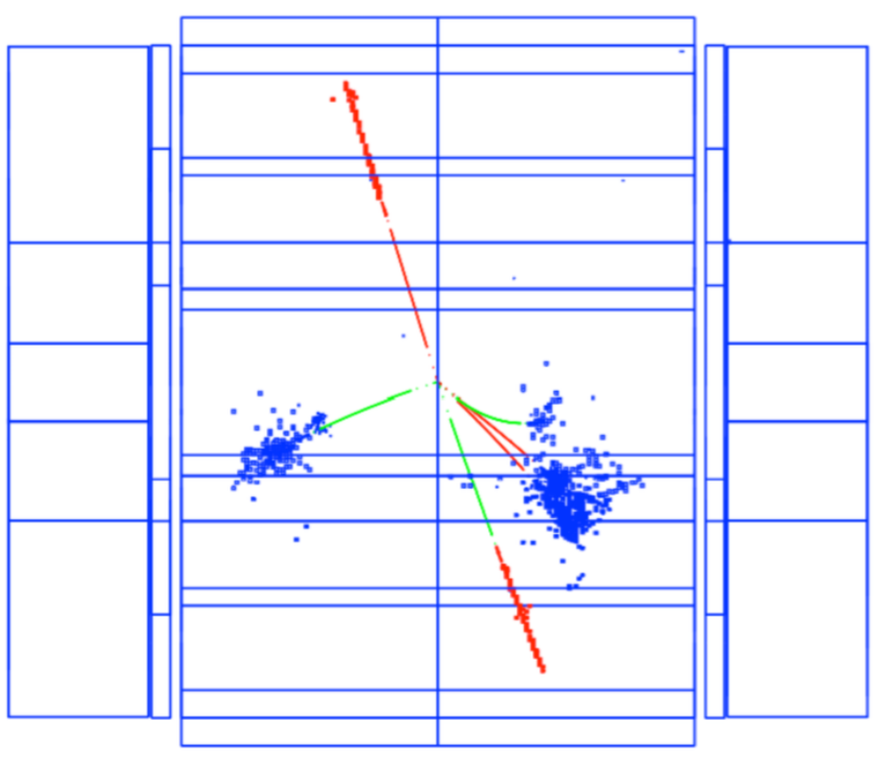
# Physics at Future Lepton Colliders



M. E. Peskin
Pheno 2018

For many members of the current generation, the word "collider" is synonymous with "hadron collider".

Of course, e+e- colliders have a glorious past:

discovery of charm, τ, gluon
precision electroweak constraints on new physics

I will argue here that they have an equally important role in our future.

Our problem: 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 BSM particles 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 we have not yet begun to exploit:

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.

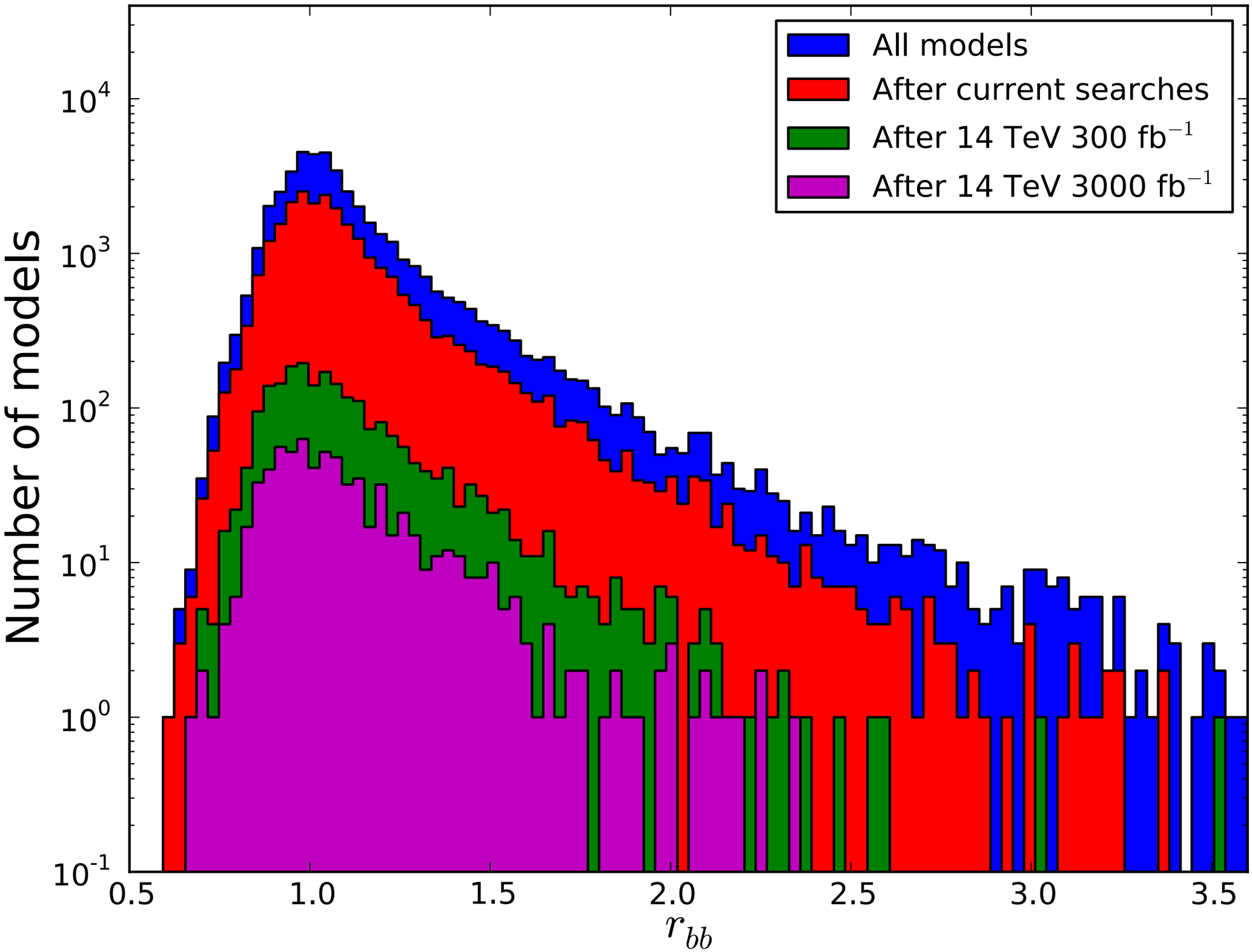
the ugly:

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

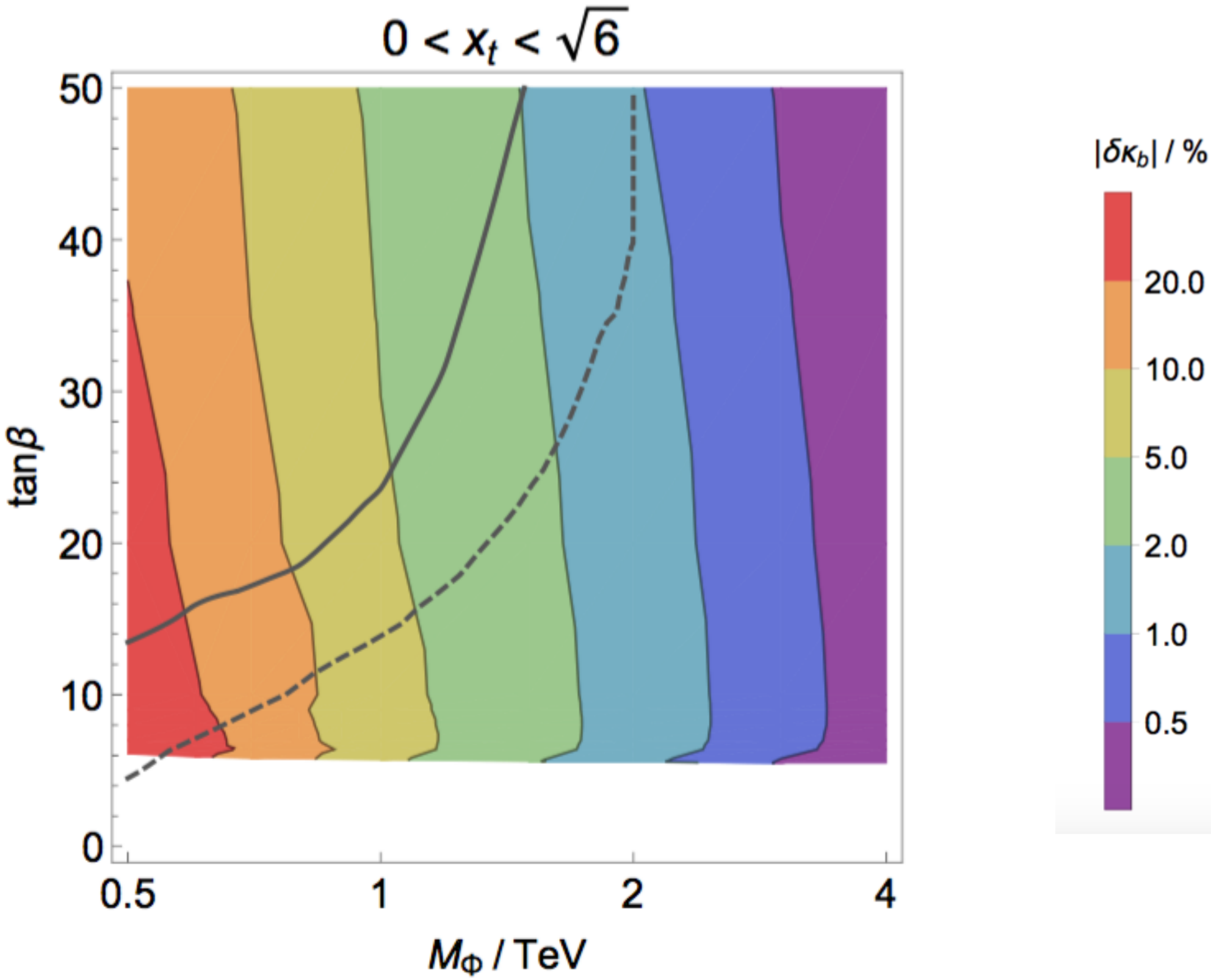
$$m_h^2/M^2$$

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.

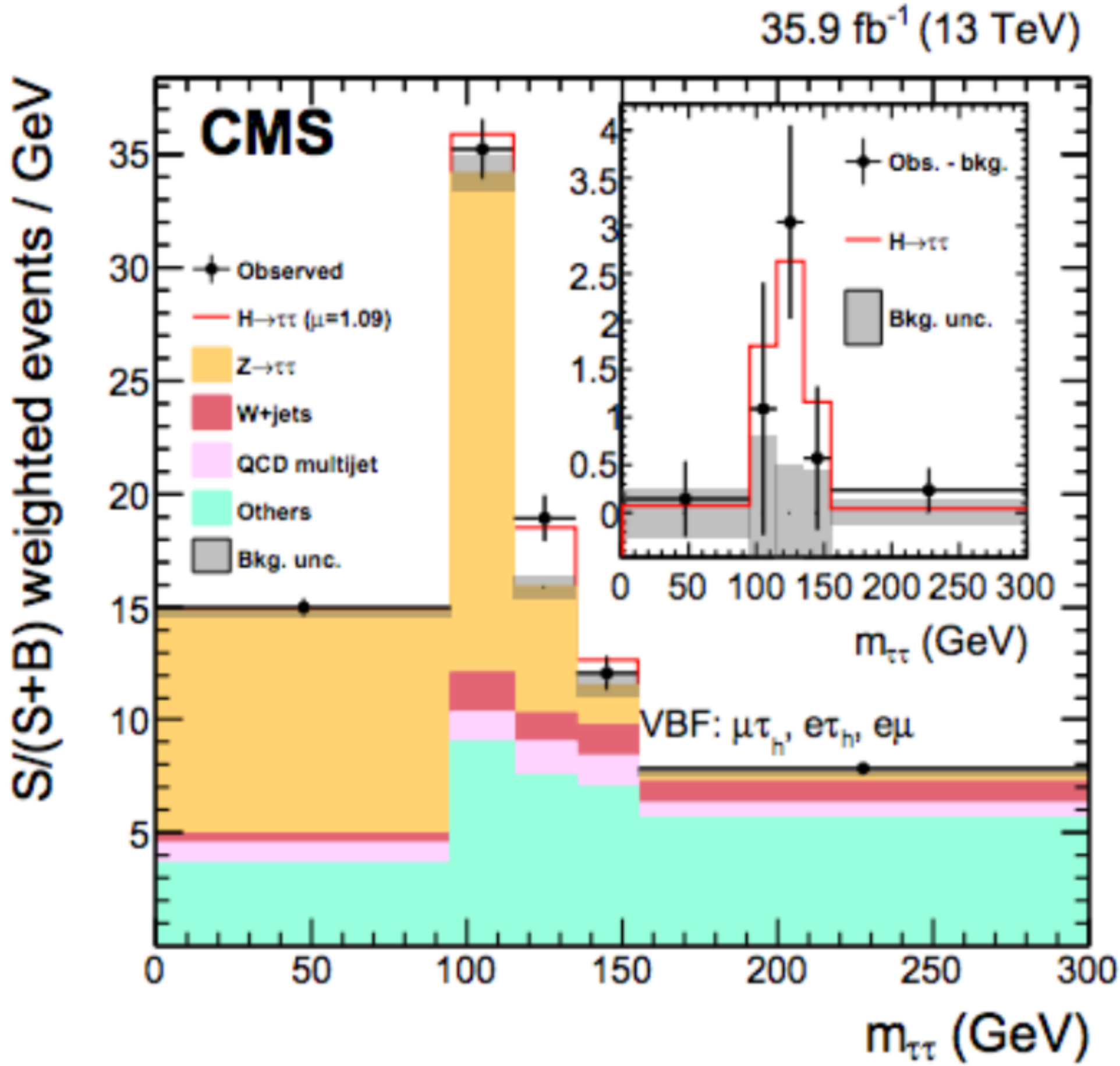
Lockyer (quoted in Physics Today):

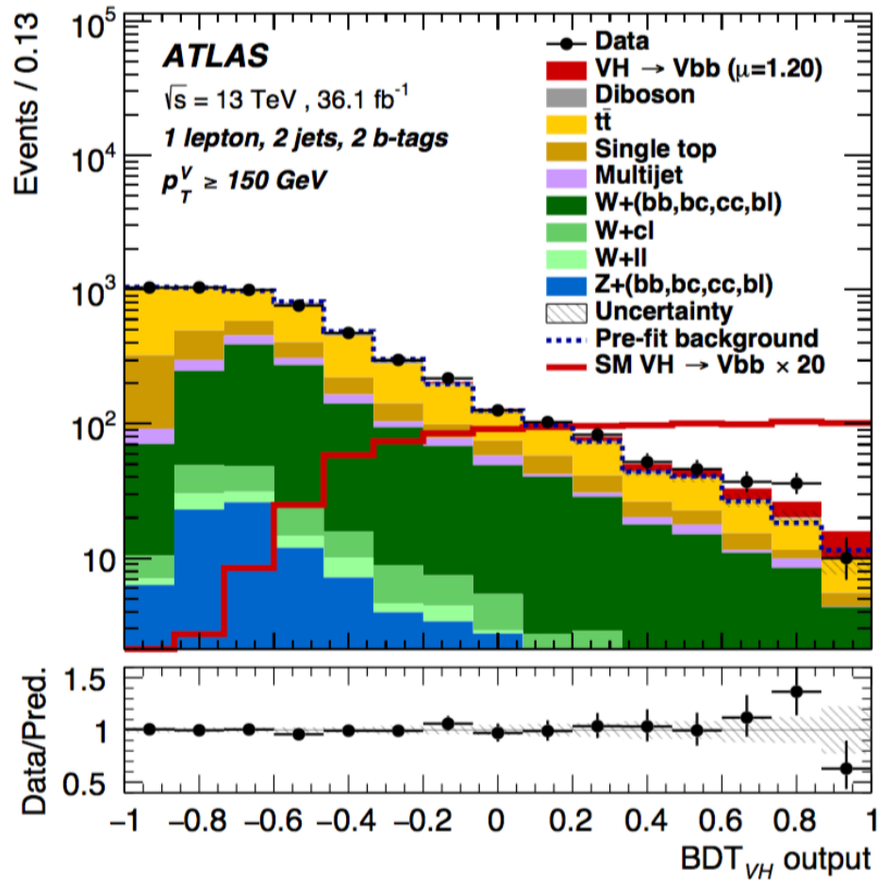
You would be nuts not to study the heck out of the Higgs.

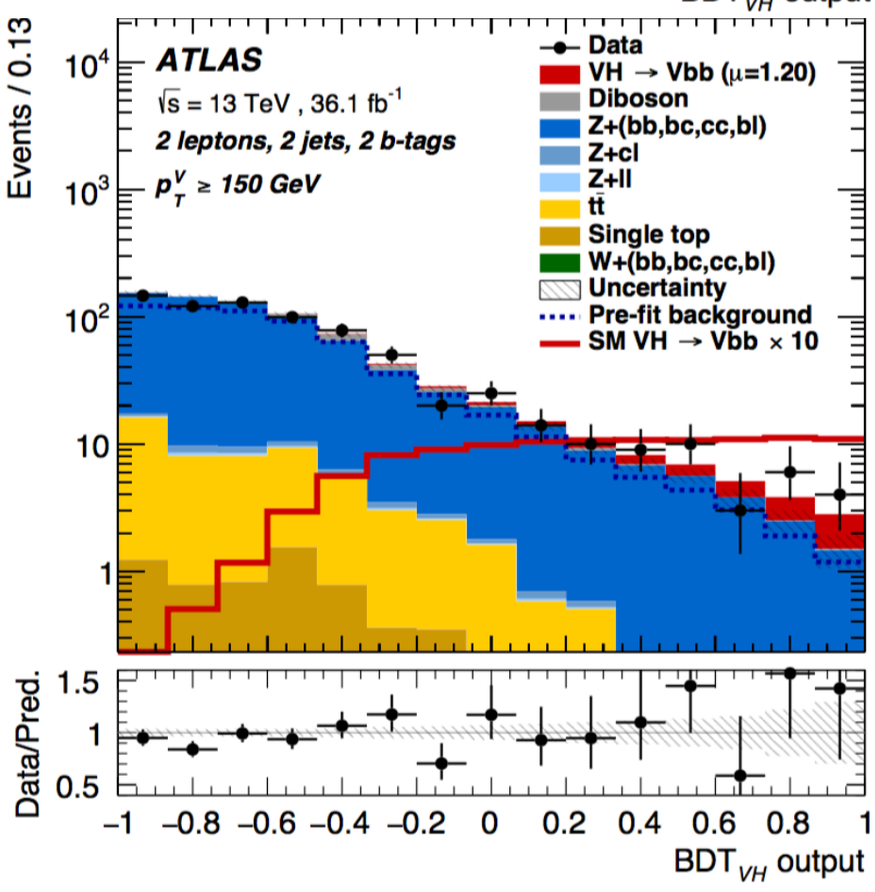
Current errors on Higgs couplings at LHC at 20-30%.

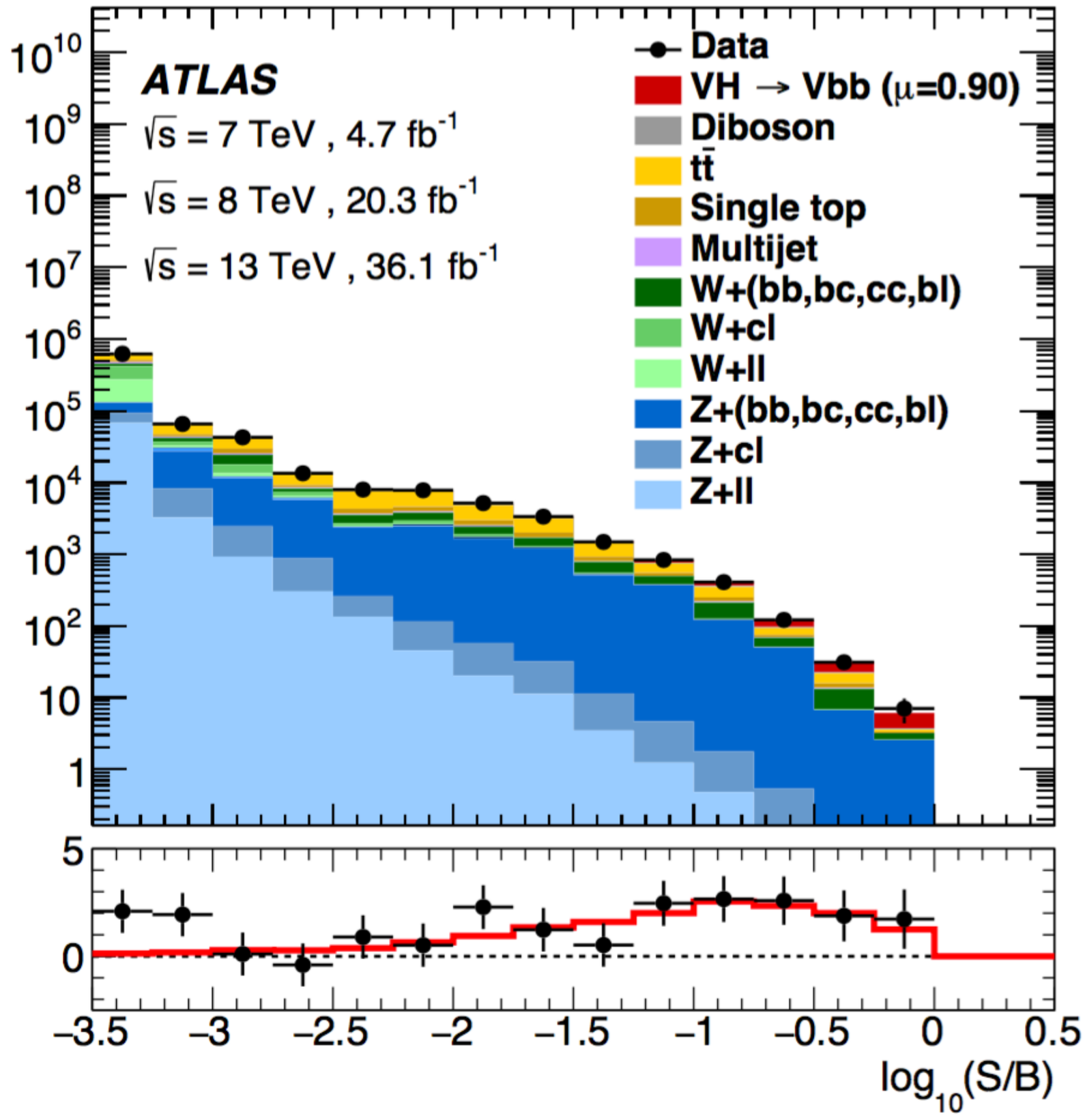
BSM models predict effects of 5-10% at best. So, we are not yet in the game at LHC.

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


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
pTV ≥ 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.
BDTVH output


ATLAS
√s = 13 TeV , 36.1 fb-1
2 leptons, 2 jets, 2 b-tags
pTV ≥ 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.
BDTVH 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)

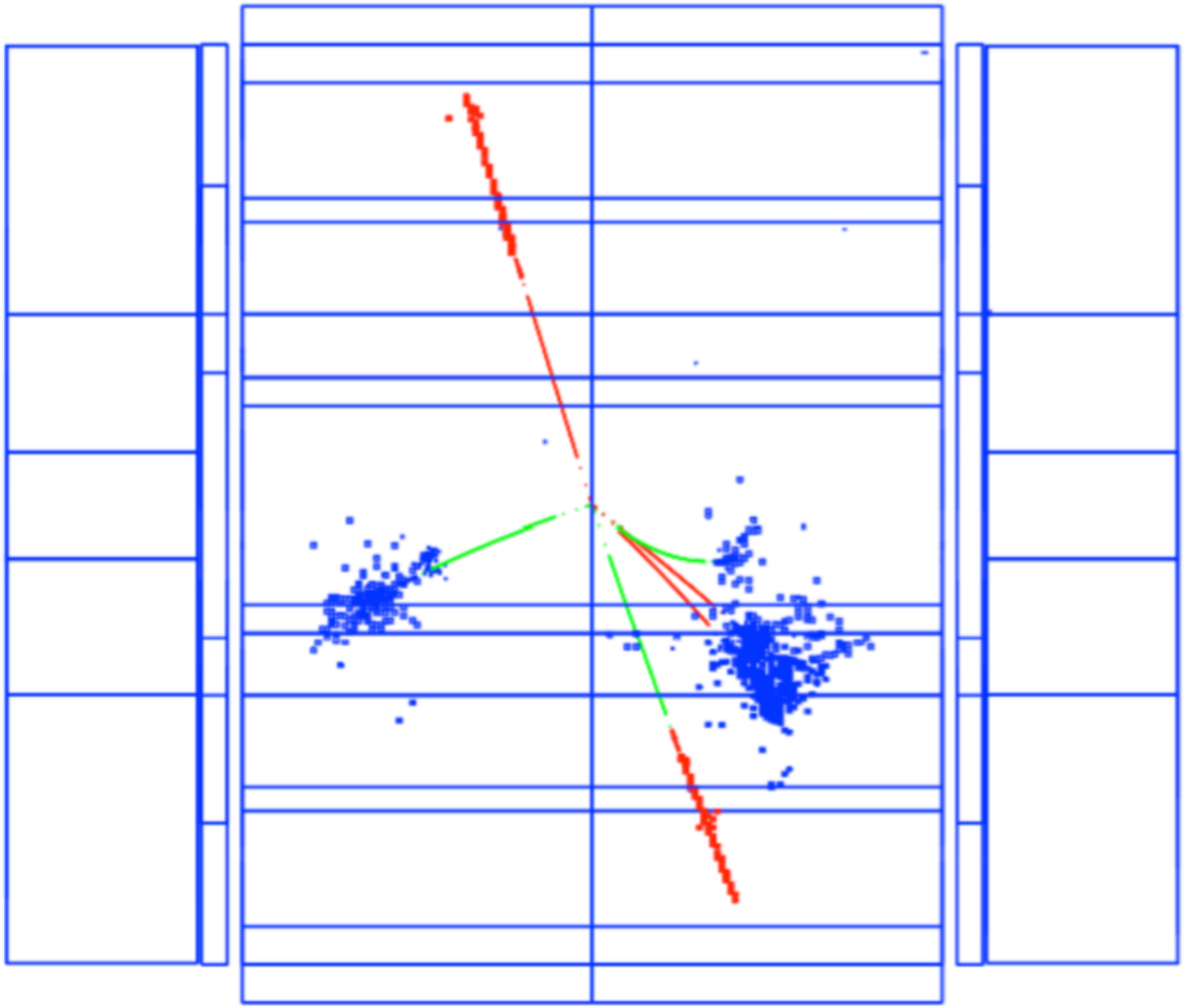
To study the Higgs with high precision, we need a different experimental technique.

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.

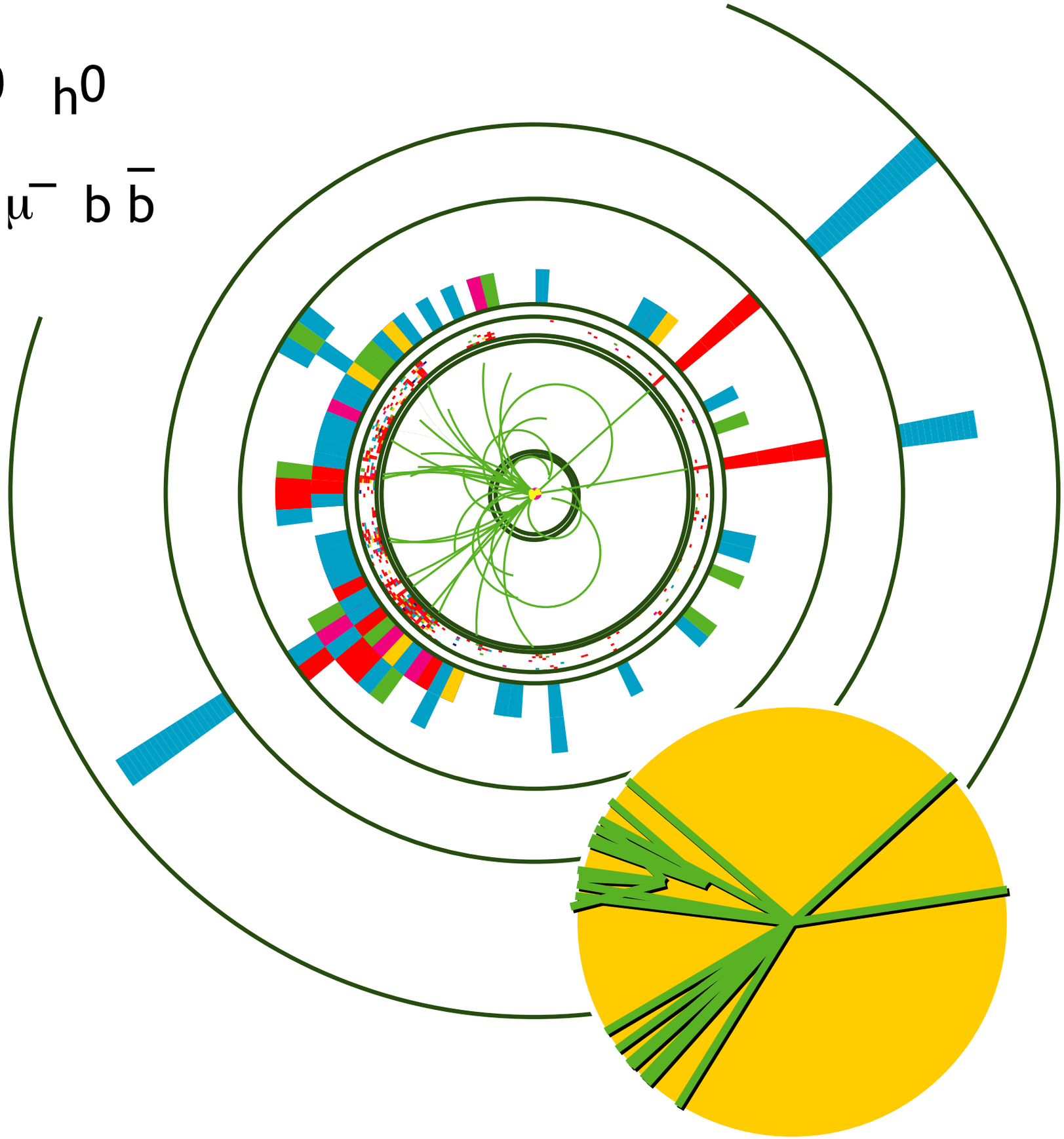
Measurement of the total cross section gives an absolute, model-independent, normalization of Higgs couplings.



(thanks to Manqi Ruan)

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

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



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 $e^+e^- \to Zh$

$$\Delta\mathcal{L} = \frac{c_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi) + \frac{c_T}{2v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi)$$

Higgs Z factor

$$-\frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3$$

triple Higgs

$$+\frac{g^2 c_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}W^{a\mu\nu} + \frac{4gg' c_{WB}}{m_W^2}\Phi^\dagger t^a\Phi W^a_{\mu\nu}B^{\mu\nu}$$

$$+\frac{g'^2 c_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g^3 c_{3W}}{m_W^2}\epsilon_{abc}W^a_{\mu\nu}W^{b\nu}{}_\rho W^{c\rho\mu}$$

h + W,Z,γ

$$+i\frac{c_{HL}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu L) + 4i\frac{c'_{HL}}{v^2}(\Phi^\dagger t^a \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu t^a L)$$

$$+i\frac{c_{HE}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{e}\gamma_\mu e)\ .$$

Precision EW

$$-\sum_i\left\{c_{\ell i\Phi}\frac{y_\tau \ell i}{v^2}(\Phi^\dagger\Phi)\overline{L}_i\cdot\Phi\,\ell_{iR} + c_{qi\Phi}\frac{y_\tau qi}{v^2}(\Phi^\dagger\Phi)\overline{Q}_i\cdot\Phi\,q_{iR}\right\}$$

$$+\mathcal{A}\frac{h}{v}G_{\mu\nu}G^{\mu\nu}\ .$$

h + q, l, g

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

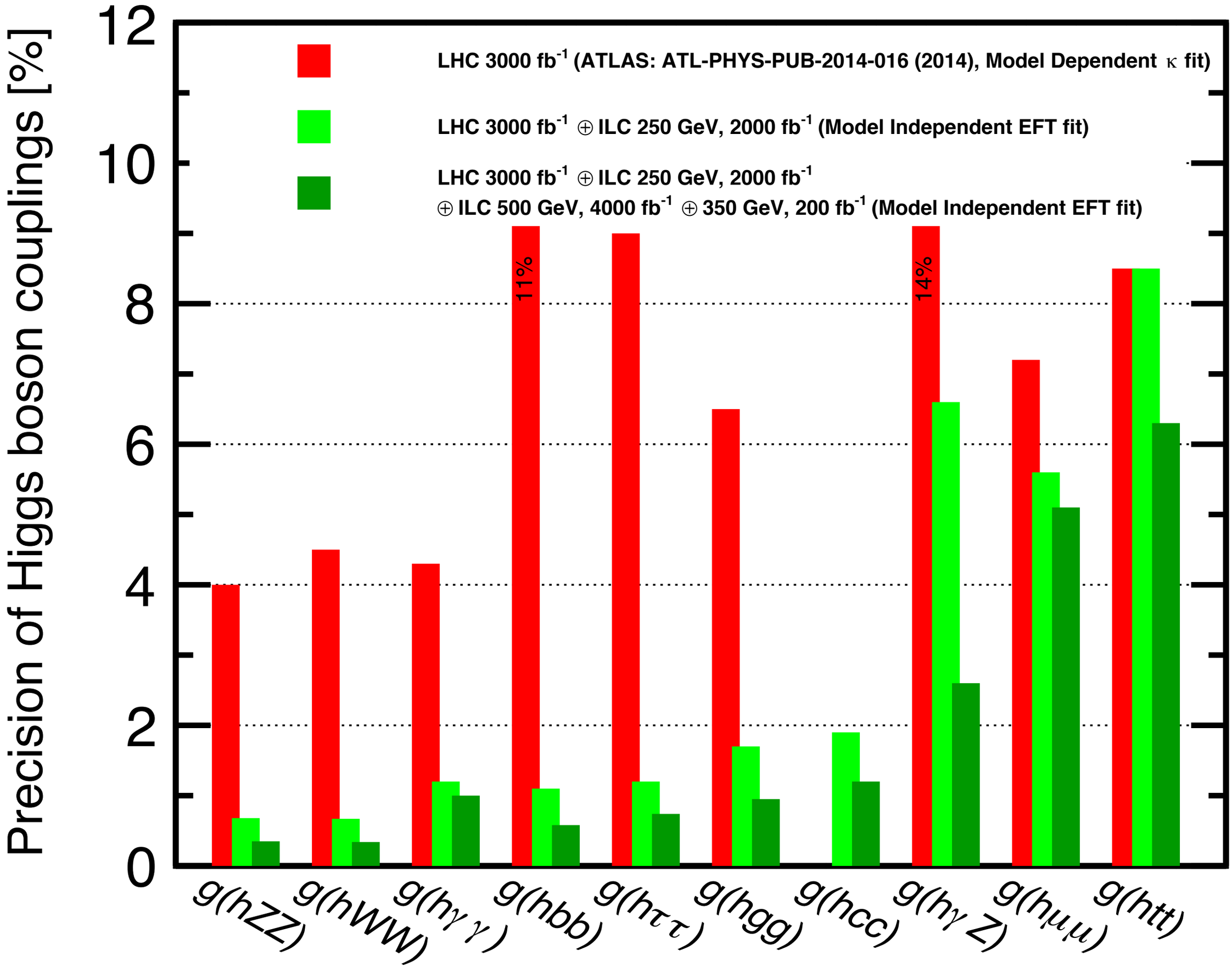
compare this analysis with ILC Higgs white paper for Snowmass 2013: (also reflects improved full-sim analyses by the KEK and DESY groups)

| | 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 | % |
| $\Gamma_{tot}$ | 4.9 | 2.3 | 2.5 | 1.6 | % |

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 |
| $\Gamma_h$ | 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 |

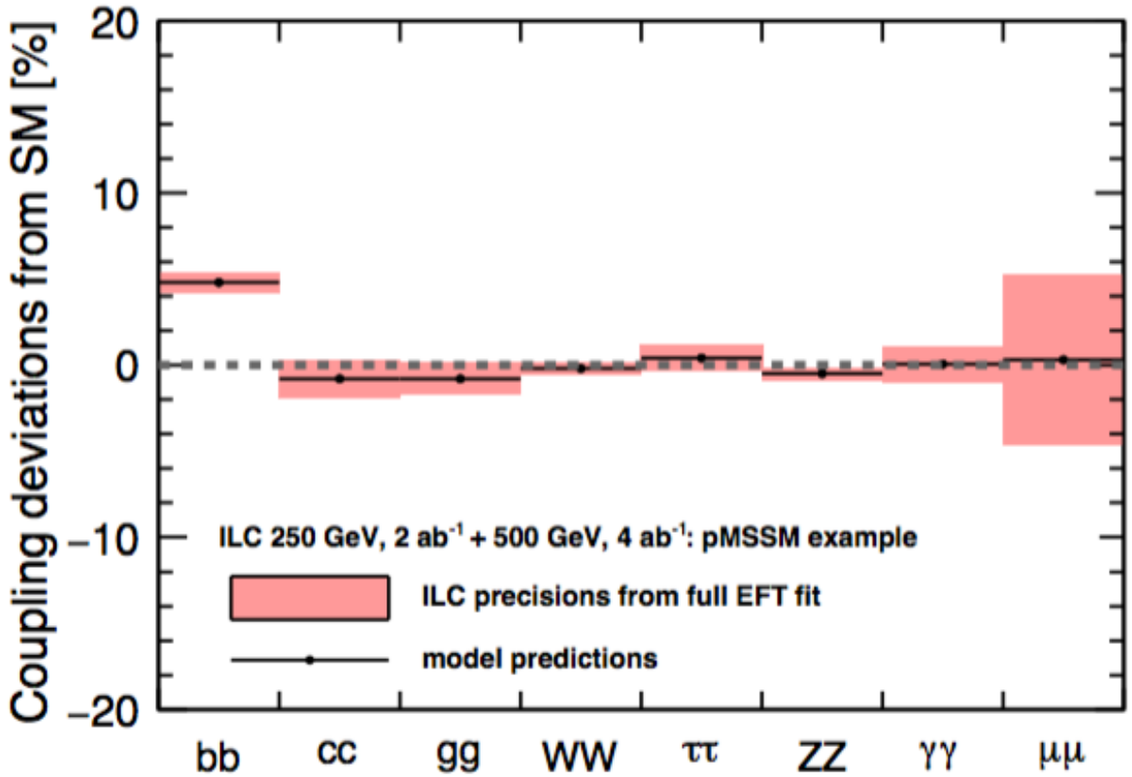
errors in %


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(hττ)
g(hgg)
g(hcc)
g(hγZ)
g(hμμ)
g(htt)

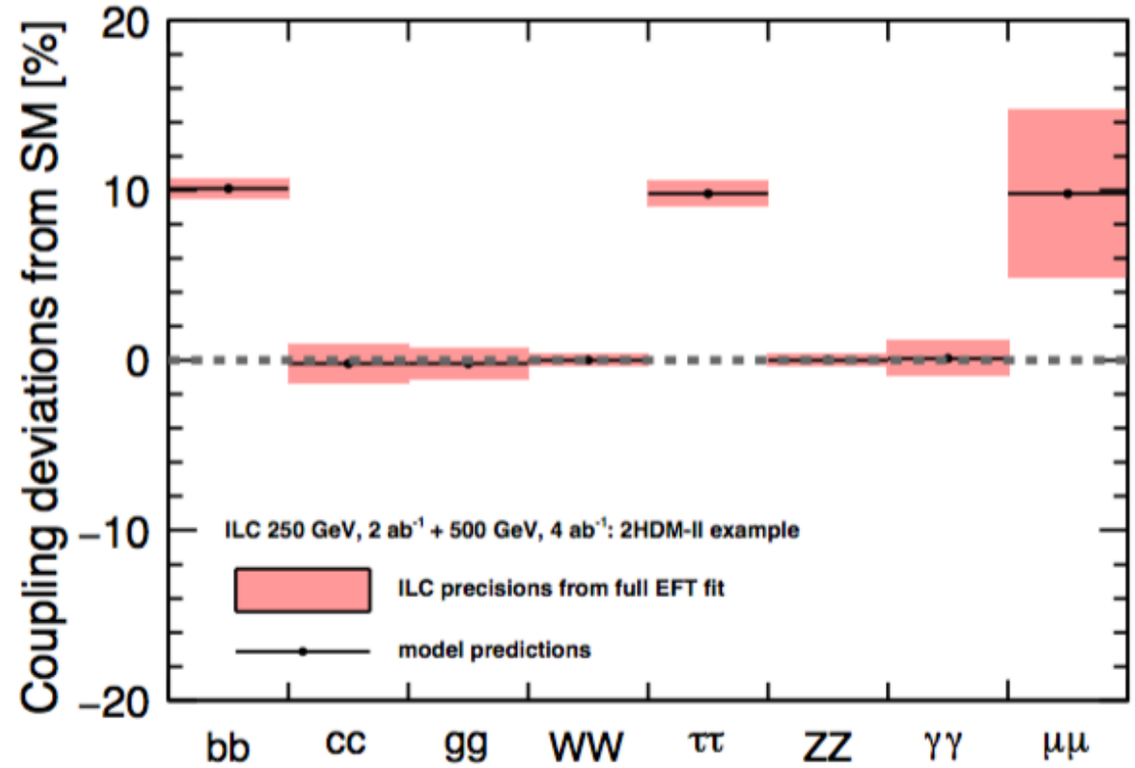
In our paper, you will also find a game in which we examined 9 diverse BSM models — all with new particles outside the range of LHC — that can gives significant effects in precision Higgs measurements.

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

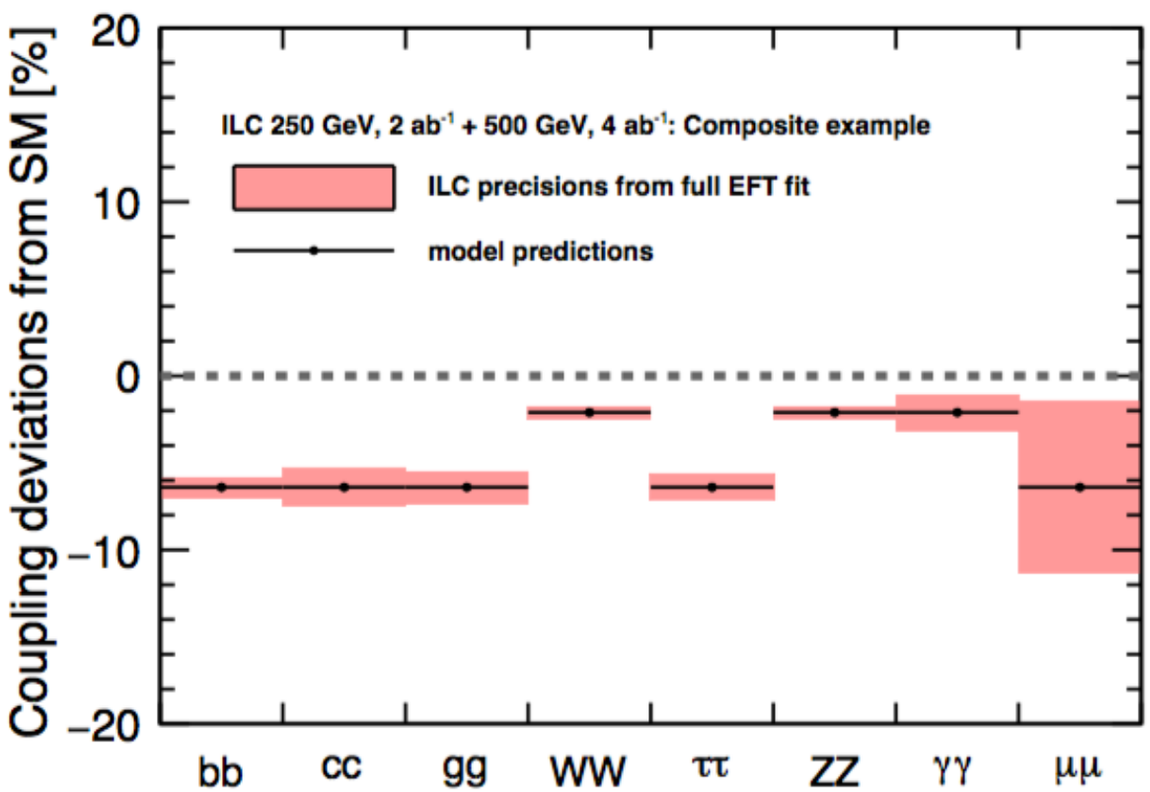
heavy SUSY



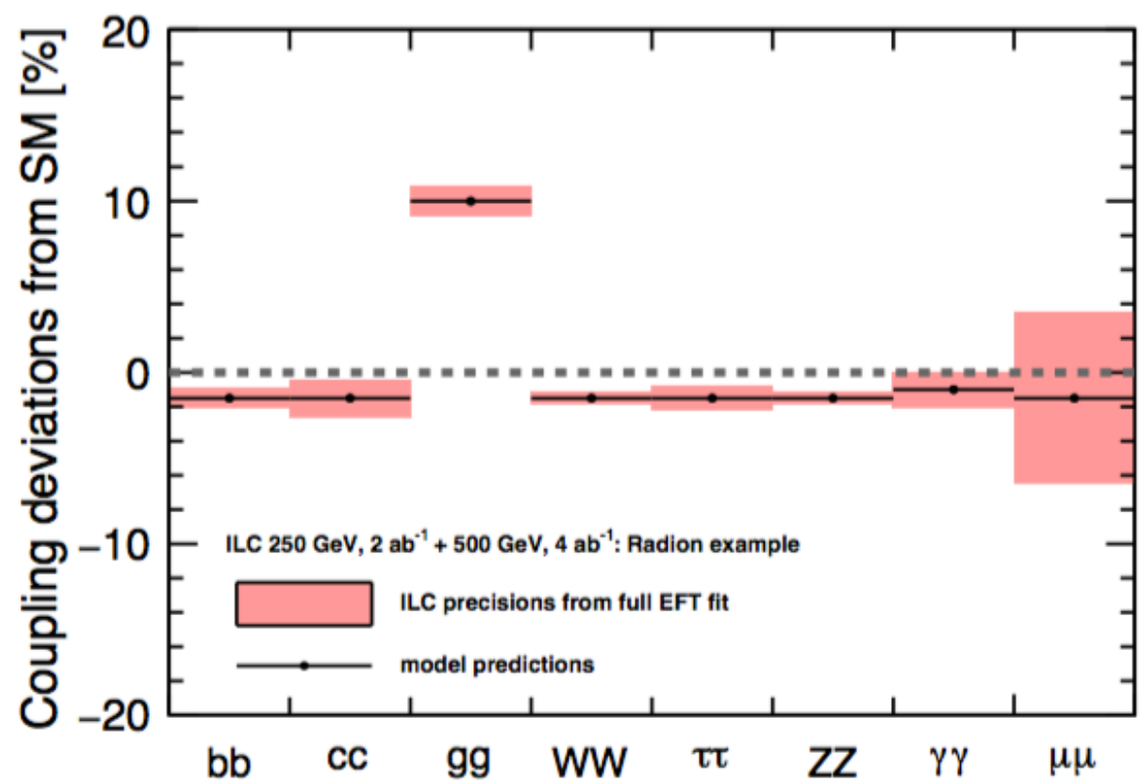

2 Higgs doublet



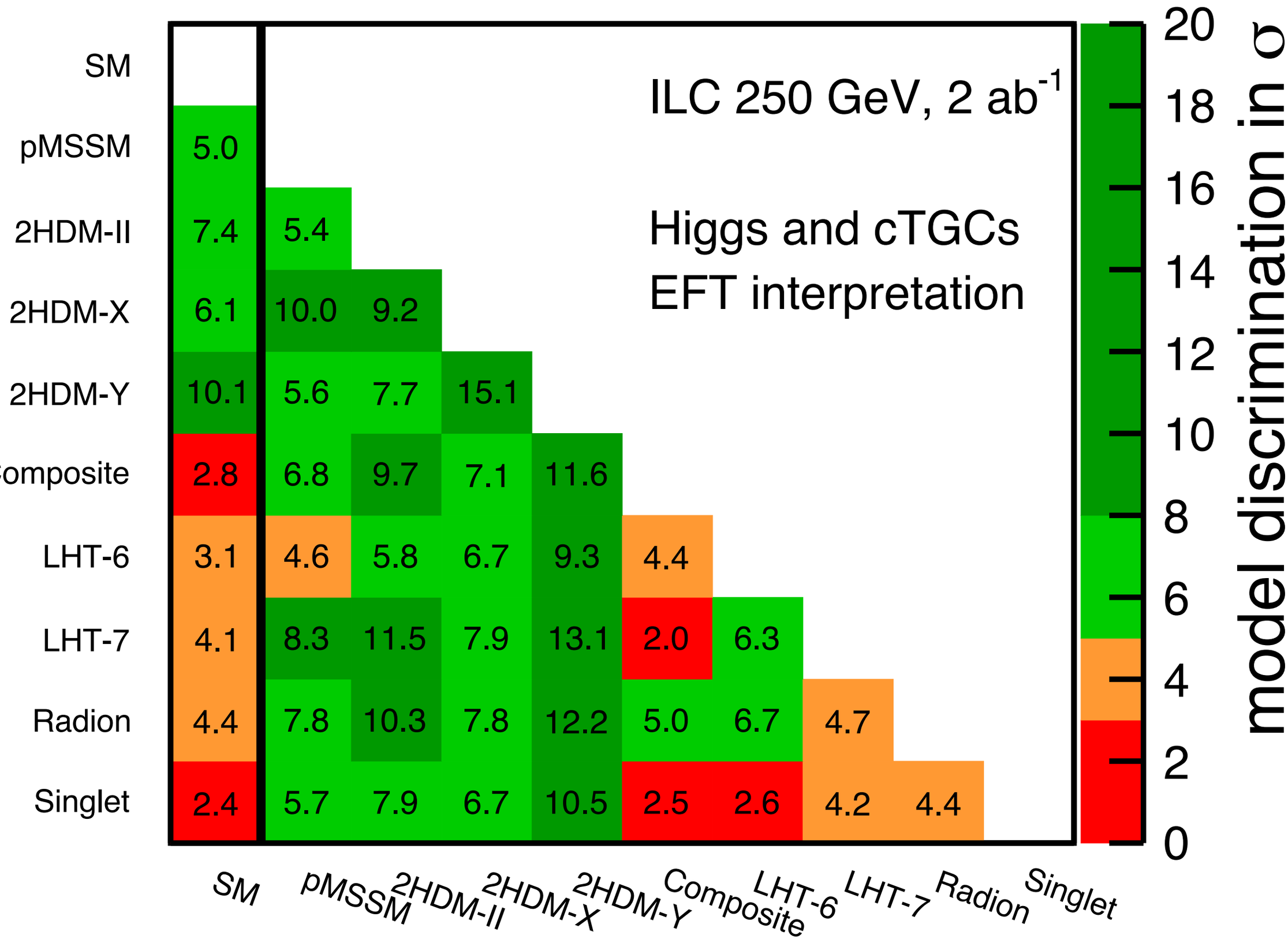

Composite Higgs



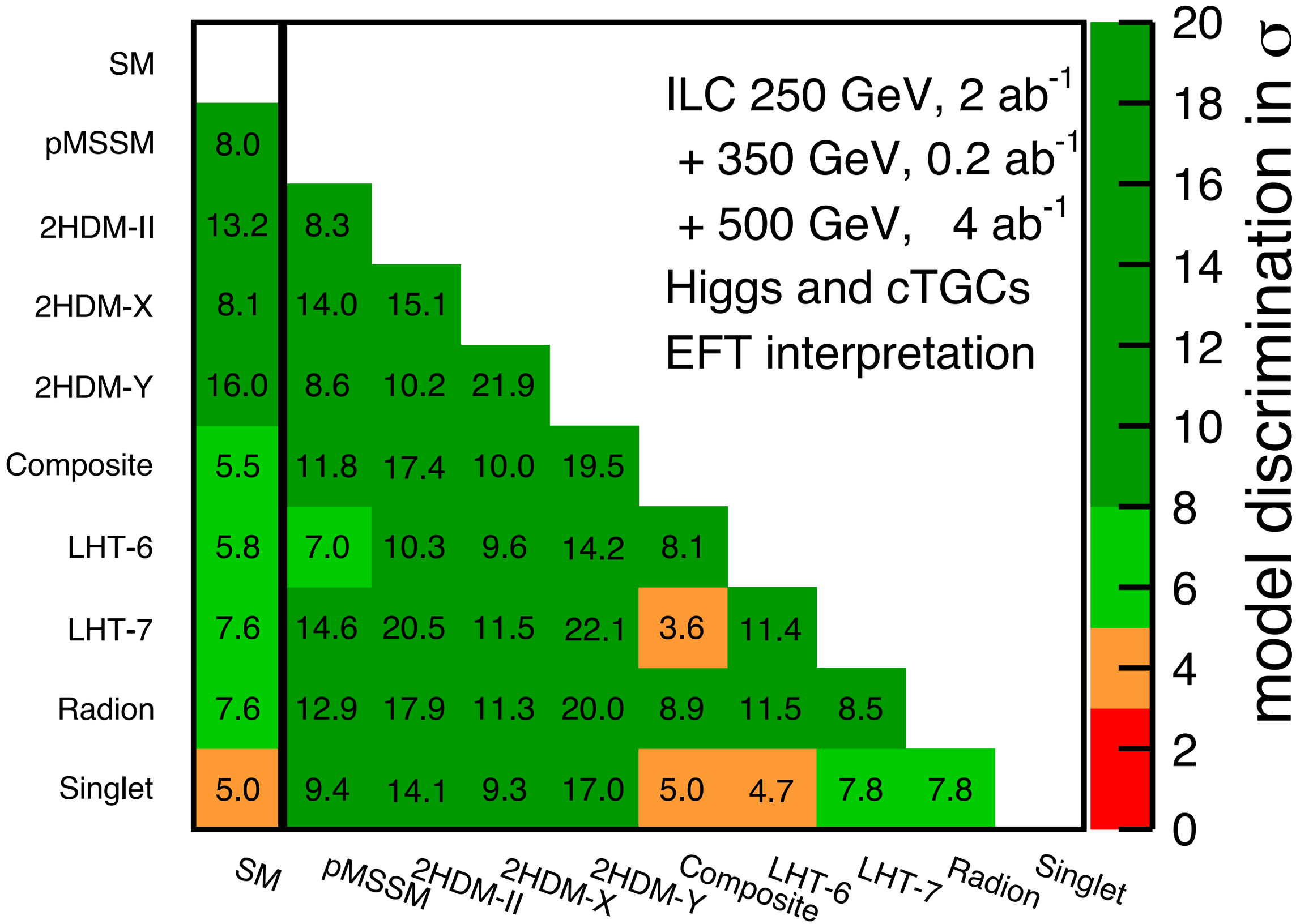

Higgs-Radion mixing



results: ILC 250 GeV 2 ab-1

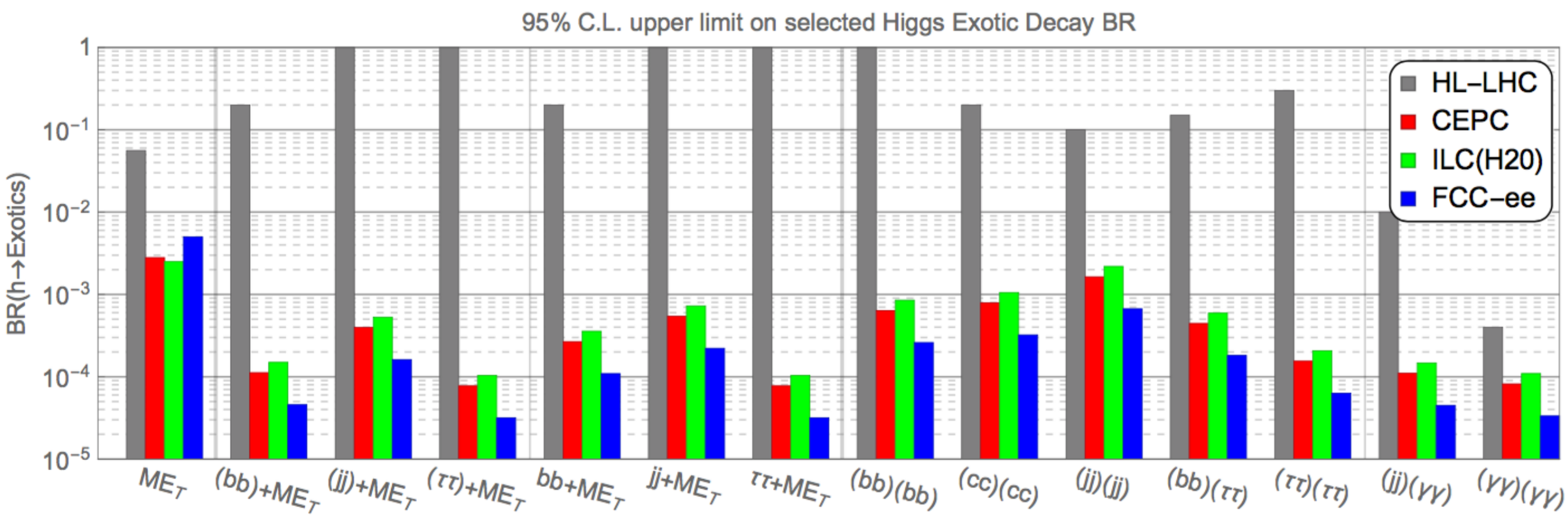


results: ILC 250 GeV 2 ab-1 + 500 GeV 4 ab-1



There are many other interesting physics topics for a 250 GeV e+e- collider.

As an example, we can search for exotic Higgs boson decays using the tagged Higgs sample from $e^+e^- \to Zh$ . The search for new physics modifications of $e^+e^- \to f\bar{f}$ is about 30 times more powerful than studies at LEP 2; see the talk of J. Yoon yesterday for discussion of $e^+e^- \to b\bar{b}$ .




Liu, Wang, and Zhang

Many other questions can be addressed by e+e- studies at higher energies. We can follow this road if we have a linear e+e- collider with continually improving technology.

350 GeV: top quark mass to 40 MeV

500 GeV: measurement of the triple Higgs coupling
27% at 500 GeV; 10% at 1 TeV
measurement of the tth coupling
6% at 500 GeV; 2% at 1 TeV
measurement of top quark form factors
< 1% already at 500 GeV

at higher energies: definitive searches
for electroweak particles

In principle, we can reach still higher energies by realizing the promise of dielectric or plasma acceleration: GeV/m or more

This is 30 TeV in a macroscopic facility (ALIC).

We are just beginning to explore the physics opportunities (e.g., study of composite Higgs models at the compositeness scale).

see: http://www.lpgp.u-psud.fr/icfaana/alegro/general-description

Now we come to the question most important to you:

Can these experiments actually happen ?

4 facilities are under discussion:

ILC: 250 GeV e+e- linear collider in Japan
(upgradable to 500 GeV, 1 TeV in later stages)

CLIC: 380 GeV e+e- linear collider at CERN

CEPC: 240 GeV e+e- circular collider in China

FCC-ee: 240 GeV e+e- circular collider at CERN

These proposals represent very different visions of the global evolution of energy frontier facilities:

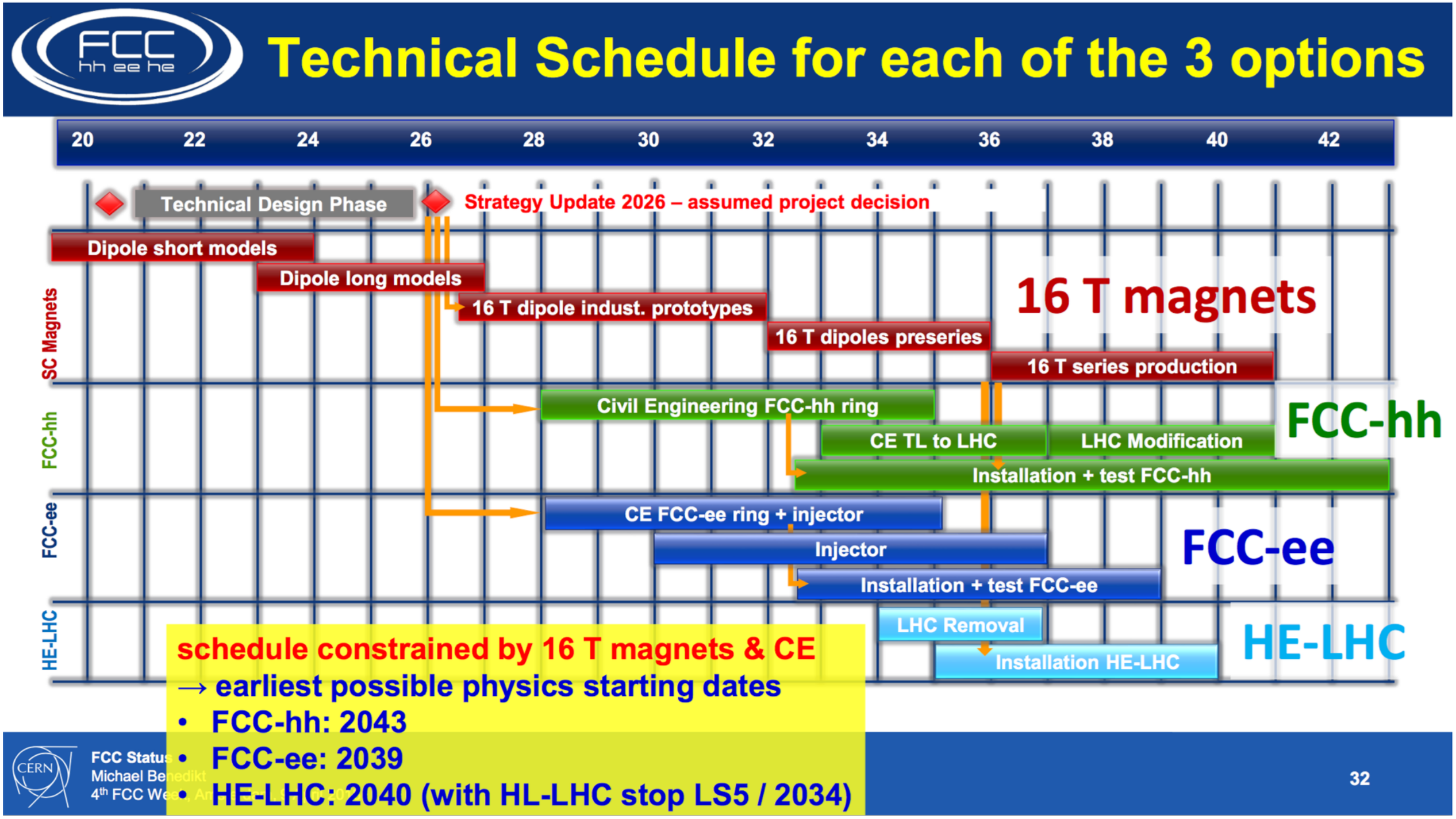
CLIC, FCC are CERN-only solutions.

ILC, CEPC would recognize the enormous recent growth of physical sciences in Asia, and would give the opportunity for a world-leading facility in Asia.

(The US apparently does not want to play in this game.)

There will be much discussion of these facilities in the 2019-2020 update of the European Strategy for Particle Physics. This has a grassroots component. Get involved!

# Michael Benedikt - FCC week 2018:




**schedule constrained by 16 T magnets & CE**

**→ earliest possible physics starting dates**

- **FCC-hh: 2043**
- **FCC-ee: 2039**
- **HE-LHC: 2040 (with HL-LHC stop LS5 / 2034)**

Geoffrey Taylor (chair of ACFA) - FCC week 2018

## China New Scientific Policies

**January 23, 2018 : The China Reform and Development Committee (led by President J.P. Xi) had the meeting on Jan 23, 2018, and passed the plan of "Chinese Initiated International Large Scientific Plan and Large Scientific Project"**

**March 28, 2018 : Chinese Government (led by Premier Minister Keqiang Li) made public details of "Chinese Initiated International Large Scientific Plan and Large Scientific Project" :**

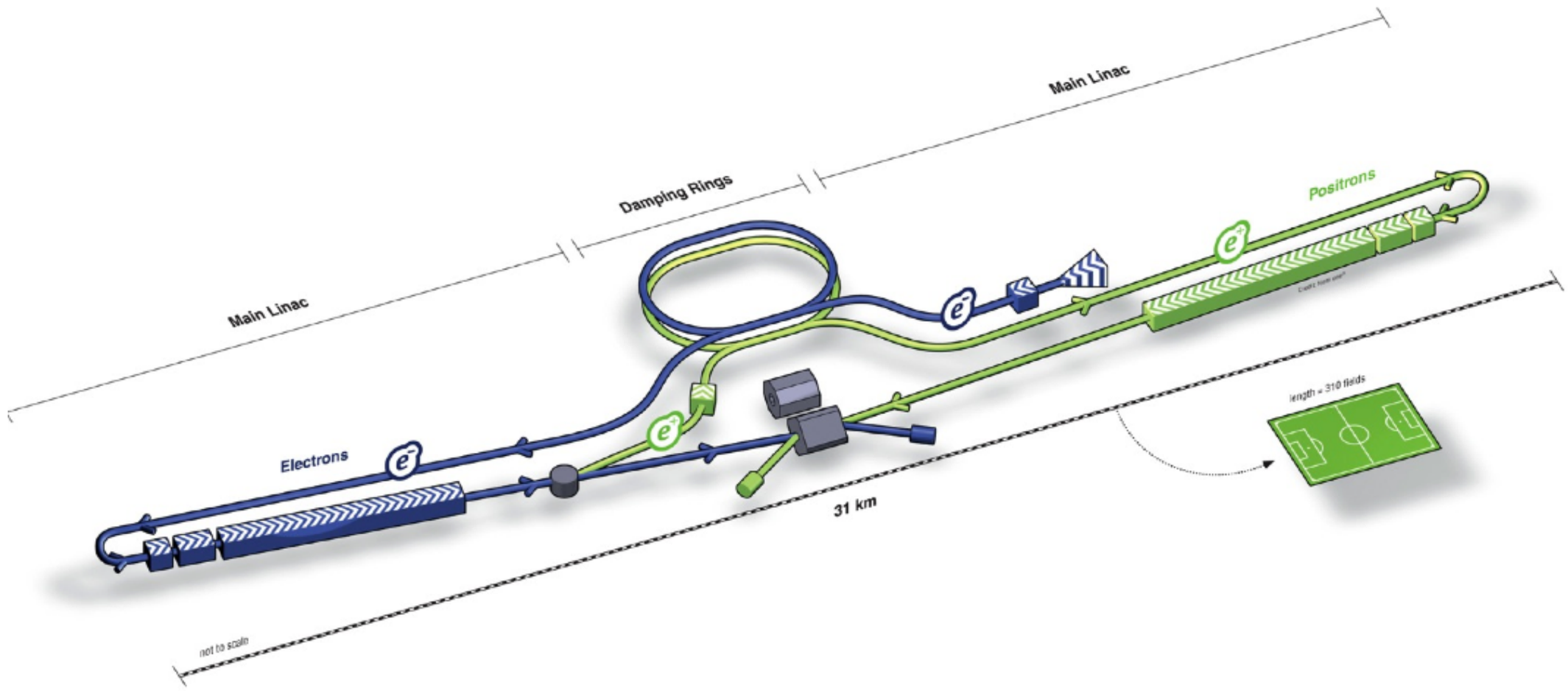
**...till 2020 China will prepare 3~5 projects ( hopefully, CEPC is inside)and finally select 1~2 projects to construct...(hopefully, CEPC will be selected)**

**...Actively participate in other country or multinational initiated Large Scientific Projects (hopefully, ILC will have good news from Japan at the end of 2018)**

**...Actively participate important international scientific organisations' scientific projects and activities...**

translation and interpretation by Jie Gao, IHEP

This brings us to ILC.  This is our next chance to have an e+e- accelerator dedicated to precision Higgs.




ILC has been in development since 2005 as a global design effort, based on 15 years of earlier regional studies.  ILC released its TDR in 2013.

This year, there is new hope that for the funding and construction of the ILC in Japan:

staged design with the first state at 250 GeV
and 40% cost reduction (arXiv:1711.00568)

reworking of the physics case for precision Higgs
and other aspects of 250 GeV program (arXiv:1710.07621)

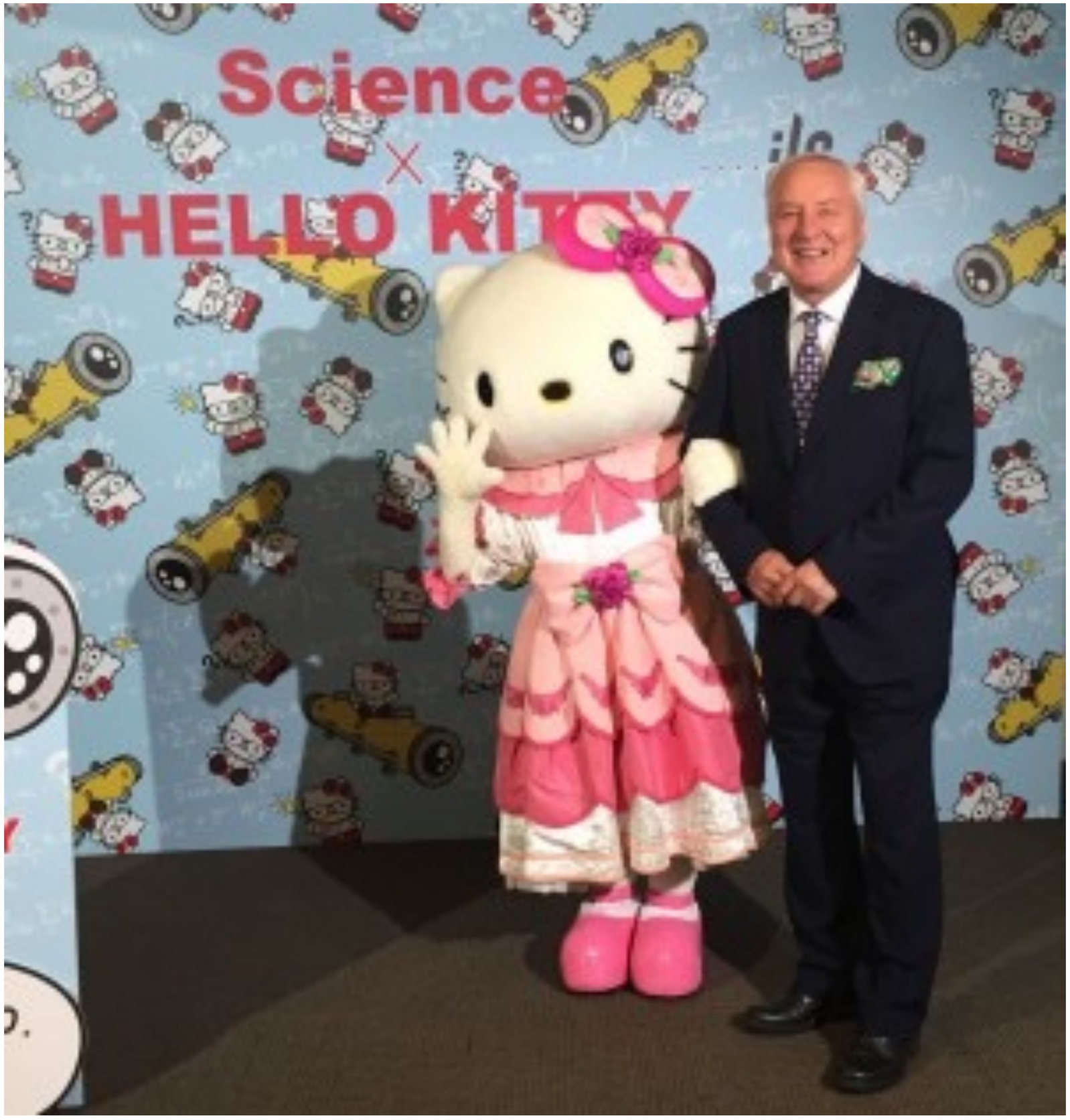
endorsement of this plan by the Japanese particle physics community (JAHEP), July 2017

endorsement of this plan by ICFA, November 2017

deadline for a decision by the Japanese government for inclusion in the European Strategy Study, fall 2018

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


Higgs Boson yurukyara


Science
×
HELLO KITTY

Conclusions:

The precision study of the Higgs boson will open a new frontier in our struggle to discover the new fundamental interactions that underlie the Standard Model.

Our community needs this opportunity.  You need it.

Let's make this a part of our future.

# from V. Barger, in ICHEP 1974 proceedings

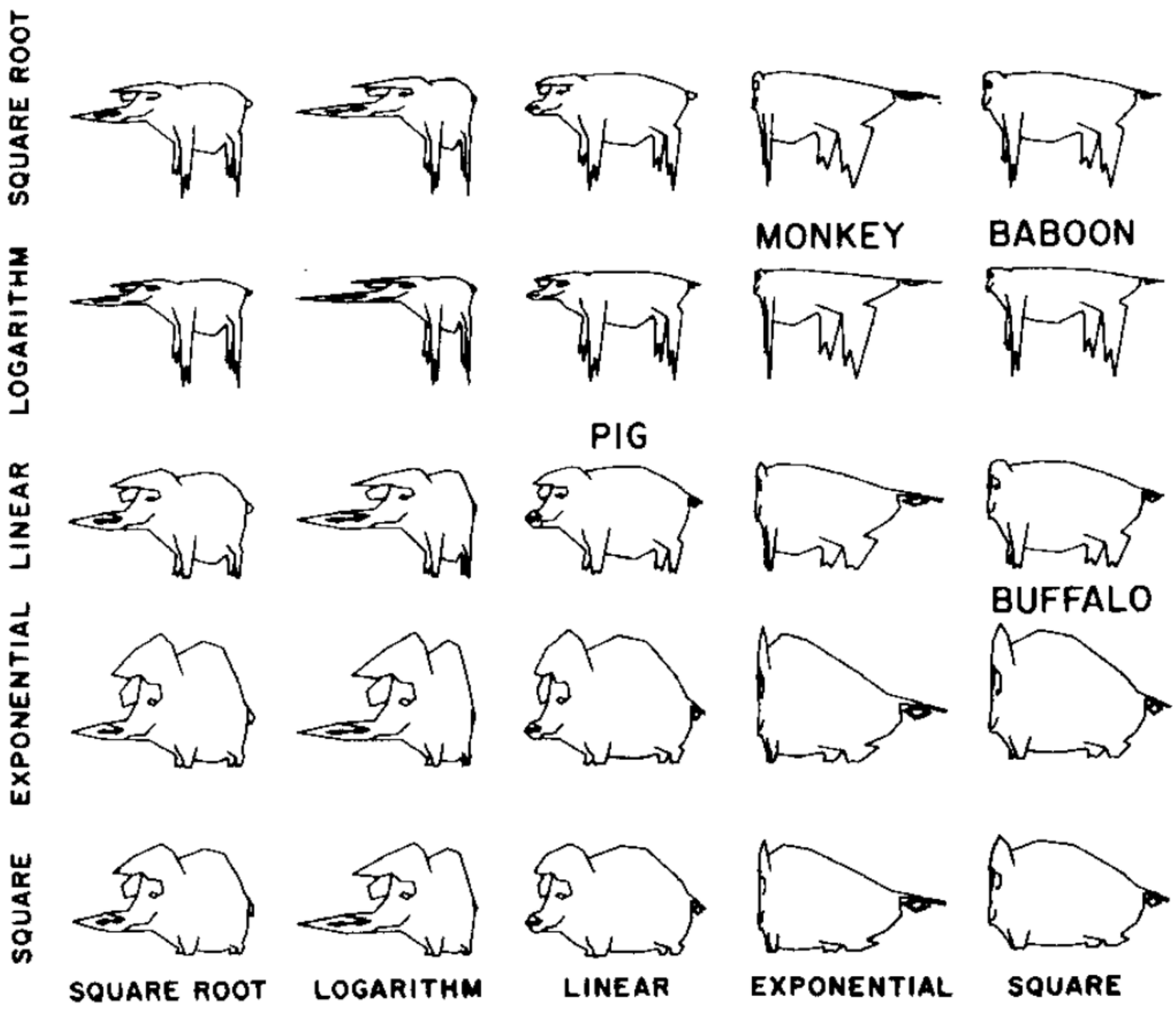



Figure 34: The art of phenomenology.

# from V. Barger, in ICHEP 1974 proceedings

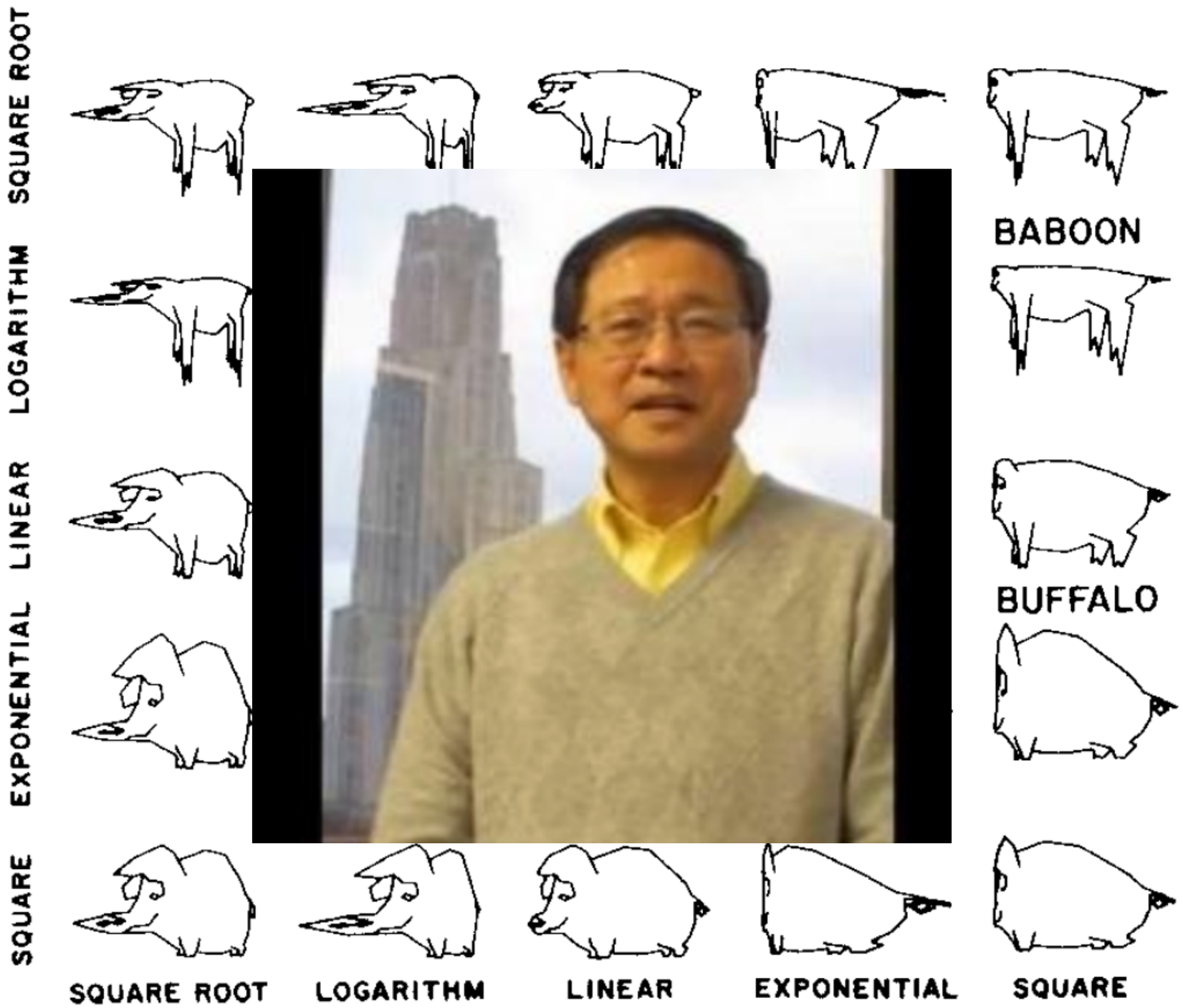



Figure 34: The art of phenomenology.