Physics at e^+e^- Linear Colliders

3. Higgs bosons

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The last heavy particle of the SM is the Higgs boson. This is the particle responsible, in this model, for electroweak symmetry breaking and for the generation of the masses of all quark, leptons, and gauge bosons.

The SM gauge theory is experimentally tested. So it is highly likely that the theory of W and t that I presented in the previous lecture is almost completely right. There may be small corrections from sources outside the SM. In the previous lecture, I presented tools for digging out anomalies that could be signals of new physics.

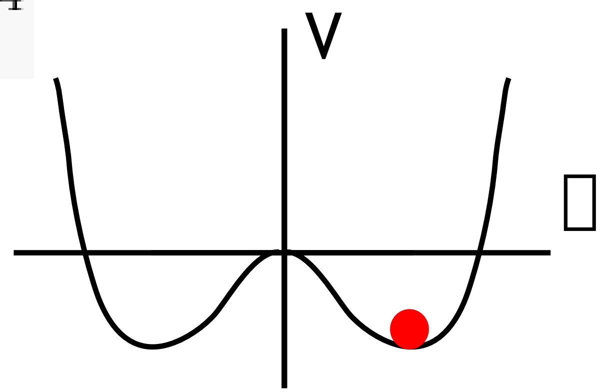
However, what I am going to talk about today is likely to be completely wrong. The SM requires symmetry breaking, but the SM Higgs boson is a crib that does not actually make sense. I will describe the SM Higgs boson in some detail because it is a useful reference point. The true experimental results, though, could be very different from these predictions.

SM theory of electroweak symmetry breaking:

Introduce a field ϕ with I= 1/2 , Y = 1/2

Write a potential $V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$

its minimum is $$\langle\phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix}$$



then $m_W^2 = \frac{g^2}{4}v^2$, etc., with v = 246 GeV.

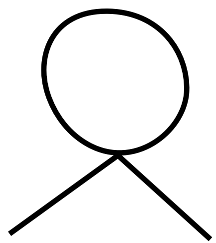
Why is electroweak symmetry broken?

Because $(-\mu^2) < 0$

This answer is not sensible, but in quantum field theory it makes even less sense:

Compute the 1-loop correction:

$$\delta(-\mu^2) =$$



$$\sim \lambda \int \frac{d^4k}{(2\pi)^4}\frac{1}{k^2} \sim \frac{\lambda}{16\pi^2}\Lambda^2$$

Λ must be less than a few TeV if we wish to avoid large cancellations

Conceptually, Λ could be much larger;
in grand unified theories $\Lambda > 10^{16}$ GeV.

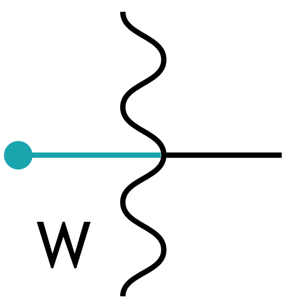
Nevertheless, I will stay with the SM Higgs theory and study its consequences.

The Higgs field begins as a doublet:

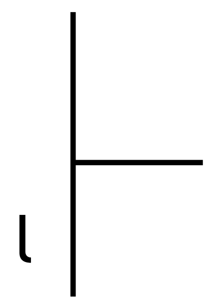
$$\phi = \begin{pmatrix} \pi^+ \\ \frac{1}{\sqrt{2}}(v + h + i\pi^0) \end{pmatrix}$$

π^+, π^-, π^0 are eaten by W^+, W^-, Z^0

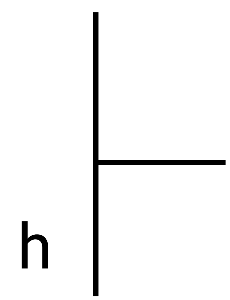
h appears in the combination (v+h), so every mass term in the model implies an h vertex:



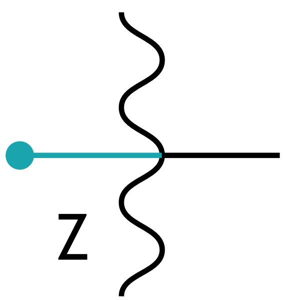
$$2i\frac{m_W^2}{v}g^{\mu\nu}$$



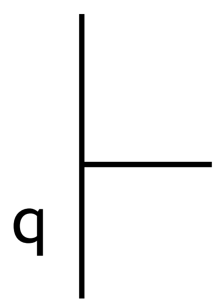
$$-i\frac{m_\ell}{v}$$



$$-3i\frac{m_h^2}{v}$$



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

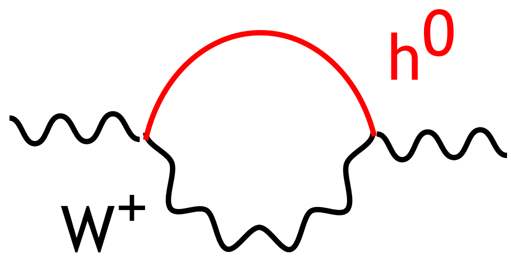


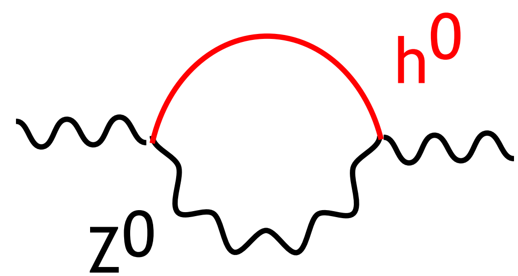
$$-i\frac{m_q}{v}$$

These vertices can be use to analyze h^0 production and decay.

However, they also have implications for the h^0 mass.

Consider the effects:

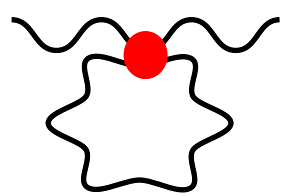




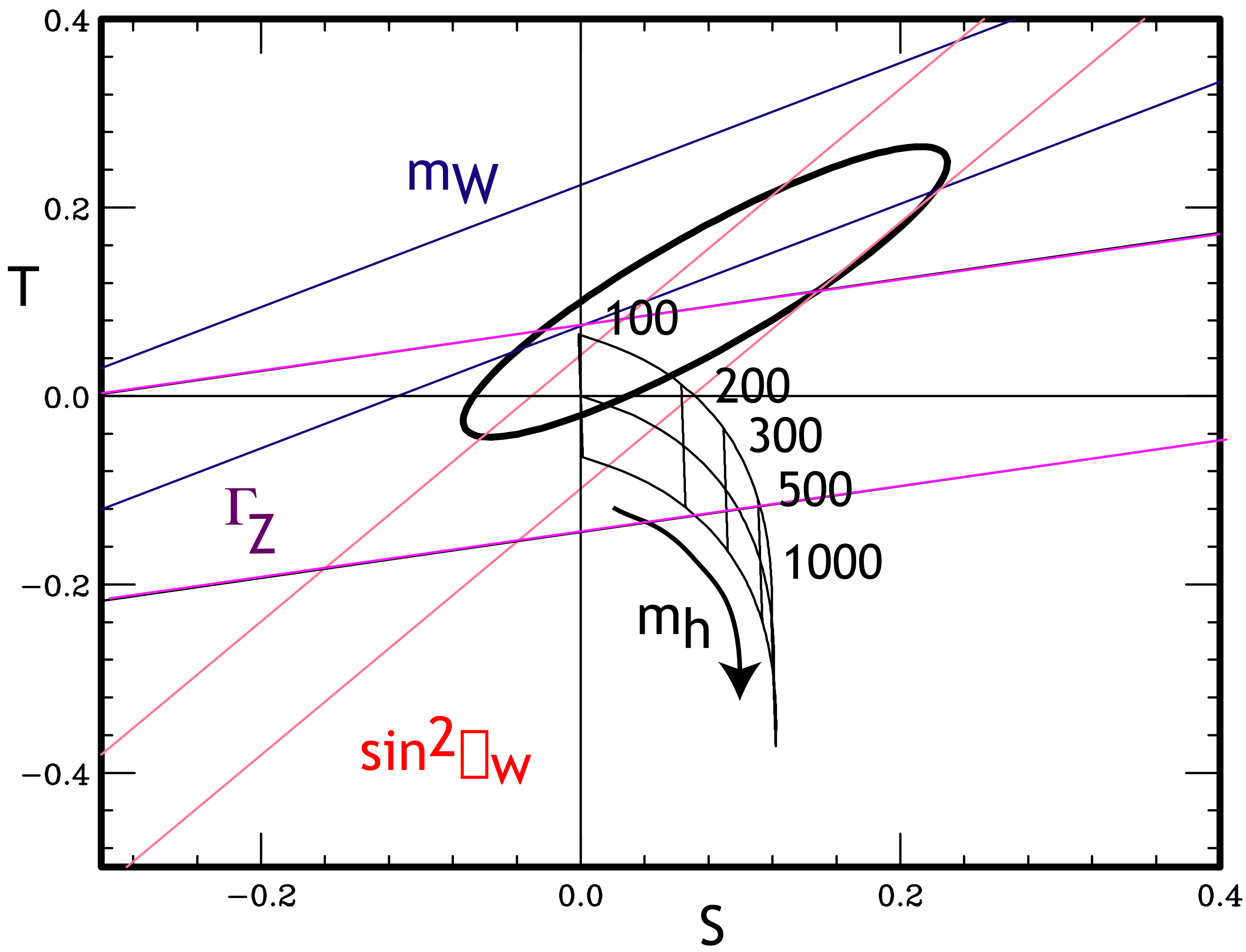
which contribute to precision electroweak observables

$$\sim \frac{\alpha}{4\pi s_w^2} \log \frac{m_h^2}{m_W^2}$$

These effects increase in size for a heavy Higgs boson,
of for "no Higgs"



Are they seen in the data ?



in the SM, m_h < 222 GeV (95% conf) (LEP EWWG)

In general, models with a strongly coupled Higgs sector give ΔS, $\Delta T \sim 1$, that is, percent-level corrections to electroweak observables.

It is possible to craft models with smaller effects. Naively, though, the success of precision electroweak predictions indicates a light, weakly coupled Higgs field.

Decays of the SM Higgs boson:

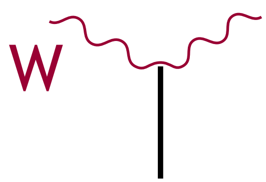
h^0 is most strongly coupled to the heaviest particles, so h^0 decays are dominated by the heaviest available states.

For a very heavy Higgs:

$$\Gamma(h^0 \to W^+W^-) = \frac{\alpha}{16 s_w^2}\frac{m_h^3}{m_W^2}\left(1 - \frac{4m_W^2}{m_h}\right)^{1/2}\left[1 - 4\frac{m_W^2}{m_h^2} + 12\frac{m_W^4}{m_h^4}\right]$$

$$\Gamma(h^0 \to Z^0Z^0) = \frac{\alpha}{32 s_w^2}\frac{m_h^3}{m_W^2}\left(1 - \frac{4m_Z^2}{m_h}\right)^{1/2}\left[1 - 4\frac{m_Z^2}{m_h^2} + 12\frac{m_Z^4}{m_h^4}\right]$$

the enhancement is easily understood:



$$= \quad \frac{2m_W^2}{v}\epsilon^* \cdot \epsilon'^* = \frac{2m_W^2}{v}\frac{s}{2m_W^2} = \frac{m_h^2}{v}$$

$$= \quad \frac{\lambda v}{2} = \frac{m_h^2}{v}$$

also

$$\Gamma(h^0 \to t\bar{t}) = \frac{3\alpha}{8s_w^2} m_h \frac{m_t^2}{m_W^2}$$

This corresponds to a 20% branching fraction.

Below the t t threshold, the t drops out. The precision electroweak constraint implies that m_h is probably also below the WW and ZZ thresholds. Then all of the leading modes are forbidden and we must go to subdominant channels.

For h^0 decay to fermion pairs:

$$\Gamma(h^0 \to f\overline{f}) = \frac{N_c \alpha}{8 s_w^2} m_h \frac{m_f^2}{m_W^2}$$

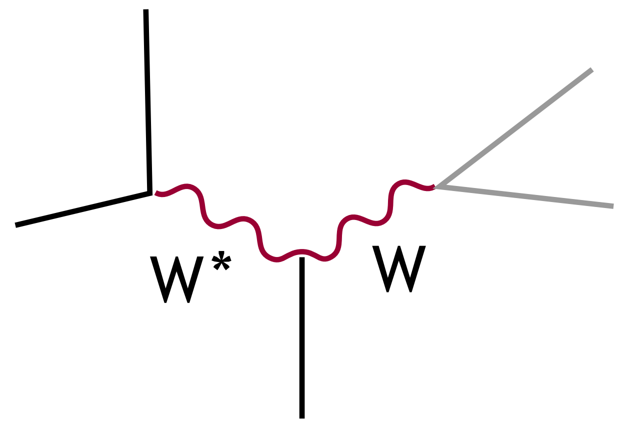
The next lighter fermions are: b, τ, c . Their values of $N_c\, m^2{}_f$ are

$3\,(3.1)^2$: $(1.7)^2$: $3\,(0.8)^2$ (using running masses at Q ~ 100 GeV)

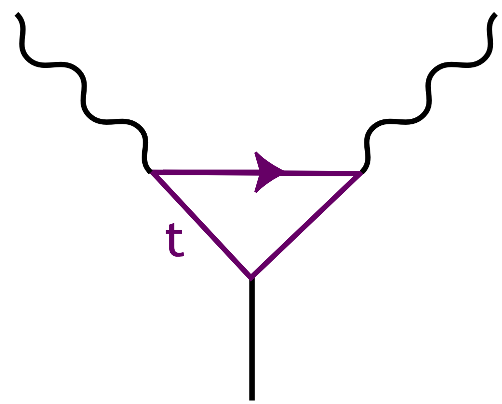
= 1 : 0.10 : 0.07

in addition,

decays to WW and ZZ are still present, with one boson off the mass shell

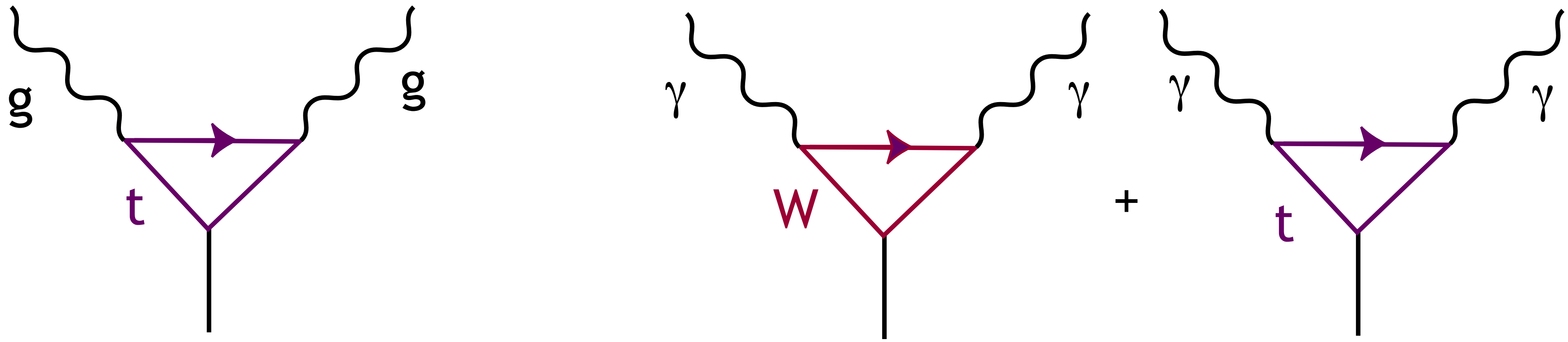


and, h^0 can decay by loop diagrams to gg or $\gamma\gamma$



The WW and gg modes are 5-15% decay modes for m_h ~ 120 GeV.

If h^0 couples to mass, h^0 must decay to gg, $\gamma\gamma$ through massive intermediate states.



Only states heavier than m_h contribute. For $m_h \ll m_W$:

$$\Gamma(h^0 \to gg) = \frac{\alpha\alpha_s^2}{144\pi^2 s_w^2}\frac{m_h^3}{m_W^2}\cdot 2$$

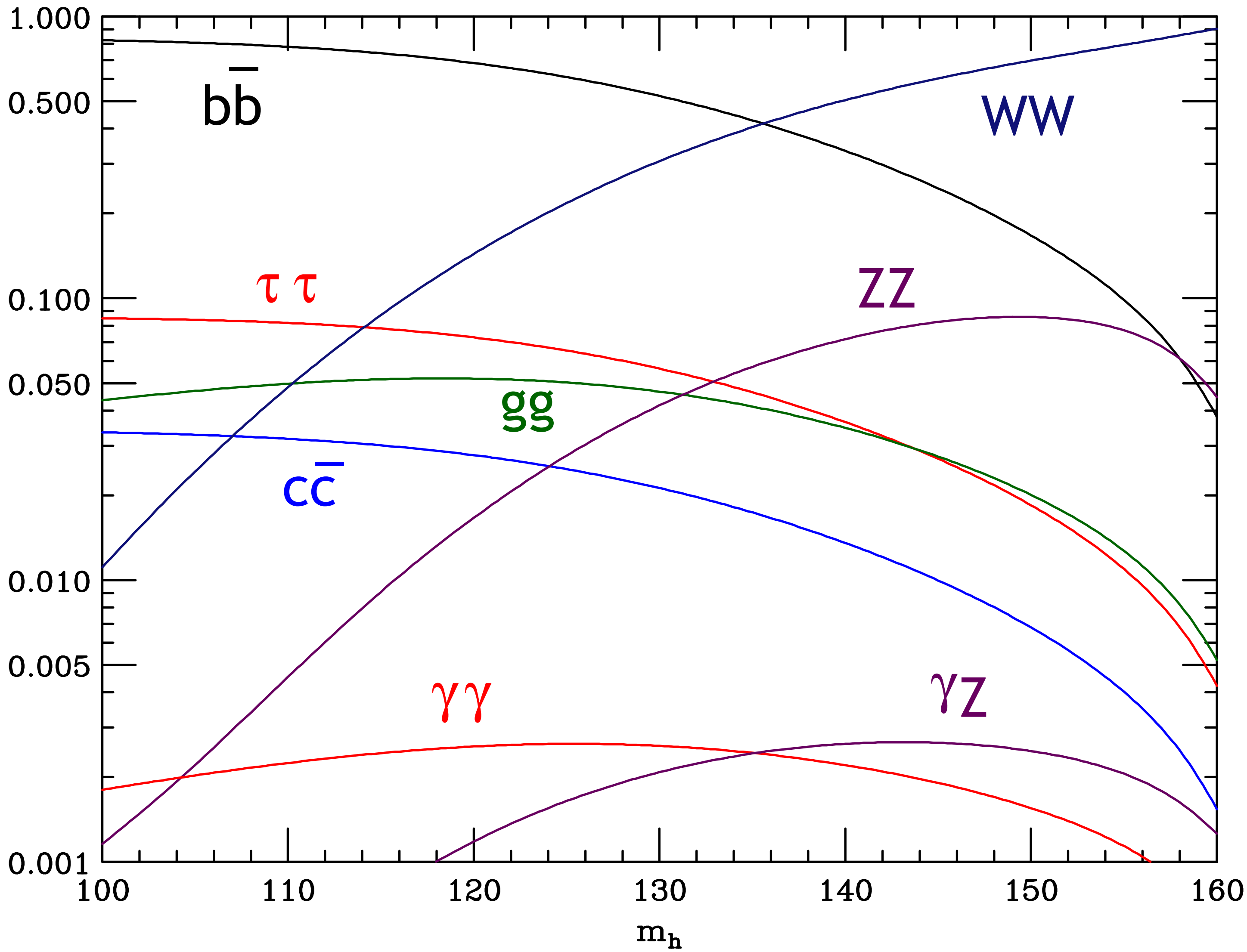
$$(\frac{1}{2}\delta^{ab})^2$$

$$\Gamma(h^0 \to \gamma\gamma) = \frac{\alpha^3}{144\pi^2 s_w^2}\frac{m_h^3}{m_W^2}\cdot\left|\frac{21}{4} - 3\cdot(\frac{2}{3})\right|^2$$

W t

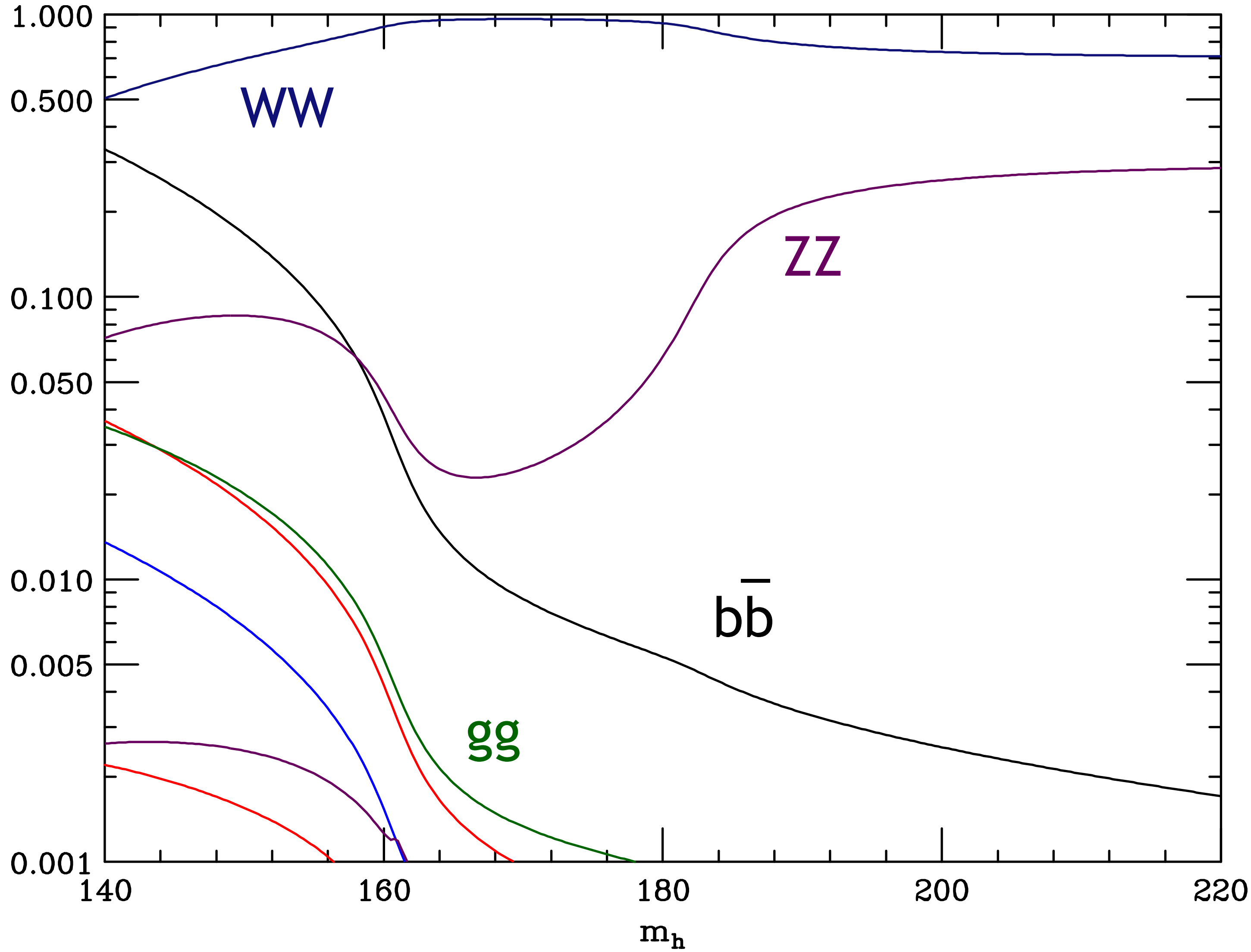
SM Higgs branching fractions

(light Higgs)



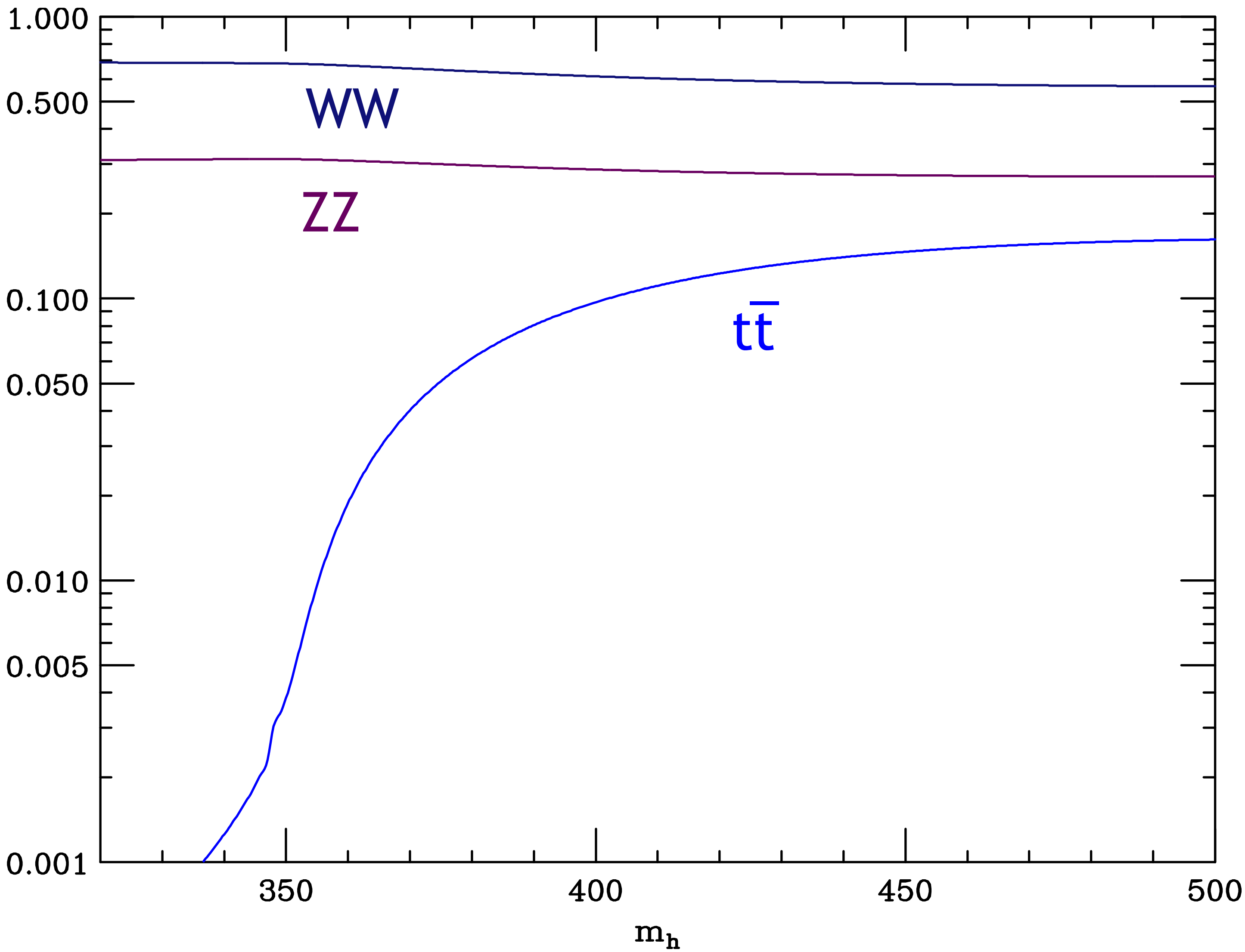
SM Higgs branching fractions

(Higgs at WW threshold)



SM Higgs branching fractions

(heavy Higgs)



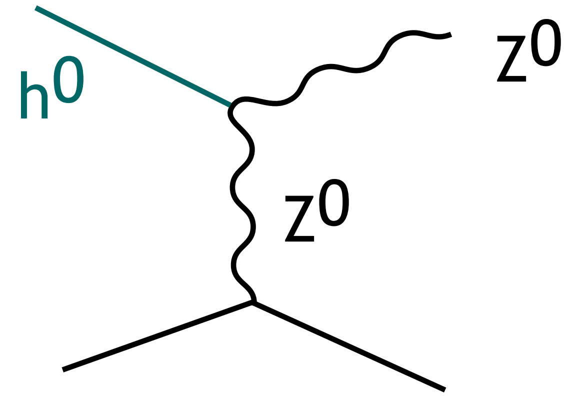
in all,

The Higgs branching fractions directly test whether the h^0 couples proportional to mass. This is precisely the question of whether the h^0 gives mass universally to all species of quarks, leptons, and bosons.

$h^0 \to gg$ and $h^0 \to \gamma\gamma$ measure sum rules over states heavier than m_h which receive mass from the Higgs VEV. In the SM, t and W are the leading contributions. Additional heavy particles may enter on the same footing.

The simplest production mechanism for h^0 in e^+e^- collisions is

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



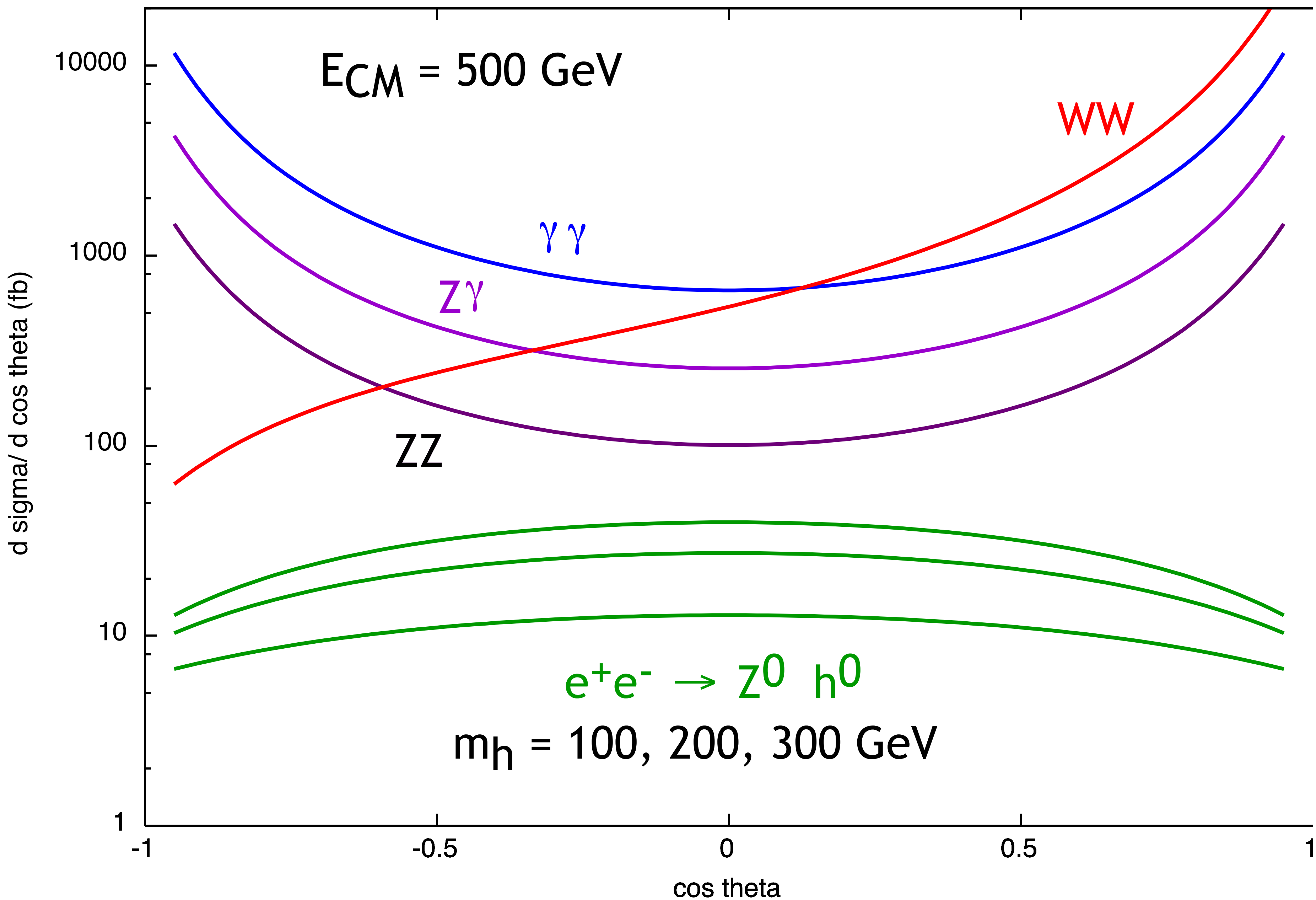
The cross section is dominated by the helicity 0 state of the Z^0

$$\mathcal{M}(e^-_L e^+_R \rightarrow h^0 Z^0_0) \sim e^2 \frac{(\frac{1}{2} - s_w^2)}{2c_w^2 s_w^2} \sin\theta$$

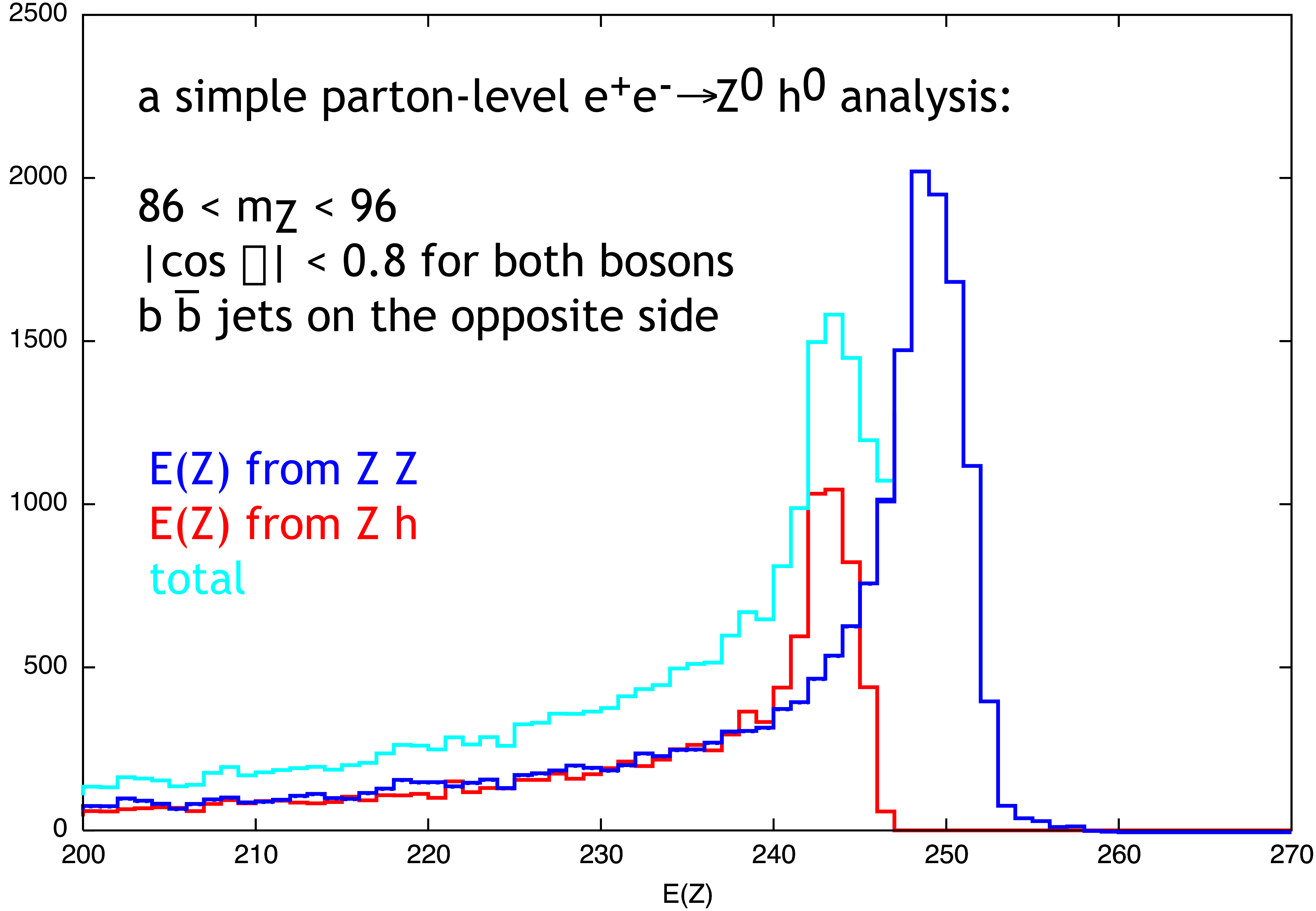
$$\mathcal{M}(e^-_R e^+_L \rightarrow h^0 Z^0_0) \sim e^2 \frac{1}{2c_w^2} \sin\theta$$

so that

$$\frac{d\sigma}{d\cos\theta} \sim \sin^2\theta$$



E_{CM} = 500 GeV
WW
γ γ
Zγ
ZZ
$e^+e^- \rightarrow Z^0\ h^0$
m_h = 100, 200, 300 GeV
d sigma/ d cos theta (fb)
10000
1000
100
10
1
-1
-0.5
0
0.5
1
cos theta



2500
2000
1500
1000
500
0
200
210
220
230
240
250
260
270
E(Z)
a simple parton-level e+e-→Z0 h0 analysis:
86 < mZ < 96
|cos □| < 0.8 for both bosons
b b jets on the opposite side
E(Z) from Z Z
E(Z) from Z h
total

Production of h^0 in recoil against the Z^0 is useful experimentally because the Z^0 of definite energy tags the event.

This gives:

an opposite-side tag for branching fraction measurements

a tag for $h^0 \to$ invisible

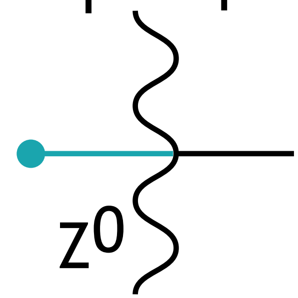
leptons from $Z^0 \to l^+l^-$ for a precision h^0 mass measurement (to 100 MeV)

For the first two items, Z^0 decay to hadrons can also be used.

$\sigma\,(e^+e^- \rightarrow Z^0\, h^0)$ is also interesting for a theoretical reason.

Consider a more general model with more than one Higgs doublet. Each doublet $□_i$ has a VEV v_i. These values appear in
the gauge boson masses and in the $□_i$ couplings to Z, W:

$$m_Z^2 = \frac{g^2 + g'^2}{4} \sum_i v_i^2$$



$$= \quad 2i \frac{m_Z^2}{v^2} v_i$$

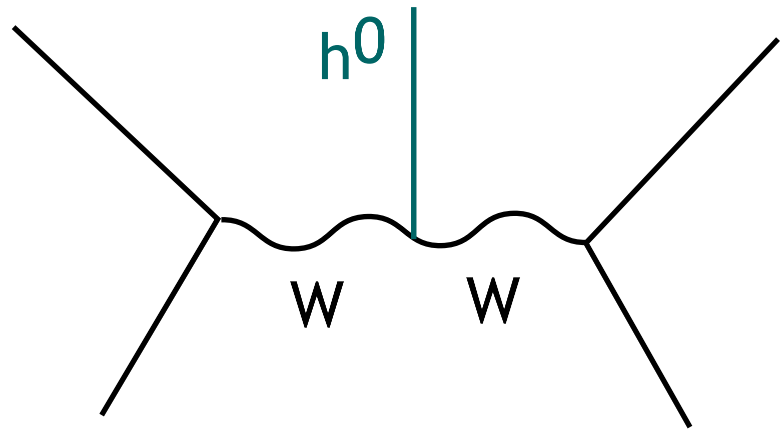
thus, $$\frac{\sigma(e^+e^- \rightarrow Z^0 h_i^0)}{\sigma(e^+e^- \rightarrow Z^0 h^0)|_{SM}} = \left(\frac{v_i}{246 \text{ GeV}}\right)^2$$

The absolute total cross section for $e^+e^- \rightarrow Z^0\, h^0$ measures the fraction of the Z^0 mass that comes from the observed Higgs resonance.

Eventually, we must find all of the bosons that contribute to the mass of the Z^0.

Other e^+e^- annihilation processes also allow measurement of the h^0 couplings.

$e^+e^- \rightarrow \nu \bar{\nu} h^0$



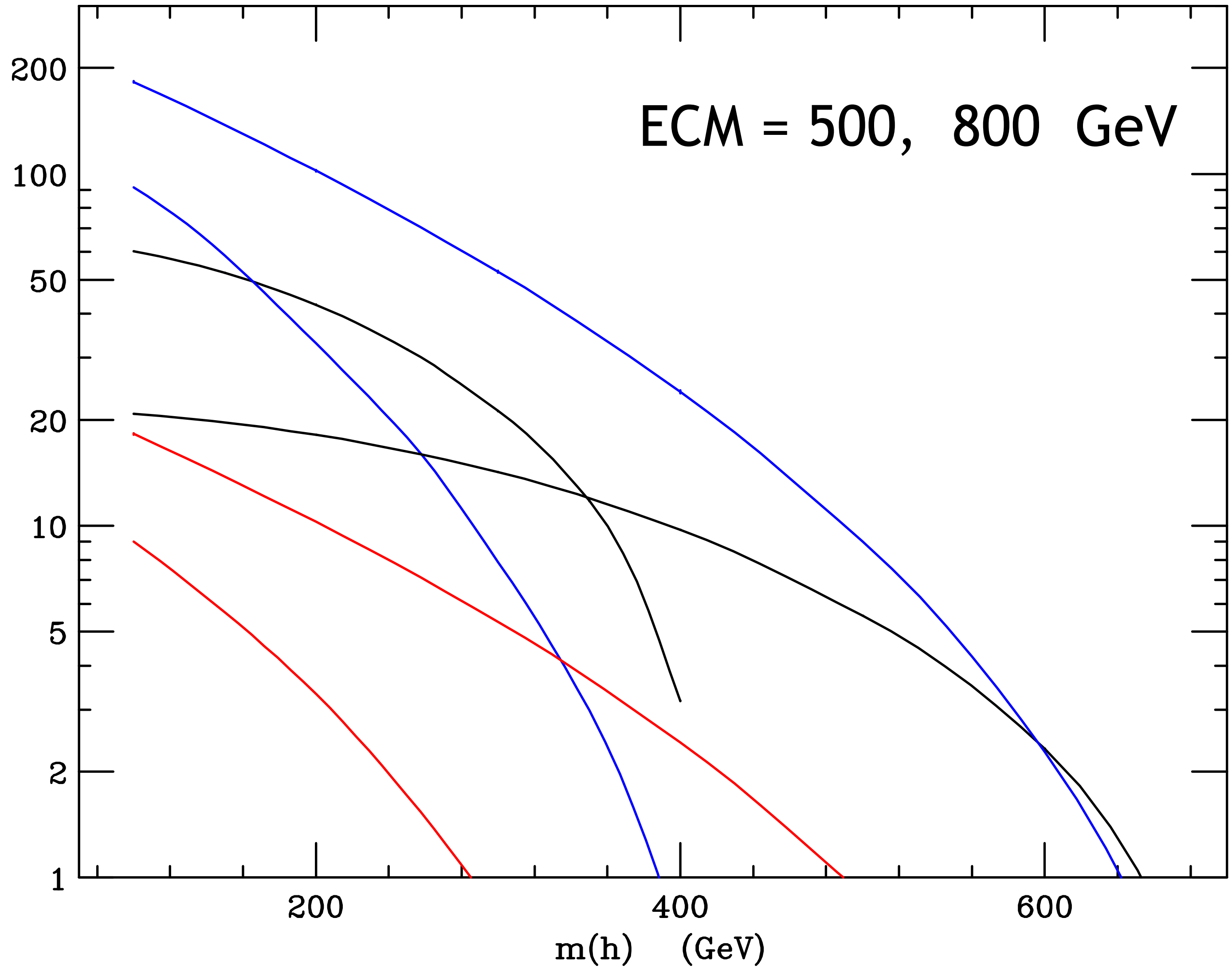
This process can be clearly identifed e.g. in $h^0 \rightarrow b\bar{b}$ if m_h is known in advance.

$\sigma \sim$ 100 fb at 500 GeV and grows logarithmically with E_{CM}.

total cross sections for $e^+e^- \to Z^0 h^0$

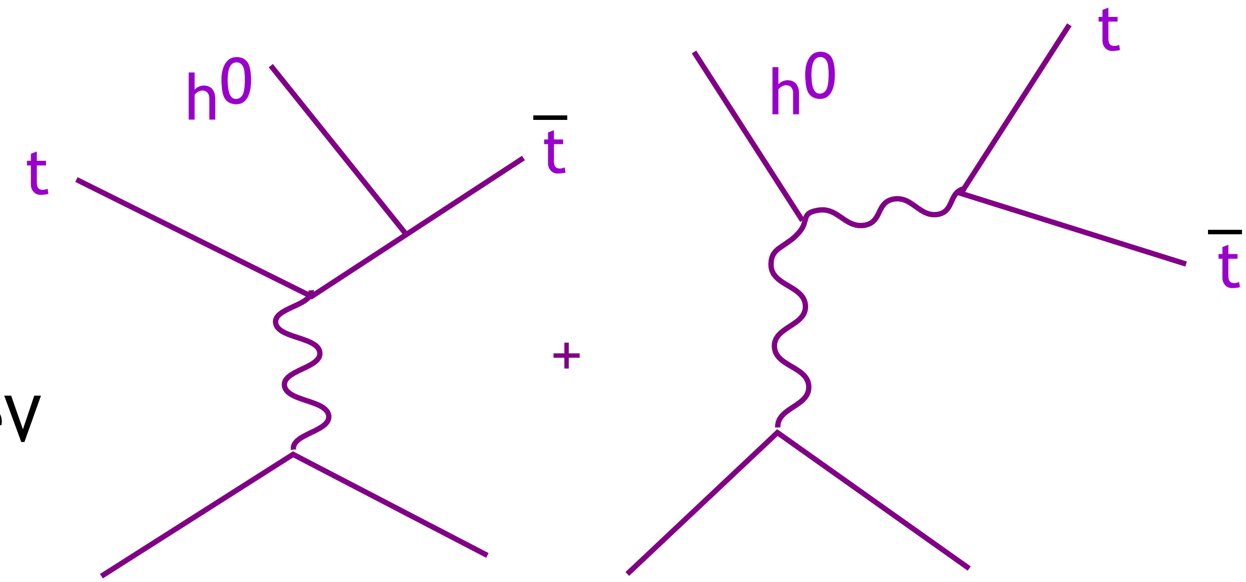
$e^+e^- \to \nu \bar{\nu} h^0$

σ (fb) $e^+e^- \to e^+e^- h^0$



$e^+e^- \to t\,\bar{t}\;\; h$

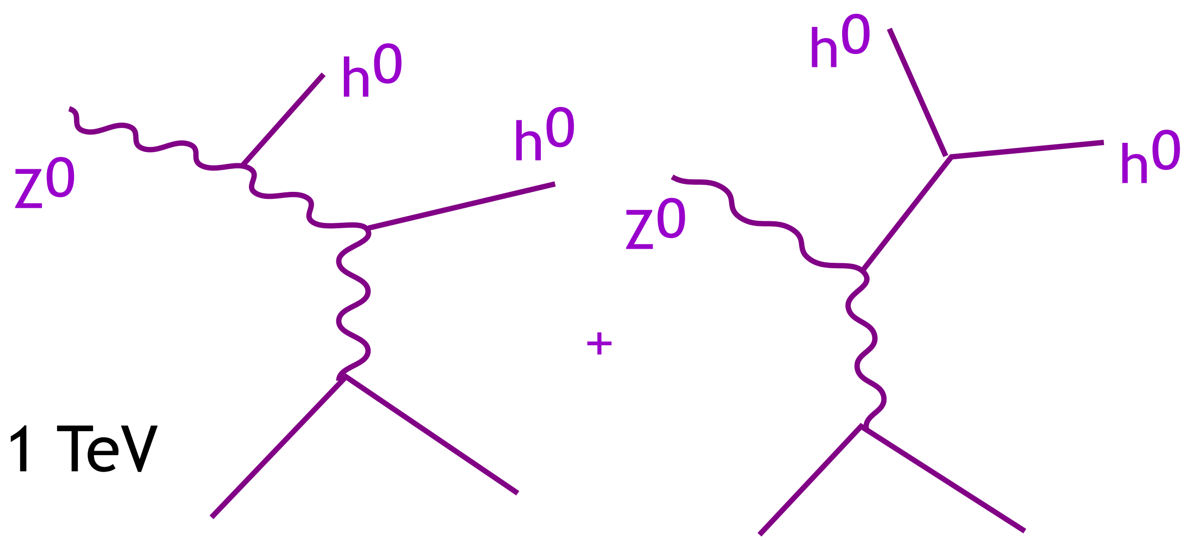
$\sigma \sim 2$ fb
at ECM = 1 TeV



but, this might be the best way to measure the $t\bar{t}h$ coupling.

$e^+e^- \to Z\;\; h\;\; h$

$\sigma \sim 0.1$ fb
at ECM = 1 TeV

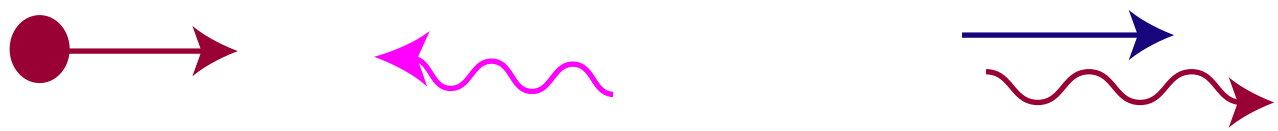


but, this process might allow a measurement of the
Higgs self-coupling

Since the h^0 decays to $\gamma\gamma$, we might try to create it as a resonance in $\gamma\gamma$ collisions. This is a promising application of another system of initial states available at the LC.

We have already seen that e^+e^- collsions naturally contain γ reactions, in which the γ's originate from bremsstrahlung or beamstrahlung. These γ spectra are very soft.

However, it is possible to manufacture a hard γ spectrum by Compton backscattering.



e- beam at 250 GeV

γ's from a laser

backscattered γ's and leftover e^-s

The hardest γ's have an energy comparable to the original beam energy and follow the trajectory of the parent electrons.

A practical backscattered γ beam requires ~ 1 joule of energy at visible/IR frequencies on each e^- pulse.

This is 10^4 W into and out of the collision region/sec. The required power and time structure can be produced by ~10 modern high-power lasers.

The kinematics of the γ - e collision is governed by

$$x = \frac{4E\omega}{m_e^2} = \frac{s}{m_e^2}$$

The highest possible value of E /E_{beam} is

$$z_{max} = \frac{x}{1+x}$$

Telnov's guideline is x = 2 + 8 = 4.8 ; this is the point at which backscattered γ's initiate $\gamma\gamma \rightarrow e^+e^-$.

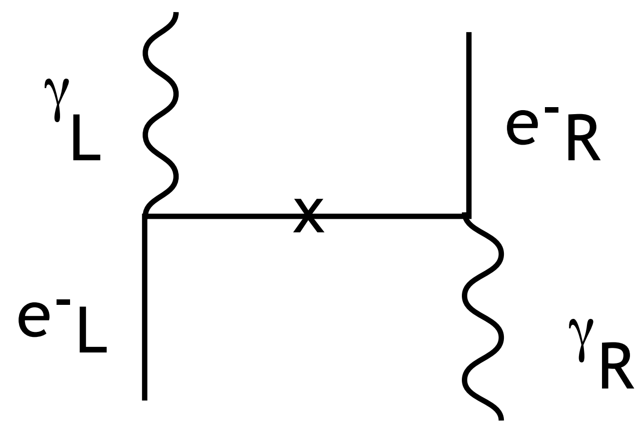
The current Livermore design uses $\lambda = 1/3\ \mu m$

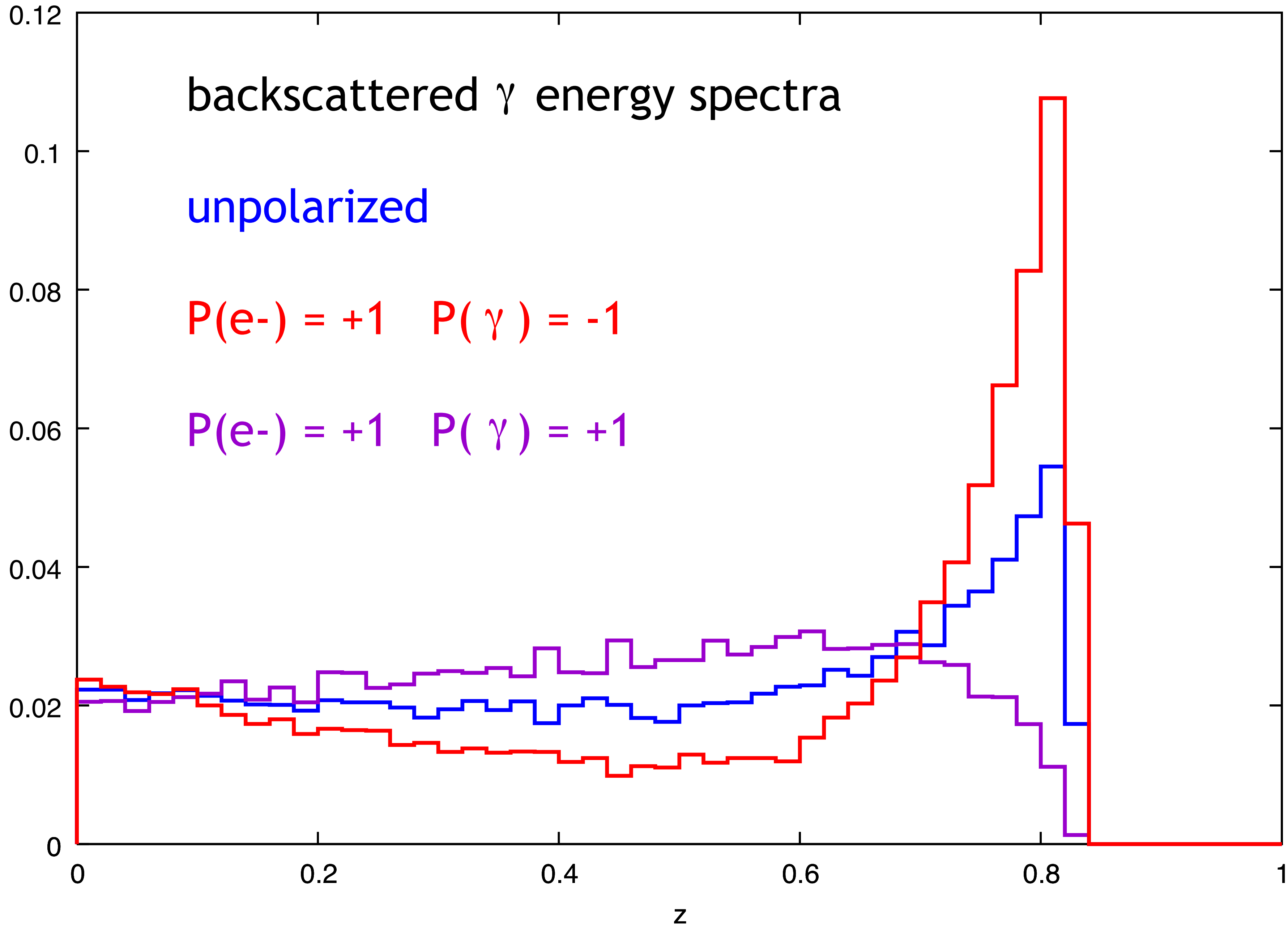
this gives $x = 4.3$ at 160 GeV (for m_h = 120 GeV);
$x = 13.5$ at 500 GeV (x = 4.5 for $\lambda = 1\ \mu m$)

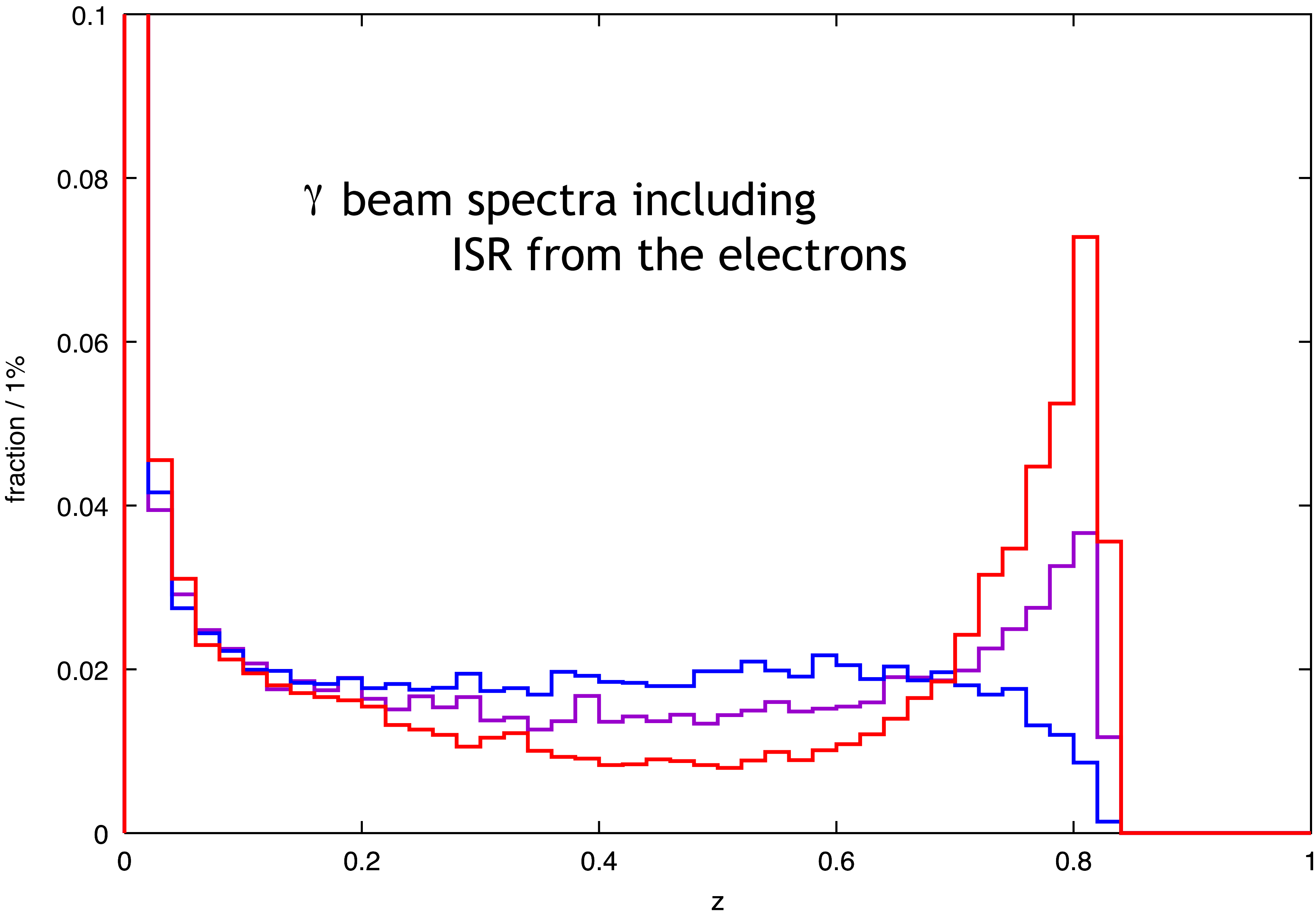
The spectra depend strongly on the e- and γ polarizations.
For high γ enegies, the most effective mode is

$$f(e^-_L \gamma_R \to \gamma_L) = f(e^-_R \gamma_L \to \gamma_R) \sim \frac{z^3}{(1-z)^2}$$

with the spectrum cut off sharply at z_{max}.

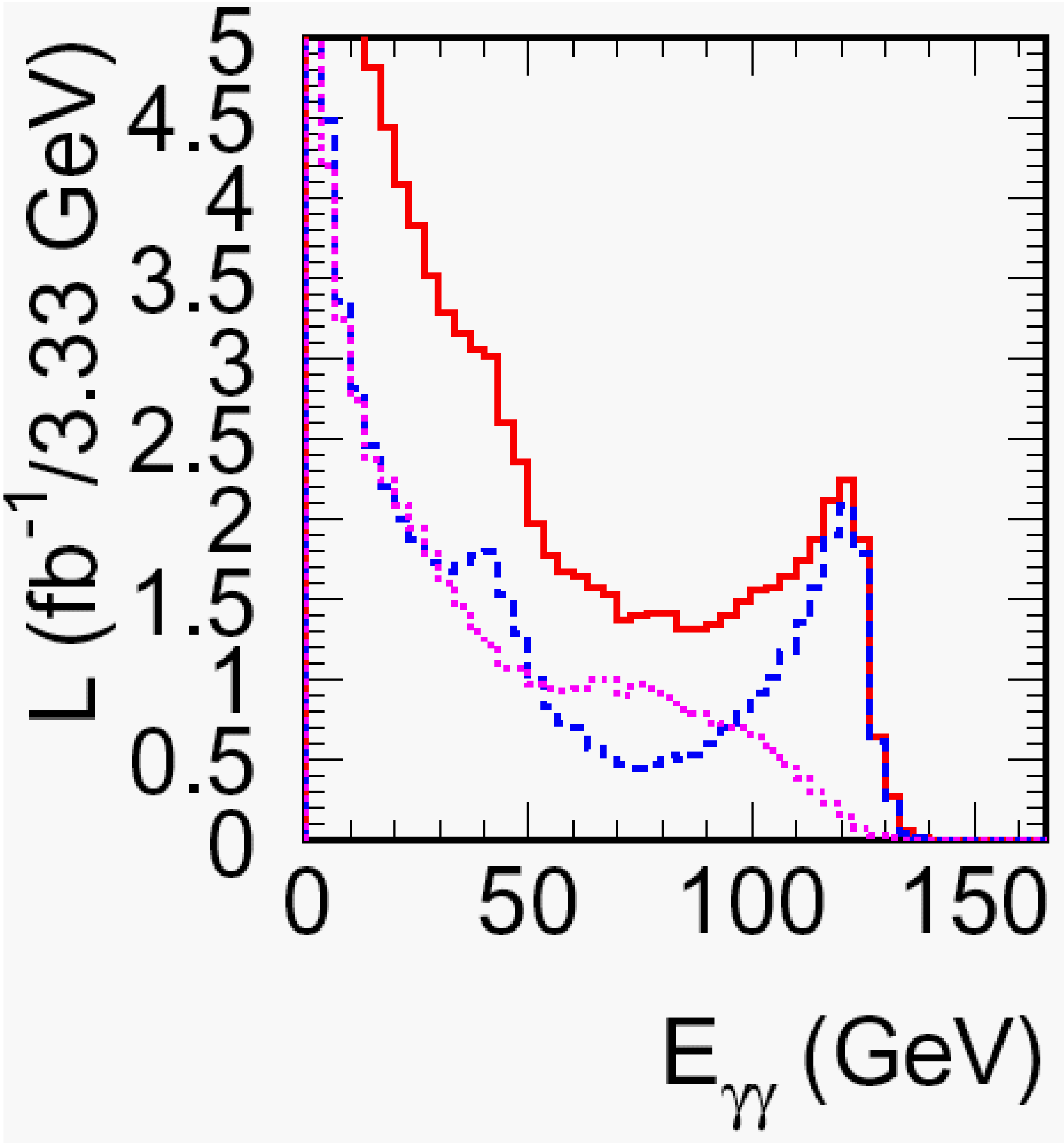



backscattered γ energy spectra
unpolarized
P(e-) = +1 P(γ) = -1
P(e-) = +1 P(γ) = +1
0.12
0.1
0.08
0.06
0.04
0.02
0
0
0.2
0.4
0.6
0.8
1
z



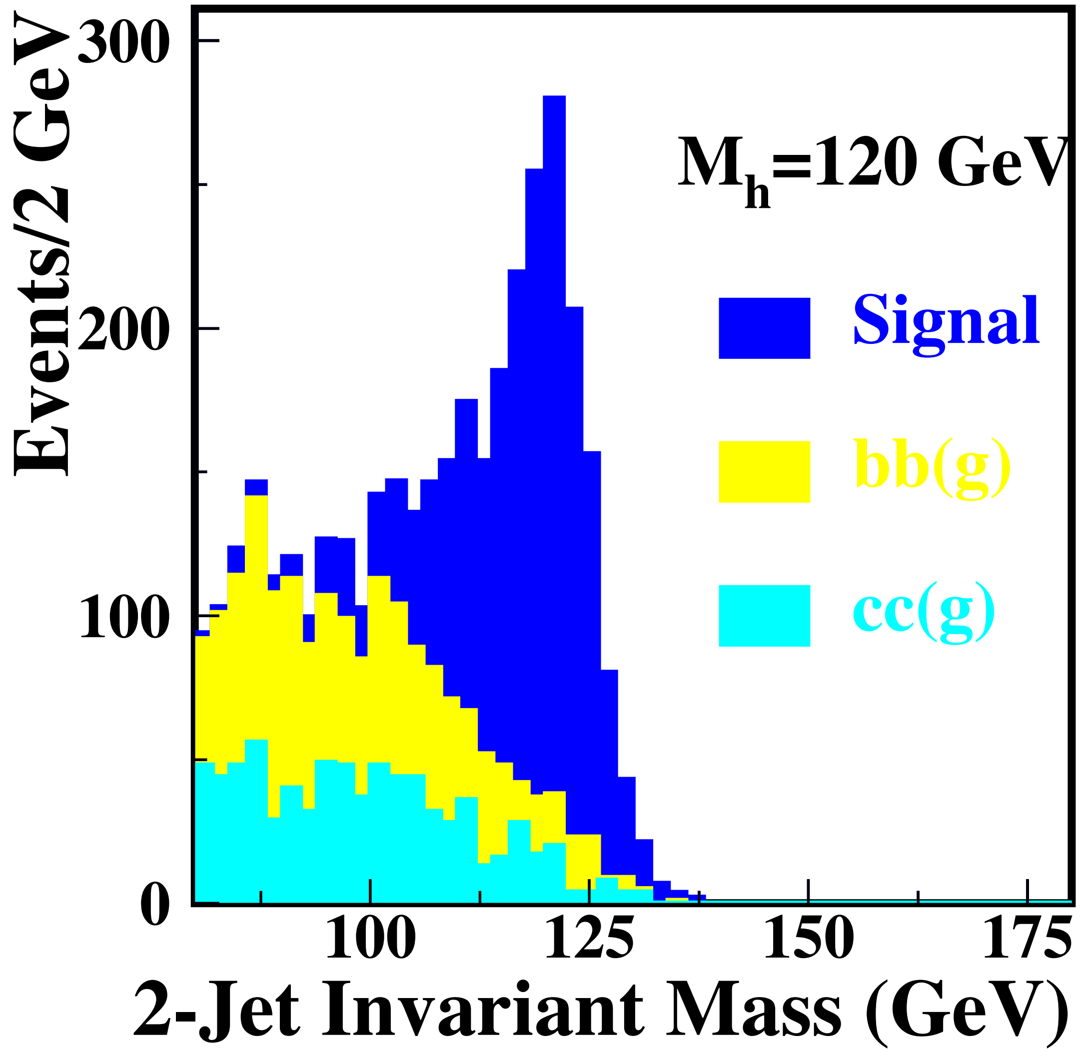
γ beam spectra including
ISR from the electrons
fraction / 1%
z
0
0.02
0.04
0.06
0.08
0.1
0.2
0.4
0.6
0.8
1

A realistic γ spectrum computed by Asner, Gronberg, and Gunion



$\gamma\gamma \rightarrow h^0 \rightarrow b\bar{b}$ 160 GeV, 80% e^- pol.

signal: 2-jet, central, b-tagged



determines $\Gamma(h^0 \rightarrow \gamma\gamma)$ to 3% accuracy.

Models of new physics often bring in extra Higgs doublets. For example, at least two Higgs doublets are required in supersymmetric models. Fermion masses are generated by

$$\mathcal{L} = y_e \overline{e}_R H_1 L + y_d \overline{d}_R H_1 Q + y_u \overline{u}_R H_2 Q + h.c.$$

with

$$L = \begin{pmatrix} \nu \\ e \end{pmatrix}_L \qquad Q = \begin{pmatrix} u \\ d \end{pmatrix}_L$$

H_1 has Y = -1/2

$$\langle H_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} v_1 \\ 0 \end{pmatrix}$$

H_2 has Y = +1/2

$$\langle H_2 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_2 \end{pmatrix}$$

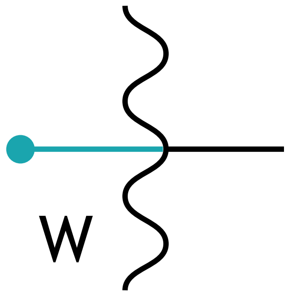
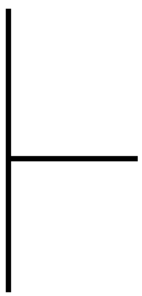
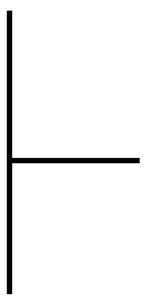
$$v_1^2 + v_2^2 = (246 \text{ GeV})^2 \qquad \frac{v_2}{v_1} = \tan\beta$$

In all, H_1, H_2 contain 8 degrees of freedom. These are realized as

CP even	h^0 H^0	mixed by α	from $h^0{}_1$ $h^0{}_2$
CP odd	A^0 $\square^0$	mixed by β	from $\pi^0{}_1$ $\pi^0{}_2$
charged	H^+ $\square^+$	mixed by β	from $\pi^+{}_1$ $\pi^+{}_2$

$\square^0 \square^+ \square^-$ are eaten by Z^0, W^+, W^-. The remaining bosons are physical.

couplings of h^0, H^0, A^0 parallel those of the SM h^0

			h^0	H^0	A^0
 W	$2i\frac{m_W^2}{v}g^{\mu\nu}$	$\cdot$	$\sin(\beta-\alpha)$	$\cos(\beta-\alpha)$	0
 b	$-i\frac{m_b}{v}$	$\cdot$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\tan\beta$
 t	$-i\frac{m_t}{v}$	$\cdot$	$-\frac{\cos\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\cot\beta$

In some regions of parameter space, deviations from the predicted SM Higgs branching fractions can clearly distinguish the h^0 of the 2-Higgs-doublet model.

However, the minimal supersymmetric model lives in a region of the model space where

h^0 is light, below 135 GeV

H^0, A^0, H^+ are heavy (200 - 600 GeV)

$\cos(\beta - \alpha)$ is small $\sim m_Z^2/m_A^2$

(mH - mA) is small $\sim \dfrac{m_Z^2}{2m_A} \sin^2 2\beta$

In this regime, the branching fractions of h^0 are superficially those of the SM and can be distinguished only by precision measurements.

However, at higher energies,

$$e^+e^- \rightarrow H^0\ A^0,\quad H^+\ H^- \qquad \gamma\gamma \rightarrow H^0\ , A^0$$

open the heavy Higgs bosons to study.

The braching fractions of these particles directly determine parameters of the extended Higgs sector such as $\tan\beta$.