

The Electroweak Standard Model

5. The Higgs Boson beyond the Standard Model

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In the last lecture of this series, I am asked by the organizers to discuss the implications of theories of physics beyond the Standard Model for the Higgs boson.

So, this lecture will discuss the following points:

My perspective on physics beyond the Standard Model

Properties of the SM Higgs and prospects for a more general theory of $SU(2) \times U(1)$ breaking

Constraints on the observation of BSM effects on the Higgs

Effects on the Higgs properties predicted by BSM theories

Prospects for precision measurements of the Higgs properties at e^+e^- colliders

First, why do we need physics beyond the Standard Model ?

I have shown you in my previous lectures that the Standard Model of weak interactions is extremely successful in its own domain.

It certainly omits some aspects of nature, and so it cannot claim to be a theory of everything. Even when we add QCD, this theory omits gravity, dark matter, and an explanation for the matter-antimatter asymmetry of the universe. Neutrino masses can be included, but most theories invoke new ingredients outside the model.

But, the Standard Model also raises fundamental questions that it does not have the power to solve.

Among these are:

Why just quarks and leptons ? What is the origin of the quantum number assignments (I, Y) of these particles ?

What explains the spectrum of quark and lepton masses ?
In the Standard Model, we have

$$m_f = y_f v / \sqrt{2}$$

But, the y_f are renormalized parameters. Within the Standard Model, they cannot be predicted. The presence of CKM and PMNS mixing angles adds another dimension to this problem.

Finally, the structure of the Standard Model requires that $SU(2) \times U(1)$ be spontaneously broken. **Why does this happen ?** The Standard Model cannot answer this question.

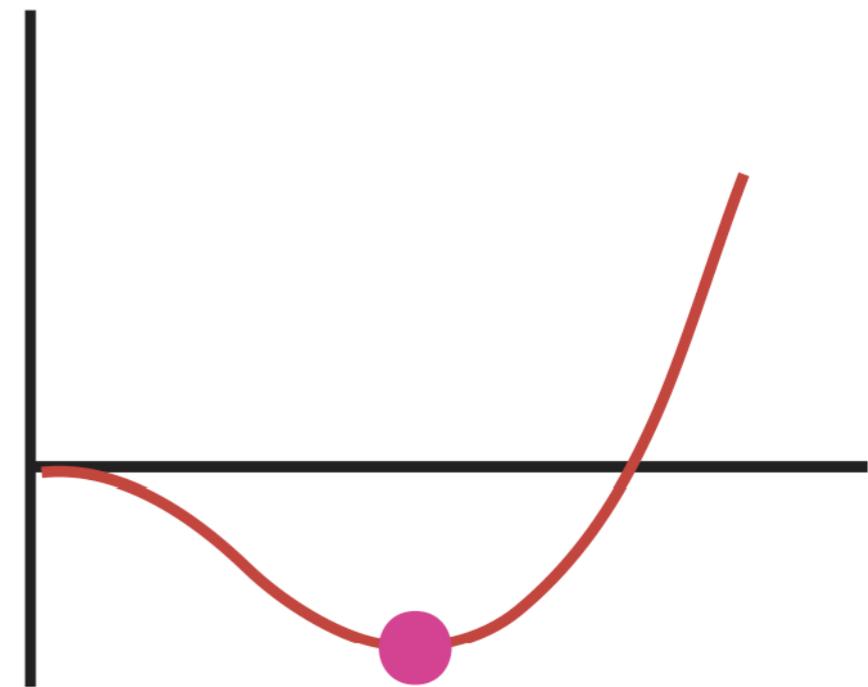
Here is the explanation for $SU(2) \times U(1)$ breaking given in the Standard Model:

Write the most general renormalizable potential for φ :

$$V(\varphi) = \mu^2 |\varphi|^2 + \lambda |\varphi|^4$$

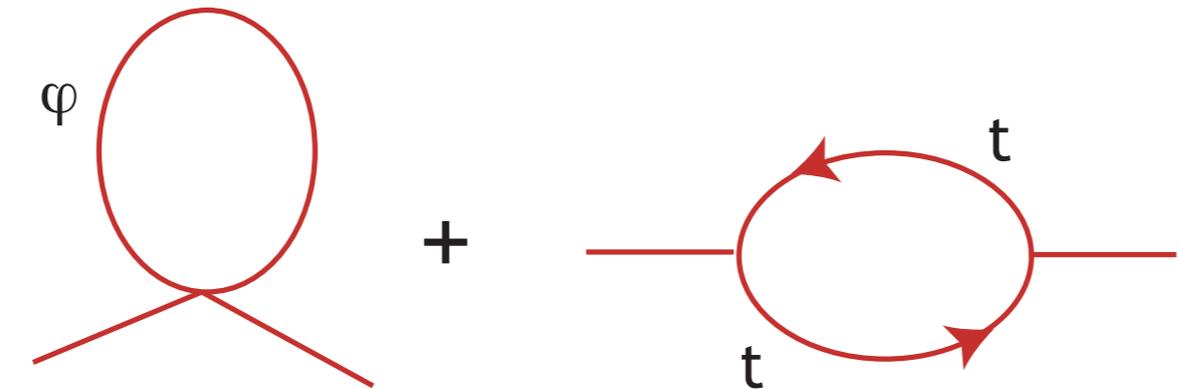
Assume $\mu^2 < 0$. Then the potential has the correct shape for symmetry breaking.

Why is $\mu^2 < 0$? That question cannot be addressed within the model.



We get into deeper trouble if we try to pursue this question by higher-order computation.

If we compute the first quantum corrections to the picture on the previous slide, we find

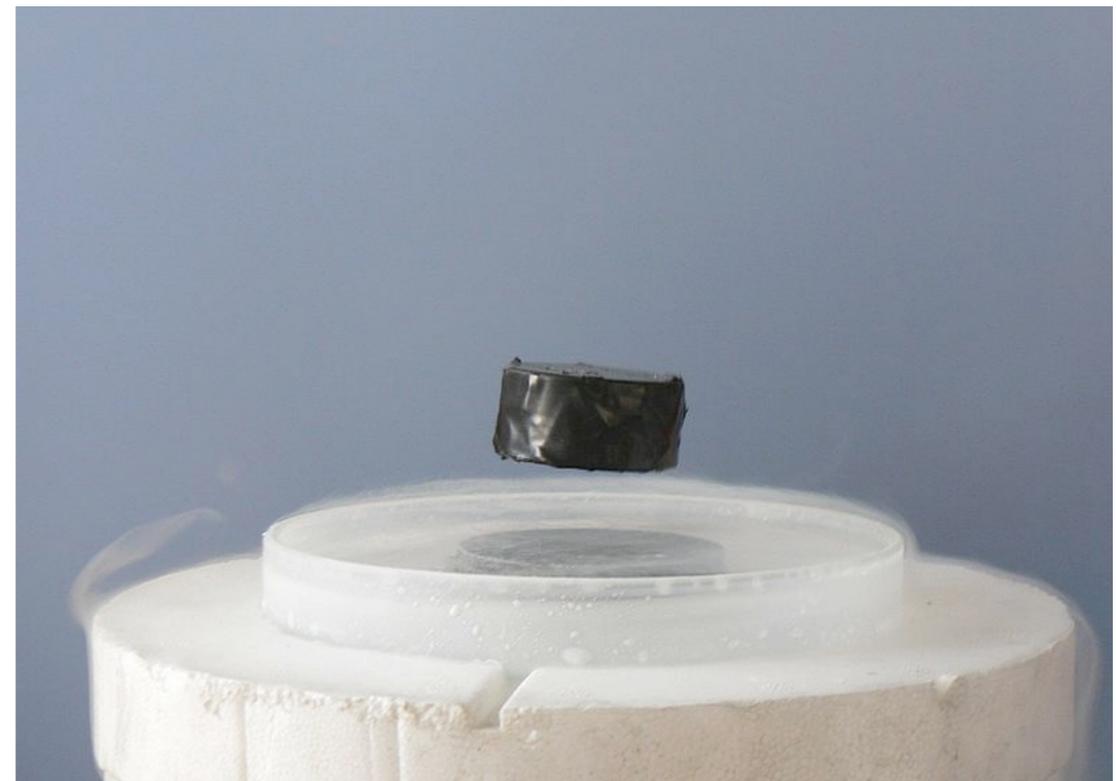


$$\mu^2 = \mu_{\text{bare}}^2 + \frac{\lambda}{8\pi^2} \Lambda^2 - \frac{3y_t^2}{8\pi^2} \Lambda^2 + \dots$$

So $|\mu^2| = (100 \text{ GeV})^2 \ll \Lambda^2$ seems ad hoc. It might be easier to understand if there were additional diagrams that cancel these at high energy. But, for this, we need new particles at the 1 TeV mass scale.

This problem is not new to high-energy physics. It is encountered in all systems where a symmetry is spontaneously broken, especially in condensed matter physics.

Superconductivity is a property of almost any metal at cryogenic temperatures. It was discovered by Kamerlingh Onnes in 1911 (in Hg) and was quickly seen to be associated with a sharp phase transition. However, the explanation was not understood for another 45 years.



In 1950, Landau and Ginzburg proposed a phenomenological theory of superconductivity, based on a scalar field – representing the electron condensate – coupled to a U(1) gauge field – electromagnetism. The condensate acquired a ground state expectation value at low temperatures

$$G[\varphi] = \int d^3x \left[|D_\mu \varphi|^2 + A(T) \mu^2 |\varphi|^2 + B |\varphi|^4 \right]$$

This theory successfully explained the form of the phase transition, the existence of Type I and Type II superconductors, the Meissner effect, the value of the critical current, and many other features.

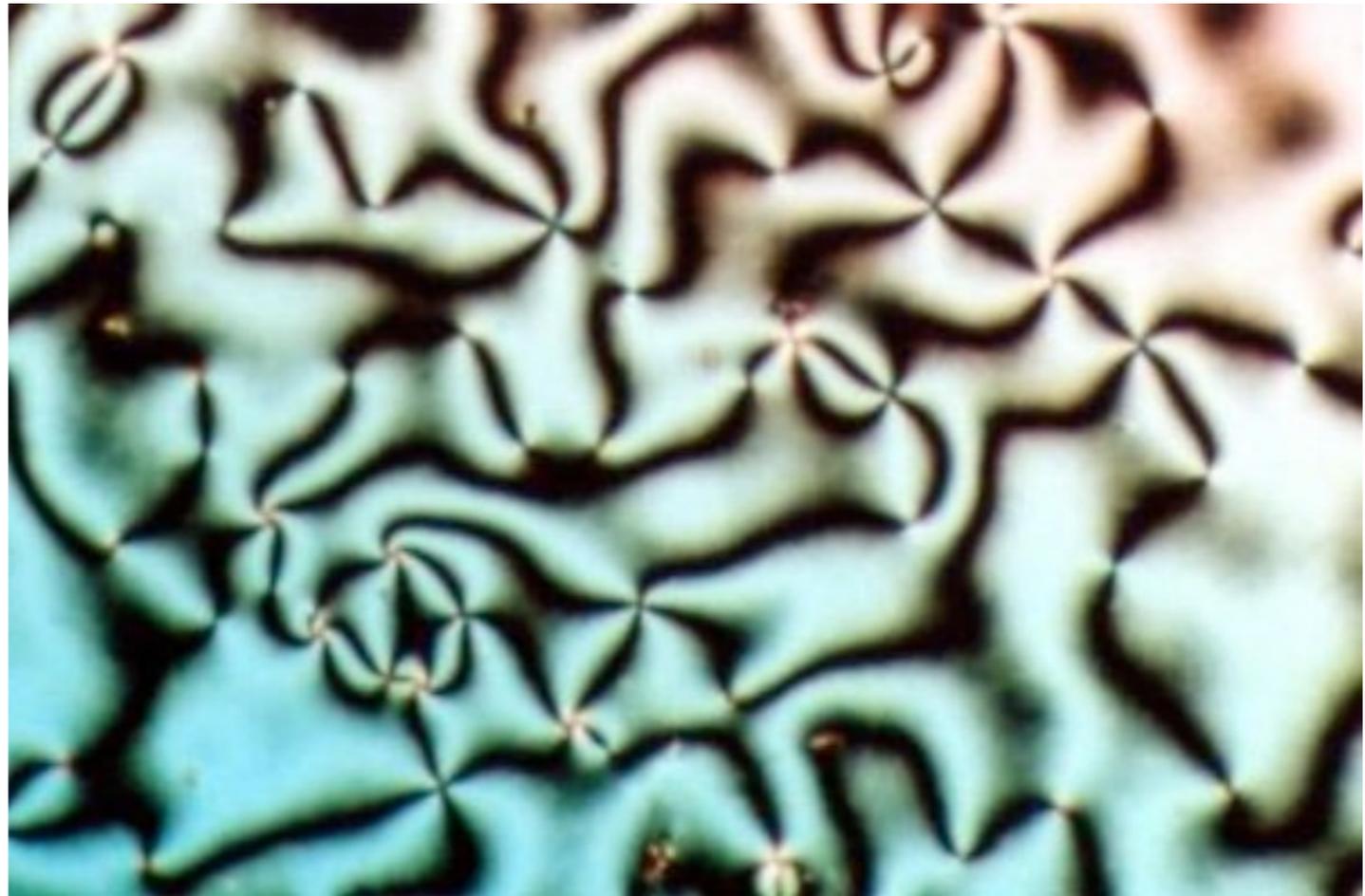
However, it could not explain why superconductivity occurs. That took until 1957, with the work of Bardeen, Cooper, and Schrieffer (BCS).

In our understanding of the phase transition to broken $SU(2) \times U(1)$, we are now at the Landau-Ginzburg stage.

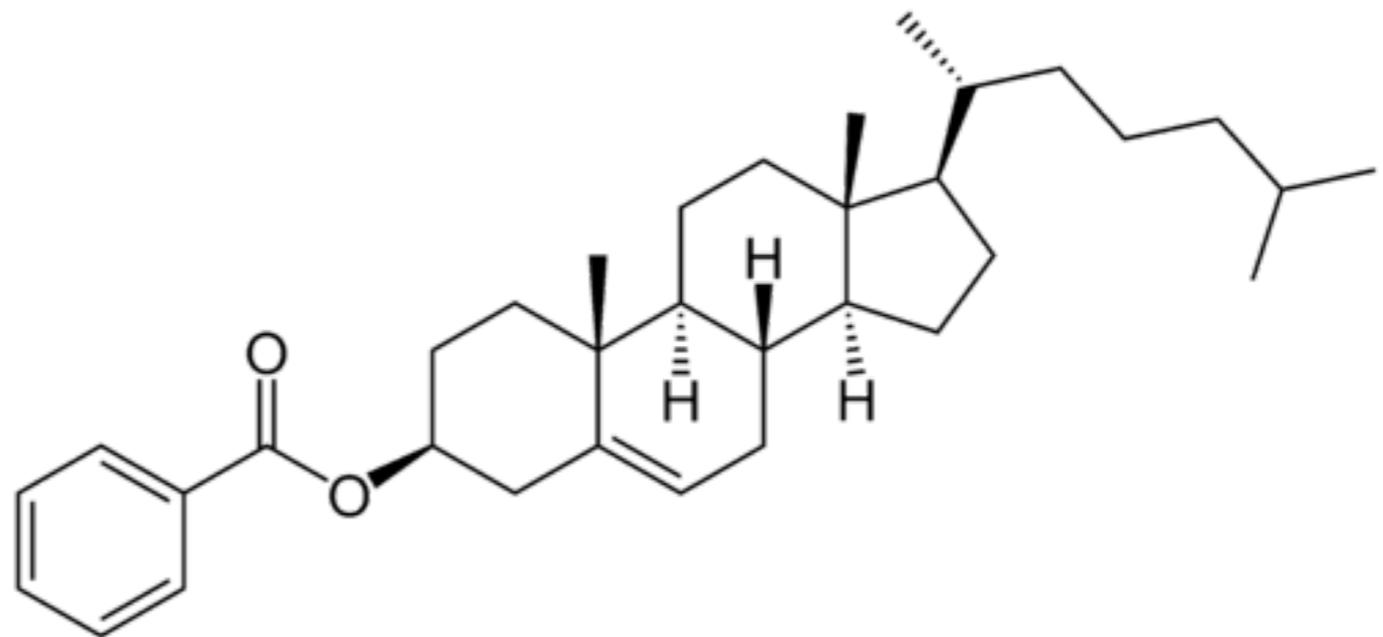
For superconductivity, physicists knew at least that the explanation had to be given in terms of the interactions of electrons and atoms.

For $SU(2) \times U(1)$, we do not know the basic ingredients out of which we must build a theory of the symmetry-breaking potential. On general principles, these must be some particles and fields. **We only know that we have not discovered them yet.**

nematic liquid
crystal



cholesterol
benzoate



There is an obstacle to setting up a quantum field theory in which we can compute the symmetry-breaking potential. If there is a Higgs scalar field, that field will have a divergent mass term, whose sign will then be ambiguous.

There are two solutions to this problem:

Find a symmetry that forbids radiative corrections to the scalar mass term

leads to → supersymmetry; Higgs as a Goldstone boson

Construct the scalar field out of more fundamental constituents

leads to → composite or strongly interacting Higgs

Ben Allanach will discuss these options later in the school.

The Standard Model has some special properties that we would like to preserve in more general models of symmetry breaking.

Look at the vector boson m^2 matrix

$$\begin{pmatrix} g^2 & & & \\ & g^2 & & \\ & & g^2 & -gg' \\ & & -gg' & g'^2 \end{pmatrix} \text{ on } \begin{pmatrix} A^1 \\ A^2 \\ A^3 \\ B \end{pmatrix}$$

This has

a zero eigenvalue, leading to $m_A = 0$

an SU(2) symmetry among (A^1, A^2, A^3) leading to
 $m_W = m_Z c_w$ (“custodial SU(2)”)

Custodial symmetry is an accidental property of the Standard Model.

In the Standard Model, if we write $\varphi = \begin{pmatrix} \varphi^1 + i\varphi^2 \\ \varphi^0 + i\varphi^3 \end{pmatrix}$
the Higgs potential depends only on

$$|\varphi|^2 = (\varphi^0)^2 + (\varphi^1)^2 + (\varphi^2)^2 + (\varphi^3)^2$$

An expectation value for φ^0 preserves the $SO(3)$ symmetry among the other components.

However, there are many other possible Higgs field assignments that also satisfy the requirements:

2- or multiple-Higgs doublet models:

In particular, the fermion-Higgs couplings of the Standard Model can be generalized. Let

$$L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \quad Q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$$

Then we can give mass to the quarks and leptons with

$$\mathcal{L} = -y_e L_a^\dagger \varphi_{1a} e_R - y_d Q_a^\dagger \varphi_{2a} d_R - y_u Q_a^\dagger \epsilon_{ab} \varphi_{3b} u_R + h.c.$$

where φ_1, φ_2 have $Y = +1/2$, φ_3 has $Y = -1/2$. In the Standard Model, we set $\varphi = \varphi_1 = \varphi_2 = \varphi_3^*$; however, we could as well introduce separate fields. The assignment

$\varphi_3^* = \varphi$ is inconsistent with supersymmetry, so in those models we must have at least two Higgs doublets.

Georgi-Machacek model:

Introduce $(2l+1)$ Higgs multiplets in an isospin l representation of $SU(2)$. For example, for $l = 1$,

$$X = \begin{pmatrix} \chi^{0*} & \xi^+ & \chi^{++} \\ -\chi^{+*} & \xi^0 & \chi^+ \\ \chi^{++*} & -\xi^{+*} & \chi^0 \end{pmatrix}$$

where the columns have $Y = -1, 0, 1$, respectively. The model can be arranged to have an $SU(2) \times SU(2)$ symmetry, and an expectation value

$$\langle X \rangle = V \cdot \mathbf{1}$$

breaks this down to the diagonal $SU(2)$. We need at least one $l = 1/2$ multiplet (equivalent to the Standard Higgs) to give mass to fermions. Otherwise, we can add fields with any l .

Technicolor:

Introduce a copy of QCD with two massless flavors (U,D), with the left-handed fields in a weak-interaction SU(2) doublet, and $M_\rho = 2 \text{ TeV}$. This model has SU(2)xSU(2) chiral symmetry, broken to the diagonal SU(2) as in ordinary QCD. This breaks SU(2)xU(1). The W mass generated is

$$m_W = \frac{gF_\pi}{2} \quad \text{with} \quad F_\pi = 250 \text{ GeV}$$

(This specific model is excluded by the measurement of S in precision electroweak, and because it contains no light Higgs boson.)

“Little Higgs”:

Introduce new strong interactions at 10 TeV with the chiral symmetry $SU(4)$ (e.g. 4 gauge multiplets in a real representation of the gauge group), such that strong interaction will break this spontaneously to $SO(4)$.

This model has $15 - 6 = 9$ pion-like Goldstone bosons.

$SO(4) = SU(2) \times SU(2)$. The 9 bosons belong to the representations

$$(0, 0) + (0, \frac{1}{2}) + (\frac{1}{2}, 0) + (\frac{1}{2}, \frac{1}{2})$$

ie. $1 + 2 + 2 + 4$ states

If we gauge the first $SU(2)$, the $(\frac{1}{2}, \frac{1}{2})$ multiplet of bosons can be identified with the Higgs field.

So, there are many possible forms for the symmetry-breaking sector, which potentially involve many new fields. But, now that we have discovered the Higgs boson and measured some of its properties, shouldn't these be excluded ?

There is a barrier: Haber's Decoupling Theorem:

If the spectrum of the Higgs sector contains one Higgs boson of mass m_h and all other particles have mass at least M , then the influence of these particles on the properties of the light Higgs boson is proportional to

$$m_h^2/M^2$$

Then the effects of new physics at 1 TeV on the properties of the Higgs are at the percent level.

Proof of the theorem:

Integrate out the heavy fields. This gives a general Lagrangian with the Standard Model field content and $SU(2) \times U(1)$ symmetry. But, the Standard model is already the most general renormalizable model meeting these conditions. So (after we have measured the effective Standard Model parameters), the only effects of new fields come from dimension 6 operators, which give effects of size q^2/M^2 .

This is depressing but not hopeless.

In this context, the current 20-30% agreement of the Higgs properties with the predictions of the Standard Model is completely expected.

But, more accurate experiments could potentially show deviations in all of the visible Higgs decay modes.

Begin with 2 Higgs doublet models. In SUSY, e.g., one Higgs φ_d gives mass to e,d, the other φ_u gives mass to u.

Now there are 8 Higgs degrees of freedom, of which 3 are eaten by W,Z. We also add a parameter: $\tan \beta = v_u/v_d$

The physical states are mixtures of the remaining fields
 fields, with mixing angle

$$\alpha : h^0, H^0$$

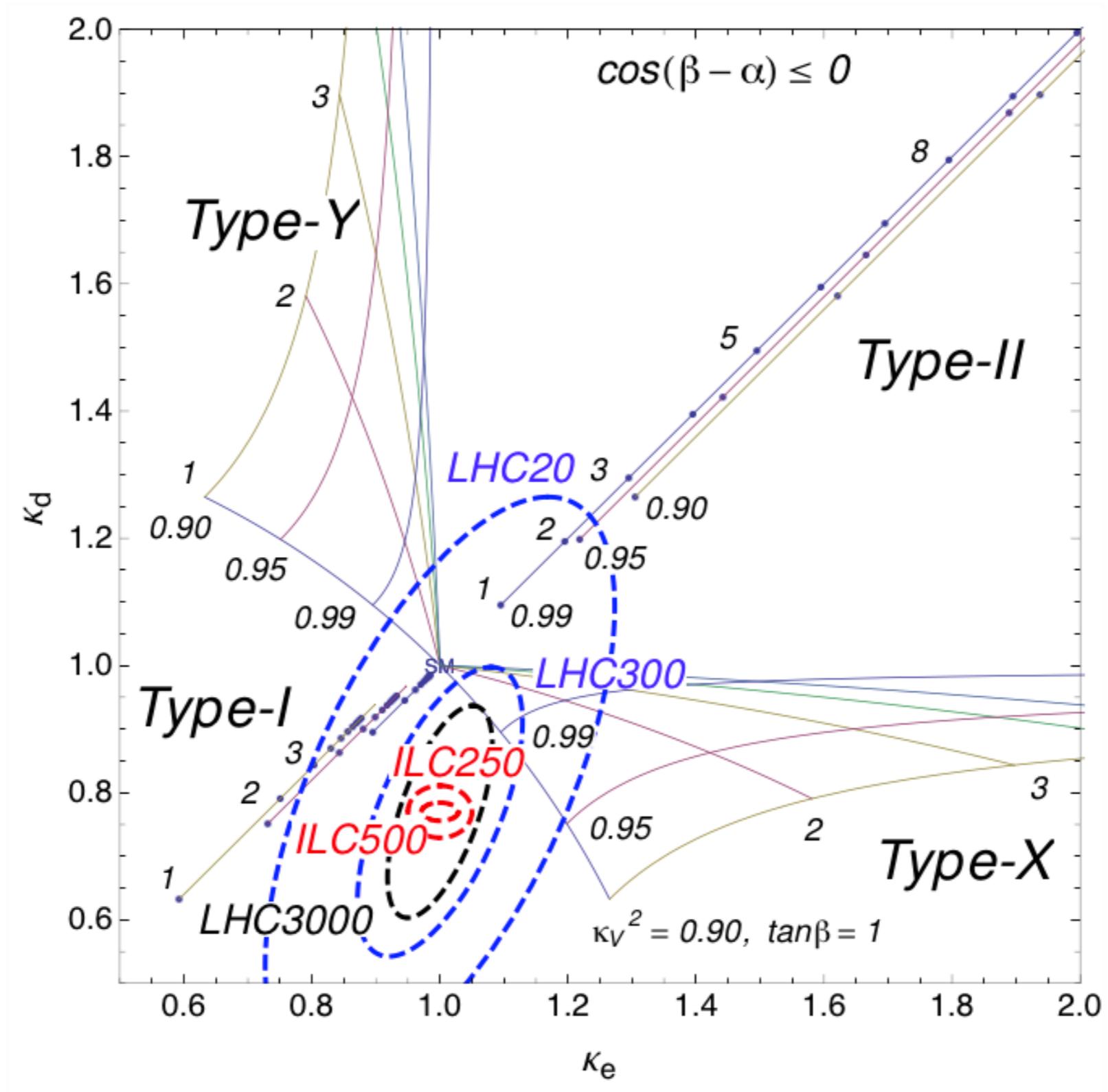
$$\beta : \pi^0, A^0 \quad \pi^\pm, H^\pm$$

Then the coupling modifications are

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

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

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

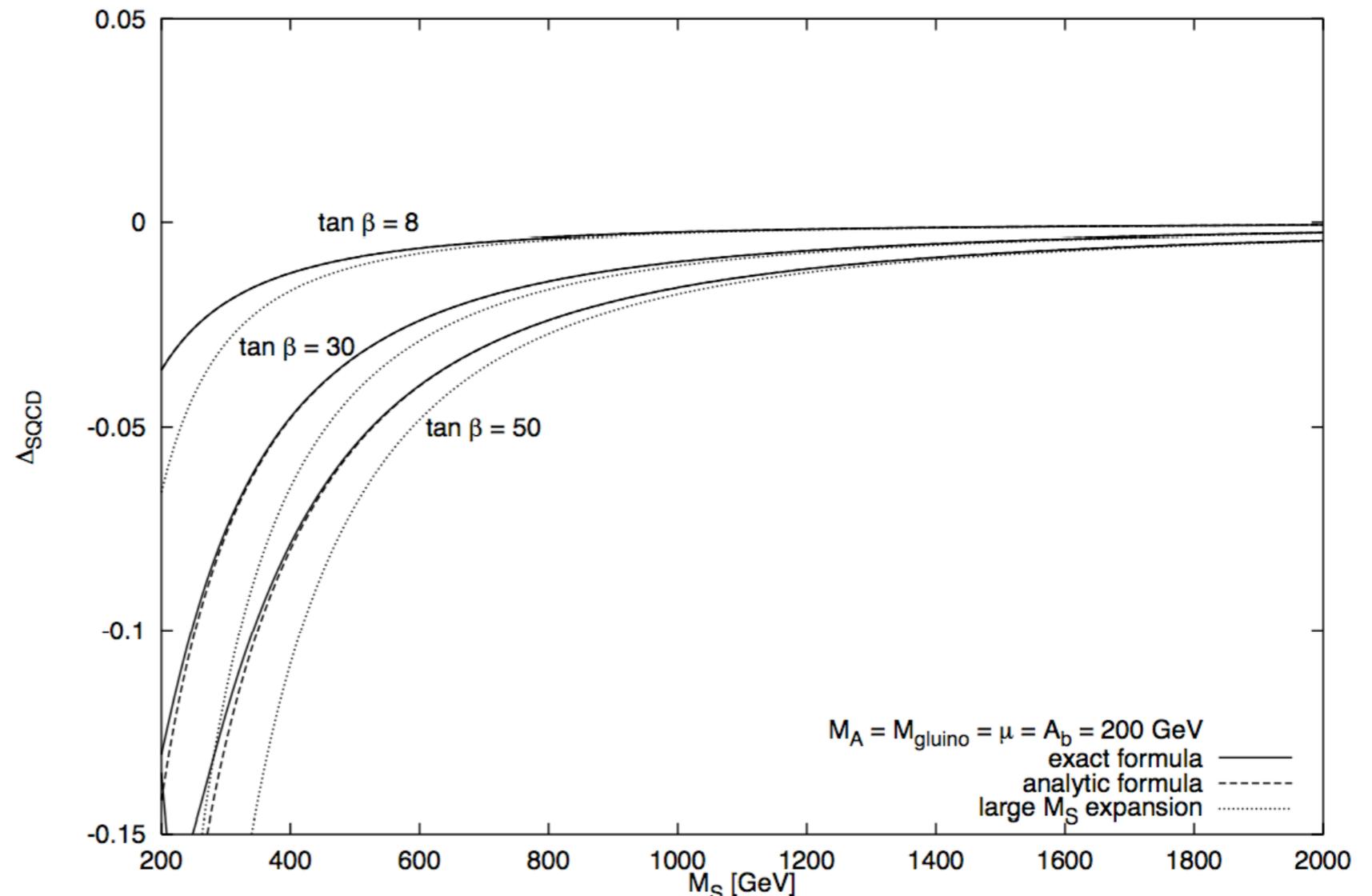


Kanemura, Tsumura, Yagyu, Yokoya

Then, typically, the corrections decrease as the SUSY mass scale becomes larger, for example

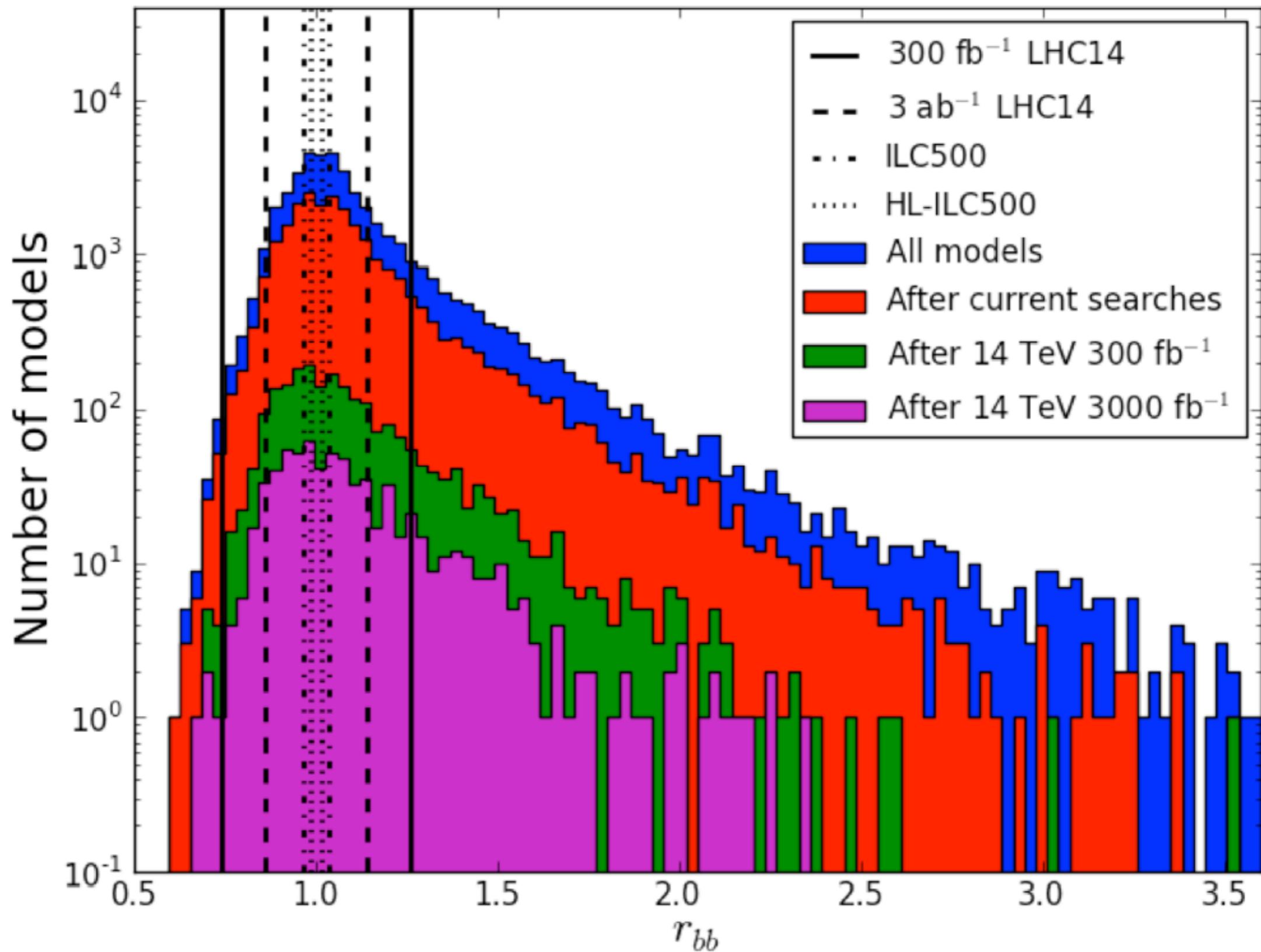
$$\frac{g_{hbb}}{g_{h_{\text{SM}}bb}} = \frac{g_{h\tau\tau}}{g_{h_{\text{SM}}\tau\tau}} \simeq 1 + 40\% \left(\frac{200 \text{ GeV}}{m_A} \right)^2$$

Loop with b,t squarks and gluinos can also modify this vertex, especially at large $\tan \beta$.



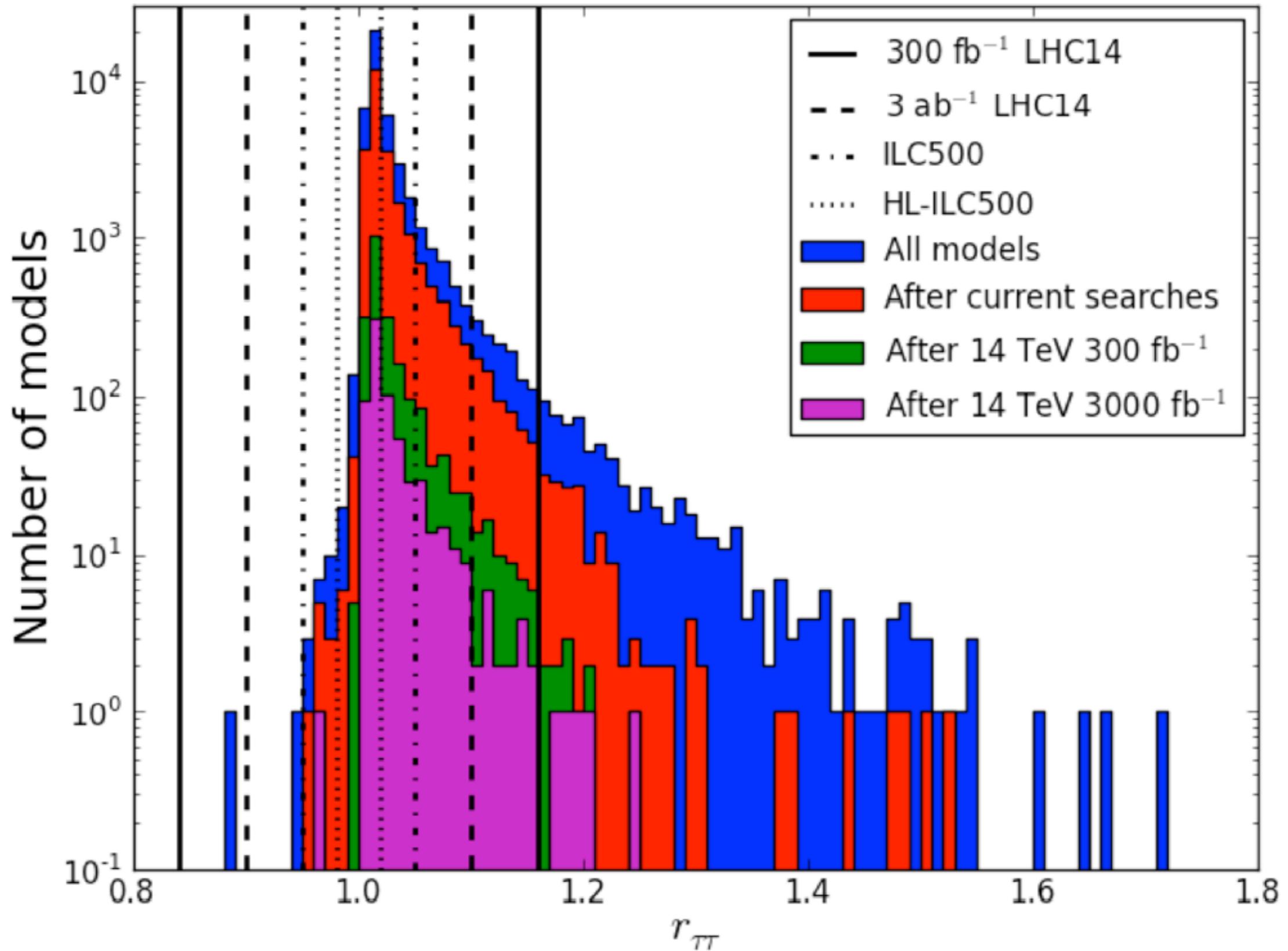
Haber, Herrero,
Logan, Penaranda,
Rigolin, Temes

$$\Gamma(h \rightarrow b\bar{b})$$



Cahill-Rowley, Hewett, Ismail, Rizzo

$$\Gamma(h \rightarrow \tau^+ \tau^-)$$



Cahill-Rowley, Hewett, Ismail, Rizzo

In 2 Higgs doublet models, corrections to the hVV are usually small. These are proportional to the contribution of each state h, H to the W, Z masses, and h has the largest vacuum expectation value. In SUSY,

$$g(hVV) = 1 + \mathcal{O}\left(\frac{m_Z^4}{m_A^4}\right)$$

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 1% level corrections (Craig and McCullough).

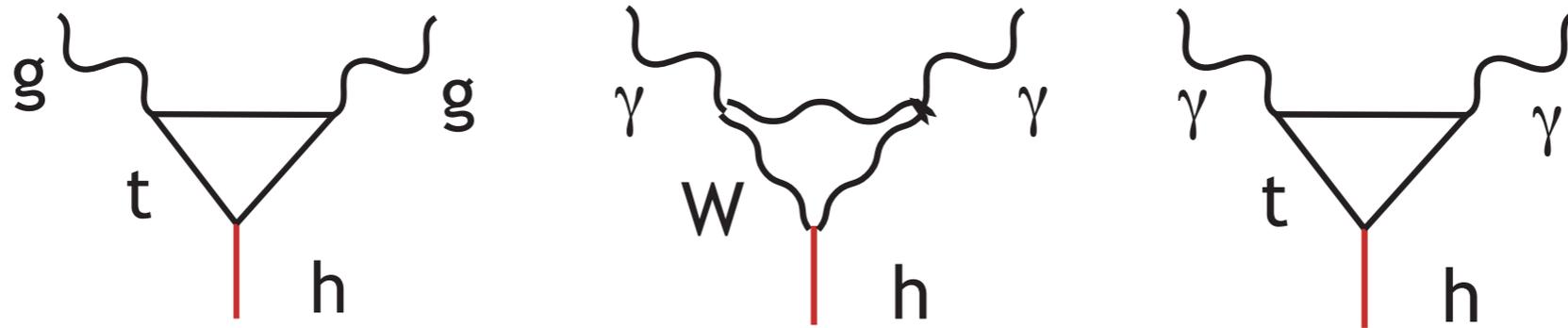
If the Higgs is a composite Goldstone boson, these couplings are corrected by ($f \sim 1$ TeV)

$$g(hVV) = (1 - v^2/f^2)^{1/2} \approx 1 - v^2/2f^2 \approx 1 - 3\%$$

The decays

$$h \rightarrow gg, \quad h \rightarrow \gamma\gamma, \quad h \rightarrow \gamma Z^0$$

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

$$g(hgg)/SM = 1 + 2.9\% \left(\frac{1 \text{ TeV}}{m_T} \right)^2$$

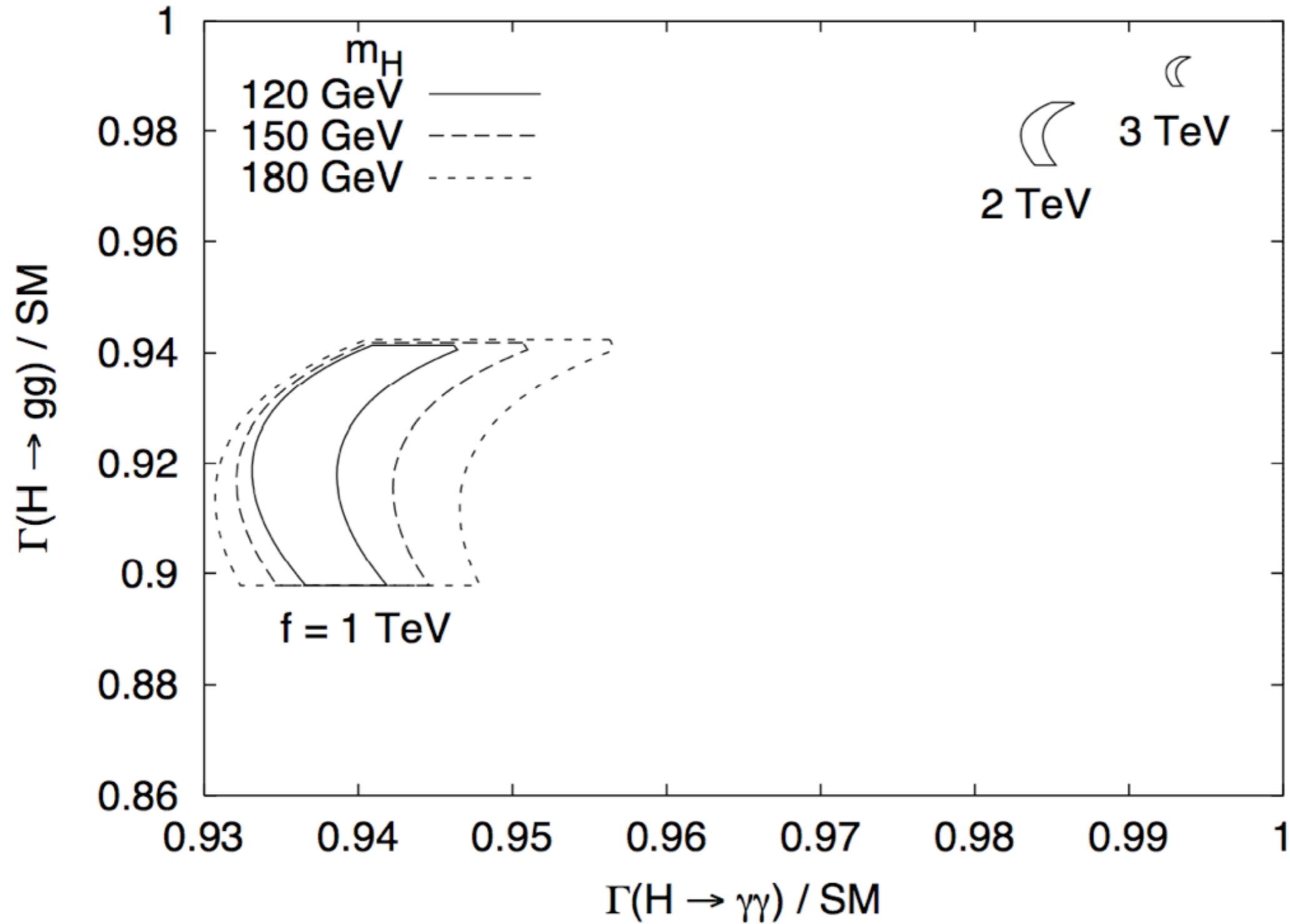
$$g(h\gamma\gamma)/SM = 1 - 0.8\% \left(\frac{1 \text{ TeV}}{m_T} \right)^2$$

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

$$g(hgg)/SM = 1 - (5 - 9\%)$$

$$g(h\gamma\gamma)/SM = 1 - (5 - 6\%)$$

Littlest Higgs model

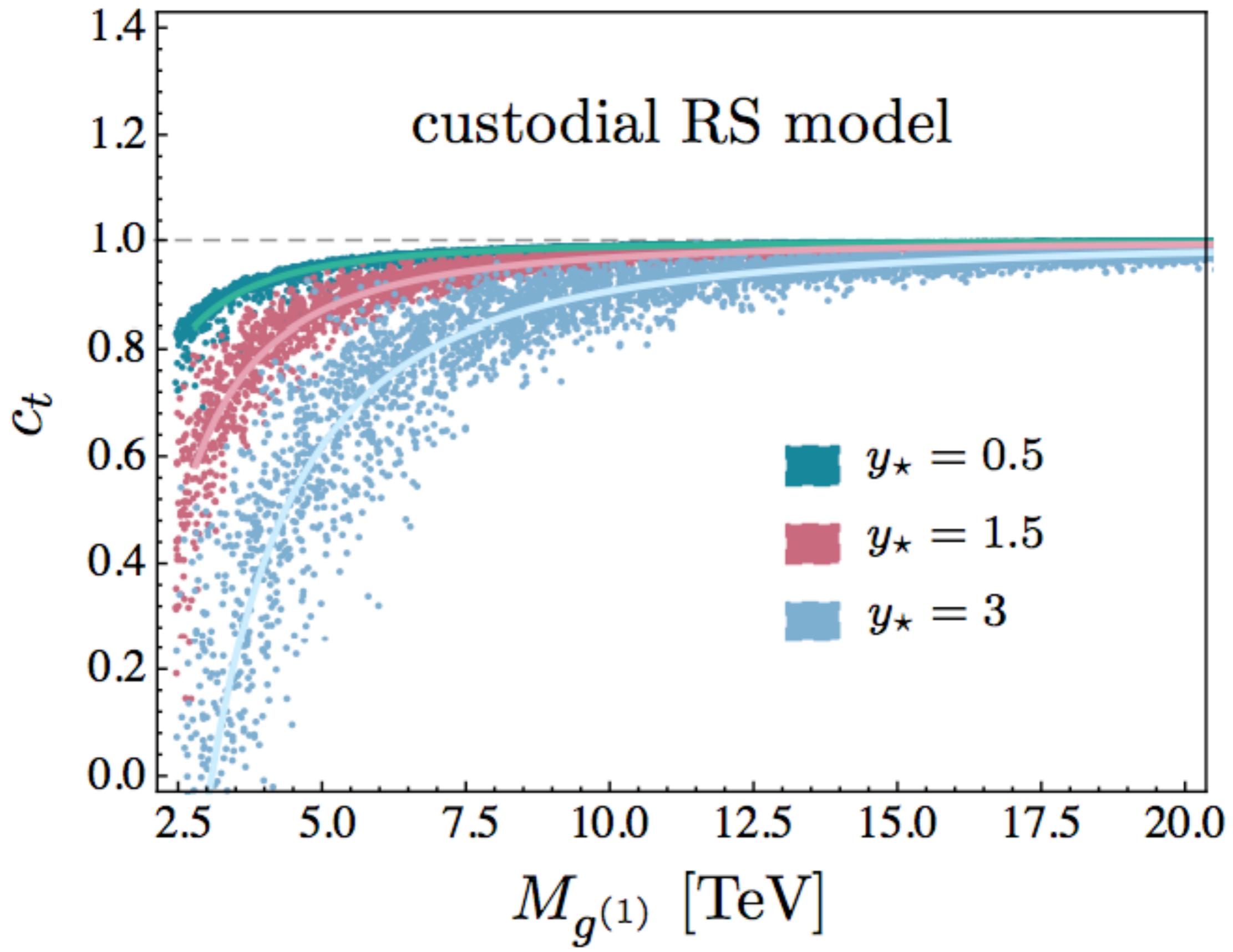


Han, Logan, McElrath, Wang

In composite Higgs models, the shifts in the $\gamma\gamma$ and gg partial widths come both from the modification of the top quark coupling and from the contributions of heavy vectorlike particles.

These effects are disentangled by direct measurement of the Higgs coupling to $t\bar{t}$.

Substantial effects are expected in 5-dimensional models, such as Randall-Sundrum models, especially those that have a special role for the top quark in $SU(2)\times U(1)$ symmetry breaking.



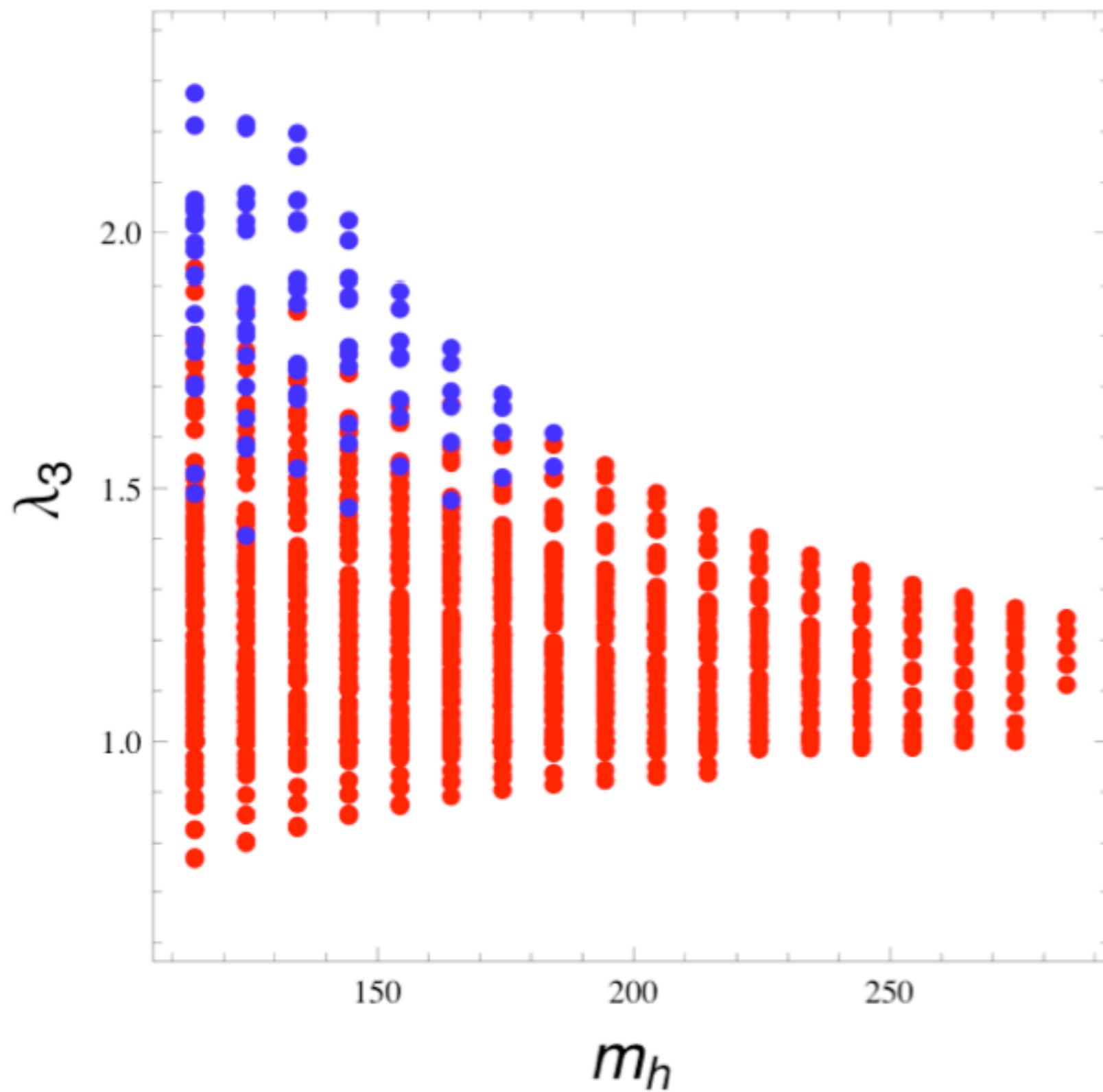
Malm, Neubert, Schmell

The Higgs self-coupling is a special case in this story.

Whereas we can expect the other Higgs couplings to be measured at the percent level, the hhh coupling is much more difficult to access.

However, order-1 deviations in the hhh coupling are expected in some scenarios, in particular, in models of baryogenesis at the electroweak scale. These may be the only models of baryogenesis testable with accelerator data.

λ_3 vs m_h for $\xi > 1$



Noble and Perelstein

The result of this survey is that each Higgs coupling has **its own personality** and is guided by different types of new physics. This is something of a caricature, but, still, a useful one.

fermion couplings - multiple Higgs doublets

gauge boson couplings - Higgs singlets, composite Higgs

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

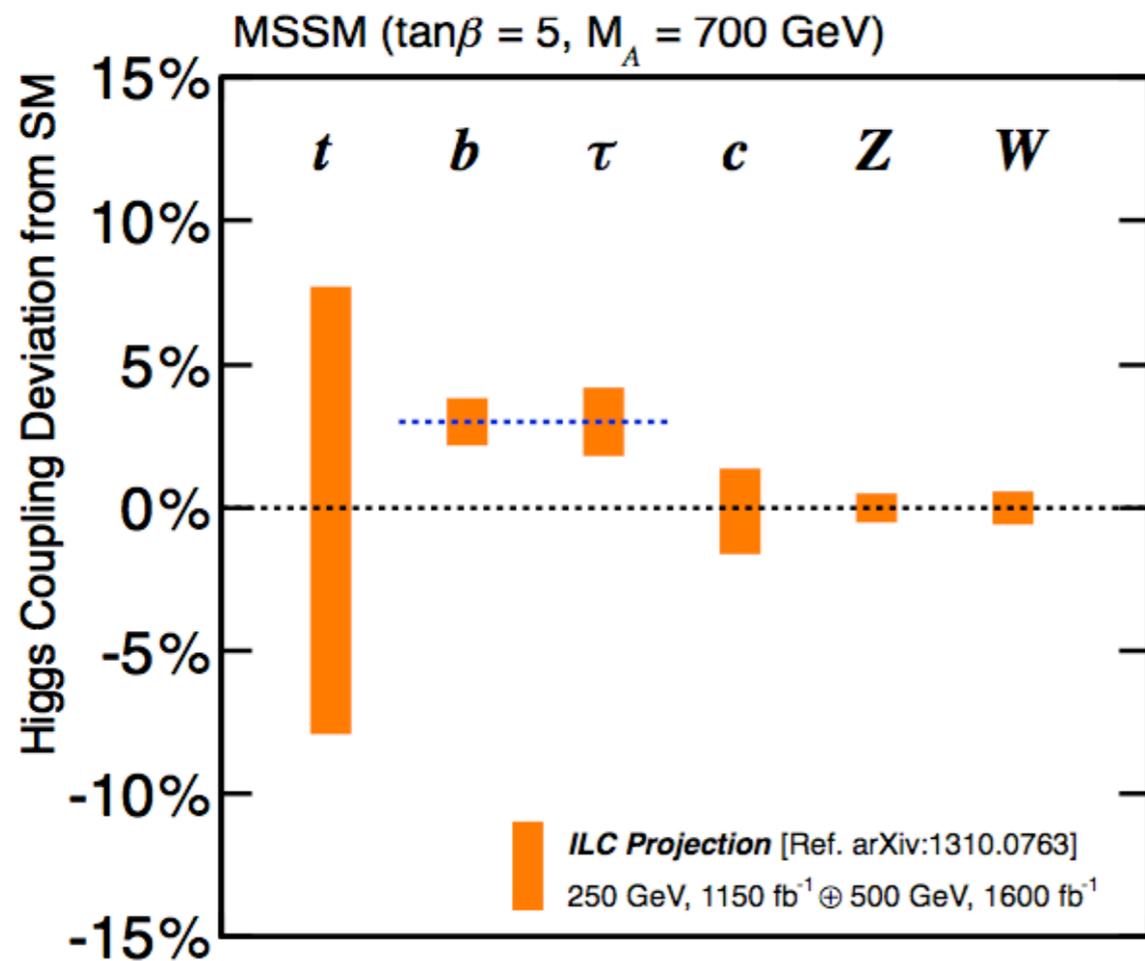
tt coupling - Higgs/top compositeness

hhh coupling (large deviations) - baryogenesis

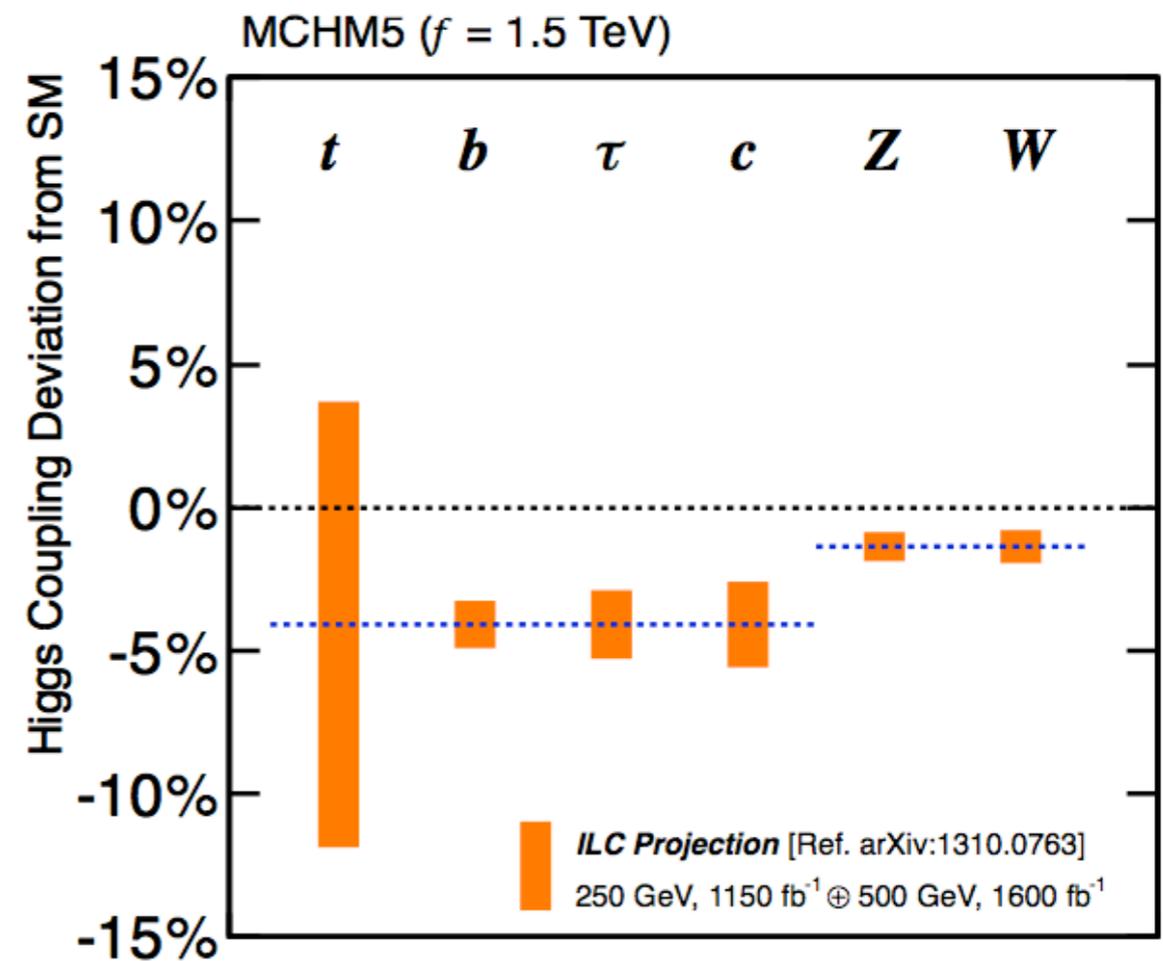
Putting all of these effects together, we find patterns of deviations from the SM predictions that are different for different schemes of new physics.

For example:

SUSY



Composite Higgs

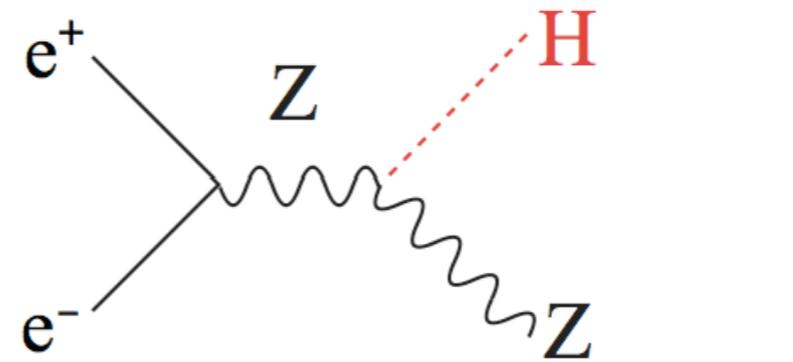


Kanemura, Tsumura, Yagyu, Yokoya

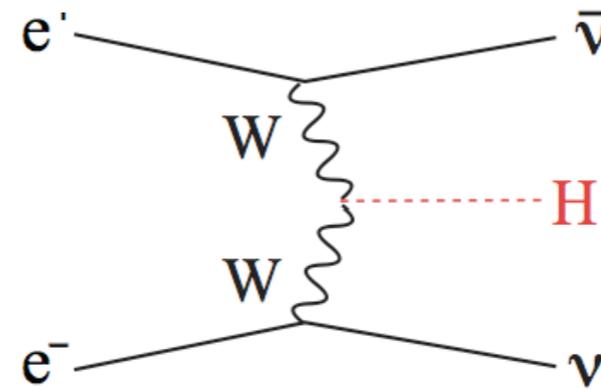
Given the interest of this program and the difficulty of reaching the required levels of precision at the LHC, it is not surprising that there are a number of proposals of new e^+e^- colliders specifically addressing precision Higgs measurements.

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

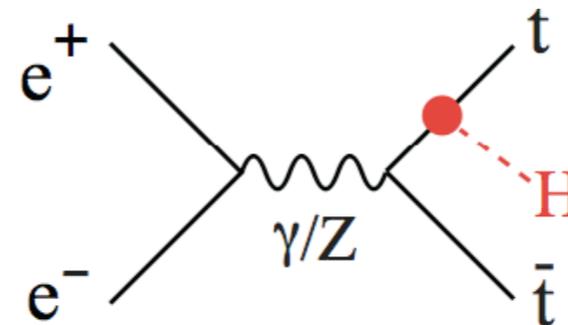
Higgsstrahlung



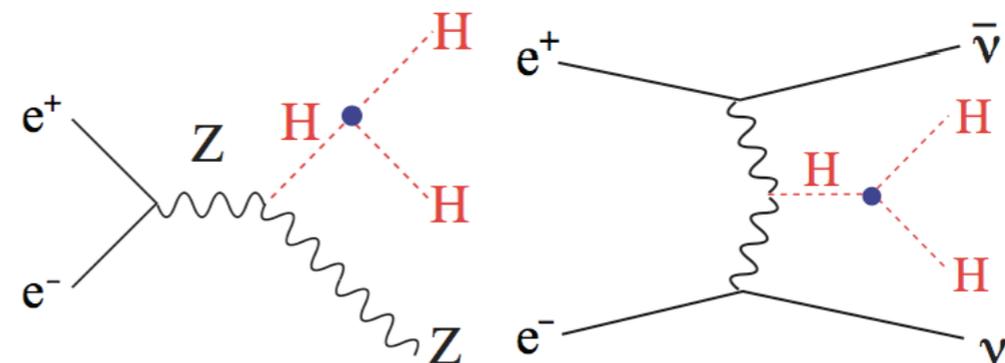
vector boson fusion



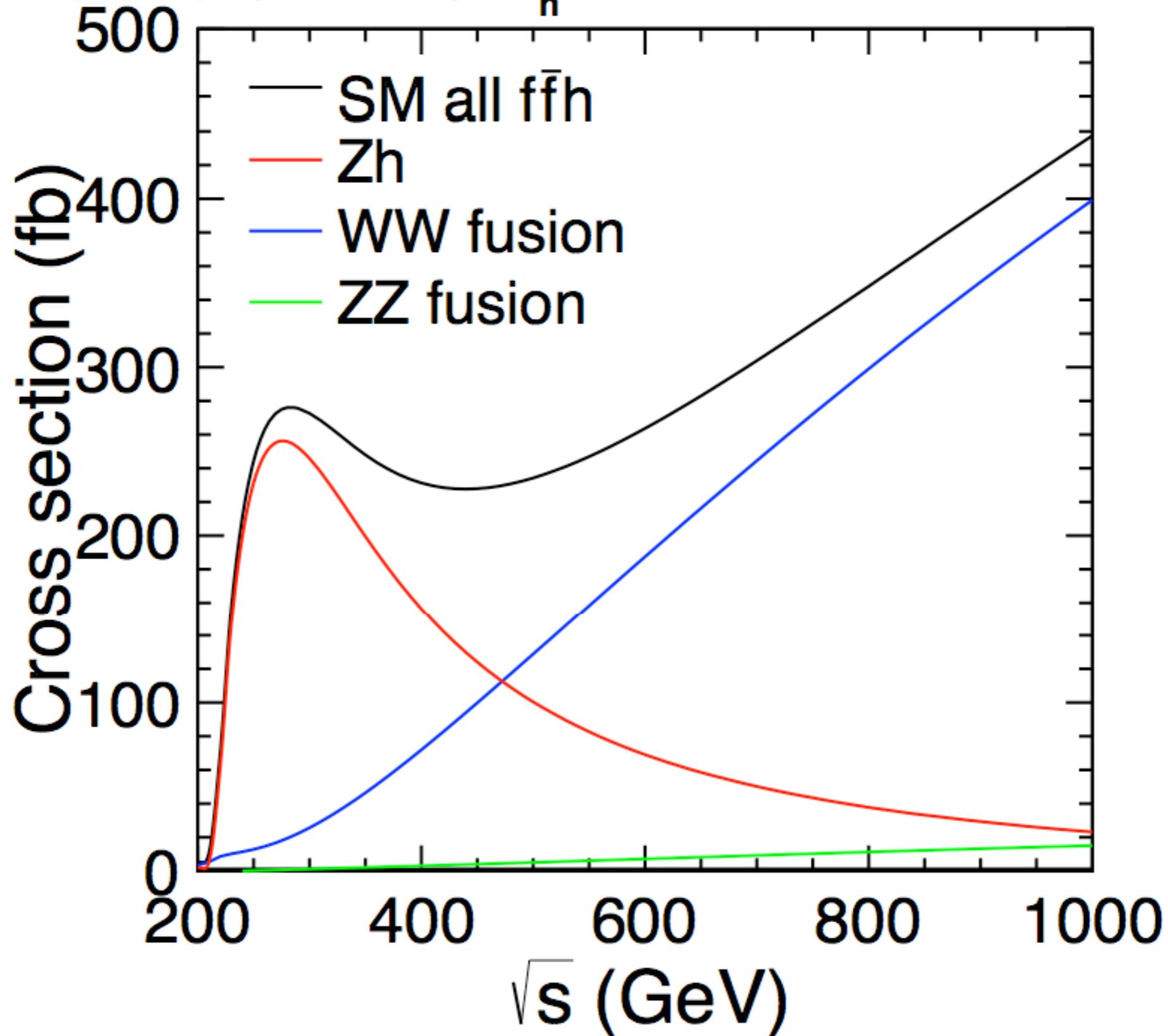
associated production with top



Higgs pair production



$P(e^-, e^+) = (-0.8, 0.2)$, $M_h = 125 \text{ GeV}$



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:

- precision normalization of Higgs couplings

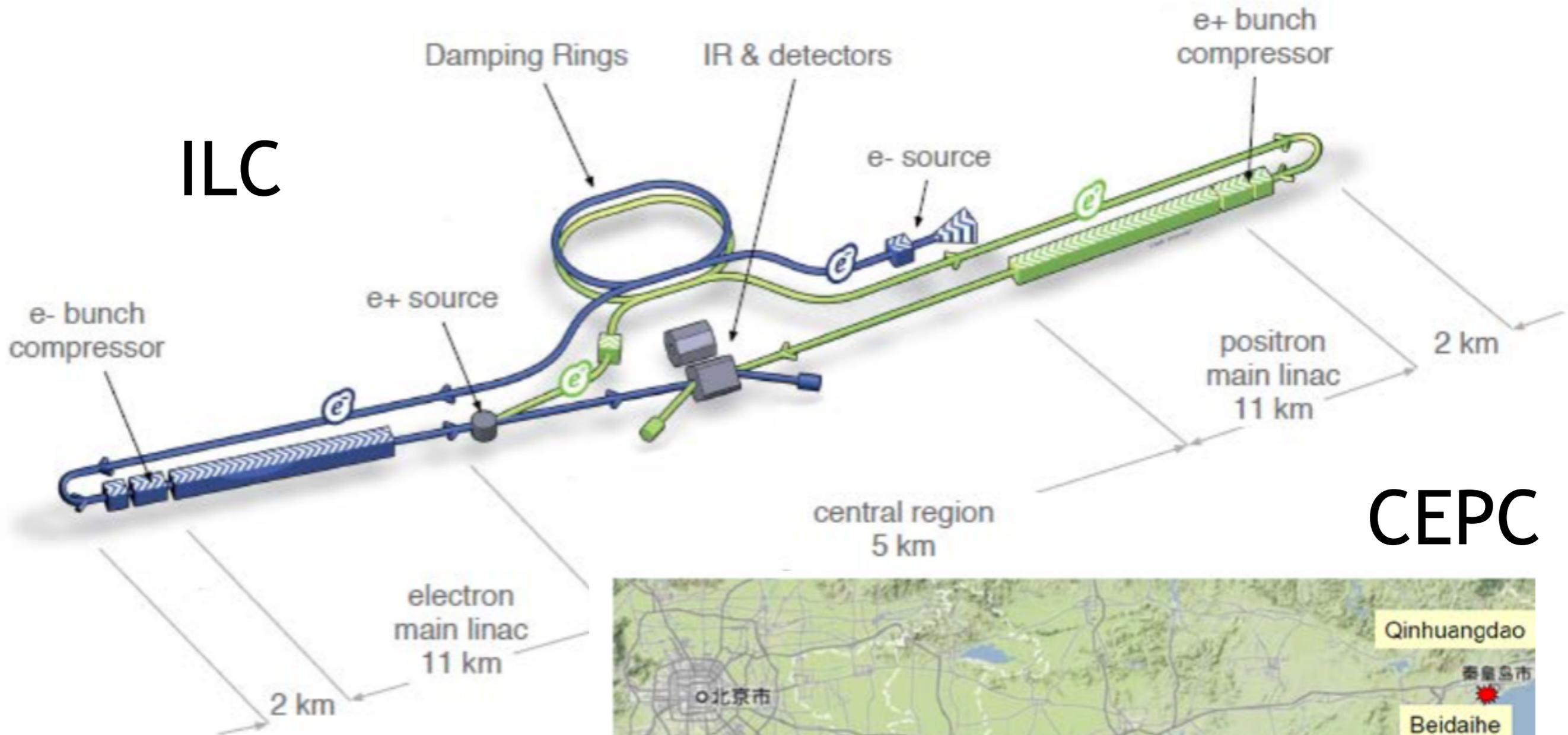
associated production with top:

- access to the Higgs coupling to top

Higgs pair production:

- access to the Higgs self-coupling

ILC



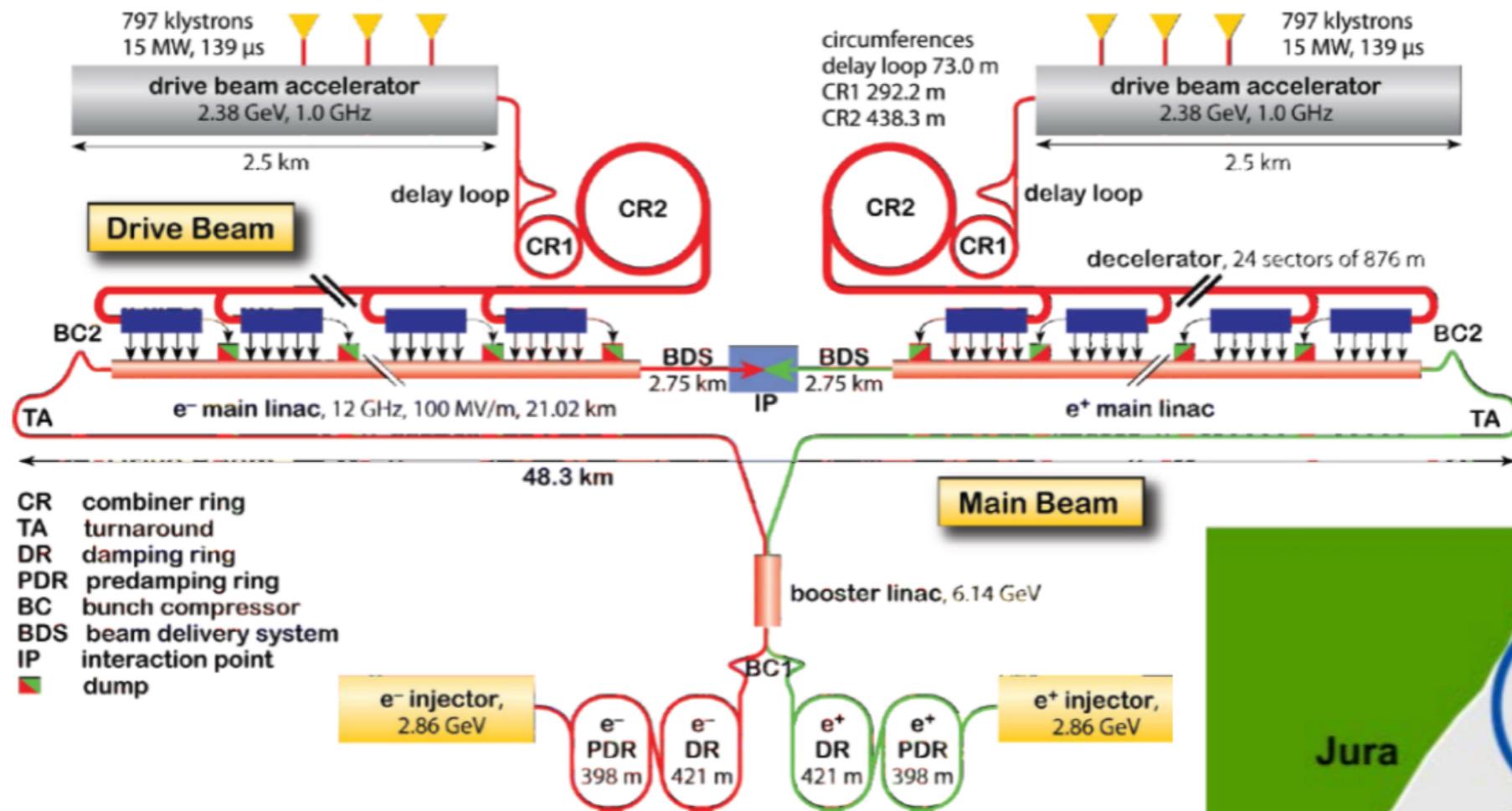
CEPC

new accelerators
proposed in Asia



- 300 km from Beijing
- 3 h by car
- 1 h by train

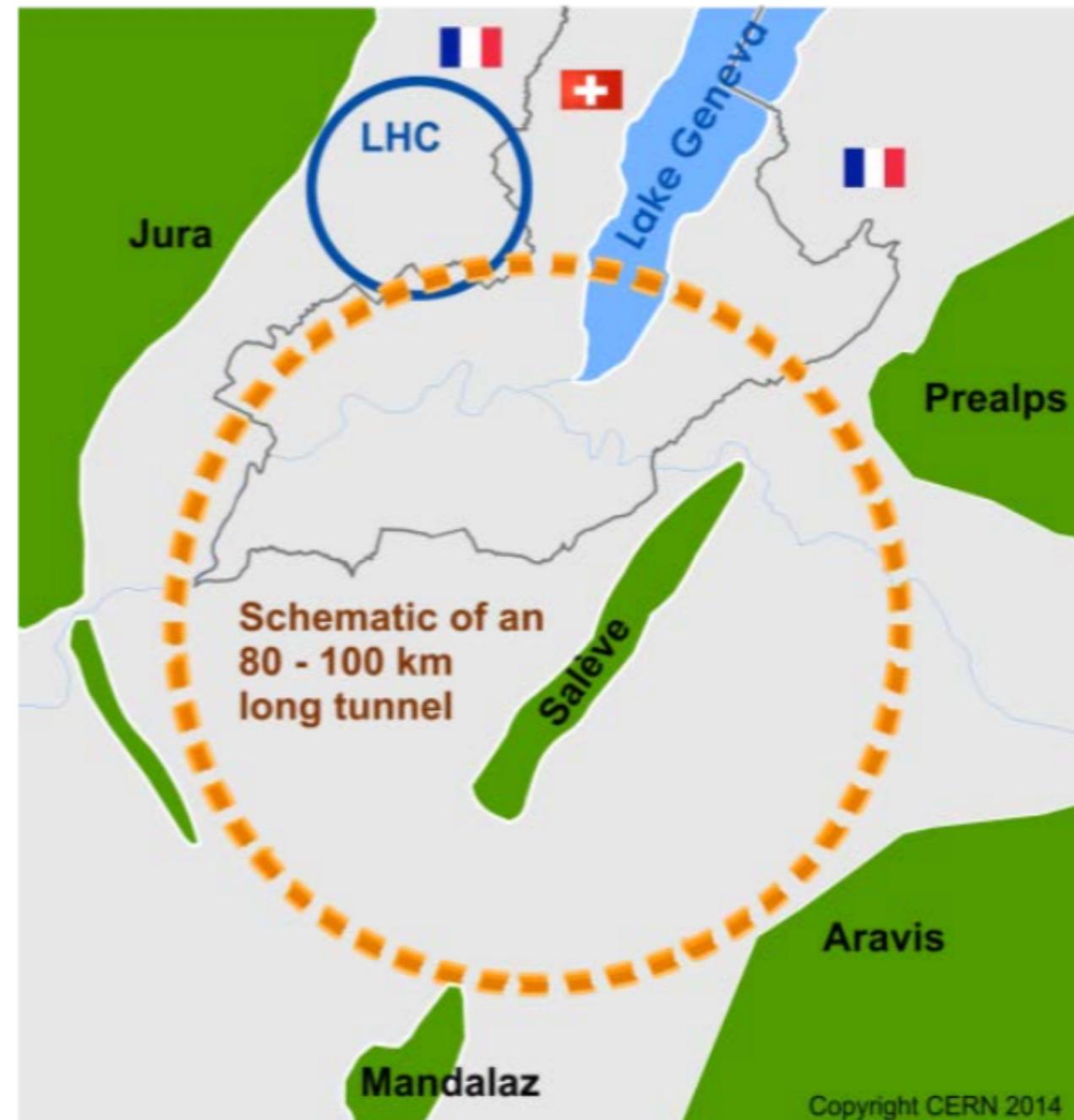




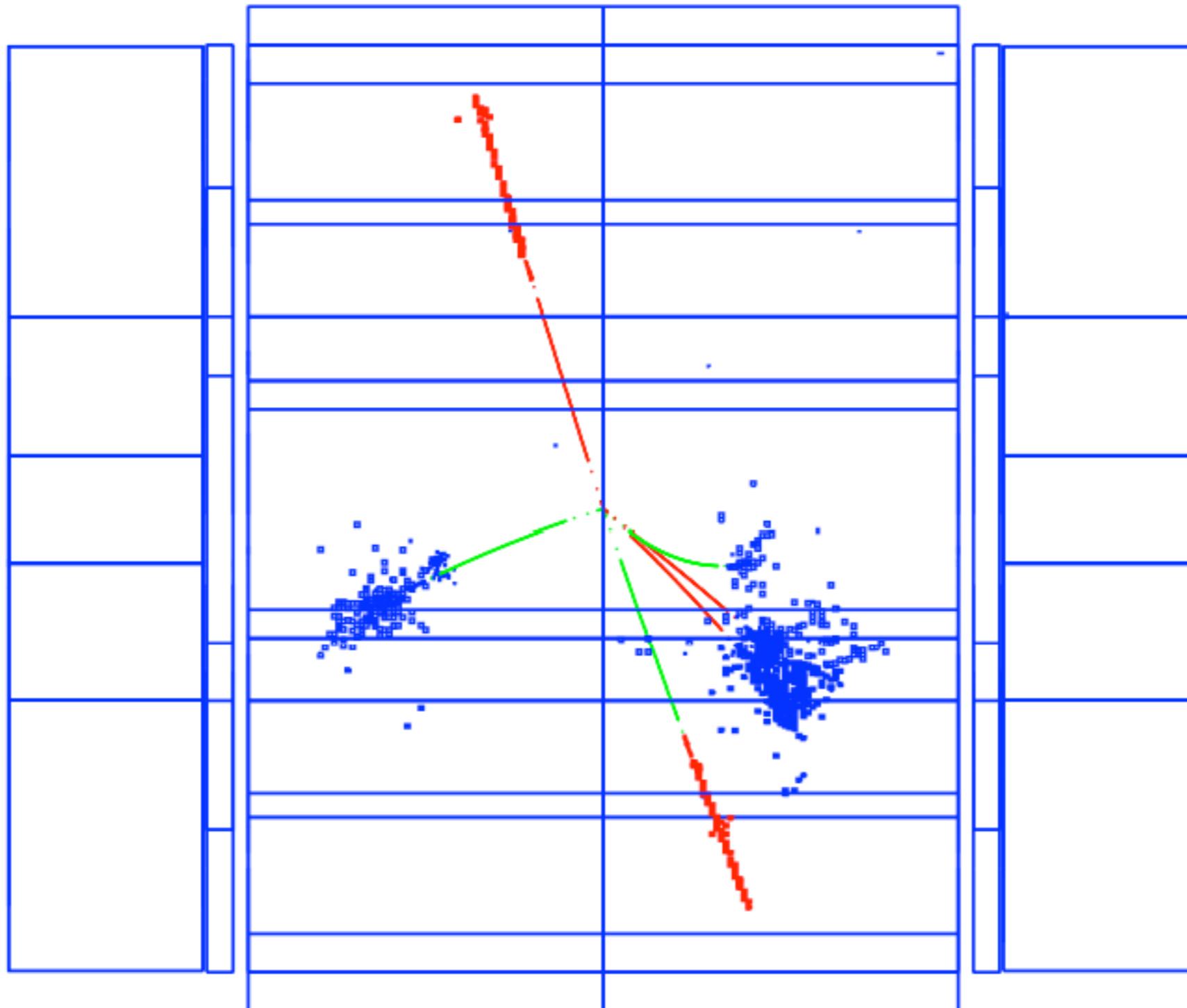
FCC-ee

CLIC

new accelerators proposed
for the next CERN project
after LHC



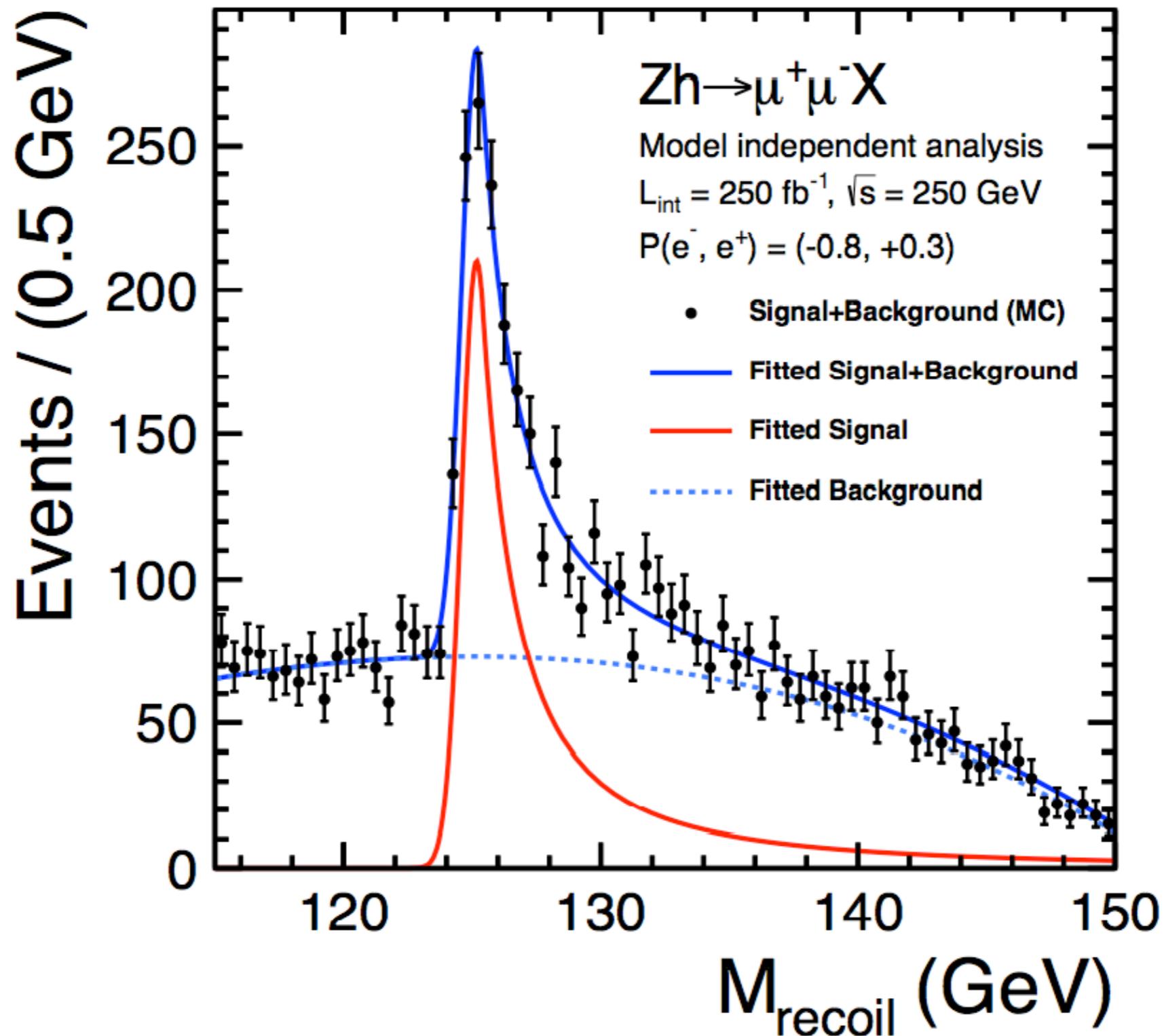
$$e^+e^- \rightarrow Zh \rightarrow (\mu^+\mu^-)(\tau^+\tau^-)$$



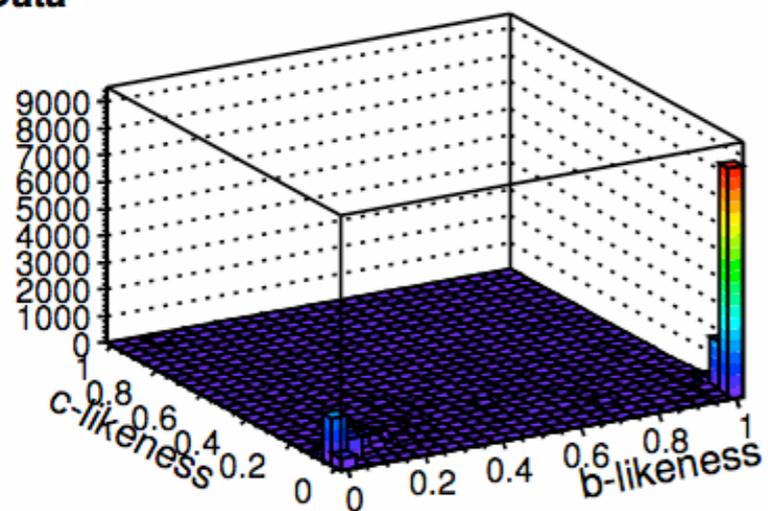
1000

ILD simulation

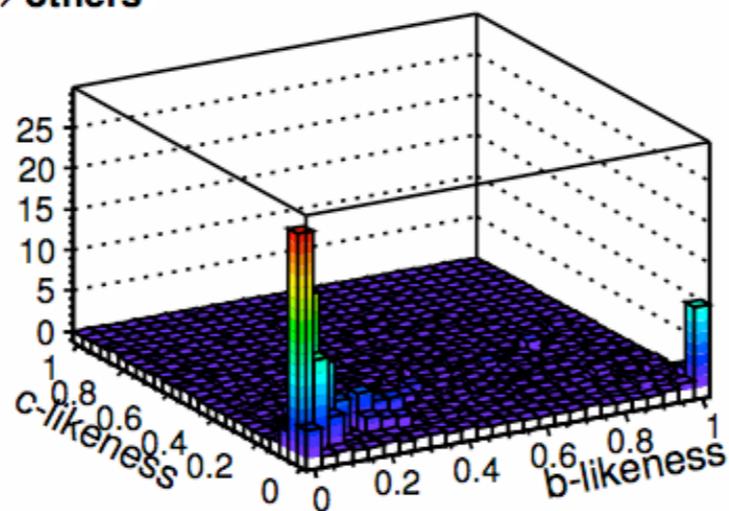
m_h to 15 MeV using recoil against Z
(corresponds to 0.1% systematic error in $g(hWW)$)



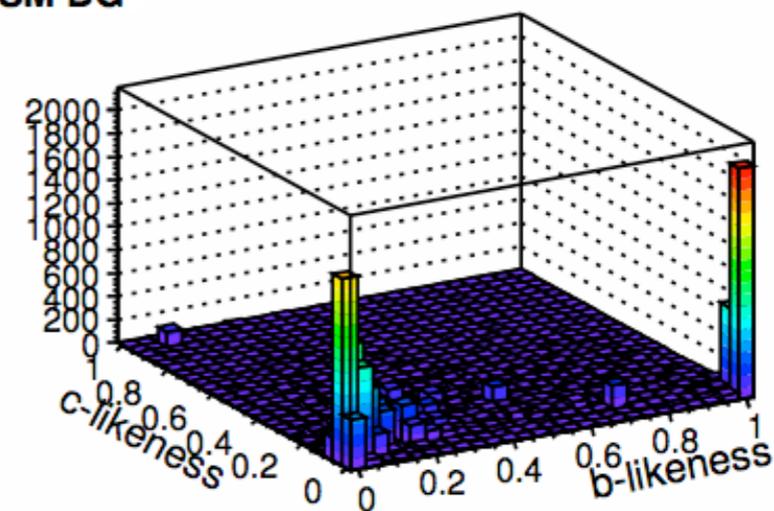
Data



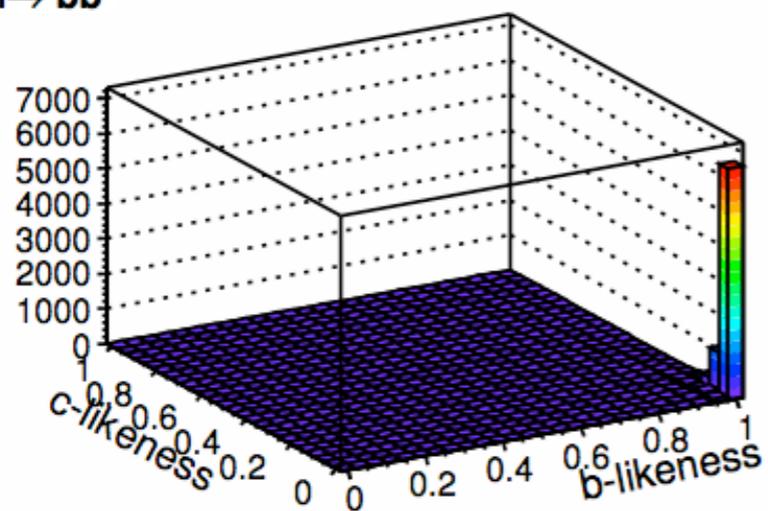
h → others



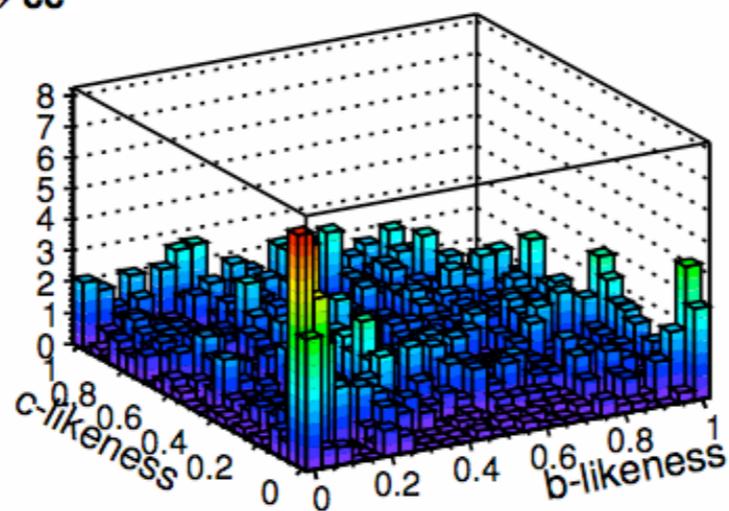
SM BG



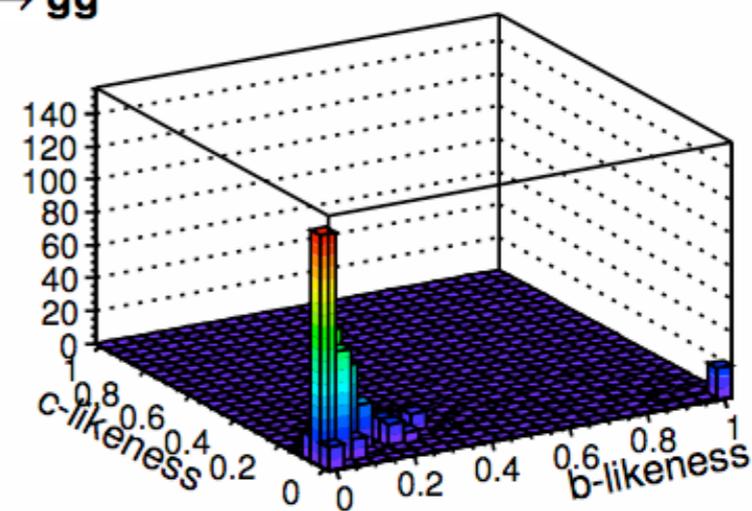
h → bb

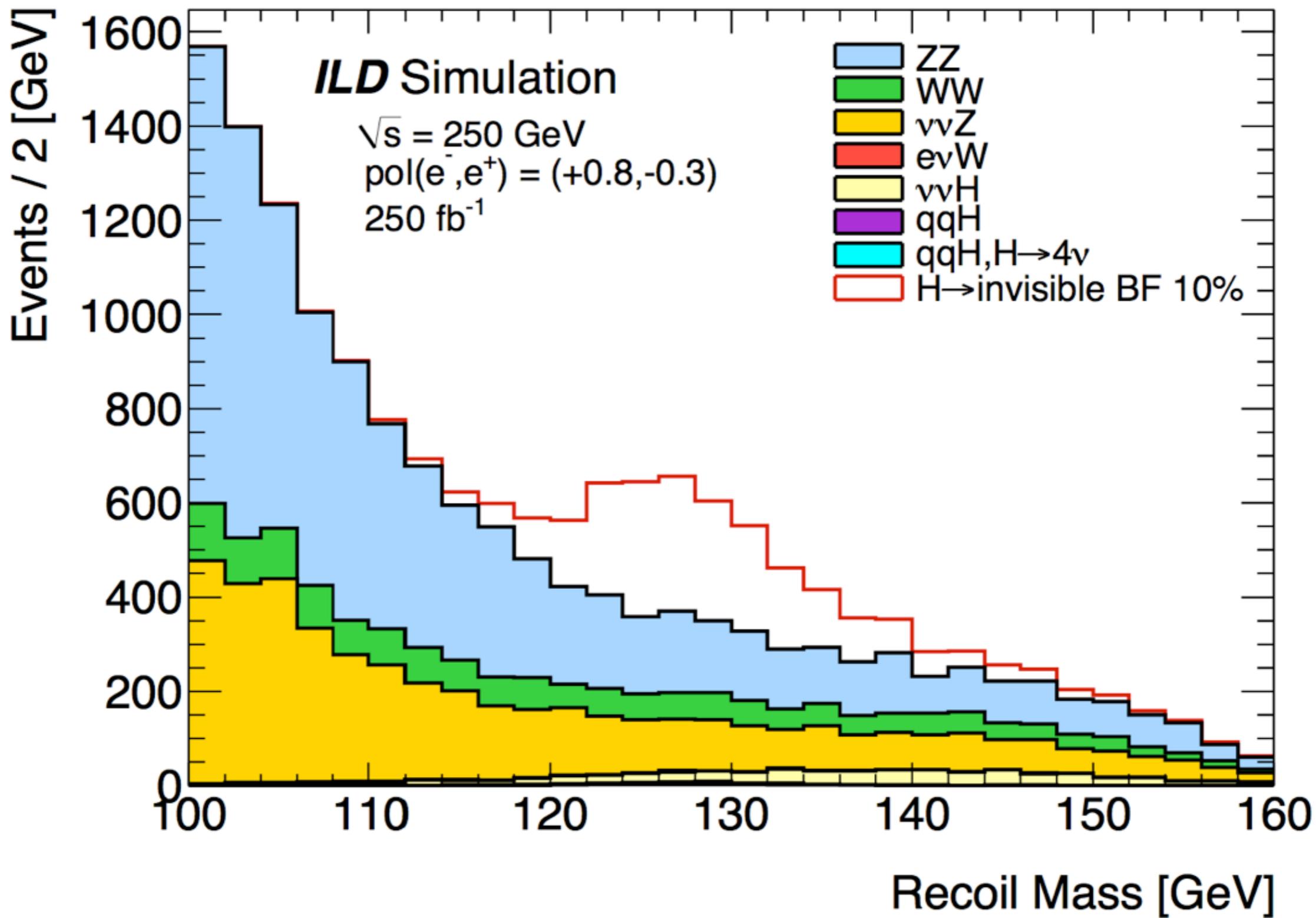


h → cc

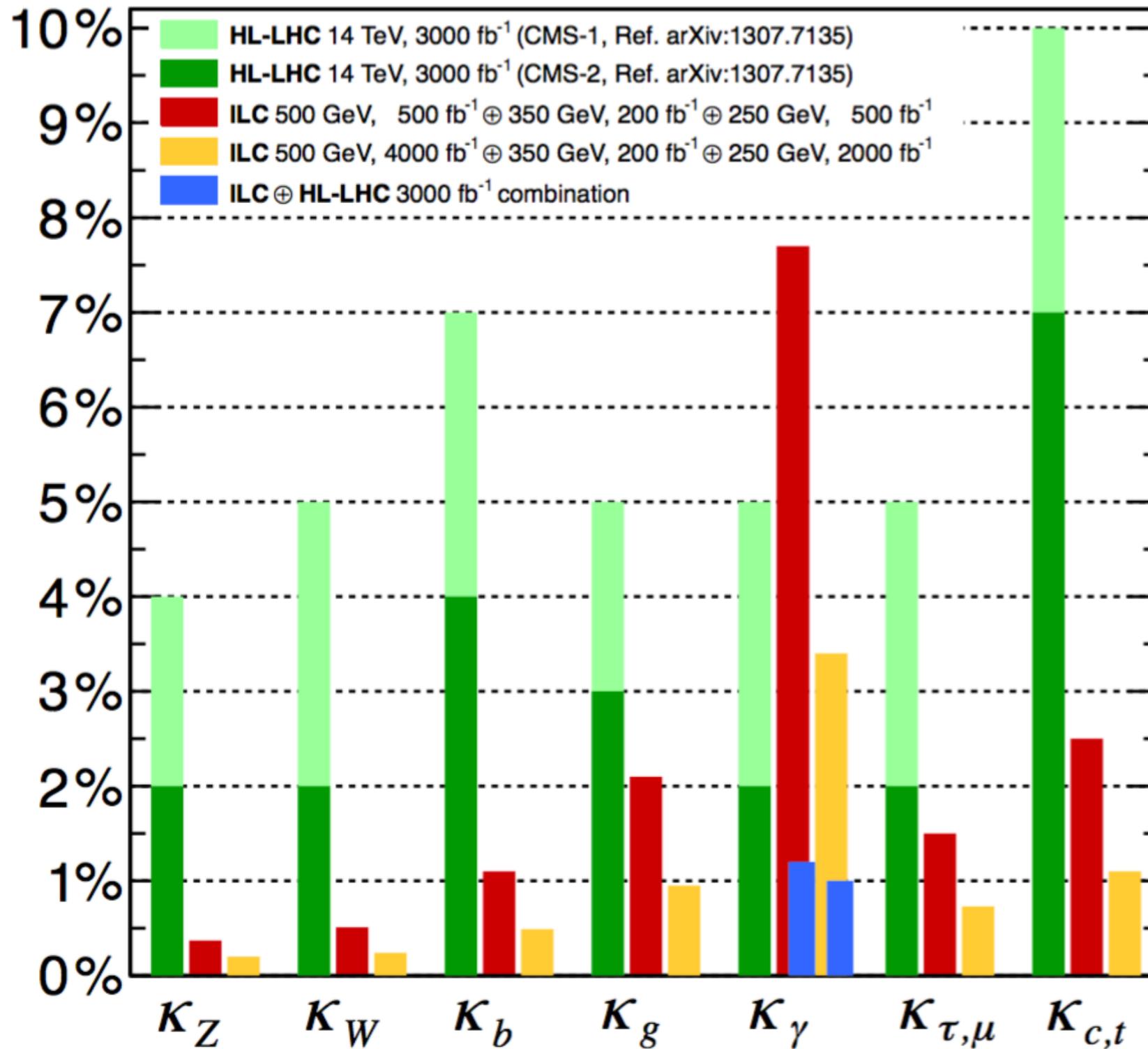


h → gg



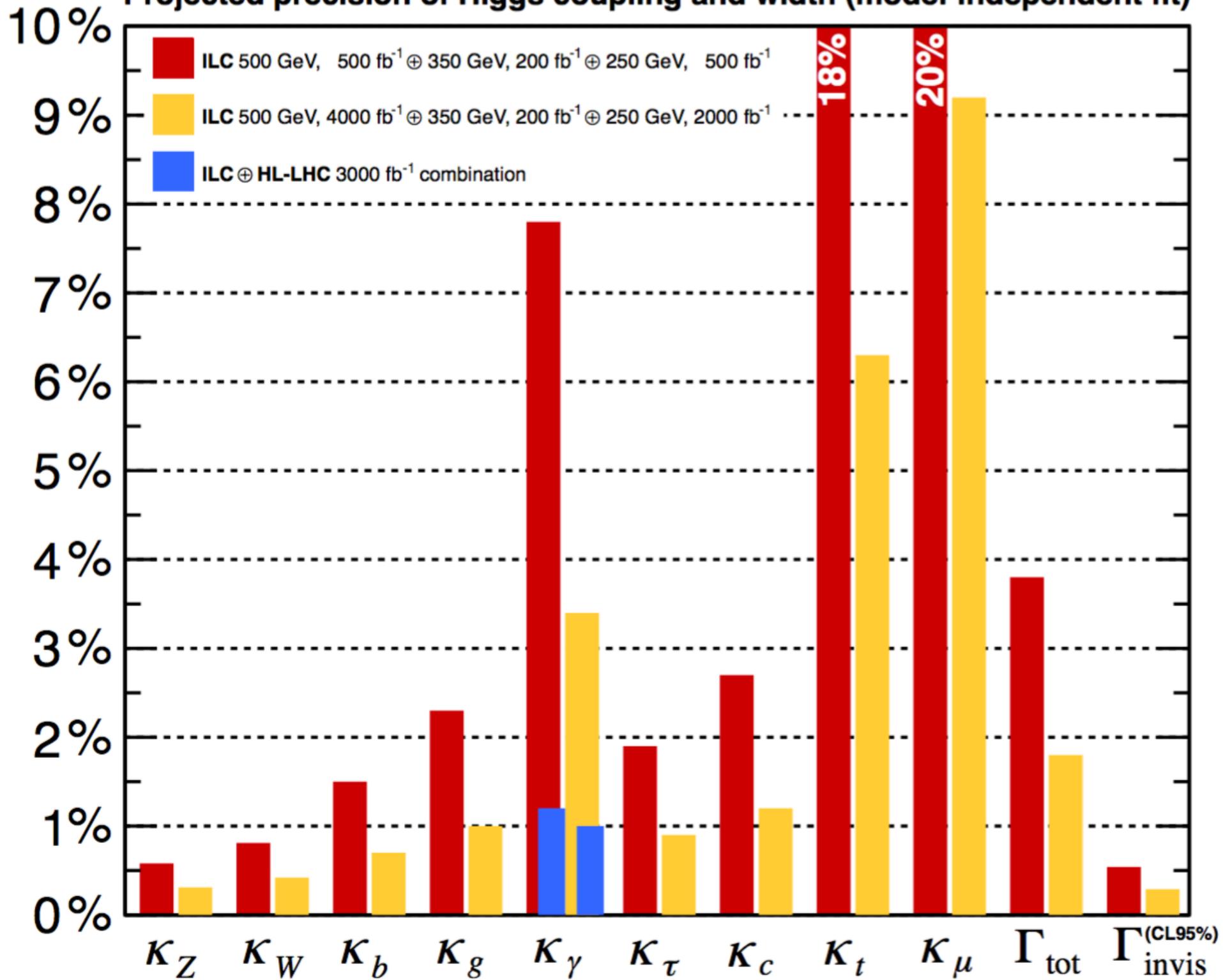


Projected Higgs coupling precision (7-parameter fit)



(fit from Snowmass 2013:
to facilitate comparison with LHC)

Projected precision of Higgs coupling and width (model-independent fit)



k_t - 3% if ILC can run at 550 GeV

k_γ - 1% using LHC $\gamma\gamma/ZZ$

A wealth of information will be available if we can study the decays of the Higgs boson with high precision.

This program will certainly establish the role of the Higgs boson, in the way that the precision study of Z has established the $SU(2) \times U(1)$ gauge theory.

This program can also give information – not only quantitative but also qualitative – on the nature of new physics beyond the Standard Model. This information will be in many ways orthogonal to what we will learn from particle searches at the LHC.

I look forward to this program as the next great project in the future of particle physics.