Higgs Physics

for the

Linear Collider

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We are at a crucial point in the study of fundamental physics.

In the 1990's, we have confirmed the Standard Model of electroweak interactions, verifying its predictions to the loop level of accuracy.

But, if the SM is finished, it is not complete. The model requires spontaneous symmetry breaking generated by some outside set of interactions. This is called the 'Higgs Sector'.

We have theories of the Higgs Sector, but there is no 'Standard Model' ; there is no preferred model.

Particles of the Higgs Sector should be accessible at the Linear Collider. The LC will allow precision studies. We need to learn how to use this precision to wring out the secrets that these particles are hiding.

1. Where is the Higgs?

2. SM Higgs: $e^+e^- \rightarrow Z^0 h^0$

3. SM Higgs: $e^+e^- \rightarrow$ 3 body reactions

4. extended Higgs sector: H^0 , A^0 , $H^\pm$

5. $\gamma\gamma \rightarrow h^0, H^0, A^0$

Must there be a Higgs sector ?

among the details verified at LEP, SLC are:

universality of the Z^0 couplings:

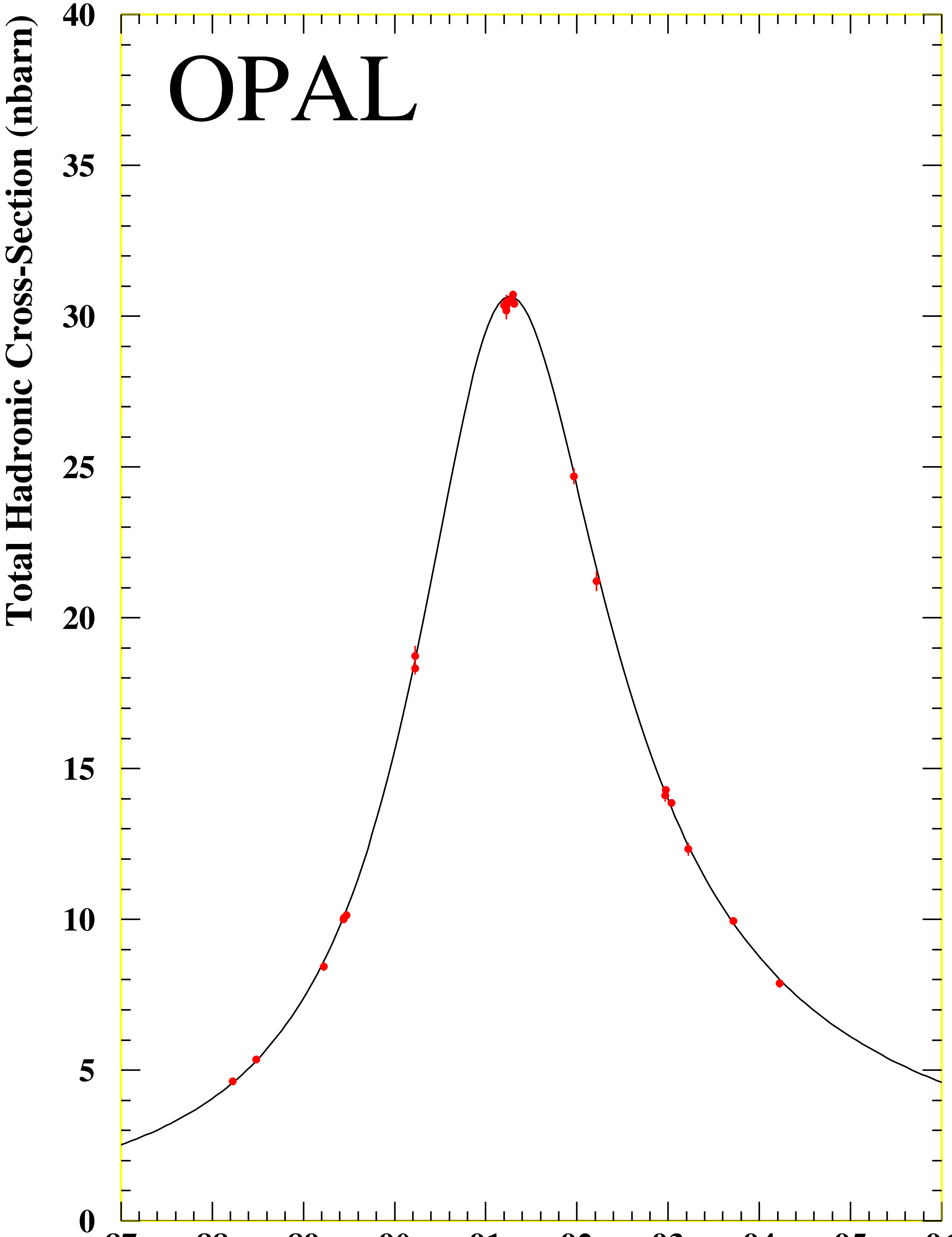
$$(T^3 - \sin^2\theta_W Q)$$

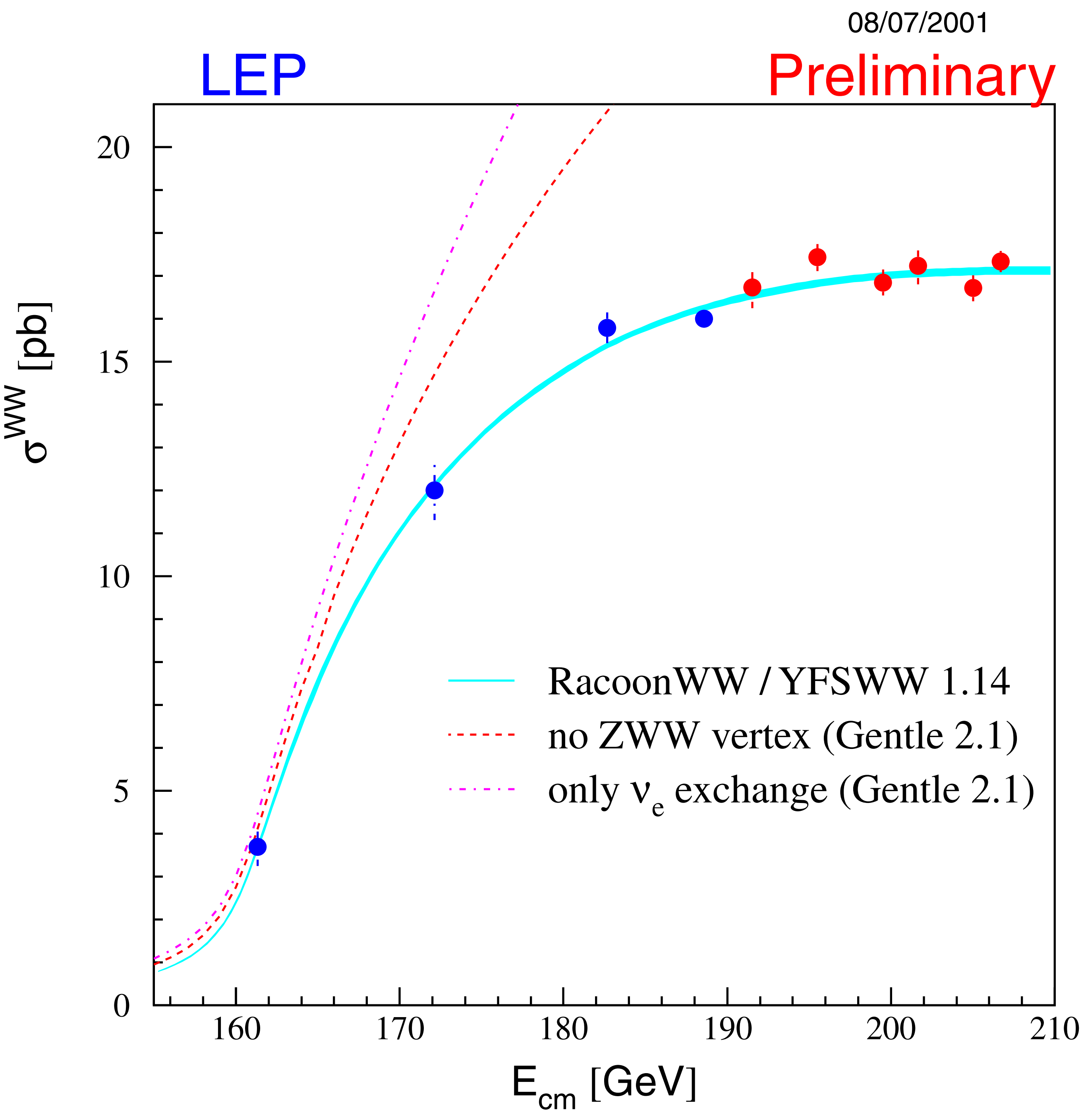
Yang-Mills structure of γWW , ZWW couplings

Both aspects of the electroweak gauge theory are tested at the % level.

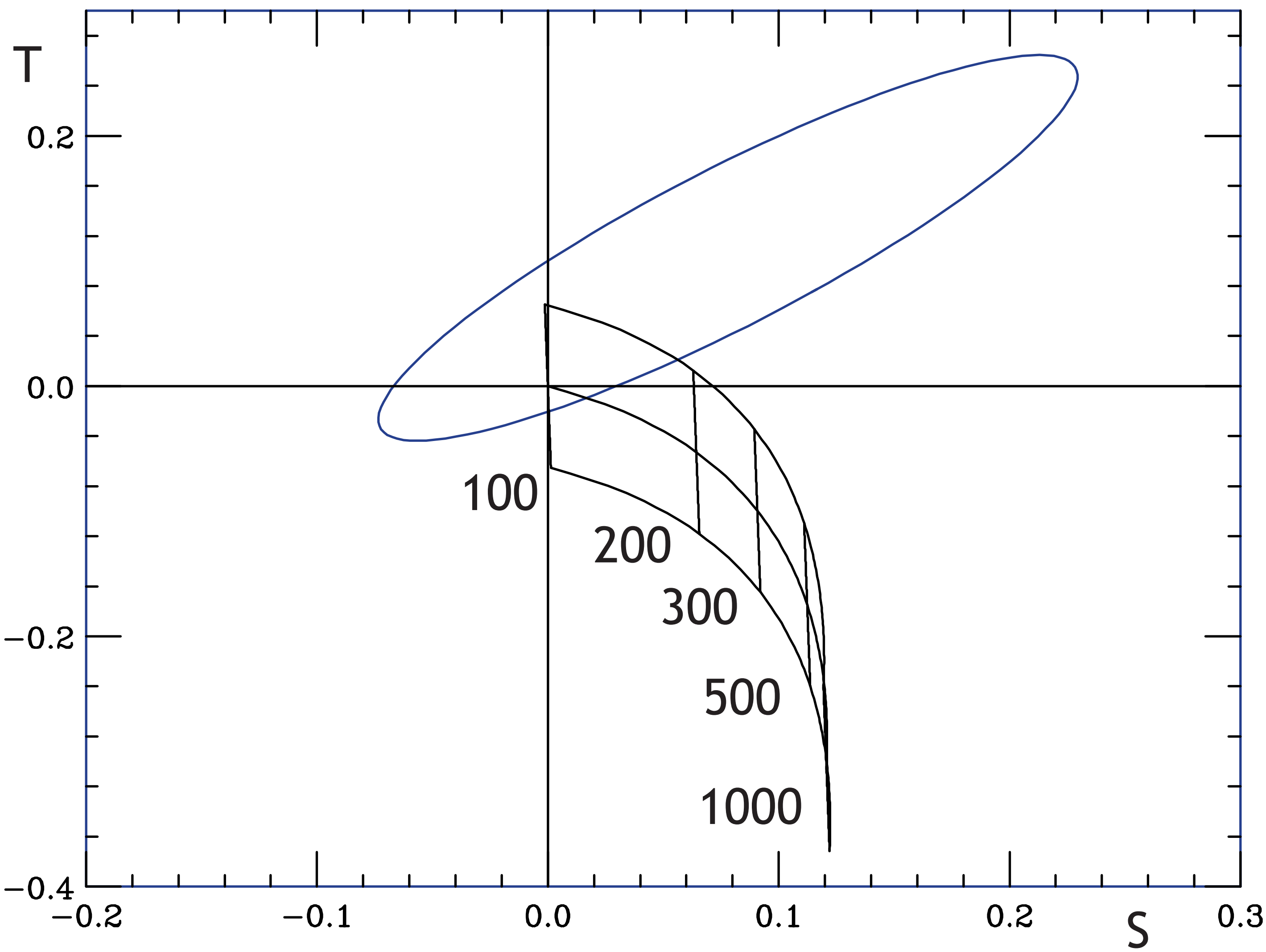
In Yang-Mills theory, only the transverse components of vector bosons are physical.

The longitudinal polarization states are taken from the fields that cause spontaneous symmetry breaking.


OPAL
Total Hadronic Cross-Section (nbarn)
Center-of-Mass Energy (GeV)
0
5
10
15
20
25
30
35
40
87
88
89
90
91
92
93
94
95
96


08/07/2001
LEP
Preliminary
20
15
10
5
0
σ^{WW} [pb]
160
170
180
190
200
210
E_{cm} [GeV]
RacoonWW / YFSWW 1.14
no ZWW vertex (Gentle 2.1)
only ν_e exchange (Gentle 2.1)

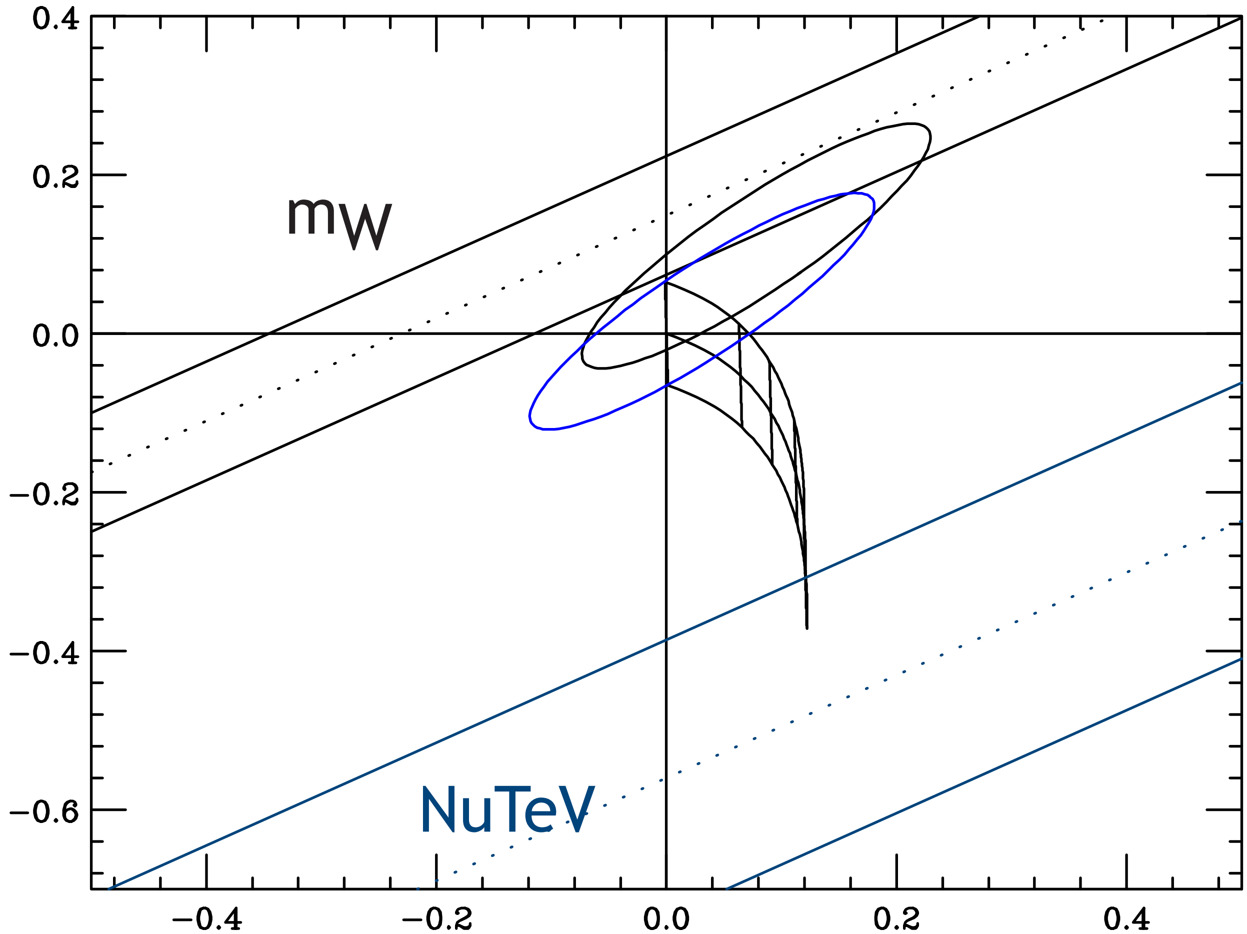
The success of precision electroweak fits and the failure to find new particles at LEP2 motivates us to assume that new physics beyond the SM makes a negligible contribution. Under this assumption, we can fit for the mass of the SM Higgs:



m(h) < 222 GeV (95% conf) (LEP EWWG)

recent changes in the upper limit mainly reflect new evaluations of $\alpha(m_Z)$.

effect of the new NuTeV measurement ? This has almost the same dependence on top, Higgs loop effects as the direct m_W measurement:



most likely explanation:

parton distributions are not so simple; even in an 'isoscalar' nucleus

$u(x) \neq d(x) \qquad s(x) \neq \bar{s}(x)$

most interesting explanation:

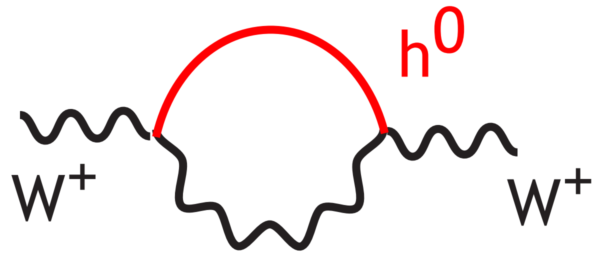
there is a Z' just beyond the reach of the run I Tevatron experiments

The assumption that the SM is a good approximation for precision electroweak need not be correct. In most models, however, extra particles lead to stronger constraints on m(h) or on new physics parameters. However, there are some counterexamples. These are reviewed in

Peskin and Wells, hep-ph/0101342

These models can be experimentally distinguished by improved precision electroweak measurements, or by characteristics signals, e.g. a Z' below 2 TeV.

In the rest of this talk, I will assume that the Higgs sector includes a particle that obeys the SM precision electroweak constraint.



Specific theories give independent upper bounds on m(h):

The Higgs self-coupling is renormalized to smaller values at smaller mass scales. So, if h^0 is effectively an elementary field at a high scale , its mass is bounded (in the SM) by

$$m(h) < \frac{1000\ \text{GeV}}{\sqrt{\log(\Lambda/v)}}$$

Putting = 10^{16} GeV, m(h) < 180 GeV.

In the context of SUSY GUT's, extensive searches have been made for models in which m(h) is large. The highest value found is

$$m(h) = 208\ \text{GeV}$$

in a model with heavy singlet and triplet Higgs.

Quiros and Espinosa, hep-ph/9802269

An important special case is the Minimal Supersymmetric Standard Model, with Higgs structure: H_u , H_d , no SU(2) singlets.

As SUSY masses become large, the mode

$$(\delta H_u^0, \delta H_d^0) \sim (\sin\beta, \cos\beta) \qquad \tan\beta = \frac{\langle H_u \rangle}{\langle H_d \rangle}$$

has no potential except from SU(2)XU(1) D-terms. In this limit, at tree level,

$$m_h = m_Z \cos 2\beta$$

However, loop corrections to this result are important. The general 1-loop relation is

$$m_h^2 < m_Z^2 \cos^2 2\beta + \frac{3\alpha_w}{2\pi m_W^2} m_t^4 \log \frac{m_{\tilde{Q}}^2}{m_t^2}$$

The absolute upper bound is 135 GeV, but values above 120 GeV are difficult to achieve.

The best possibility is that LEP observed h^0 at 115 GeV ! Can CDF, D0 confirm it ?

The process $e^+e^- \to Z^0 h^0$
gives a highly constrained environment to study Higgs bosons.

For fixed h^0 mass, up to beams effects, the Z^0 appears at a fixed lab energy. This allows an absolute determination of the cross section independent of the values of Higgs branching fractions.

Most studies of this process assume $Z^0 \to l^+l^-$. But,

$$BR(Z \to e, \mu) = 7\% \quad BR(Z \to q\bar{q}) = 70\%$$

so there is much to gain by recognizing Z's in hadronic modes.

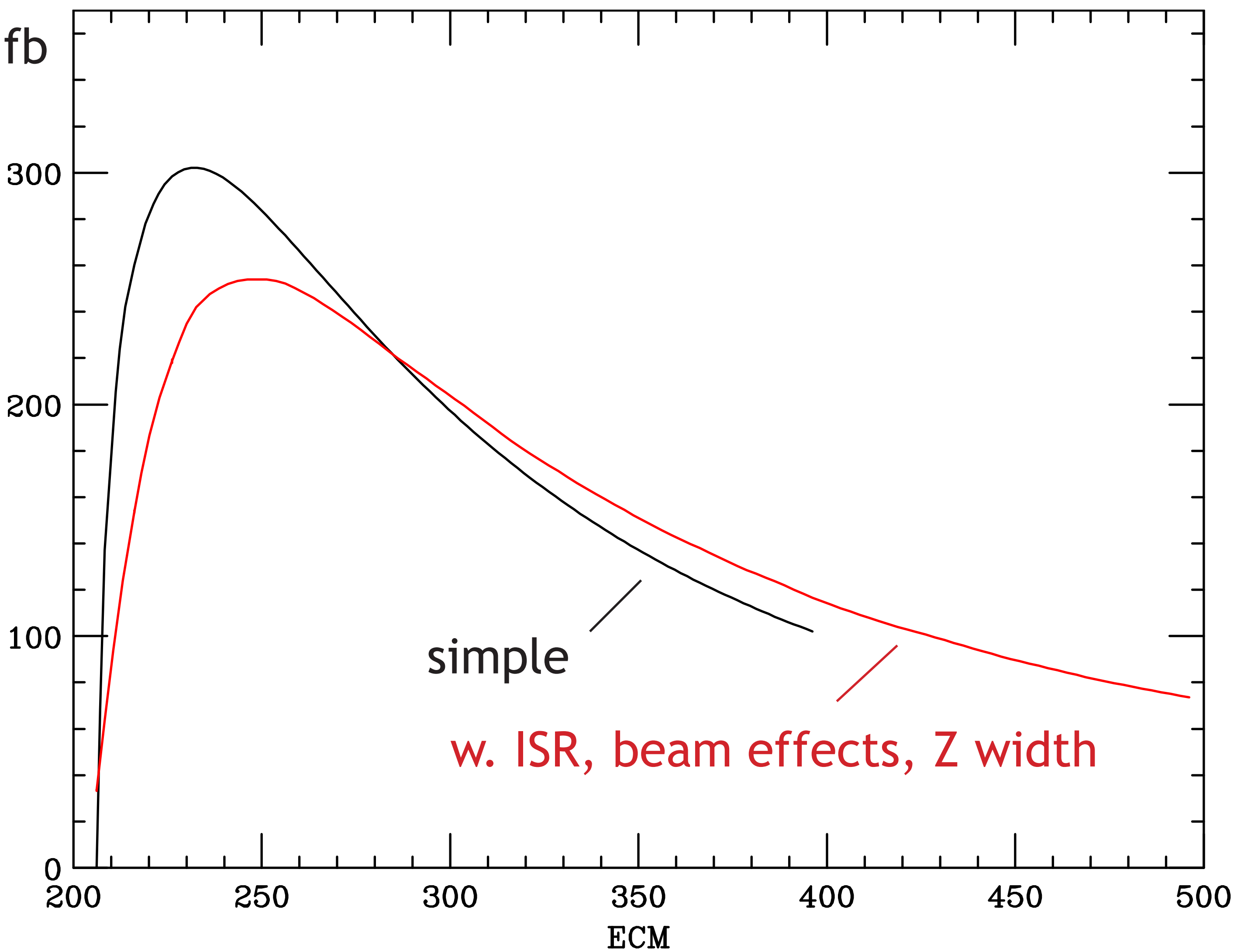
The dominant background comes from

$$e^+e^- \to Z^0 Z^0$$

with one Z off-shell. This highlights the importance of polarization analysis of the 2-jet system.

$\sigma\,(e^+e^- \to Z^0\,h^0)$ (fb)

for m_h = 115 GeV

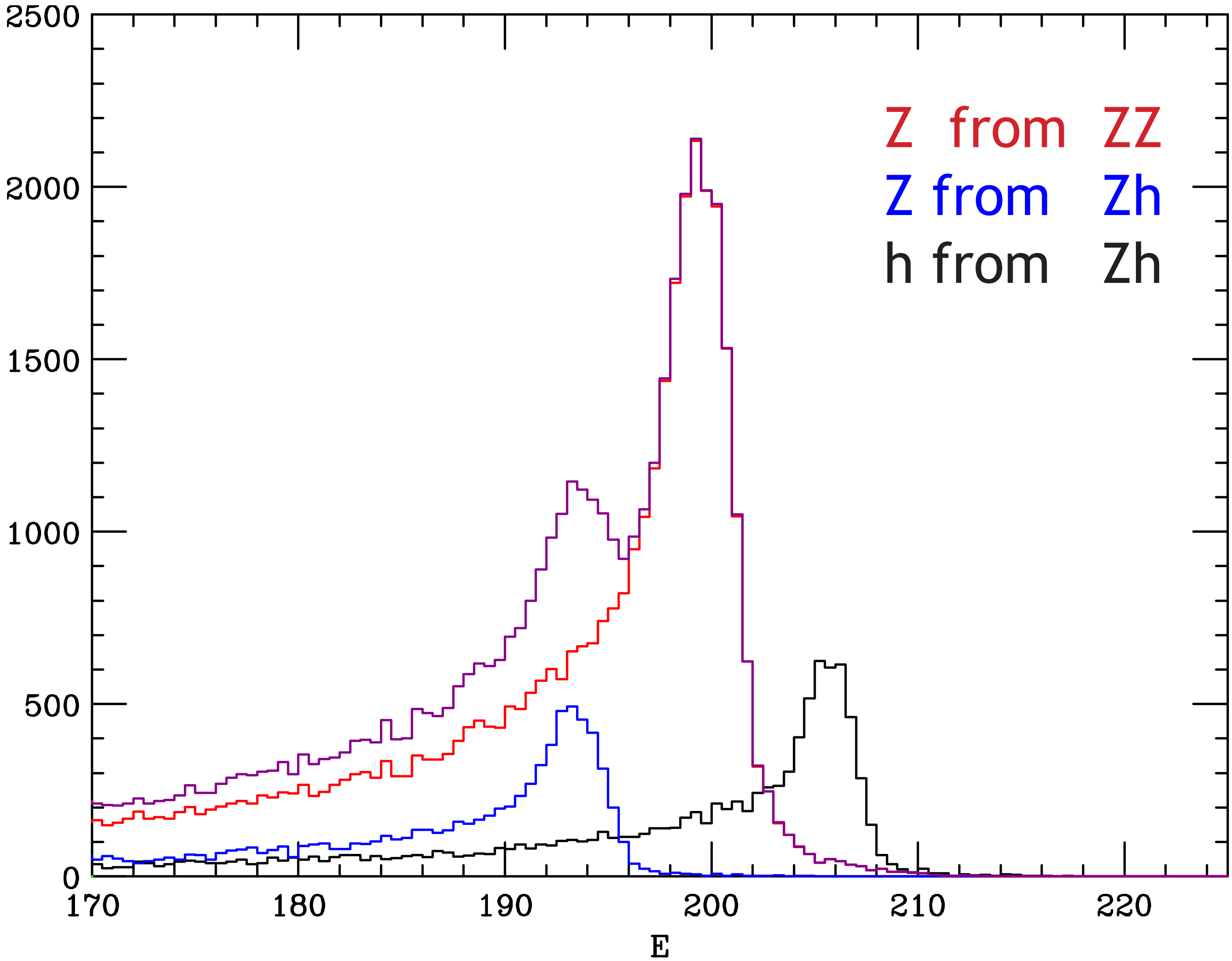


(unpolarized beams)

lab-frame energy distributions in

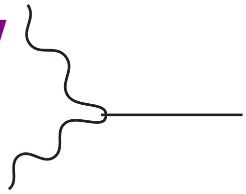
$e^+e^- \rightarrow Z^0 h^0$

400 GeV, all hadronic Z, h with $\cos\theta < 0.8$

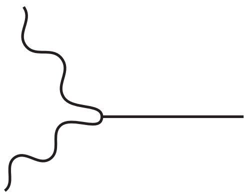


Z, W coupling to h:

in the SM: $v = 246$ GeV

W


$$= 2i \frac{g^2}{4} v\, g^{\mu\nu} = 2i \frac{m_W^2}{v} g^{\mu\nu}$$

Z


$$= 2i \frac{g^2 + g'^2}{4} v\, g^{\mu\nu} = 2i \frac{m_Z^2}{v} g^{\mu\nu}$$

in a multi-Higgs model (all doublets), substitute

$\langle h_i \rangle$ for v

That is,

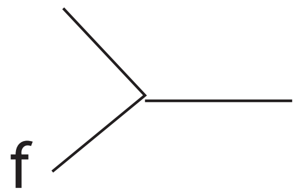
$$\sigma(e^+e^- \to Z^0 h^0) \,/\, \sigma(\text{SM}) = \langle h \rangle^2 / v^2$$

The linear collider directly measures the fraction that each h^0 contributes to m_Z !

Note also: $\lambda(hWW)/\lambda(hZZ) = m_W^2/m_Z^2 = \cos^2\theta_W$

fermion coupings to h :

in the SM:

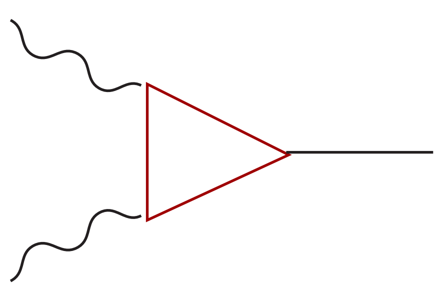


$$= i \frac{m_f}{v}$$

If there is one Higgs boson, its couplings must be proportional to mass.

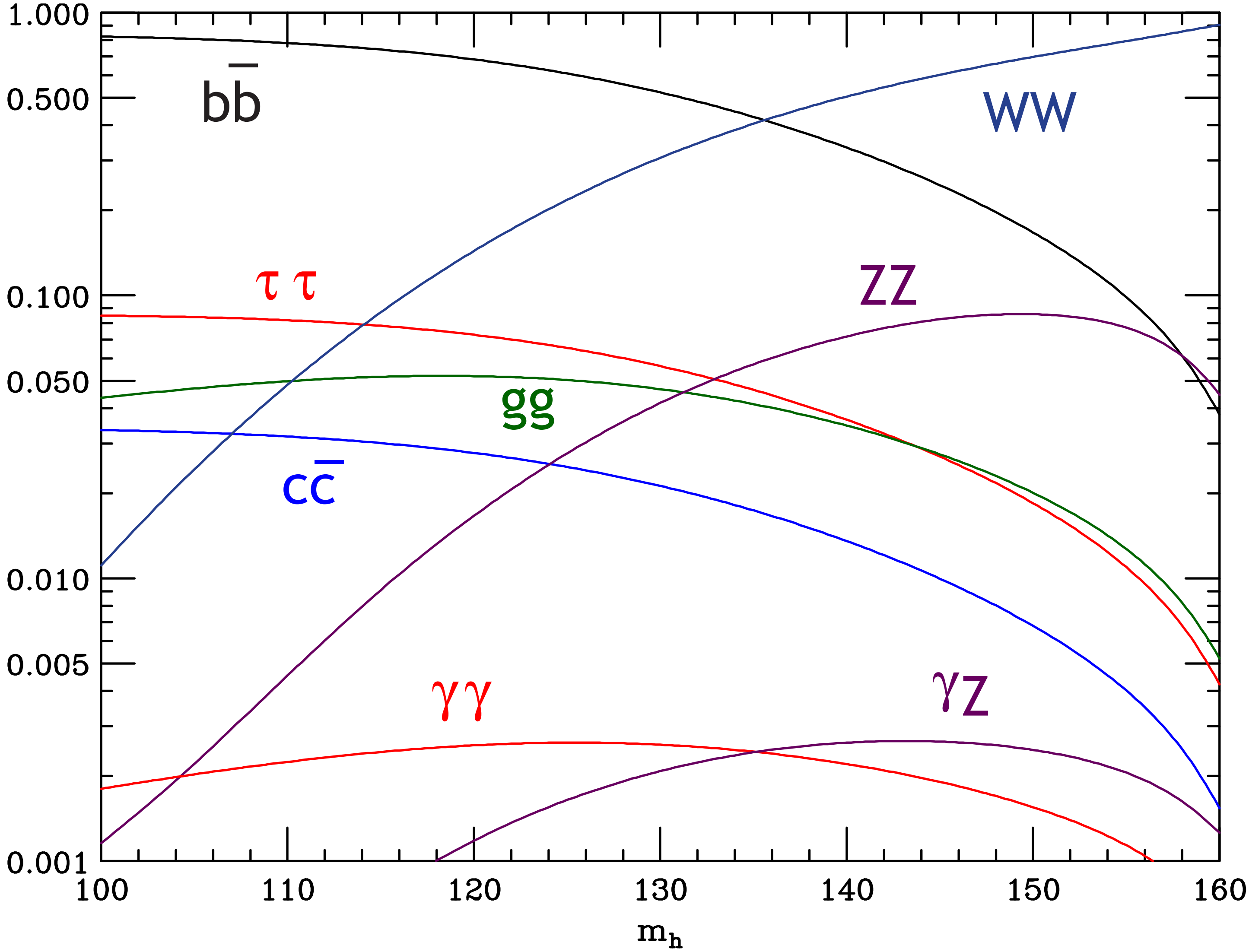
The Higgs branching fractions test this hypothesis.

The Higgs couplings to $\gamma\gamma$, gg are generated at 1-loop. These are sum rules over species heavier than h: t, W, ...

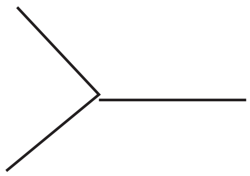


SM Higgs branching fractions

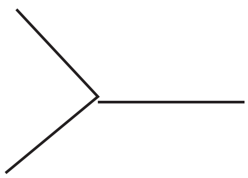
(light Higgs)



in a 2-Higgs doublet model such as the MSSM,


d

$$= i \frac{m_d}{v} \frac{-\sin\alpha}{\cos\beta}$$


u

$$= i \frac{m_u}{v} \frac{\cos\alpha}{\sin\beta}$$

but, in the MSSM, these ratios are close to 1 if m_A is large

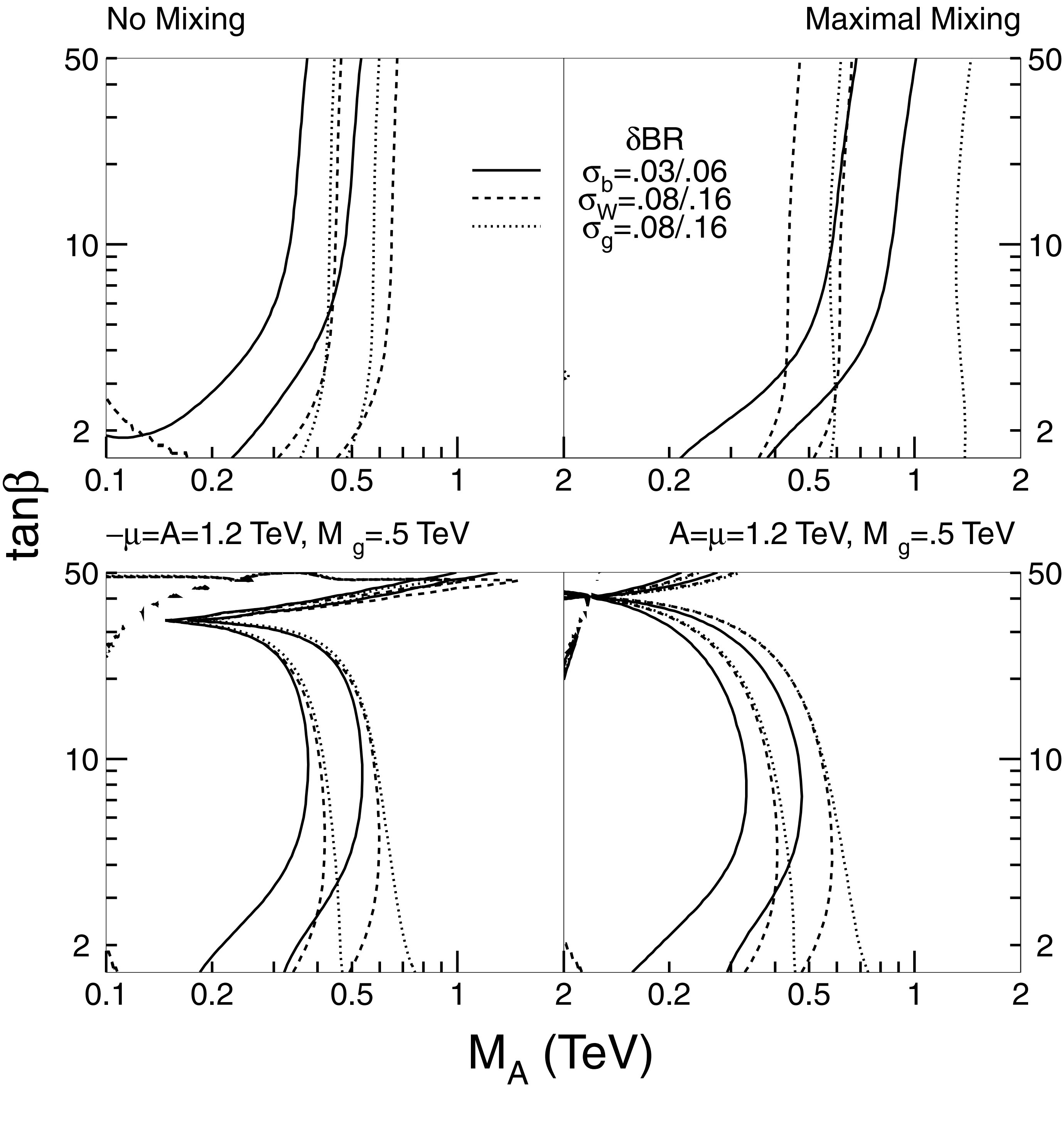
$$\cos(\beta - \alpha) = \frac{m_Z^2}{m_A^2} \cos 2\beta \, \sin 2\beta + \cdots$$

For small variations from the SM, radiative corrections are relelvant.

These can have uexpected effects, e.g.

$$\lambda(h\tau\tau)/\lambda(hbb) \neq m(\tau)/m(b)$$

Borzumati, Farrar, Polonsky, Thomas, hep-ph/9712428 deviations of h BRs to b, W, g for various parameter choices of the MSSM



Carena, Haber, Logan, Mrenna, hep-ph/0106116

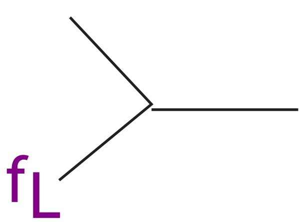
Spin and CP of the Higgs boson:

Only a scalar (0^+) can couple to WW, ZZ at tree level.

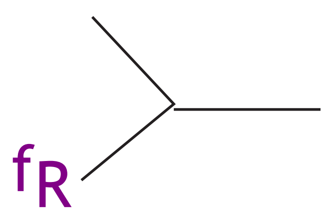
The scalar coupling gives characteristic dependences on ECM, $\cos\theta$, Z polarization that can be tested:

$d\sigma / d\cos\theta \sim \sin^2\theta$ Z longitudinally pol.

It is harder to see a CP-violating admixture of h and a (0^-). Helicity-dependent couplings acquire a phase:



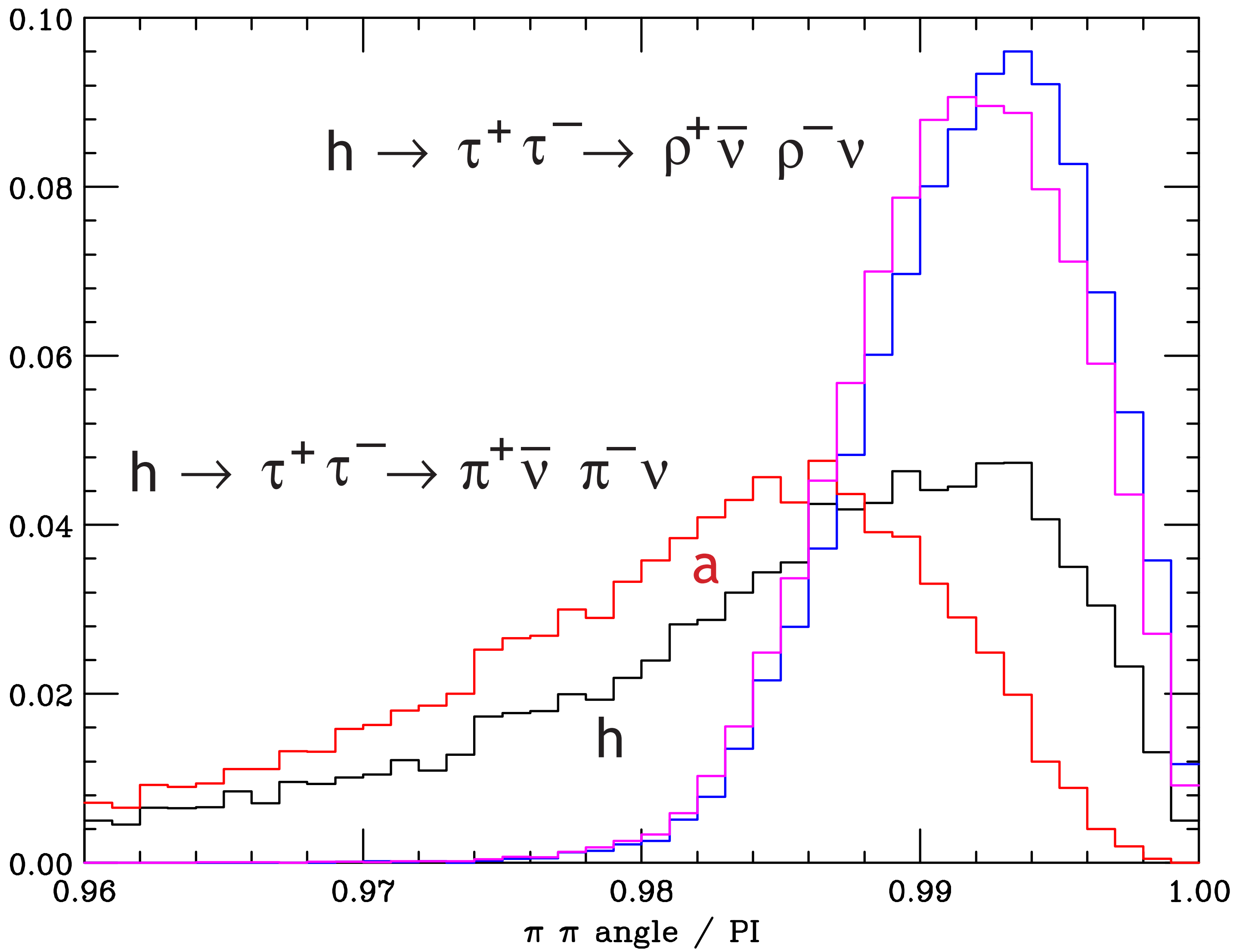
$= i \frac{m_f}{v} e^{i\alpha}$



$= i \frac{m_f}{v} e^{-i\alpha}$

but the phase is visible only when L,R interfere.

Kramer, Kuhn, Stong, Zerwas showed a subtle effect in $h \to \tau^+\tau^- \to \pi^+\bar{\nu}\ \pi^-\nu$



angle between π^+ and π^- in h rest frame for heavier Higgs bosons, some issues are different:

m_h > 160 GeV:

here WW, ZZ decays dominate,
$h \to b\bar{b}$ becomes a rare decay mode

Yet, it should still be observable and test
$\lambda(hb\bar{b})/\lambda(hWW)$

m_h > 350 GeV:

here the mode $h \to t\bar{t}$ becomes relevant,
rising to a BR of 20%.

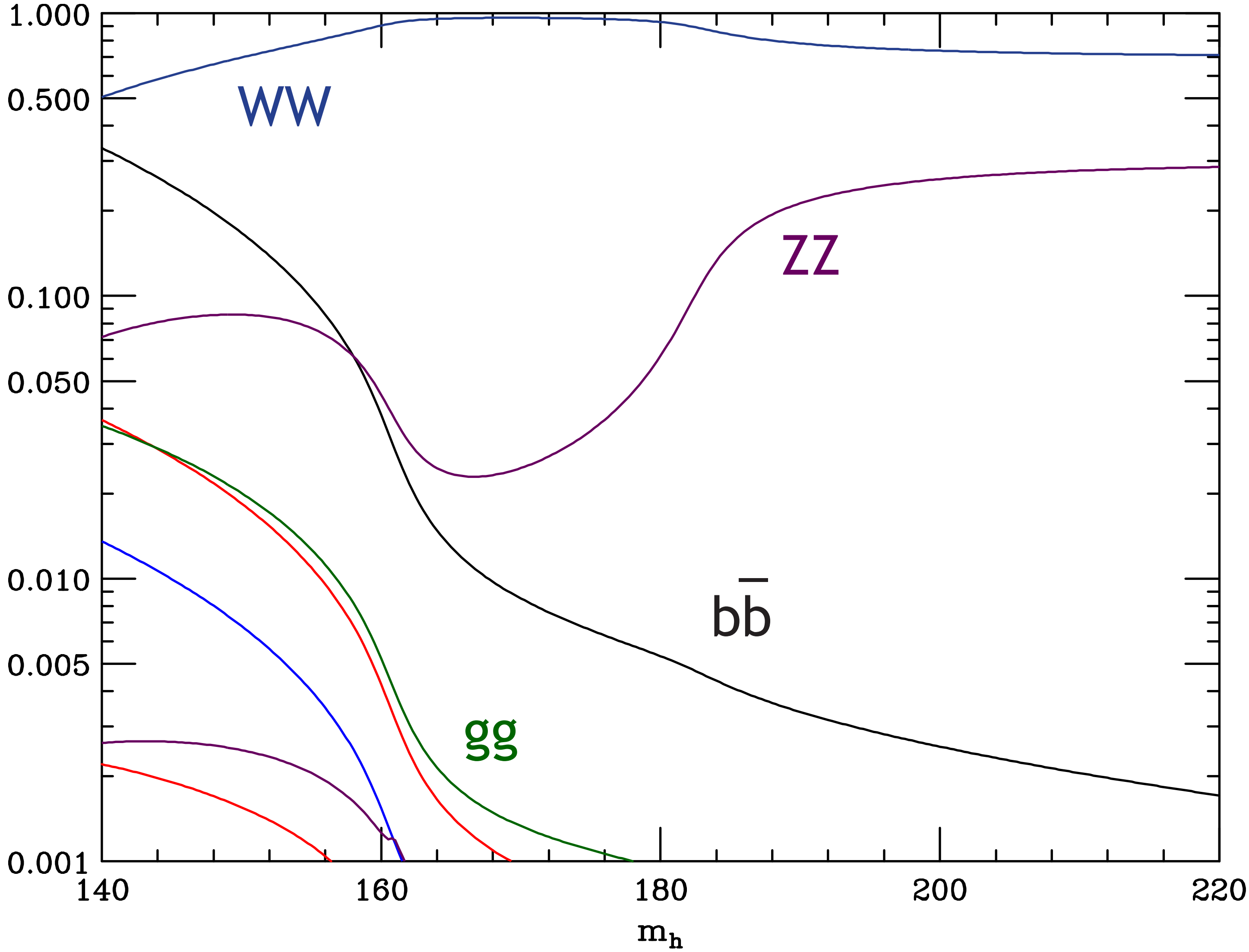
This can be measured accurately using
the h resonance contribution to

$$e^+e^- \to \nu\bar{\nu}t\bar{t}$$

Alcaraz and Ruiz Morales, hep-ph/0012109

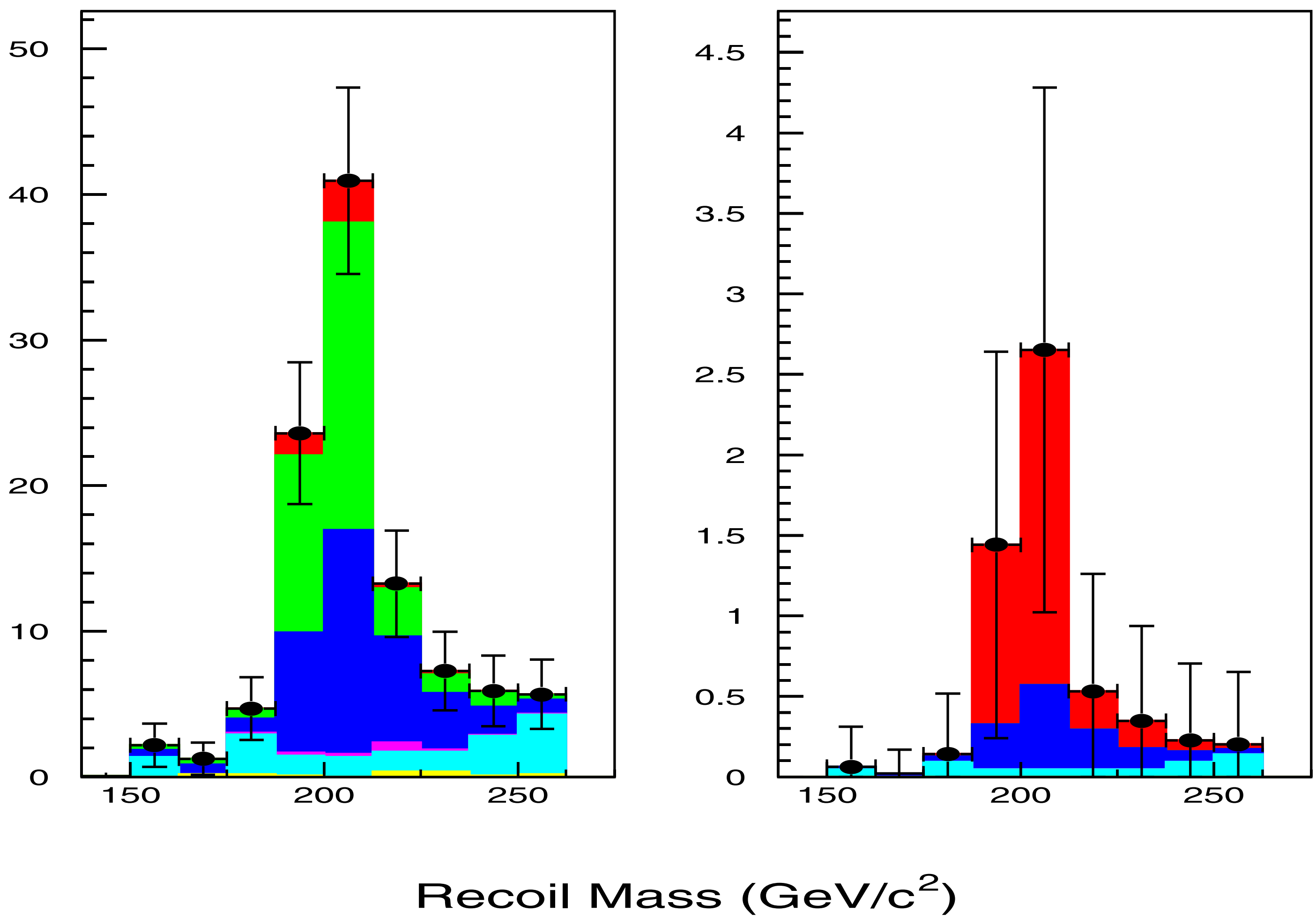
SM Higgs branching fractions

(Higgs at WW threshold)



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

m(h) = 200 GeV, analyzed at ECM = 350 GeV

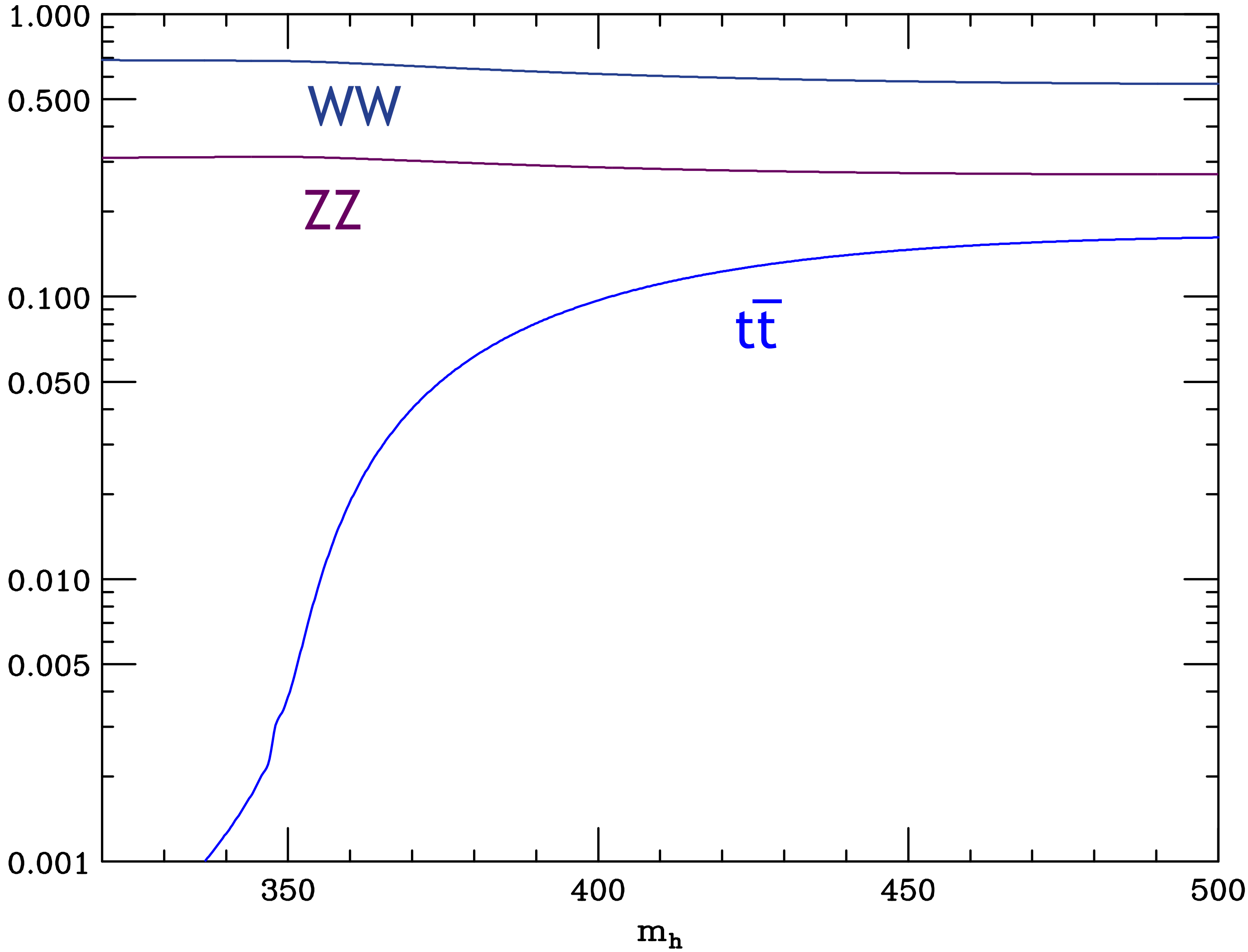


apply b-tagging, a small residue of $b\bar{b}$ events remain, giving a Yukawa coupling determination to 15-20%.

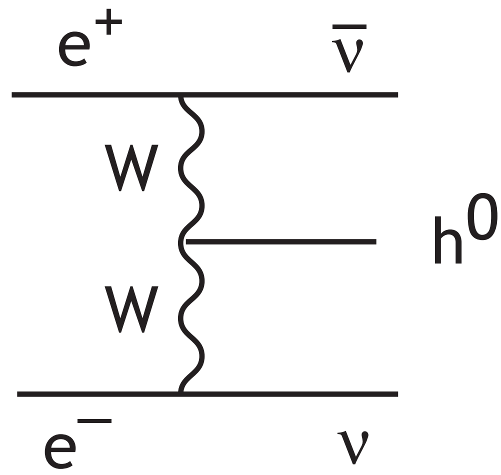
Battaglia and Desch, Warsaw

SM Higgs branching fractions

(heavy Higgs)



An alternative mode of Higgs production is WW fusion



Like $\sigma(e^+e^- \rightarrow Z^0 h^0)$, this σ depends only on the fraction that h^0 contributes to the W, Z masses.

If m_h is known, the process is very clean, since it produces a hadronic system with the mass m_h plus missing energy.

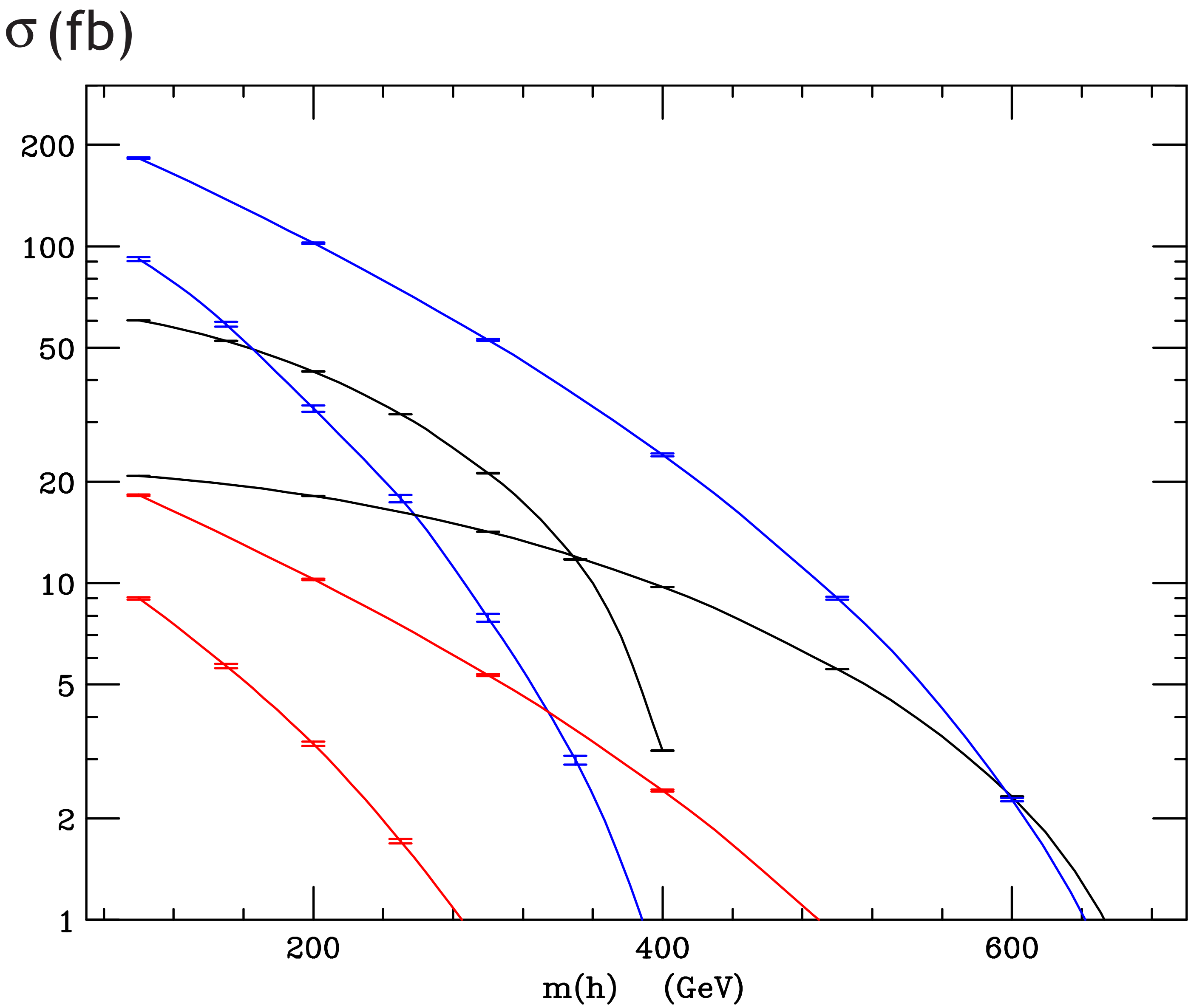
The cross section increases logarithmically with energy. Battaglia and De Roeck have suggested using the high yield at multi-TeV energies to measure $\lambda(h\mu\mu)$!

total cross sections for

$e^+e^- \to Z^0\ h^0$

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

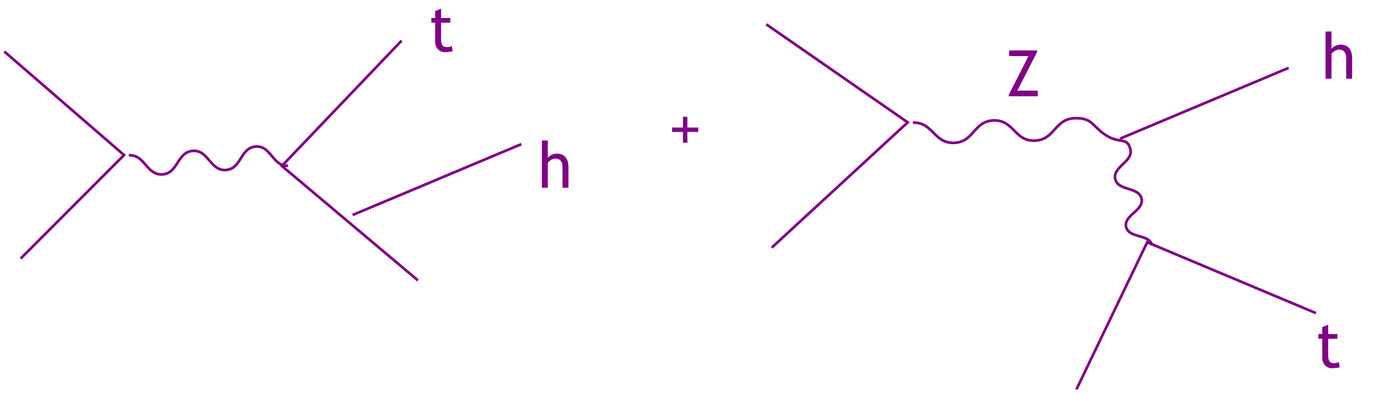
$e^+e^- \to e^+e^-\ h^0$



ECM = 500, 800 GeV

two more important 3-body processes are:

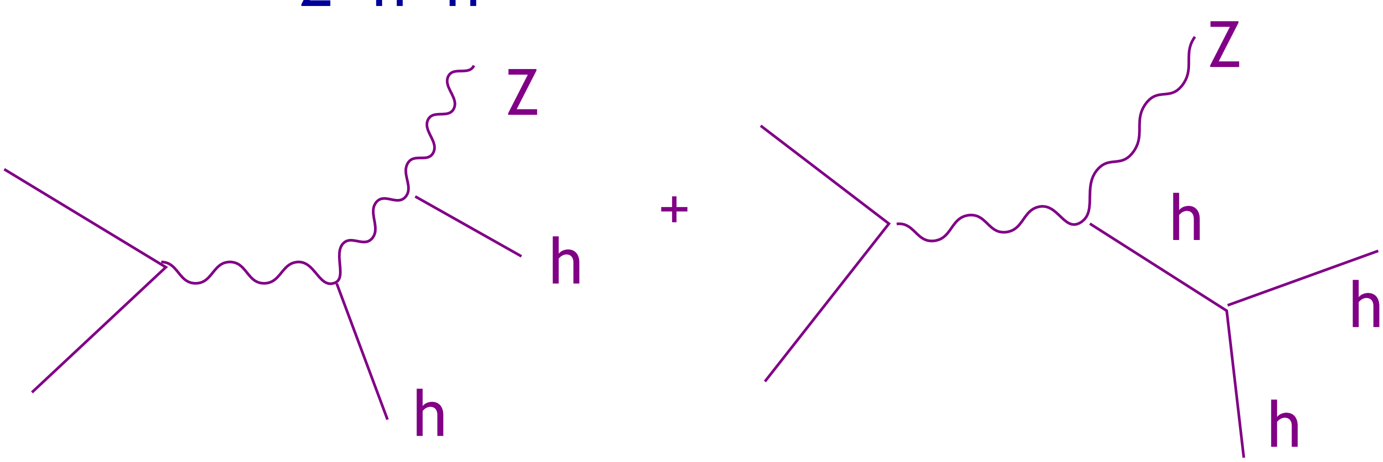
$e^+e^- \rightarrow t\,\bar{t}\,h$



σ ~ 2 fb at ECM = 1 TeV
sensitive to λ(htt)

Juste and Merino, hep-ph/9910301

$e^+e^- \rightarrow Z\,h\,h$



σ ~ 0.1 fb at ECM = 1 TeV
sensitive to λ(hhh)

Lafarge et al., hep-ph/0001169
Castanier et al., hep-ex/0101028

Estimated relative accuracy of Higgs coupling measurements (%)

m_h	120	140	160	200	400
Z	3	3	3	3.5	5*
W	2	3	9		
b	1.5	1.5	2	15-40	
τ	4	5	18		(add σ norm in quad.)
c	9-20	10-22			
g	10	12.5			
γ	7	10			
t	7-20 *				10 *
h	23 *				

500 fb^{-1} at 500 GeV except * 1000 fb^{-1} at 800 GeV

The table shows large uncertainties (and disagreement between groups) for the hardest measurements. Larger errors typically reflect more realistic pattern recognition for vertices and more conservative treatment of ZZ background. Much more work is needed on the optimal methods for these measurements.

2-Higgs-doublet spectrum:

H_u , H_d $\rightarrow$

CP even	h^0 H^0	mixing angle α
CP odd	A^0 (Π^0)	mixing angle β
charged	$H^\pm$ $(\Pi^\pm)$	$\tan\beta = \frac{\langle H_u \rangle}{\langle H_d \rangle}$

for VV = WW, ZZ

$$\lambda(hVV)/SM = \sin(\beta - \alpha)$$
$$\lambda(HVV)/SM = \cos(\beta - \alpha)$$

so the cross section sum rule for $e^+e^- \rightarrow Z^0 h_i^0$ is saturated by h^0, H^0.

	h^0	H^0	A^0
$\lambda(Xbb)/SM$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\tan\beta$
$\lambda(Xtt)/SM$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\cot\beta$

In the special case of the MSSM, h^0 must be light, but H^0, A^0, $H^\pm$ are typically heavy (200-600 GeV).

$\cos(\beta - \alpha)$ is small ~ m_Z^2/m_A^2 , and
$m_H - m_A$ is small:

$$m_H - m_A = (m_Z^2/2m_A) \sin^2 2\beta ,$$

comparable to the widths of H^0 and A^0.

In this case, H^0 decouples from WW, ZZ;
its dominant production mechanism is

$$e^+e^- \to H^0 A^0$$

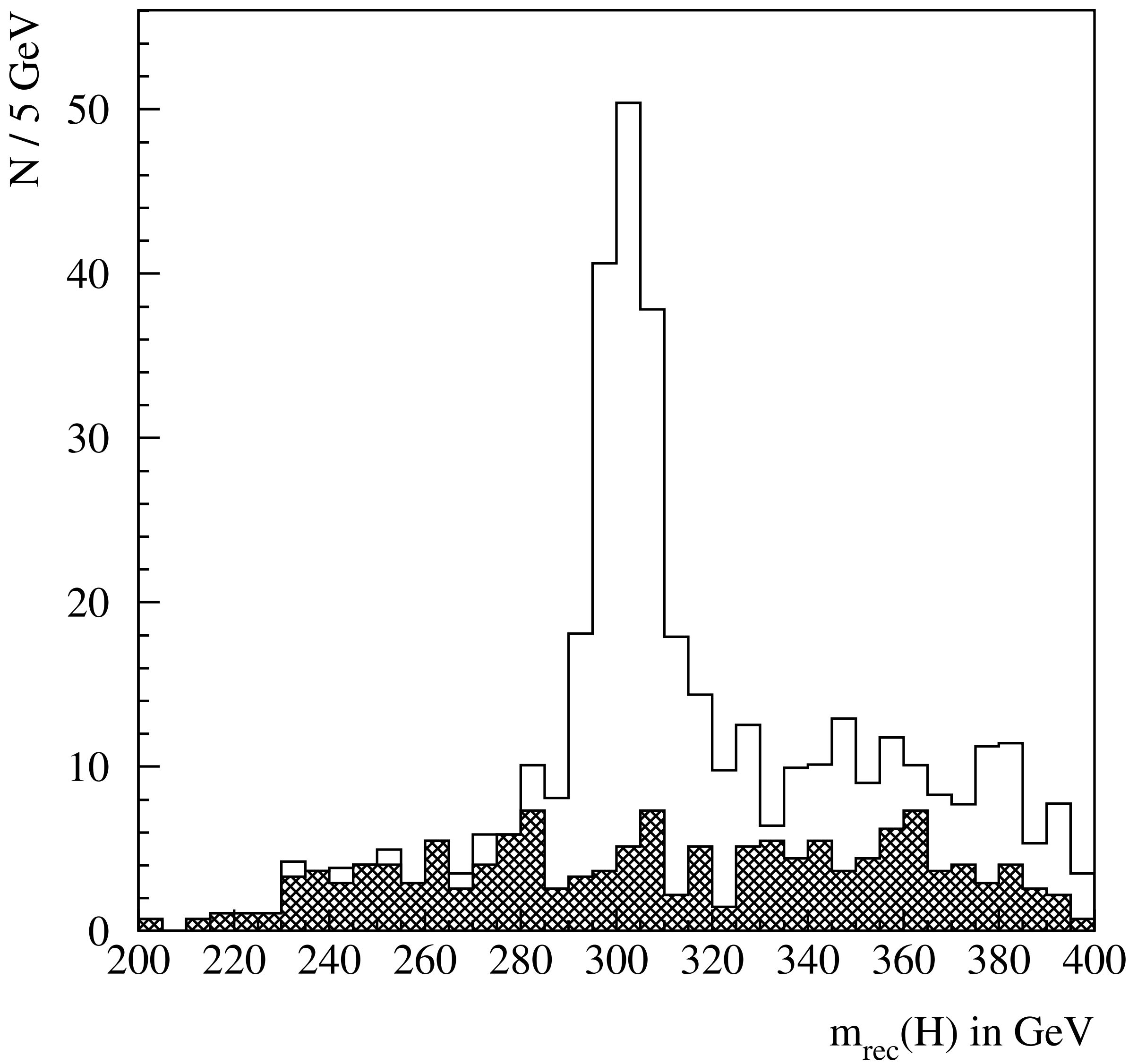
For both H^0 and A^0,

$\lambda(bb)/SM = \tan\beta$ $\lambda(tt)/SM = \cot\beta$

so, measurement of the H^0 and A^0 branching fractions or couplings to b and t determines the ubiquitous SUSY parameter $\tan\beta$.

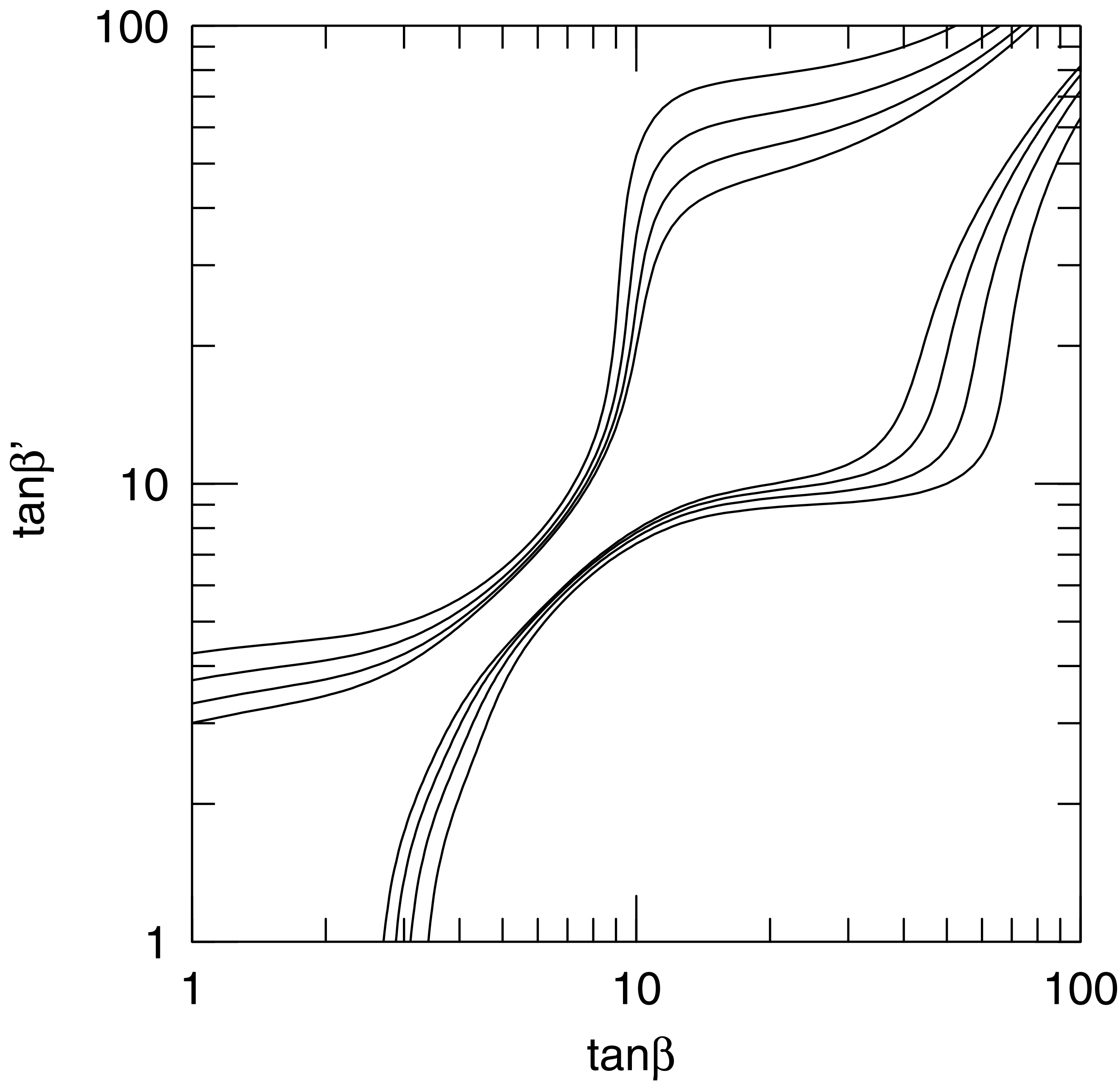
Reconstruction of $e^+e^- \to H^+H^- \to t\,\bar{b}\,\bar{t}\,b$

at 800 GeV, 1000 fb^{-1}.



Battaglia, Ferrari, Kiiskinen, Maki, hep-ph/0112015 an example: m_A = 300 GeV, ECM = 1 TeV

200, 400, 600, 800 fb^{-1}



Feng and Moroi, hep-ph/9612333

Since h^0, H^0, A^0 decay to $\gamma\gamma$, they can appear as resonances at a $\gamma\gamma$ collider.

Use characteristic peaked $\gamma\gamma$ luminosity spectrum, with ECM adjusted to m_h

detection with b-tagging to suppress $\gamma\gamma \to c\bar{c}$

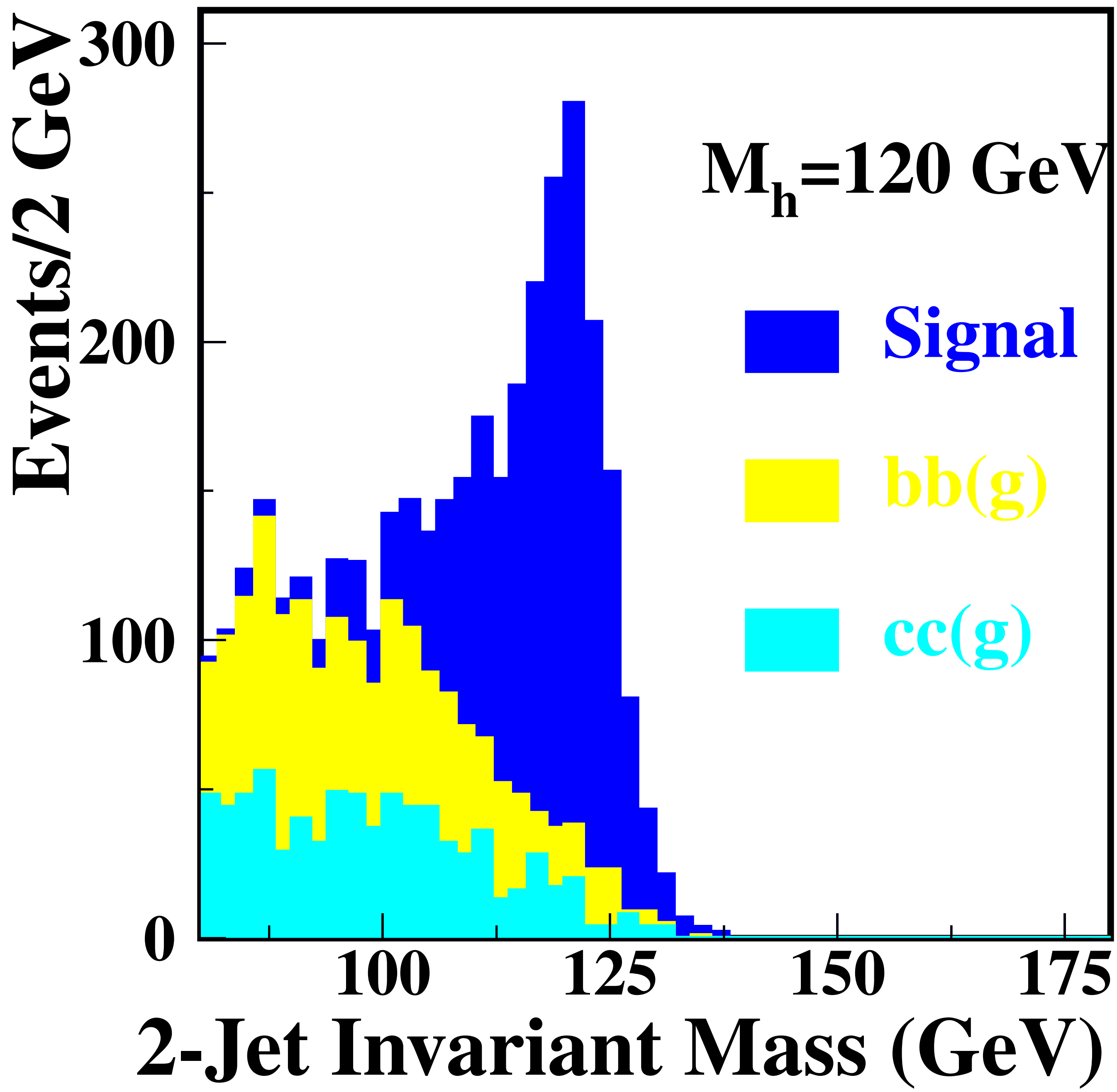
polarized γs with $J_z = 0$ to suppress dominant $J_z = 2$ state in $\gamma\gamma \to f\bar{f}$.

A new intensive study of these processes builds on the recent technical progress toward $\gamma\gamma$ colliders at Livermore:

Asner, Gronberg, Gunion, hep-ph/0110320

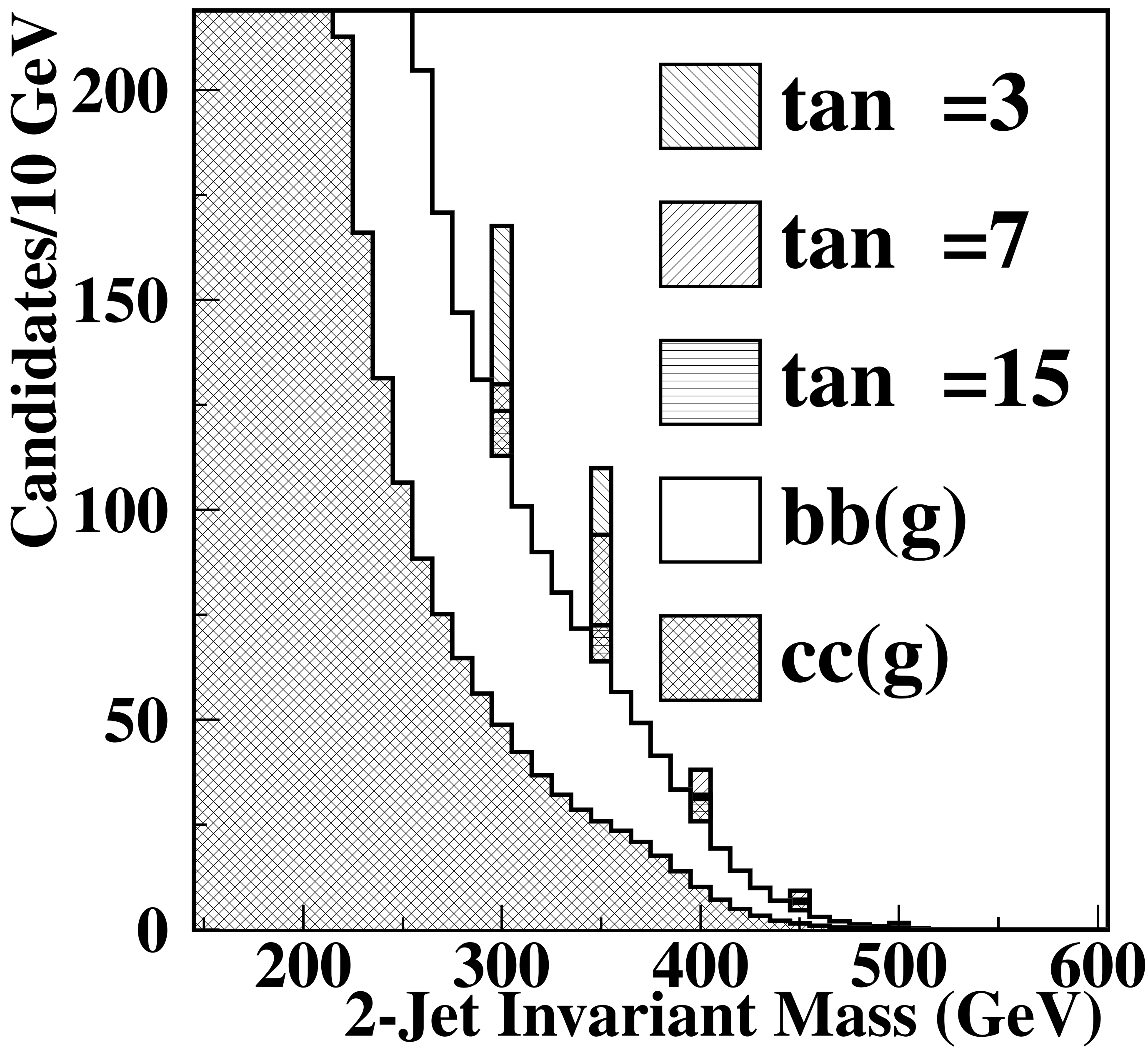
$\gamma\gamma \to h^0 \to b\bar{b}$ 160 GeV,, 80% e^- pol.

signal: 2-jet, central, b-tagged



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

$\gamma\gamma \rightarrow H^0, A^0 \rightarrow b\bar{b}$ 630 GeV



Asner, Gronberg, Guion

Using linear polarization of the photons at a $\gamma\gamma$ collider, it is possible to test the CP properties of H^0, A^0.

In fact, it might be possible to observe interference of the H^0, A^0 resonances decaying to $t\bar{t}$. This effect is sensitive both to the relative CP assignments and to the small mass splitting.

Asakawa, Choi, Hagiwara, Lee, hep-ph/0005313

Higgs particles stand outside the Standard Model, but they are essential to its structure. We do not know where they came from or why they operate as they do.

The Linear Collider offers many experimental probes of these mysterious particles. Experiments at the Linear Collider can prove explicitly that these particles are the origin of the mass of all quarks, leptons, and gauge bosons -- or they can prove that this explanation is not sufficient.

The level of detail that the Linear Collider makes available allows us to search for clues to the deeper mystery of their origin.