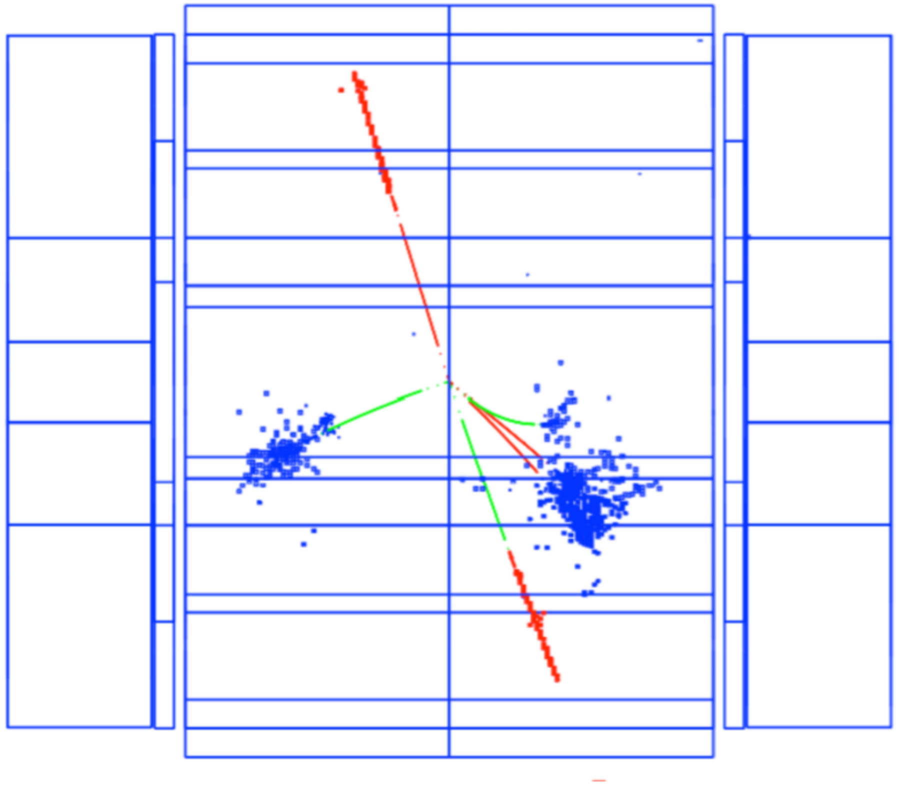
What Will We Learn from the Higgs Boson ?



M. E. Peskin
SSI 2018
August 2018

In the past two weeks, you have heard much about the successes and remaining mysteries of the Standard Model.

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:

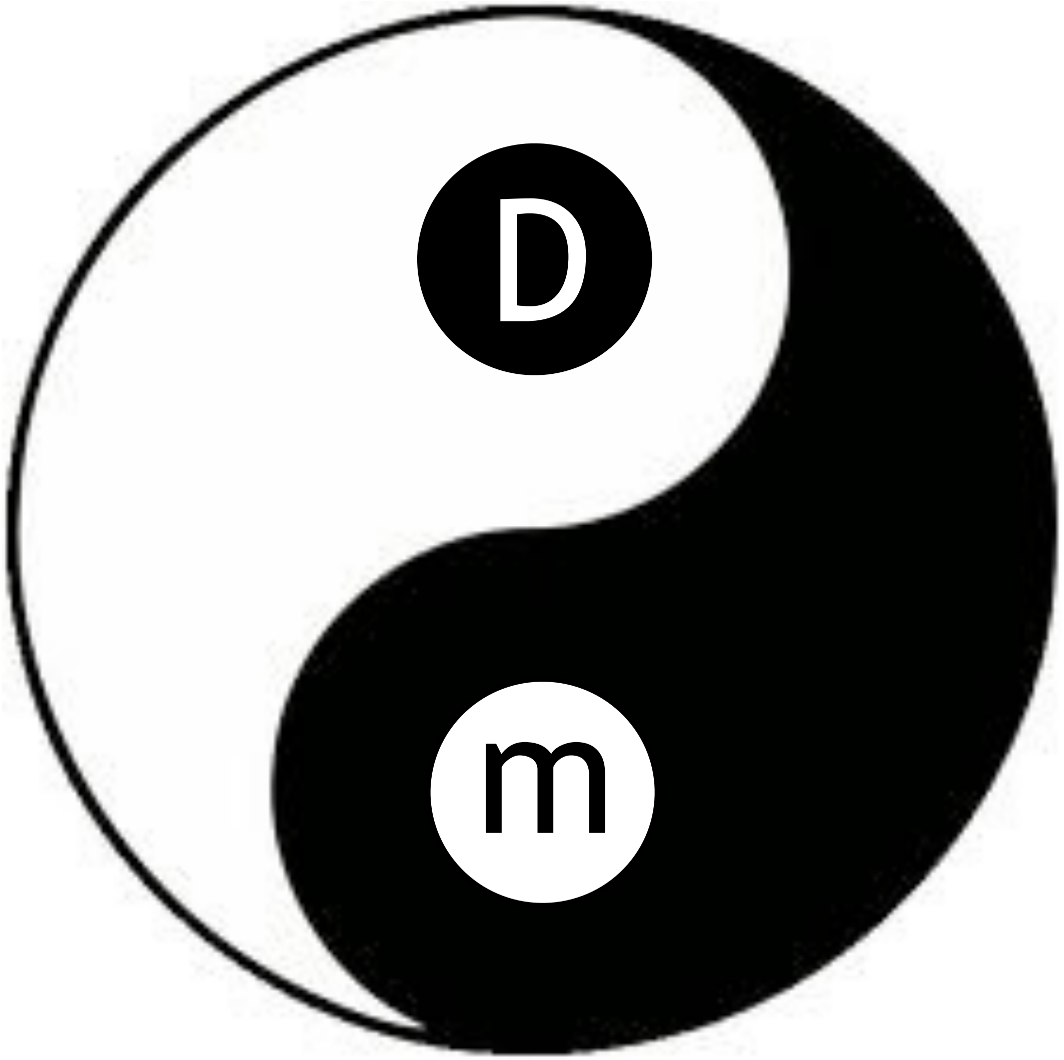
cannot predict electroweak symmetry breaking
cannot predict the spectrum of quark and lepton masses
cannot predict the cosmic matter/antimatter asymmetry
cannot predict the existence of dark matter

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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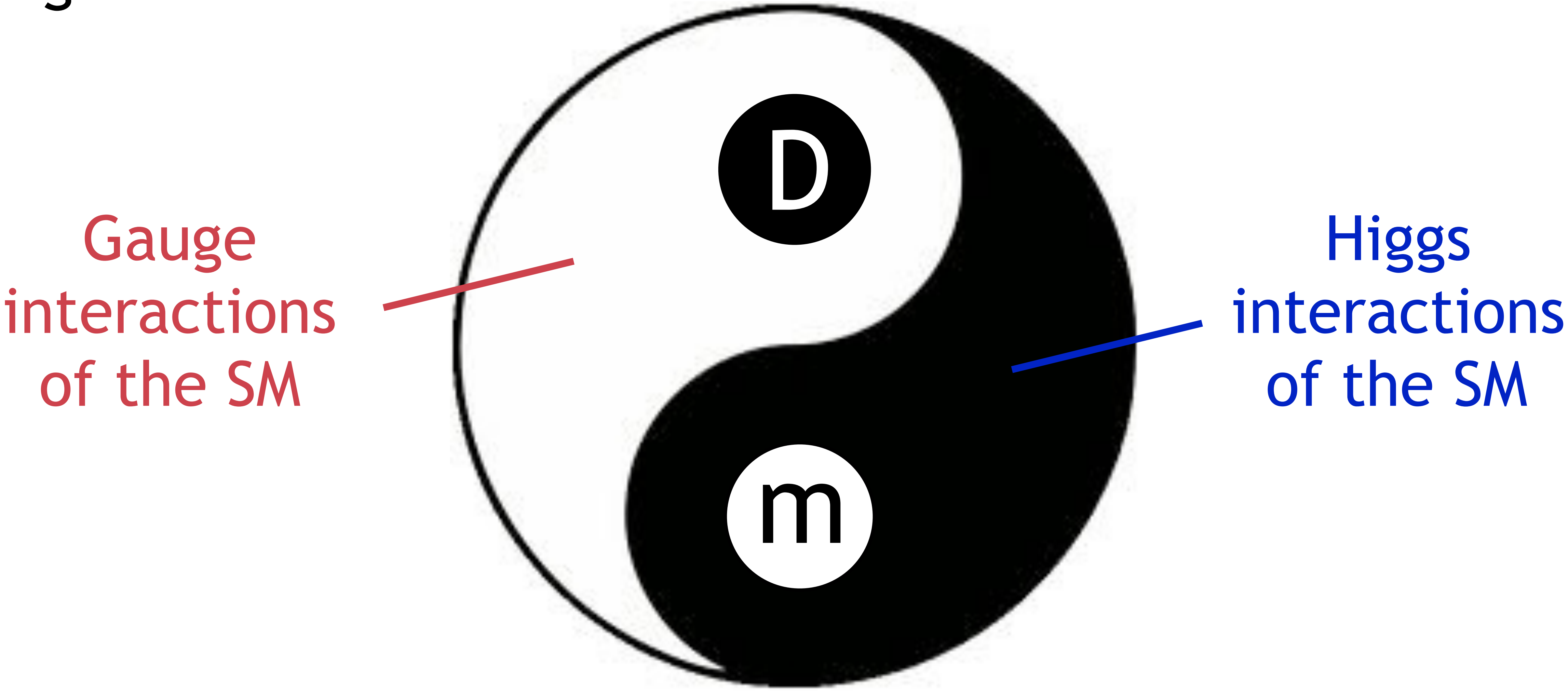


Gauge interactions of the SM

Higgs interactions of the SM

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 again and again in this school 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 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

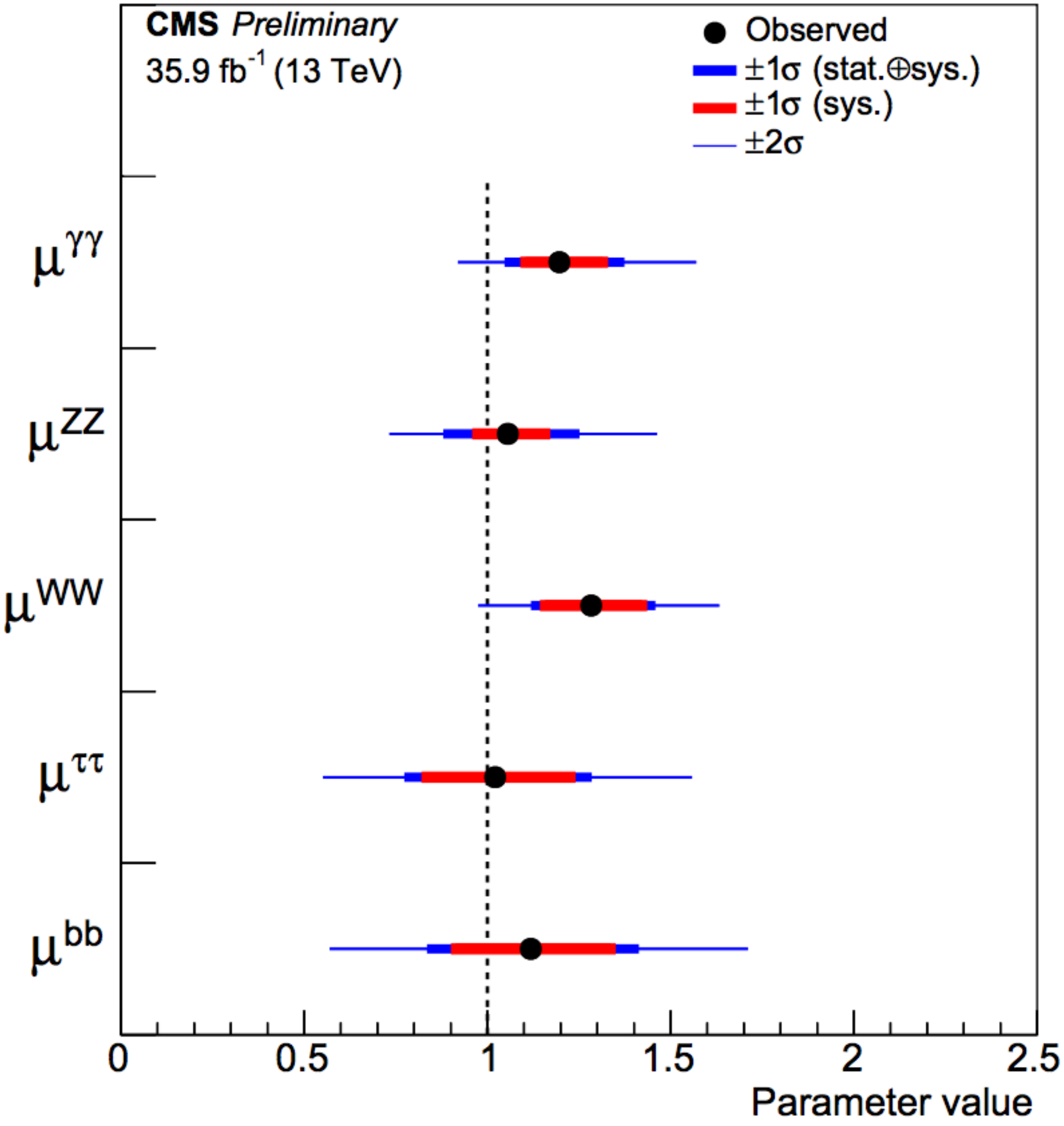
In all cases, a large parameter space of possibilities has been excluded. Now the limits of these techniques with current facilities are in sight.

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.

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

This explains some otherwise confusing statements made by all three speakers on Monday.

Despite the good agreement between the LHC data and the SM description of the Higgs, 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. However, all of this is hidden from us by the Decoupling Theorem.

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

Then the coupling modifications are

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

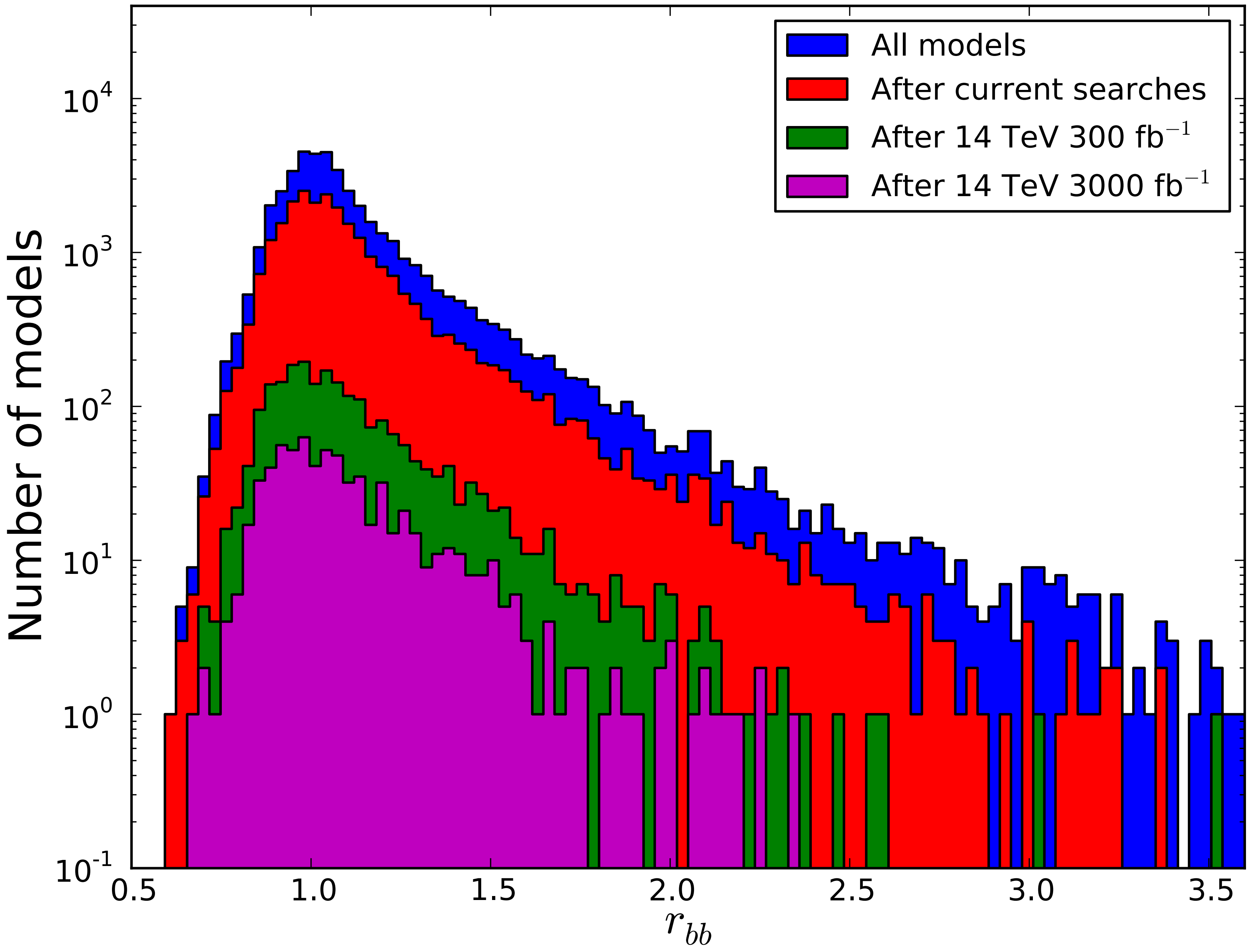
In full models such as SUSY, the two angles are not independent. In fact, typically,

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

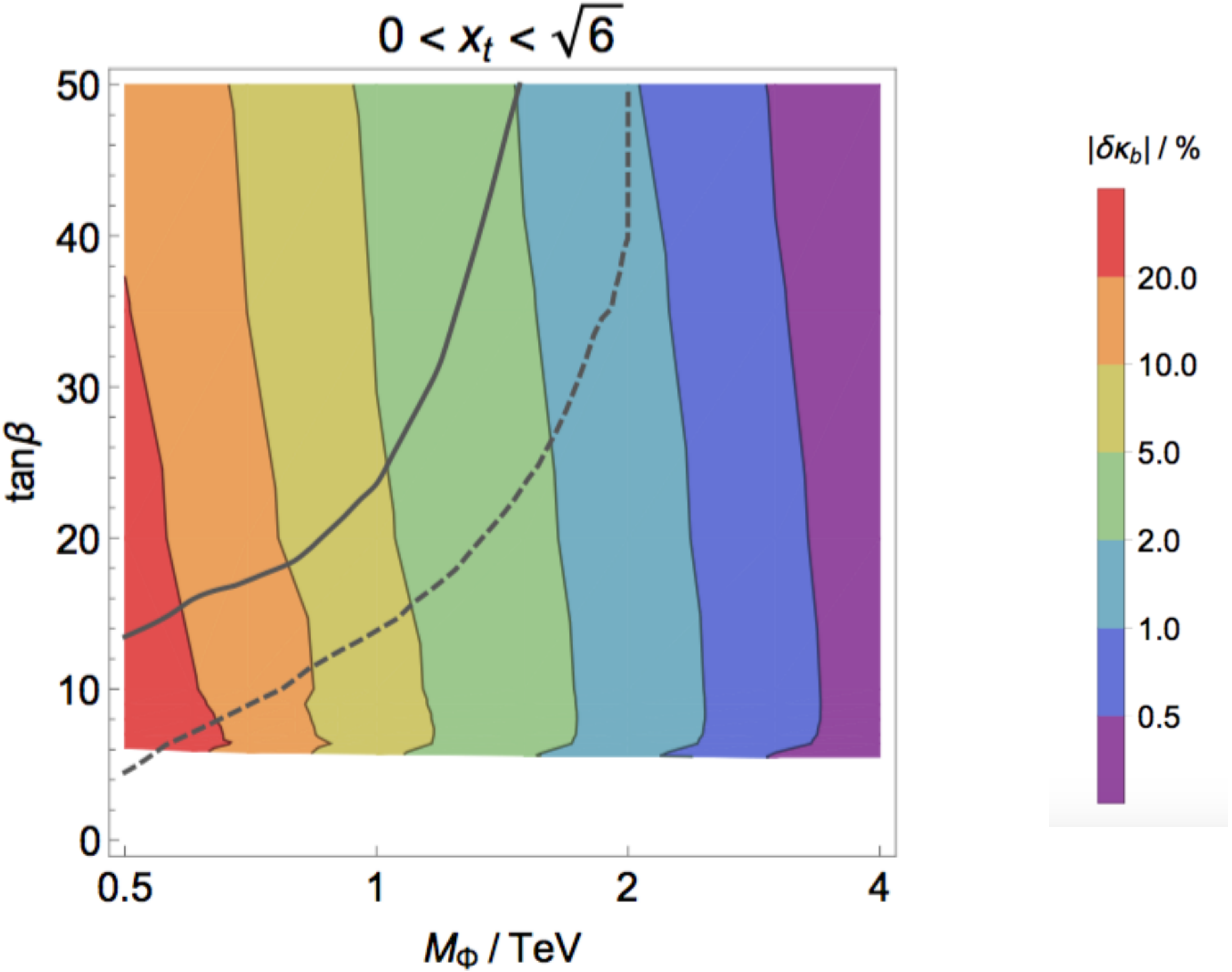
so that

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

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

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.

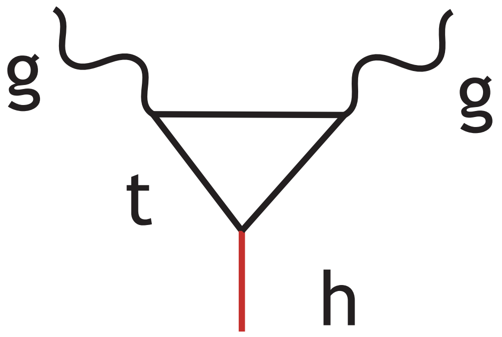
If the Higgs is a composite Goldstone boson, these couplings are corrected by

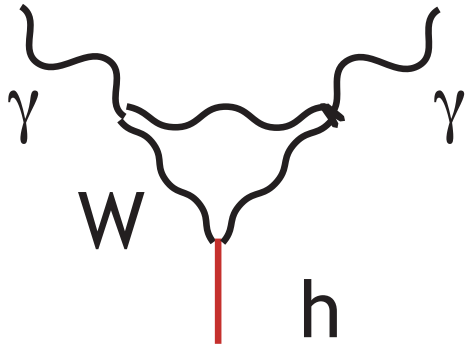
$$g(hVV) \sim (1 - v^2/f^2)^{1/2} \sim \text{few } \%$$

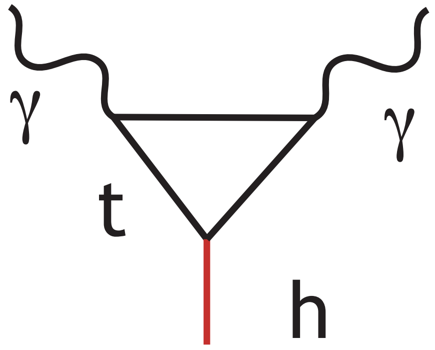
The decays

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

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 $\tilde{t}$ 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

γγ, gg couplings - heavy top quark partners

tt coupling - top quark compositeness

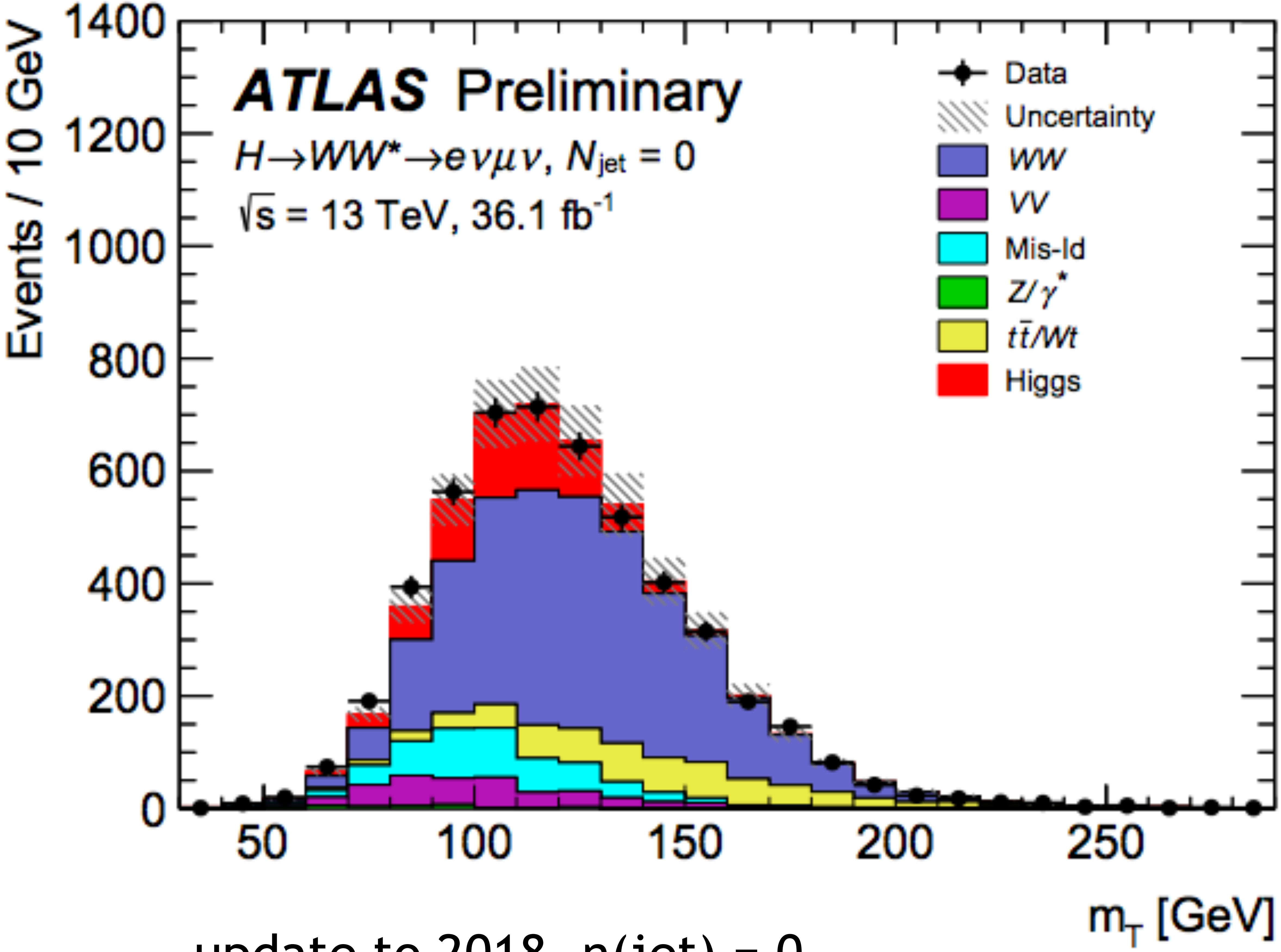
hhh coupling (large deviations) - baryogenesis

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

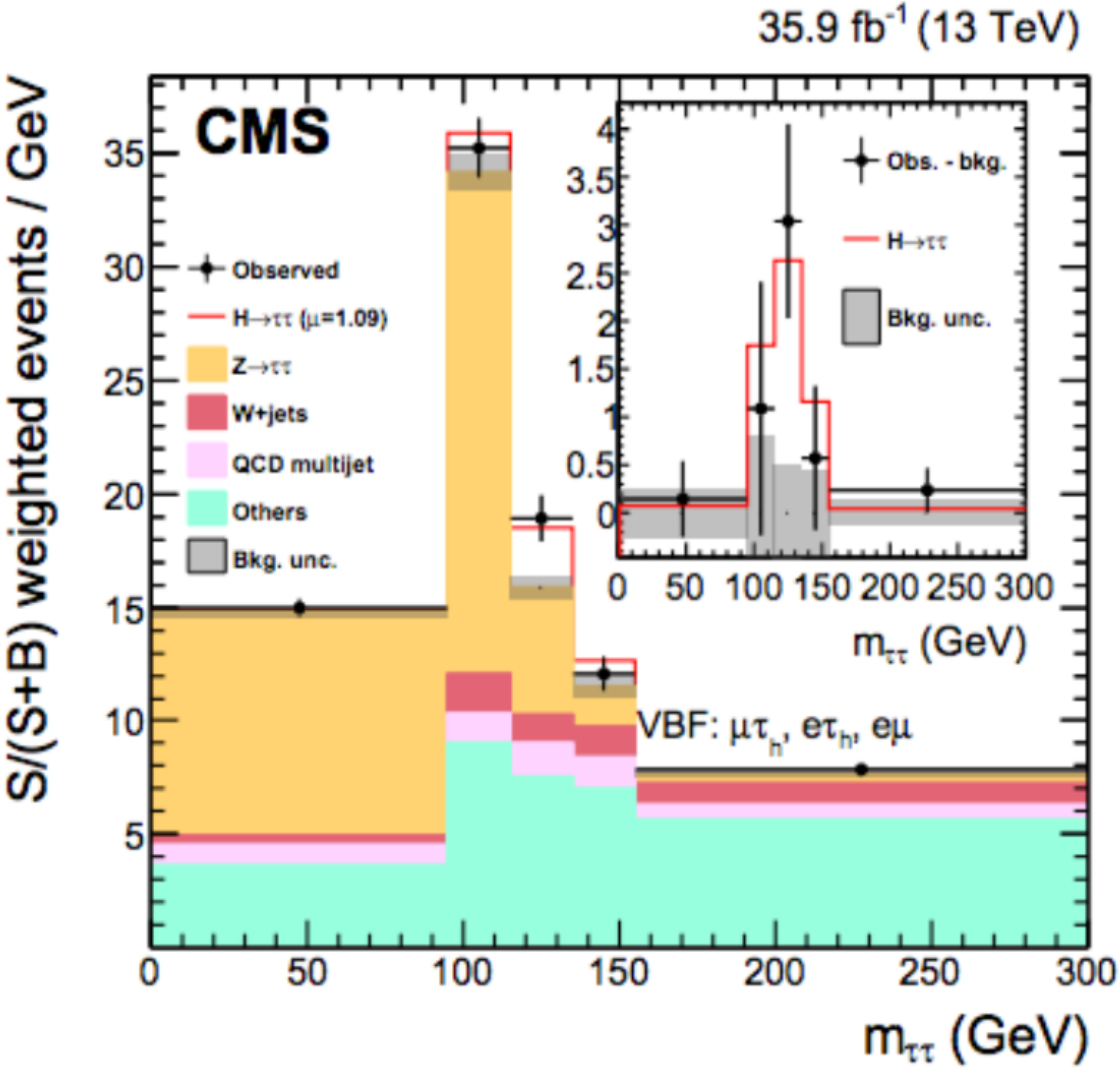
1% measurement accuracy or better is required.

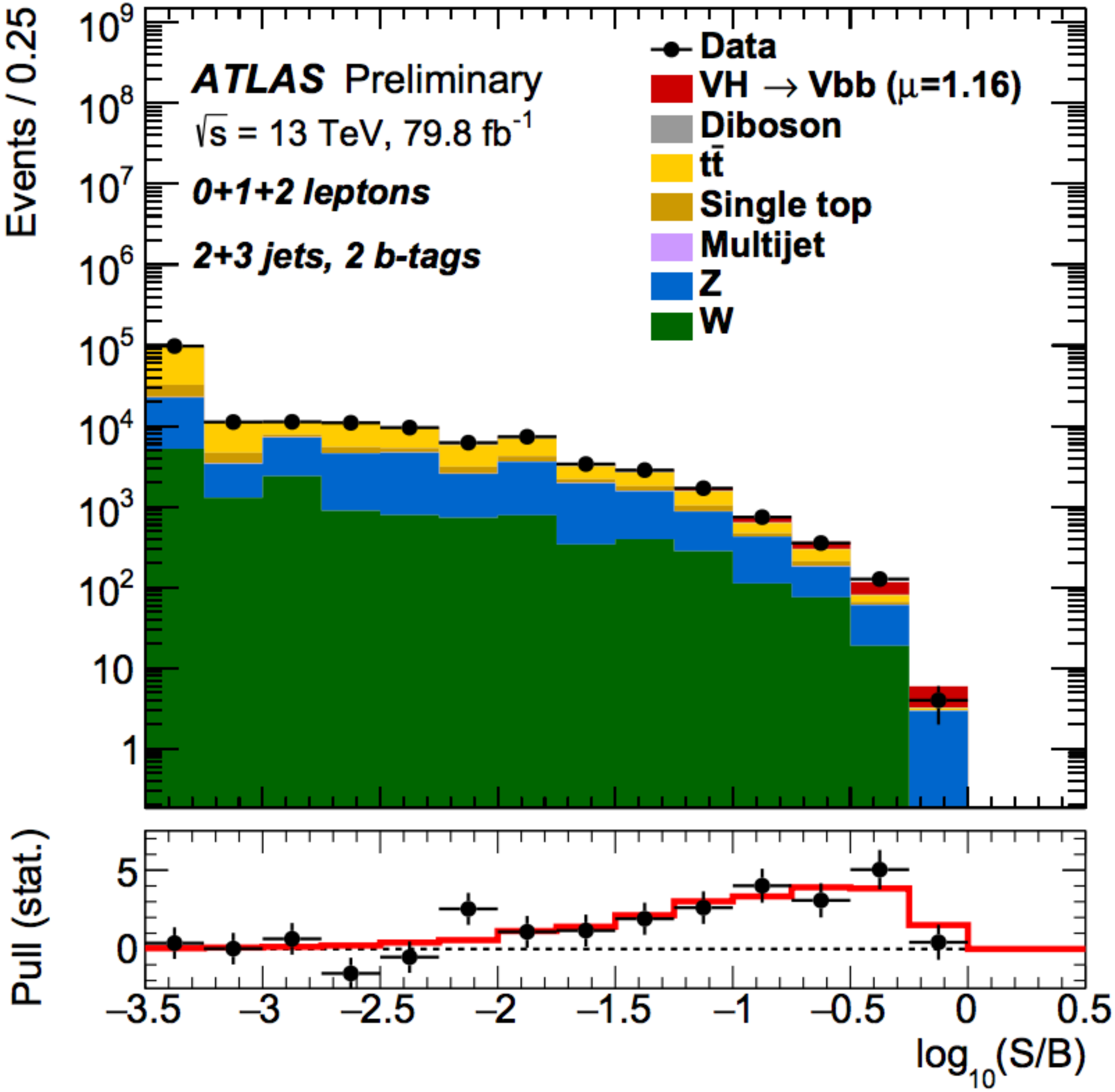
This is a challenge for measurements at hadron colliders.

At the LHC — except for rare, fully reconstructable channels such as γγ, 4 lepton — Higgs events are not characteristic.   We start with samples that are 10% Higgs, 90% background and work hard to remove the 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.
VBF: $\mu\tau_h$, $e\tau_h$, $e\mu$
Obs. - bkg.
H→ττ
Bkg. unc.
0
0.5
1
1.5
2
2.5
3
3.5
4
0
50
100
150
200
250
300
$m_{\tau\tau}$ (GeV)
5
10
15
20
25
30
35
0
50
100
150
200
250
300
$m_{\tau\tau}$ (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

Also, since LHC cannot observe all Higgs decay modes, we cannot measure the total rate or normalize Higgs couplings absolutely.

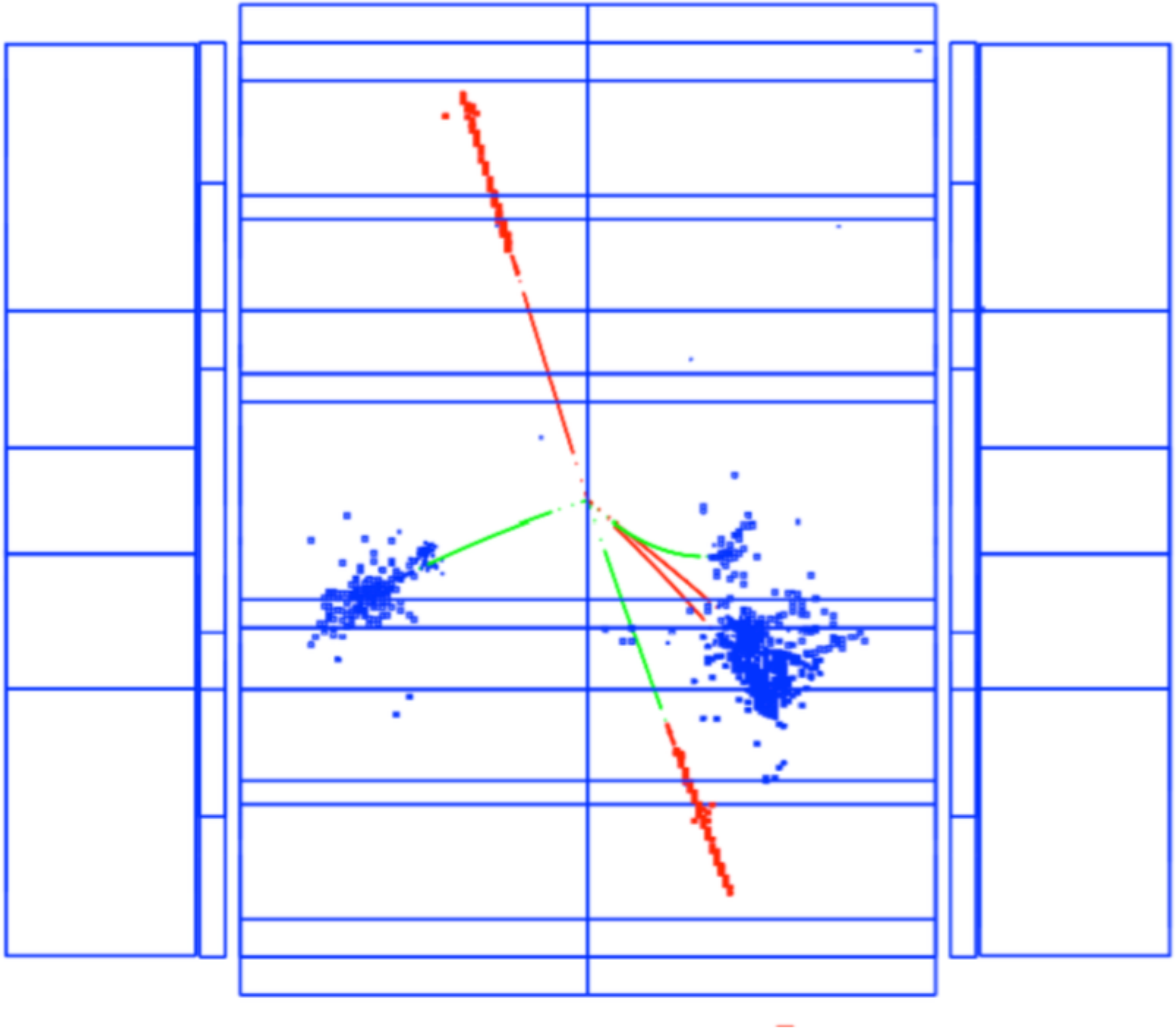
A different experimental technique is needed. This technique should make it easy to observe the Higgs rate to order 1. Then, with effort, we can achieve 1% accuracies.

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

To a first approximation, any Z boson with a lab energy of 110 GeV is recoiling against a Higgs boson.

By counting events we can,

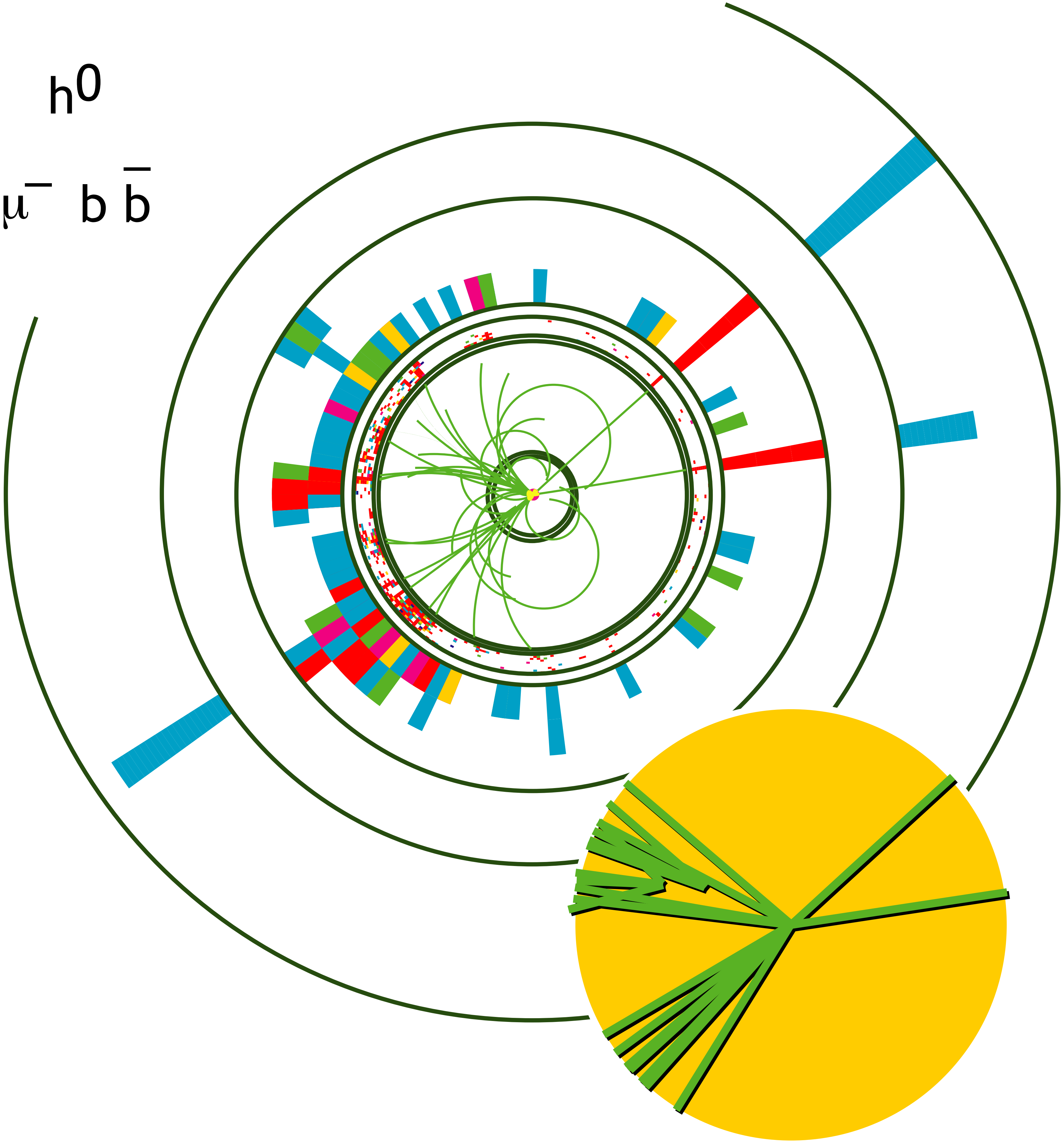
- measure the total Higgs rate independently of the decay pattern
- measure the Higgs branching ratios directly
- search for invisible, partially invisible, and other exotic Higgs decays



(thanks to Manqi Ruan)

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

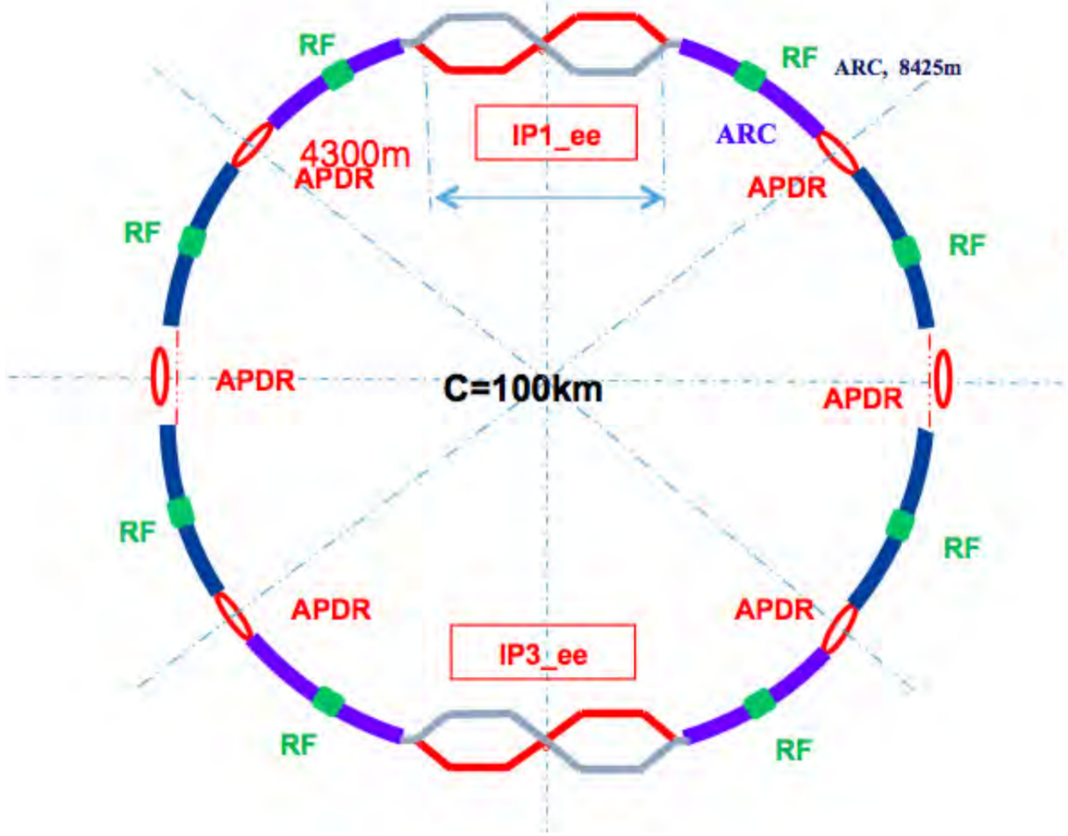
$\rightarrow \mu^+\mu^- \; b \, \bar{b}$



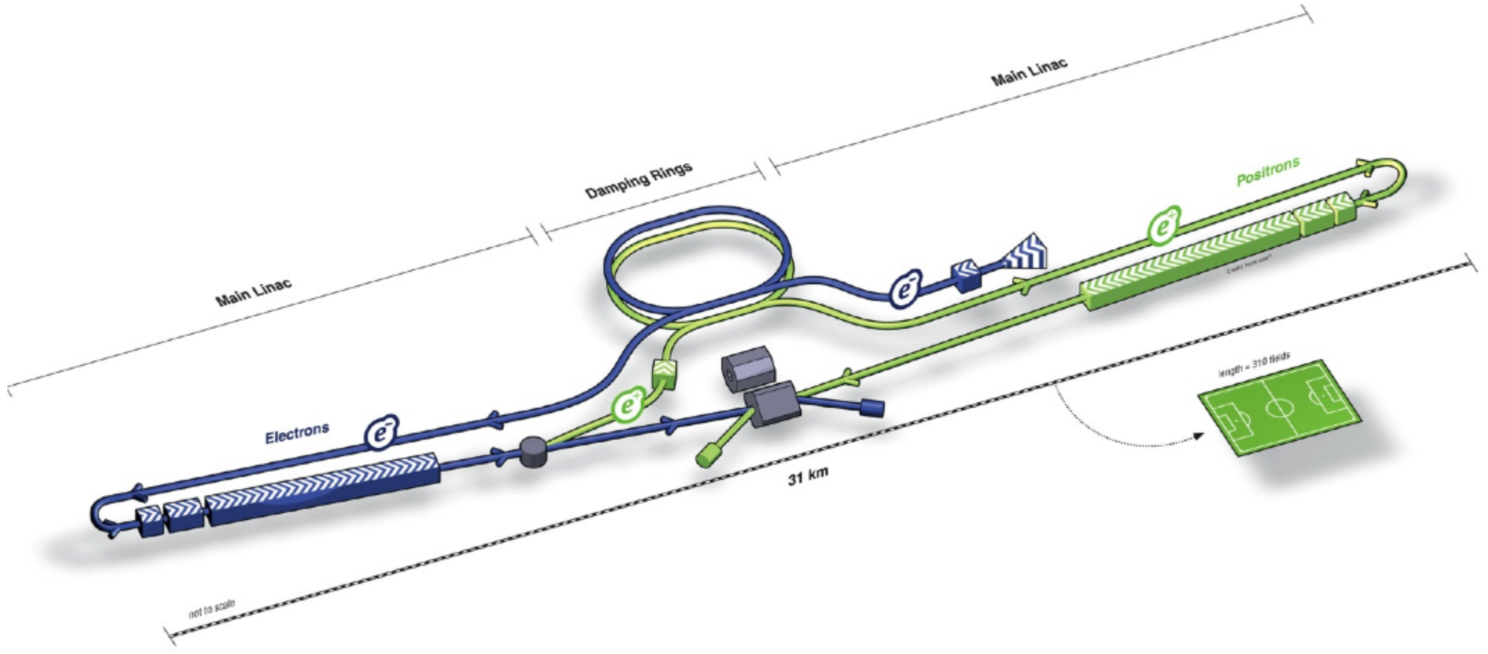
To do this experiment, we need an e+e- collider with CM energy of 250 GeV capable of acquiring several ab-1 of integrated luminosity.

Two potential facilities are now under consideration for a start of experiments in the early 2030's:

CEPC in China



ILC in Iwate Province, Japan



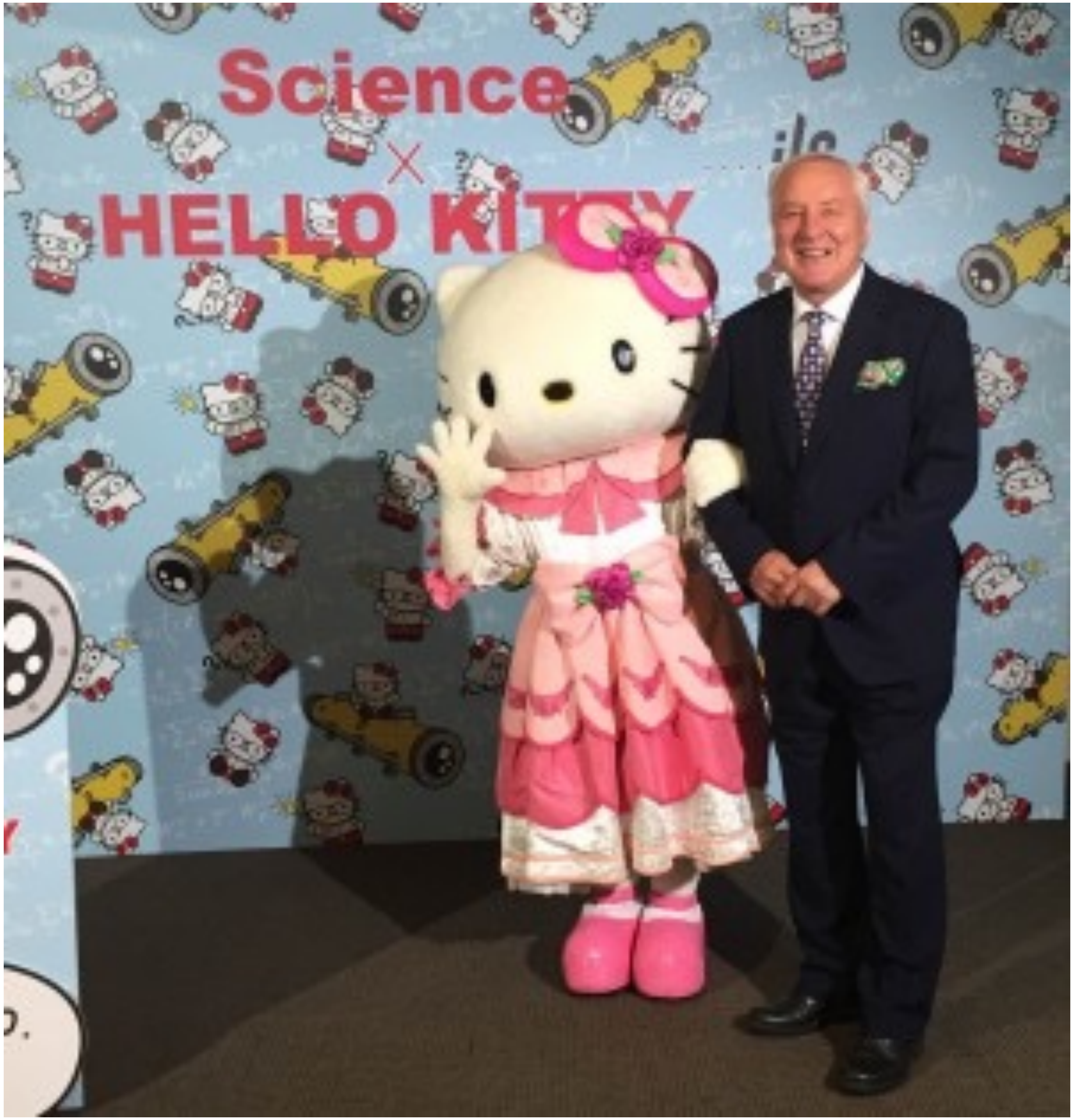
Both of these accelerators are under formal consideration by their respective governments.

Both governmental processes are, unfortunately, shrouded in secrecy.

For ILC, at least, I have some pictures to give evidence of its seriousness.

Hon. Shintaro Ito (Sendai) meeting with the American Linear Collider Coordinating Committee, AWLC 2017 at SLAC, June 2017

Higgs Boson yurukyara



Lyn Evans and Hello Kitty

The Science Council of Japan is meeting today to discuss the final report prepared by the MEXT ministry giving answers to a long list of questions asked about the ILC.

A positive decision by Japan to host the ILC would then be discussed in the next European Strategy for Particle Physics study (2019-2020) and by the US DOE to negotiate terms of a global collaboration.

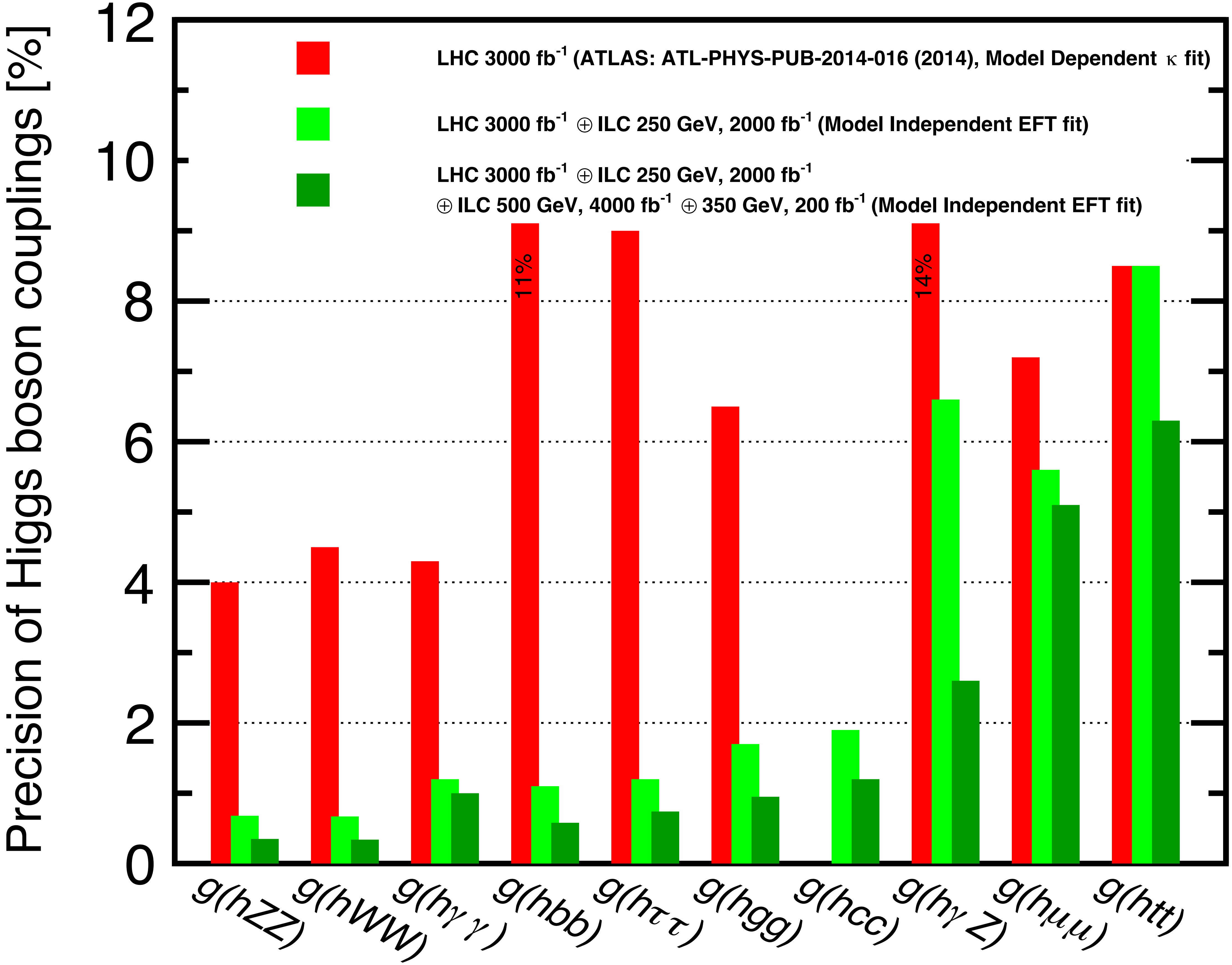
ILC and CEPC will measure a large number of Higgs Boson couplings:

W, Z, b, c, τ, g, γ, μ, invisible

At these accelerators, all of these modes can be seen directly and distinguished. The couplings are measured in absolute terms, not just as branching ratios.

The pattern of coupling deviations indicates the nature of the new physics at high energies.

ILC can be upgraded in energy to 500 GeV and above. This gives access to the Higgs coupling to t and the Higgs self-coupling (as well as precision top quark physics).



arXiv:1710.07621

Conclusions:

Today, we know nothing about the Higgs Boson beyond its existence.

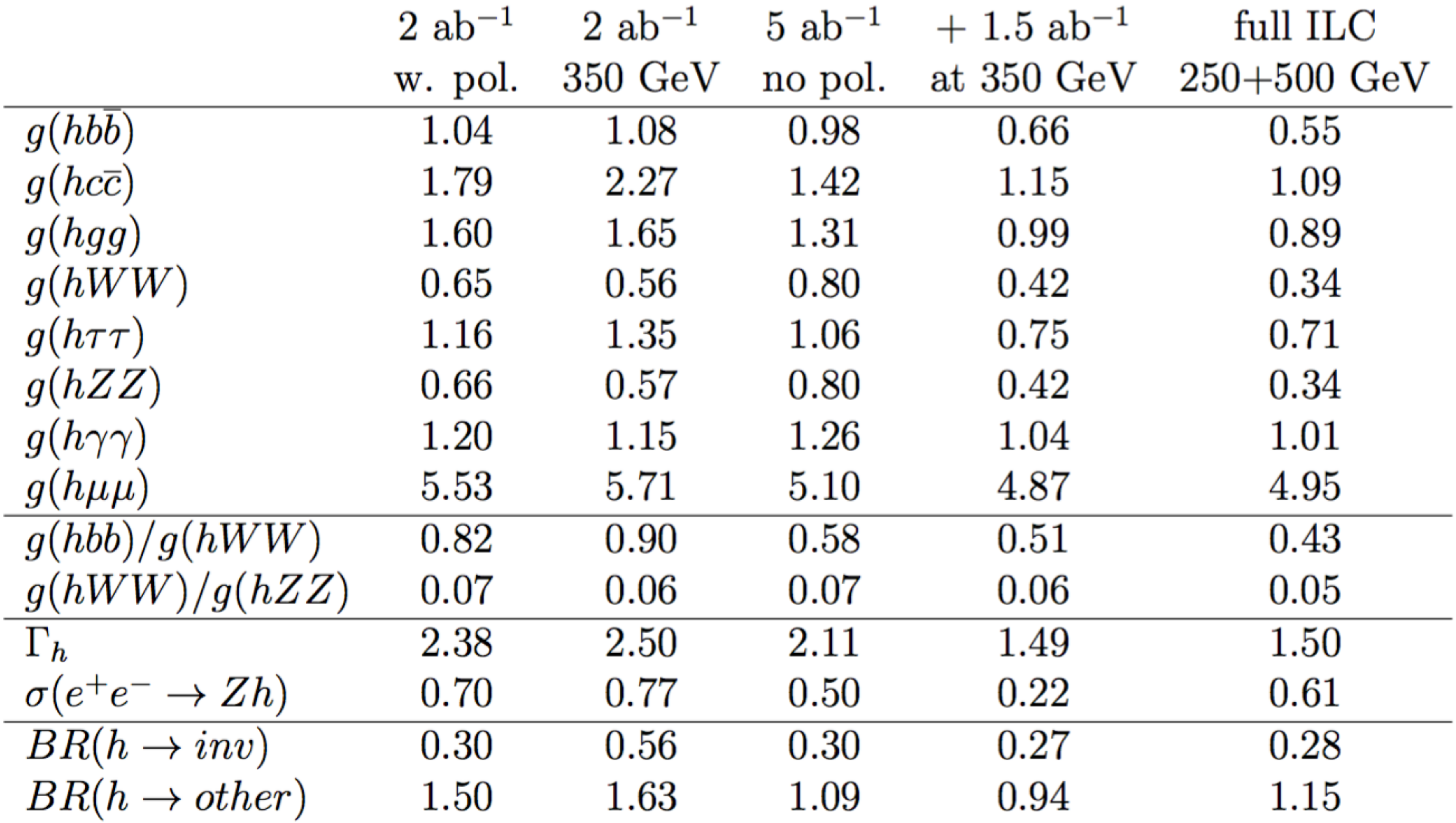
To extract information from the Higgs Boson about new physics beyond the SM, we will need a new e+e- collider operating at 250 GeV.

There are possibilities on the horizon. Detector design and construction would begin within 10 years from now.

Maybe this is your opportunity to personally discover new physics beyond the Standard Model.

BACKUP SLIDES

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



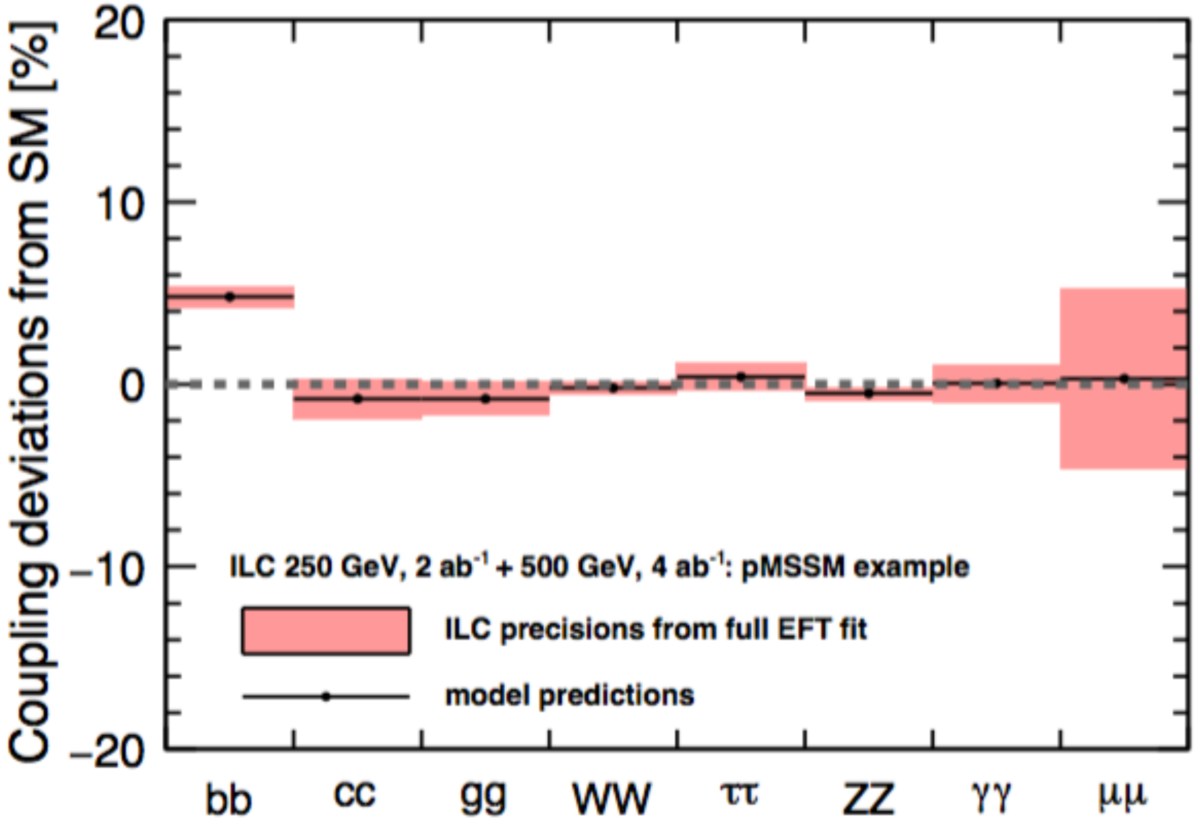
	ILC 250	CLIC	CEPC	FCC-ee	ILC 500
	2 ab^{-1} w. pol.	2 ab^{-1} 350 GeV	5 ab^{-1} no pol.	+ 1.5 ab^{-1} at 350 GeV	full ILC 250+500 GeV
$g(hb\bar{b})$	1.04	1.08	0.98	0.66	0.55
$g(hc\bar{c})$	1.79	2.27	1.42	1.15	1.09
$g(hgg)$	1.60	1.65	1.31	0.99	0.89
$g(hWW)$	0.65	0.56	0.80	0.42	0.34
$g(h\tau\tau)$	1.16	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 %

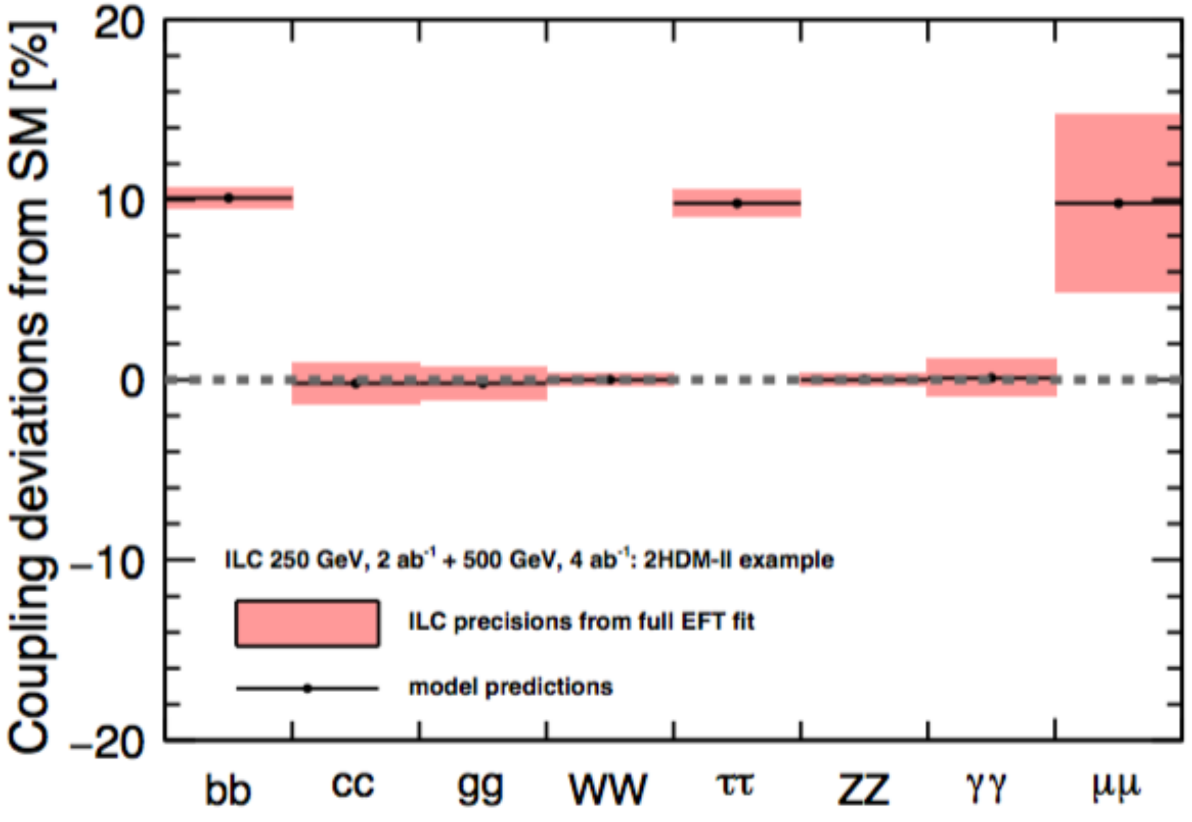
In our paper, you will also find a game in which we examined 9 diverse BSM models — all with new particles outside the range of LHC — that can gives significant effects in precision Higgs measurements.

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

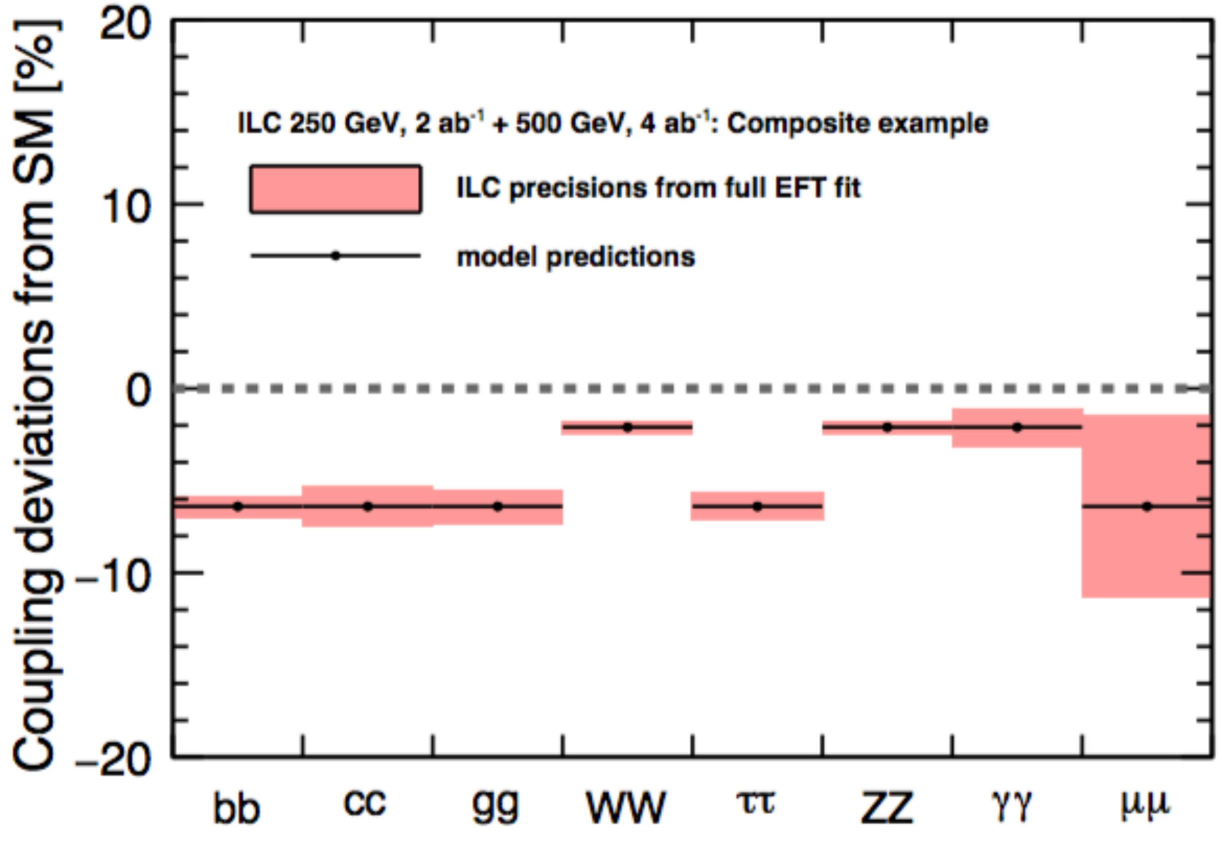
heavy SUSY



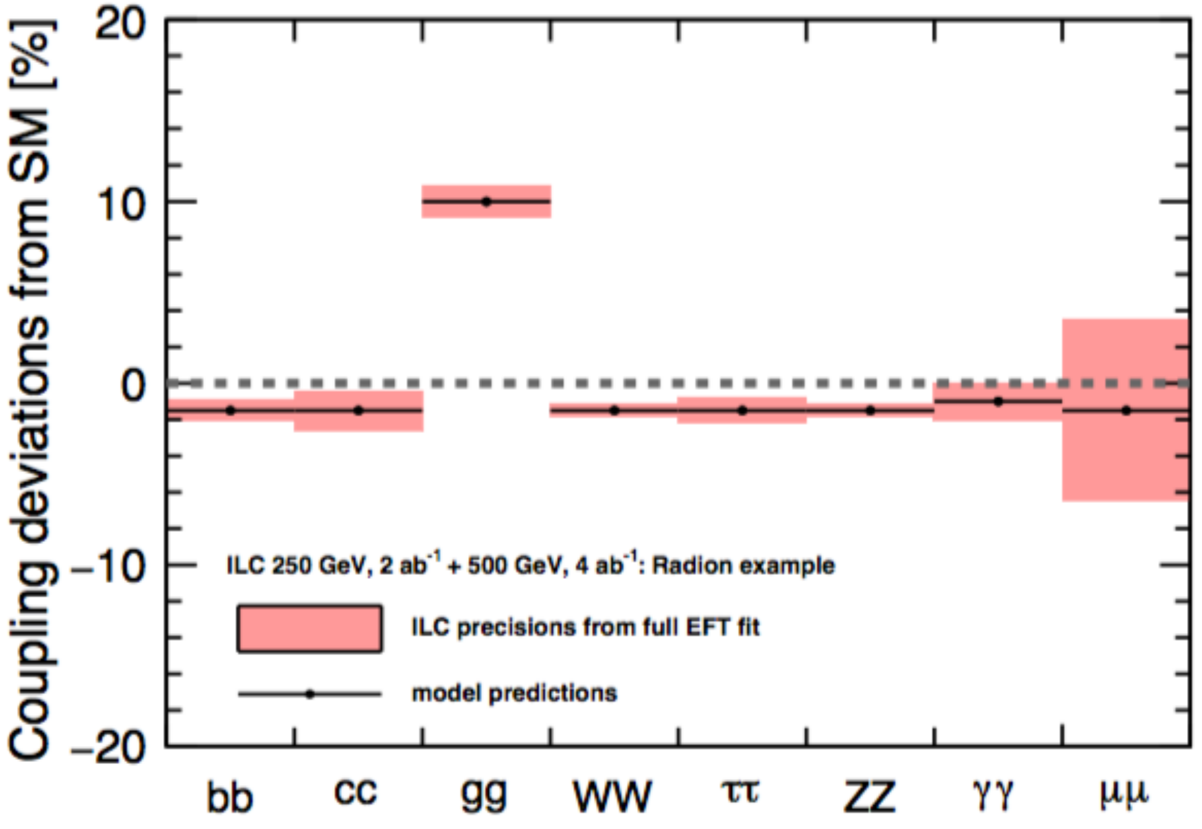
2 Higgs doublet



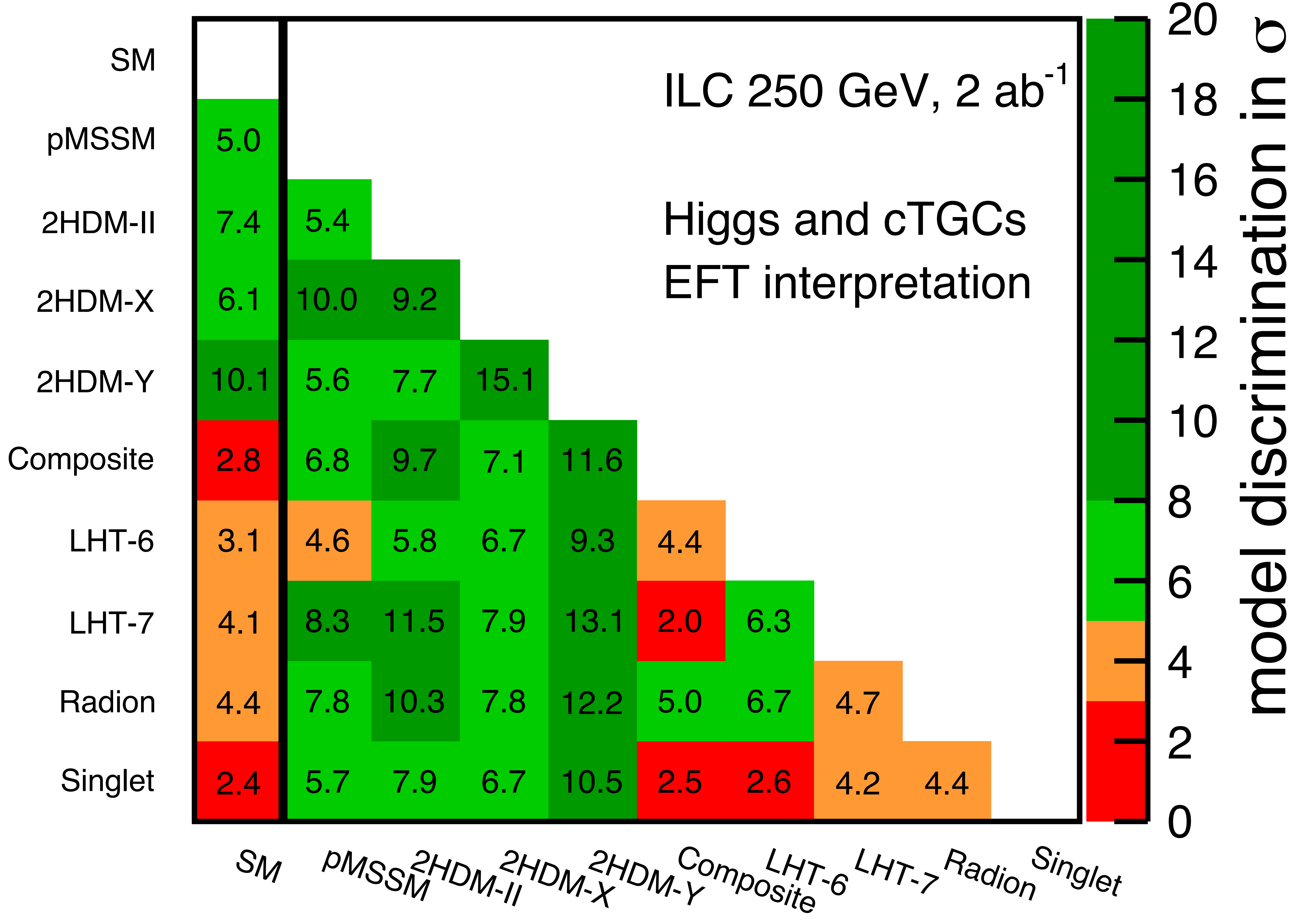
Composite Higgs



Higgs-Radion mixing

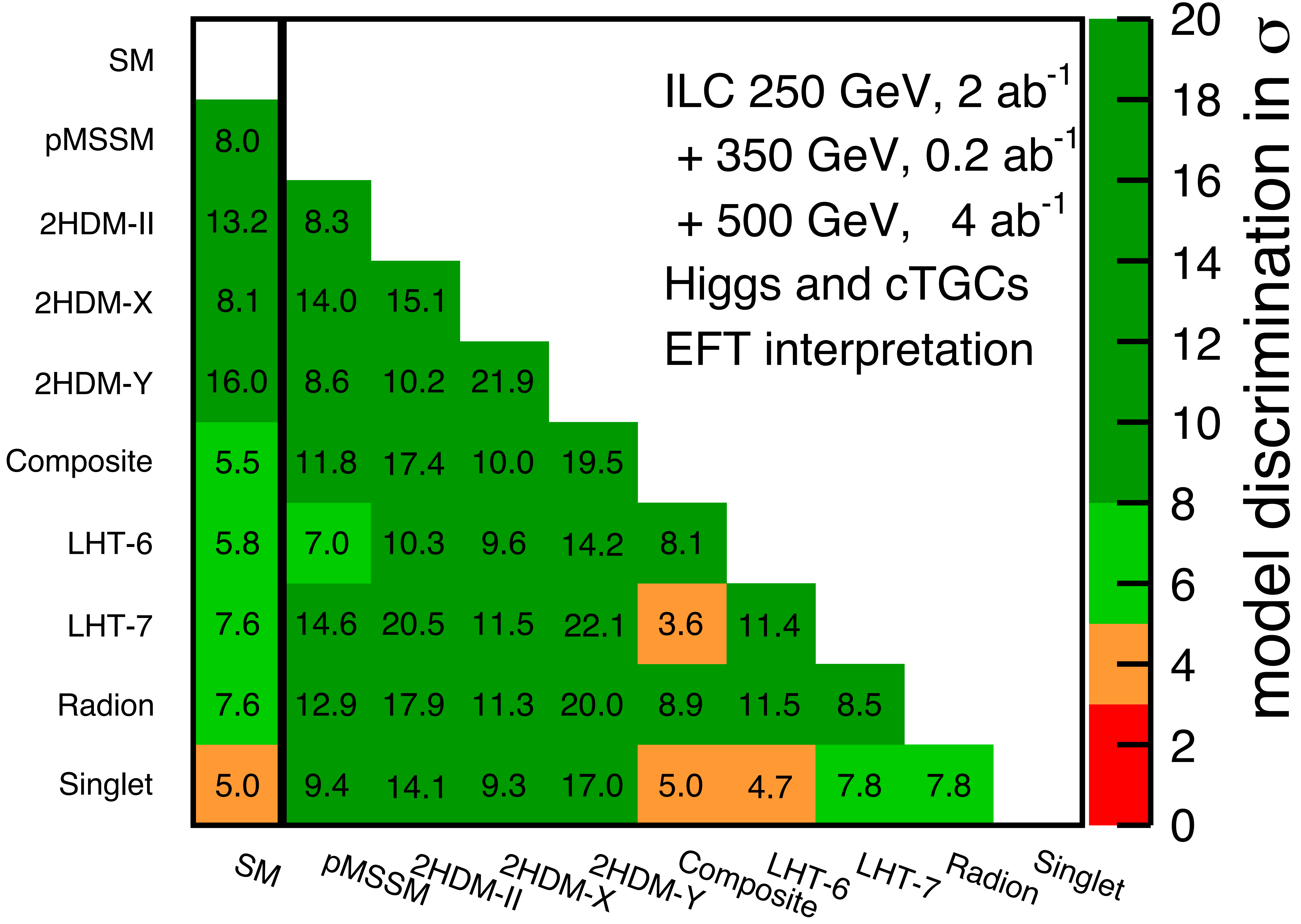


results: ILC 250 GeV 2 ab-1



	SM	pMSSM	2HDM-II	2HDM-X	2HDM-Y	Composite	LHT-6	LHT-7	Radion	Singlet
SM										
pMSSM	5.0									
2HDM-II	7.4	5.4								
2HDM-X	6.1	10.0	9.2							
2HDM-Y	10.1	5.6	7.7	15.1						
Composite	2.8	6.8	9.7	7.1	11.6					
LHT-6	3.1	4.6	5.8	6.7	9.3	4.4				
LHT-7	4.1	8.3	11.5	7.9	13.1	2.0	6.3			
Radion	4.4	7.8	10.3	7.8	12.2	5.0	6.7	4.7		
Singlet	2.4	5.7	7.9	6.7	10.5	2.5	2.6	4.2	4.4	

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


ILC 250 GeV, 2 ab^{-1}

+ 350 GeV, 0.2 ab^{-1}

+ 500 GeV, 4 ab^{-1}

Higgs and cTGCs

EFT interpretation

	SM	pMSSM	2HDM-II	2HDM-X	2HDM-Y	Composite	LHT-6	LHT-7	Radion	Singlet
SM										
pMSSM	8.0									
2HDM-II	13.2	8.3								
2HDM-X	8.1	14.0	15.1							
2HDM-Y	16.0	8.6	10.2	21.9						
Composite	5.5	11.8	17.4	10.0	19.5					
LHT-6	5.8	7.0	10.3	9.6	14.2	8.1				
LHT-7	7.6	14.6	20.5	11.5	22.1	3.6	11.4			
Radion	7.6	12.9	17.9	11.3	20.0	8.9	11.5	8.5		
Singlet	5.0	9.4	14.1	9.3	17.0	5.0	4.7	7.8	7.8	