Motivations for Precision Higgs Physics

M. E. Peskin
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Yesterday, we discussed the promise of precision measurements of the Higgs couplings from the ILC.   In this lecture, I will discuss the physics goals of that study.

What are we looking for? What kinds of physics affect the HIggs couplings.

What is the specific motivation to look for small deviations from the Standard Model predictions?

Outline of the talk:

1. Review of the Standard Model Higgs at 125 GeV
2. The Decoupling Theorem
3. Multiple-Higgs models
4. Mixing with Exotic Scalars
5. The Loop-Induced Couplings
6. Radiative Corrections
7. The Higgs Portal

The Standard Model is a gauge theory of SU(3)XSU(2)XU(1). At this level, its only parameters are the gauge couplings

$$g_s, g, g'$$

All couplings in the model are determined by the principles of gauge invariance and renormalizability. These couplings are now well tested, especially in the precision electroweak experiments at LEP and SLC.

The only problem with this model is that the gauge invariance forbids any particle from obtaining a mass. To solve this problem, we introduce a new sector whose job is to spontaneously break the SU(2)XU(1) symmetry.

We still know almost nothing about this sector.

Okun,   Lepton-Photon 1981:

This is “Problem #1”   for high energy physics.

The minimal solution to this problem is to introduce one new field, a scalar with SU(2)XU(1) quantum numbers

$$(I, Y) = (\frac{1}{2}, \frac{1}{2})$$

The self-interactions of this field are described by the invariant Lagrangian

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

Gauge symmetry and renormalizability do not permit any additional interactions. The symmetry is spontaneously broken if

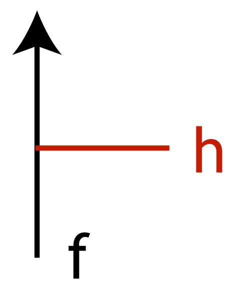
$$\mu^2 < 0$$

We can now couple this field to the quarks and leptons. All flavor violating terms can be tranformed away, except for, precisely, the four CKM angles. At the price of 14 new parameters, we give mass to all quarks and charged leptons.

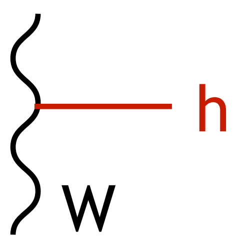
After mass generation for W, Z, one new particle remains, the Standard Model Higgs boson.

The mass of the Higgs boson is free, since it depends on λ , which has not yet entered our formulae. However, once the mass of the Higgs boson is known, all other properties of this particle are predicted.

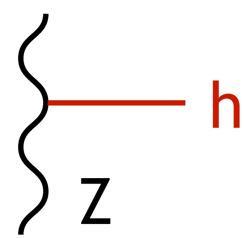
For example,



$$= -i\frac{m_f}{v}$$

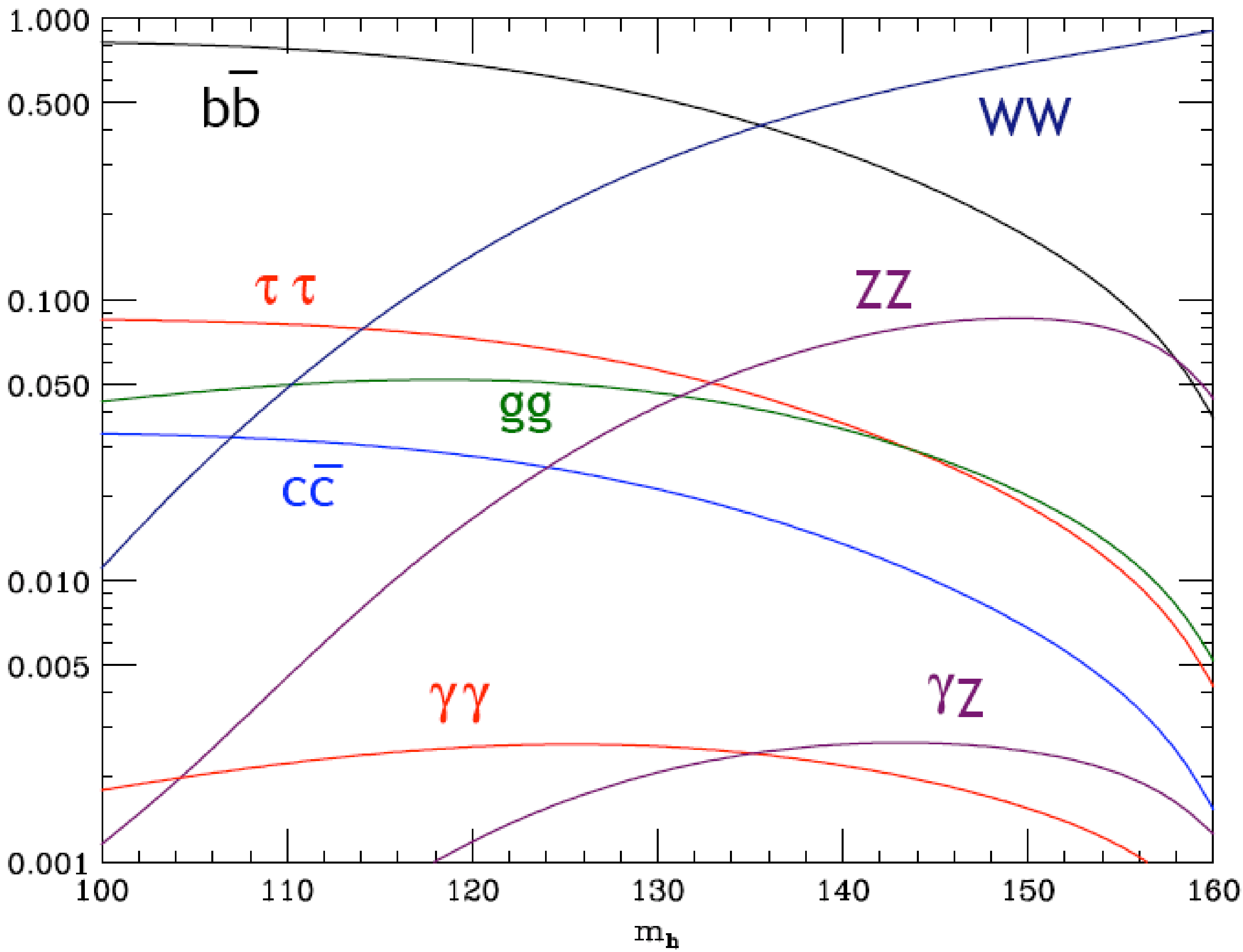


$$= 2i\frac{m_W^2}{v}g^{\mu\nu}$$

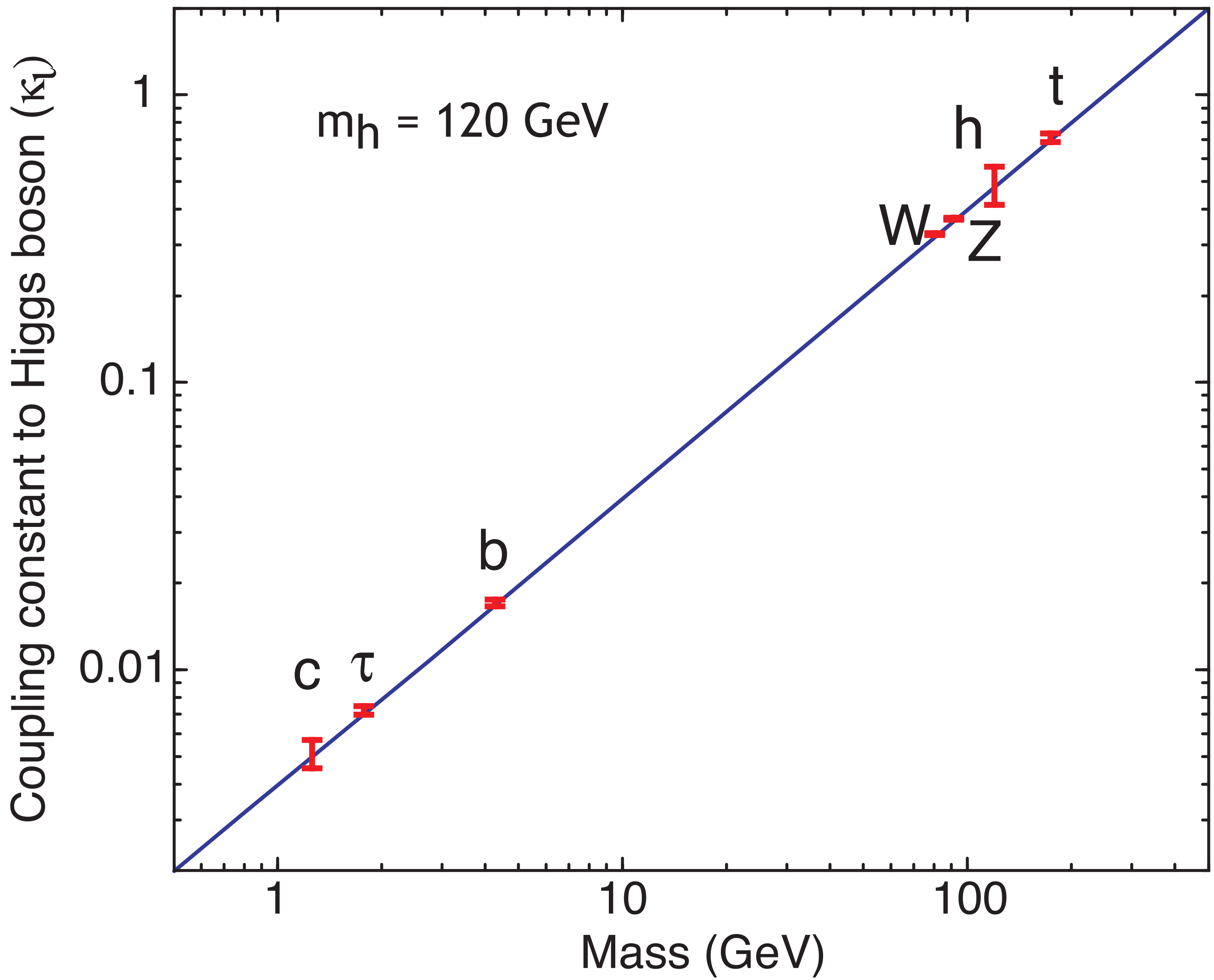


$$= 2i\frac{m_Z^2}{v}g^{\mu\nu}$$

These formulae lead to a rich pattern of Higgs decays, especially in the low mass region $m_h < 150\ \mathrm{GeV}$.



The ability of the ILC to access all of these modes, and other more exotic modes, is well documented.



ACFA LC study

But -- unlike the SU(3)xSU(2)xU(1) gauge symmetry, there is nothing sacred about the minimal Higgs model.

It is just a guess. There is no actual physics in it.

Reality could well be different.   How would this show up in the HIggs properties?

The effect of new physics on the Higgs is constrained by the Decoupling Theorem:

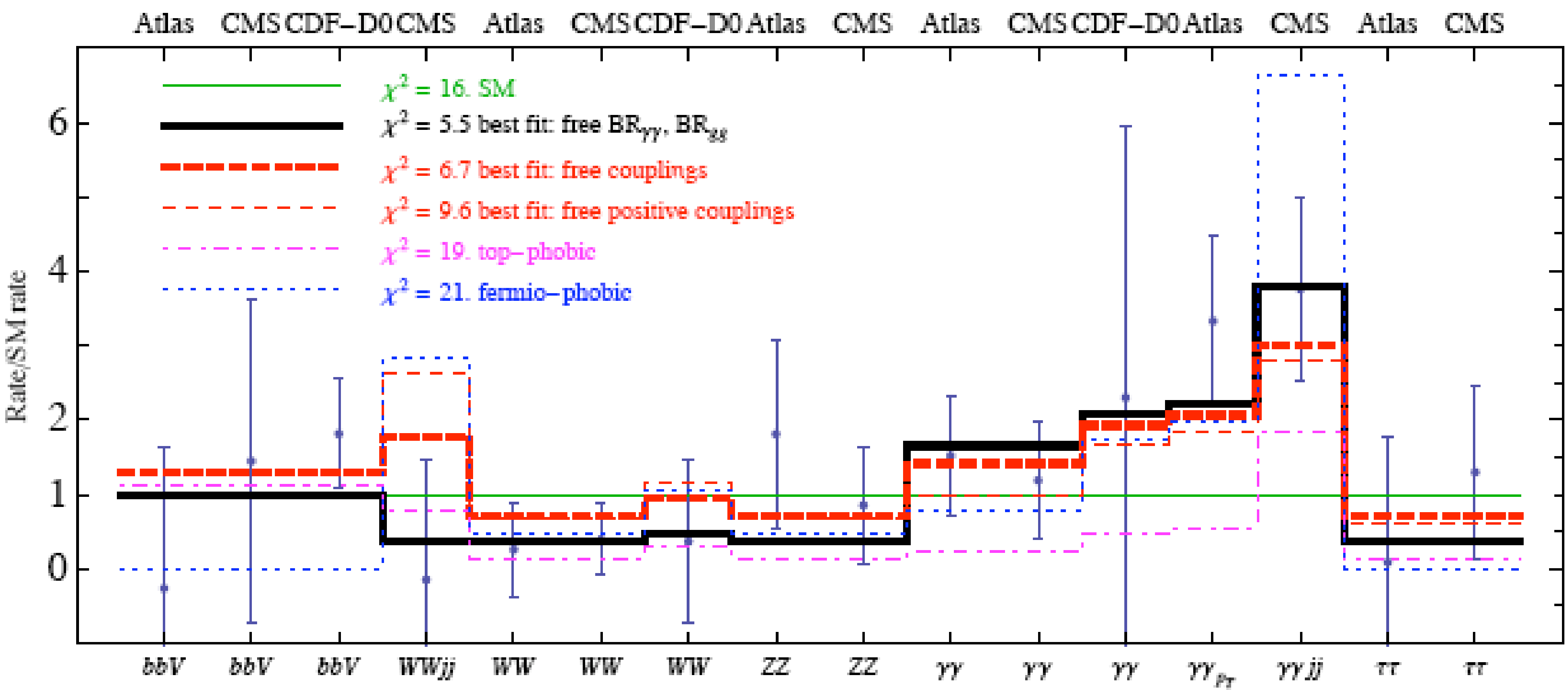
Consider a general model of electroweak symmetry breaking, with many new fields and even non-perturbative interactions.

Assume that, for some reason, the only field lighter than a mass M is an $(I,Y) = (\frac{1}{2}, \frac{1}{2})$ doublet. This happens naturally in SUSY, Little Higgs models, and all other currently viable models of EWSB.

Then we can integrate out all new physics corrections to the potential of the doublet from heavy states. The leading term that results will be the unique SU(2)xU(1) Lagrangian written above. All corrections to this result come from higher-dimension operators; then they are of the order of

$$m_h^2/M^2$$

At the moment, there is much interest in models that give large deviations from the Standard Model Higgs properties.



Giardino, Kannike, Raidal Strumia

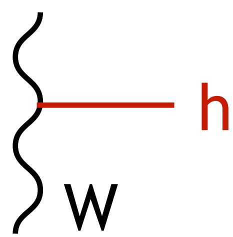
It would be wonderful if such effects would be real, but most likely they will disappear with higher statistics. Then we enter the precision Higgs story.

Next, we discuss multi-Higgs models. There is much complex to say, but there is a simple story if we have mixing of $I = 0, 1/2$ fields only:

Vacuum expectation value of the $I = 1/2$ scalar fields break SU(2)xU(1). There is a sum rule

$$\sum_i v_i^2 = (246 \text{ GeV})^2$$

The tree level W,Z couplings are modified to:



$$= 2i \frac{m_W^2}{v^2} v_i$$

So,

Only scalars, not pseudoscalars, have $h^0 \to W^+W^-, Z^0Z^0$ at leading-order rates.

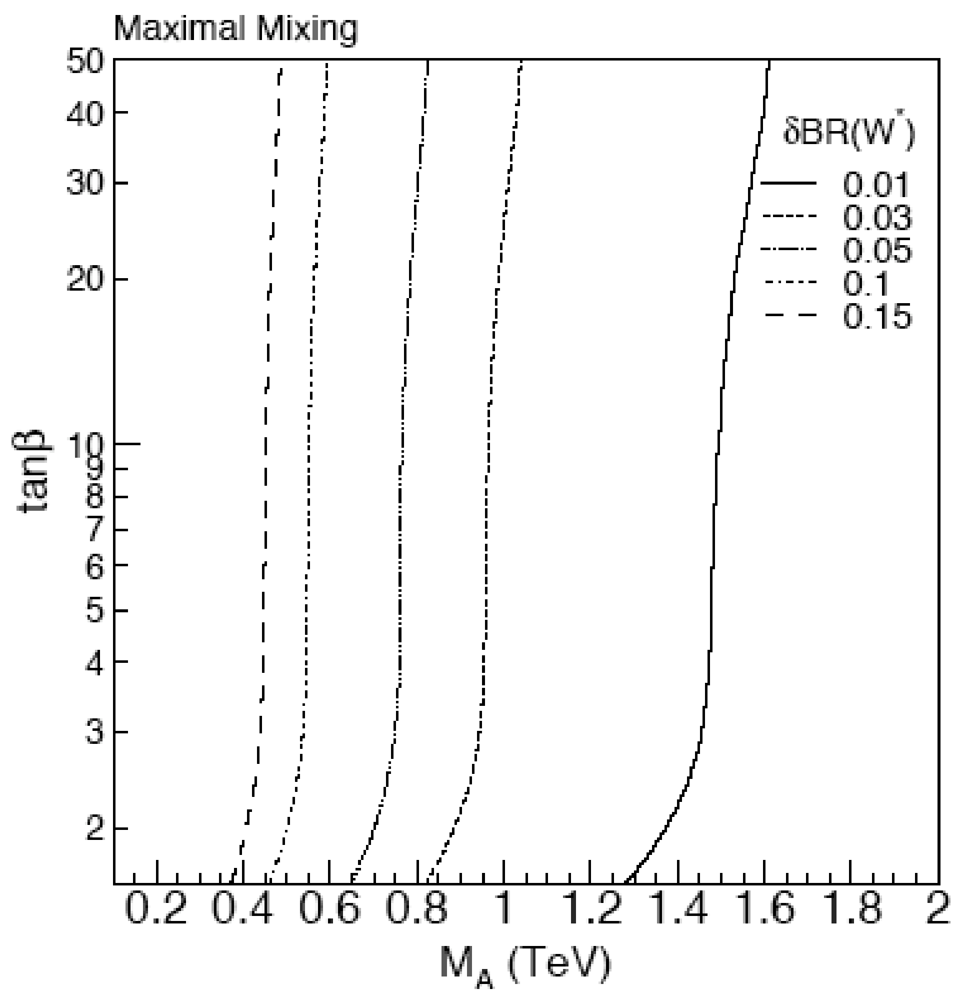
The rates of these processes tell us what fraction of the W and Z masses are generated by the mass eigenstate scalar we are studying.

It is possible but not so easy to obtain $m_h = 125\ \mathrm{GeV}$ in the MSSM. This requires maximal mixing and at least one large stop mass.

The solution to this problem could well be that the model includes an extra scalar (and singlino) that mixes with the Higgs doublets. In this case, the measurement of the purity of the Higgs boson is especially important.

It might be that the singlino is the lightest supersymmetric particle. SUSY decays to this particle dilute missing energy and make SUSY more difficult to find.

Here are some estimates of this effect in the MSSM. The decoupling limit is $m_A \gg m_h$.



Carena, Haber, Logan, Mrenna

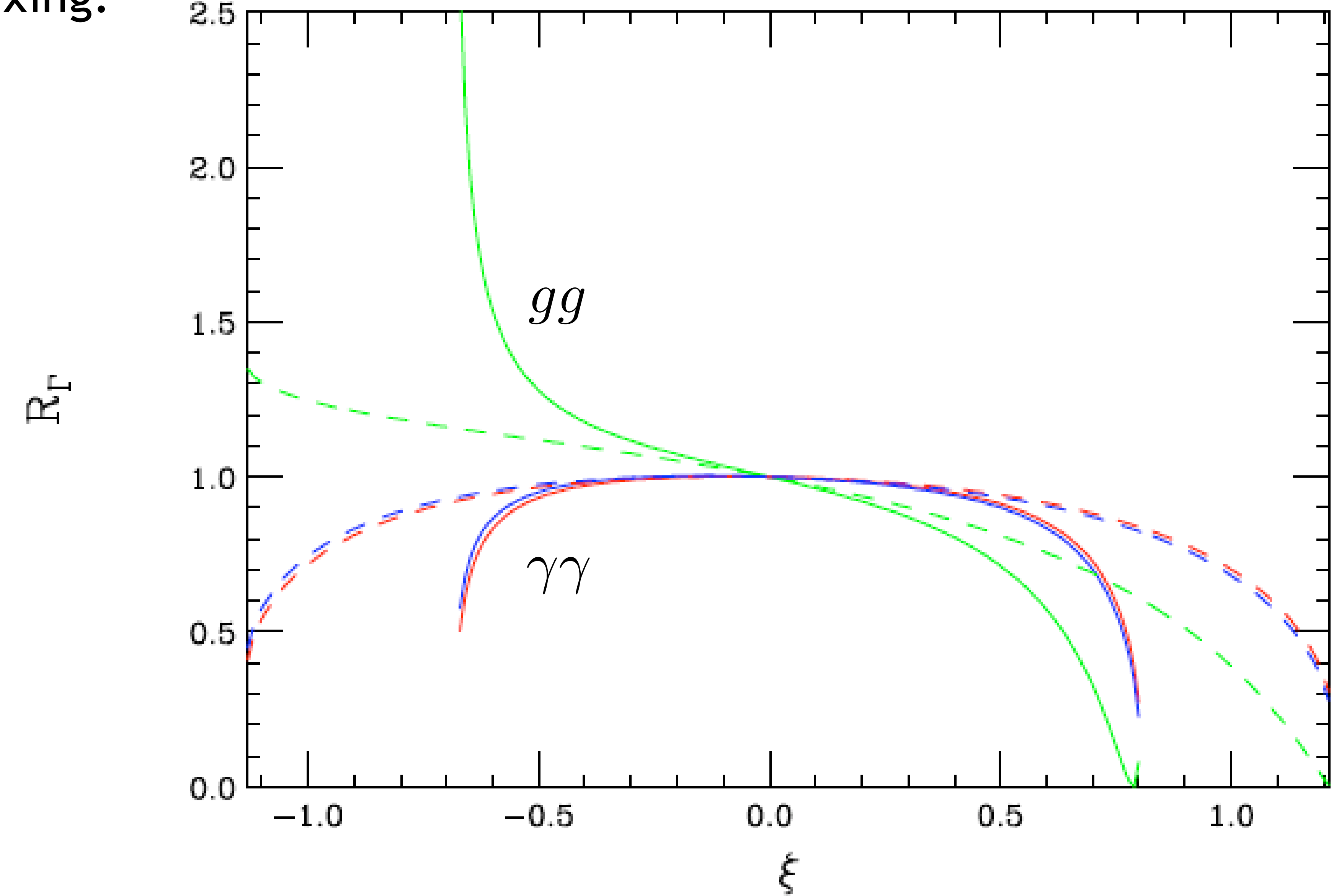
Models with larger effects were discussed by Shindou this morning.

It is possible that there are other scalars in Nature, there for different purposes than to break electroweak symmetry.

An important example is the dilaton. In extra-dimensional models, this is a fluctuation in the size of the extra dimensions.

Often, the effect on fermion and W,Z couplings is still proportional to mass, but the loop-induced coupling to γ , g is altered.

Here are some estimates of the ratio of $\Gamma(h^0 \to gg)$ and $\Gamma(h^0 \to \gamma\gamma)$ in Randall-Sundrum models from Higgs-radion mixing.

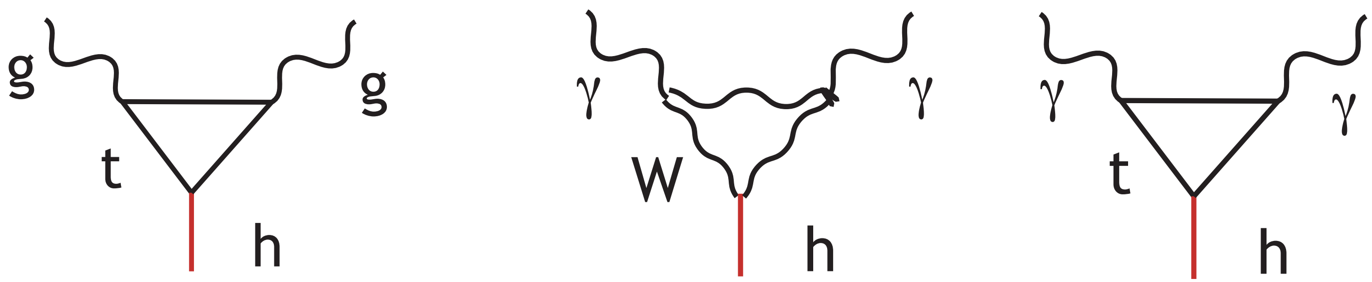


Hewett-Rizzo

Now we discuss more specifically the loop-induced decays

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

In the Standard Model, these decays go through



$$\Gamma(h \to gg) = \frac{\alpha\alpha_s^2}{576\pi^2 s_w^2}\frac{m_h^3}{m_W^2} \cdot 2$$

$$m_h \ll 2m_W$$

$$\Gamma(h \to \gamma\gamma) = \frac{\alpha\alpha_s^2}{576\pi^2 s_w^2}\frac{m_h^3}{m_W^2} \cdot \left| \frac{21}{4} - 3(\frac{2}{3})^2 \right|^2$$

More generally, these decays measure sum rules over the spectrum of heavy particles with QCD/electroweak interactions that obtain mass from the Higgs boson. Only particles with $2M > m_h$ contribute. This is because, for heavy particles in the loop, the diagrams have the dependence:

$$\mathcal{A} \sim \frac{\lambda v/\sqrt{2}}{M} = 1$$

The denominator is the mass of the particle in the loop, since a dimension 5 operator is generated.

This becomes interesting in composite Higgs models such as Little Higgs, Randal-Sundrum, gauge-Higgs unification.

In these models, the important particles are vectorlike. The bulk of their masses come from mechanisms other than electroweak symmetry breaking. So we get the formula above, but the result is no longer equal to 1 .

Here is an example. In composite Higgs bosons, the divergent contribution to the Higgs mass from the top quark is cancelled by contributions from a vectorlike heavy quark T. The masses of t,T are generated from

$$\Delta\mathcal{L} = -M\overline{T}_L\hat{T}_R - \lambda t_L\frac{(v+h)}{\sqrt{2}}(\hat{t}_R + b\hat{T}_R) - h.c.$$

The masses are

$$\begin{aligned} m_t &= \frac{\lambda_t v}{\sqrt{2}}(1 - \frac{b^2 m_t^2}{M^2}) + \cdots \\ m_T &= M(1 - \frac{b^2 m_t^2}{2M^2}) + \frac{\lambda_t v}{\sqrt{2}}\frac{b m_t^2}{M^2} + \cdots \end{aligned}$$

The Higgs couplings are proportional to the $\lambda_t v$ terms. So there is an extra (decoupling) contribution to the loops, effectively multiplying the top quark contribution by

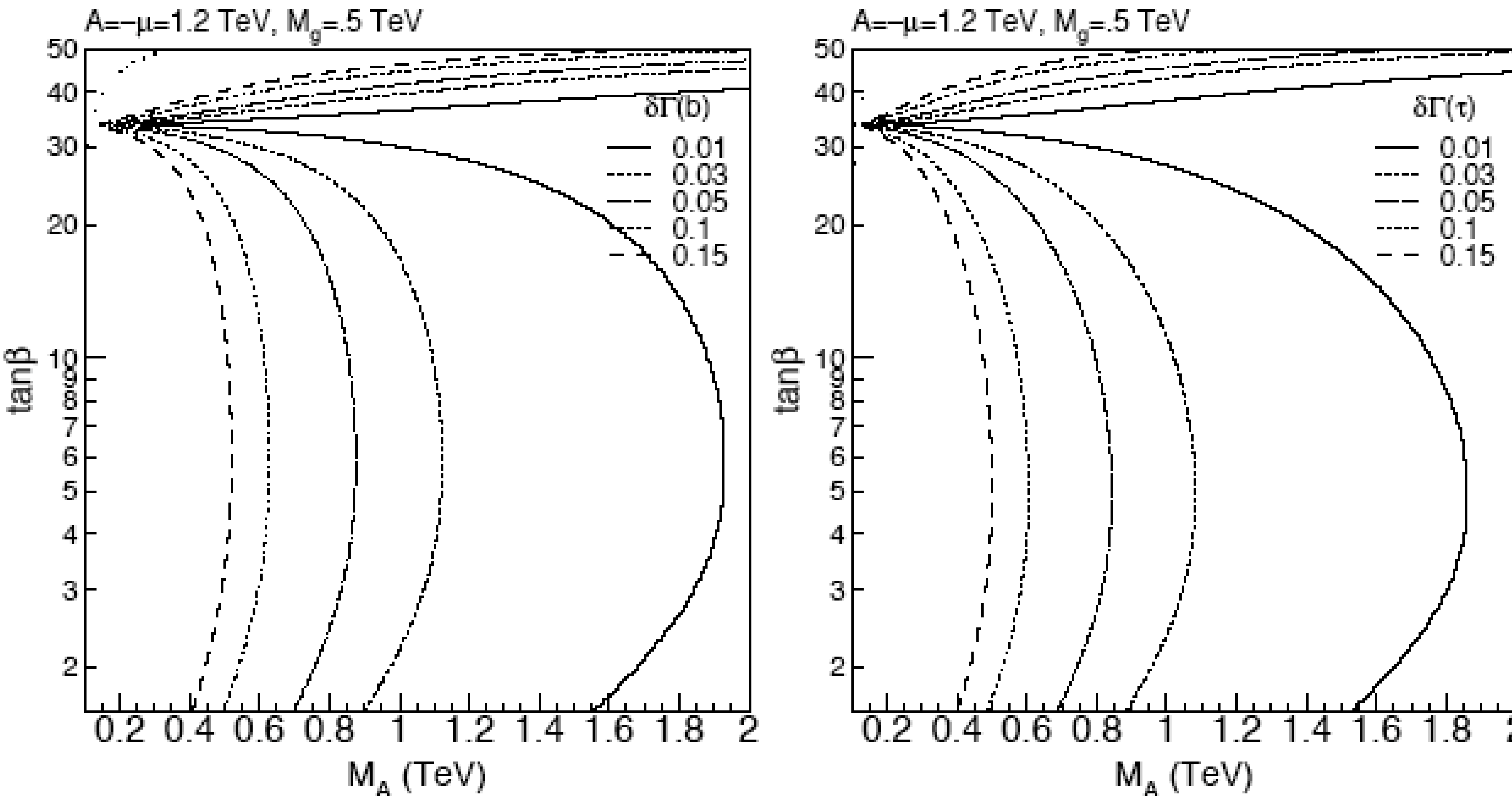
$$1 + b\frac{m_t^2}{M^2}$$

For M = 1 TeV, this is 5-10% correction to $\Gamma(h^0 \to gg)$.

If there is a spectrum of new particles at the TeV mass scale, these particles can generate radiative corrections to the Higgs boson vertices that are relatively large.

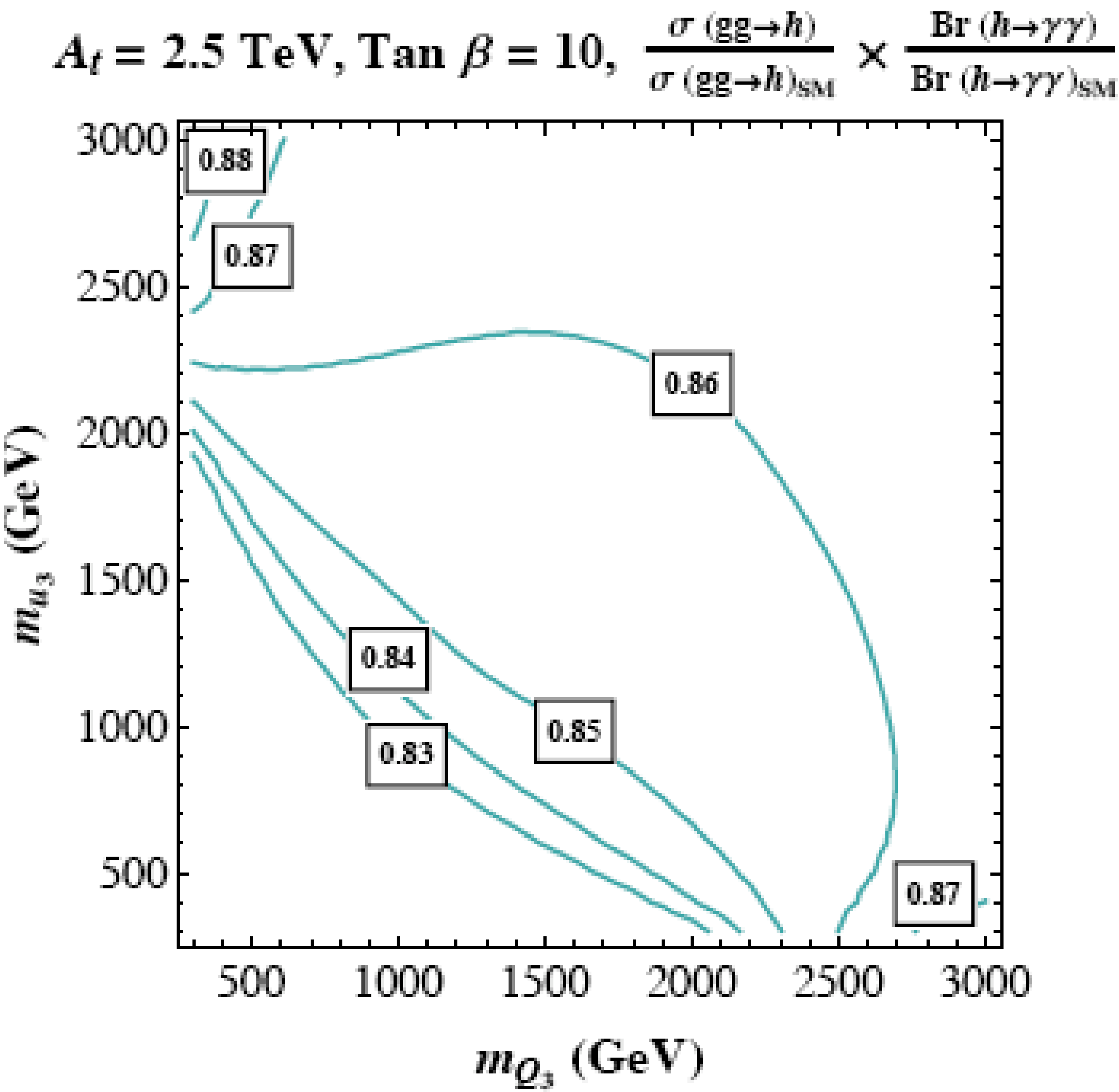
This effect can be especially significant in SUSY, where part of the b, τ masses can come from radiative corrections using A terms rather than from the usual Higgs couplings. The same radiative corrections modify the Higgs vertices.

Fractional deviations in $\Gamma(h^0 \rightarrow b\bar{b})$ and $\Gamma(h^0 \rightarrow \tau^+\tau^-)$ generated by radiative corrections.



Carena, Haber, Logan, Mrenna

Here is a recent calculation of SUSY radiative corrections for a 125 GeV Higgs in the MSSM. These effects probably cannot be seen at LHC but will be visible at ILC.



Carena, Gori, Shah, Wagner

Finally, because the Higgs comes from a completely new sector of particles, not related to the quarks, leptons, and gauge bosons, it is possible that that Higgs decays to other new particles not connected to the particles of the Standard Model.

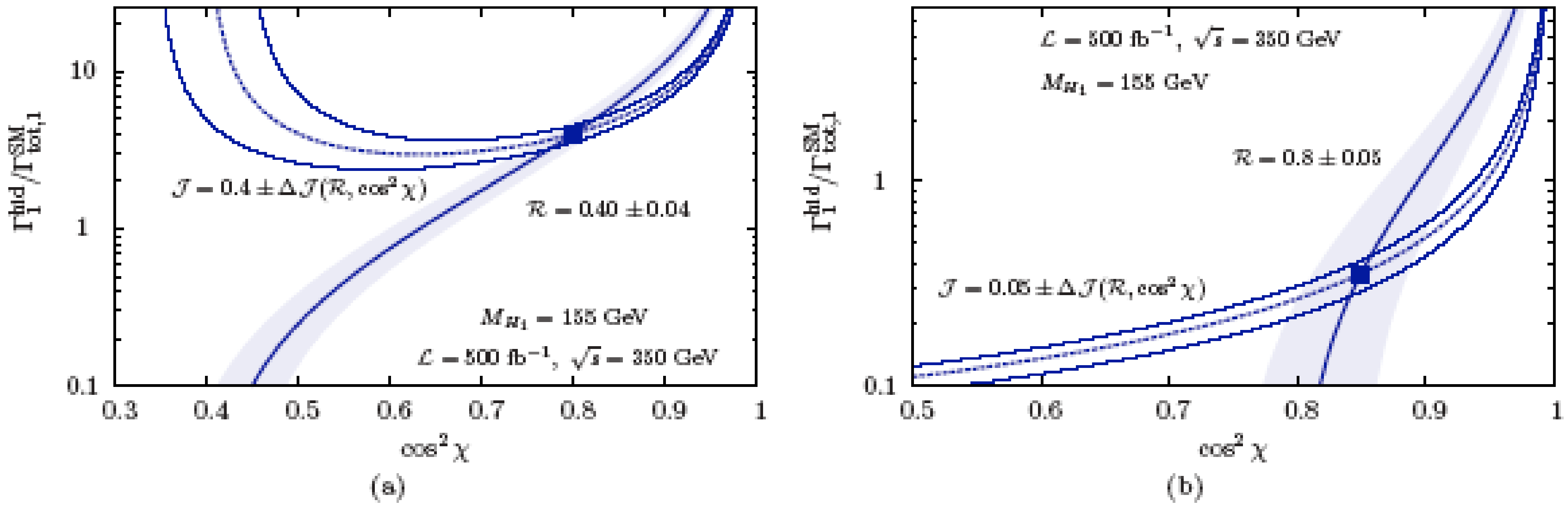
In the theory of dark matter, this idea is called the "Higgs portal".

It leads to potentially large Higgs branching ratios to invisible modes.

Because the Higgs is a scalar, Higgs exchange gives coherent contributions to elastic scattering of dark matter. Usually, this is the leading contribution to the direct detection cross section. So, the observation of Higgs decays to invisible particles can be correlated with observation of dark matter direct detection.

Higgs portal models can involve mixing between Higgs bosons coupling to the Standard Model and Higgs bosons coupling to the hidden sector. This leads to modifications of the cross section correlated with the appearance of an invisible branching ratio.

Englert has shown how to disentangle these effects using ILC data.



Thus, the Higgs boson opens a window into new physics that can access a wide variety of new particles and phenomena.

The multiplicity of Higgs decay modes at 125 GeV gives a wealth of observables that can be explored.

With the right tool -- the ILC -- we can go down this path to fascinating discoveries.