Testing the Higgs mechanism

Heather Logan
(Carleton University)

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Outline:

- Introduction
    - How to test the Higgs mechanism
    - Standard Model versus New Physics
- Higgs couplings at the ILC
    - Impact of theoretical uncertainties
- Higgs couplings at the LHC
    - Advantages and disadvantages of model assumptions
- Invisible Higgs
    - Model assumptions, good and bad
- Conclusions

Introduction: the Higgs mechanism

Introduce a scalar "Higgs" field H
- Doublet under SU(2)$_L$: $H = (\phi^+, \phi^0)^T$
- Carries U(1)$_Y$ hypercharge

Write down couplings of H:
- To gauge bosons via the covariant derivative, $\mathcal{L} = |\mathcal{D}_\mu H|^2$.
- To itself via the Higgs potential, $-\mathcal{L} = V = m^2 H^\dagger H + \lambda (H^\dagger H)^2$.
- To fermions via Yukawa couplings, $\mathcal{L} = y_f \overline{f_R} H^\dagger F_L$.
  e.g., $F_L = (u_L, d_L)^T$, $f_R = d_R$.

These couplings are all gauge invariant.

Choose the signs of the terms in the Higgs potential:

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

where m^2 is negative and λ is positive

Potential is symmetric under SU(2)$_L$×U(1)$_Y$ gauge symmetry, but the minimum of the potential is away from zero field value: SU(2)×U(1) symmetry is spontaneously broken.

At the minimum, Higgs field has a nonzero vacuum expectation value v.

Expand about the minimum:

$$H = \begin{pmatrix} G^+ \\ (h+v)/\sqrt{2} + iG^0/\sqrt{2} \end{pmatrix}$$

h is the massive excitation of the field: the physical Higgs boson.

G^0 and G^+ are the would-be Goldstone bosons: they become the third polarization degree of freedom of the Z and W^+ gauge bosons.

With $v \neq 0$, the Higgs couplings to gauge bosons and fermions give those particles mass.

Covariant derivative gives gauge boson masses and coups to h:

$$\mathcal{L} = (\mathcal{D}_\mu H)^\dagger (\mathcal{D}^\mu H) + \cdots$$

where [$Q = T_3 + Y/2$]

$$\begin{aligned}\mathcal{D}_\mu &= \partial_\mu - igW_\mu^a T^a - ig'\frac{Y}{2}B_\mu \\ &= \partial_\mu - i\frac{g}{\sqrt{2}}\left(W_\mu^+ T^+ + W_\mu^- T^-\right) \\ &\quad -i\frac{g}{\cos\theta_W} Z_\mu \left(T^3 - \sin^2\theta_W Q\right) - ieQA_\mu\end{aligned}$$

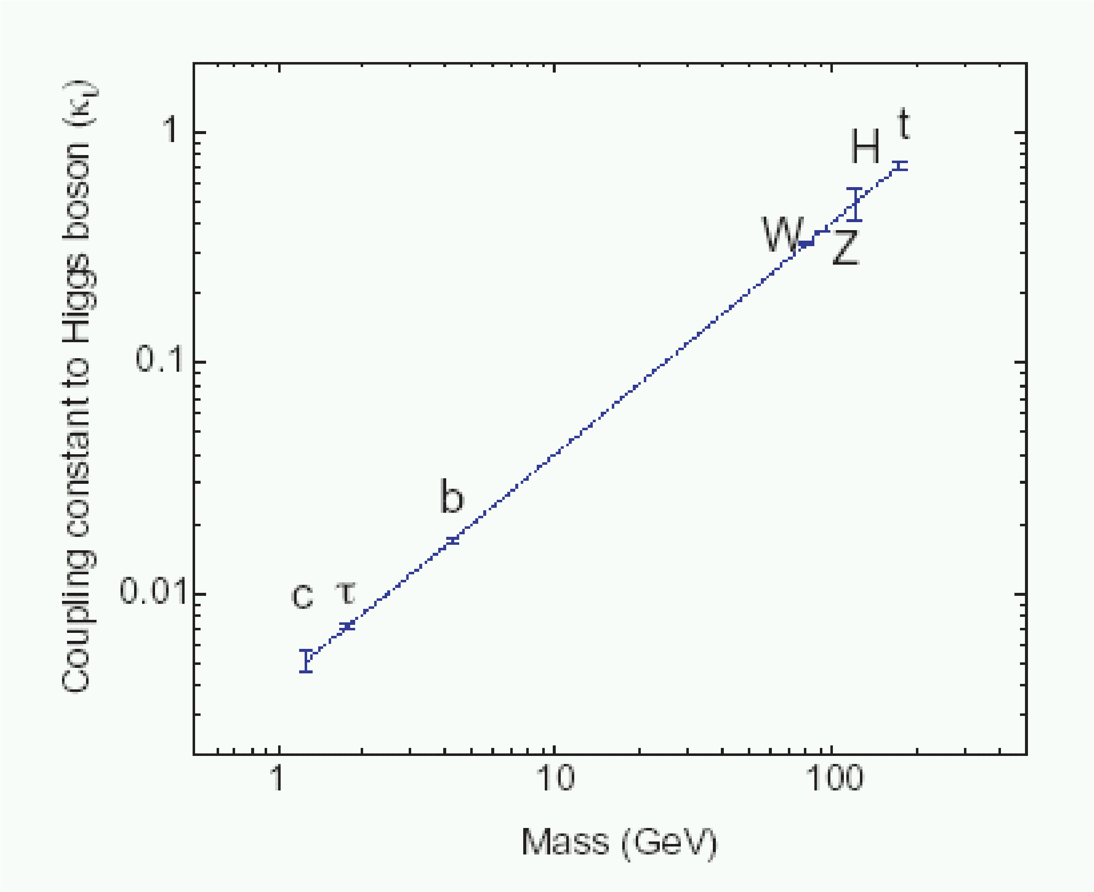
This gives: [extra 1/2 for the ZZ terms is a symmetry factor]

$$\begin{aligned}\mathcal{L} = {} & (g^2v^2/4)W^+W^- + (g^2v/2)hW^+W^- + (g^2/4)hhW^+W^- \\ & +(g_Z^2v^2/8)ZZ + (g_Z^2v/4)hZZ + (g_Z^2/8)hhZZ\end{aligned}$$

where $g_Z = \sqrt{g^2 + g'^2}$.

Yukawa couplings $y_f \overline{f_R} H^\dagger F_L$ give fermion masses and couplings to h:

$$\mathcal{L} = (y_f v/\sqrt{2})\bar{f}_R f_L + (y_f/\sqrt{2}) h \bar{f}_R f_L + \text{h.c.}$$

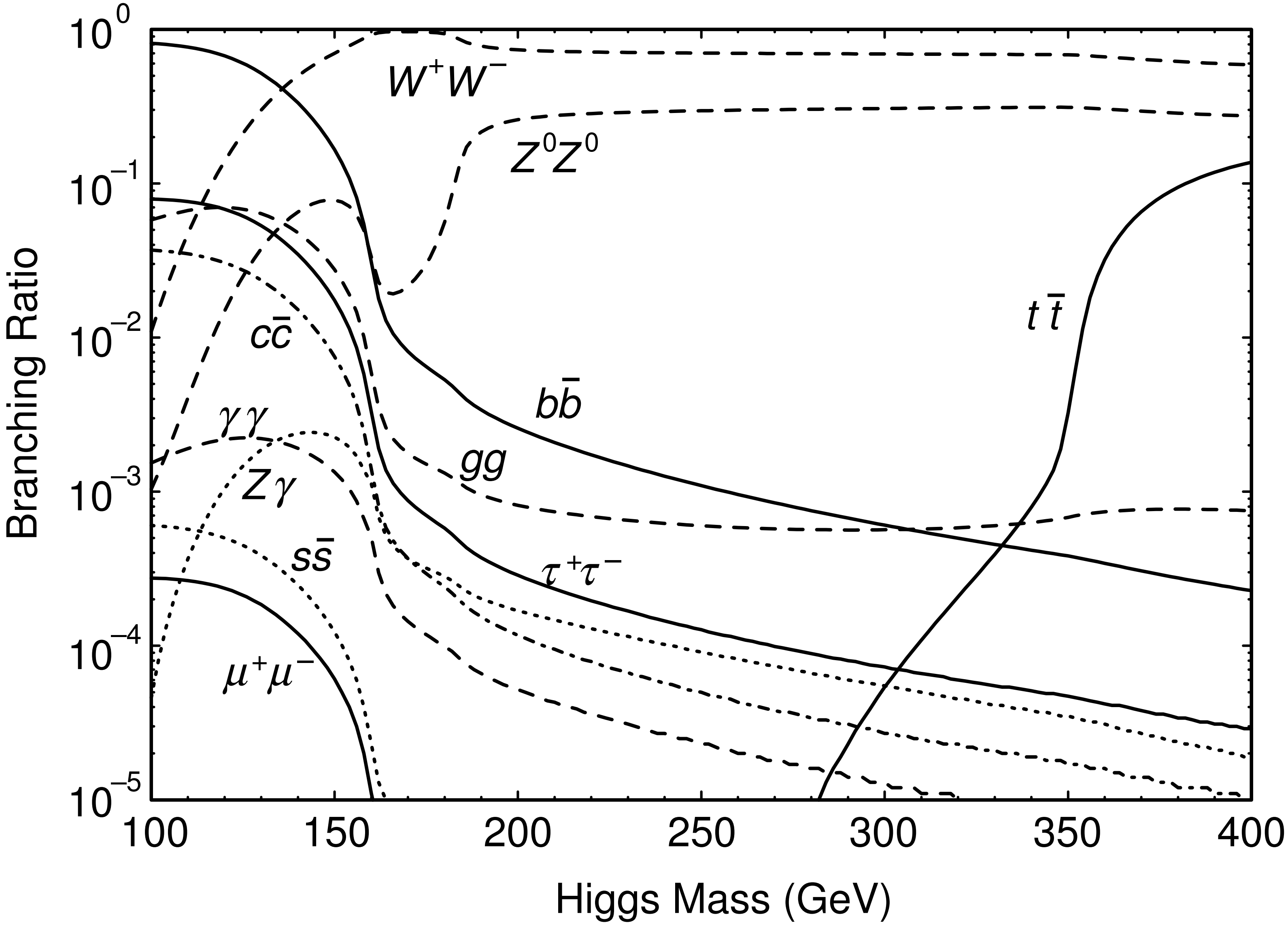


Mass of each particle is proportional to its Higgs coupling!

Slope is predicted by $v = 2M_W/g = 246$ GeV.

Test the SM Higgs mechanism by measuring the Higgs couplings to SM particles.

Because of fixed couplings, Standard Model Higgs decay modes depend only on M_H:



HDECAY

This simple linear relation between masses and Higgs couplings holds in the Standard Model.

But beyond the Standard Model, Higgs couplings can vary.

An example: Minimal Supersymmetric Standard Model (MSSM)

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

W boson mass comes from sum of two covariant derivatives:
$\mathcal{L} = |\mathcal{D}_\mu H_1|^2 + |\mathcal{D}_\mu H_2|^2$, which gives $M_W^2 = \frac{g^2 v_1^2}{4} + \frac{g^2 v_2^2}{4} = \frac{g^2 v_{SM}^2}{4}$.

So v_1 and v_2 must obey $v_1^2 + v_2^2 = v_{SM}^2 = 2M_W/g$.
One unknown combination is left free: $v_2/v_1 \equiv \tan\beta$.

Two complex doublets → 8 degrees of freedom
- h: lightest CP-even Higgs
- H, A, and $H^\pm$: heavier CP-even, CP-odd, and charged Higgses
- G^0 and $G^\pm$: unphysical Goldstone bosons

Mix to form mass eigenstates:

$$H_1 \cos\beta + H_2 \sin\beta = \begin{pmatrix} G^+ \\ [v_{SM} + iG^0 + h\sin(\beta-\alpha) + H\cos(\beta-\alpha)]/\sqrt{2} \end{pmatrix}$$

$$-H_1 \sin\beta + H_2 \cos\beta = \begin{pmatrix} H^+ \\ [iA^0 + h\cos(\beta-\alpha) - H\sin(\beta-\alpha)]/\sqrt{2} \end{pmatrix}$$

Couplings of h get modified from their SM values:

$g_{hWW} = \sin(\beta-\alpha) g_{H_{SM}WW}$ likewise Z
$g_{hb\bar{b}} = [\sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)] g_{H_{SM}b\bar{b}}$ likewise d, s, e, μ, τ
$g_{ht\bar{t}} = [\sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha)] g_{H_{SM}t\bar{t}}$ likewise u, c

In most MSSM parameter space, H, A, and $H^\pm$ are fairly heavy.

Mixing angle: $\cos(\beta-\alpha) \simeq \frac{1}{2}\sin 4\beta \frac{M_Z^2}{M_A^2} \longrightarrow 0$ for $M_A \gg M_Z$

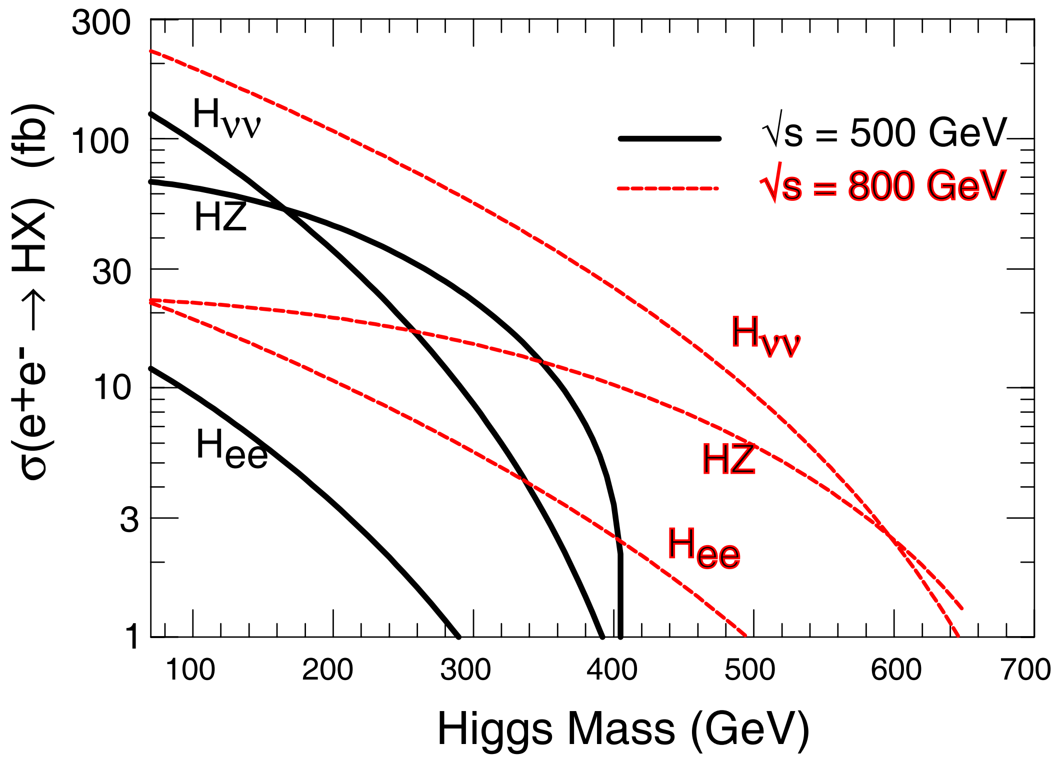
Couplings of h approach their SM values – the decoupling limit.

Search for coupling deviations → test Higgs sector structure!

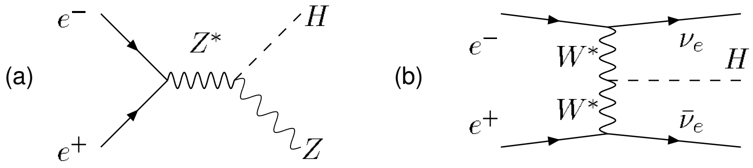
Higgs couplings at the ILC

Clean environment – no large QCD backgrounds

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

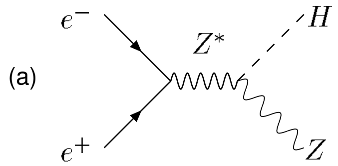


Large cross sections



$\gtrsim 100\ \mathrm{fb}^{-1}$ 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: $e^- \longrightarrow \star \longleftarrow e^+$

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

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

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.

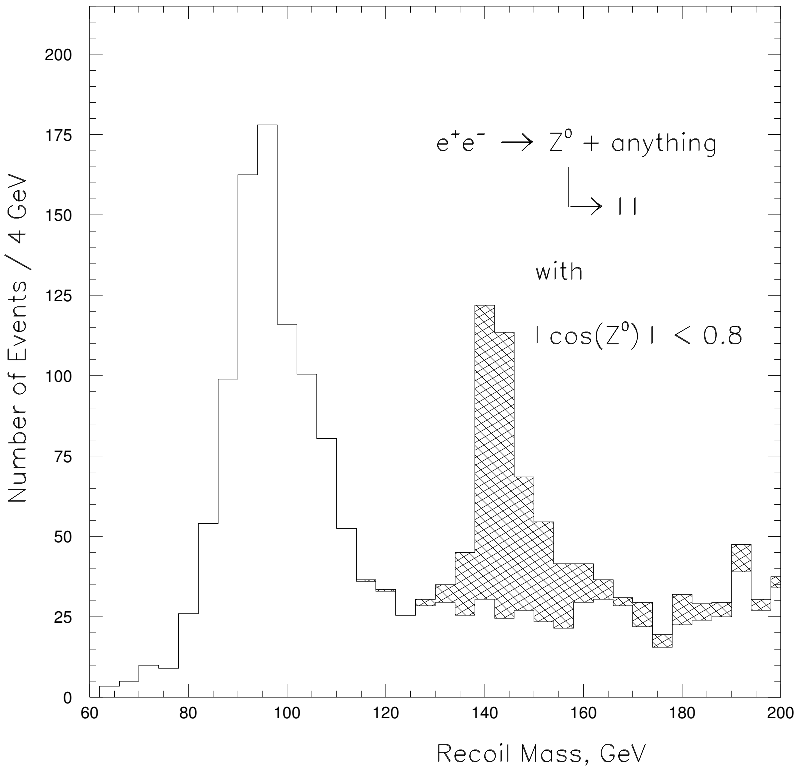
Measure the 4-momenta of the Z decay leptons: $p(\ell^-)$ and $p(\ell^+)$.

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:

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



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!!

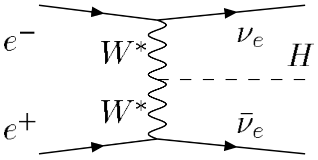
ZH cross section measurement does not depend on Higgs decay mode.

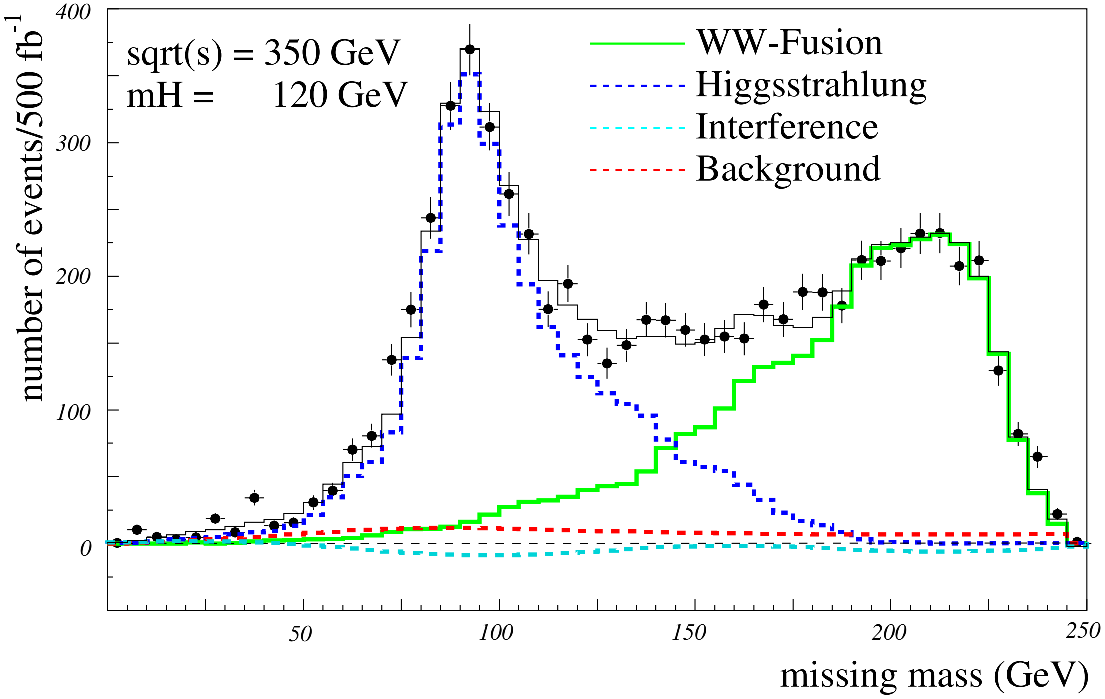
BR measurements do not depend on production cross-section assumptions.

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 $\to H$.

(b)





Battaglia & Desch, hep-ph/0101165

From $WW \to H$ cross section, get WWH coupling

→ predict $H \to WW$ partial width

→ Combine with BR($H \to WW$) to extract total width

→ Extract all the other Higgs couplings from respective BRs

Totally model independent!

Measure Higgs branching ratios to high precision:

Table 1: Summary of expected precisions on Higgs boson branching ratios from existing studies within the ECFA/DESY workshops. (a) for 500 fb^{-1} at 350 GeV; (b) for 500 fb^{-1} at 500 GeV; (c) for 1 ab^{-1} at 500 GeV; (d) for 1 ab^{-1} at 800 GeV; (e) as for (a), but method described in [35] (see text).

Mass(GeV)	120	140	160	180	200	220	240	280	320
Decay	Relative Precision (%)								
$b\bar{b}$	2.4 (a) / 1.9 (e)	2.6 (a)	6.5 (a)	12.0 (d)	17.0 (d)	28.0 (d)			
$c\bar{c}$	8.3 (a) / 8.1 (e)	19.0 (a)							
$\tau\tau$	5.0 (a) / 7.1 (e)	8.0 (a)							
$\mu\mu$	30. (d)								
gg	5.5 (a) /4.8 (e)	14.0 (a)							
WW	5.1 (a) / 3.6 (e)	2.5 (a)	2.1 (a)		3.5 (b)		5.0 (b)	7.7 (b)	8.6 (b)
ZZ			16.9 (a)		9.9 (b)		10.8 (b)	16.2 (b)	17.3 (b)
$\gamma\gamma$	23.0 (b) / 35.0 (e)								
$Z\gamma$		27.0 (c)							

review talk by K. Desch, hep-ph/0311092

With a 1 TeV ILC one does even better (larger cross sections, more statistics):

	Higgs Mass (GeV)				
	115	120	140	160	200
$\Delta(\sigma \cdot B_{bb})/(\sigma \cdot B_{bb})$	± 0.003	± 0.004	± 0.005	± 0.018	± 0.090
$\Delta(\sigma \cdot B_{WW})/(\sigma \cdot B_{WW})$	± 0.021	± 0.013	± 0.005	± 0.004	± 0.005
$\Delta(\sigma \cdot B_{gg})/(\sigma \cdot B_{gg})$	± 0.014	± 0.015	± 0.025	± 0.145	
$\Delta(\sigma \cdot B_{\gamma\gamma})/(\sigma \cdot B_{\gamma\gamma})$	± 0.053	± 0.051	± 0.059	± 0.237	
$\Delta(\sigma \cdot B_{ZZ})/(\sigma \cdot B_{ZZ})$					± 0.013

from Barklow, hep-ph/0312268

ILC at 1000 GeV, 1000 fb^{-1}
-80% e^- polarization, $+50\%$ e^+ polarization

With experimental uncertainties at the percent level, must consider theory uncertainties too.

$H \to q\bar{q}$: QCD corrections to 3 loops, EW corrections to 1 loop. Dominant corrections absorbed by using $\overline{m_q}(M_H)$ in partial width.
Uncertainty $\sim$ 1% remaining.

$H \to \ell\ell$: EW corrections to 1 loop.
Uncertainty negligible for our purposes.

$H \to W^{(*)}W^{(*)}/Z^{(*)}Z^{(*)} \to 4f$: NLO EW + QCD corrections including off-shell gauge boson effects now available – `PROPHECY4F`.
Uncertainty $\sim$ 0.5% remaining.

$H \to gg$: N^{3}LO QCD corrections known, plus leading EW.
Remaining scale dependence $\sim$ 3%.

$H \to \gamma\gamma$: NLO EW + NNLO QCD corrections known.
Uncertainty negligible for our purposes.

WBF$\to H$ production cross section: 1-loop EW known.

Uncertainty $\sim 0.5\%$ remaining.

Summary:

Higgs partial width	Theory uncertainty in literature	 in `HDECAY`
$\Gamma_{b\bar{b}}$, $\Gamma_{c\bar{c}}$	1%	1%
$\Gamma_{\tau\tau}$, $\Gamma_{\mu\mu}$	0.01%	0.01%
Γ_{WW}, Γ_{ZZ}	0.5%	5%
Γ_{gg}	3%	16%
$\Gamma_{\gamma\gamma}$	0.1%	4%
$\Gamma_{Z\gamma}$	4%	4%
Higgs production cross section		
$\sigma_{e^+e^-\to\nu\bar{\nu}H}$	0.5%	–

[Droll & H.L., hep-ph/0612317]

There are also uncertainties in the “inputs”: mostly m_b, m_c, α_s.

Parameter	Value	Percent uncertainty	Source
$\alpha_s(m_Z)$	0.1185 ± 0.0020	1.7%	PDG
$\overline{m_b}(M_b)$	4.20 ± 0.04 GeV	0.95%	B decays
$\overline{m_c}(M_c)$	1.224 ± 0.057 GeV	4.7%	B decays

$\overline{m_b}(M_b)$ and $\overline{m_c}(M_c)$ extracted from fits to semileptonic B meson decay spectra using HQET.

Can also get the masses from $e^+e^- \to$ hadrons or unquenched lattice QCD. Methods developing; close to being competitive to B decays.

Input uncertainties propagate into uncertainties in the SM Higgs partial widths:

Normalized derivatives of Higgs partial widths

	$\alpha_s(m_Z)$			$\overline{m_b}(M_b)$			$\overline{m_c}(M_c)$		
m_H	120 GeV	140 GeV	160 GeV	120 GeV	140 GeV	160 GeV	120 GeV	140 GeV	160 GeV
$\Gamma_{b\bar{b}}$	−1.177	−1.217	−1.249	2.565	2.567	2.568	0.000	0.000	0.000
$\Gamma_{c\bar{c}}$	−4.361	−4.400	−4.432	−0.083	−0.084	−0.084	3.191	3.192	3.192
Γ_{gg}	2.277	2.221	2.175	−0.114	−0.112	−0.104	−0.039	−0.032	−0.027
$\Gamma_{\gamma\gamma}$	0.002	0.002	0.001	0.010	0.008	0.005	0.012	0.009	0.005

[Droll & H.L., hep-ph/0612317]

Concentrate on lower Higgs mass region.

Precisions from before:

SM Higgs BR uncertainties from 500 fb^{-1} at 350 GeV (no beam pol'n)		
	m_H = 120 GeV	140 GeV
BR($b\bar{b}$)	2.4%	2.6%
BR($c\bar{c}$)	8.3%	19.0%
BR($\tau\tau$)	5.0%	8.0%
BR(WW)	5.1%	2.5%
BR(gg)	5.5%	14.0%

[Desch, hep-ph/0311092]

SM Higgs $\sigma\times$BR statistical uncertainties from 1000 fb^{-1} at 1000 GeV			
	m_H = 115 GeV	120 GeV	140 GeV
$\sigma \times$ BR($b\bar{b}$)	0.3%	0.4%	0.5%
$\sigma \times$ BR(WW)	2.1%	1.3%	0.5%
$\sigma \times$ BR(gg)	1.4%	1.5%	2.5%
$\sigma \times$ BR($\gamma\gamma$)	5.3%	5.1%	5.9%

Beam pol'ns of −80% for electrons and +50% for positrons assumed.

[Barklow, hep-ph/0312268]

To evaluate impact of theory uncertainties, need a “benchmark”:

choose differentiation of SM from MSSM Higgs.

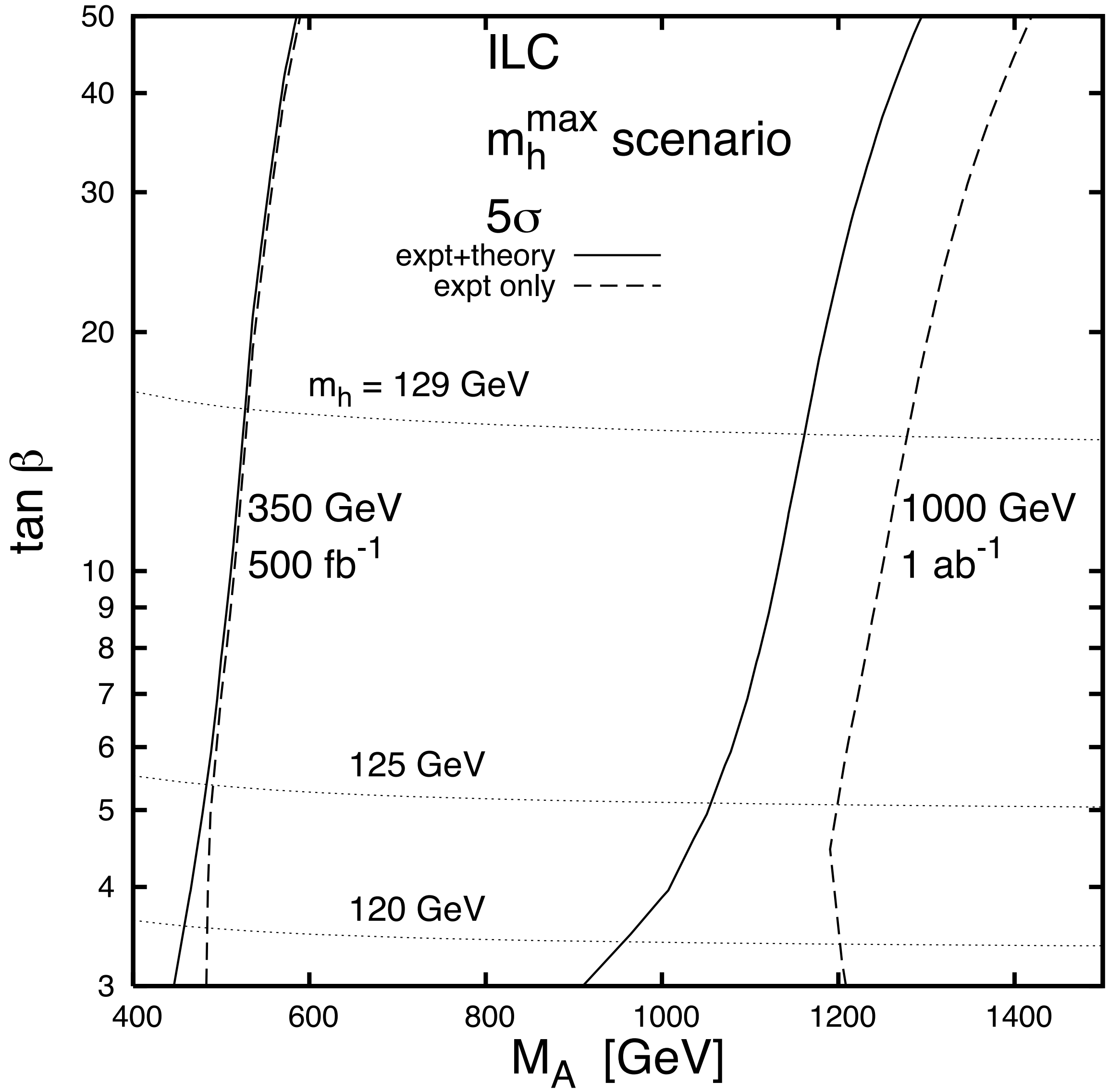
Choose a particular MSSM scenario: $m_h^{\rm max}$ benchmark scenario.

Compute a $\Delta\chi^2$ both without and with theory and parametric uncertainties; see how this affects the “distinguishing power” of ILC.

Consider “ILC early phase”: 500 fb^{-1} at 350 GeV C.o.M. energy, and “ILC late phase”: 1000 fb^{-1} at 1000 GeV C.o.M. energy.

chosen to match experimental studies.

Results:

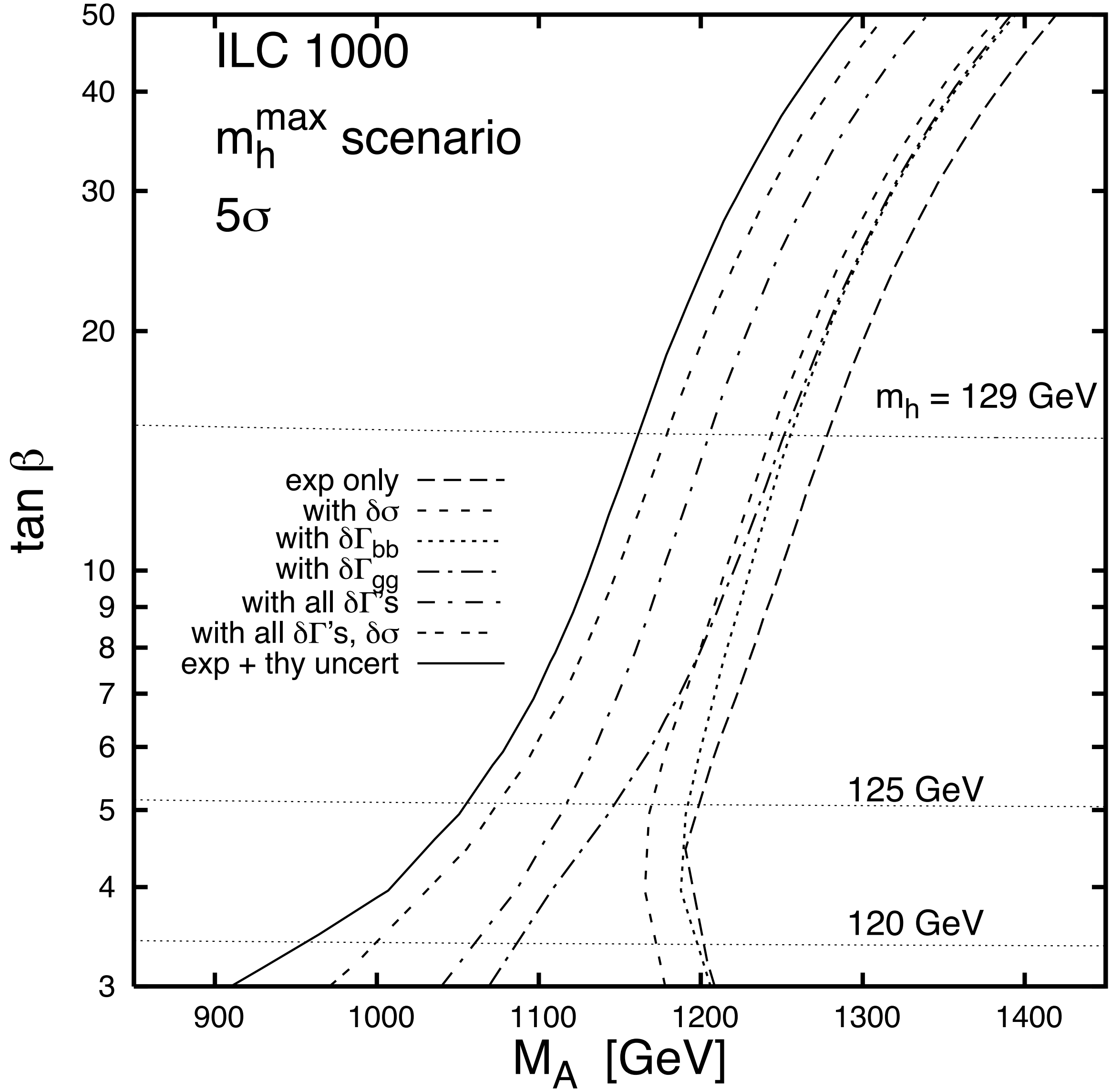


[Droll & H.L.,

hep-ph/0612317]

Theory/param uncerts not important in early-phase running.
Reduce "reach" in M_A by about 15% in late-phase running.

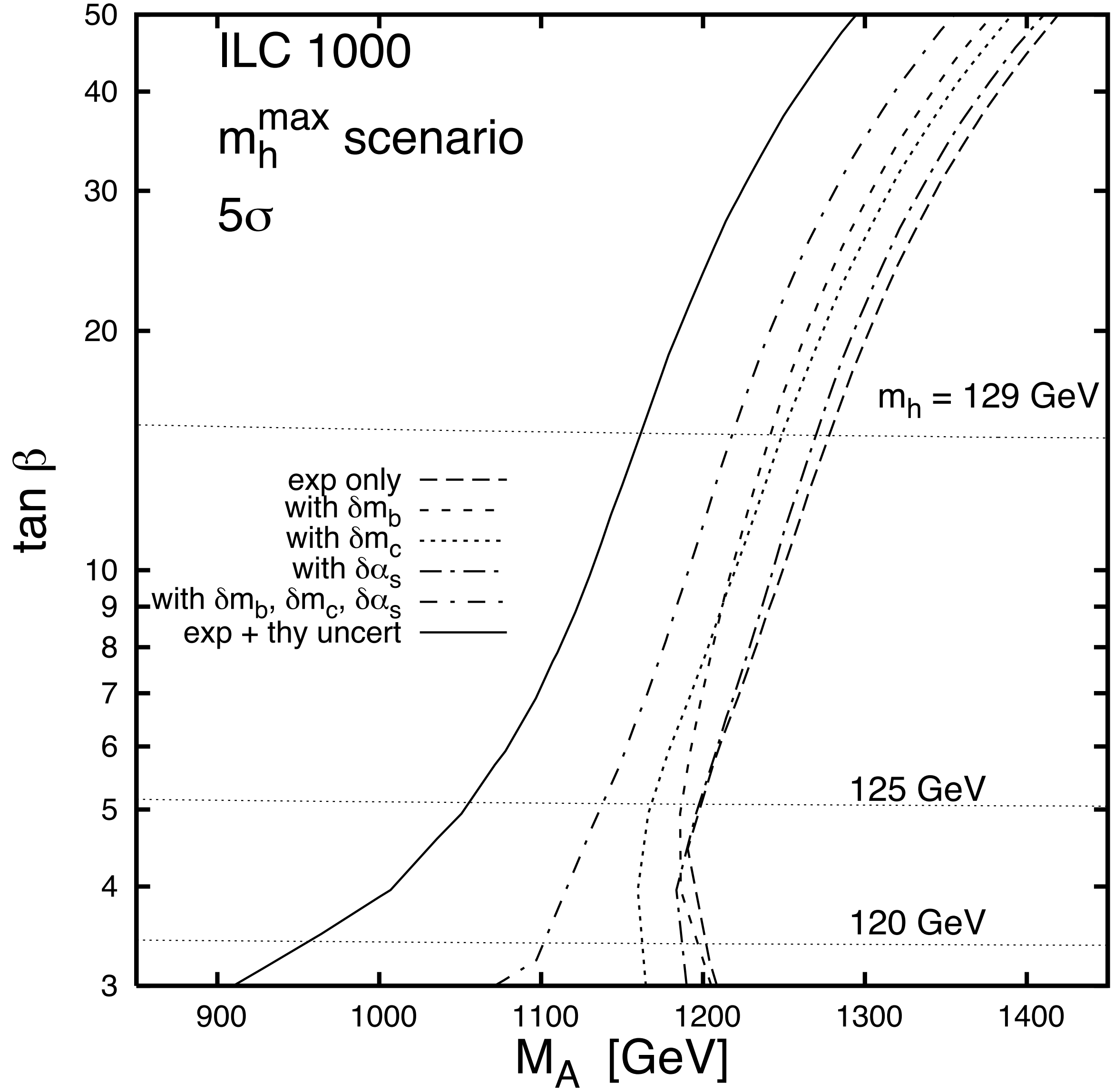
Breakdown of sources of theory uncertainty:



[Droll & H.L., hep-ph/0612317]

No single source gives majority of the effect.

Breakdown of sources of parametric uncertainty:



[Droll & H.L.,

hep-ph/0612317]

No single source gives majority of the effect.

Results:

- Theory and parametric uncertainties not an issue for initial phase of ILC: we are in good shape.

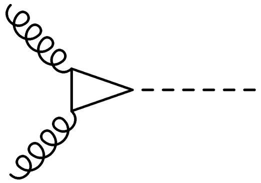
- After TeV-phase ILC running, though, thy/param uncerts reduce the "reach" in M_A by about 15%.
  Starting to become relevant.

- No single source dominates the theory uncertainties:
Need to take multiple calculations to the next level to improve this situation.

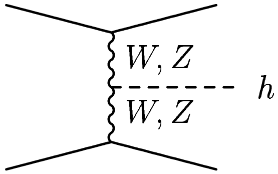
Higgs couplings at the LHC

Higgs will be accessible via multiple production mechanisms:

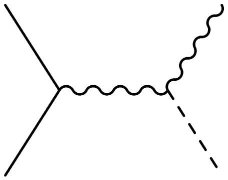
- Gluon fusion, $gg \rightarrow H$



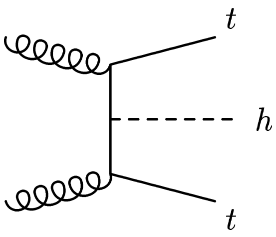
- Weak boson fusion, $qq \rightarrow Hqq$



- WH, ZH associated production

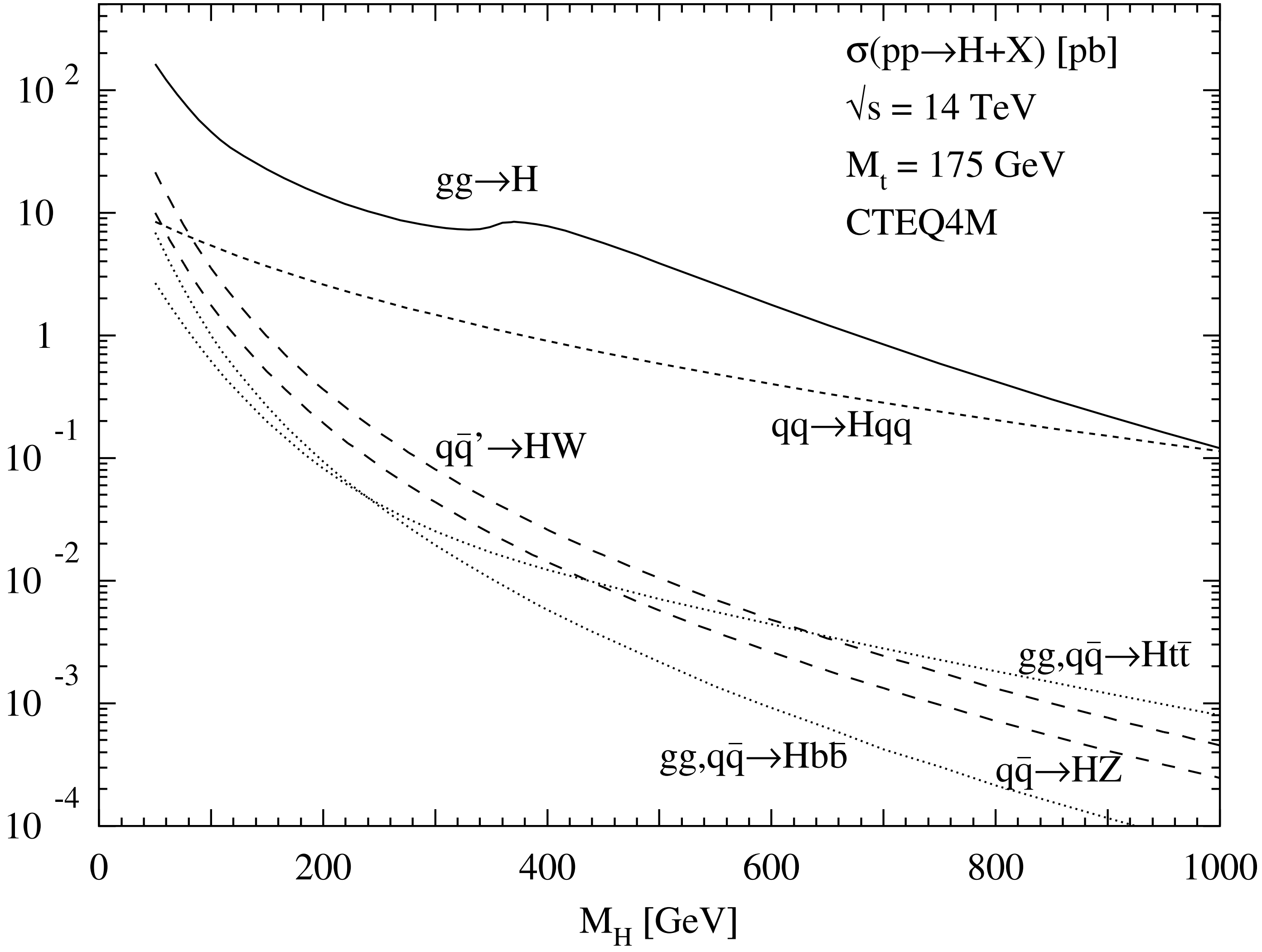


- ttH associated production



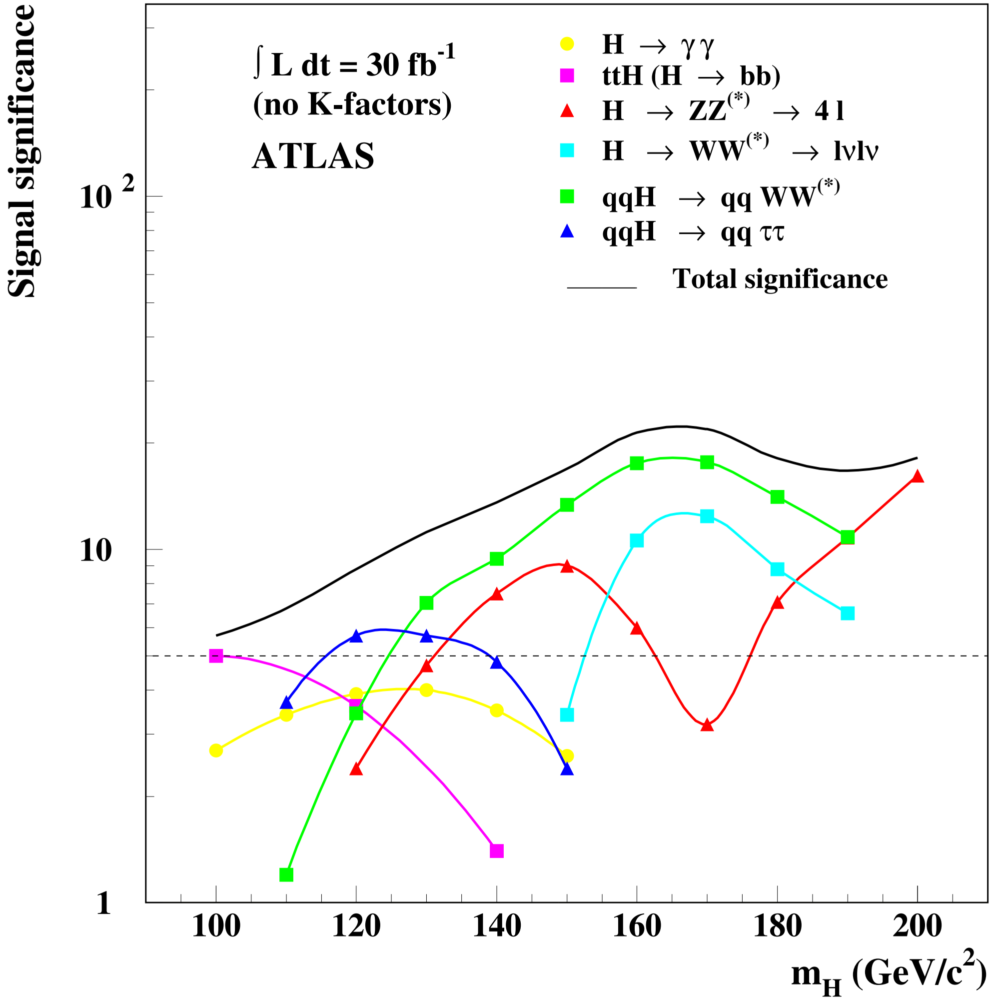
Higgs production cross sections are reasonably large:

$1 \text{ pb} \times 1 \text{ fb}^{-1} = 1000$ events



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

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 in many production and decay channels:

(GF = gluon fusion, WBF = weak boson fusion)

GF $gg \to H \to ZZ$

WBF $qqH \to qqZZ$

GF $gg \to H \to WW$

WBF $qqH \to qqWW$

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

WH, $H \to WW$

Inclusive $H \to \gamma\gamma$

WBF $qqH \to qq\gamma\gamma$

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

WH, $H \to \gamma\gamma$

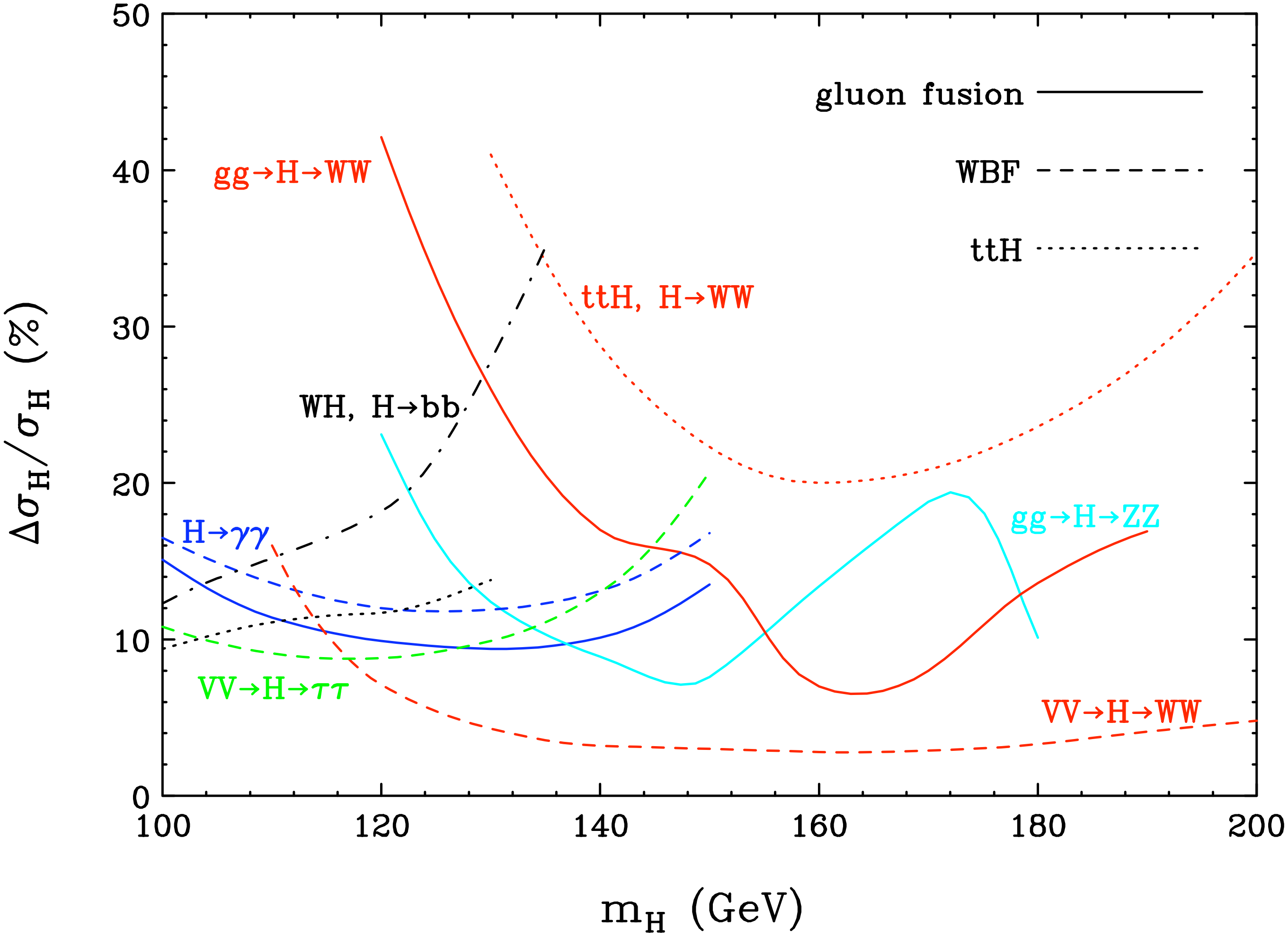
ZH, $H \to \gamma\gamma$

WBF $qqH \to qq\tau\tau$

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

Higgs couplings determine production cross sections and decay branching ratios ⟶ determine the rates in each channel.

Measure rates: test the SM!



LHC, 200 fb^{-1} (except 300 fb^{-1} for $ttH, H \to bb$, $WH, H \to bb$). Zeppenfeld, hep-ph/0203123

If there's a discrepancy, want to know where it comes from.

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

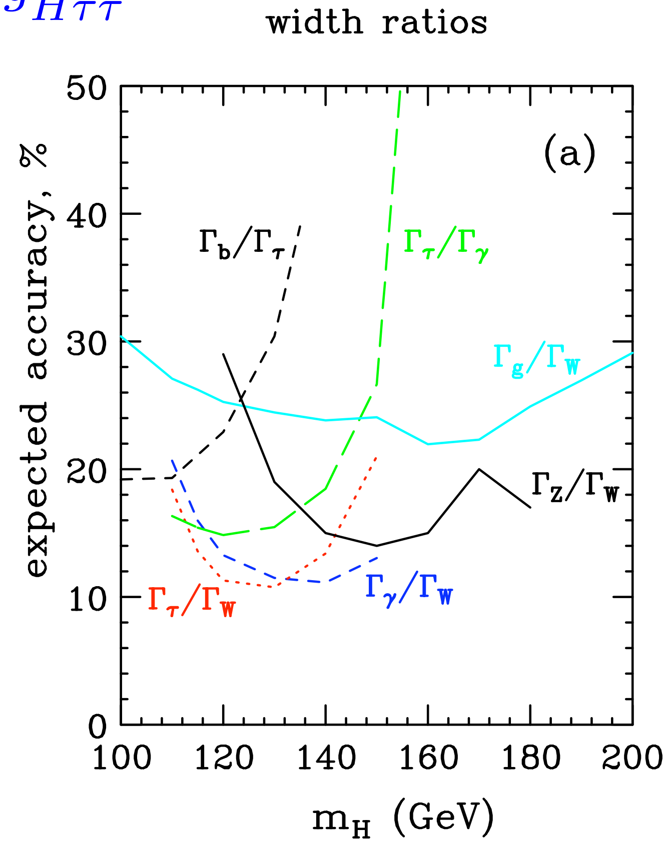
$$\frac{WBF \to H \to WW^*}{WBF \to H \to \tau\tau} = \frac{\Gamma(H \to WW^*)}{\Gamma(H \to \tau\tau)} \propto \frac{g^2_{HWW}}{g^2_{H\tau\tau}}$$

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

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

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)



LHC, 200 fb^{-1} (except 300 fb^{-1} for $ttH, H \to bb$, $WH, H \to bb$). Zeppenfeld, hep-ph/0203123

Ratios of couplings are nice.
But can we measure each coupling independently?

Difficulties:
- No measurement of total production rate.
- Some decays cannot be directly observed at LHC due to backgrounds: $H \to gg$, $H \to$ light quarks, etc.

Incomplete data: can't extract individual couplings in a totally model-independent way.

Multi-dimensional "error ellipsoid" is unbounded in some directions.

Observation of Higgs production
$\longrightarrow$ lower bound on production couplings
$\longrightarrow$ lower bound on Higgs total width.

But: no model-independent upper bound on Higgs total width.

To make progress, have to make some theoretical assumptions.

Consider Higgs models containing only SU(2) doublets/singlets.
- hWW, hZZ couplings related by custodial SU(2).
- hWW, hZZ couplings bounded from above by SM values.

This is a mild assumption!
- True in most good models: MSSM, NMSSM, 2HDM, etc.
- Larger Higgs multiplets stringently constrained by ρ parameter.

Theoretical constraint $\Gamma_V \leq \Gamma_V^{\text{SM}}$
$\oplus$ measurement of $\Gamma_V^2/\Gamma_{\text{tot}}$ from WBF $\to H \to VV$
$\longrightarrow$ upper bound on Higgs total width.

...slicing the error ellipsoid...

Combine with lower bound on Higgs total width from production couplings.
- Interplay constrains remaining Higgs couplings.
- Make no assumptions on unexpected/unobserved Higgs decay modes.

Must include the appropriate systematic uncertainties:

5% overall Luminosity normalization

Theory uncertainties on Higgs production:

- 20% Gluon Fusion
- 15% $t\bar{t}H$ assoc. prod.
- 7% WH, ZH assoc. prod.
- 4% Weak Boson Fusion

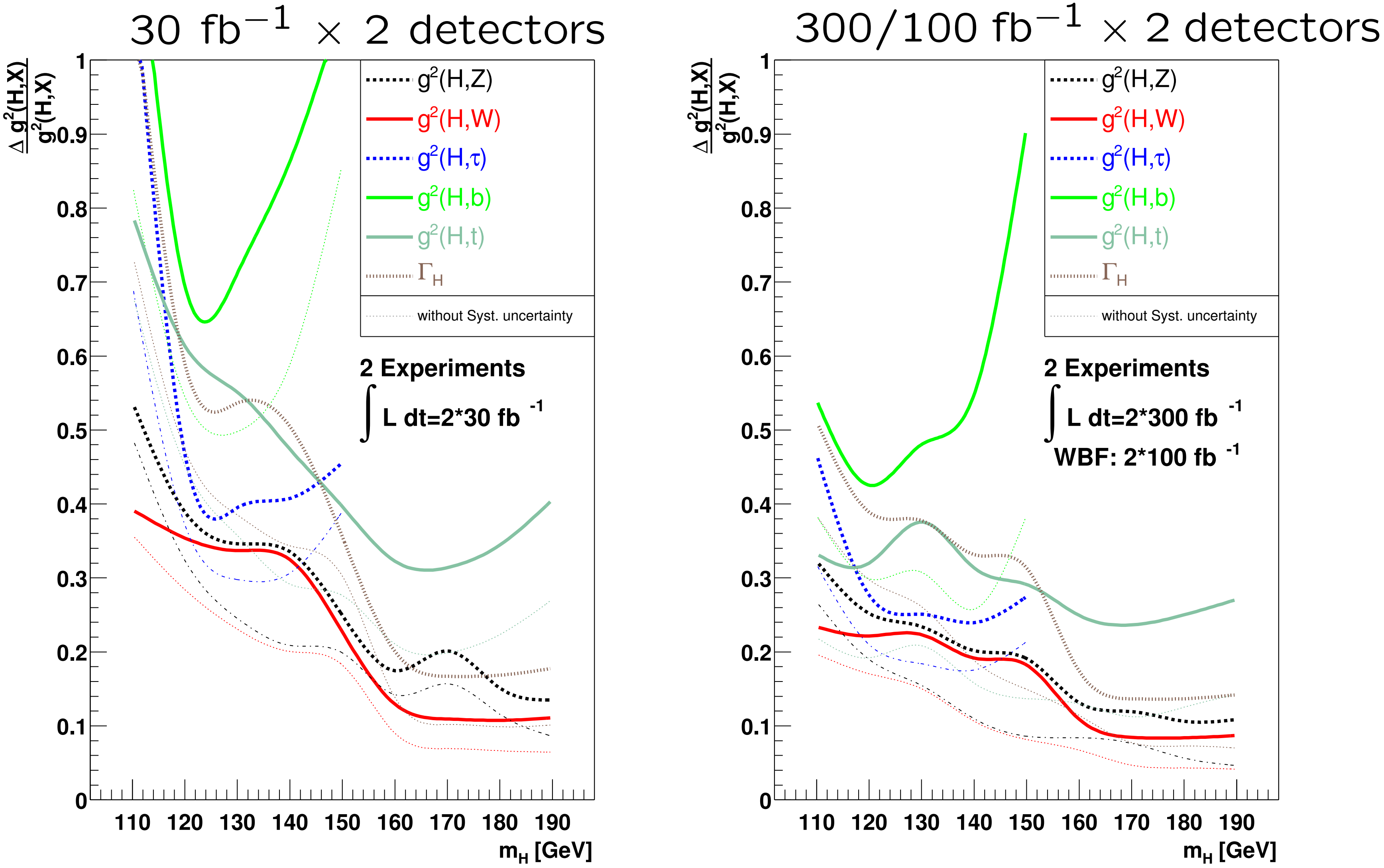
Reconstruction/identification efficiencies:

- 2% leptons
- 2% photons
- 3% b quarks
- 3% τ jets
- 5% forward tagging jets and veto jets (for 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 $H \to b\bar{b}$

Result: fit of Higgs couplings-squared



Dührssen, Heinemeyer, H.L., Rainwater, Weiglein & Zeppenfeld, hep-ph/0406323

Another approach: fit observed rates to a particular model.

Fits within a model are more constrained than a general fit of independent Higgs couplings.

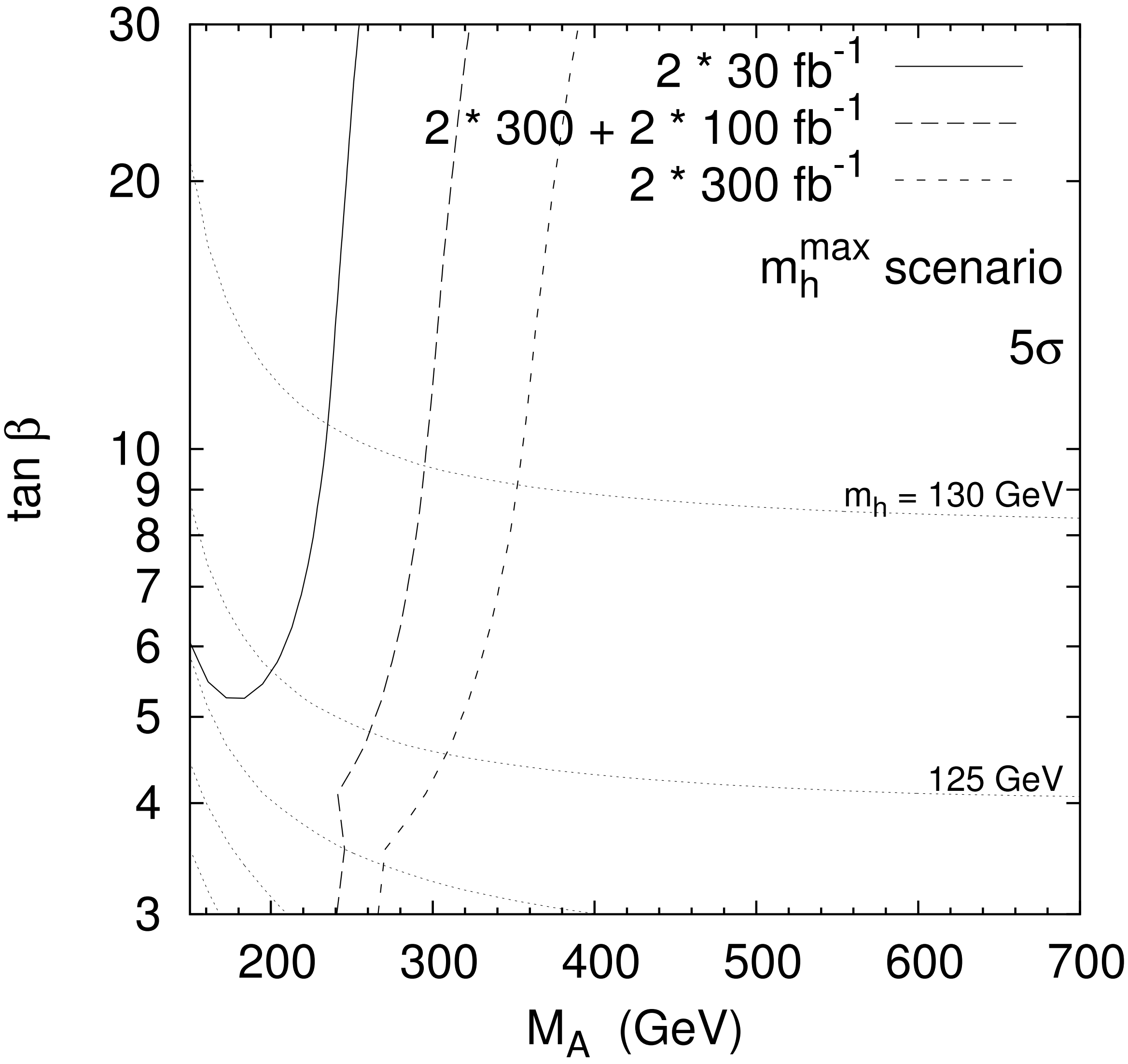
Model constraints → fewer parameters:
taking a slice through the "error ellipsoid."

Get tighter constraints as a result of the model assumption.
We saw this already when taking $g_{HWW,HZZ} \leq g_{HWW,HZZ}^{\mathrm{SM}}$.

Lose generality, but gain constraining power:
This is fine as long as you know what your assumptions are!

Can use this approach to test consistency with individual models.

Example: chi-squared fits in MSSM, m_h^{max} scenario

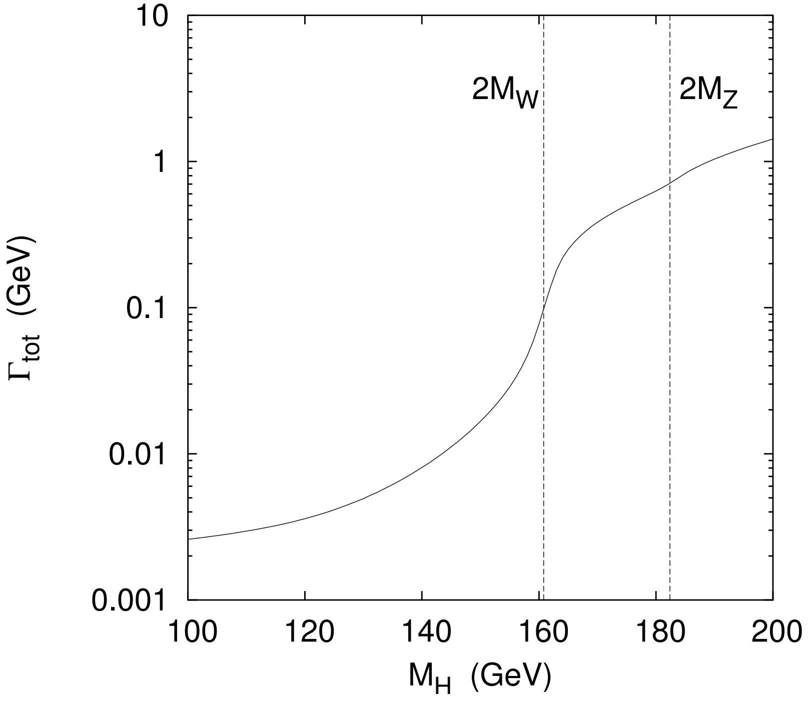


LHC sensitive to MSSM nature of h up to $M_A \lesssim 300$ GeV

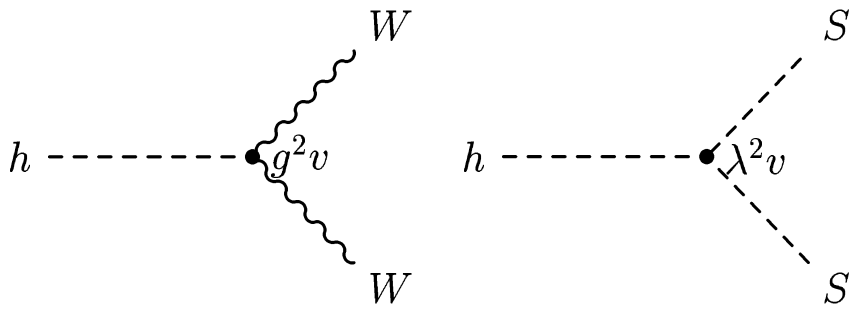
from Dührssen, Heinemeyer, H.L., Rainwater, Weiglein & Zeppenfeld, hep-ph/0406323

Invisibly-decaying Higgs

The SM Higgs is very narrow for $M_H \lesssim 160$ GeV.



If Higgs couples with electroweak strength to a neutral (quasi)stable particle (e.g., dark matter) with mass $< M_h/2$, then $h \rightarrow$ invisible can be the dominant decay mode.



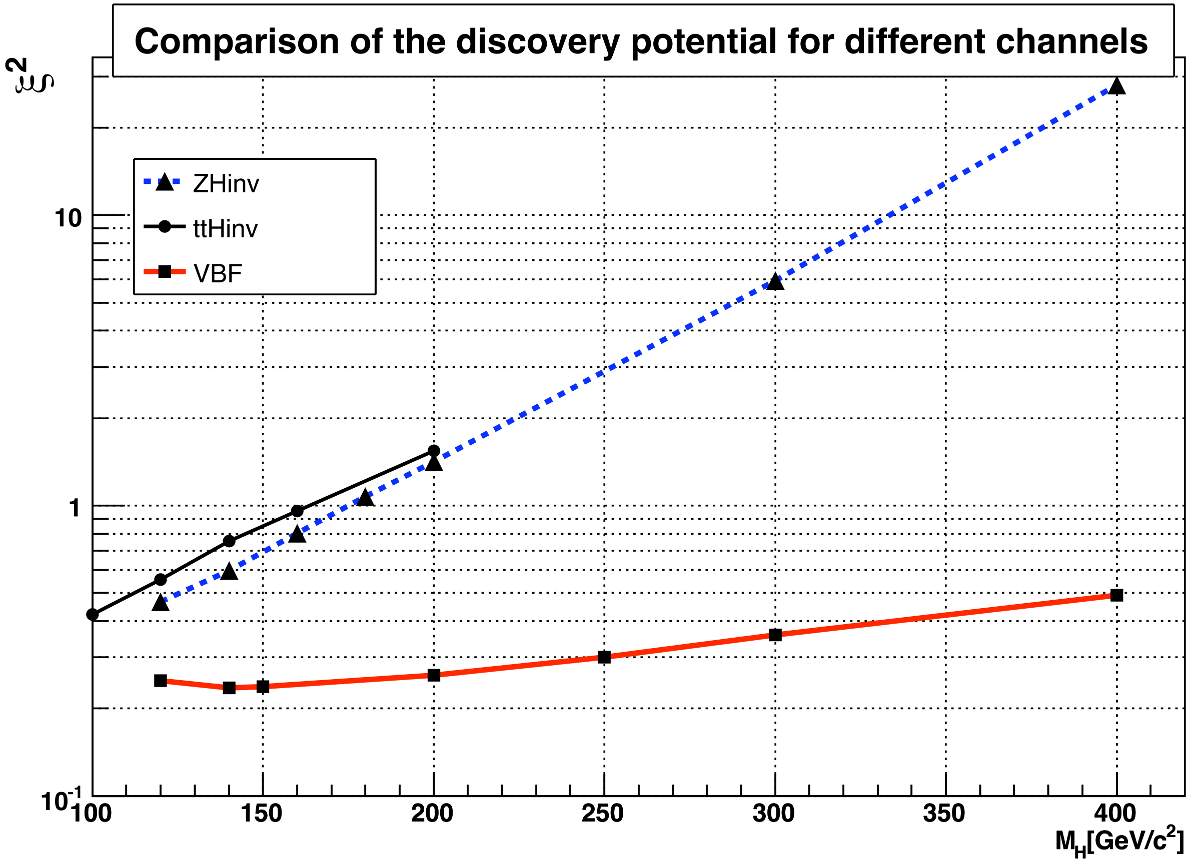
The Higgs *could* decay invisibly

- $h \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$ in MSSM, NMSSM
- $h \to SS$ in simple models of scalar dark matter
- $h \to$ KK neutrinos in extra dimensions
- $h \to$ Majorons
- …

Shouldn't just assume Higgs will be SM-like.
Even small additions (e.g., singlet scalar dark matter) can make BR($h \to$ invis.) large.
Let's cover all our bases!

"Invisible" Higgs is not that hard to "see":
missing transverse momentum ($\not{p}_T$).
$h \to jj$ is much harder.

Limits on invisible decay modes:



ZH_{inv} uses $Z \to \ell^+\ell^-$

VBF looks promising (but it's not clear how well those events can be triggered)

$t\bar{t}H_{\text{inv}}$ – may be room for improvement?

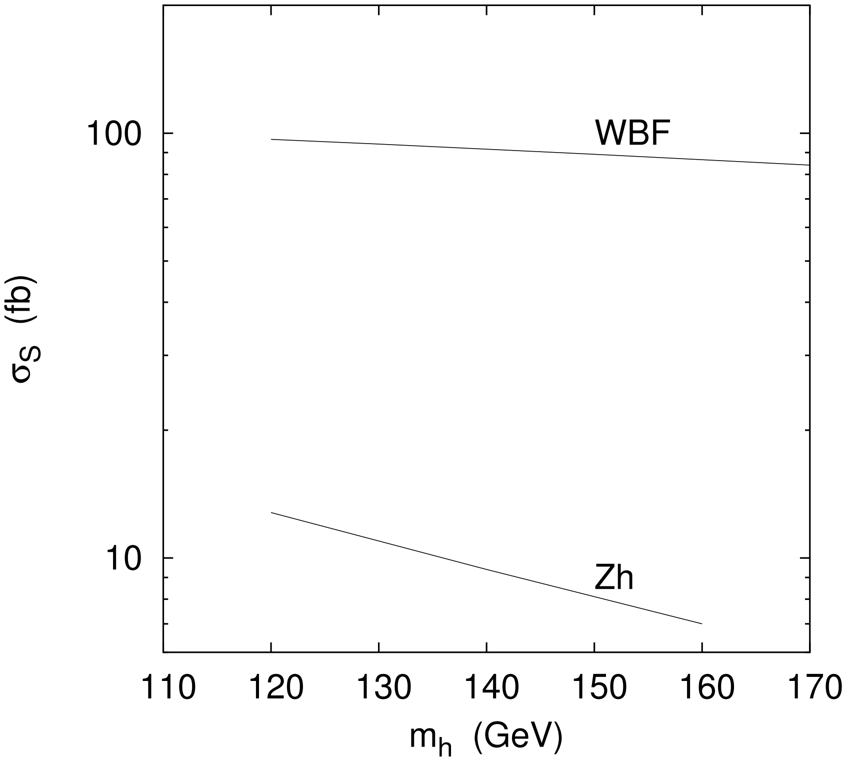
95% CL exclusion limits with 30 fb^{-1} at LHC [ATL-PHYS-PUB-2006-009]

ξ^2 is a scaling factor: $\sigma \times \text{BR}(H \to \text{invis}) \equiv \xi^2 \sigma_{\text{SM}}$

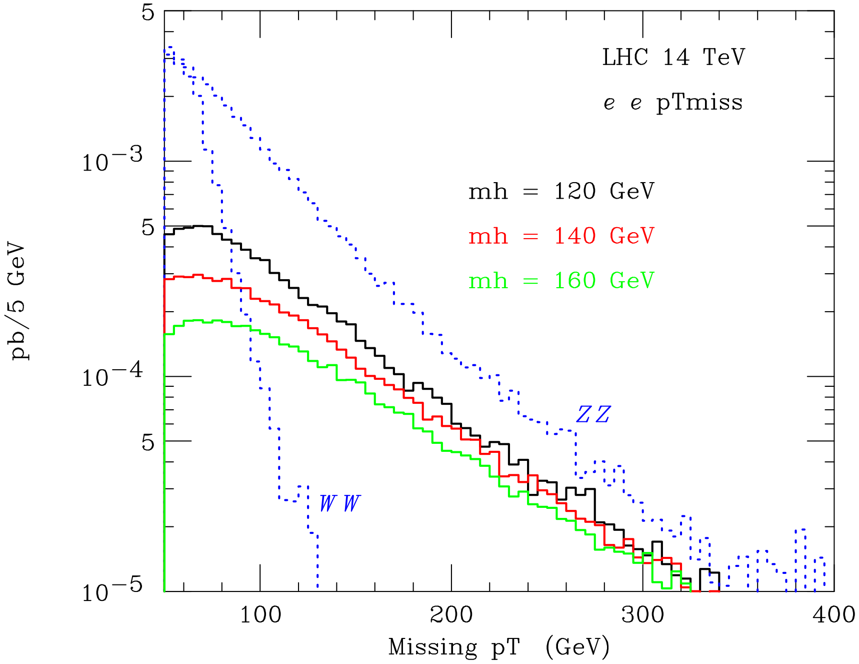
Extracting the mass of an invisible Higgs:

Mass of h_{inv} accessible only through production process.

Cross section



Kinematic distributions



(needs more study)

Davoudiasl, Han & H.L. (2004)

Measure signal rate.

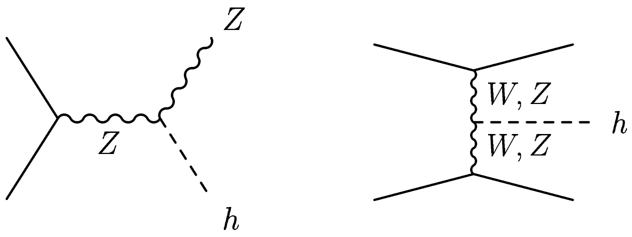
Assuming SM production cross section and 100% invisible decay:

- $Z + h_{inv}$: $\Delta m_h = 30$–40 (12–14) GeV with 10 (100) fb^{-1}.
- WBF: $\Delta m_h \simeq 40$ (30) GeV with 10 (100) fb^{-1}.

What if production rate is not SM-like?
What if decay is not 100% invisible?

For a more model-independent M_h extraction, take the ratio of $Z + h_{inv}$ and WBF rates. Davoudiasl, Han & H.L. (2004)

$Z + h_{inv} \sim hZZ$ coupling; WBF $\sim hWW, hZZ$ couplings – related by SU(2) in models with only Higgs doublets/singlets.



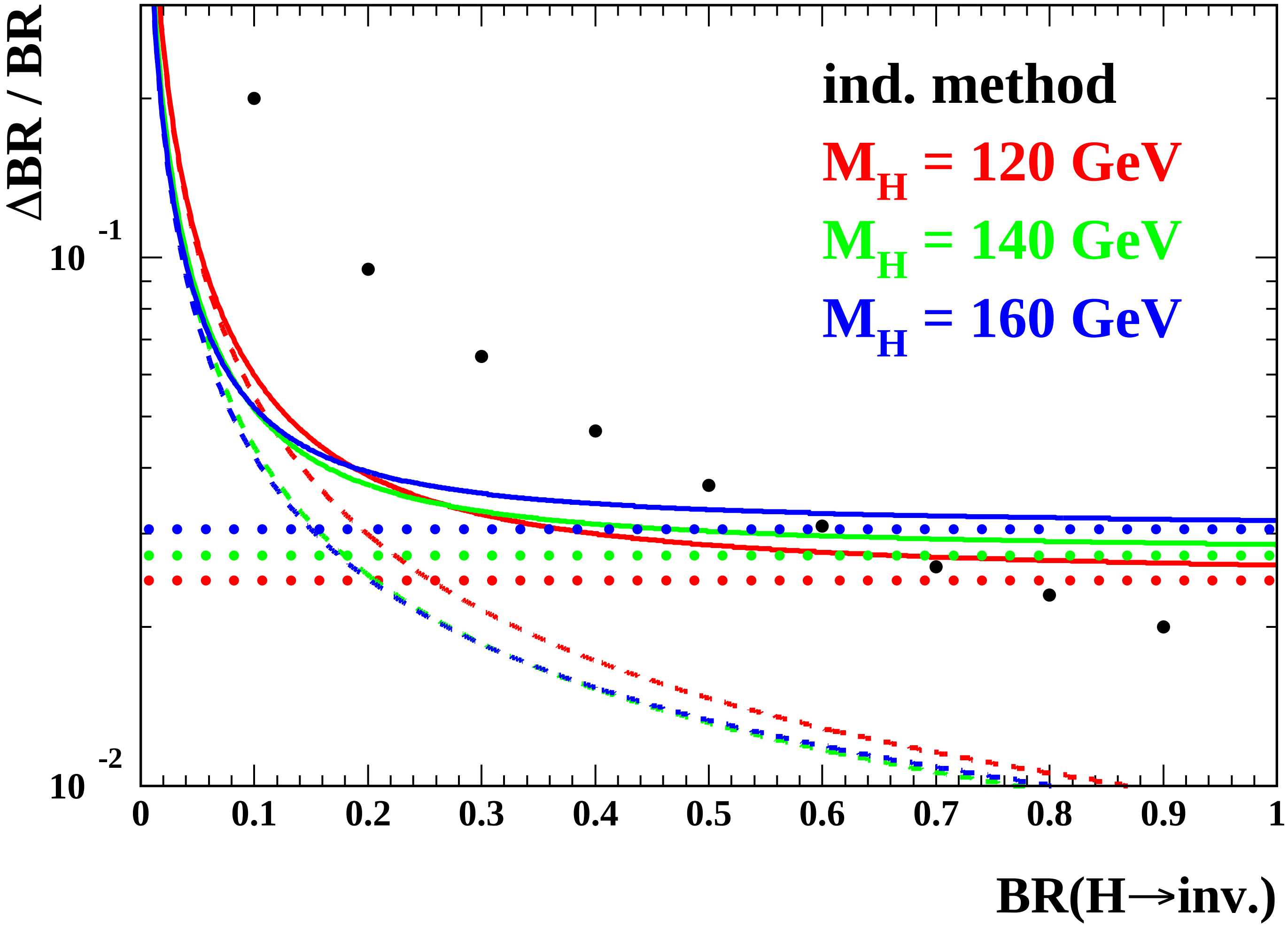
Example: MSSM or 2HDM:
ZZh coup $= (gm_Z/\cos\theta_W)\sin(\beta-\alpha)$
WWh coup $= gm_W \sin(\beta-\alpha)$

Ratio method: $\Delta m_h \simeq$ 35–50 (15–20) GeV with 10 (100) fb^{-1}.

Not great, but rather model-independent.

At ILC, invisible Higgs decay is easy:

↓ 5σ exclusion at BR $\sim 2\%$



$\sim 3\%$ meas
for large BR

500 fb^{-1} at 350 GeV. Dashes = invisible rate; dots = Higgsstrahlung cross section

M. Schumacher, LC-PHSM-2003-096

Get the Higgs mass from recoil method.

Conclusions

If the Higgs mechanism is realized in nature, LHC and ILC data will let us test it.

In high precision measurements, theory uncertainties begin to play a role.

- Production cross section, decay partial widths, SM input parameters at late-phase ILC
- Higgs production cross sections at LHC

Model-independent measurements are always best, but model assumptions are sometimes necessary.

- Nothing wrong with testing individual models
- Keep assumptions as mild as possible for maximum generality
- Appropriate theory assumptions can reveal interesting relations in the data