# Physics at the International Linear Collider

## 2. Reactions of the Higgs boson

M. E. Peskin
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In the previous lecture, I discussed many interesting measurements that can be carried out at the ILC.

However, there is a most important set, which will be the topic of this lecture:

the precision study of the Higgs boson.

I believe that this has become the most important goal in particle physics.

Today, the Standard Model is in excellent agreement with particle physics measurements. However, it is widely accepted to be incomplete. The reasons usually given are its inability to account for manifest features of the universe:

dark matter, dark energy

the asymmetry of matter and antimatter in the universe

neutrino masses

Still, the SM has deeper problems that stand in the way of understanding these and many other issues.

All particle masses in the SM arise from the spontaneous breaking of the SU(2)xU(1) electroweak symmetry.

But, we have no understanding of why this occurs.

Instead, we postulate a fundamental scalar field, the Higgs field, and assign it a symmetry-breaking potential.

Every parameter and coupling of the Higgs field is put in by hand. There is no logic and no underlying principle. Thus, in principle, we cannot understand

- the mass spectrum of quarks and leptons
- the origin of CP violation
- the origin of neutrino masses and mixings (which ultimately derive from the Higgs field)
- the origin of the symmetry breaking itself

The situation is very similar to that of superconductivity in 1956. We had the very successful Landau-Ginzburg model.

This correctly predicts the presence of superconductivity, the thermodynamics of the phase transition, the existence of a critical current and a critical magnetic field, the Abrikosov vortex state and the existence of Type I and Type II superconductors.

However, the model is purely phenomenological. It does not allow the properties of a superconductor to be computed for any metal.

Thus, we needed the more fundamental Bardeen-Cooper-Schrieffer theory (1957).

For electroweak symmetry breaking, we are still in the Landau-Ginzburg era.

There is an important difference, however:

For superconductivity, we knew that the explanation had to come from the interaction of electrons and nuclei.

For electroweak symmetry breaking, we do not know what new particles and forces are the cause. We only know that they are not include in the SM !

I view this as an tremendous opportunity:

There must be new fundamental particles and interactions waiting to be discovered.

In principle, we could discover new particles just by going to high energies and producing them, or by searching for particles produced in the cosmos.

This was the motivation for building the LHC and dark matter detection experiments.

However, a discovery has not been made. The window is not exhausted, but it is closing, we need a new approach.

An obvious suggestion is to explore the imprint of these new particles on the Higgs boson. This particle is at the center of the mystery. Any new particles that solve the mystery must couple to the Higgs boson.

We have now determined all parameters of the SM with high precision. So, within the SM, the couplings of the Higgs boson to all SM particles are predicted. Though this is not accomplished yet, it is feasible to work out these predictions with 0.1% precision.

Any deviation from these predictions would demonstrate that the SM is incorrect.

For a Higgs boson mass of 125 GeV, many individual couplings are measurable. The predicted BRs are:

| | | | | | |
|---|---|---|---|---|---|
| $b\bar{b}$ | 56% | $\tau^+\tau^-$ | 6.2% | $\gamma\gamma$ | 0.23% |
| $WW^*$ | 23% | $ZZ^*$ | 2.9% | $\gamma Z$ | 0.16% |
| $gg$ | 8.5% | $c\bar{c}$ | 2.8% | $\mu^+\mu^-$ | 0.02% |

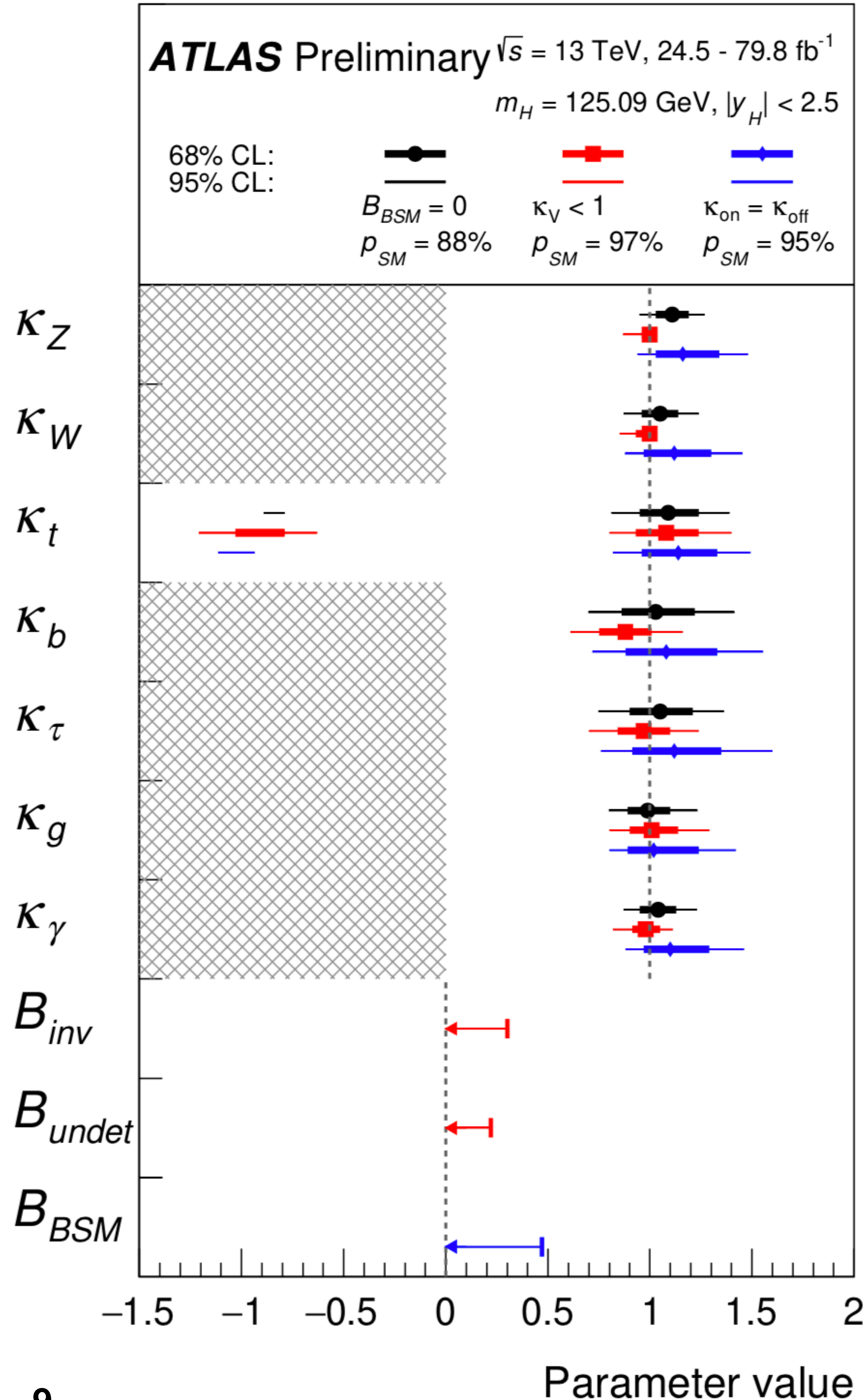
These 9 modes, plus $s\bar{s}$ and the Higgs coupling to $t\bar{t}$ and the Higgs self-coupling, each provide a stringent test.

Currently, we know from LHC that the Higgs boson is “SM-like”.

7 of these couplings are observed and agree with the SM prediction within the errors.

$$\kappa_f = \Gamma(h \to f\overline{f})/SM$$

ATLAS-CONF-2019-005



Is this an impressive verification of the SM predictions for the Higgs couplings, or not ?

Haber's Decoupling Theorem:

In models of the Higgs sector beyond the SM, if the mass scale of new physics is $M$, the effect on Higgs boson couplings is parametrically

$$\Delta g/g \sim m_h^2/M^2$$

So, if $M$ is out of reach of the LHC, this is at most a set of 5-10% corrections.

The decoupling theorem is easily proved using effective Lagrangian ideas:

Assume that the new particles are heavy, with minimum mass M. To describe processes at the scale of $m_h$, integrate them out. The resulting effective Lagrangian will be of the form

$$\mathcal{L} = \mathcal{L}_4 + \sum_i \frac{\overline{c}_i}{M^2}\mathcal{O}_i + \sum_j \frac{\overline{d}_i}{M^4}\mathcal{O}_j + \cdots$$

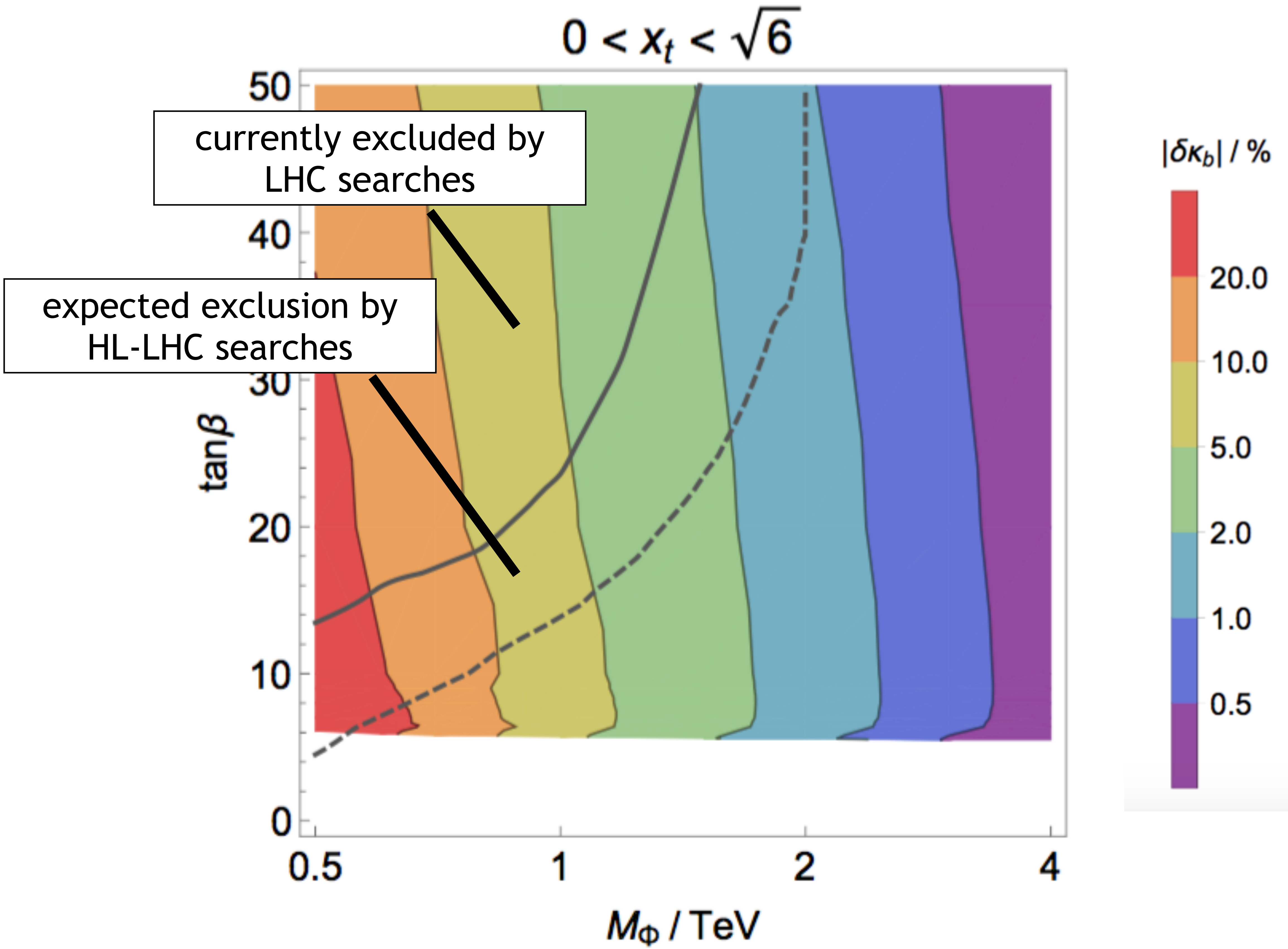
where $\mathcal{L}_4$ contains the most general set of gauge-invariant dimension 2 and 4 operators built from SM fields, and $\mathcal{O}_i$, $\mathcal{O}_j$ are operators of dimension 6, 8, … The coefficients are estimated by dimensional analysis.

But, $\mathcal{L}_4$ is exactly the SM. QED.

The decoupling theorem tells us

* the current level of agreement of the Higgs couplings with experiment is completely to be expected. It is only a consequence of SU(2)xU(1) gauge invariance.

* if we could reach the 1% level of precision in Higgs couplings, deviations from the SM of arbitrary form will have a chance to appear.




Wells and Zhang : models with b-τ unification

The story is more interesting. The study of models shows that, at the few-% level of precision each Higgs coupling has its own personality and is guided by different types of new physics. Very roughly, deviations appear in

fermion couplings - multiple Higgs doublets

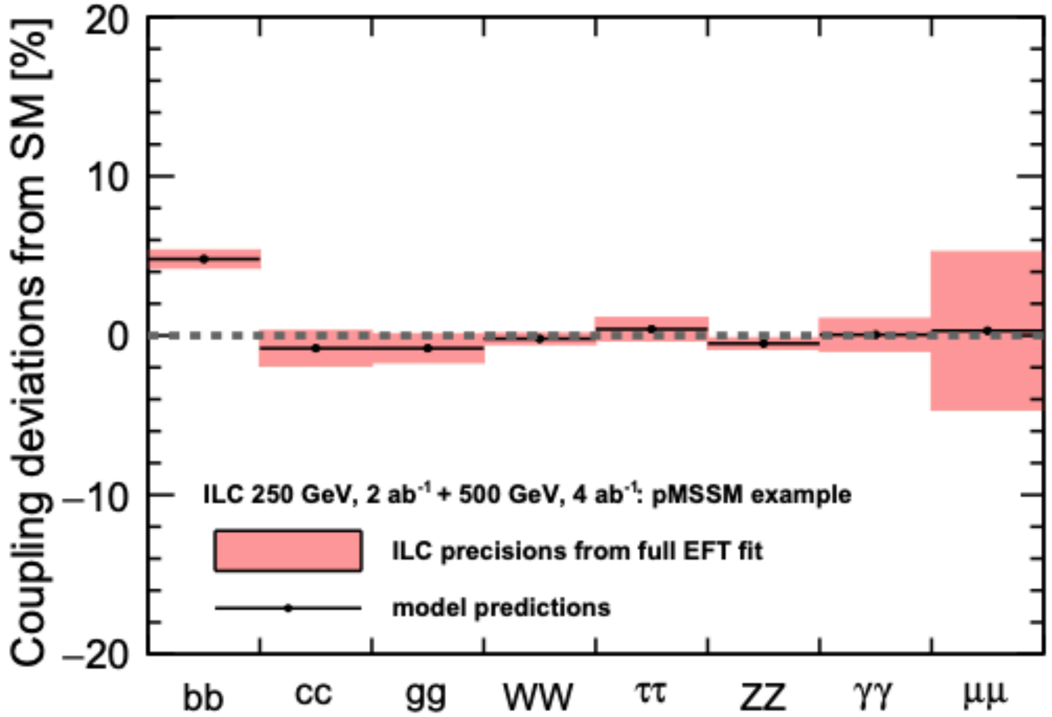
gauge boson couplings - Higgs singlets, composite Higgs

$\gamma\gamma$, gg couplings - heavy vectorlike particles

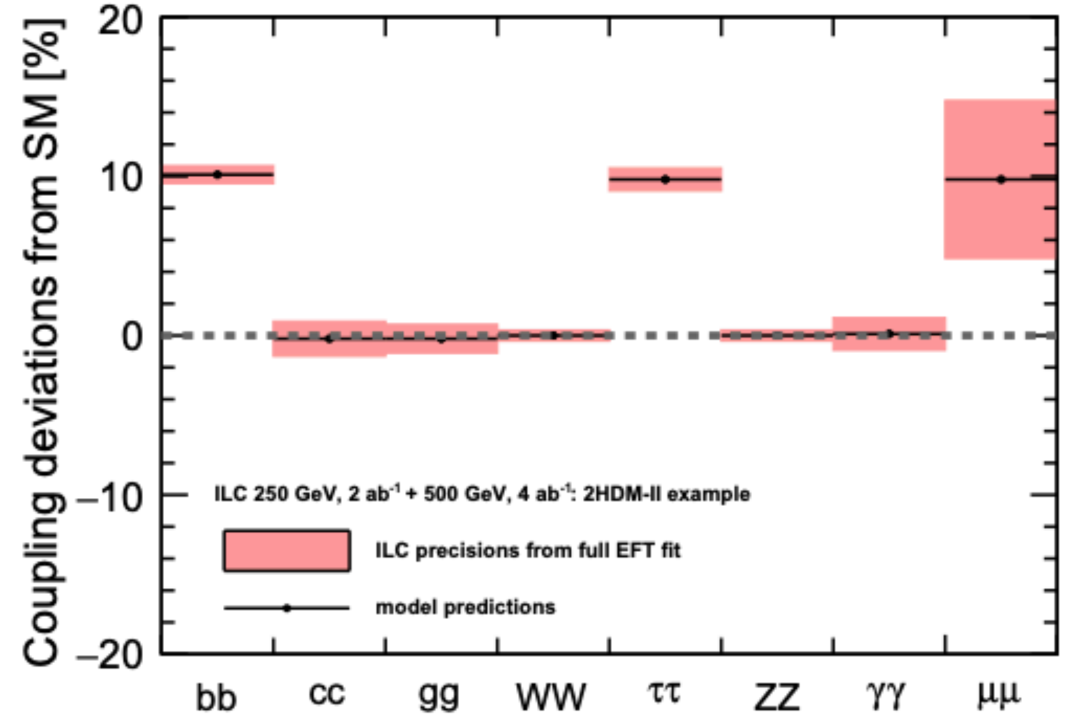
tt coupling - Higgs/top compositeness

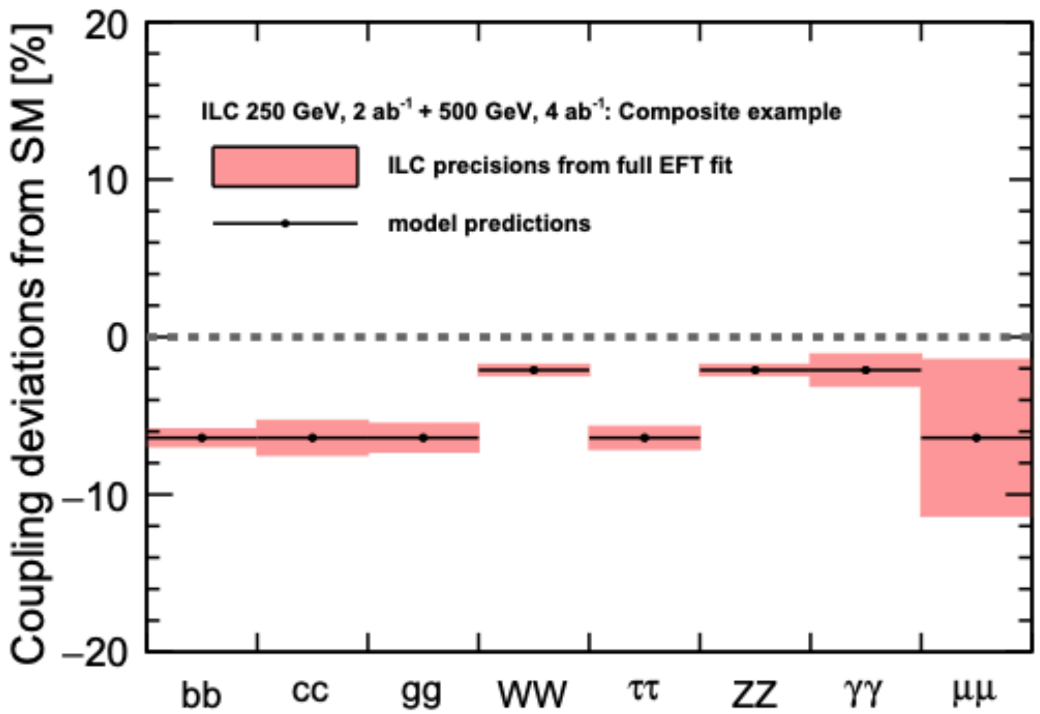
hhh coupling (large deviations) - baryogenesis

## SUSY model

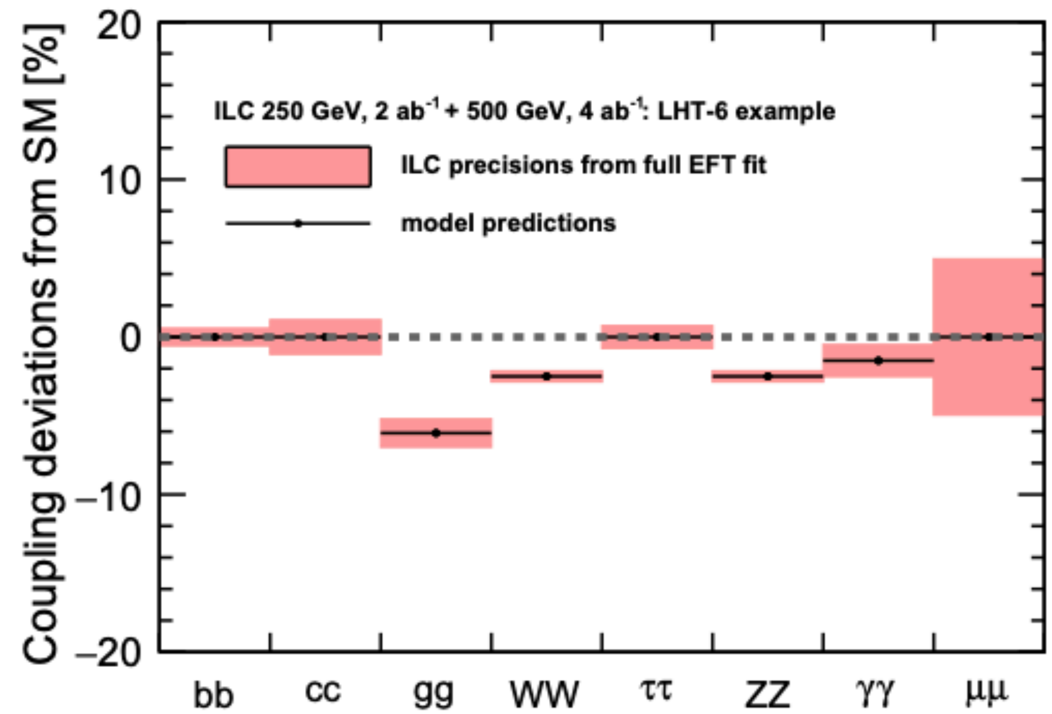



## 2 Higgs doublet model




## composite Higgs model




## Little Higgs model

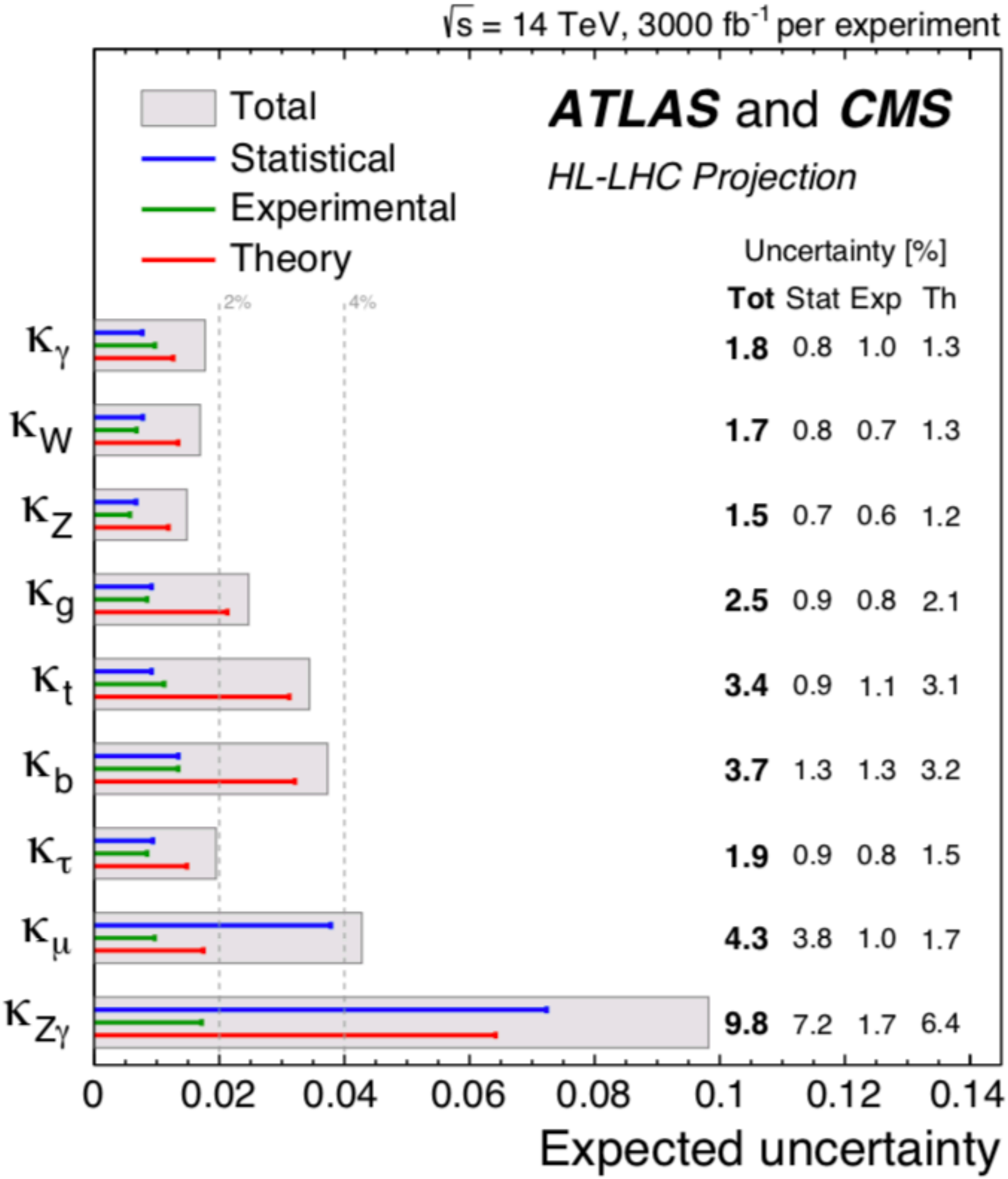


arXiv:1708.08912

We expect to make major progress in the precision understanding of the Higgs boson couplings in the High-Luminosity stage of the LHC.

We will have 10x more statistics, but systematic uncertainties must also improve in a way that scales with these. Except in the $\gamma\gamma$ and $4\ell$ decay modes, LHC Higgs events are not obviously separate from background. We begins with samples with S/B ~ 1/10 and then we must separate S from B using sophisticated classifiers.

On the other hand, having much larger statistics for the subdominant Vh and VV production modes brings a large new advantage.




arXiv: 1902.00134

caution: modelling uncertainty appears here in "theory"

This would be a dramatic improvement of our knowledge, but will it be enough ?

A 5% deviation in the hWW coupling is a 2.9$\sigma$ effect, of which a major component is systematic. Will anyone believe it ?

This last point deserves even more emphasis.

Our goal in collider physics is not to improve the error bars on Higgs measurements. It is to prove that the SM is violated.

This requires

* measurements that show SM violations at many $\sigma$

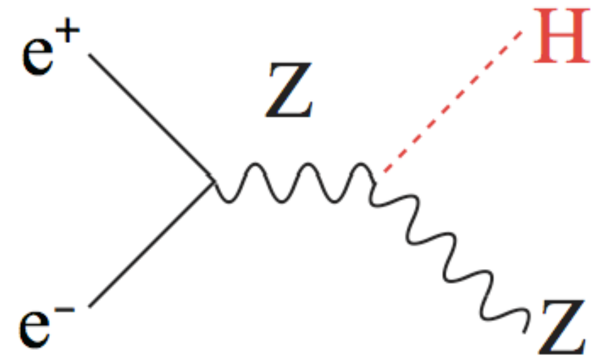
* measurements that are statistically dominated

* measurements that are improvable in a systematic program

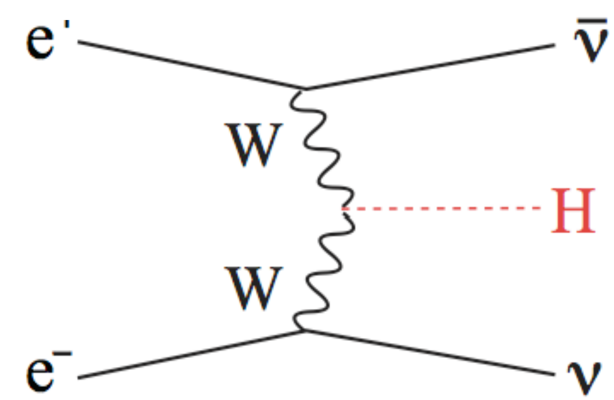
e+e- experiments can provide these.

The important production modes for the Higgs boson at $e^+e^-$ colliders are:

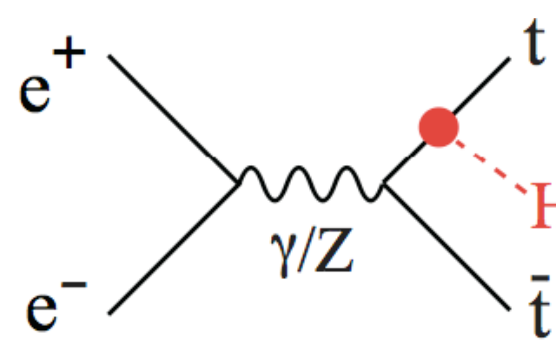
Higgsstrahlung



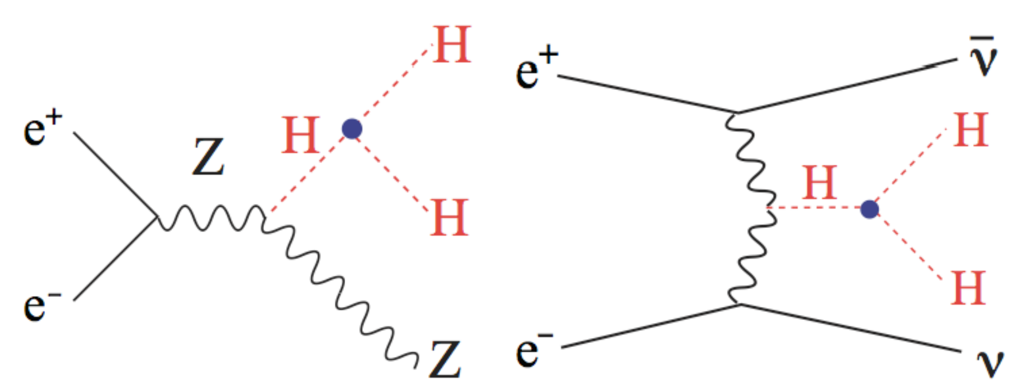

vector boson fusion

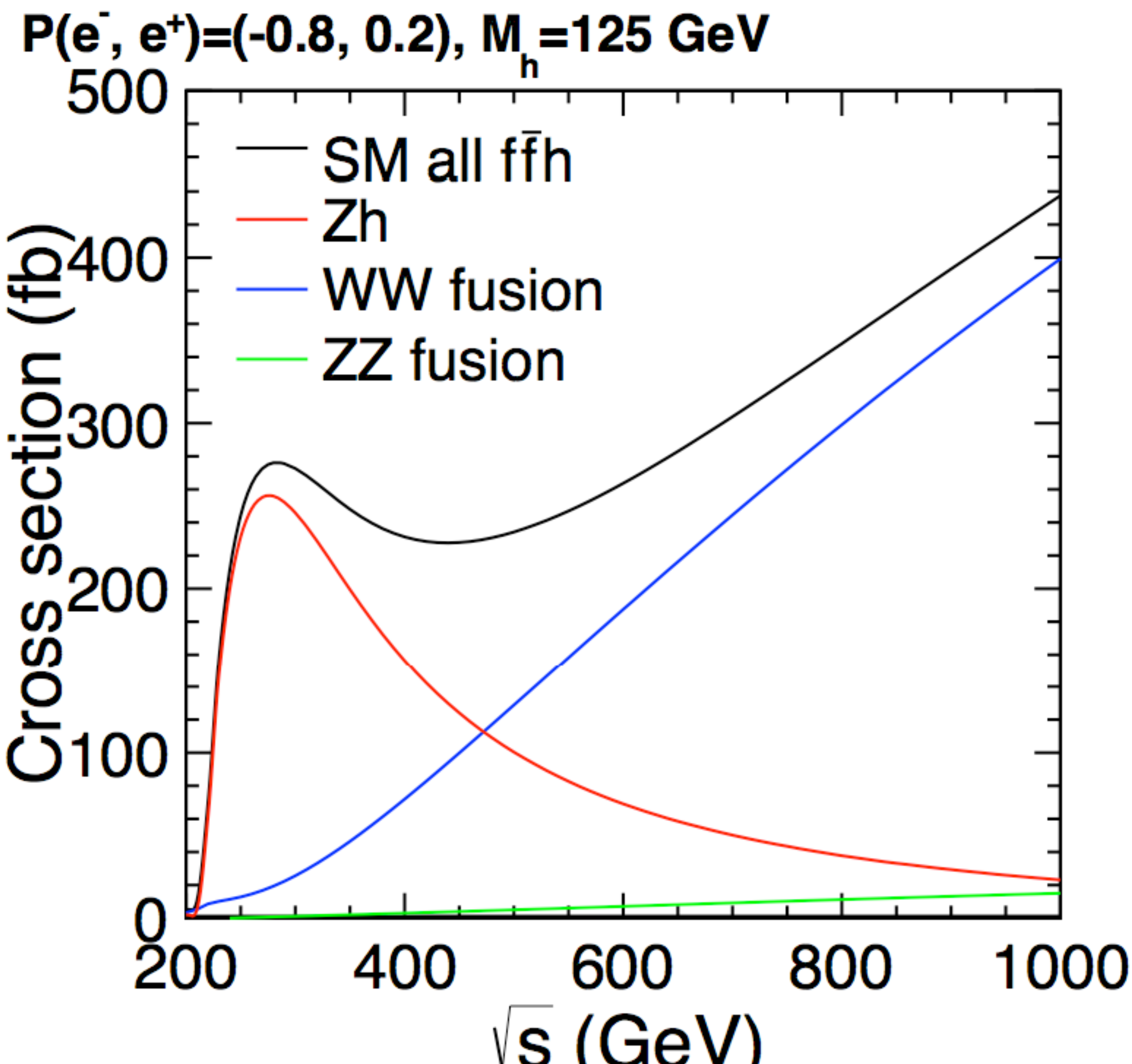



associated production with top




Higgs pair production





P(e⁻, e⁺)=(-0.8, 0.2), M_h=125 GeV
SM all f f̄ h
Zh
WW fusion
ZZ fusion
Cross section (fb)
0
100
200
300
400
500
200
400
600
800
1000
√s (GeV)

These four reactions have different advantages for the precision study of Higgs decays:

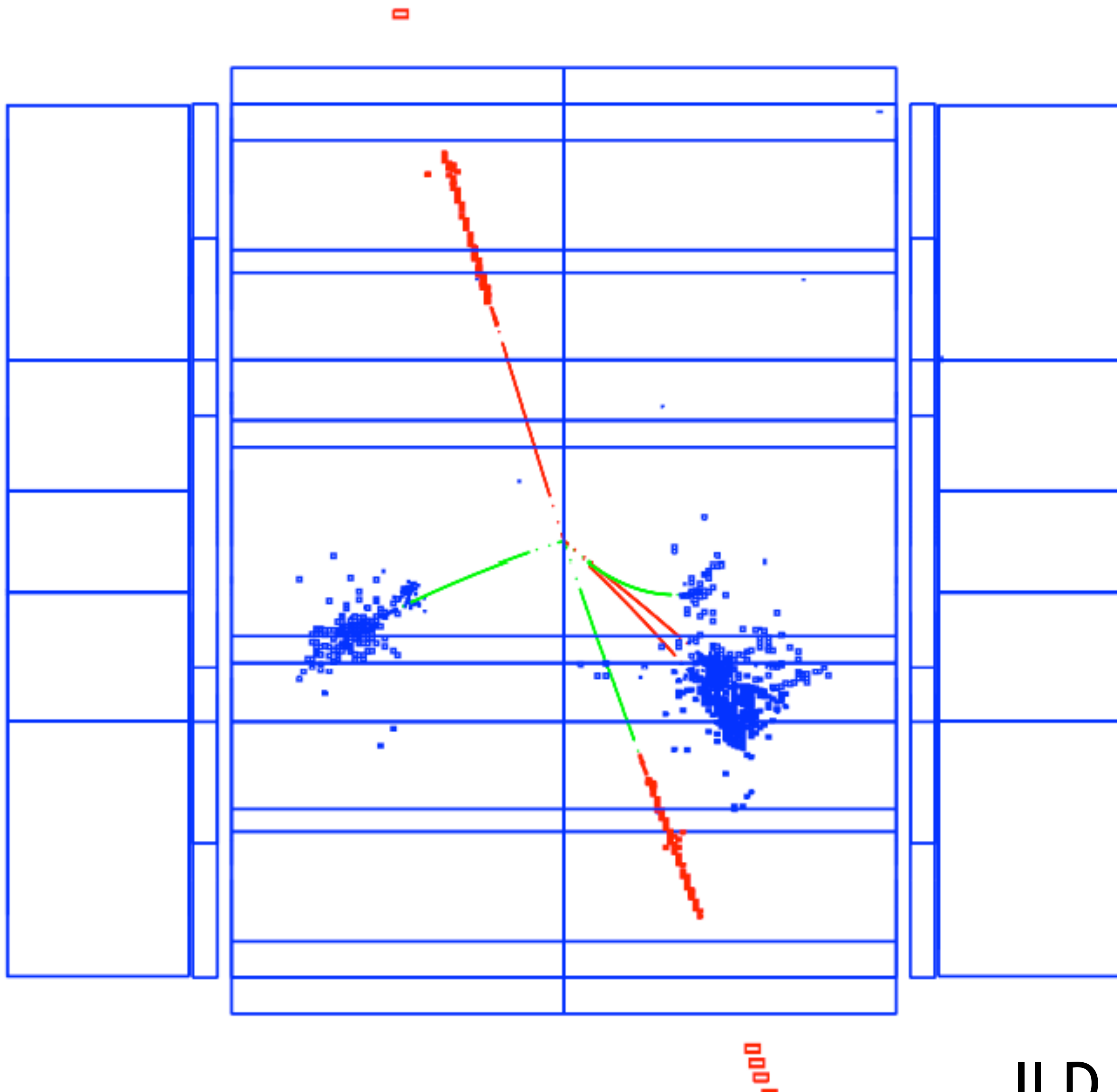
Higgsstrahlung:
- available at the lowest CM energy
- tagged Higgs decay, access to invisible and exotic modes
- direct measurement of the ZZh coupling

WW fusion:
- complementary, high-statistics measurements

associated production with top:
- access to the Higgs coupling to top

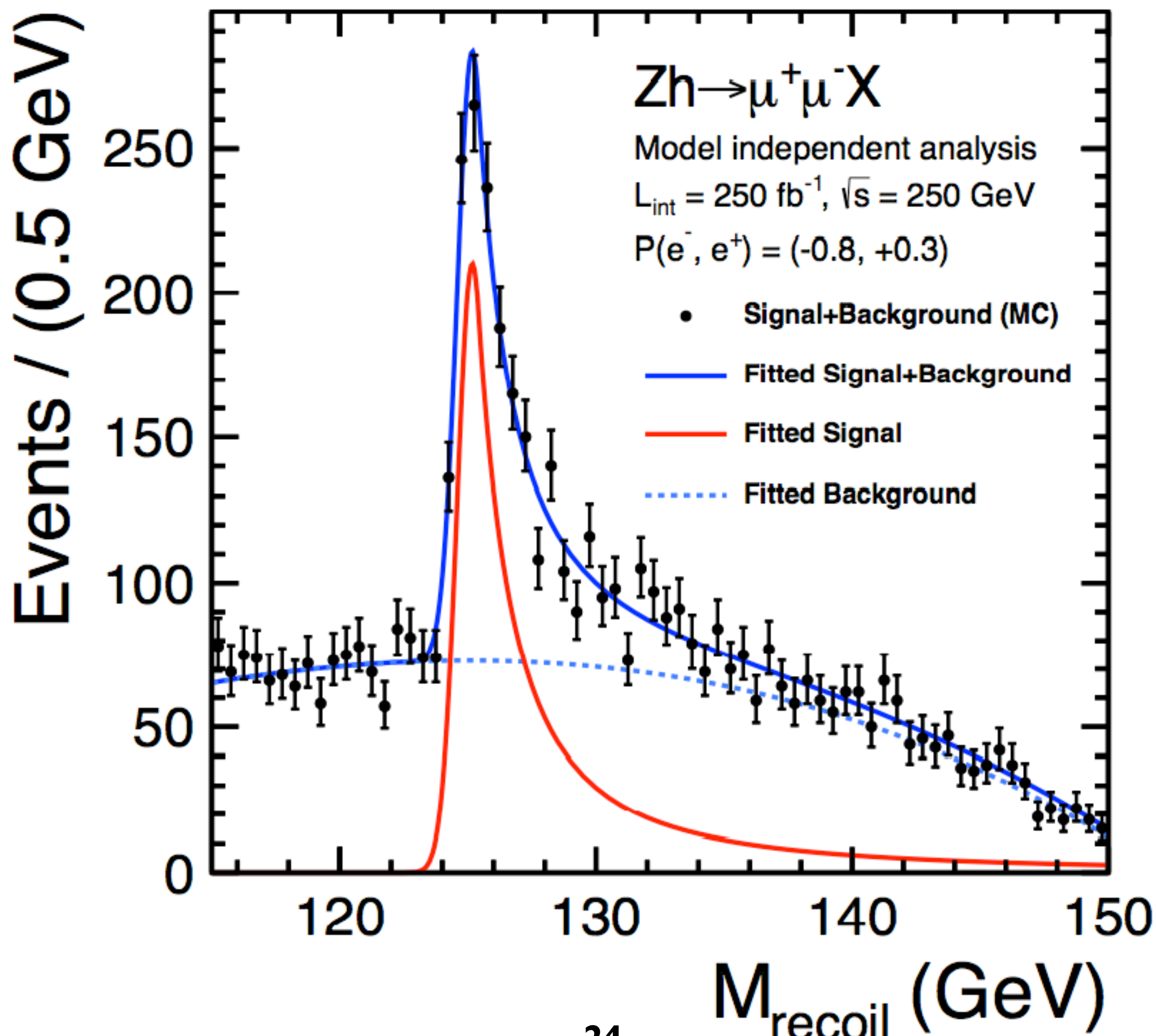
Higgs pair production:
- access to the Higgs self-coupling

$$e^+e^- \to Zh \to (\mu^+\mu^-)(\tau^+\tau^-)$$

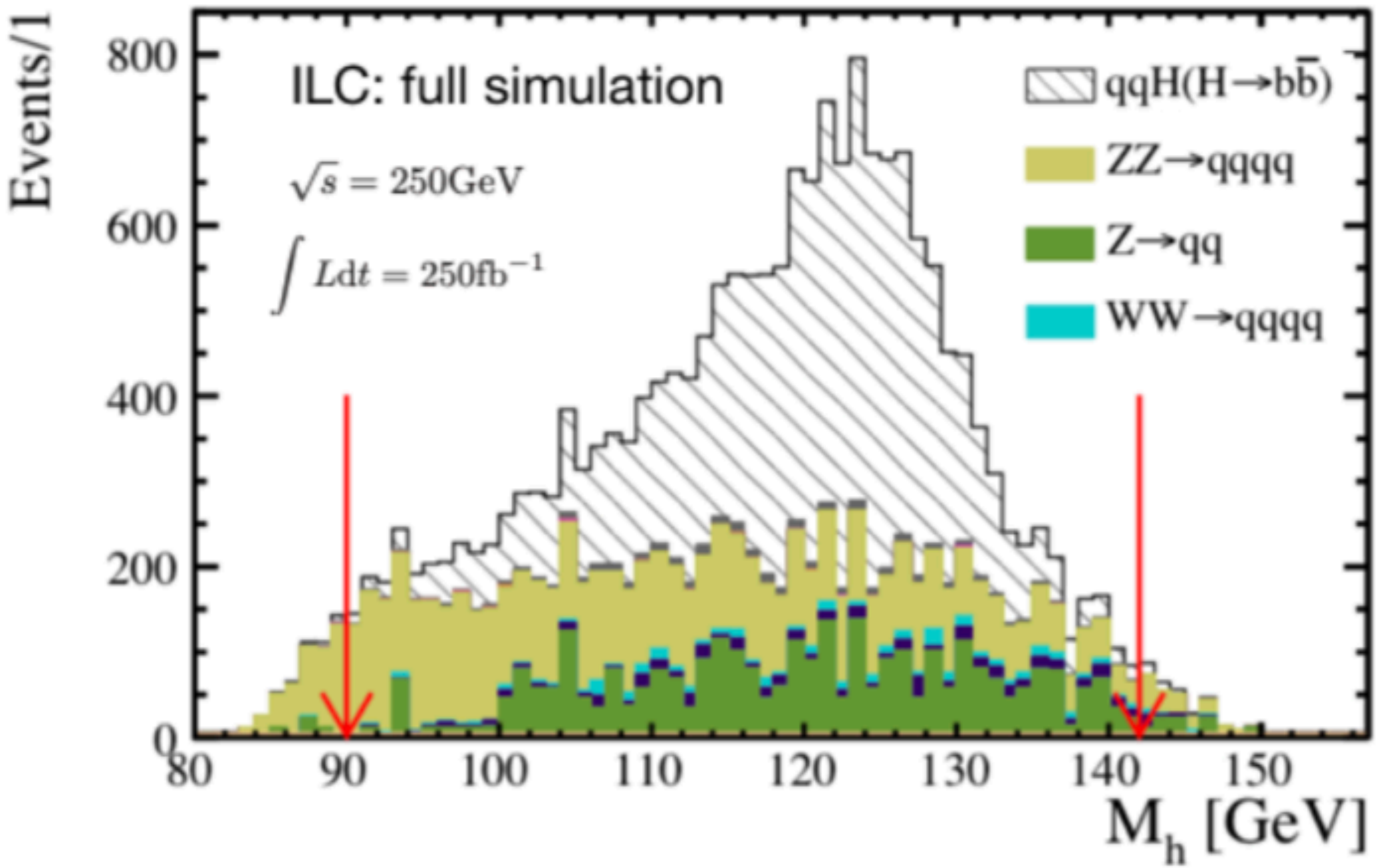


ILD simulation

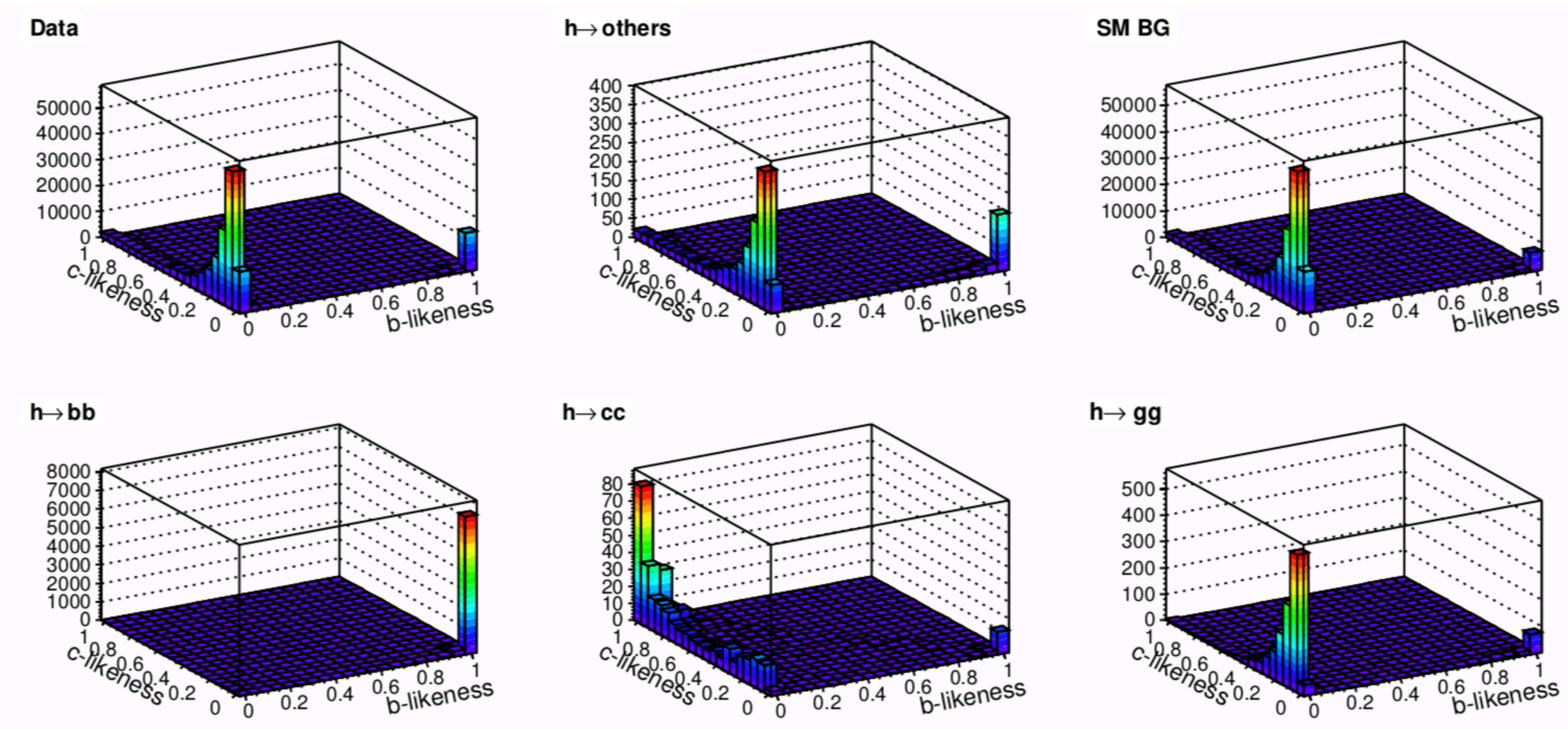
# $m_h$ to 15 MeV using recoil against Z (corresponds to 0.1% systematic error in g(hWW) )

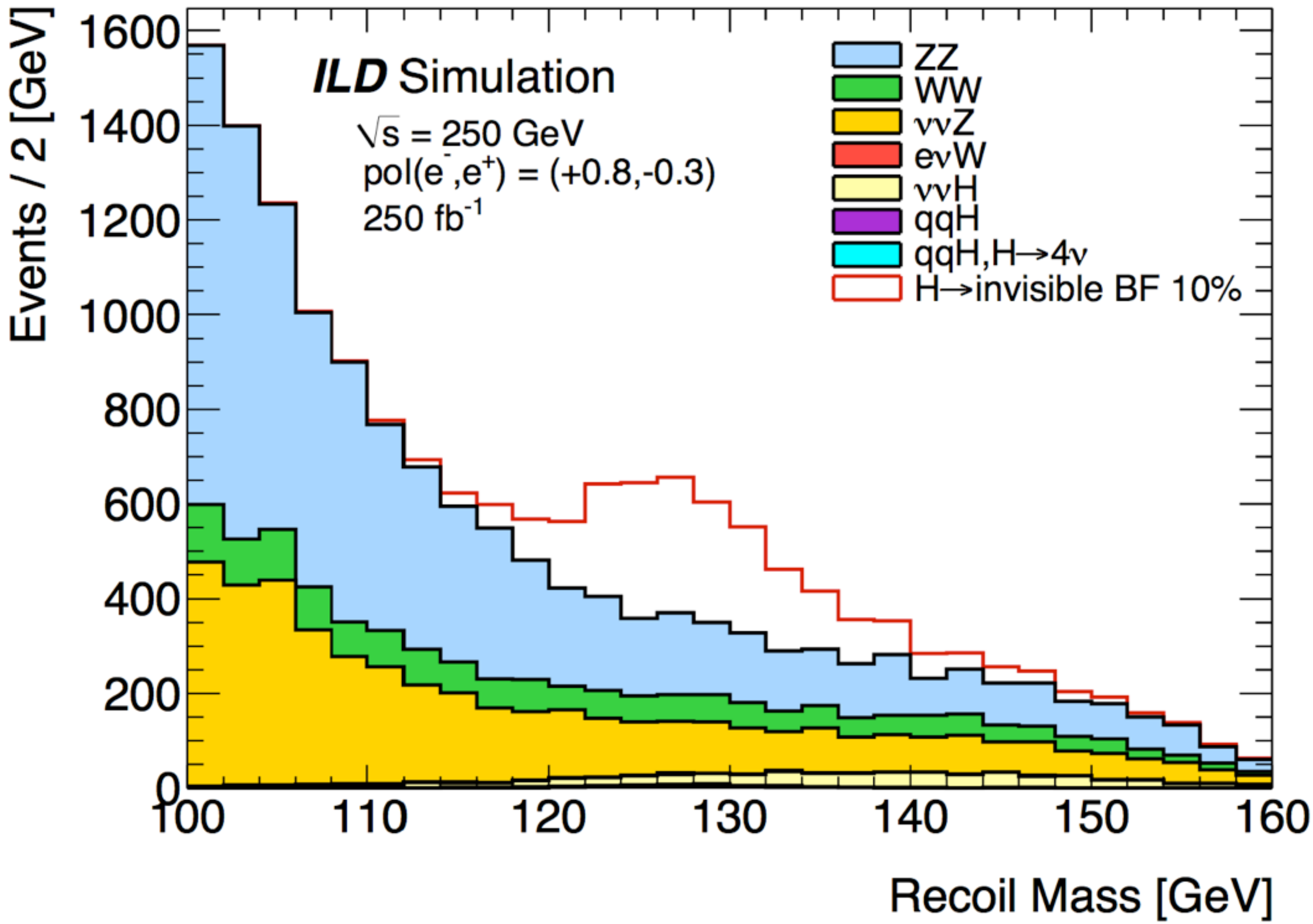


## reconstructed Higgs mass in $e^+e^- \to Zh$ , $h \to b\bar{b}$



# Higgs decay to each hadronic mode can be measured separately: $h \to b\bar{b}$ , $c\bar{c}$ , $gg$




ILD Simulation
√s = 250 GeV
pol(e⁻,e⁺) = (+0.8,-0.3)
250 fb⁻¹
ZZ
WW
ννZ
eνW
ννH
qqH
qqH,H→4ν
H→invisible BF 10%
Events / 2 [GeV]
Recoil Mass [GeV]
0
200
400
600
800
1000
1200
1400
1600
100
110
120
130
140
150
160

The observation of tagged Higgs bosons at 250 GeV makes it straightforward to measure the total cross section for

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

and the individual branching ratios for decay models of the Higgs boson.

However, there is an additional problem in determining the absolute partial widths of the Higgs boson, which are directly proportional to the squares of Higgs coupling constants.

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

The SM expectation for the Higgs width, 4.1 MeV, is too small to be directly measured at any collider.

To determine $\Gamma_{tot}$ , we need a model framework, which, hopefully, is as general as possible.

We propose to use for this framework the SM Effective Field Theory with the most general set of dimension-6 coefficients.

In general, the SMEFT contains 59 baryon- and lepton-number conserving dimension-6 operators for 1 generation and 2499 for 3 generations. It is a challenge to fix all of these coefficients uniquely.

However, e+e− reactions give a special situation. There are only 7 (CP-conserving) operators that involve γ, Z, W, h only, and for operators with fermion fields, we usually deal with the electron fields specifically.

Thus, the Higgs couplings are determined by a system of 17 CP-conserving operators only. Further, $e^+e^- \to W^+W^-$ and precision electroweak involve the same set of operators, so we can use these processes together to generate the most powerful constraints.

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

Higgs Z factor

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

triple Higgs

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

h + W,Z,γ

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

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

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

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

Deviations in the Higgs boson couplings to b, c, τ, g are each controlled by a single coefficient in the dim-6 Lagrangian.   However, the couplings of W and Z have two possible independent structures:

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

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

So it is naive to think that measurement of the cross section for $e^+e^- \to Zh$ measures "the" hZZ coupling. We need a more sophisticated viewpoint.

For example, here is the solution to the problem of multiple possible Higgs couplings for W and Z:

The dim-6 Lagrangian gives nontrivial but tractable relations between the Z and W parameters:

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

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

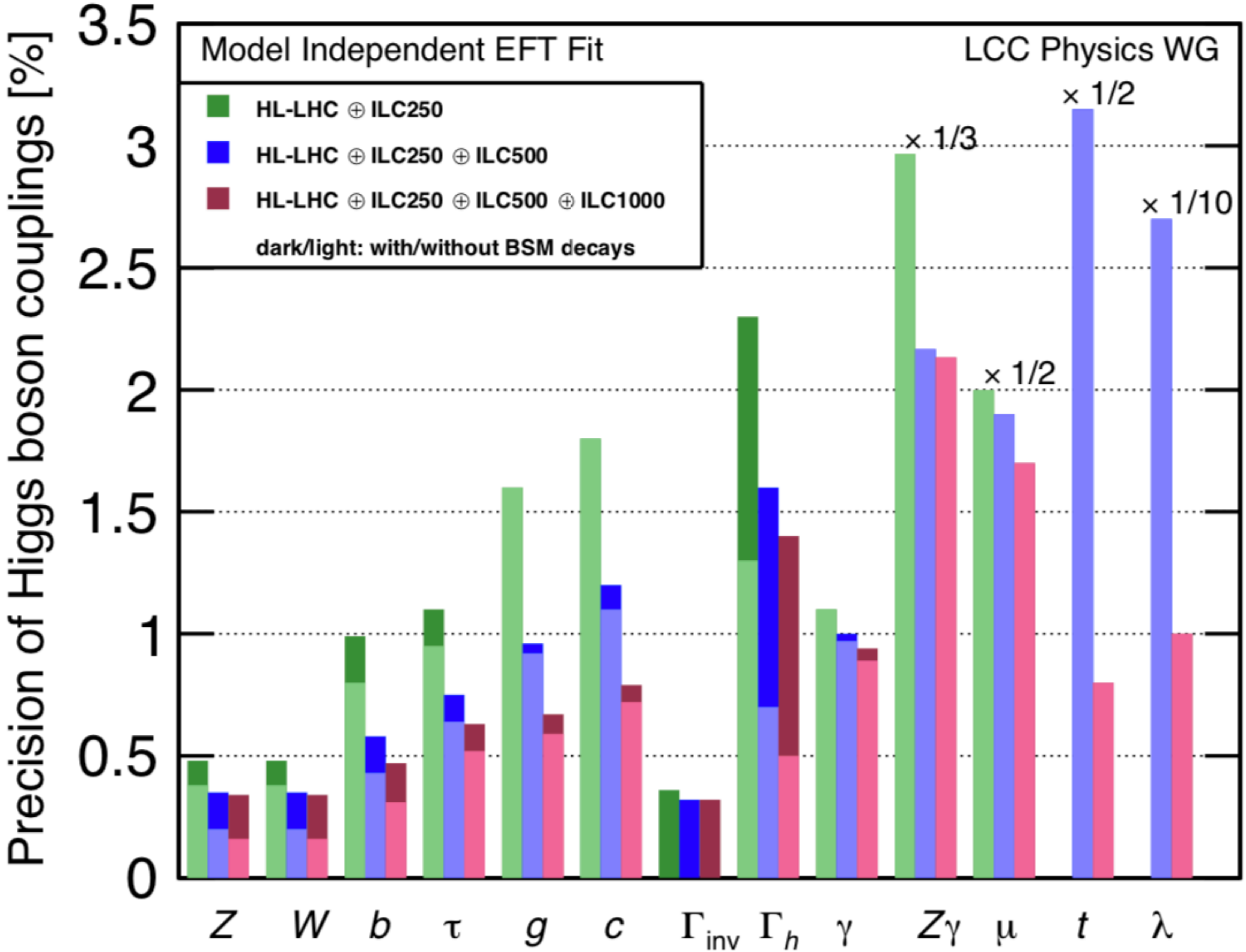
The parameter $\zeta_Z$ is very sensitive to the polarization asymmetry in $\sigma(e^+e^- \to Zh)$. (This gives special power to an accelerator with beam polarization.)

These ideas lead to extraction of the Higgs boson couplings from a "model-independent" fit with 22 parameters:

- 4 SM parameters
- 16 coefficients of dimension-6 operators
- 2 parameters for invisible and unclassified exotic decays

Precision electroweak measurements, precision measurement of $e^+e^- \to W^+W^-$, and some HL-LHC inputs assist in the determination of these parameters.

see: arXiv:1908.11299, 2003.0543 [hep-ph]




**dark**/light : allowing/not allowing invisible and exotic decays



arXiv:1908.11299

Comparing the Higgs factor proposals, it turns out that they all have essentially equivalent projected performance.  Polarized beams at linear machines compensate higher luminosity at circular machines.

| | HL-LHC | ILC250 | ILC500 | CLIC380 | CLIC1500 | CEPC | FCCee240 | FCCee350 |
|---|---|---|---|---|---|---|---|---|
| $hZZ$ | 3.6 | 0.47 | 0.22 | 0.66 | 0.27 | 0.52 | 0.47 | 0.26 |
| $hWW$ | 3.2 | 0.48 | 0.23 | 0.65 | 0.24 | 0.51 | 0.46 | 0.27 |
| $hbb$ | 5.1 | 0.83 | 0.52 | 1.0 | 0.47 | 0.67 | 0.70 | 0.56 |
| $hcc$ | - | 1.8 | 1.2 | 4.0 | 1.9 | 1.9 | 1.4 | 1.3 |
| $h\tau\tau$ | 3.5 | 0.85 | 0.60 | 1.3 | 0.93 | 0.70 | 0.70 | 0.57 |
| $hgg$ | 2.2 | 1.1 | 0.79 | 1.3 | 0.97 | 0.79 | 0.95 | 0.82 |
| $h\gamma\gamma$ | 3.7 | 1.3 | 1.1 | 1.4 | 1.2 | 1.2 | 1.2 | 1.2 |

projected uncertainties in Higgs boson couplings, in %
(SMEFT without flavor universality)

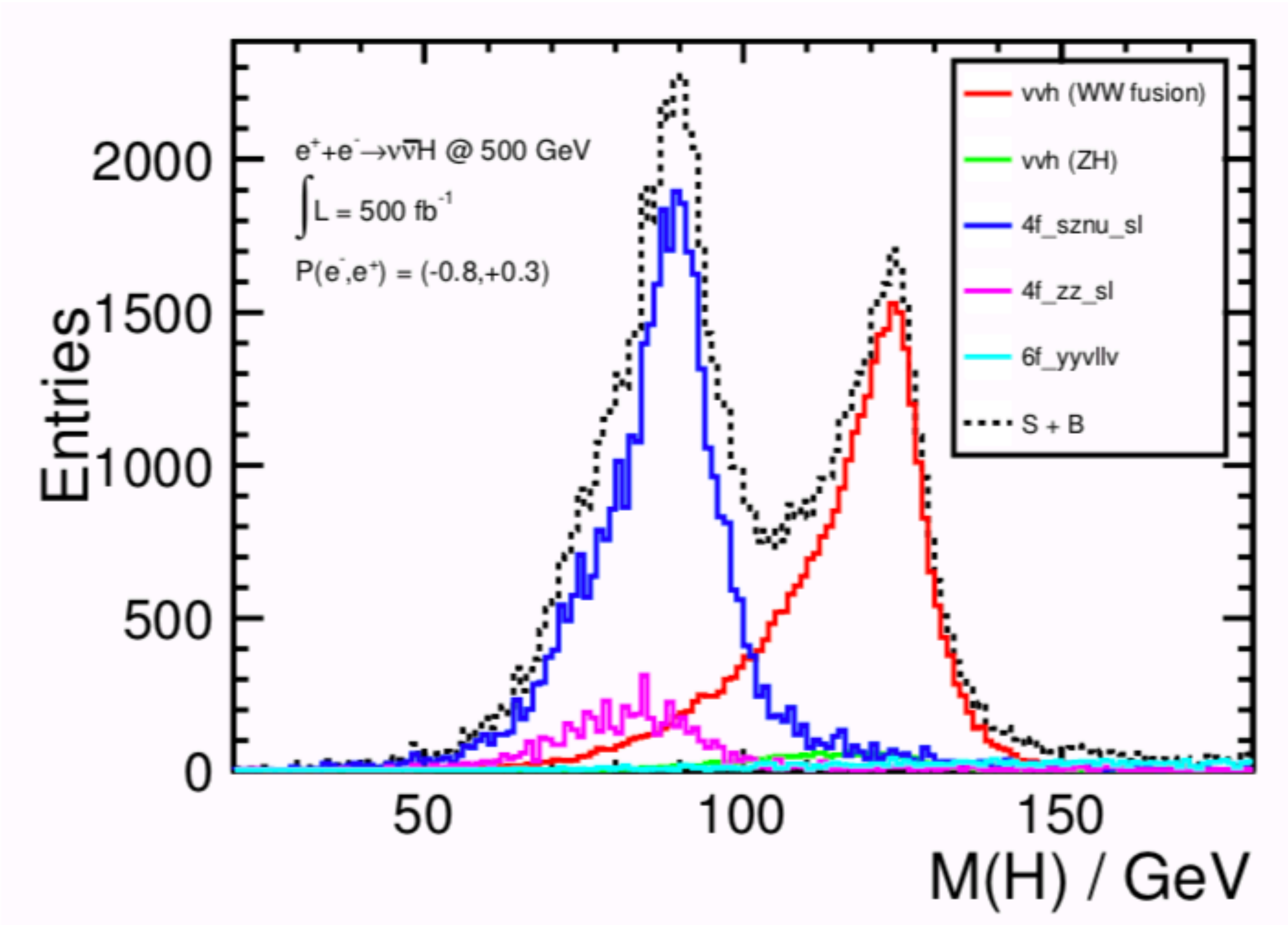
ECFA Higgs@Future Colliders arXiv:1905.03764v1

As the figure above shows, the determinations of the Higgs  boson couplings will be improved by an independent data set collected at 500 GeV.

Higgs production at this and higher energies are dominated by the WW fusion process

$$e^+e^- \to \nu\overline{\nu}h$$

reconstructed Higgs mass in $e^+e^- \to \nu\bar{\nu}h$ , $h \to b\bar{b}$



Also, at these higher energies, the ILC can fill in two more essential parameters of the Higgs boson profile:

| | | 500 GeV | 550 GeV | 1000 GeV |
|---|---|---|---|---|
| $g(tth)$ | | 6 | 3.3 | 1.6 |
| $g(hhh)$ | (direct) | 27 | | 10 |
| | (w. indirect) | 22 | | 10 |

(uncertainties in %)

Note that the interference of the hhh coupling with other SM terms is constructive for $e^+e^- \to Zhh$ and destructive for $e^+e^- \to \nu\bar{\nu}hh$. Thus, any large deviation from the SM value is measured much better using one of these reactions.

Finally, how can you enter the field of e+e- physics and prepare to make these measurements ?

It is an opportune time.   In the US, the APS-DPF is conducting a community study of the future of particle physics, “Snowmass 2021”.  Many US LHC experimenters will dip their toes in the e+e- water and see if it is congenial.

Because of the coronavirus, all meetings so far are by video. So, set your clock forward 8 hours and join us !

https://www.snowmass21.org/energy/start

We have written an introductory handbook for studies of physics at e+e- Higgs factories:

"ILC Study Questions for Snowmass 2021", arXiv:2007.03650

We are preparing a new version of Delphes for e+e- studies. We will make available large samples of e+e- events at 250, 350, 500, and 1000 GeV in stdhep and other formats. These will become available at

https://ilcsnowmass.org

hopefully, later this month.

We believe it is time now to prepare for the adventure of studying the Higgs boson with high precision.

This will open a new door through which we can finally glimpse new fundamental interactions beyond the SM.

This will be one of many opportunities made available by the construction of the ILC.