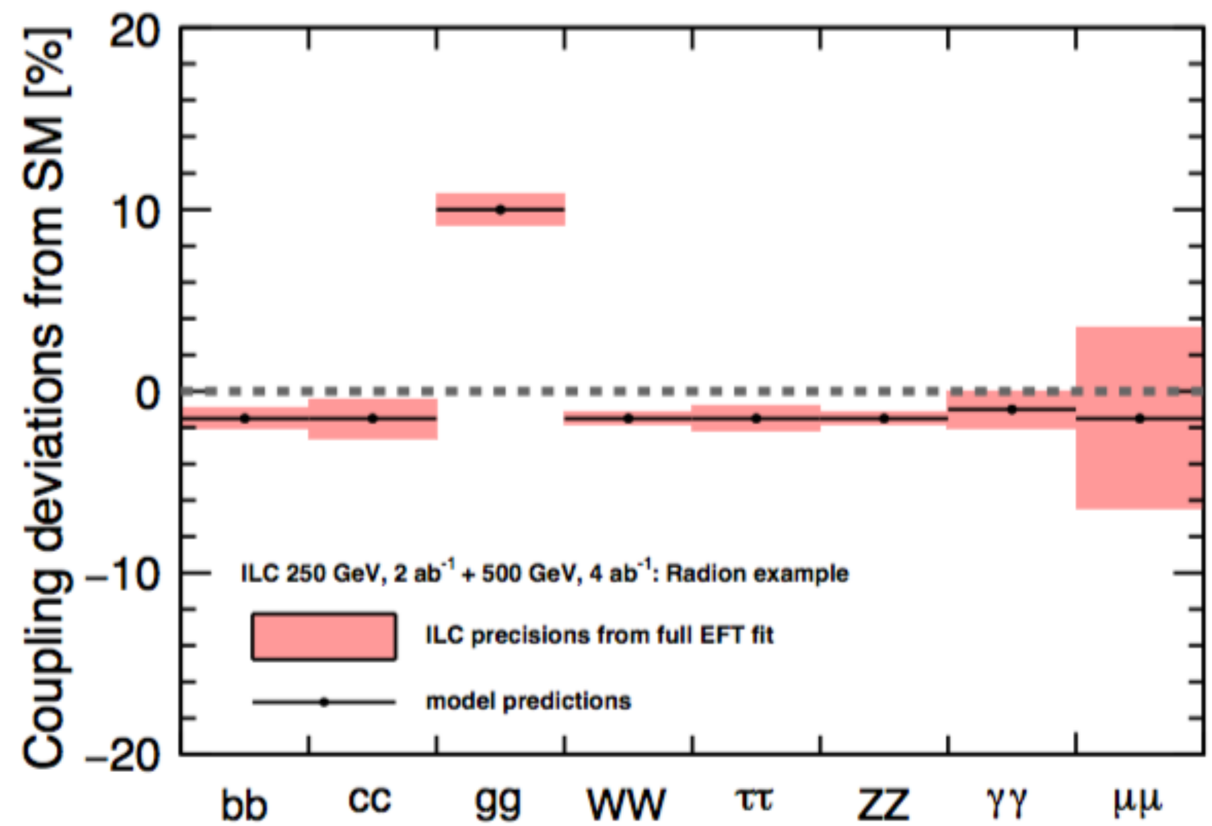
2 Higgs doublet



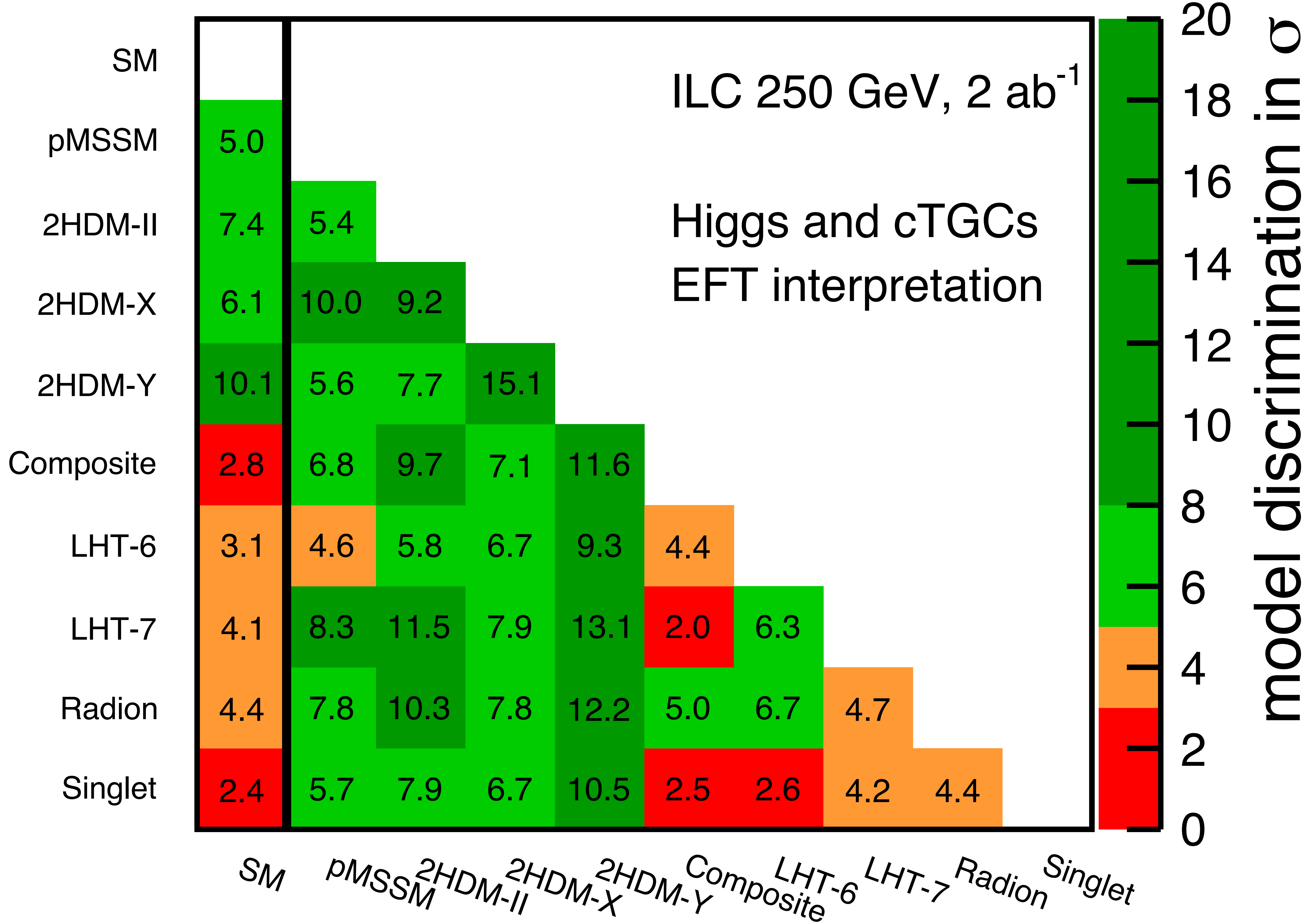
Composite Higgs



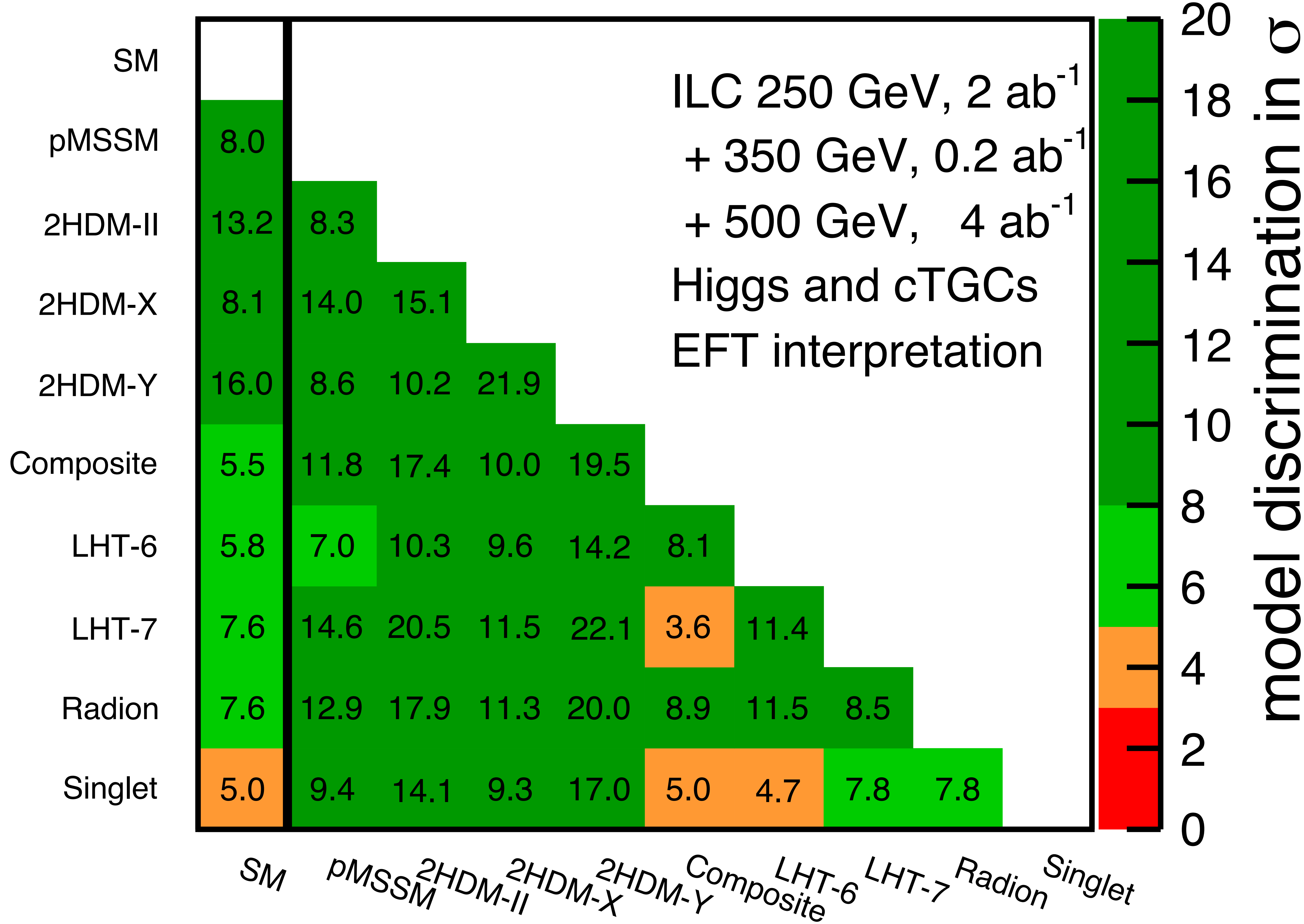
Higgs-Radion mixing



results: ILC 250 GeV 2 ab-1



results: ILC 250 GeV 2 ab-1 + 500 GeV 4 ab-1



There is a tremendous opportunity for discovery here, one that you are well prepared to realize.

I will say more about this in tomorrow’s lecture.