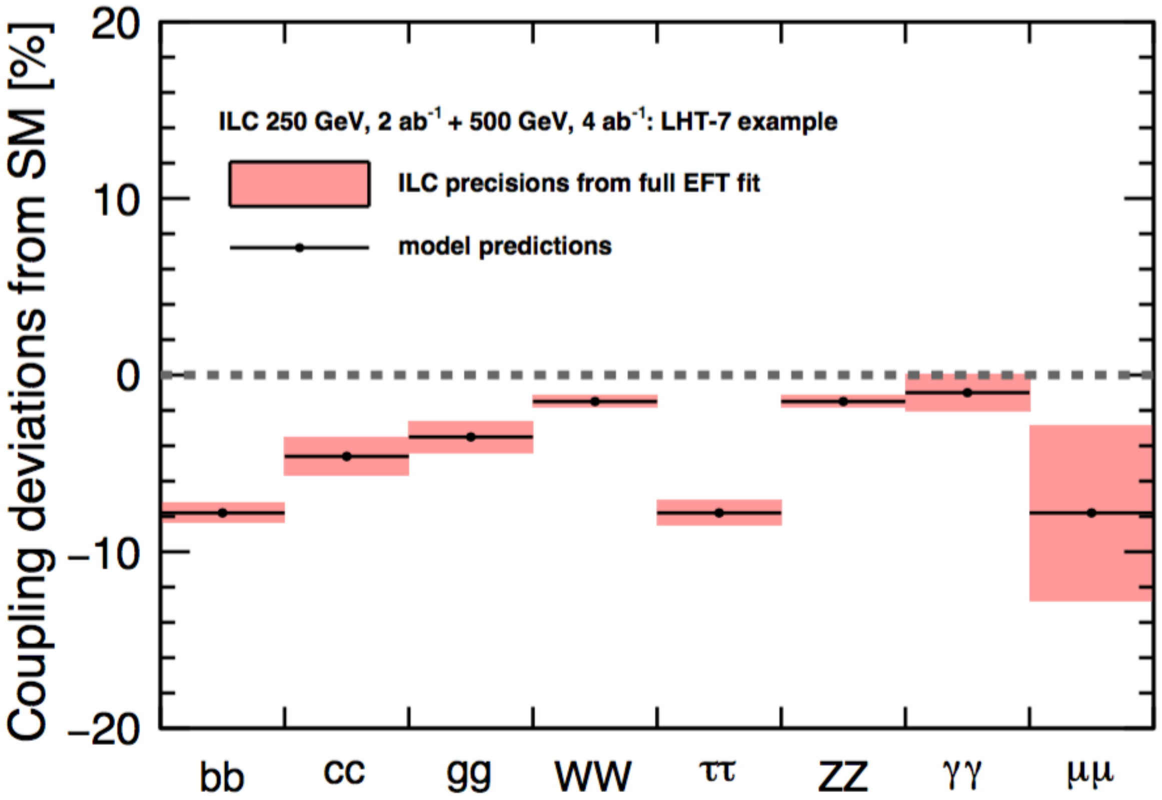
Physics Opportunities of e+e- colliders at 250 GeV and above



M. E. Peskin

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The physics opportunities of next-generation e+e- colliders include:

precision measurement of Higgs boson couplings

search for exotic modes of Higgs boson decay

search for dark matter particles and other invisible states

search for heavy resonances through 2-fermion processes

precision measurement of the top quark mass

precision measurement of top quark electroweak couplings

measurement of the triple Higgs boson coupling

The prospects for these measurements are documented in a number of reports, including:

CLIC Conceptual Design Report	arXiv:1209.2543
ILC TDR, Vol. 2: Physics	arXiv:1306.6352
First Look at the Physics case of TLEP	arXiv:1308.6176
CEPC-SPPC Preliminary CDR	IHEP-TH-2015-01
Physics Case for the ILC	arXiv:1506.05992
Higgs Physics at CLIC	arXiv:1608.07538

Very recently, the LCC Physics Working Group has produced a new report on the physics prospects for e+e- at 250 GeV

Physics Case for the 250 GeV Stage of the ILC
arXiv:1710.07621

In this brief talk, I will mainly discuss new results on Higgs boson couplings presented in this recent report. These improve the physics prospects for all proposed e+e- Higgs factories.

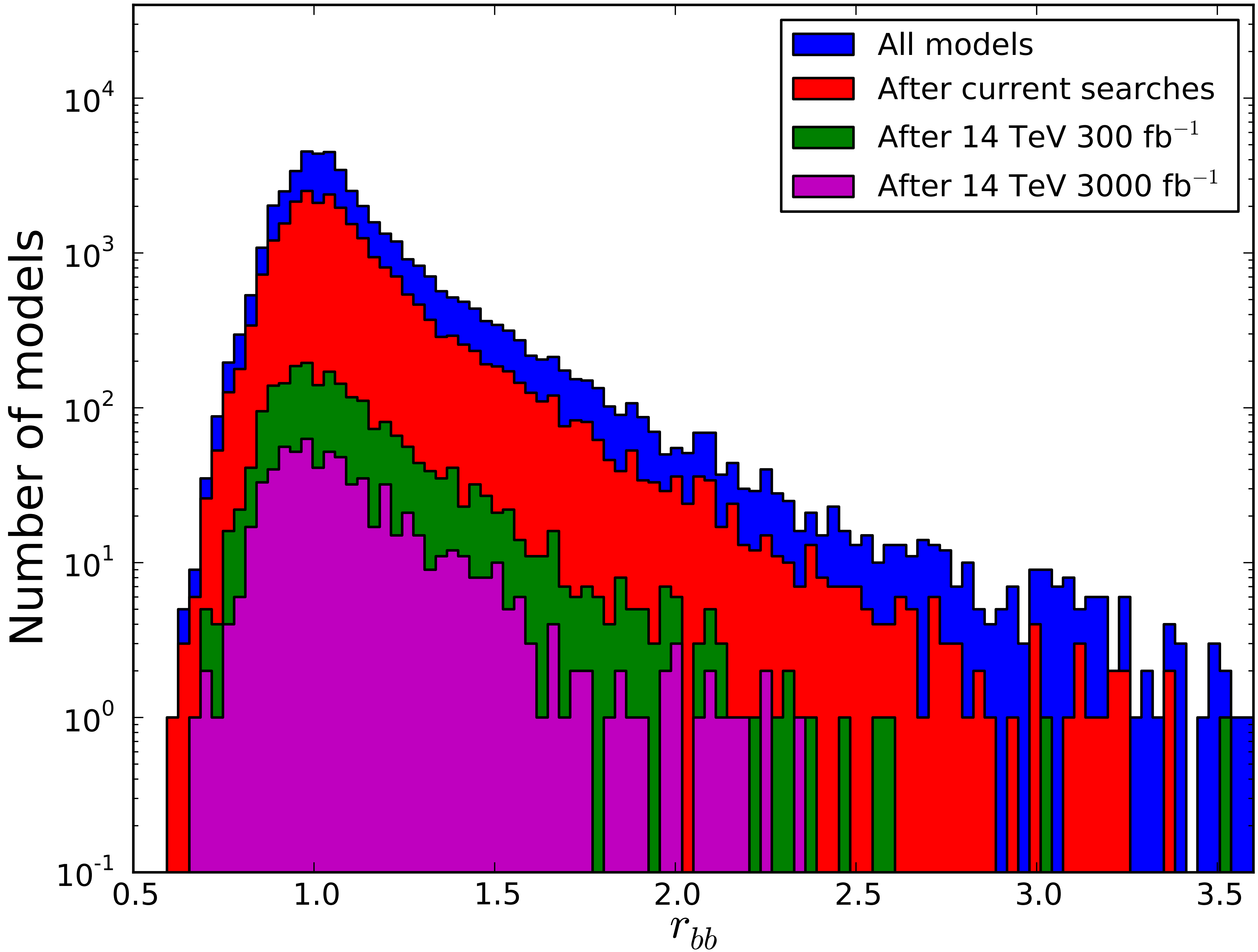
I will also comment on additional opportunities available from e+e- at higher energies.

Why do we want to study the Higgs boson in detail ?

Almost all free parameters of the SM involve the Higgs boson mass, potential, and couplings. None of these numbers are explained. All are put in by hand. Higgs is central to the mysteries of particle physics.

The Higgs field is a scalar that couples to all SM particles, and more strongly to the heaviest ones. The invariant $\Phi^\dagger \Phi$ is a complete singlet that can couple to any particle, even those with no SM interactions.

Radiative corrections from new physics or mixing with heavy particles at TeV masses will affect the properties of the 125 GeV Higgs boson.



Cahill-Rowley, Hewett, Ismail, Rizzo

Why is this difficult at hadron colliders ?

The expected effects of new physics on the 125 GeV Higgs boson are small, at the few-percent level, due to Haber's decoupling theorem.

Higgs events are not characteristic at hadron colliders, except in a few rare modes. Typical Higgs boson samples are 10% Higgs, 90% other.

Not all Higgs decay modes can be observed at hadron colliders. So, it is not possible there to determine Higgs couplings in a model-independent way. LHC experiments typically measure μ, a combination of couplings.

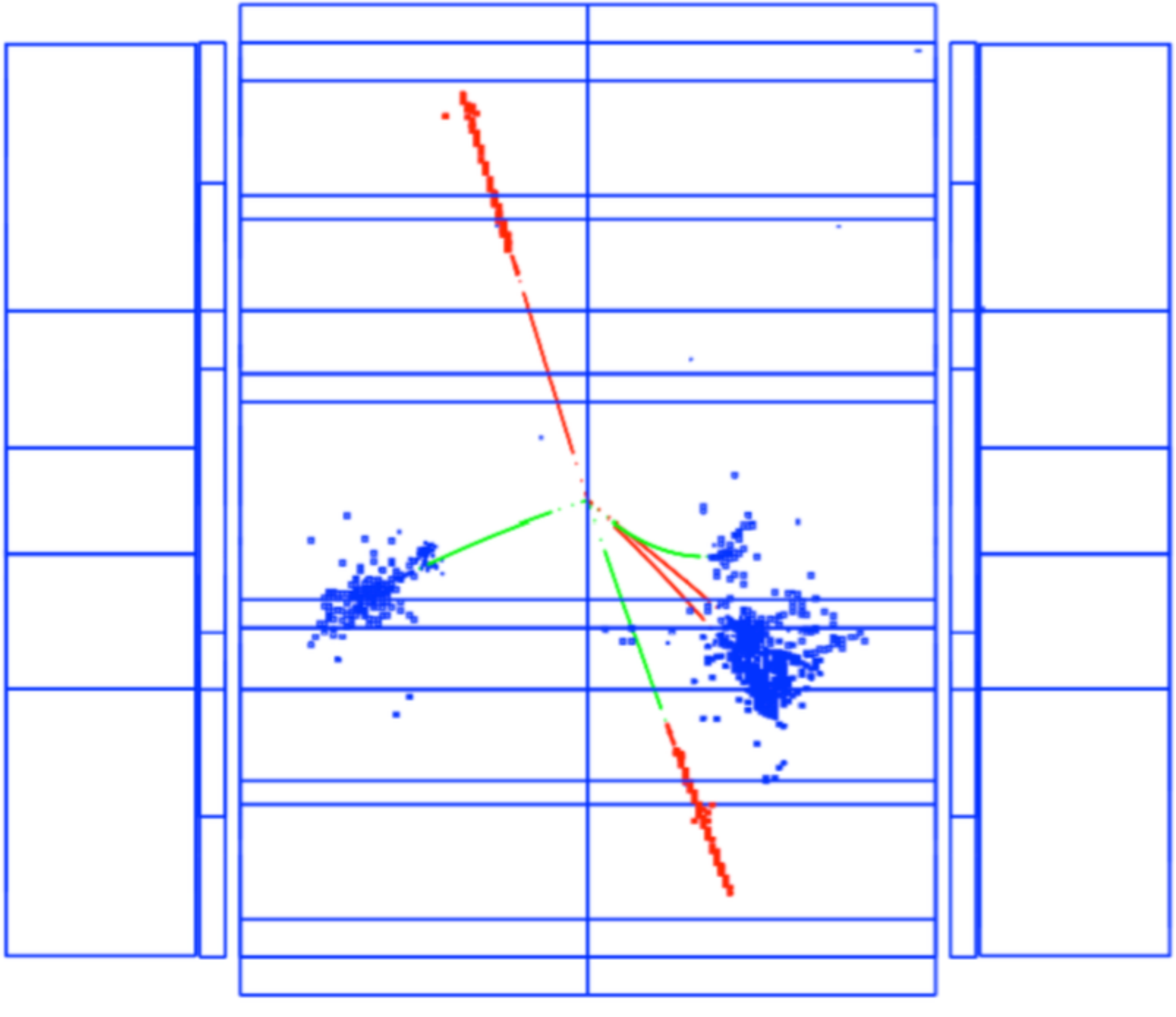
Why do we expect e+e- colliders to overcome these difficulties ?

Higgs events are readily isolated from background.
All standard Higgs decay modes are visible.

Measurement accuracies are such that 1% coupling measurements are feasible.

The absolute cross section for $e^+e^- \to Zh$ can be measured.

At 250 GeV, to first approximation, any Z boson with $E_{lab} = 110\ \mathrm{GeV}$ is recoiling against a Higgs boson.



(thanks to Manqi Ruan)

Proposed 240-250 GeV e+e- colliders with 2 - 5 ab-1 will produce of order 1 million Higgs bosons in the reaction

$$e^+e^- \to Zh$$

This will make it possible to measure Higgs branching ratios directly and carry out deep searches for exotic Higgs decay modes.

To test models of new physics, we would like to have the absolute sizes of Higgs boson coupling constants.

This is trickier.

$$BR(h \to A\overline{A}) = \Gamma(h \to A\overline{A}) \ / \ \Gamma_{h,tot}$$

But, in the Standard Model, $\Gamma_{h,tot} = 4.1 \text{ MeV}$, too small to be measured directly.

To extract $\Gamma_{h,tot}$, we need a theoretical framework, hopefully as model-independent as possible.

In the past year, we have realized that the framework called "Standard Model Effective Field Theory" is an excellent fit to this problem.

The most general effects of new physics are described by dimension-6 operators added to the Standard Model. This is already the standard representation of new physics for tests of the Standard Model at the LHC. Its difficulty is that it has many (~50) free parameters.

The magic is that, at lepton colliders, there are only 17 free parameters. Using the many observables from

precision electroweak, $e^+e^- \to W^+W^-$, Higgs reactions

all of these can be determined to high precision.

Promised measurement accuracies of Higgs couplings, Snowmass 2013 and today (arXiv:1710.07621)

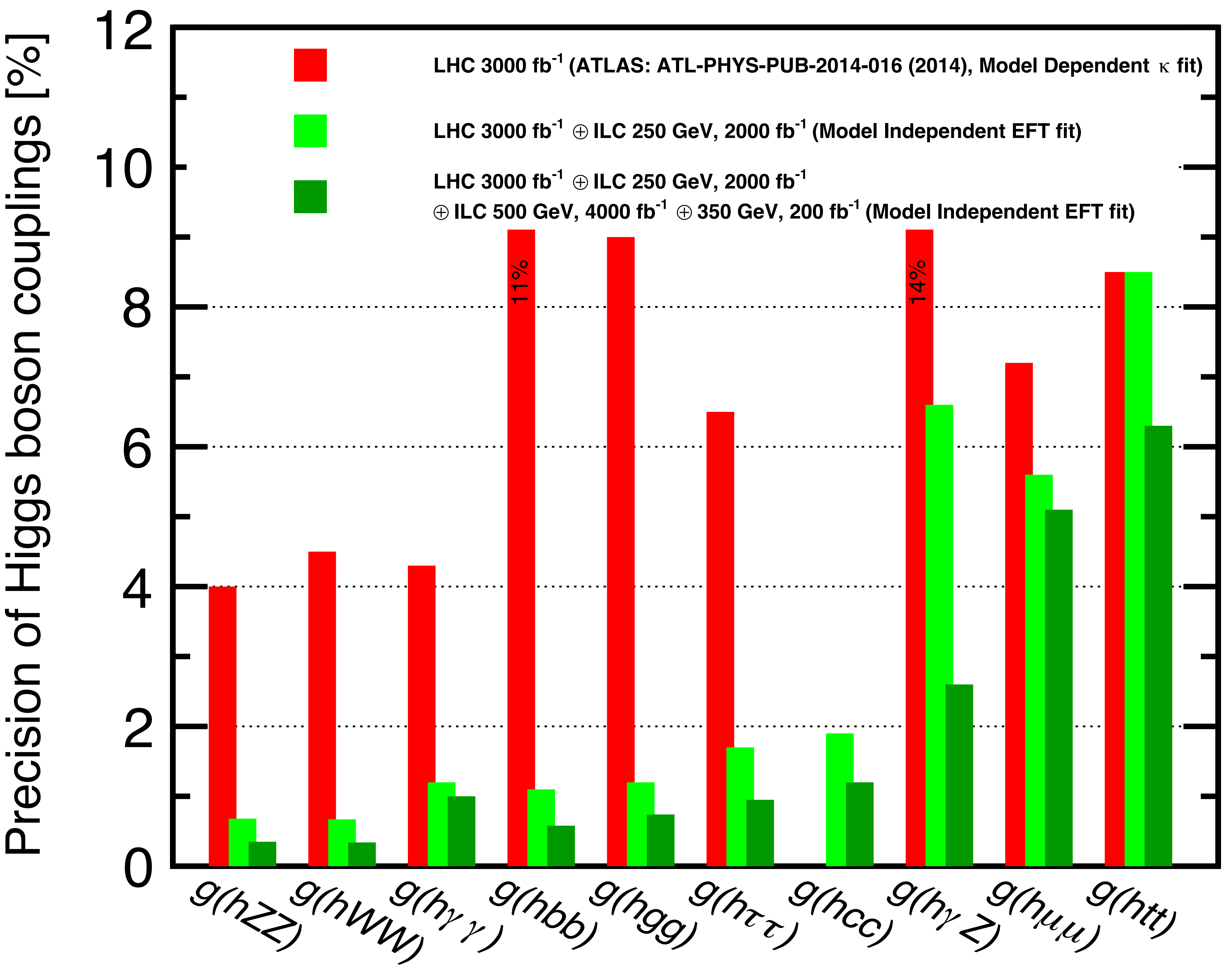
Parameter	Snowmass 2013 : ILC(500)	ILC(LumUp)	this report : 250 GeV	250+500 GeV	units
$g(hb\bar{b})$	1.6	0.7	1.1	0.58	%
$g(hc\bar{c})$	2.8	1.0	1.9	1.2	%
$g(hgg)$	2.3	0.9	1.7	0.95	%
$g(hWW)$	1.1	0.6	0.67	0.34	%
$g(h\tau\tau)$	2.3	0.9	1.2	0.74	%
$g(hZZ)$	1.0	0.5	0.68	0.35	%
$g(ht\bar{t})$	14	1.9	-	6.3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

The new analysis includes new Higgs observables, including the polarization asymmetry of $e^+e^- \to Zh$.
It also benefits from much hard work by the KEK/Tokyo and DESY groups in improving full simulation analyses with the ILD detector.

Here are some final results for various proposed colliders:

	ILC250	CLIC350	CEPC	FCC-ee	ILC250+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
$g(hb\bar{b})$	1.1	1.1	0.98	0.66	0.58
$g(hc\bar{c})$	1.9	2.3	1.4	1.2	1.2
$g(hgg)$	1.7	1.7	1.3	0.99	0.95
$g(hWW)$	0.67	0.56	0.80	0.42	0.34
$g(h\tau\tau)$	1.2	1.4	1.1	0.75	0.74
$g(hZZ)$	0.68	0.57	0.80	0.42	0.35
$g(h\gamma\gamma)$	1.2	1.2	1.3	1.0	1.0
$g(h\mu\mu)$	5.6	5.7	5.1	4.87	5.1
$g(hbb)/g(hWW)$	0.88	0.90	0.58	0.51	0.46
$g(hWW)/g(hZZ)$	0.07	0.06	0.07	0.06	0.05
Γ_h	2.5	2.5	2.1	1.5	1.6
$BR(h \to inv)$	0.32	0.56	0.30	0.27	0.29
$BR(h \to other)$	1.6	1.6	1.1	0.94	1.2

errors in %



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} ⊕ ILC 250 GeV, 2000 fb^{-1} (Model Independent EFT fit)
LHC 3000 fb^{-1} ⊕ ILC 250 GeV, 2000 fb^{-1}
⊕ ILC 500 GeV, 4000 fb^{-1} ⊕ 350 GeV, 200 fb^{-1} (Model Independent EFT fit)
11%
14%
g(hZZ)
g(hWW)
g(hγγ)
g(hbb)
g(hgg)
g(hττ)
g(hcc)
g(hγZ)
g(hμμ)
g(htt)

It is instructive to compare the sensitivity to Higgs couplings to the predicts of BSM models. We approached this in the following way:

We chose a set of BSM models of various types that give substantial deviations in the Higgs couplings but for which the new particles are too heavy to be discovered at HL-LHC.

For each pair of models, including the SM, we computed the $\delta\chi^2$ between the predictions, using the covariance matrix that comes out of our fit.

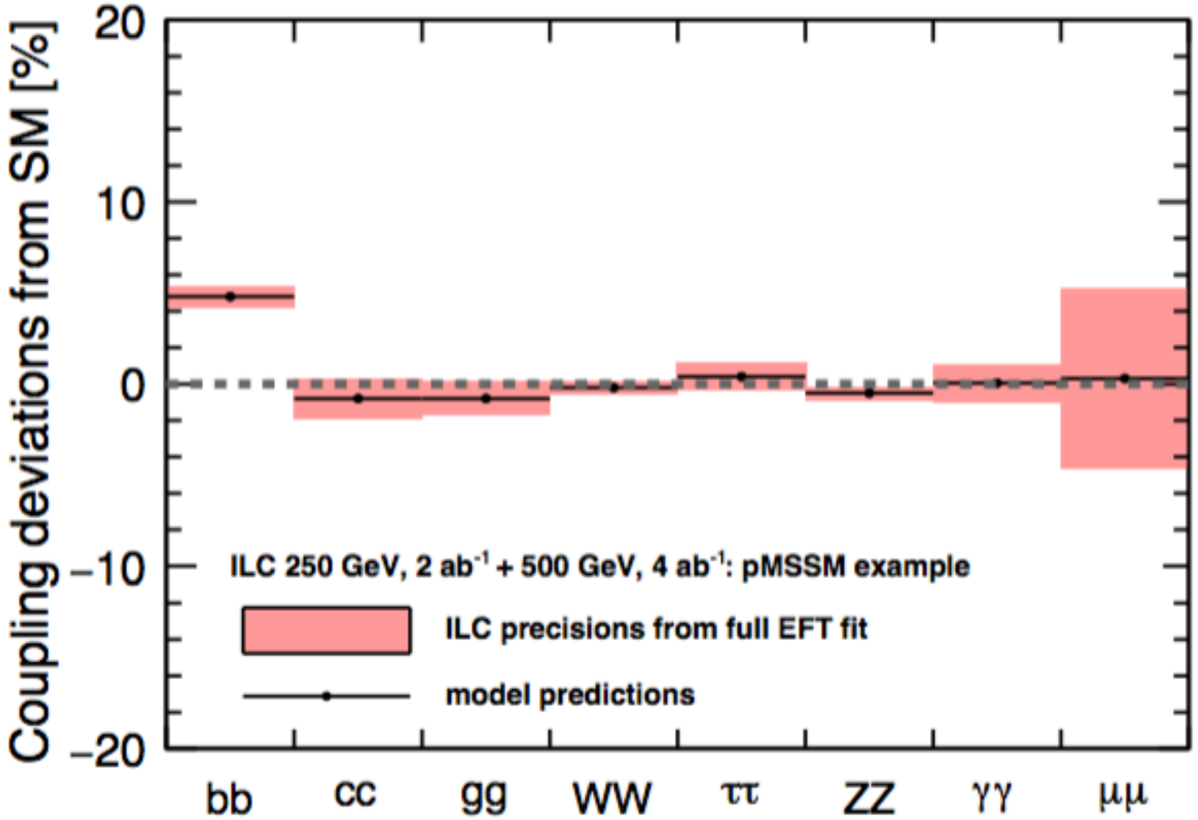
The addresses the question of whether these models can be distinguished from the SM and whether they can be distinguished from one another.

the models:

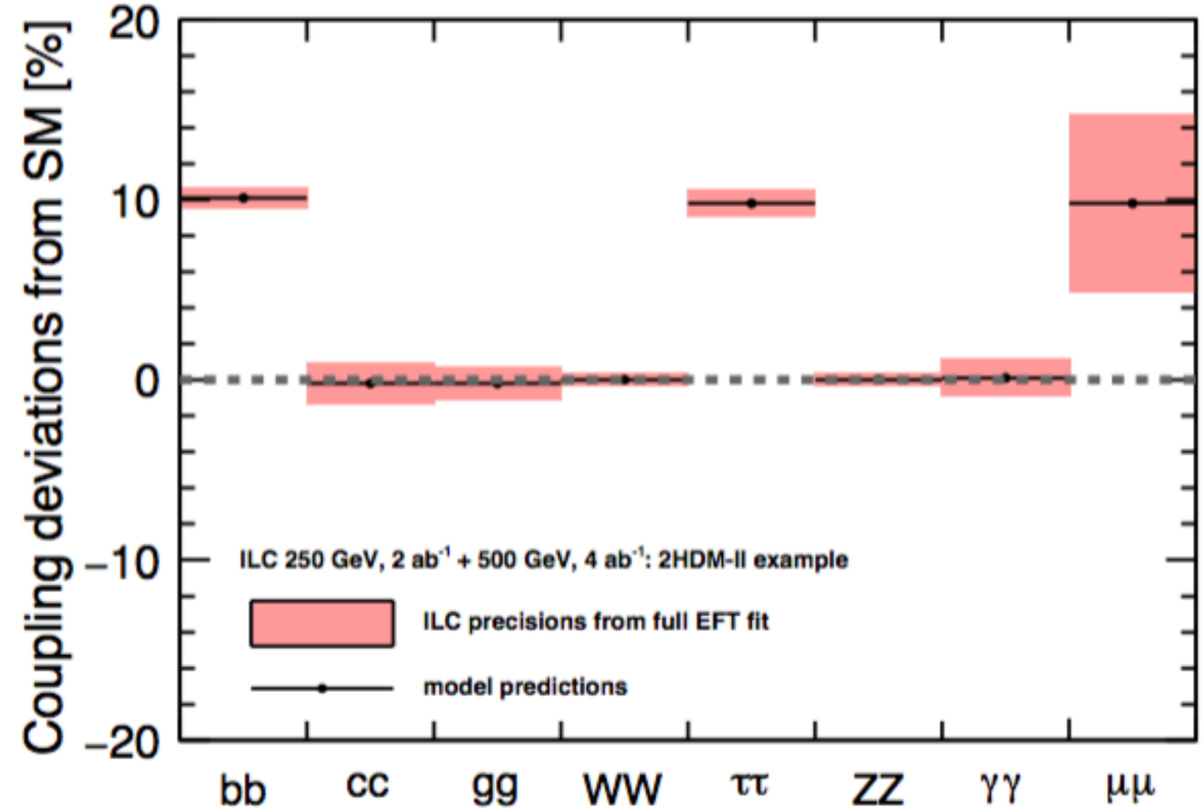
1. PMSSM model with b squarks at 3.4 TeV.
2. Type II 2-Higgs-doublet model with H at 600 GeV
3. Type X 2-Higgs-doublet model with H at 450 GeV
4. Type Y 2-Higgs-doublet model with H at 600 GeV
5. MCHM5 Composite Higgs model, with f = 1.2 TeV
6. Little Higgs model w. T-parity, f = 0.8 TeV
7. Little Higgs 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

These cover the whole range of new physics possibilities.

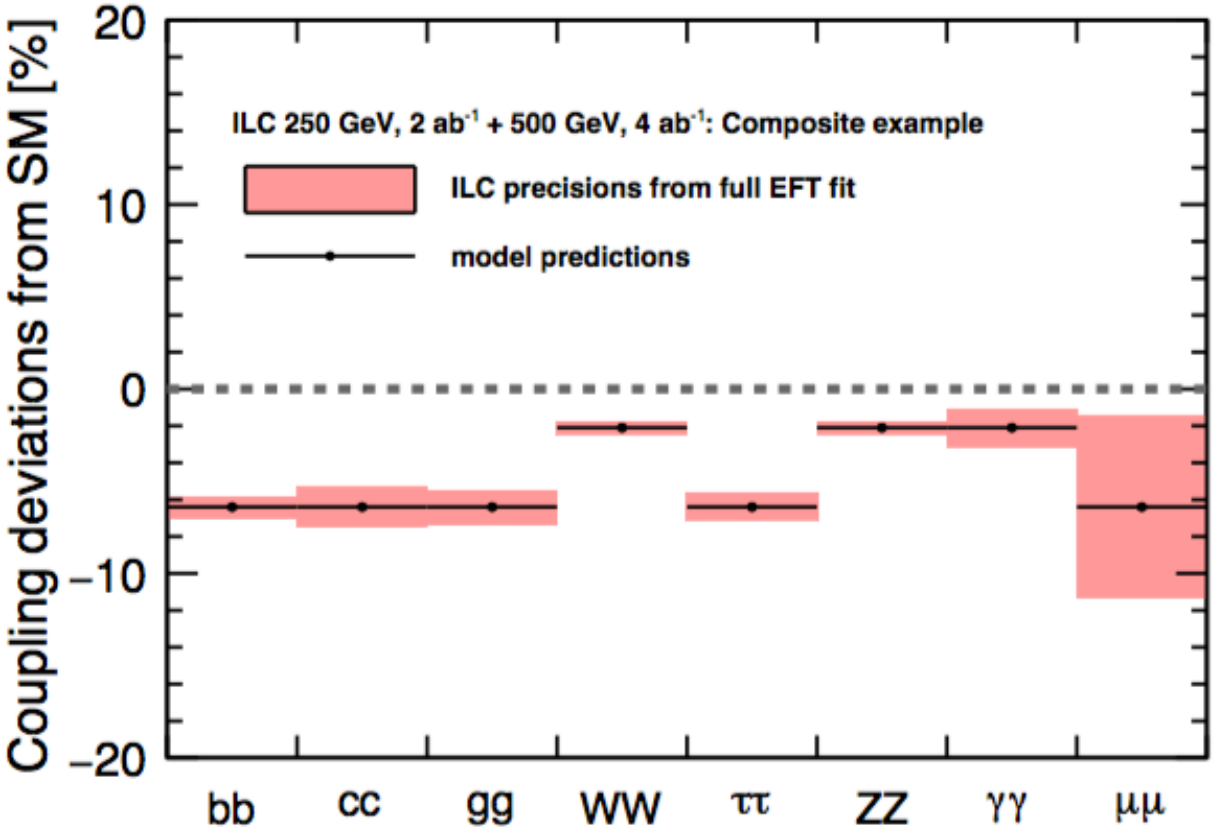
heavy SUSY



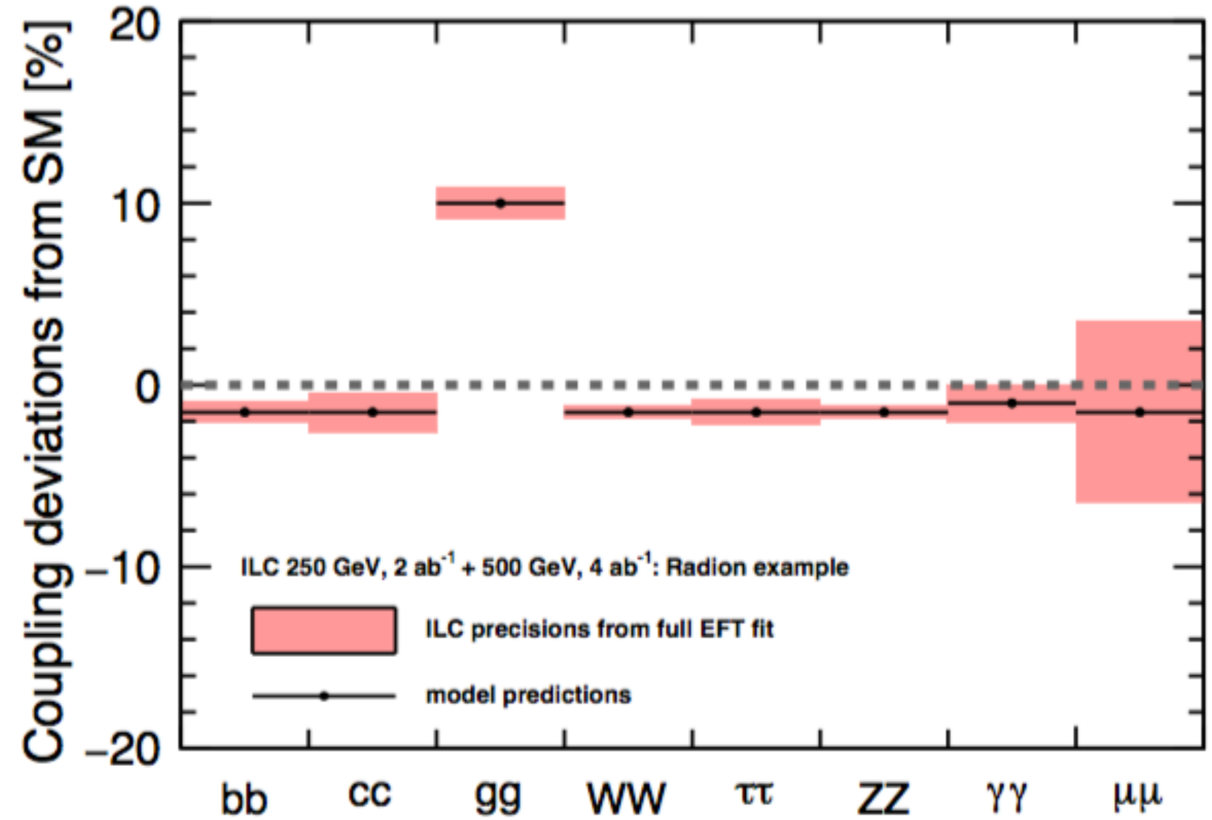
2 Higgs doublet



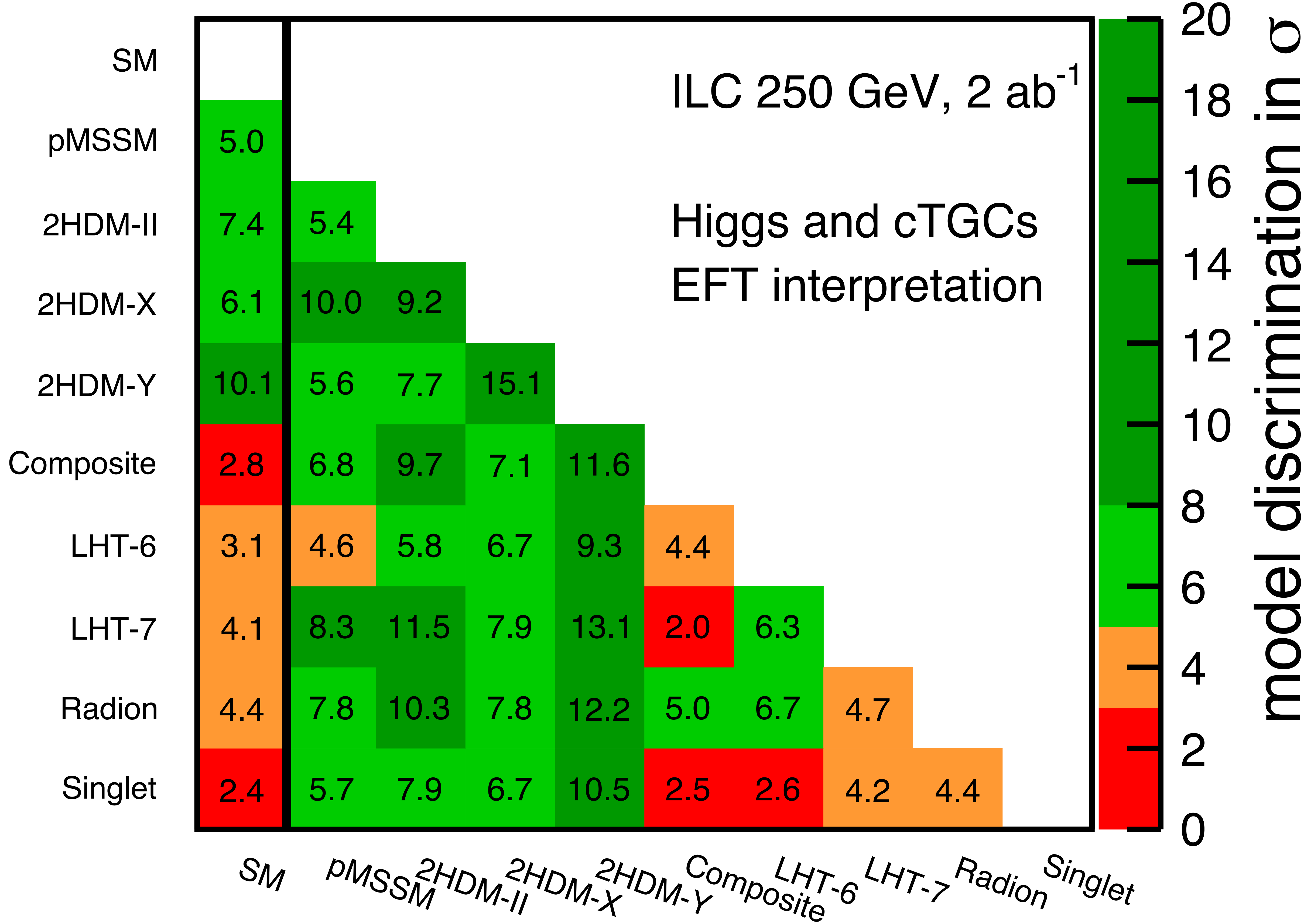
composite Higgs

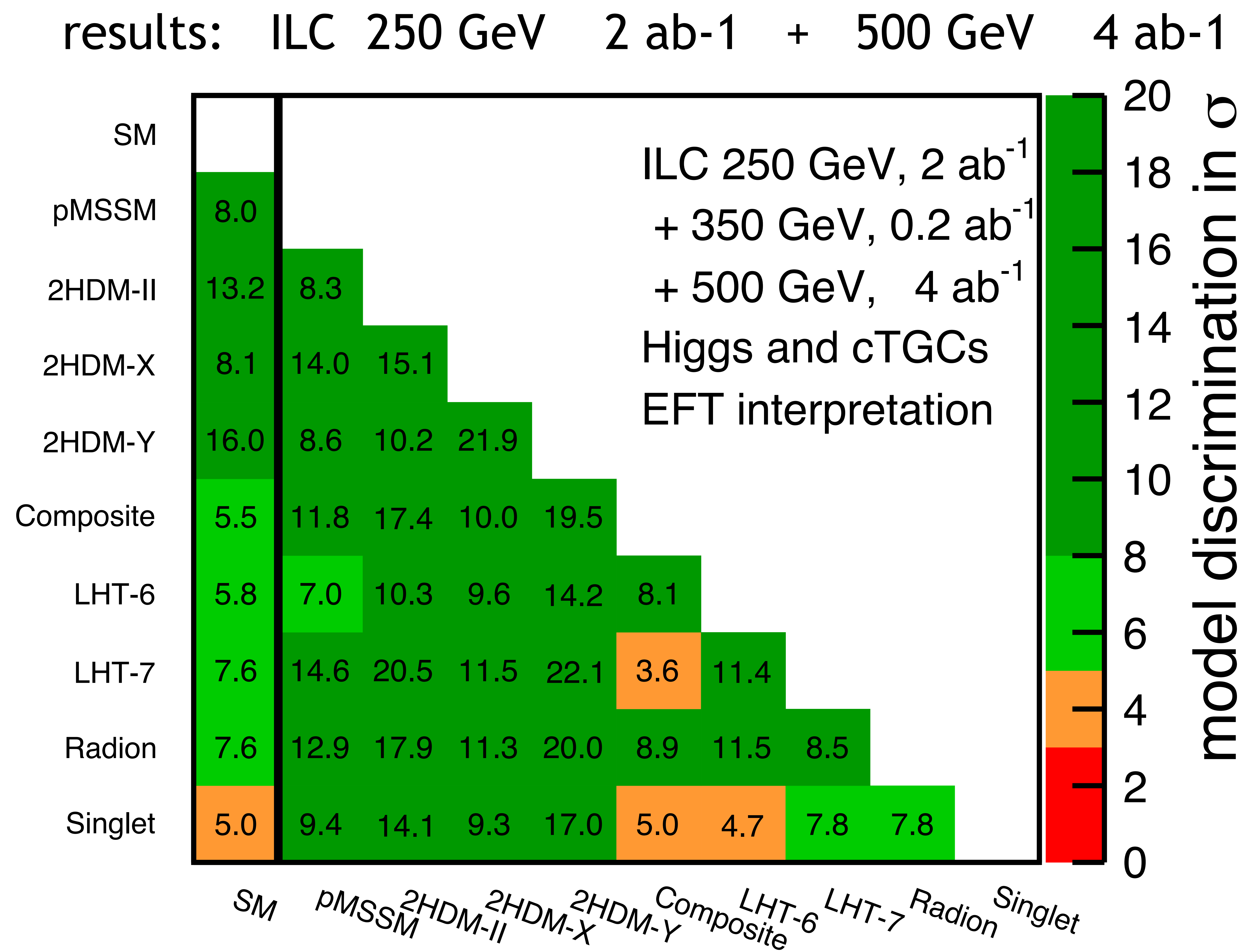


Higgs-Radion mixing



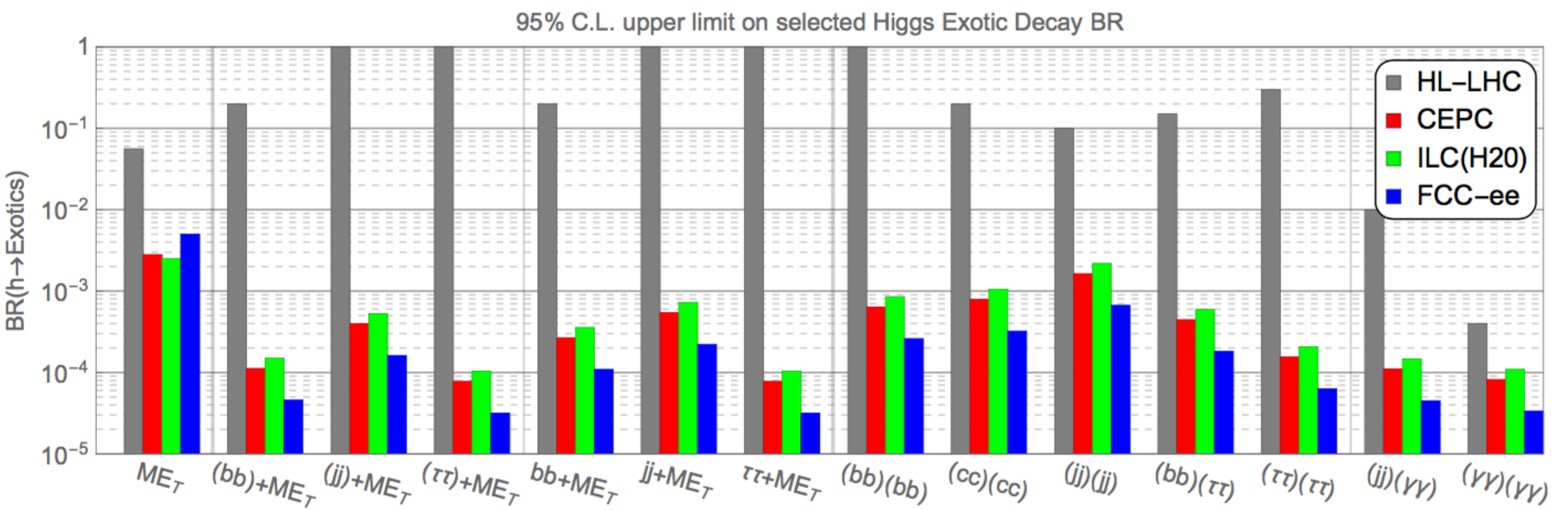
results: ILC 250 GeV 2 ab-1




results: ILC 250 GeV 2 ab-1 + 500 GeV 4 ab-1
ILC 250 GeV, 2 ab^{-1}
+ 350 GeV, 0.2 ab^{-1}
+ 500 GeV, 4 ab^{-1}
Higgs and cTGCs
EFT interpretation
model discrimination in σ
0 2 4 6 8 10 12 14 16 18 20
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
SM pMSSM 2HDM-II 2HDM-X 2HDM-Y Composite LHT-6 LHT-7 Radion Singlet

In addition, we are sensitive to Higgs decays to dark matter or hidden sectors, through the "Higgs" or "neutrino" portal. It is possible to have substantial BRs to completely new sectors with no Standard Model interactions.

Using tagged Higgs decays from $e^+e^- \to Zh$, we can look for the most general exotic decay signals to BRs below 10^{-3} (1000 produced events).

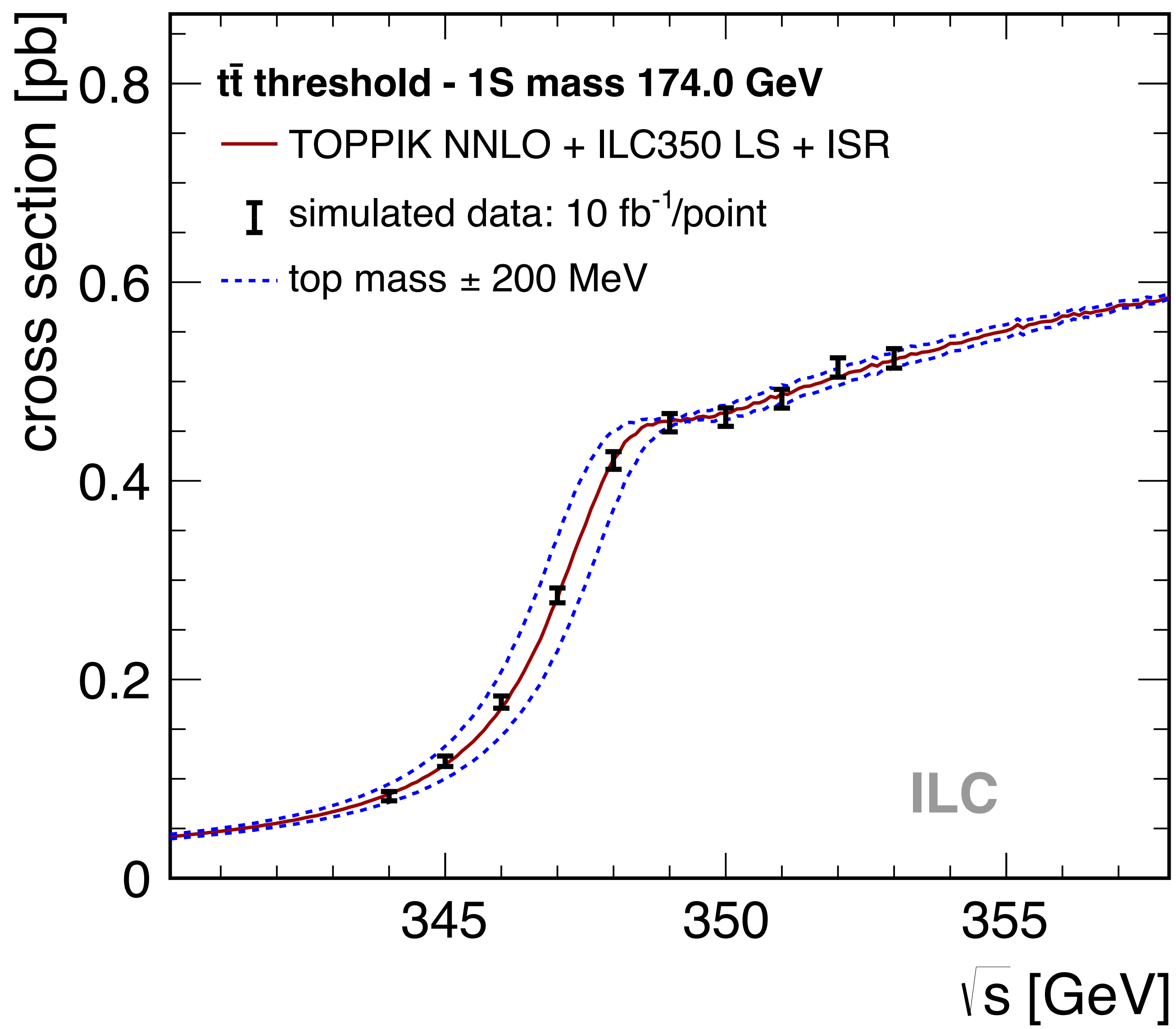


Liu, Wang, and Zhang

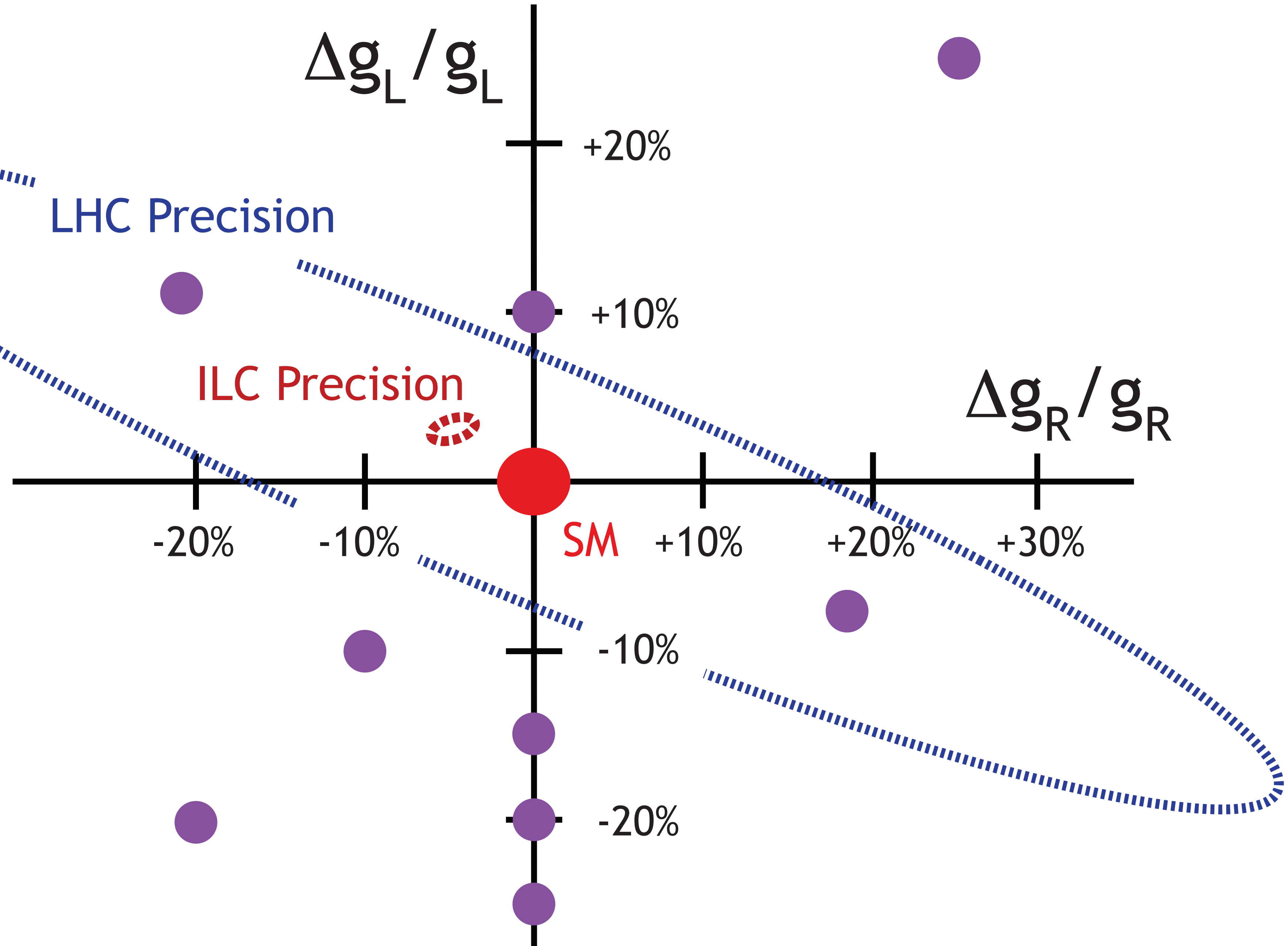
The Higgs program is already available at 250 GeV. Additional physics becomes available at higher energies.

The threshold for $e^+e^- \to t\bar{t}$ is very sharp, allowing a measurement of the top quark mass to 40 MeV (limited by theory uncertainties).

The "1S top mass" is a short-distance quantity, directly useful as input to grand unification, weak interactions, vacuum stability.



Models with composite Higgs bosons typically also have partially composite top quarks. In these models the electroweak couplings of the top quark can have large deviations from the Standard Model expectation.



(expectation for polarized ILC with 4 ab-1 at 500 GeV)

At 500 GeV and above, e+e- colliders can access the reactions

$$e^+e^- \to Zhh \ , \ e^+e^- \to \nu\bar{\nu}hh$$

which are sensitive to the 3-Higgs boson coupling. This gives an opportunity to measure the shape of the Higgs potential.

Models of electroweak baryogenesis expect a deviation of 1.5 - 3 x in this parameter. We expect accuracies

ILC	27%	(500 GeV, 4 ab-1)
CLIC	19%	(1.4 TeV, 1.5 ab-1 + 3 TeV 2 ab-1)

We have argued (arXiv:1708.09079) that the interpretation of the observables in terms of a change in the triple Higgs coupling is unambiguous at e+e- colliders, in a way that is not possible at hadron colliders.

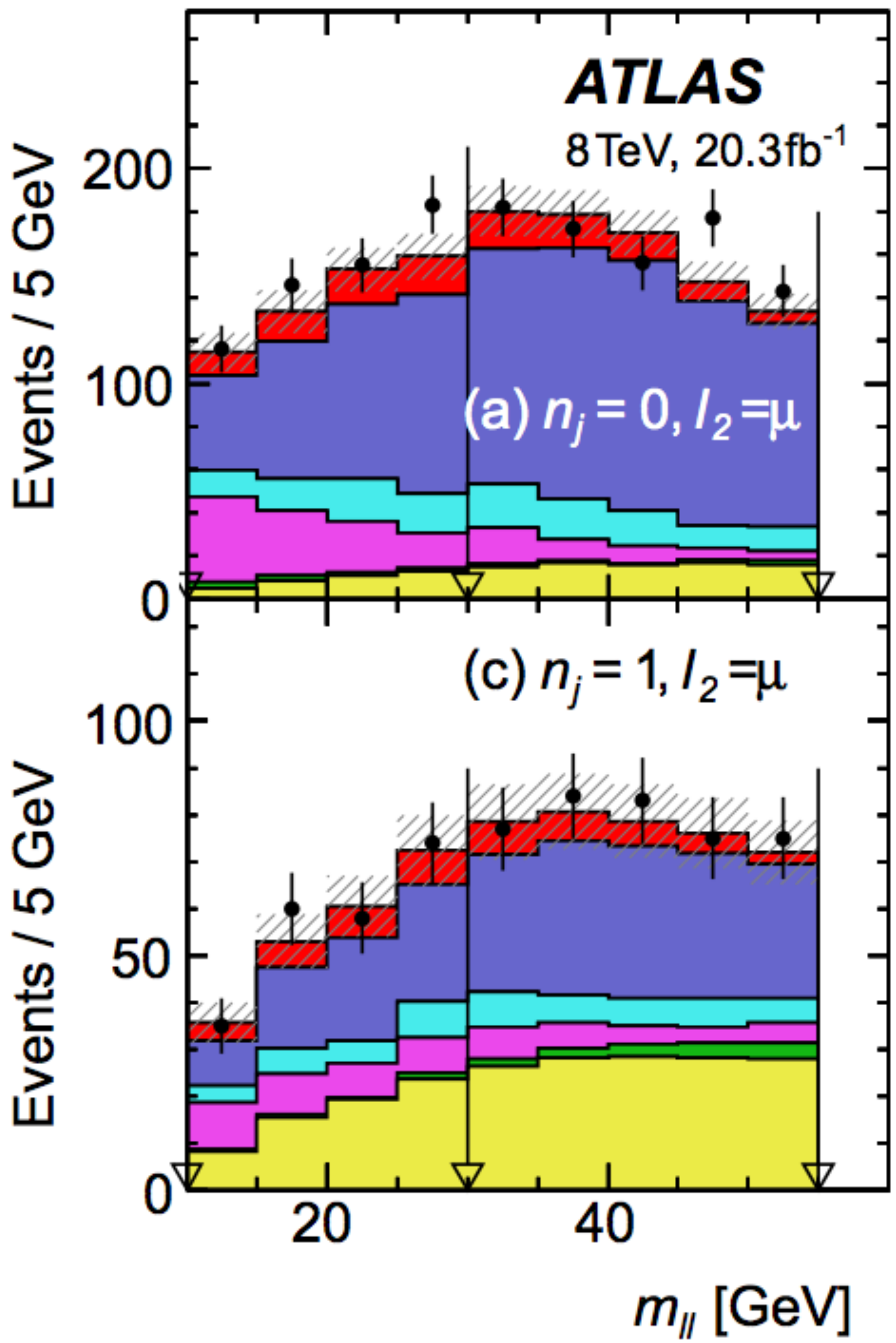
The precision study of the Higgs boson and top quark at e+e- colliders gives a new way to search for new fundamental interactions. This technique can access models inaccessible to the LHC.

We must now find a way to finance and carry out these measurements.

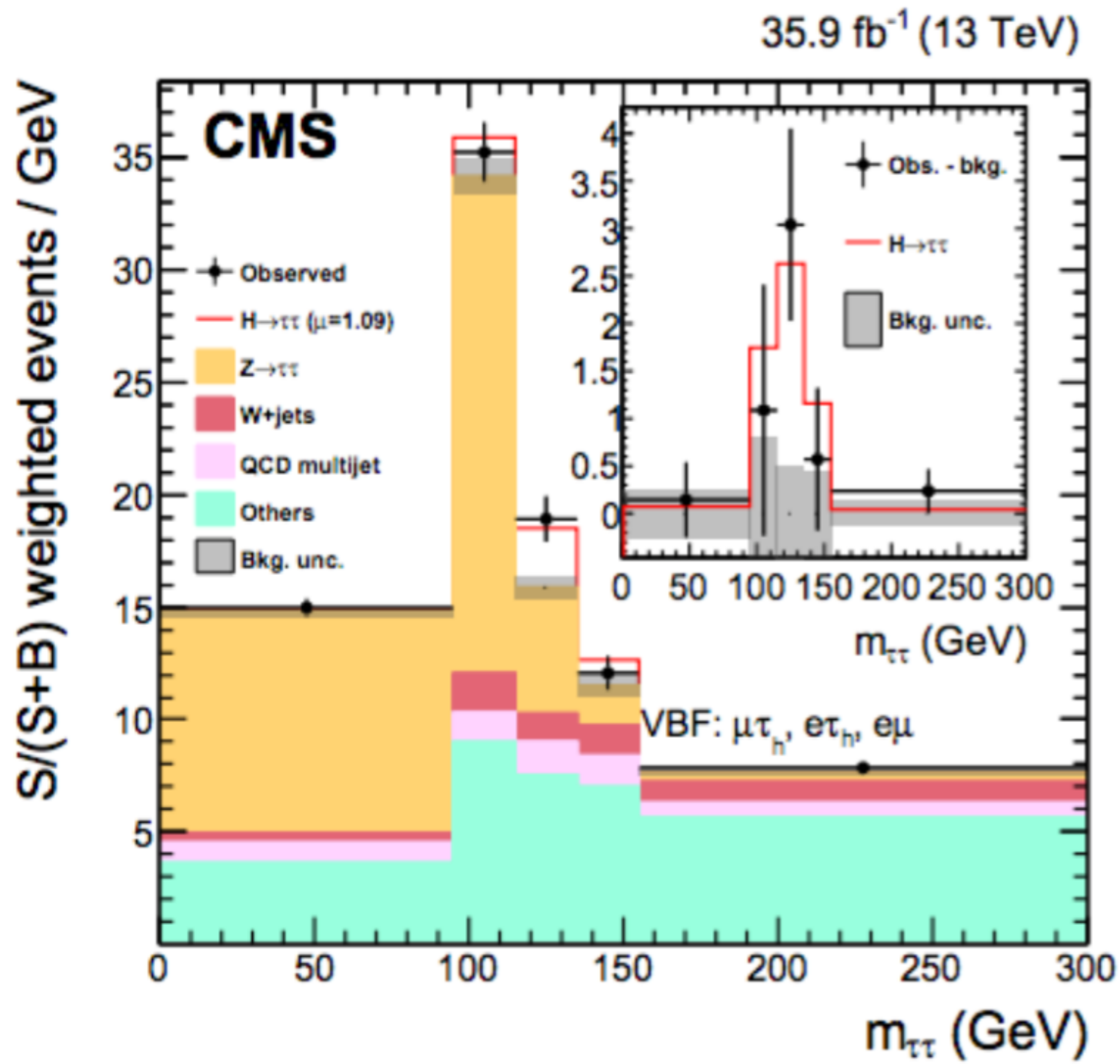
Backup Slides

examples of Higgs observation at LHC:

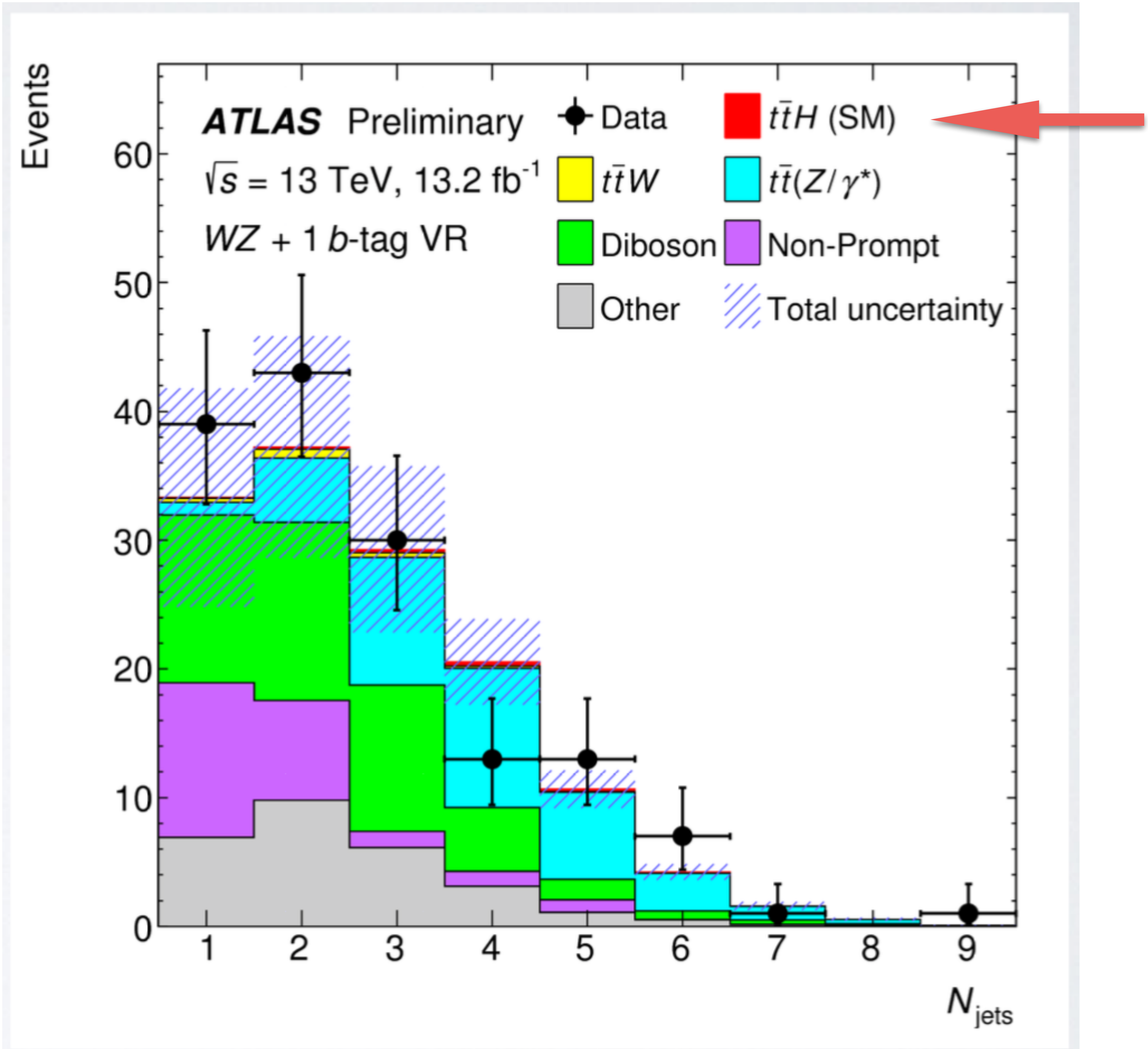
$$h \to W^+W^-$$



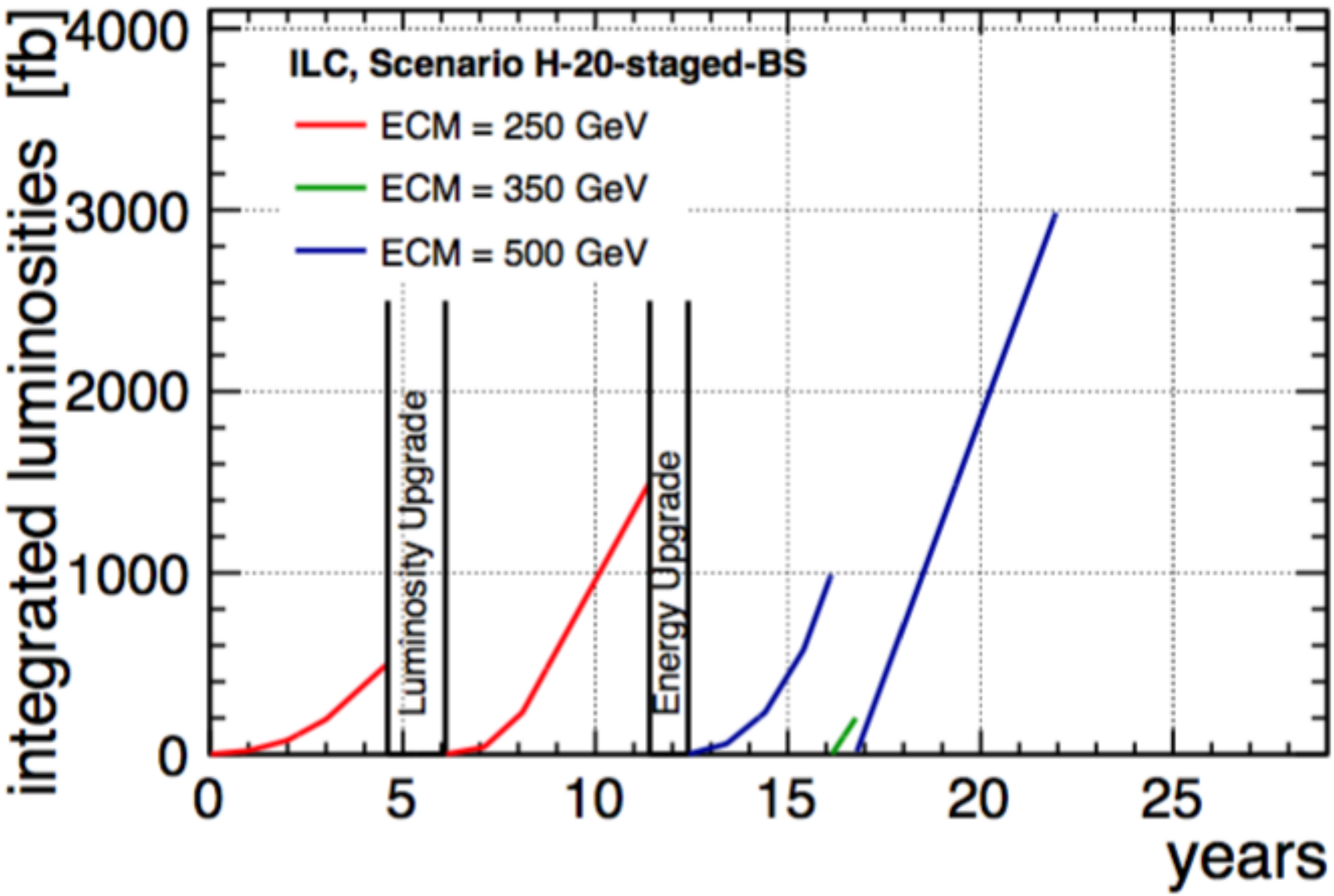
$$h \to \tau^+\tau^-$$



from Giulia Zanderighi's talk this morning:



Integrated Luminosities [fb]



Polarization-dependence of Higgs coupling measurements at 250 GeV

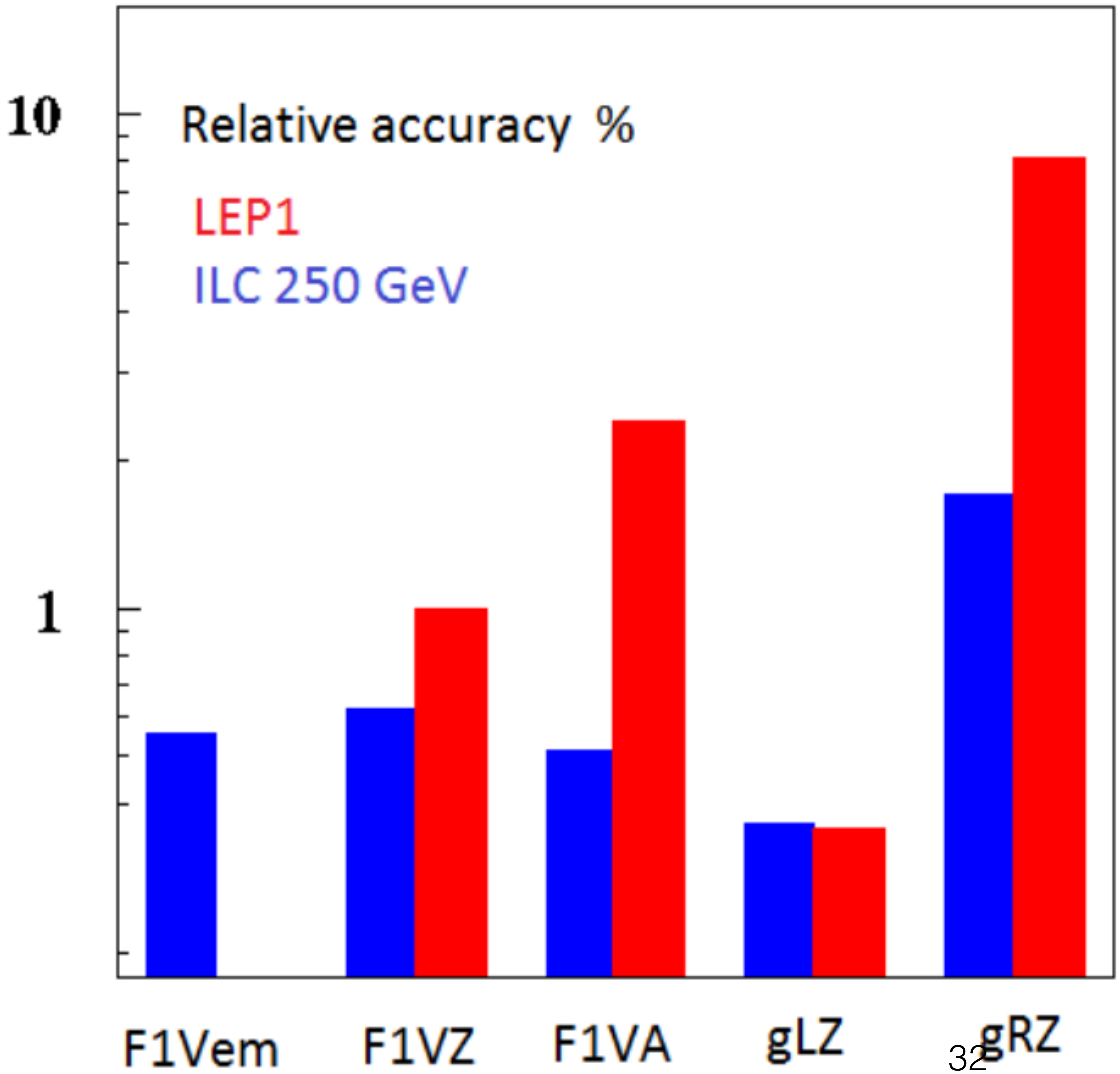
	no pol.	80%/0%	80%/30%
$g(hbb)$	1.3	1.1	1.1
$g(hcc)$	2.1	2.0	1.9
$g(hgg)$	1.9	1.8	1.7
$g(hWW)$	0.98	0.68	0.67
$g(h\tau\tau)$	1.5	1.3	1.2
$g(hZZ)$	0.97	0.69	0.68
$g(h\gamma\gamma)$	1.4	1.2	1.2
$g(h\mu\mu)$	5.7	5.6	5.6
$g(h\gamma Z)$	14	6.7	6.6
$g(hbb)/g(hWW)$	0.91	0.91	0.86
$g(h\tau\tau)/g(hWW)$	1.1	1.1	1.0
$g(hWW)/g(hZZ)$	0.07	0.07	0.07
Γ_h	2.9	2.6	2.5
$BRh \to inv$	0.36	0.33	0.32
$BRh \to other$	1.7	1.7	1.6

ILC, 250 GeV, 2 ab-1

Coupling deviations in the 9 models (in %):

	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

Measurement of the b quark electroweak form factors in $e^+e^- \to b\bar{b}$ at 250 GeV.



Bilokhin, Poeschl, Richard, arXiv:1709.04289

accuracies in %