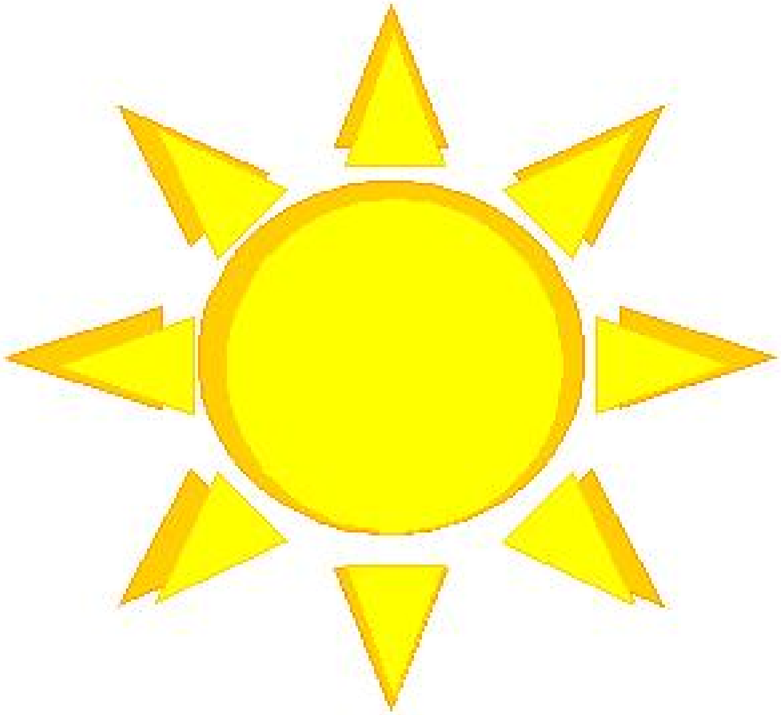
Higgs coupling measurements: a bright future



Heather Logan
University of Wisconsin, Madison

UW Madison Pheno/Theory seminar, October 29, 2004

Outline

Introduction

The Higgs mechanism and the origin of mass

Higgs couplings: the test of the model

Other models where Higgs couplings can be nonstandard

The far future: International Linear Collider (ILC)

Model-independent, high precision Higgs coupling measurements

The near future: Large Hadron Collider (LHC)

Higgs discovery (if Tevatron misses it)

Our first shot at coupling measurements

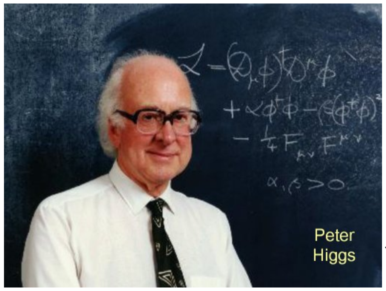
Introduction

If all we knew were QED and QCD, we could write down fermion masses as

$$\mathcal{L} = -m\bar{f}_R f_L + \text{h.c.}$$

But in the Standard Model, fermions are chiral: f_L and f_R have different SU(2)×U(1) quantum numbers.
The mass term above is not gauge invariant!

We also know that the W and Z bosons have a nonzero mass.
This also violates gauge invariance!
Massless gauge bosons have two polarizations; massive ones have three:
Where does the third polarization degree of freedom come from?

The simplest solution (thanks to this clever person $\longrightarrow$ 

)

The Higgs mechanism

Introduce a scalar "Higgs" field H
– doublet under SU(2)
– carries U(1) hypercharge

Write down couplings of H to gauge bosons (via the covariant derivative) and to fermions (Yukawa couplings, $\mathcal{L} = y_f \bar{f}_L H f_R$).
– These are all gauge invariant.

Write down a mass and self-interaction for H: the Higgs potential

$$V = m^2 H^\dagger H + \lambda (H^\dagger H)^2$$

– also gauge invariant.

Now the trick:

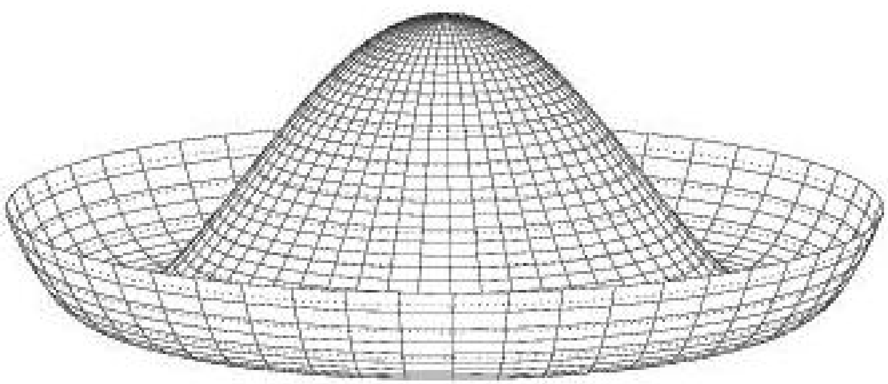
Choose the signs of the terms in the Higgs potential.

$$V = m^2 H^\dagger H + \lambda (H^\dagger H)^2$$

m^2 is negative

λ is positive (why? we don't know.)

The Higgs potential looks like this:



The zero field value is an unstable equilibrium.

The Higgs field instead sits in the minimum of the potential, at nonzero field value.

This breaks the SU(2)×U(1) symmetry spontaneously.

At the minimum of the potential (the ground state), the Higgs field has a nonzero vacuum expectation value v.

$$\langle H \rangle = (0, v/\sqrt{2})$$

The fermions get masses and couplings to the physical Higgs field: $\mathcal{L} = y_f v \bar{f}_R f_L + y_f H \bar{f}_R f_L + \text{h.c.}$

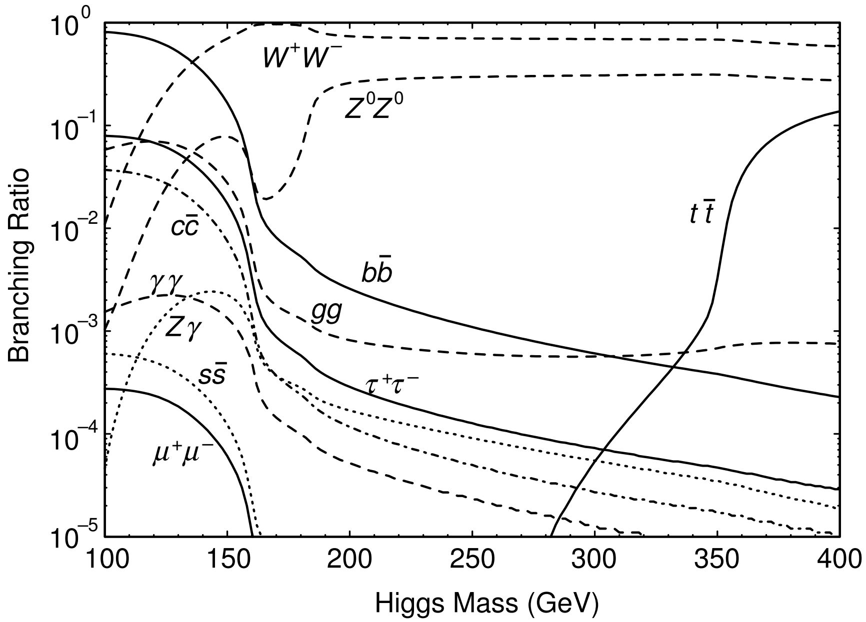
The gauge bosons get masses and couplings to the physical Higgs field: $\mathcal{L} = (g^2 v^2/4) W^+ W^- + (g^2 v/2) H W^+ W^-$

Notice that the mass is proportional to the Higgs coupling!

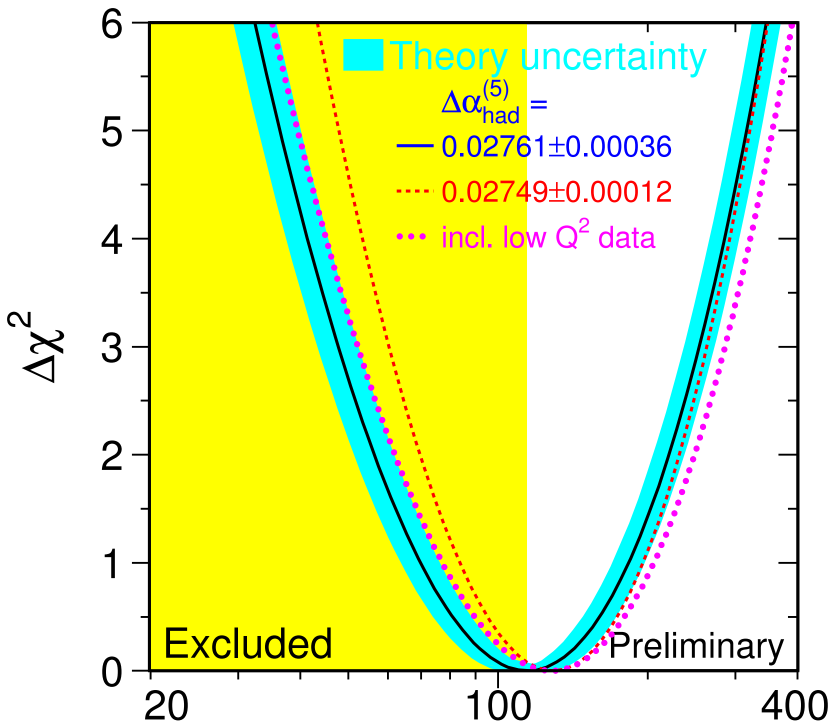
And we know the proportionality constant since we know the gauge coupling g and the W boson mass: $v = 246$ GeV.

Test of the Higgs mass-generation mechanism in the Standard Model: Measure the Higgs couplings to SM particles.

HDECAY



LEPEWWG, summer 2004



Unique predictions for Higgs branching fractions in the SM – only unknown parameter is the Higgs mass.

Electroweak precision data is sensitive to Higgs mass through radiative corrections $\longrightarrow$ fit to Higgs mass, assuming SM.

Combined LEP and Tevatron (m_t, M_W) data favor an intermediate-mass Higgs in the SM.

Most interesting mass range: lots of decay branching ratios are large enough to be accessible!

Beyond the Standard Model, Higgs couplings could be different.

For example: MSSM

The MSSM has two Higgs doublets, H_1 and H_2 with two different vacuum expectation values, v_1 and v_2.

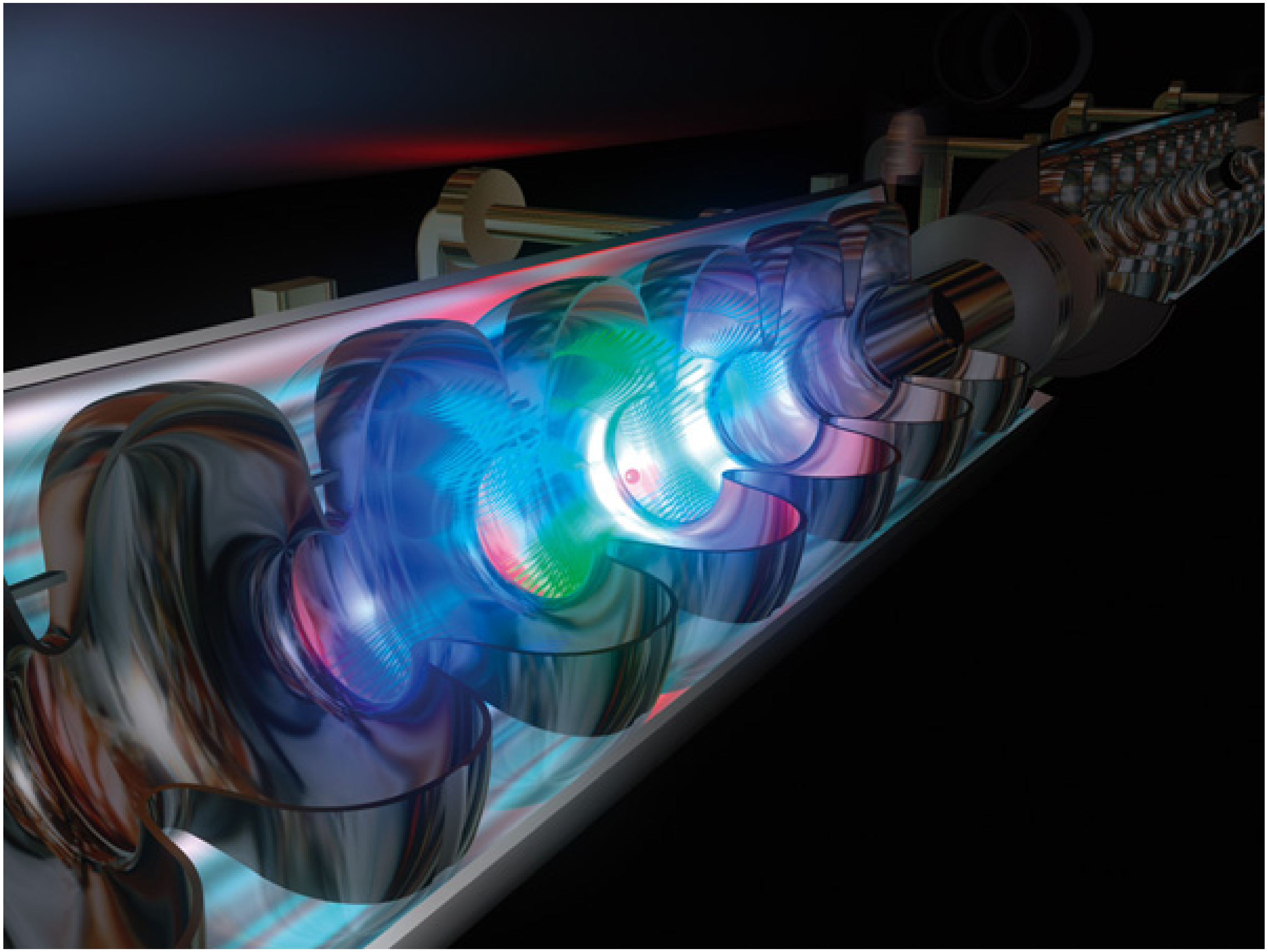
These must obey $v_1^2 + v_2^2 = v_{SM}^2$ to give the correct W boson mass.
There is one unknown combination, $v_2/v_1 = \tan\beta$.

Down-type quarks and charged leptons get mass from H_1.
Up-type quarks get mass from H_2.
W and Z bosons get mass from both H_1 and H_2.

The lightest MSSM Higgs boson h is a linear combination of H_1 and H_2 (by a mixing angle α).

In most of SUSY parameter space, the couplings of h are pretty similar to those of the SM Higgs. But any deviations from the SM expectation will tell us a lot about the structure of the Higgs sector!

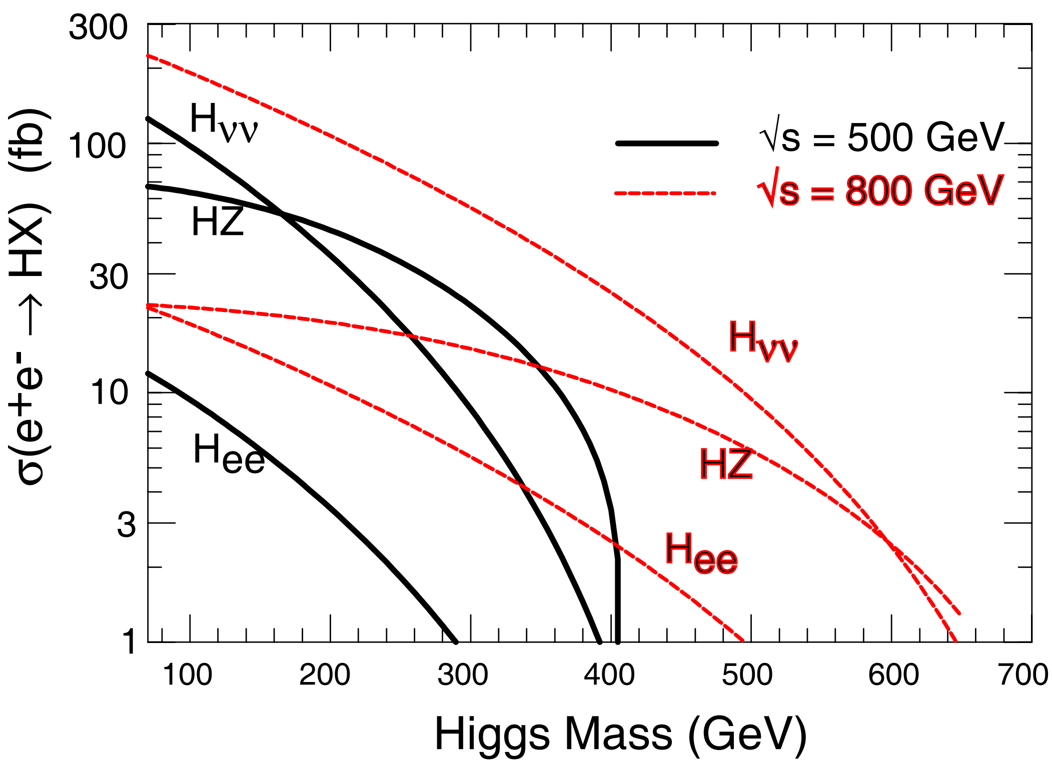
The far future:
International Linear Collider



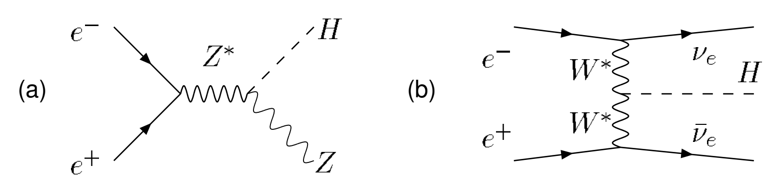
Why an e^+e^- collider?

Clean environment – no large QCD backgrounds

Well-known initial state – no parton distributions; energy/momentum of initial state known



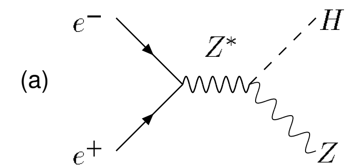
Large cross sections



$\gtrsim 100$ fb^{-1} per year

Lots of events

E. Accomando et al., Phys.Rept.299, 1 (1998)



Model-independent technique: Z recoil

Use 4-momentum conservation to reconstruct Higgs events looking only at the recoiling Z.

Initial state: $e^- \longrightarrow \star \longleftarrow e^+$

$$p(e^-) = (E_{cm}/2, 0, 0, E_{cm}/2), \qquad p(e^+) = (E_{cm}/2, 0, 0, -E_{cm}/2)$$

Initial 4-momentum $= p(e^-) + p(e^+) = (E_{cm}, 0, 0, 0)$

Final state: $Z \longleftarrow \star \longrightarrow H$

Z decays to dileptons (e^+e^- or $\mu^+\mu^-$) and the Higgs goes off in the other direction.

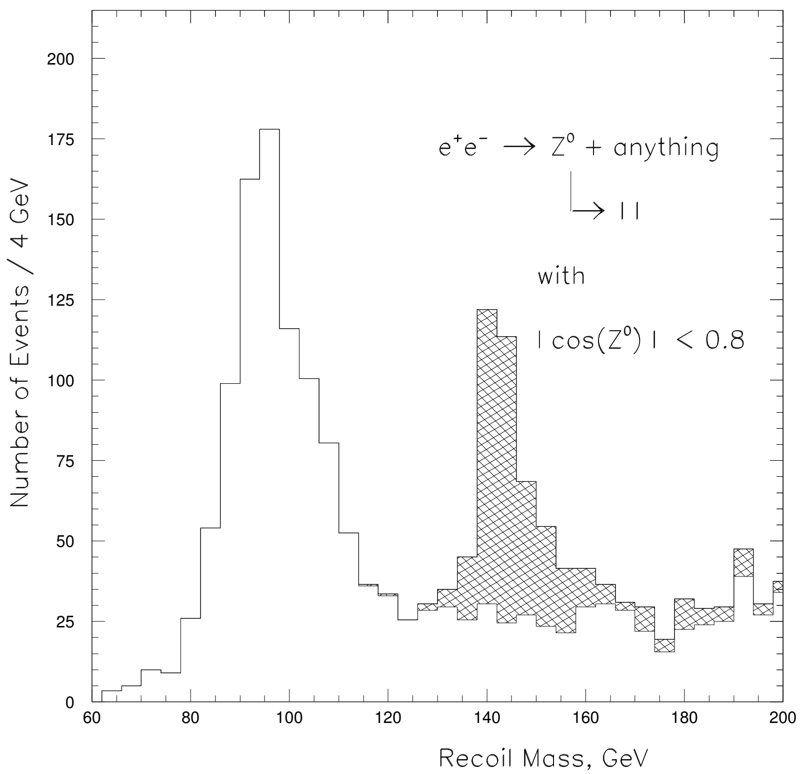
Measure the 4-momenta of the Z decay leptons: $p(\ell^-)$ and $p(\ell^+)$.

Require that $p(\ell^-)$ and $p(\ell^+)$ reconstruct the Z:

$$[p(\ell^-) + p(\ell^+)]^2 = M_Z^2$$

Use energy-momentum conservation to get the Higgs 4-momentum:

$$p(Higgs) = p(e^-) + p(e^+) - p(\ell^-) - p(\ell^+) \ .$$



H.J. Schreiber et al., DESY-ECFA Conceptual LC Design Report (1997)

"Recoil mass" is $[p(Higgs)]^2 = M_H^2$.

See a Higgs mass peak in the Z recoil spectrum.

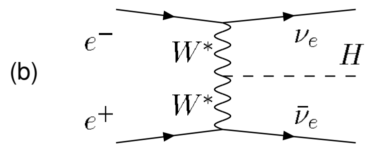
Count events in the recoil Higgs mass peak: get the ZH cross section.

Count Higgs decay products in the recoil Higgs mass peak: get the Higgs branching ratios.

Model-independent!!

ZH cross section measurement does not depend on Higgs decay mode.

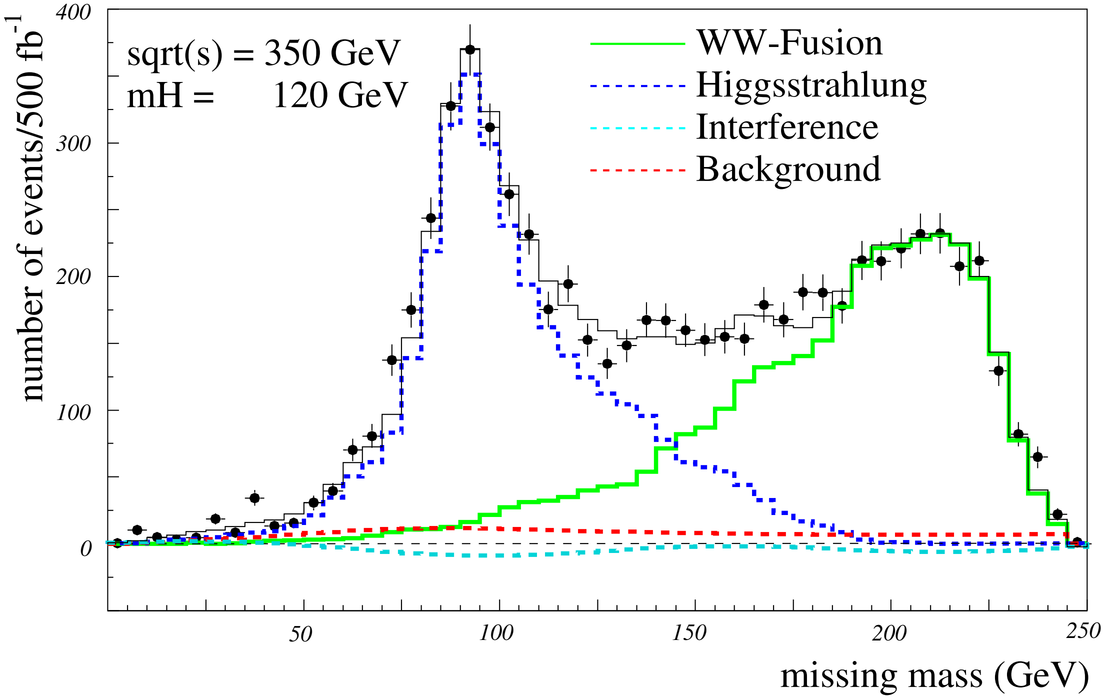
BR measurements do not depend on production cross-section assumptions.



Next, measure HWW coupling: WW fusion

Look for (e.g.) Higgs $\longrightarrow b\bar{b}$ plus missing mass:

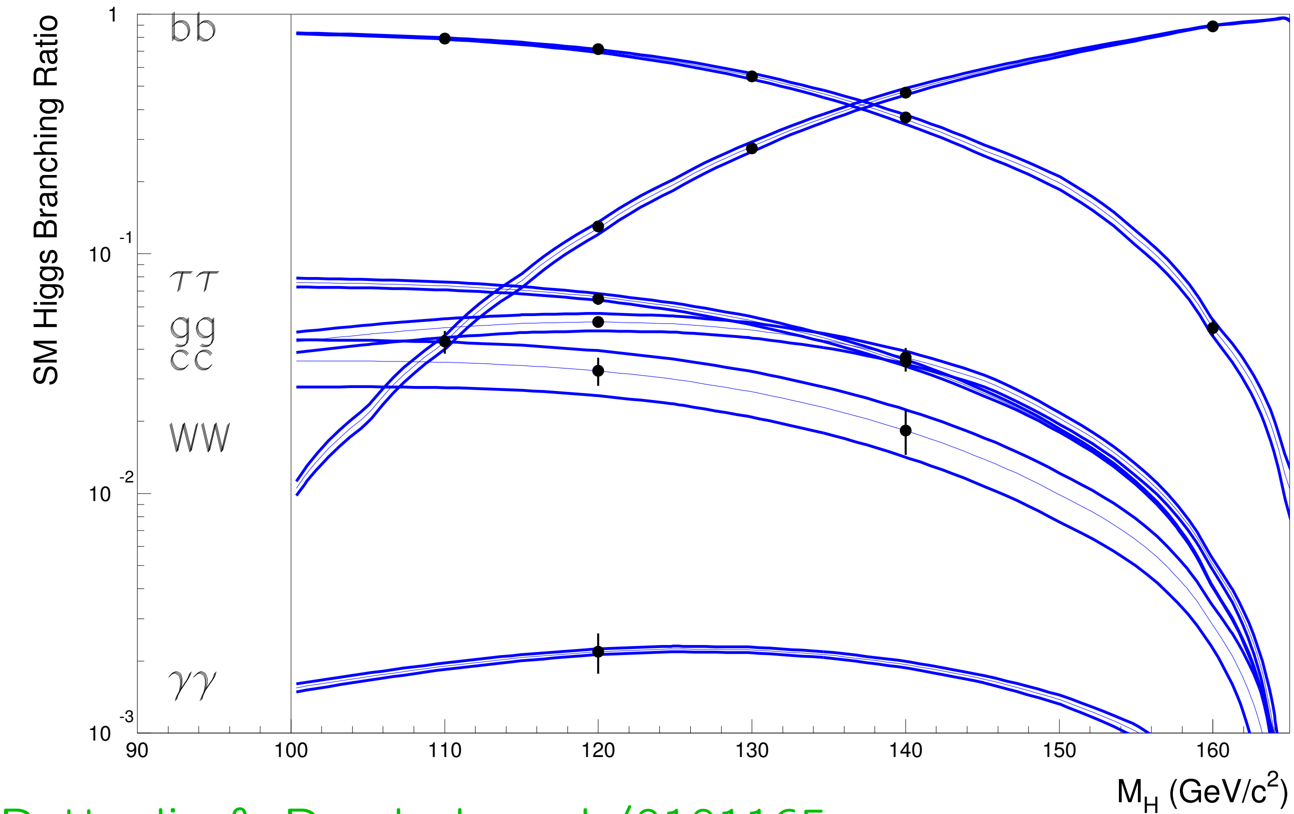
ZH, $Z \to \nu\bar{\nu}$ and WW fusion $\to H$.



Battaglia & Desch, hep-ph/0101165

If nothing funny is going on in the WWH coupling, can add in WW fusion events for increased statistics in BR measurements. (No longer model-independent.)

Measure Higgs branching ratios to high precision!



Battaglia & Desch, hep-ph/0101165

For a 120 GeV SM-like Higgs boson:

BR	$b\bar{b}$	WW^*	$\tau\tau$	$c\bar{c}$	gg	$\gamma\gamma$
Precision	2.4%	5.1%	5.0%	8.3%	5.5%	23%

K. Desch, hep-ph/0311092

Determine Higgs total width:

1. Measure $\mathrm{BR(W)} = \Gamma(\mathrm{H} \rightarrow \mathrm{WW})/\Gamma_{\mathrm{tot}}$

2. Measure HWW coupling and calculate $\Gamma(H \rightarrow WW)$

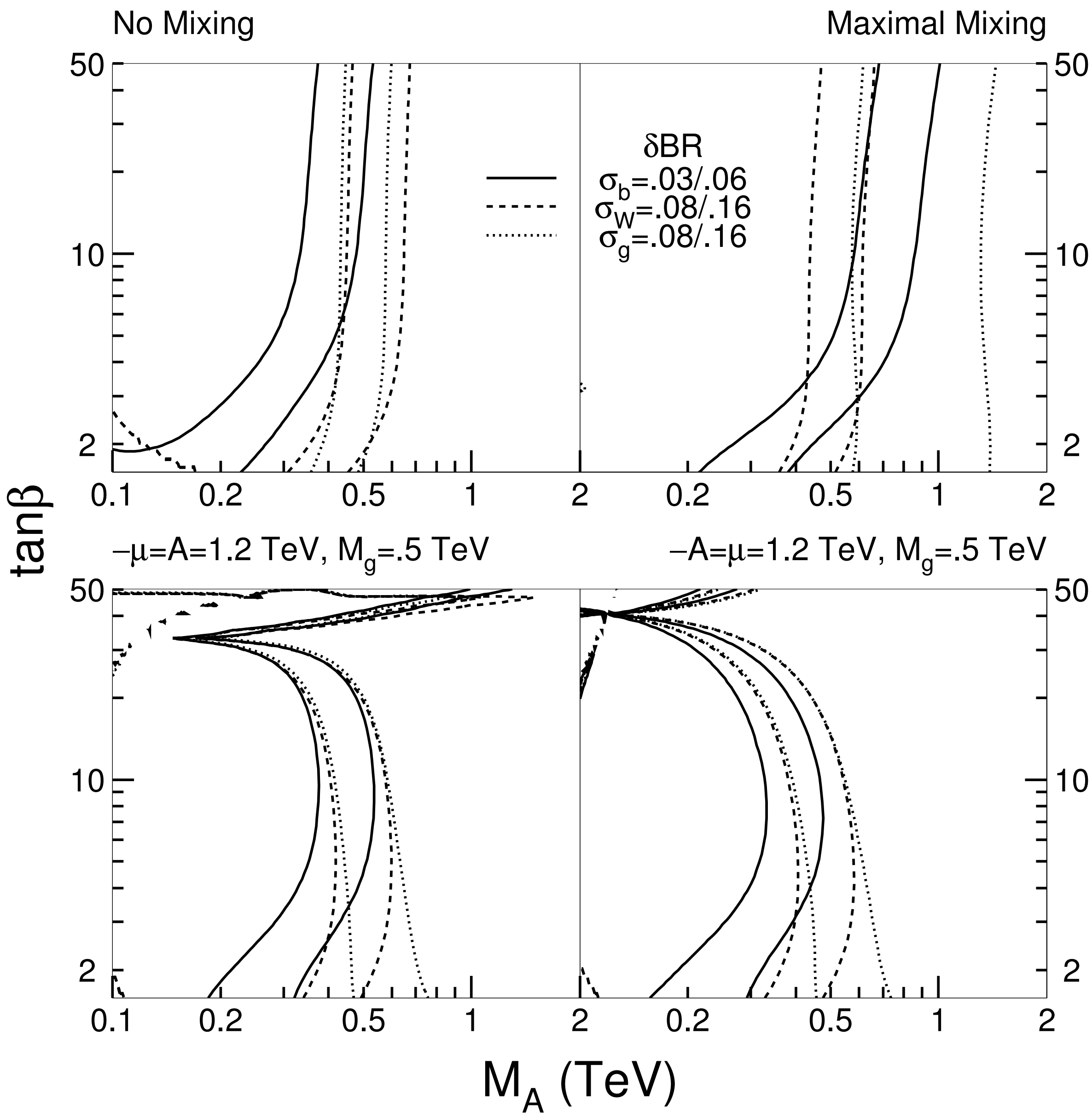
   (a) Measure HZZ coupling from $e^+e^- \rightarrow Zh$ total cross section then use SU(2) relation for HWW coupling, OR

   (b) Measure WW fusion $\rightarrow$ Higgs cross section times $\mathrm{BR(H} \rightarrow \mathrm{b\bar{b})}$ and use $\mathrm{BR(H} \rightarrow \mathrm{b\bar{b})}$ from ZH to get HWW coupling

3. Solve for Γ_{tot}

Both the ZH and WW fusion techniques give a total cross section measurement of about 6%.

Use the high-precision measurements of Higgs couplings to look for deviations from the Standard Model

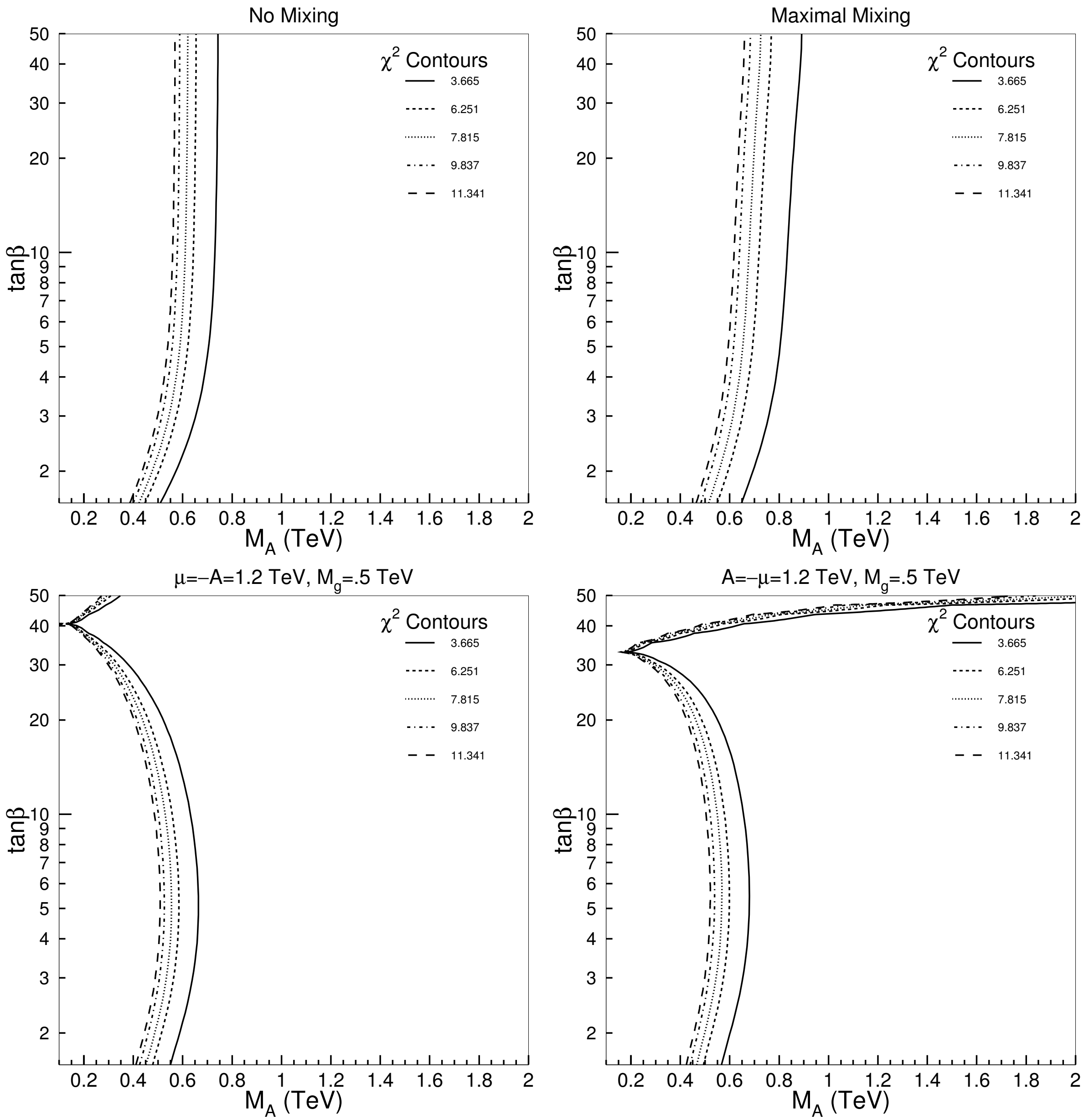


Example:
MSSM benchmark scenarios

Contours of
$\delta BR(b) = 3\%,\ 6\%$
(solid),
$\delta BR(W) = 8\%,\ 16\%$
(long-dashed),
$\delta BR(g) = 8\%,\ 16\%$
(short-dashed)
($\sim$ 1, 2 sigma).

Carena, Haber, H.L., Mrenna (2002)

Combine multiple Higgs couplings into a chi-squared:



Chi-squared contours combining g^2_{hbb}, $g^2_{h\tau\tau}$, and g^2_{hgg}.

Right to left: 68, 90, 95, 98 and 99% confidence levels.

Carena, Haber, H.L., Mrenna (2002)

Another Linear collider option: Photon collider

Use Compton backscattering to produce high-energy photon beam:

high-energy electron + low-energy photon (laser)
$\longrightarrow$ low-energy electron + high-energy photon

Can produce Higgs bosons in the s-channel via loop-induced $\gamma\gamma \to H$ coupling.

Aim for a better measurement of the $H\gamma\gamma$ coupling!

e^+e^- collider, 120 GeV SM-like Higgs boson:

BR	$b\bar{b}$	WW^*	$\tau\tau$	$c\bar{c}$	gg	$\gamma\gamma$
Precision	2.4%	5.1%	5.0%	8.3%	5.5%	23%

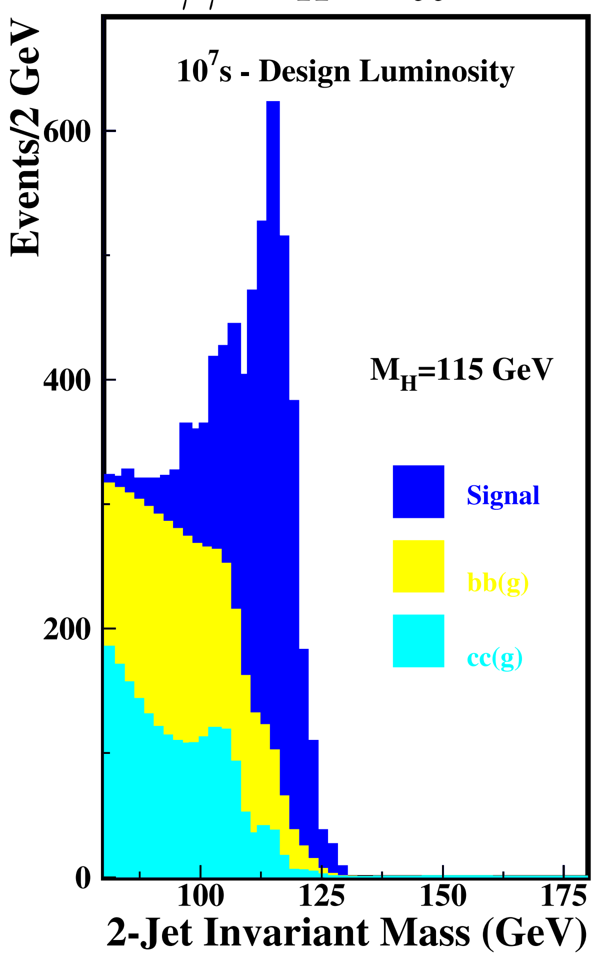
K. Desch, hep-ph/0311092

Higgs production at a photon collider

Higgs is produced via the loop-induced $\gamma\gamma H$ coupling.
$\longrightarrow$ Sensitive to New Physics running in the loop!

Asner et al, 2001

$\gamma\gamma \to H \to b\bar{b}$



Expected precisions: $\gamma\gamma \to H \to XX$

Expt.	M_H	$b\bar{b}$	WW^*	$\gamma\gamma$
CLICHE	115	2%	5%	22%
NLC	120	2.9%	–	–
TESLA	120	1.7–2%	–	–
	130	1.8%	–	–
	140	2.1%	–	–

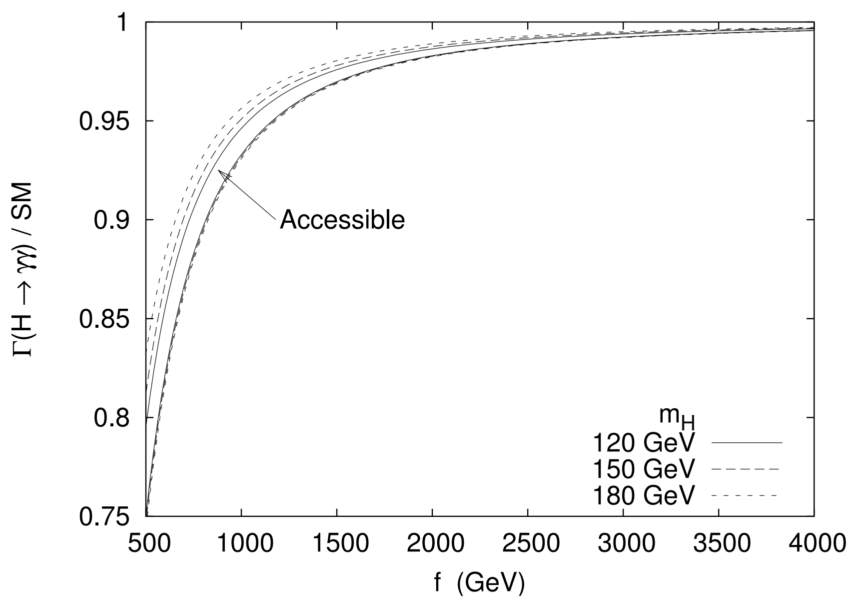
- Rate for $\gamma\gamma \to H \to b\bar{b}$ can be measured to about 2% for 115 GeV $\leq M_H \lesssim$ 140 GeV.
- $b\bar{b}$ will be the best-measured decay mode for this Higgs mass range in $\gamma\gamma$ collisions.
- Compare LHC or LC: Γ_γ to 15–20%.

Example: Corrections to $\gamma\gamma \to H$ in the Littlest Higgs model

• $\gamma\gamma \to H$ is loop induced: TeV-scale charged particles $W_H^{\pm}$, T, $\Phi^{\pm}$, $\Phi^{\pm\pm}$ can run in the loops.

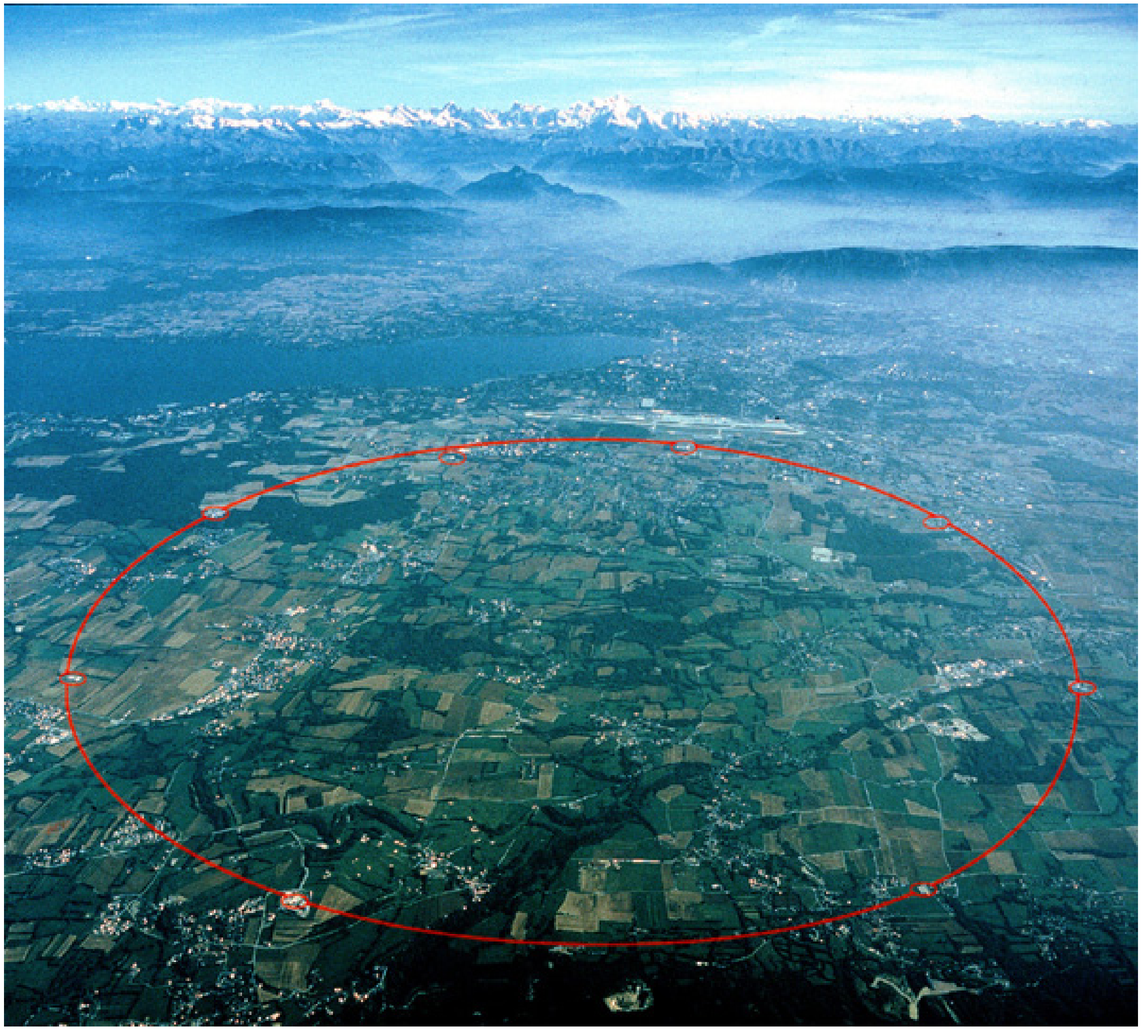
• Higgs couplings to SM particles are modified due to mixing between SM and TeV-scale particles and corrections to SM parameters.

Han, H.L., McElrath, Wang '03

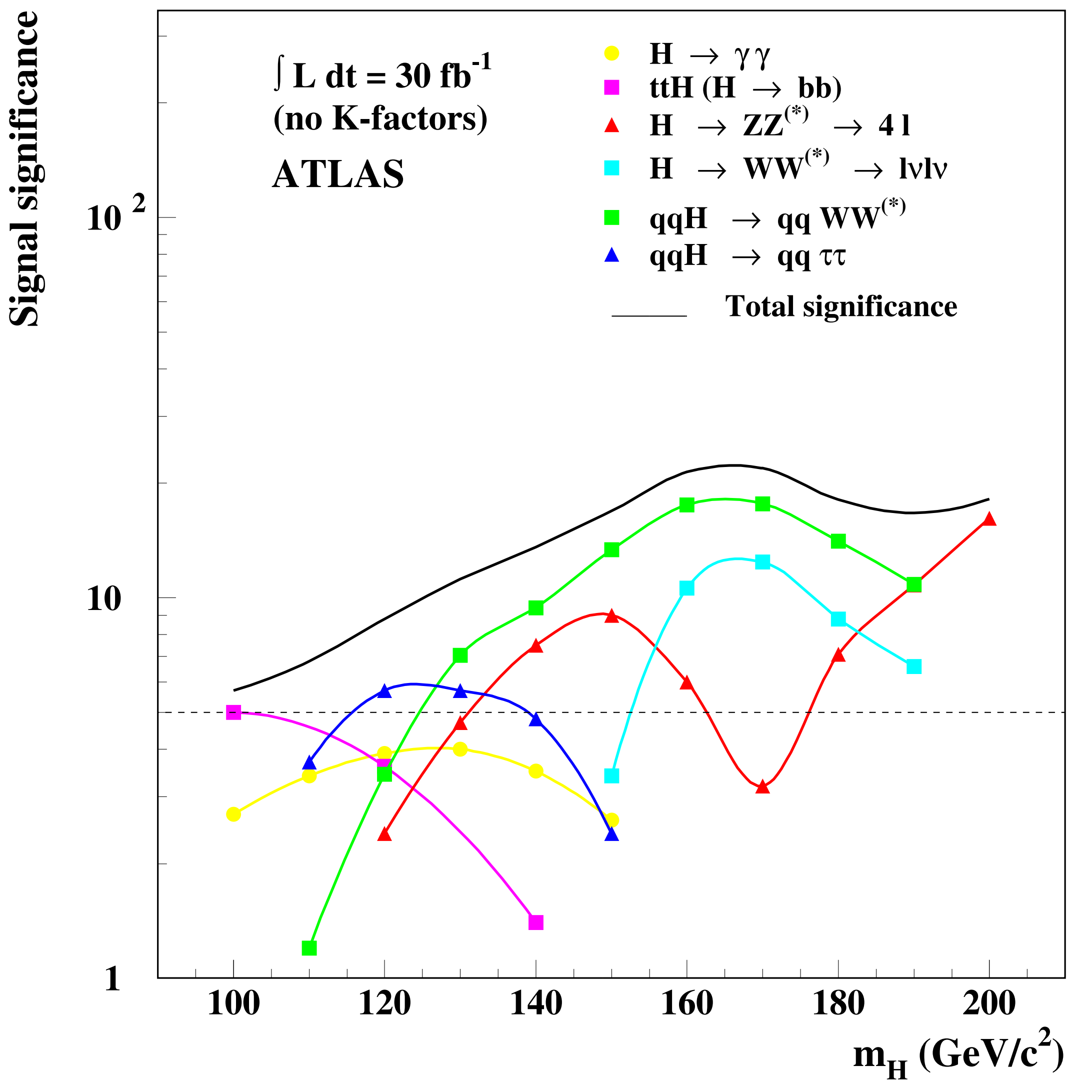


Accessible range found by scanning over model parameters. Corrections are of order v^2/f^2.

The near future:
Large Hadron Collider



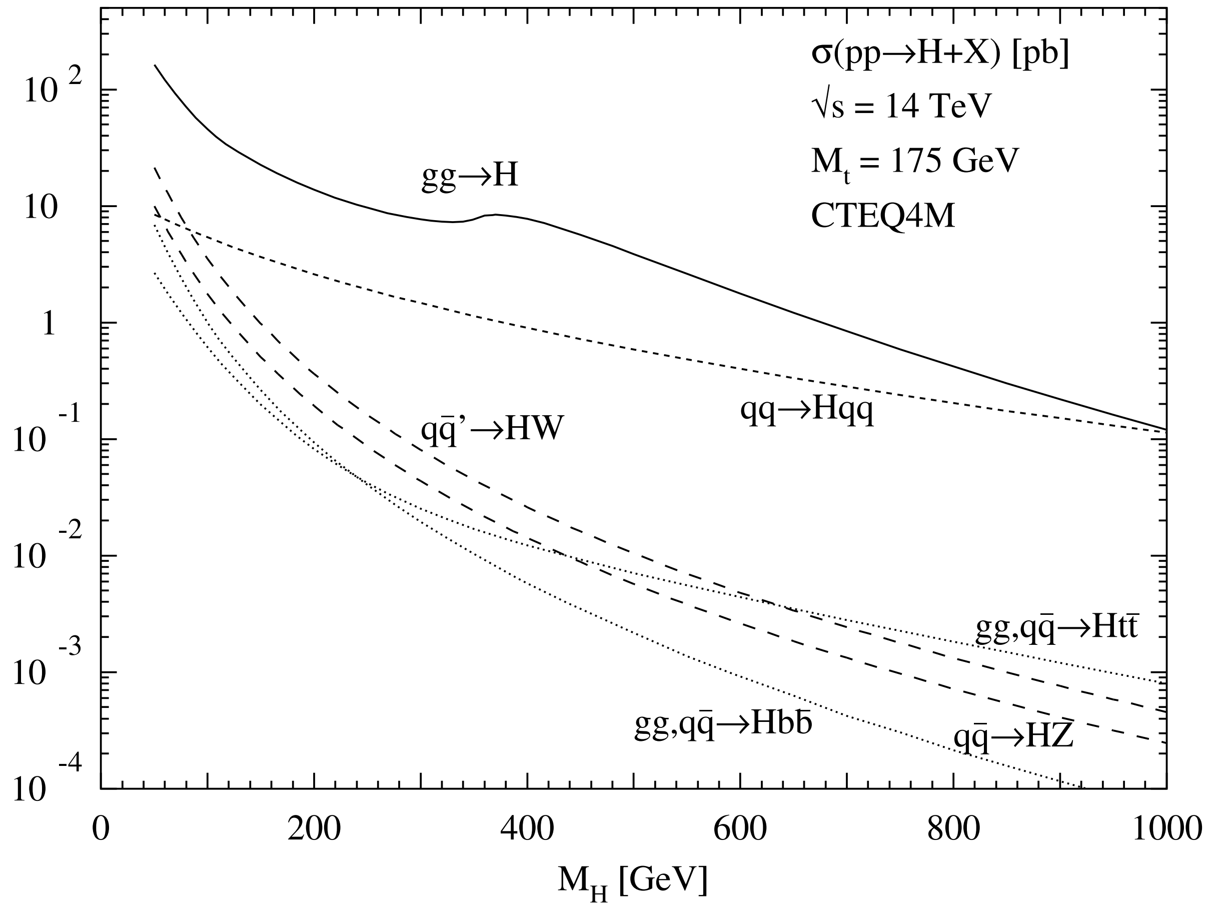
If the Higgs is Standard Model-like, LHC will discover it.



S. Asai et al., Eur.Phys.J.C 32S2, 19 (2004)

Higgs will be accessible via multiple production mechanisms –

Key to determining Higgs couplings!



gluon fusion,
$gg \to H$

weak boson fusion,
$qq \to Hqq$

WH, ZH
associated
production

ttH associated
production

M. Spira, Fortsch. Phys. 46, 203 (1998)

The Higgs couplings fix the production cross sections and decay branching ratios $\longrightarrow$ determine the rates in each channel.

By measuring rates in multiple channels, various combinations of couplings can be determined.

Take ratios of rates with same production and different decays: production cross section and Higgs total width cancel out.

$$\frac{WBF \to H \to WW^*}{WBF \to H \to \tau\tau} = \frac{\Gamma(H \to WW^*)}{\Gamma(H \to \tau\tau)} \propto \frac{g^2_{HWW}}{g^2_{H\tau\tau}} \qquad (1)$$

Take ratios of rates with different production and same decay: decay BRs cancel out.

$$\frac{gg \to H \to \gamma\gamma}{WH, H \to \gamma\gamma} = \frac{\sigma(gg \to H)}{\sigma(q\bar{q} \to WH)} \propto \frac{g^2_{Hgg}}{g^2_{HWW}} \qquad (2)$$

Ratios of Higgs couplings-squared to WW^*, ZZ^*, $\gamma\gamma$, $\tau\tau$ and gg can be extracted to 15–30% for $M_H = 120$ GeV.

Zeppenfeld et al., PRD62, 013009 (2000)

Ratios of couplings are better than nothing.
But we want to get the individual couplings if we can!

No missing-mass spectrum measurement like at LC. :-(
Some decays cannot be directly observed at LHC due to backgrounds: $H \to gg$, $H \to$ light quarks, ...

Absolute measurements of partial decay widths are only possible with additional theoretical assumptions.

Some strategies:

- Assume no unexpected decay channels
  $\longrightarrow$ total width extraction from observed modes
- Assume SM ratio of H couplings to $b\bar{b}$ and $\tau\tau$ Zeppenfeld, Kinnunen, Nikitenko, Richter-Was (2000) – needed since no $b\bar{b}$ channel included in analysis (tough – QCD bg).
  $\longrightarrow$ Not necessarily true in MSSM!

Improved analysis Belyaev & Reina, (2002) included ttH, $H \to b\bar{b}$ channel to remove $b\bar{b}/\tau\tau$ assumption.

A new strategy:

Dührssen, Heinemeyer, H.L., Rainwater, Weiglein & Zeppenfeld (2004)

Assume HWW and HZZ couplings are bounded from above by their SM values.

A mild assumption: true in general multi-Higgs-doublet models (with or without additional Higgs singlets) – MSSM!

No assumptions on unexpected/unobserved Higgs decay modes.

Observation of Higgs production

$\longrightarrow$ lower bound on production couplings

$\longrightarrow$ lower bound on Higgs total width.

Theoretical constraint $\Gamma_V \leq \Gamma_V^{\mathrm{SM}}$

$\oplus$ measurement of $\Gamma_V^2/\Gamma_{\mathrm{tot}}$ from WBF $\to H \to VV$

$\longrightarrow$ upper bound on Higgs total width.

This interplay provides constraints on remaining Higgs couplings.

A second approach: fit the observed rates to a particular model. E.g., chi-squared fits in specific MSSM scenarios.

Higgs boson channels

GF $gg \rightarrow H \rightarrow ZZ$

WBF $qqH \rightarrow qqZZ$

GF $gg \rightarrow H \rightarrow WW$

WBF $qqH \rightarrow qqWW$

$t\bar{t}H$, $H \rightarrow WW$

WH, $H \rightarrow WW$

Inclusive $H \rightarrow \gamma\gamma$

WBF $qqH \rightarrow qq\gamma\gamma$

$t\bar{t}H$, $H \rightarrow \gamma\gamma$

WH, $H \rightarrow \gamma\gamma$

ZH, $H \rightarrow \gamma\gamma$

WBF $qqH \rightarrow qq\tau\tau$

$t\bar{t}H$, $H \rightarrow b\bar{b}$

GF = gluon fusion
WBF = weak boson fusion

Systematic uncertainties:
correlated between the various channels.

5% overall Luminosity normalization

Theory uncertainties on Higgs production:

- 20% GF
- 15% $t\bar{t}H$
- 7% WH, ZH
- 4% WBF

Reconstruction/identification efficiencies:

- 2% leptons
- 2% photons
- 3% b quarks
- 3% τ jets
- 5% forward tagging jets and veto jets (WBF)

Background extrapolation from side-bands (shape):

- from 0.1% for $H \to \gamma\gamma$
- to 5% for $H \to WW$ and $H \to \tau\tau$
- to 10% for $H \to b\bar{b}$

Fit all the Higgs couplings:
Method good in general multi-Higgs-doublet models.

• Assume $g^2_{W,Z} < 1.05 \ \left(g^2_{W,Z}\right)_{\rm SM}$
(Extra 5% margin allows for theoretical uncertainties in the translation between couplings-squared and partial widths and also for small admixtures of exotic Higgs states, like SU(2) triplets.)

• Allow for possibility of additional particles running in the loops for $H \to \gamma\gamma$ and $gg \to H$, fitted by a positive or negative new partial width to these contributions.

• Allow for additional light hadronic decays, fitted with a partial width for unobservable decays.

(Invisible decays, e.g. Higgs $\to$ neutralinos, could still be observable at the LHC in WBF Eboli & Zeppenfeld (2000). Not yet considered in our fit.)

Put all the LHC measurements into a chi-squared.
Find the maximum excursion of each Higgs coupling at 1-sigma.
Our fit assumptions constrain the error ellipse in directions with otherwise-uncontrolled correlations.

Assume three LHC luminosity scenarios:

- Low lumi, 30 fb^{-1} $\times$ 2 detectors

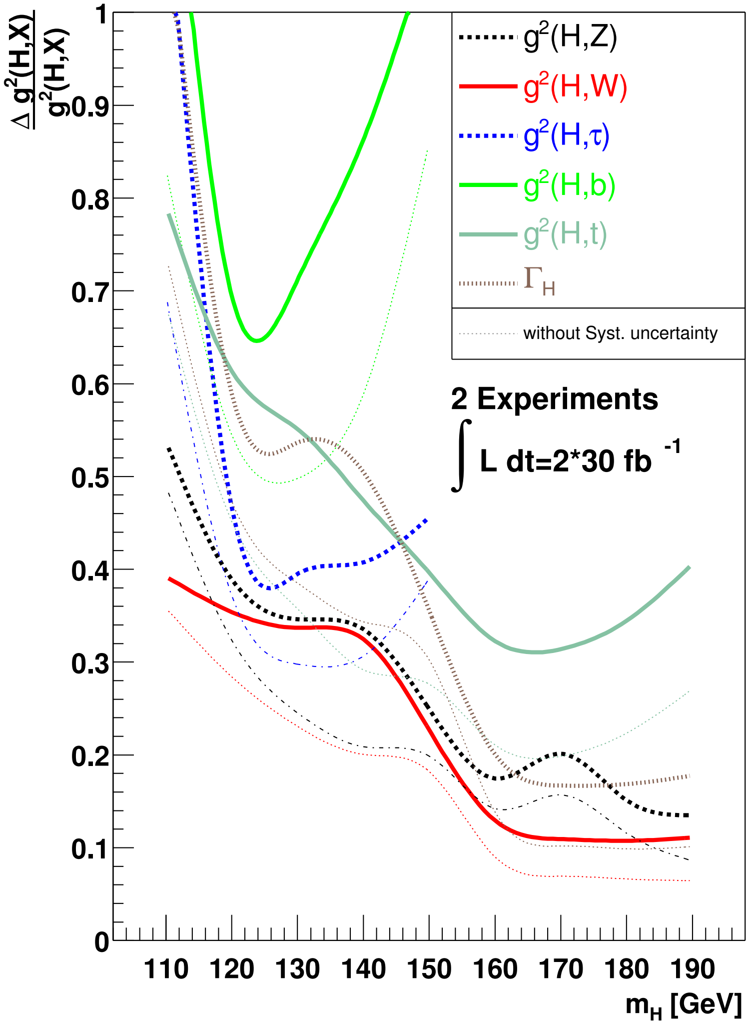
- High lumi, 300 fb^{-1} $\times$ 2 detectors

- Mixed, 300 fb^{-1}, with only 100 fb^{-1} usable for WBF channels, $\times$ 2 detectors

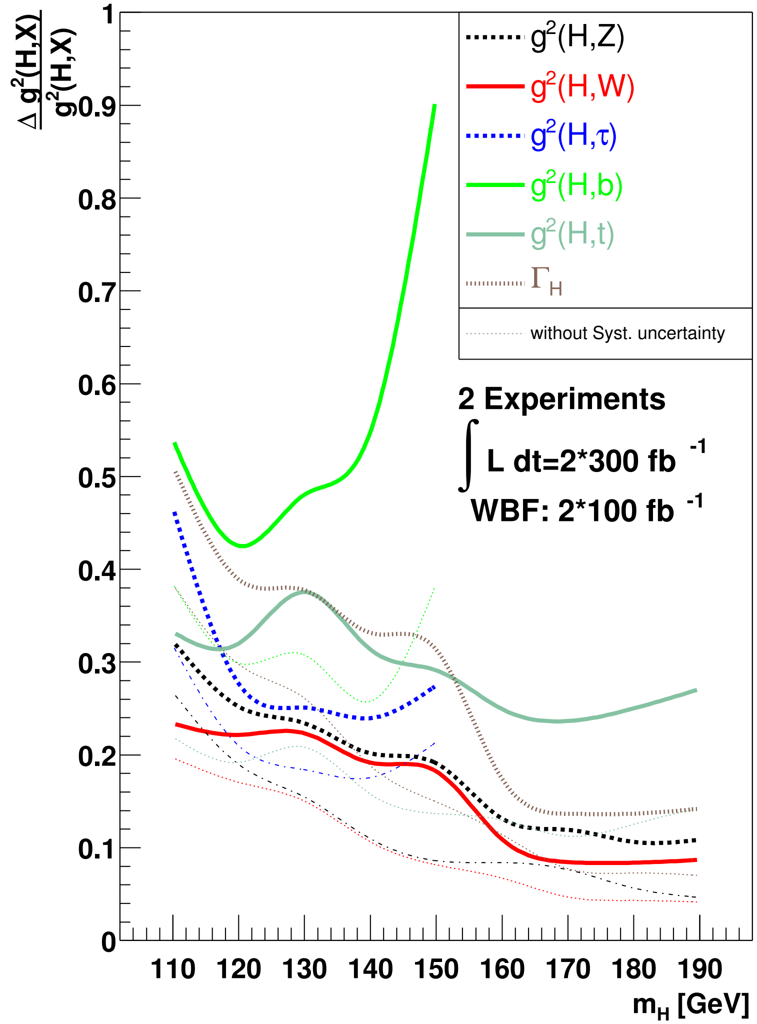
The WBF channels have not yet been studied for high-luminosity LHC running:
The "Mixed" scenario will be important if underlying events from high-lumi running significantly degrade the efficiency of WBF channels.

Fit of Higgs couplings-squared: precisions

Low lumi



Mixed lumi

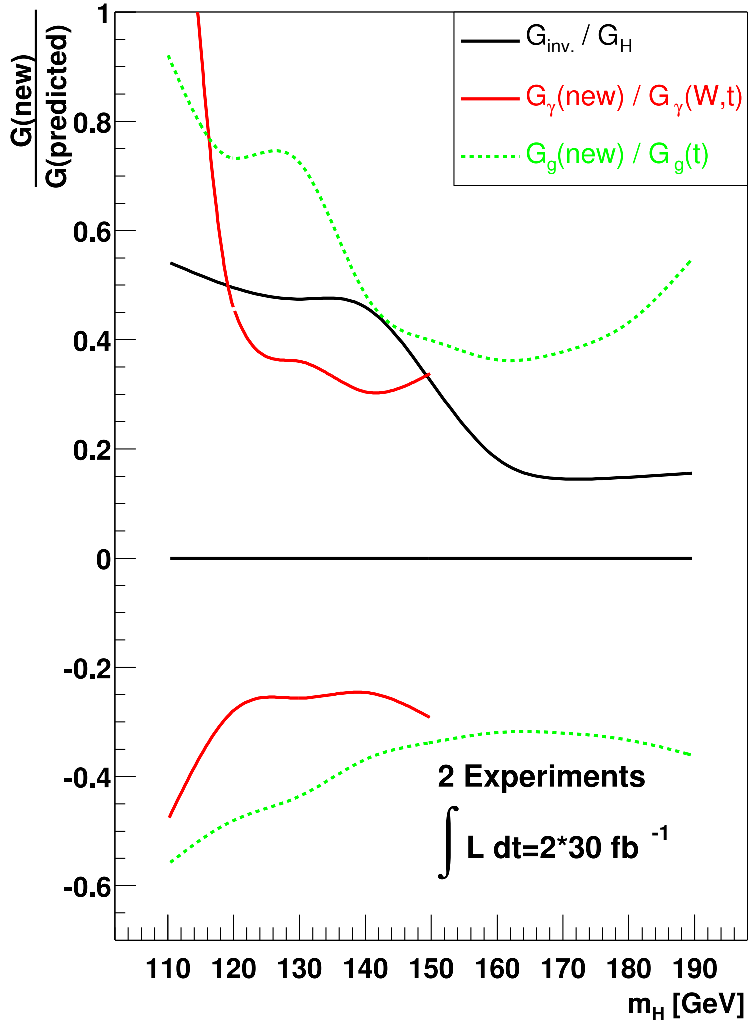


Dührssen, Heinemeyer, H.L., Rainwater, Weiglein & Zeppenfeld (2004)

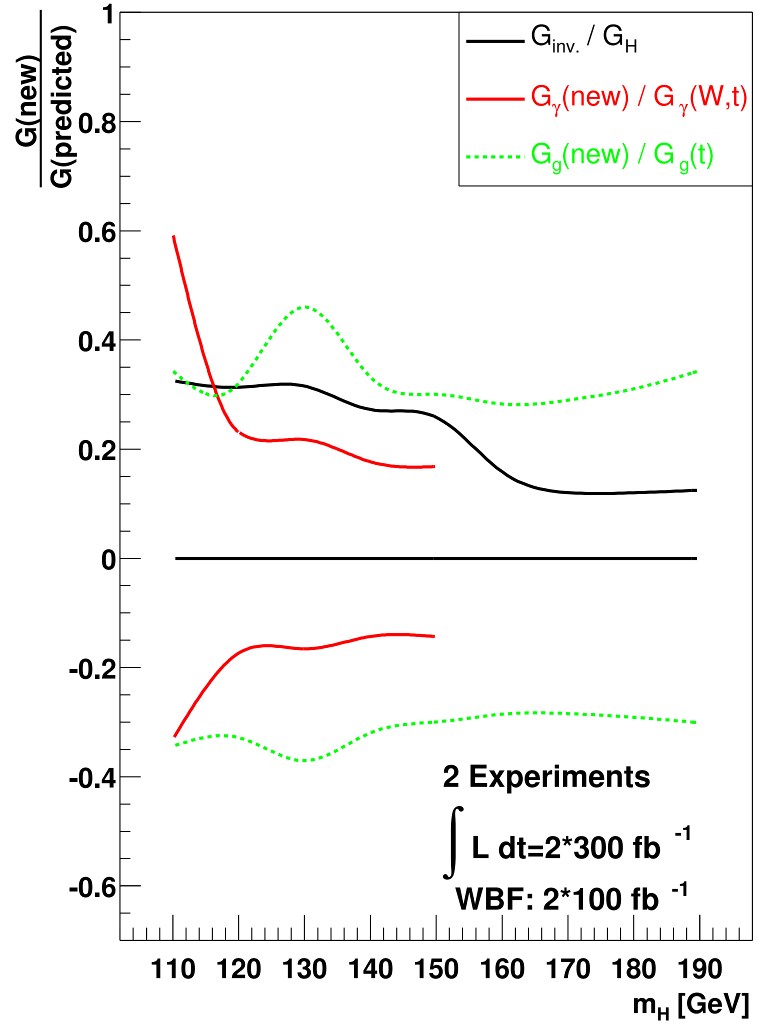
High lumi about the same except τ improves.

Fit of unobservable decays, new particles in gg, $\gamma\gamma$ loops

Low lumi



Mixed lumi

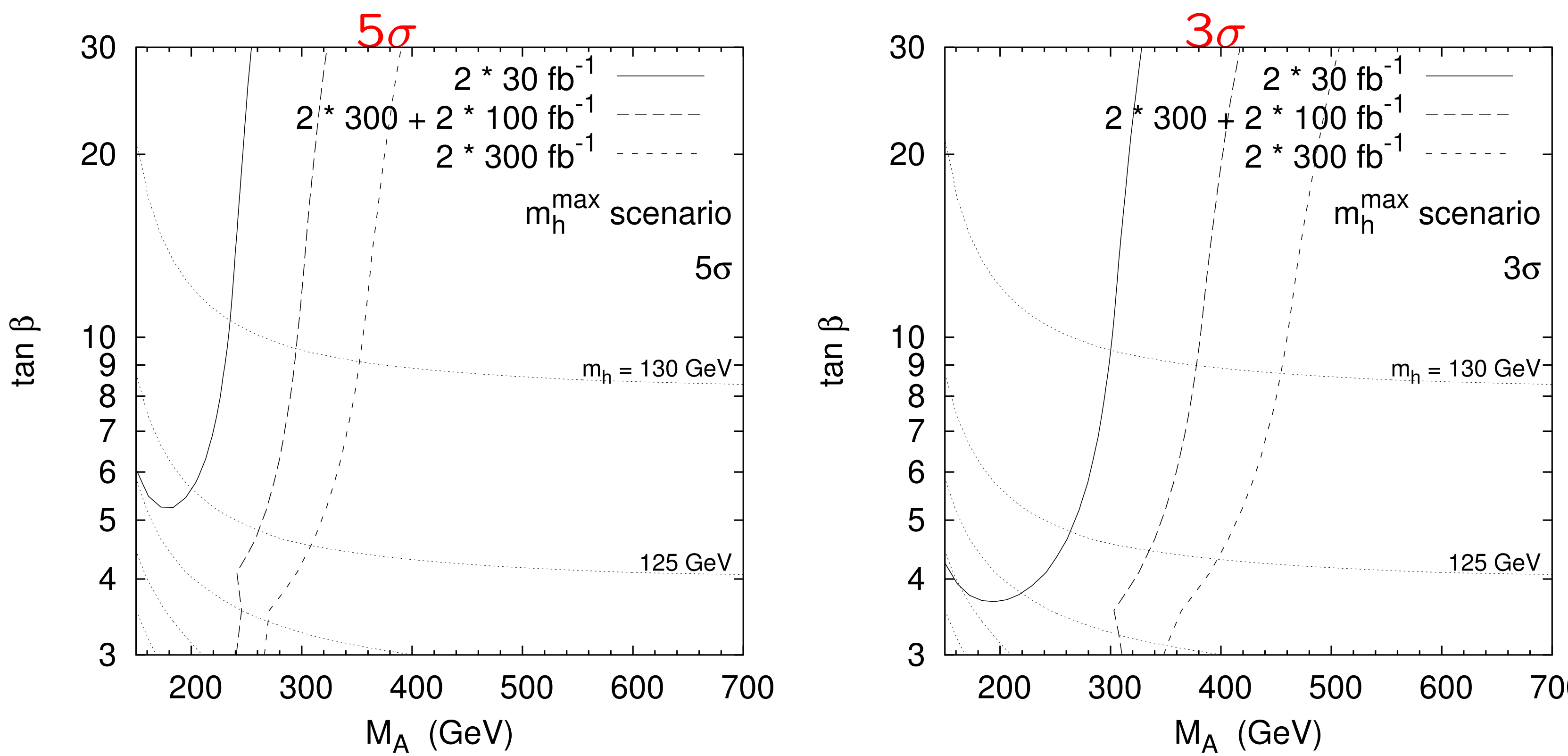


Dührssen, Heinemeyer, H.L., Rainwater, Weiglein & Zeppenfeld (2004)

High lumi about the same.

Use the sensitivity to Higgs couplings to look for deviations from the Standard Model

Example: MSSM, m_h^{max} scenario



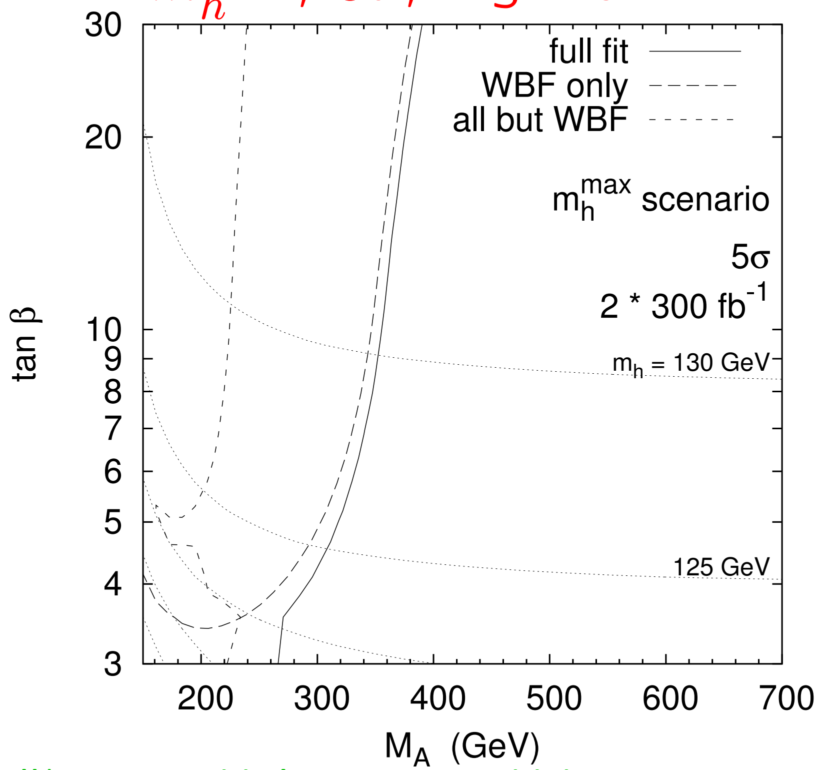
Dührssen, Heinemeyer, H.L., Rainwater, Weiglein & Zeppenfeld (2004)

Sensitive to MSSM nature of h up to $M_A \lesssim 350$ GeV!
(m_h^{max}, 5σ, high lumi)

Impressive sensitivity! Where does it come from?

– mostly from WBF channels.

$m_h^{\rm max}$, 5σ, high lumi



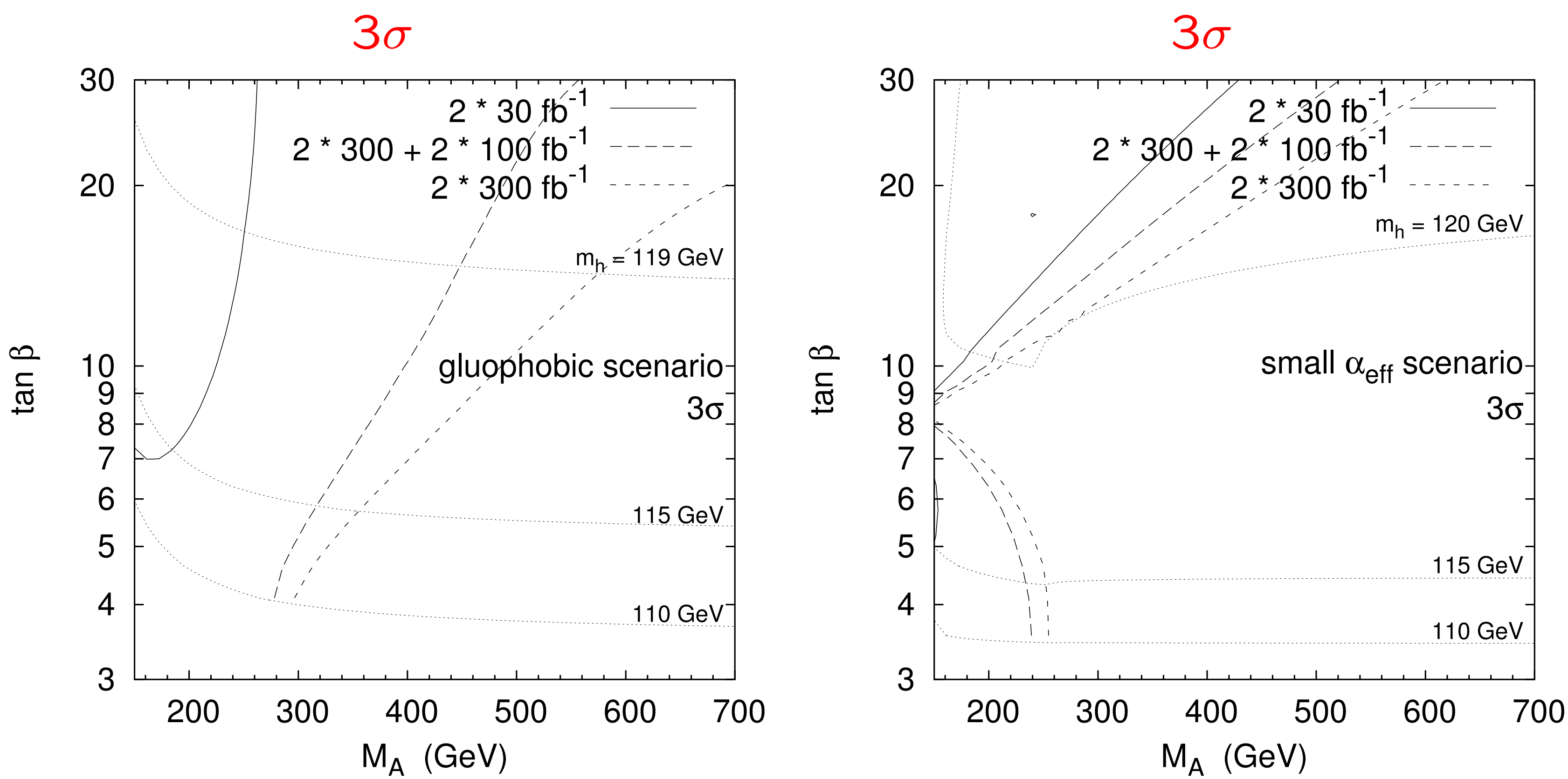
Dührssen, Heinemeyer, H.L., Rainwater, Weiglein & Zeppenfeld (2004)

MSSM Higgs couplings:

- hWW, hZZ, hgg, $h\gamma\gamma$ decouple quickly
- $hb\bar{b}$, $h\tau\tau$ decouple slowly!
- BR($h \to WW$) decouples slowly – sensitive to $hb\bar{b}$ via $\Gamma_{\rm tot}$.
- WBF $qqH \to qqWW$ sensitive to BR($h \to WW$)
- But systematics (lumi 5%, WBF thy 4%, tag/veto jets 5%) kill the sensitivity!
- Need to combine with WBF $qqH \to qq\tau\tau$ to normalize out the systematics.

Other MSSM scenarios:

benchmarks from Carena, Heinemeyer, Wagner, Weiglein (2003)



Dührssen, Heinemeyer, H.L., Rainwater, Weiglein & Zeppenfeld (2004)

Sensitivity depends strongly on MSSM parameters!

$\longrightarrow$ Need more information before one can use h coupling deviations as an indirect measurement of M_A.

Going further at the LHC: non-standard Higgs scenarios

bbH associated production: could be visible in SUSY with large $\tan\beta$. Use together with $H \to b\bar{b}$.

$H \to \mu\mu$: could be visible at large $\tan\beta$ or if other decays are suppressed.

WBF Plehn & Rainwater; gluon fusion Han & McElrath

$H \to$ invisible: could be significant in SUSY, or models with scalar dark matter.

WBF Eboli & Zeppenfeld; ZH Davoudiasl, Han & H.L., in progress

Conclusions

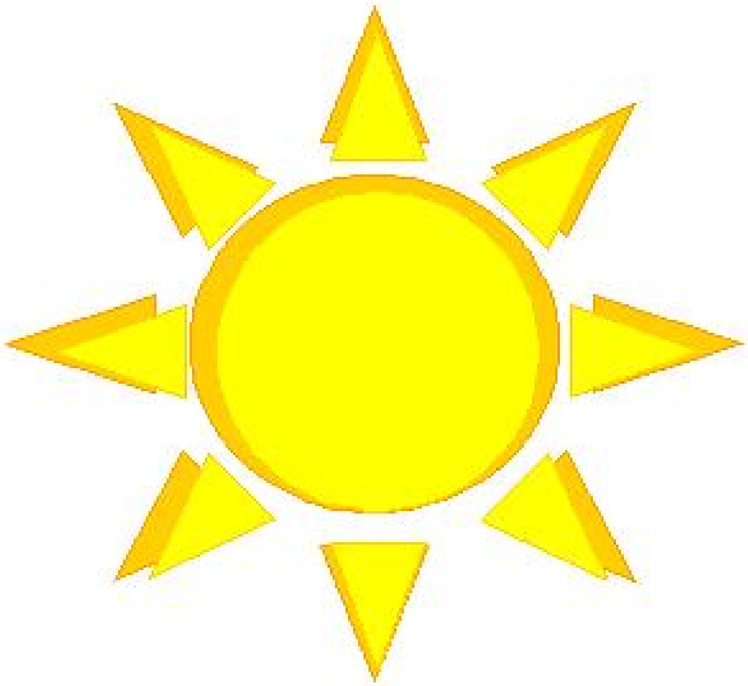
Upcoming high-energy physics experiments will illuminate the twin mysteries of electroweak symmetry breaking and particle mass.

A Linear Collider will give us high-precision, model-independent measurements of the Higgs couplings to SM particles.
1–few %-level measurements

The LHC will be sensitive to Higgs couplings, but theoretical assumptions are needed to overcome correlations/degeneracies caused by incomplete data.
10–40%-level measurements

The next step: refine the LHC studies, improve understanding of signals and backgrounds, add more channels for standard and nonstandard Higgs decays.

LHC starts in 3 years...



We will soon test the mass generation mechanism and probe for new physics in the electroweak symmetry breaking sector!