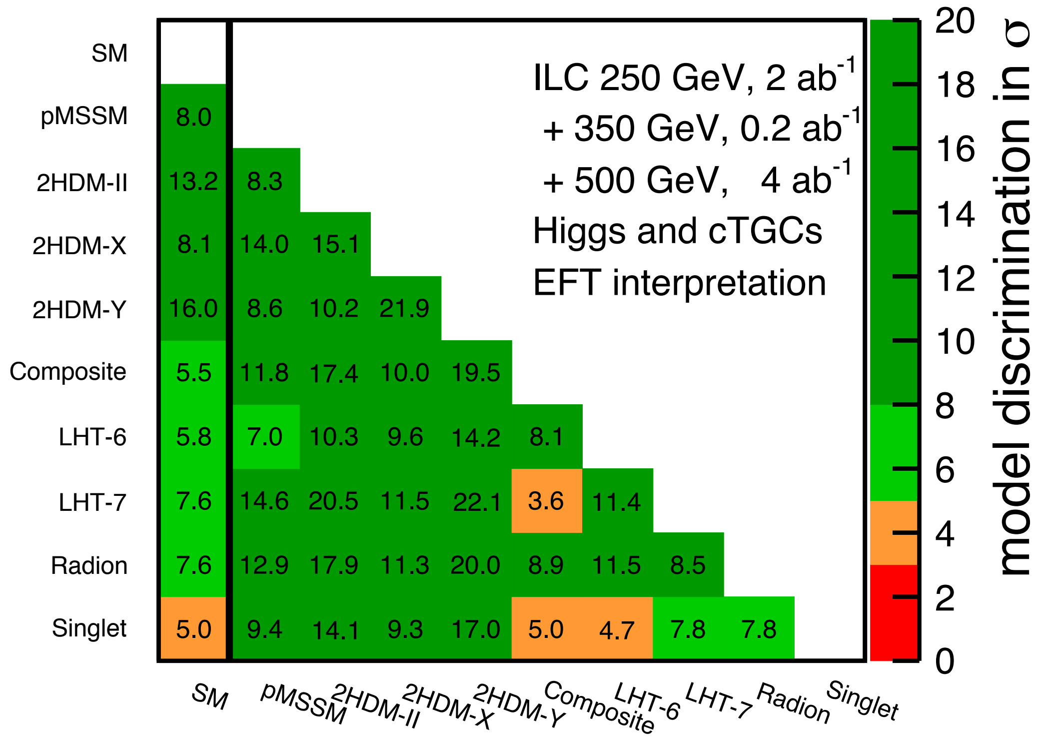
Precision Higgs Measurements at Linear Colliders



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The Standard Model is extremely successful in explaining the measured properties of elementary particles. But, it is manifestly incomplete.

The Standard Model:

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

Many theories are proposed. How can we have a clue as to which is right ?

Over the past decades, we have searched for Beyond-Standard-Model effects in many ways:

direct particle searches at 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, and the limits of the technique with current facilties are in sight.

However, there is one method that is available to us but we have not yet begun to exploit:

This is the study of the couplings of the Higgs boson.

the good:

The Higgs is at the heart of all of the mysteries of the SM. It couples to all gauge bosons, quarks, and leptons, and possibly also to new sectors with no SM interactions.

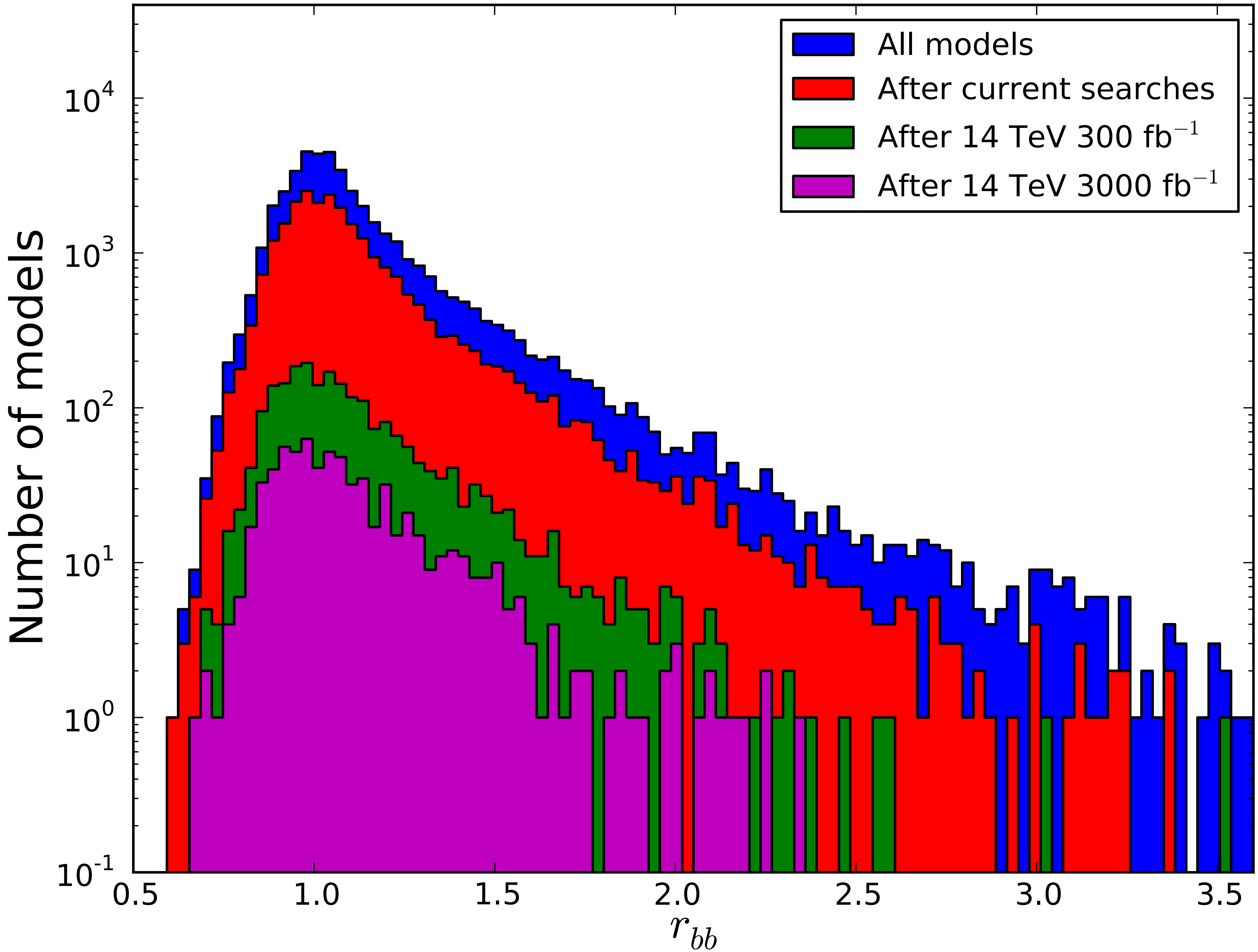
the ugly:

BSM effects on the Higgs couplings are small. For new physics at the scale M, they are of order

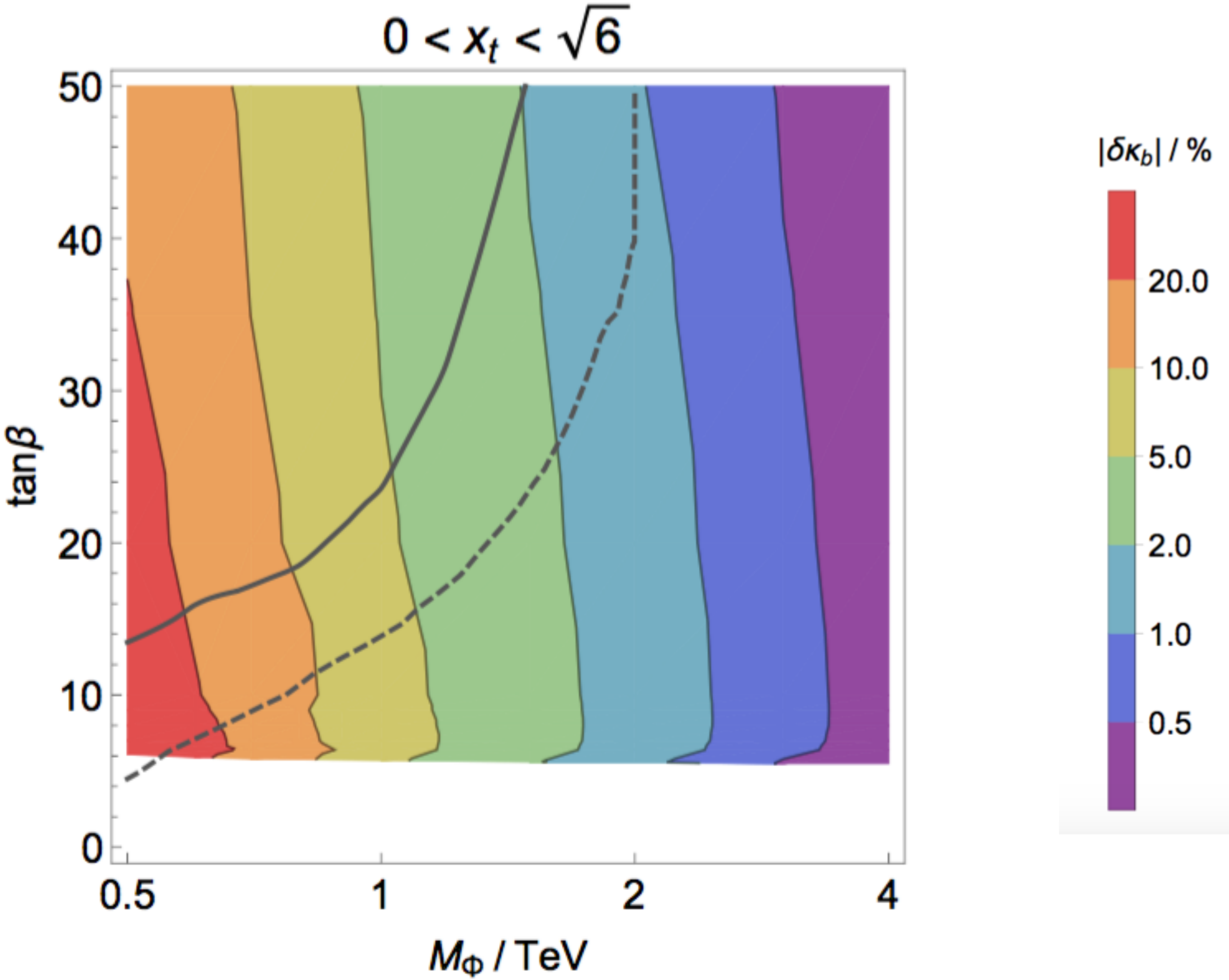
$$m_h^2/M^2$$

However, if we can reach the required level of precision, the study of Higgs boson couplings provides a new and orthogonal way to discover BSM physics.

→ 1% errors on Higgs couplings are required. ←



Cahill-Rowley, Hewett, Ismail, Rizzo



Wells and Zhang : models with b-τ unification

Wells and Zhang: (arXiv:1711:04774)

Our results show a nice complementarity between direct superpartner searches and precision Higgs measurements, as they probe the SUSY parameter space from different directions.

Lockyer (quoted in Physics Today):

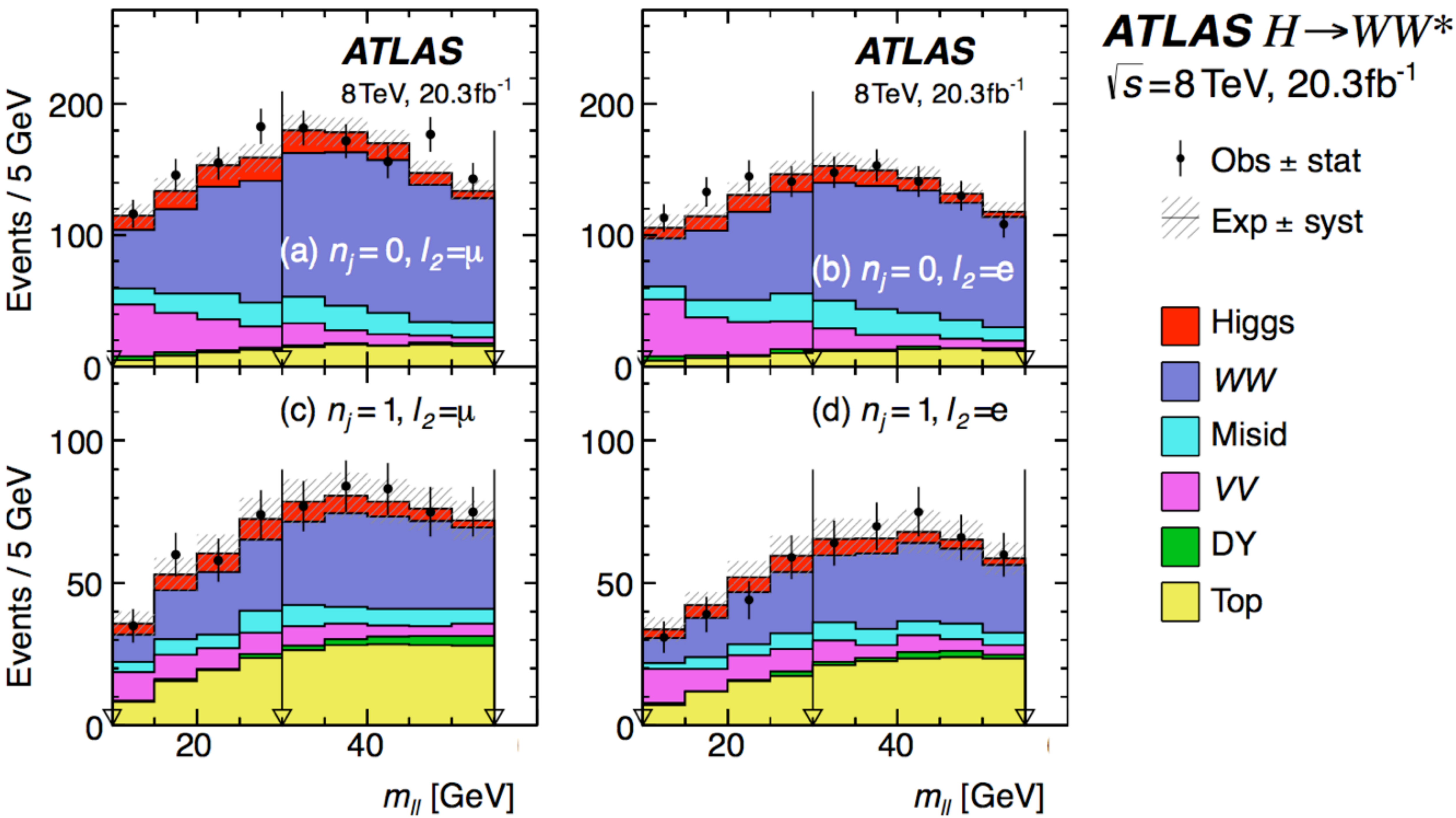
You would be nuts not to study the heck out of the Higgs.

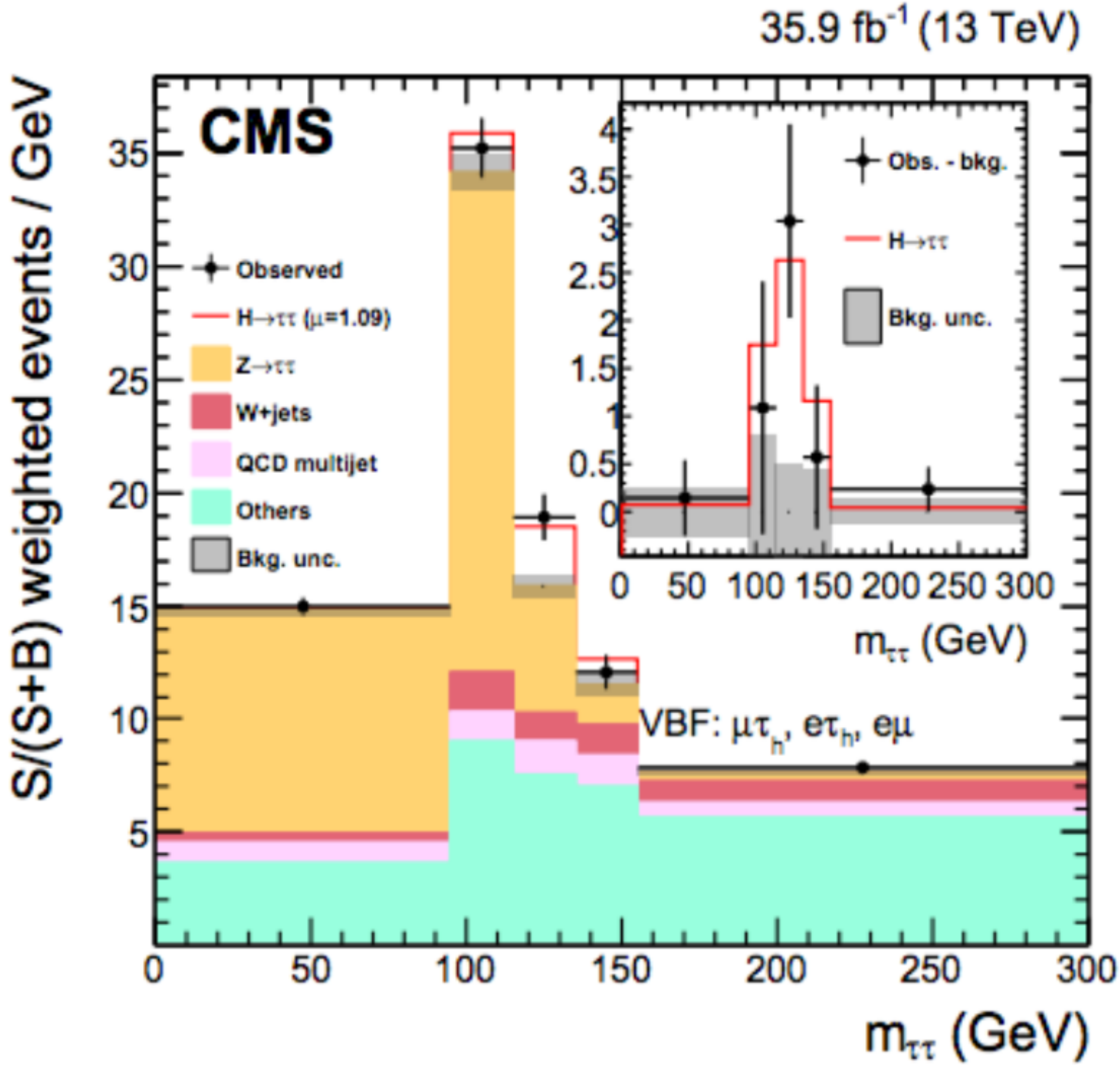
Current errors on Higgs couplings at LHC at 20-30%.

BSM models predict effects of 5-10% at best. So, we are not yet in the game at LHC.

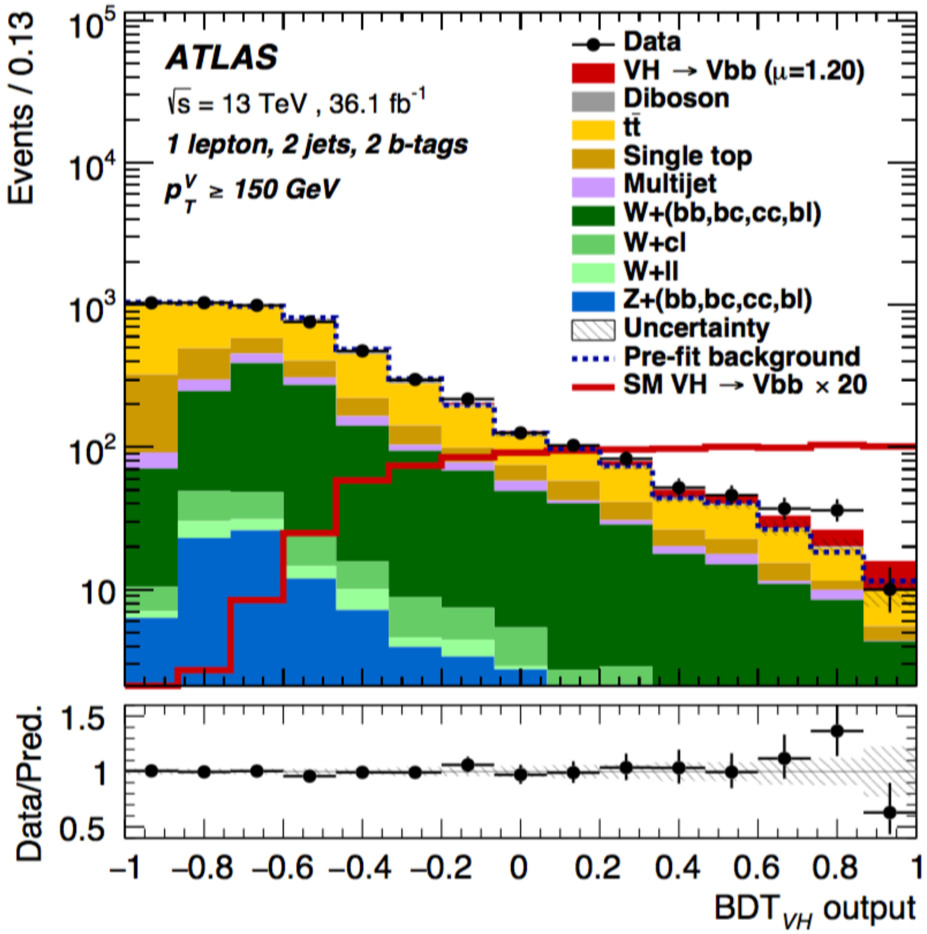
It is likely that we never will be, even at the high-luminosity stage of the LHC.

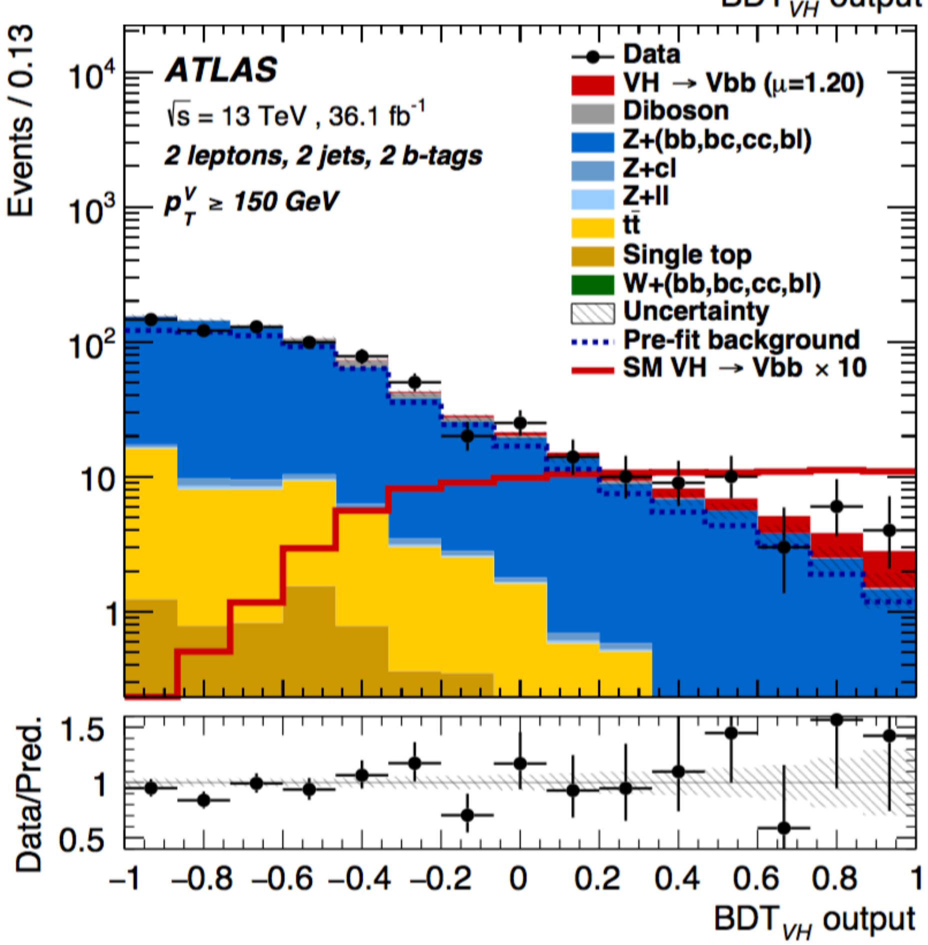
Remember also that the accuracy of confirmation of the Standard Model is not the issue. We need to find a discrepancy, and this should be provable by subsequent measurements. That is not possible in a systematics-limited analysis.

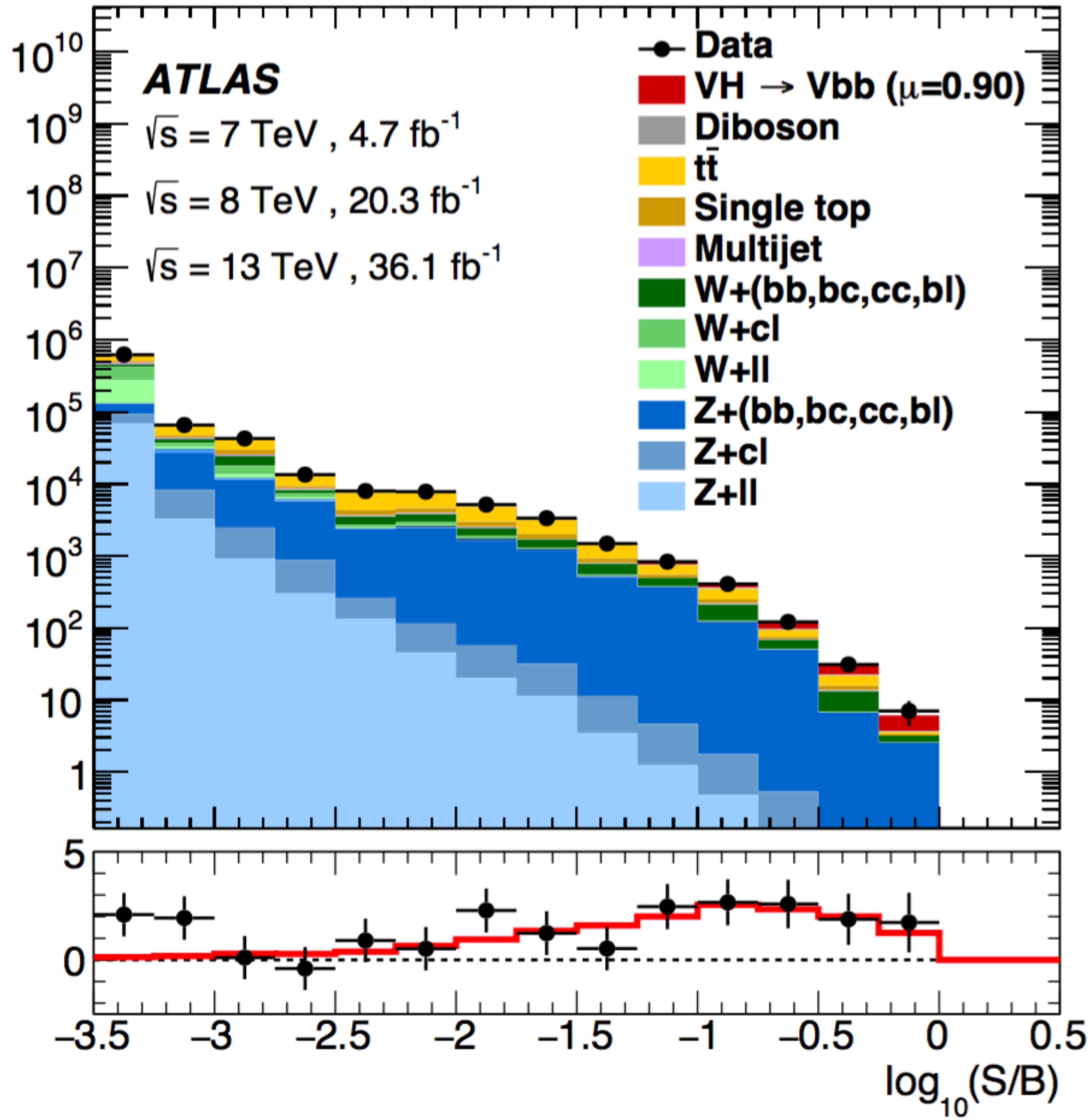

ATLAS
8 TeV, 20.3fb-1
(a) $n_j = 0$, $l_2 = \mu$
(b) $n_j = 0$, $l_2 = e$
(c) $n_j = 1$, $l_2 = \mu$
(d) $n_j = 1$, $l_2 = e$
Events / 5 GeV
m_{ll} [GeV]
ATLAS $H \rightarrow WW^*$
$\sqrt{s} = 8$ TeV, 20.3fb-1
Obs ± stat
Exp ± syst
Higgs
WW
Misid
VV
DY
Top



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.
$m_{\tau\tau}$ (GeV)
VBF: $\mu\tau_h$, $e\tau_h$, $e\mu$
$m_{\tau\tau}$ (GeV)


ATLAS
√s = 13 TeV , 36.1 fb-1
1 lepton, 2 jets, 2 b-tags
p_T^V ≥ 150 GeV
Data
VH → Vbb (μ=1.20)
Diboson
tt̄
Single top
Multijet
W+(bb,bc,cc,bl)
W+cl
W+ll
Z+(bb,bc,cc,bl)
Uncertainty
Pre-fit background
SM VH → Vbb × 20
Events / 0.13
Data/Pred.
BDT_VH output


ATLAS
√s = 13 TeV , 36.1 fb-1
2 leptons, 2 jets, 2 b-tags
p_T^V ≥ 150 GeV
Data
VH → Vbb (μ=1.20)
Diboson
Z+(bb,bc,cc,bl)
Z+cl
Z+ll
tt̄
Single top
W+(bb,bc,cc,bl)
Uncertainty
Pre-fit background
SM VH → Vbb × 10
Events / 0.13
Data/Pred.
BDT_VH output


ATLAS
√s = 7 TeV , 4.7 fb-1
√s = 8 TeV , 20.3 fb-1
√s = 13 TeV , 36.1 fb-1
Data
VH → Vbb (μ=0.90)
Diboson
tt̄
Single top
Multijet
W+(bb,bc,cc,bl)
W+cl
W+ll
Z+(bb,bc,cc,bl)
Z+cl
Z+ll
log10(S/B)

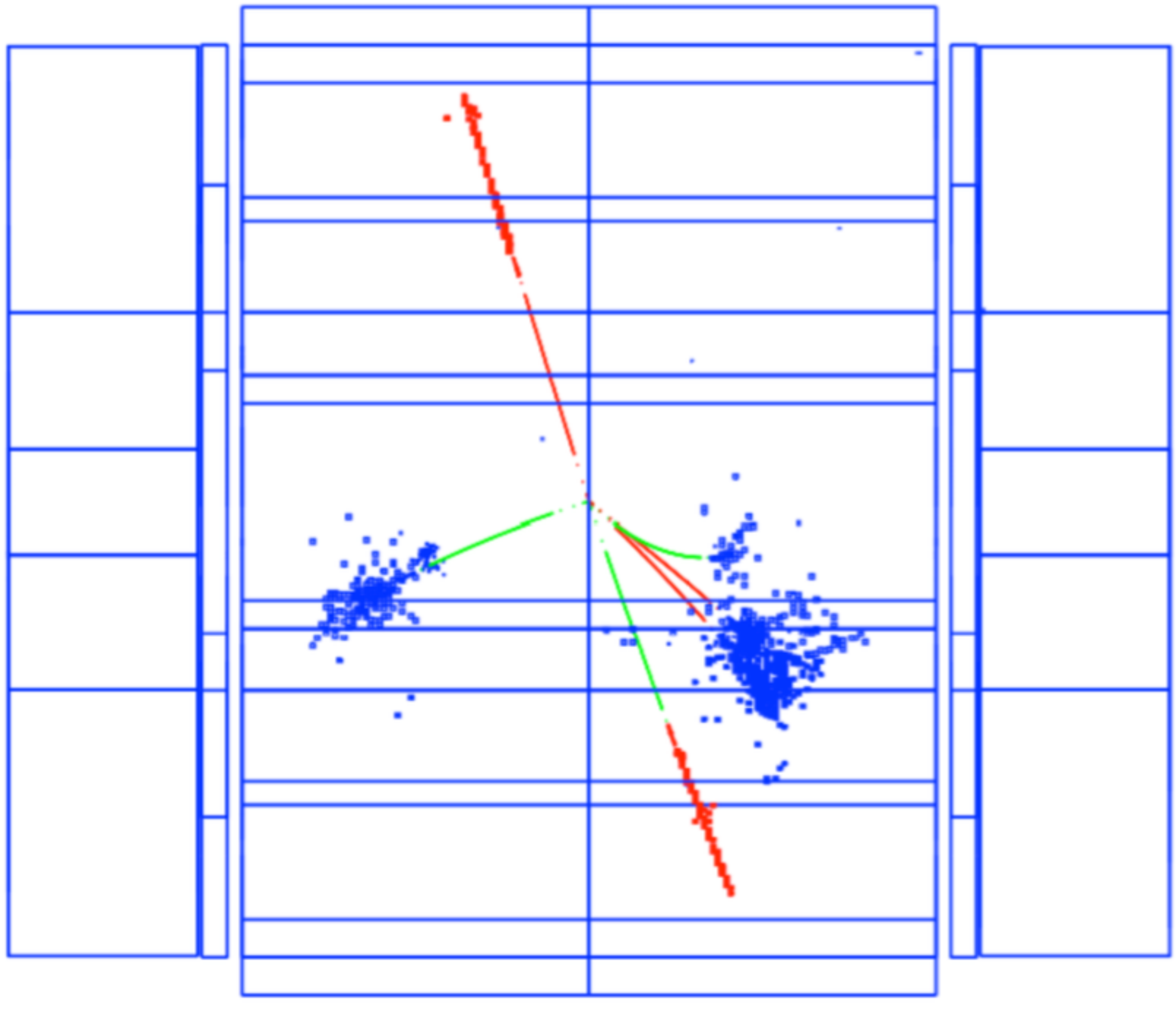
To study the Higgs with high precision, we need a different experimental technique.

I recommend the use of $e^+e^- \to Zh$ at 250 GeV.

Higgs events are directly recognizable above a small, calculable background.

Higgs events are tagged: Find a Z at 110 GeV in the lab. Whatever is on the other side is a Higgs decay.

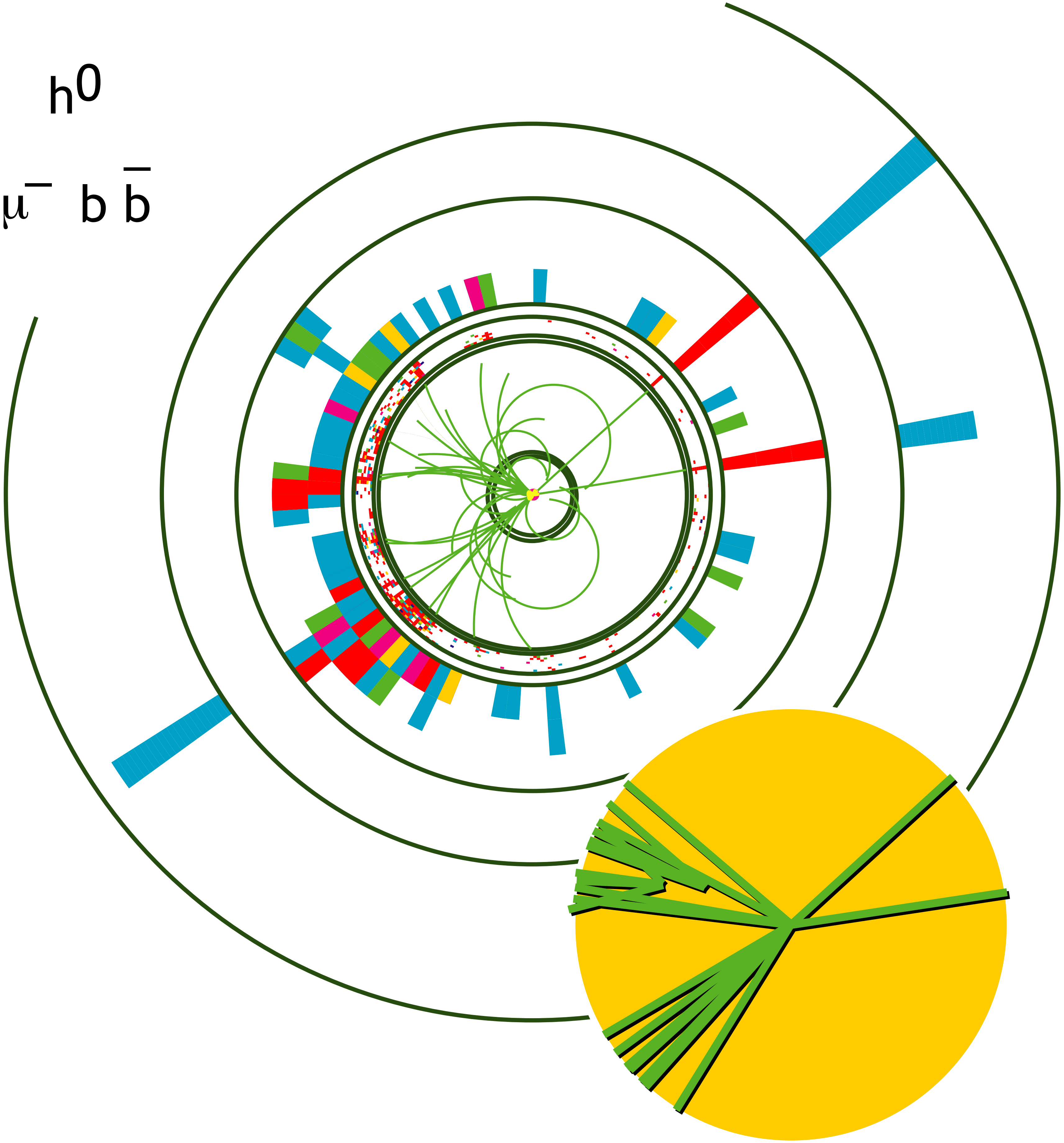
Measurement of the total cross section gives an absolute, model-independent, normalization of Higgs couplings.



(thanks to Manqi Ruan)

$$e^+e^- \to Z^0 \quad h^0$$

$$\to \mu^+\mu^- \; b\,\bar{b}$$



How accurately can we measure Higgs couplings in the e+e- environment ?

Recently, several groups have analyzed this problem using SM Effective Field Theory with dimension-6 operators as the parametrization of BSM effects:

Ge, He, and Xiao, arXiv:1603.03385
Ellis, Roloff, Sanz, and You, arXiv:1701.04804
Khanpour and Najafabadi, arXiv:1702.00951
Durieux, Grojean, Gu, and Wang, arXiv:1704.02333

This technique is manifestly model-independent — as long as all relevant operators are included. It allows new observables, including precision electroweak and $e^+e^- \to W^+W^-$ measurements, to refine the constraints from Higgs processes.

I will show results from

Barklow, Fujii, Jung, Karl, List, Ogawa, MEP, and Tian, arXiv:1708.08912

We include:

a simultaneous fit using all 17 EFT coefficients that appear in tree-level formulae, plus allowance for invisible and exotic Higgs decays

the best current estimates of experimental errors on σ and σ x BR's from ILC and CEPC full-simulation studies of Higgs and W processes

inclusion of new observables, in particular, polarization asymmetries and angular distributions in $e^+e^- \to Zh$

$$
\begin{aligned}
\Delta\mathcal{L} = {} & \frac{c_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi) + \frac{c_T}{2v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) \\
& -\frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3 \\
& +\frac{g^2 c_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}W^{a\mu\nu} + \frac{4gg' c_{WB}}{m_W^2}\Phi^\dagger t^a\Phi W^a_{\mu\nu}B^{\mu\nu} \\
& +\frac{g'^2 c_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g^3 c_{3W}}{m_W^2}\epsilon_{abc}W^a_{\mu\nu}W^{b\nu}{}_\rho W^{c\rho\mu} \\
& +i\frac{c_{HL}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu L) + 4i\frac{c'_{HL}}{v^2}(\Phi^\dagger t^a \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu t^a L) \\
& +i\frac{c_{HE}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{e}\gamma_\mu e)\ . \\
& -\sum_i\left\{c_{\ell i\Phi}\frac{y_\tau \ell i}{v^2}(\Phi^\dagger\Phi)\overline{L}_i\cdot\Phi\,\ell_{iR} + c_{qi\Phi}\frac{y_\tau qi}{v^2}(\Phi^\dagger\Phi)\overline{Q}_i\cdot\Phi\,q_{iR}\right\} \\
& +\mathcal{A}\frac{h}{v}G_{\mu\nu}G^{\mu\nu}\ .
\end{aligned}
$$

Higgs Z factor

triple Higgs

h + W,Z,γ

Precision EW

h + q, l, g

The EFT approach leads to a more model-independent method than that used in previous analyses, and much more powerful use of the available data.

Here is an example:

In the general EFT treatment, the coupling of the Higgs boson to WW and ZZ is governed by two independent coupling constants.

$$\Delta L_{hWW} = 2(1+\eta_W) m_h^2 \frac{h}{v} W_\mu^+ W^{-\mu} + \zeta_W \frac{h}{v} W_{\mu\nu}^+ W^{-\mu\nu}$$

$$\Delta L_{hZZ} = (1+\eta_Z) m_h^2 \frac{h}{v} Z_\mu Z^\mu + \frac{1}{2}\zeta_Z \frac{h}{v} Z_{\mu\nu} Z^{\mu\nu}$$

This has been ignored in previous analyses.

EFT also give the solution to this problem:

EFT gives nontrivial but tractable relations between the Z and W parameters:

$$\eta_W = -\frac{1}{2}c_H \qquad \eta_Z = -\frac{1}{2}c_H - c_T$$

$$\zeta_W = (8c_{WW})$$
$$\zeta_Z = c_w^2(8c_{WW}) + 2s_w^2(8c_{WB}) + (s_w^4/c_w^2)(8c_{BB})$$

The parameter ζ_Z is very sensitive to the polarization asymmetry in $\sigma(e^+e^- \to Zh)$. This gives special power to an accelerator with beam polarization.

Here are coupling error estimates for various proposed e+e- colliders:

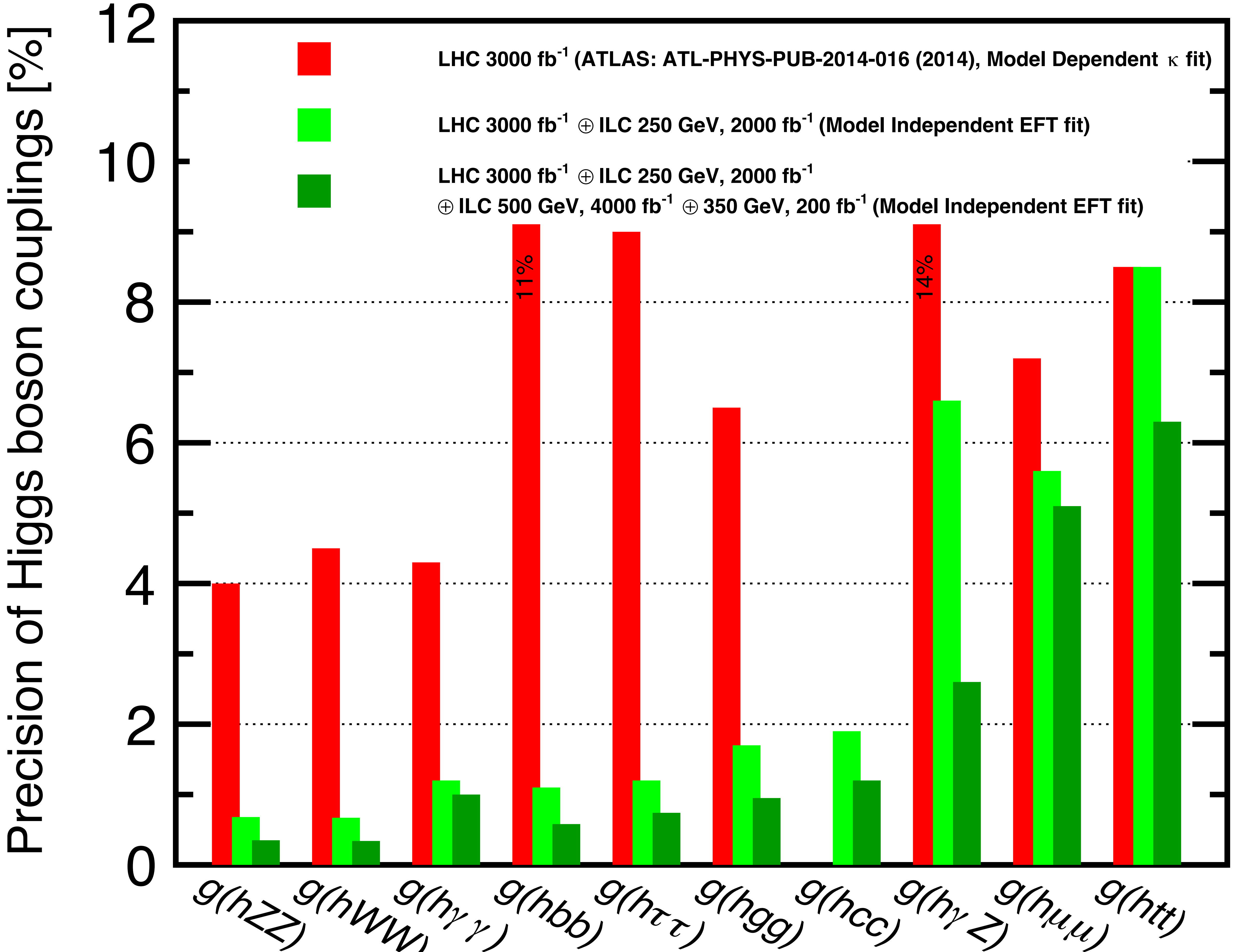
	ILC 250	CLIC	CEPC	FCC-ee	ILC 500
	2 ab^{-1} w. pol.	2 ab^{-1} 350 GeV	5 ab^{-1} no pol.	+ 1.5 ab^{-1} at 350 GeV	full ILC 250+500 GeV
$g(hb\bar{b})$	1.04	1.08	0.98	0.66	0.55
$g(hc\bar{c})$	1.79	2.27	1.42	1.15	1.09
$g(hgg)$	1.60	1.65	1.31	0.99	0.89
$g(hWW)$	0.65	0.56	0.80	0.42	0.34
$g(h\tau\tau)$	1.16	1.35	1.06	0.75	0.71
$g(hZZ)$	0.66	0.57	0.80	0.42	0.34
$g(h\gamma\gamma)$	1.20	1.15	1.26	1.04	1.01
$g(h\mu\mu)$	5.53	5.71	5.10	4.87	4.95
$g(hbb)/g(hWW)$	0.82	0.90	0.58	0.51	0.43
$g(hWW)/g(hZZ)$	0.07	0.06	0.07	0.06	0.05
Γ_h	2.38	2.50	2.11	1.49	1.50
$\sigma(e^+e^- \to Zh)$	0.70	0.77	0.50	0.22	0.61
$BR(h \to inv)$	0.30	0.56	0.30	0.27	0.28
$BR(h \to other)$	1.50	1.63	1.09	0.94	1.15

errors in %

For ILC, the new method predicts a much greater sensitivity of the e+e- data to the underlying Higgs couplings. The most important of these already reach the 1% accuracy goal at 250 GeV.

Compare this analysis with ILC Higgs white paper for Snowmass 2013: (also reflects improved full-sim analyses by the KEK and DESY groups)

	Snowmass 2013 :		this report :		
Parameter	ILC(500)	ILC(LumUp)	250 GeV	250+500 GeV	units
$g(hb\bar{b})$	1.6	0.7	1.1	0.58	%
$g(hc\bar{c})$	2.8	1.0	1.9	1.2	%
$g(hgg)$	2.3	0.9	1.7	0.95	%
$g(hWW)$	1.1	0.6	0.67	0.34	%
$g(h\tau\tau)$	2.3	0.9	1.2	0.74	%
$g(hZZ)$	1.0	0.5	0.68	0.35	%
$g(ht\bar{t})$	14	1.9	-	6.3	%
Γ_{tot}	4.9	2.3	2.5	1.6	%



Precision of Higgs boson couplings [%]
0
2
4
6
8
10
12
LHC 3000 fb^{-1} (ATLAS: ATL-PHYS-PUB-2014-016 (2014), Model Dependent κ fit)
LHC 3000 fb^{-1} $\oplus$ ILC 250 GeV, 2000 fb^{-1} (Model Independent EFT fit)
LHC 3000 fb^{-1} $\oplus$ ILC 250 GeV, 2000 fb^{-1}
$\oplus$ ILC 500 GeV, 4000 fb^{-1} $\oplus$ 350 GeV, 200 fb^{-1} (Model Independent EFT fit)
11%
14%
g(hZZ)
g(hWW)
g(h$\gamma\gamma$)
g(hbb)
g(h$\tau\tau$)
g(hgg)
g(hcc)
g(hγZ)
g(h$\mu\mu$)
g(htt)

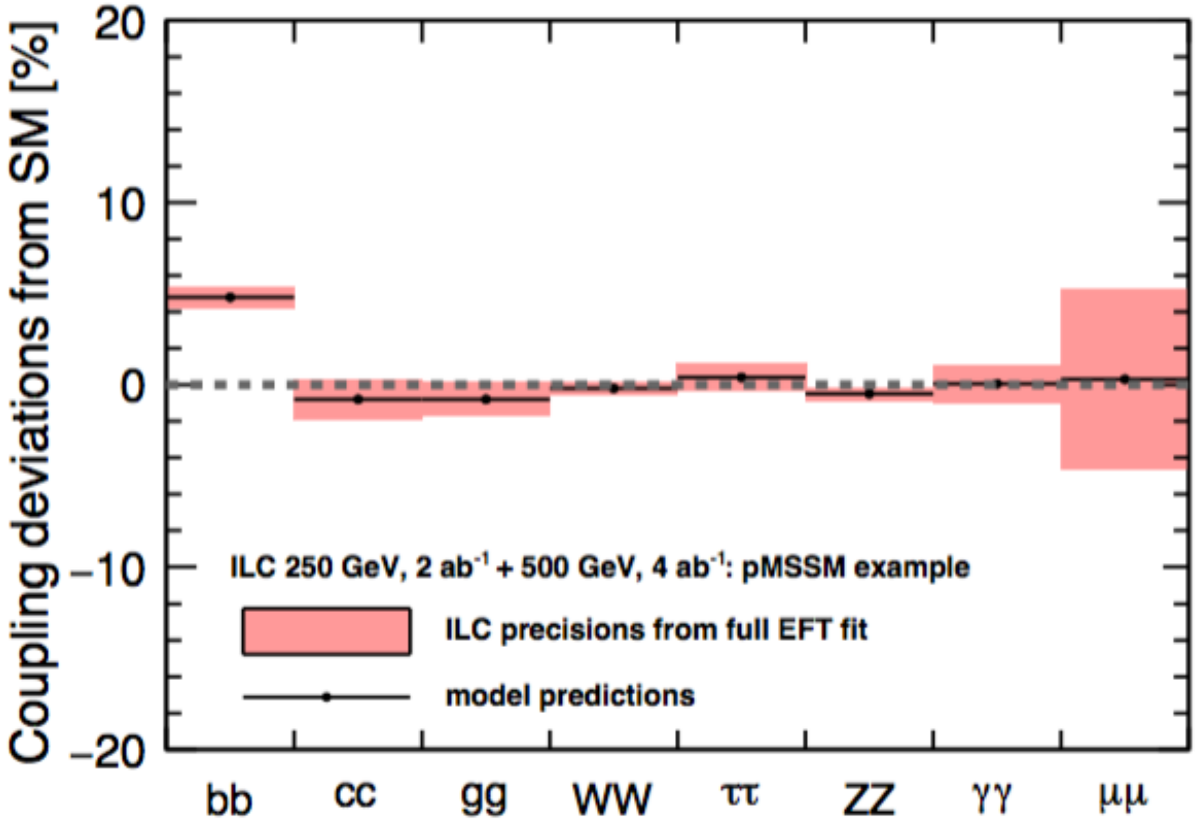
In last year's JAHEP discussion, we were asked: Do these accuracies in Higgs couplings allow us to be sensitive to new models beyond the reach of LHC ?

To answer this question, we made a collection of BSM models that predict modifications of Higgs couplings but for which the new particles are expected to be out of the reach of HL-LHC.

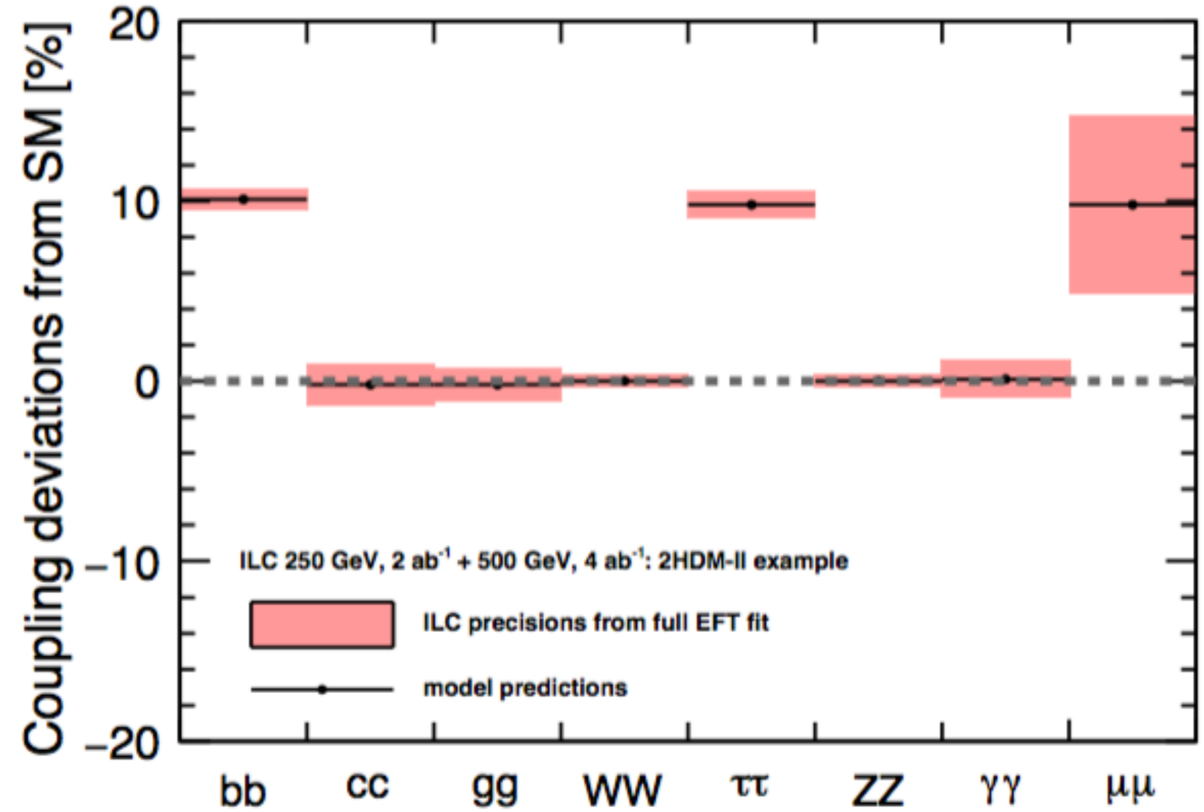
These models included many types of BSM models
— SUSY, 2-Higgs doublet, Little Higgs, composite Higgs, …

Each model has its own pattern of deviations. Thus, in Higgs precision, we can not only discover BSM physics but also we can obtain clues as to the nature of this physics.

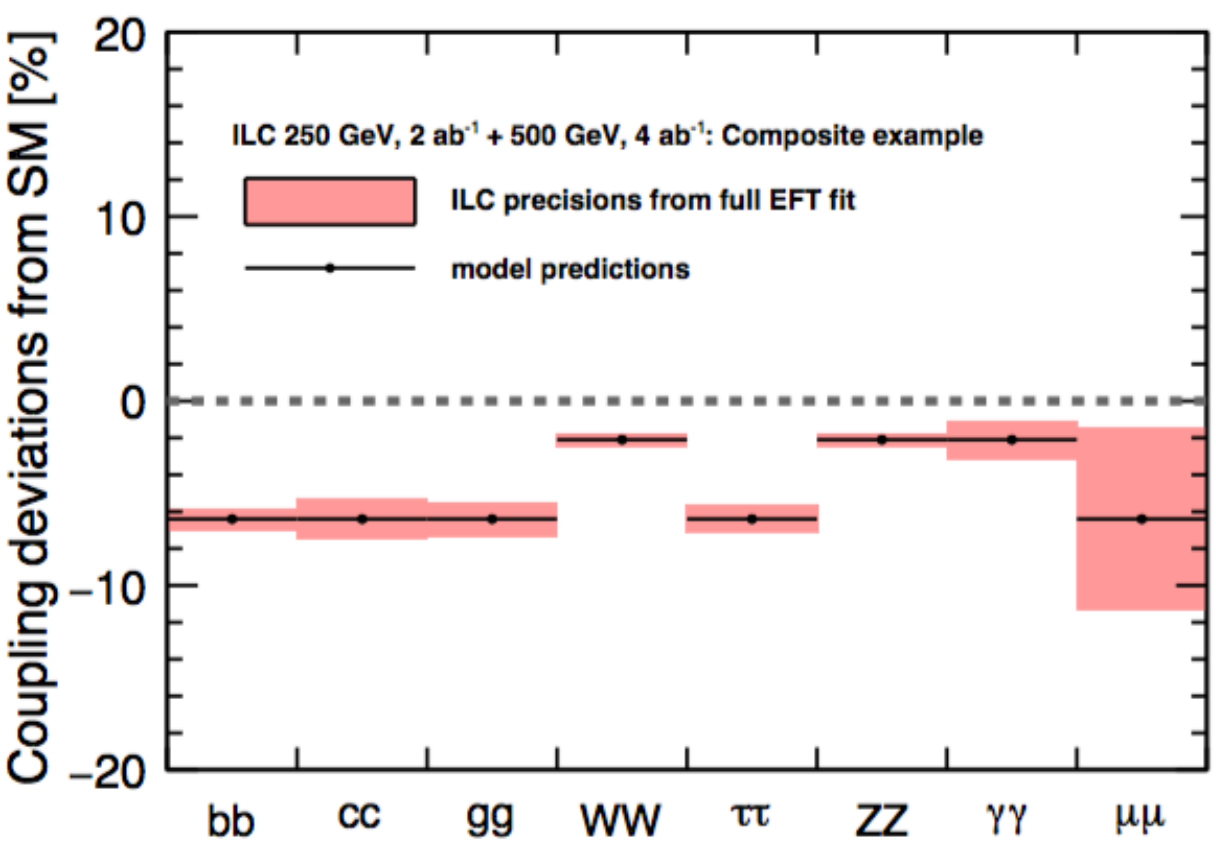
heavy SUSY



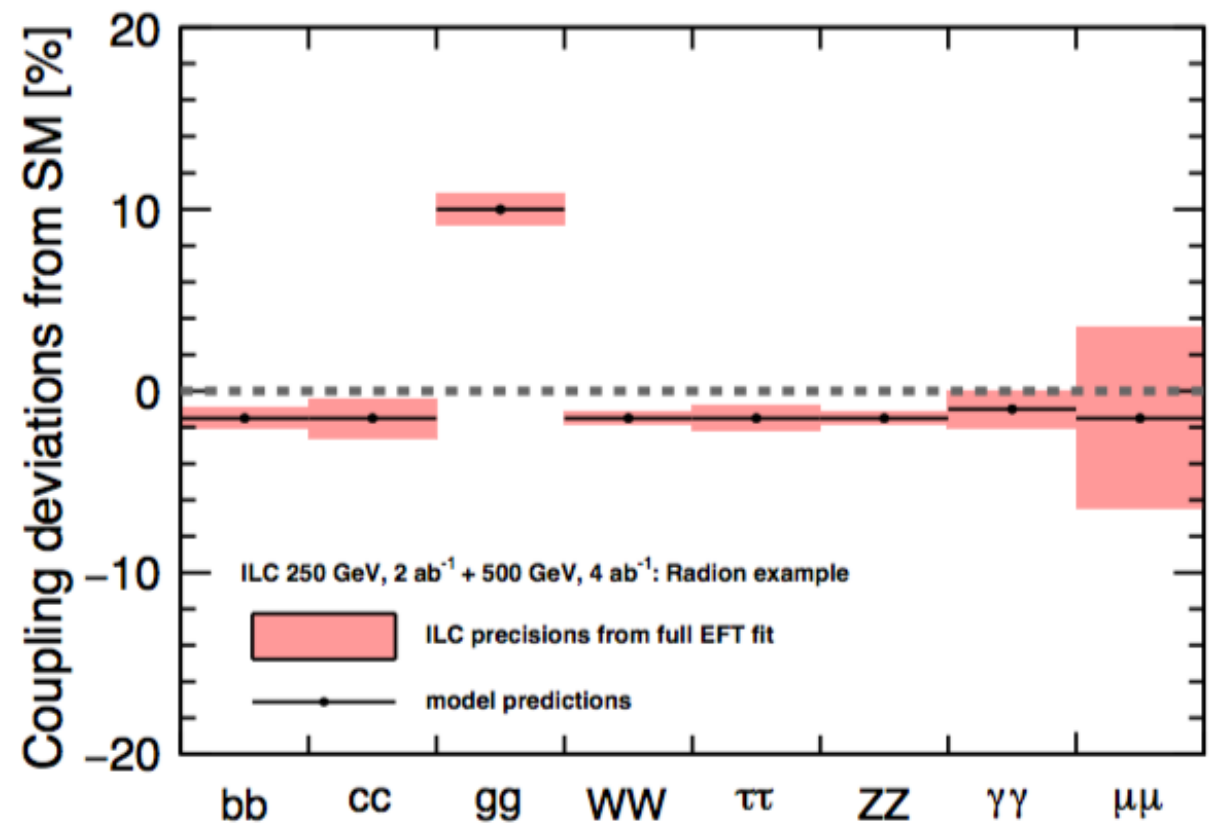
2 Higgs doublet



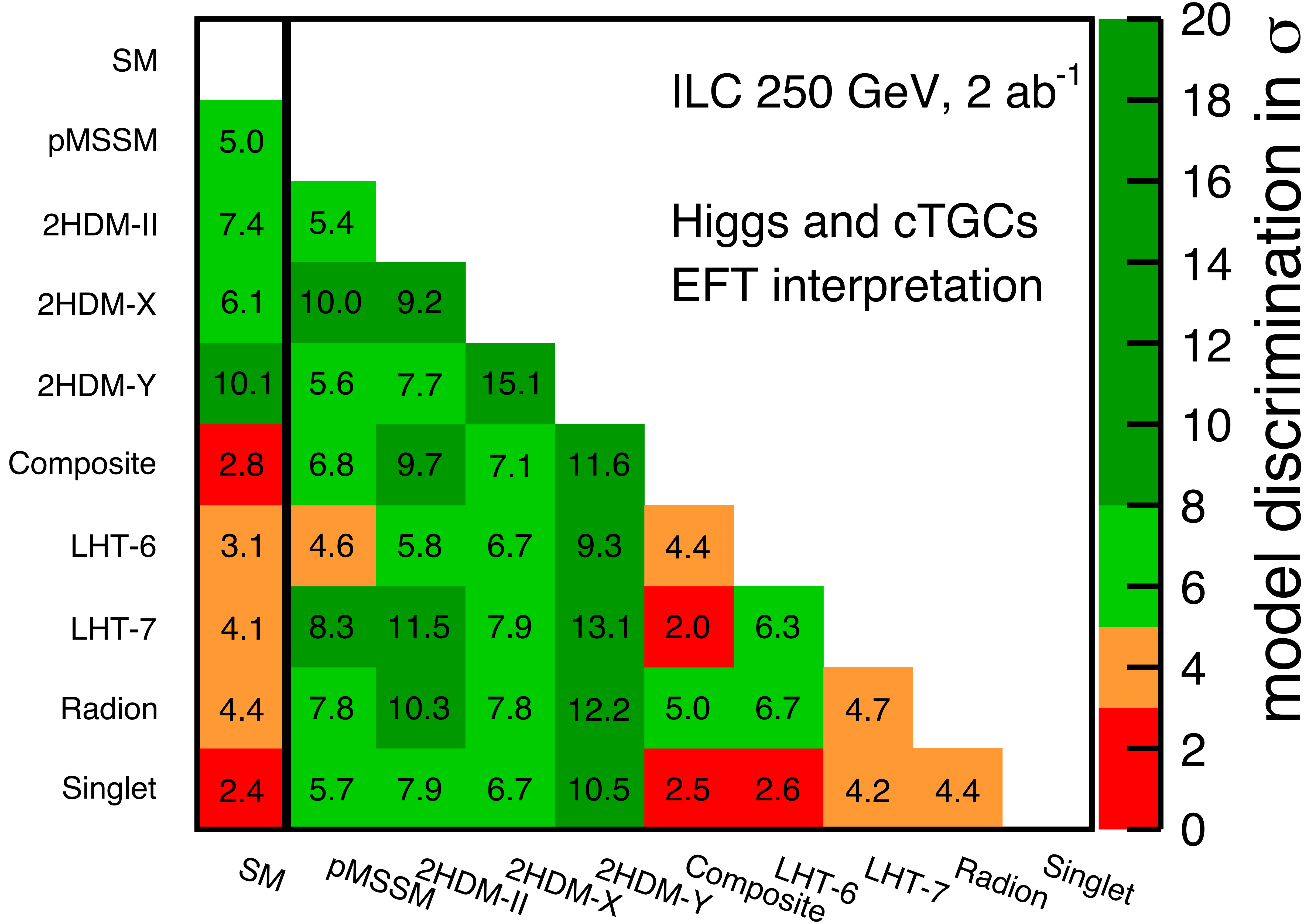
Composite Higgs



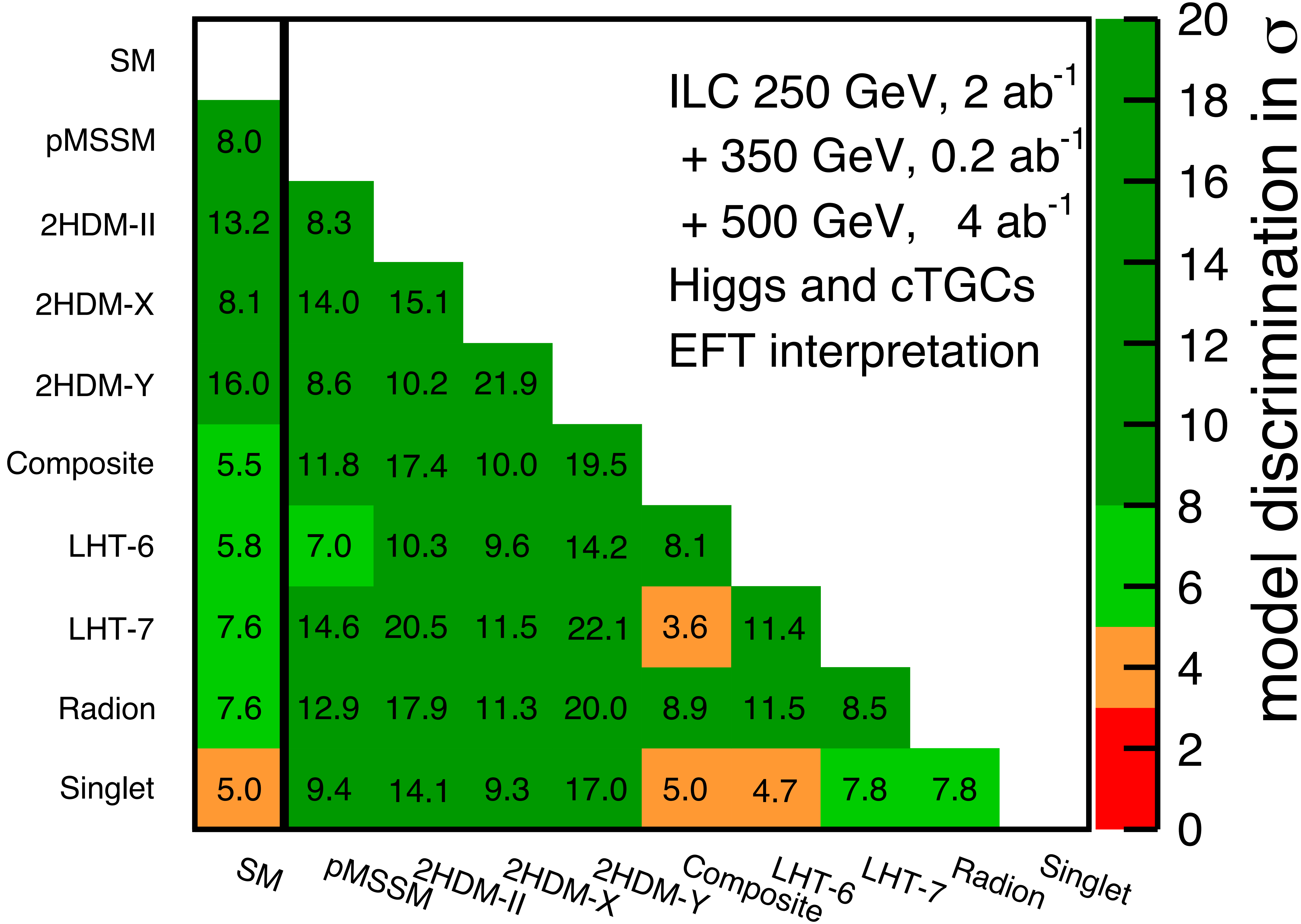
Higgs-Radion mixing



results: ILC 250 GeV 2 ab-1



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



The precision study of the Higgs boson thus offers a new opportunity to discover the presence of novel fundamental interactions beyond the Standard Model.

This method does not compete with direct particle searches but rather opens an orthogonal direction to probe the space of new physics models.

The observation of the pattern of anomalies in the Higgs couplings gives evidence on the nature of the new physics. It points out the path for future study.

The study of the Higgs boson couplings is an opportunity that our community needs to pursue.

Let’s get on with this by constructing the ILC !