

Higgs Theory

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The LHC Early Phase for the ILC
Fermilab – April 12, 2007

LHC data is coming very soon!

Early LHC data (the first $1-10 \text{ fb}^{-1}$) will impact plans for ILC.

This talk: **Higgs theory**.

The scenario:

Detection of only one state with properties compatible with those of a Higgs boson.

The questions:

How sure can we be that it's really a Higgs? *The Higgs?*

- What do we need to know about the properties of the new state?
- Which phenomena can fake a Higgs-like signal?

What kind of scenarios can give rise to (possibly similar) Higgs-like signatures?

- How can we distinguish different scenarios?

What is a Higgs?

- Scalar particle, CP-even, neutral component of an electroweak doublet.
- Gives mass to the SM particles via the Higgs mechanism
 - It is the excitation along the “radial direction” of the EWSB condensate: $\Phi \sim (v + h)$

The Standard Model Higgs:

One field alone accomplishes EWSB; the Higgs doesn't mix with any other states.

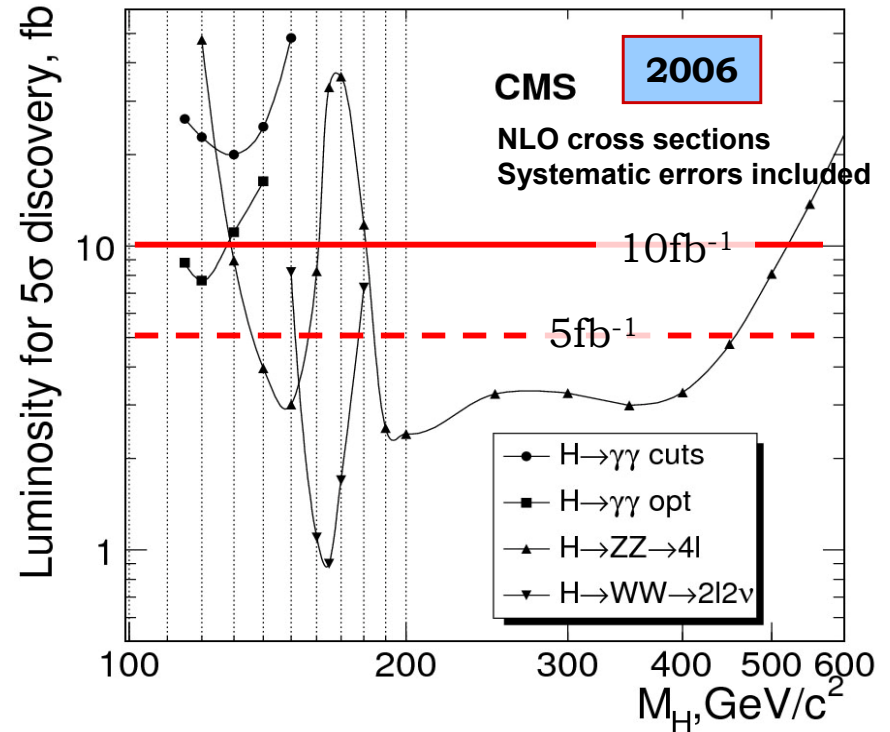
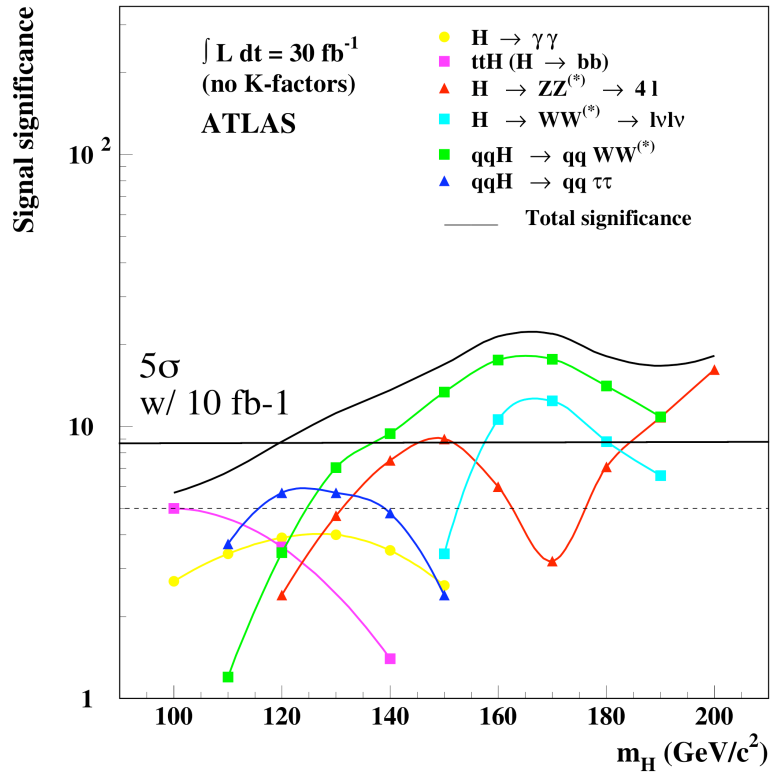
Beyond the Standard Model:

Can have more than one Higgs field. “Higgs-like” state typically a mixture of the vev-carrying doublet and some other scalar field(s).

Typically get additional neutral scalars – CP-odd, etc.

Higgs can be a bound state – composite object.

What will we know? – Discovery modes: depend on M_H



WBF $\rightarrow H \rightarrow WW$

Inclusive $H \rightarrow WW \rightarrow 2\ell 2\nu$

Inclusive $H \rightarrow ZZ \rightarrow 4\ell$

Evidence in WBF $\rightarrow H \rightarrow \tau\tau, t\bar{t}H(H \rightarrow b\bar{b})$

Inclusive $H \rightarrow \gamma\gamma$

Inclusive $H \rightarrow ZZ \rightarrow 4\ell$

Inclusive $H \rightarrow WW \rightarrow 2\ell 2\nu$

Good mass measurement from $ZZ, \gamma\gamma$ modes.

Assume our new state looks like the SM Higgs.

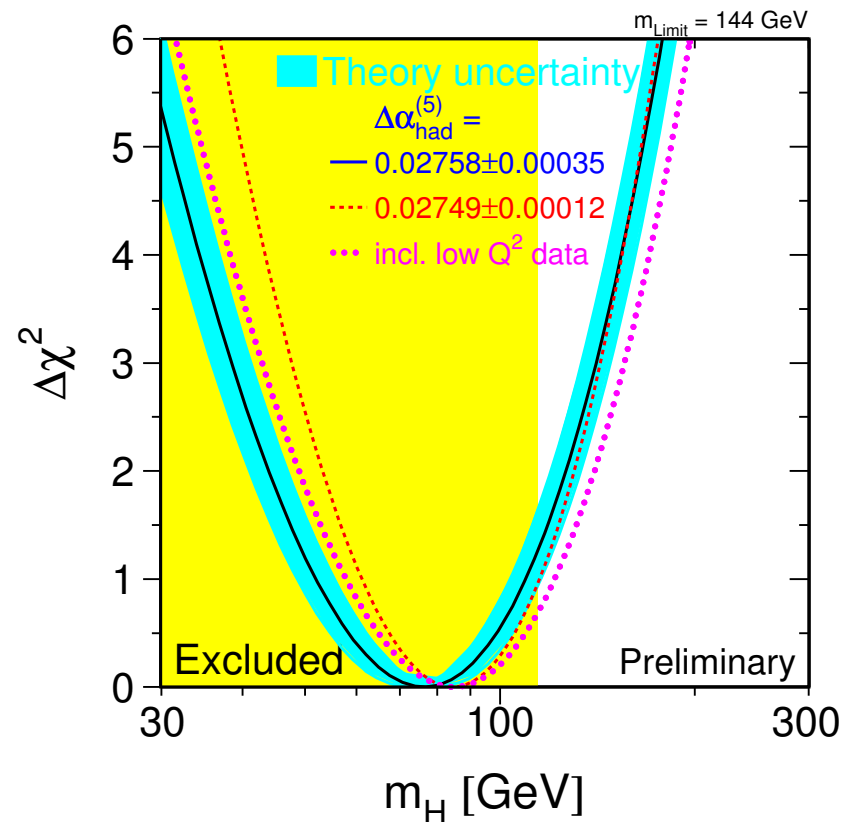
- Apparently spin-zero
- Apparently CP-even
- Rates in observed channels consistent with SM Higgs

Higgs mass:

Check that Higgs mass + electroweak fit is consistent with SM

EW precision fit *within the SM* favors a light Higgs $M_H \lesssim 150\text{--}200$ GeV.

If we discover a SM-like Higgs well above 200 GeV, something BSM is going on.



Winter 2007

There are still a wide variety of BSM possibilities.

SUSY

- MSSM
- NMSSM and other extensions
- Fat Higgs, etc.

Composite Higgs

- Topcolor
- Little Higgs (various models)
- Randall-Sundrum

Extra Dimensions

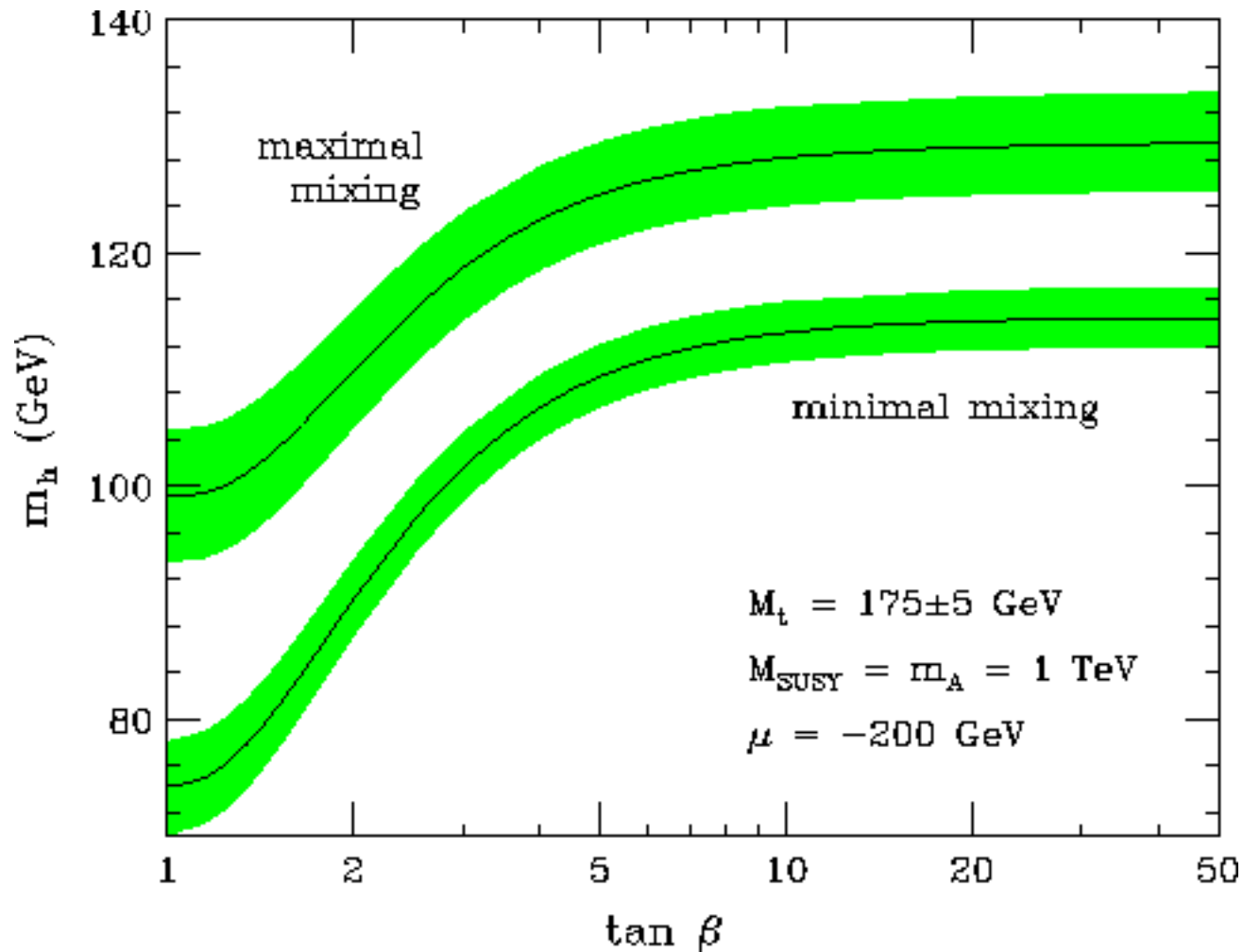
- Large extra dimension(s) / ADD
- Universal extra dimension(s)
- Radion

Generic models with extra scalar multiplets

[Left out: Technicolor, Higgsless models – no SM-like Higgs!]

Higgs mass measurement will favor or disfavor various models.

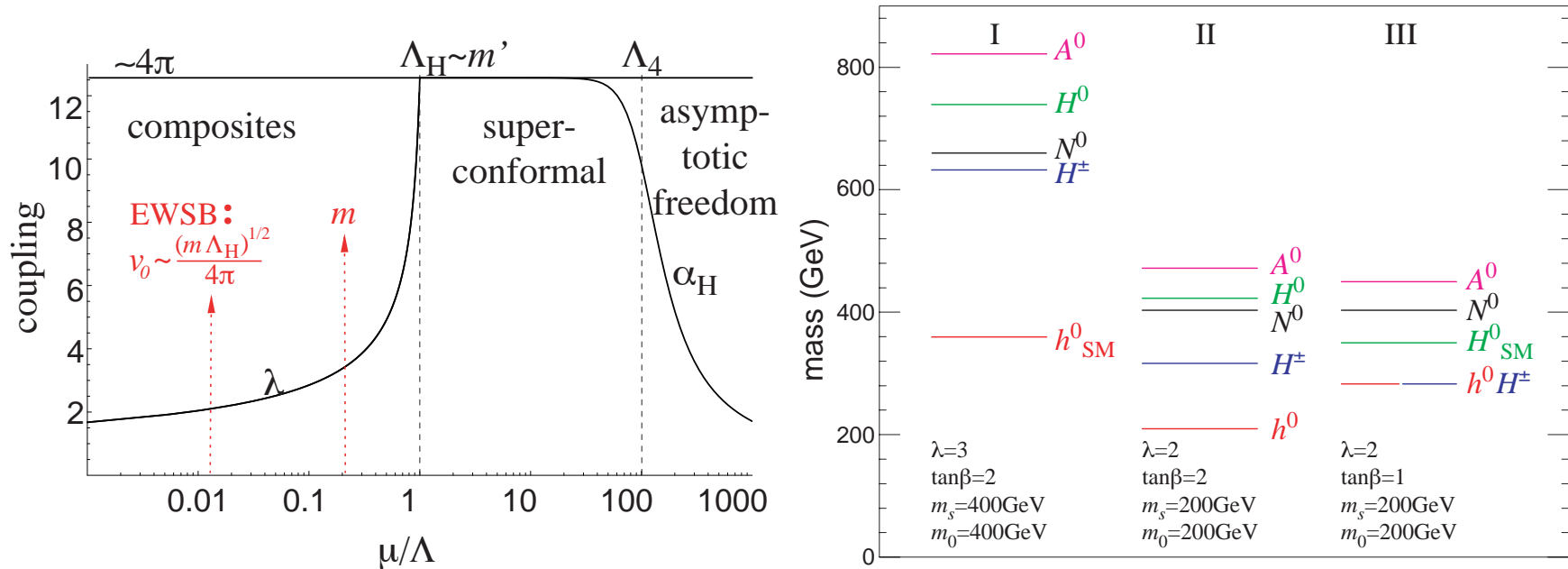
The MSSM is only really viable for $m_h \lesssim 135$ GeV...



Carena & Haber, hep-ph/0208209

Higgs mass measurement will favor or disfavor various models.

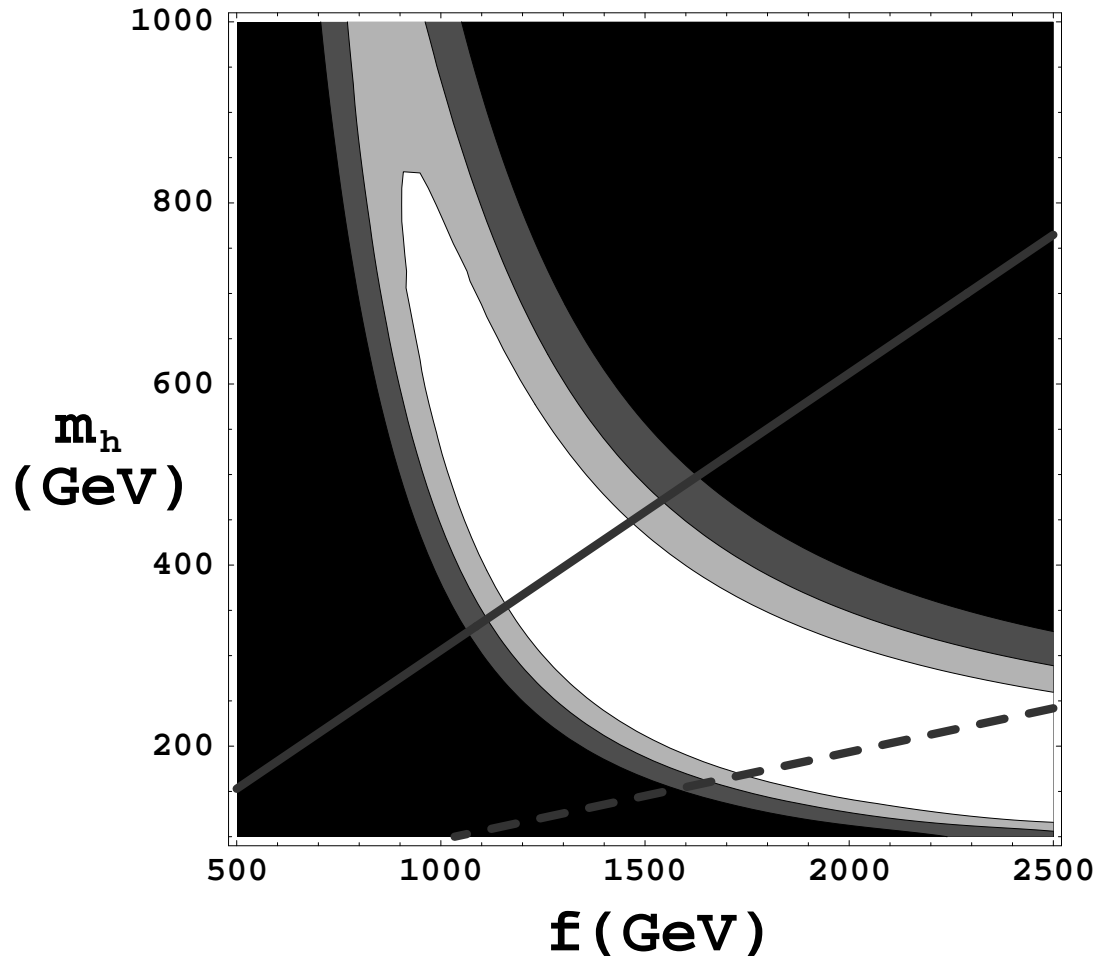
...whereas the “Fat Higgs” model prefers a heavier SM-like Higgs...



Harnik, Kribs, Larson, Murayama, hep-ph/0311349

Higgs mass measurement will favor or disfavor various models.

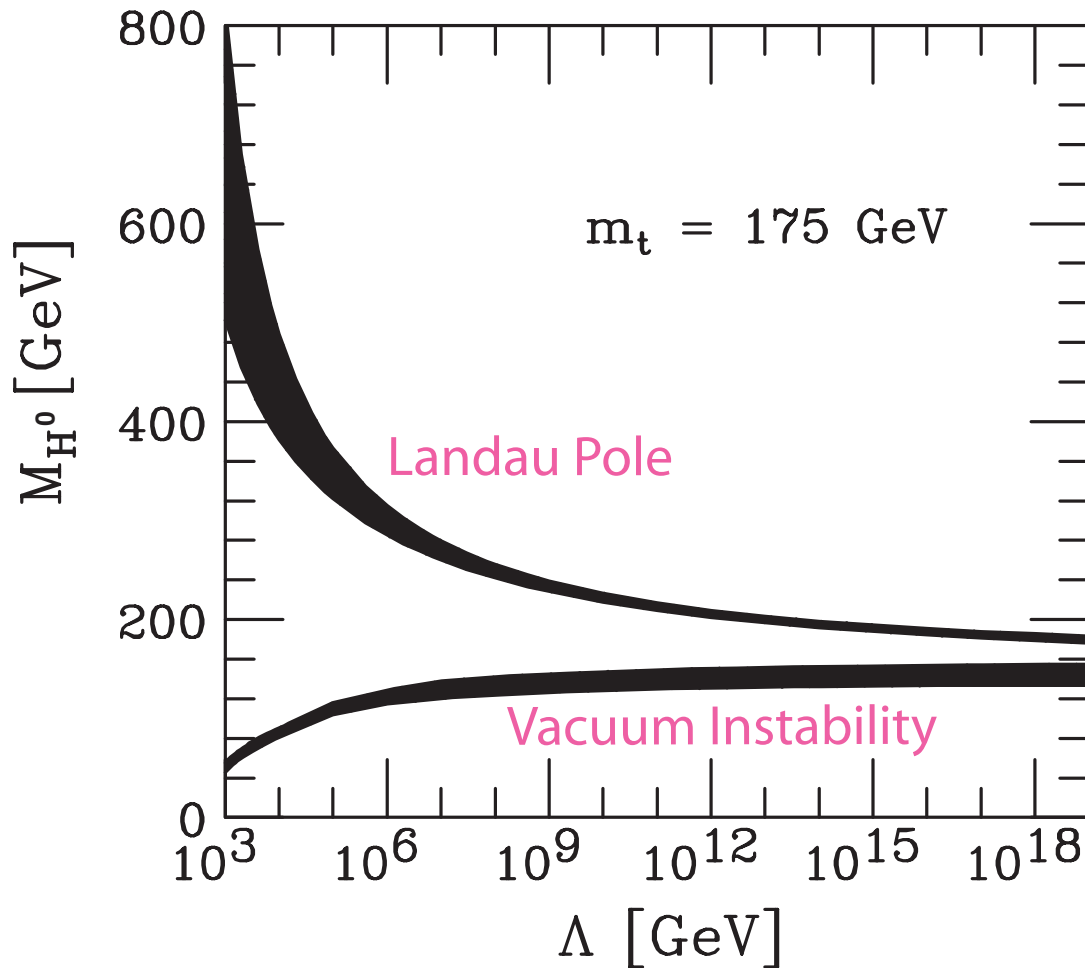
...and Little Higgs w/ T-parity is least fine-tuned for $m_H \gtrsim 350$ GeV.



Hubisz, Meade, Noble, Perelstein, [hep-ph/0506042](https://arxiv.org/abs/hep-ph/0506042)

Higgs mass measurement will favor or disfavor various models.

Even the “Standard Model All the Way Up” is only viable for $140 \lesssim m_H \lesssim 180$ GeV.



Landau Pole:

Higgs self-coupling too large; blows up at scale Λ

Vacuum Instability:

Higgs self-coupling too small; runs negative at scale Λ

[PDG 2002]

Early LHC data will already slash the parameter space of all the models.

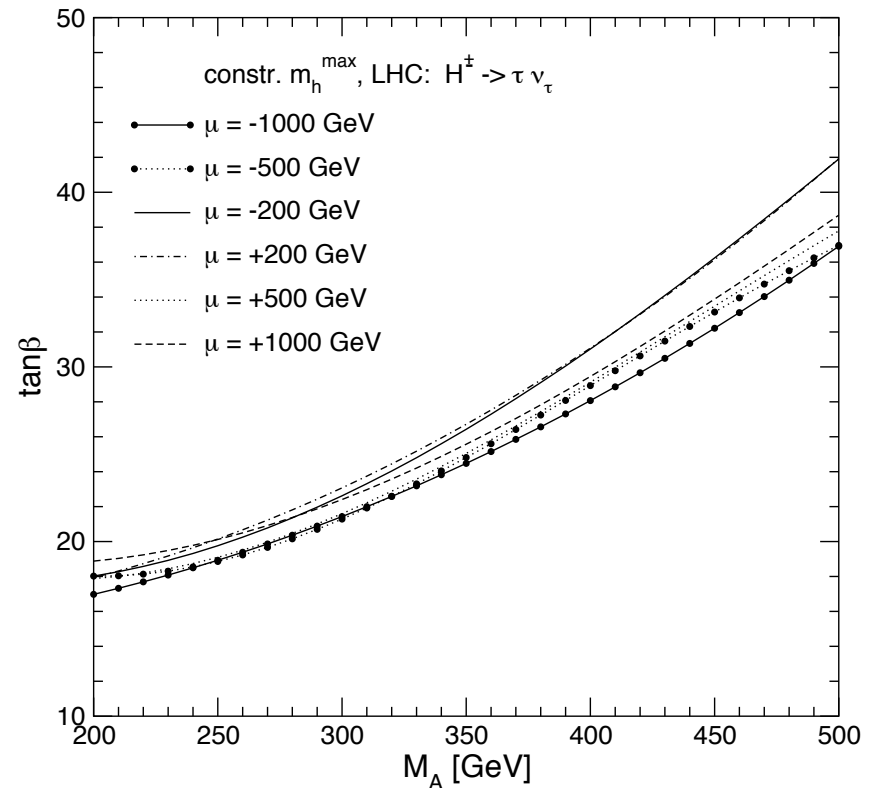
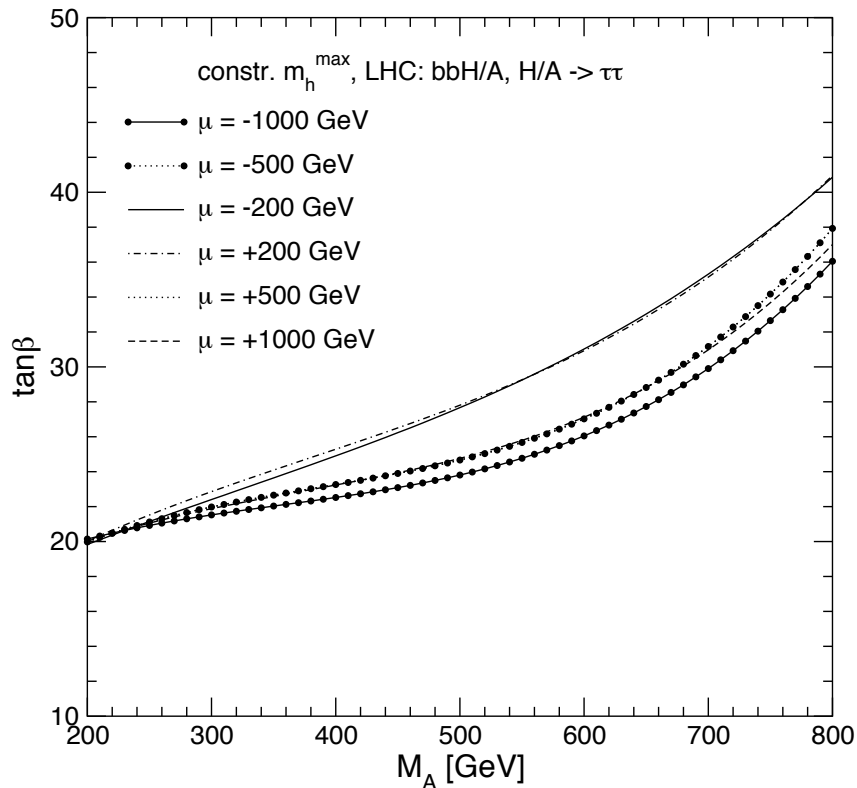
Measurement of the Higgs mass will reduce parameter space dimensionality by one.

Non-observation of additional states (as assumed in this scenario) will further constrain the parameter space.

Example: MSSM $H^0/A^0/H^\pm$ non-observation

5σ discovery contours with 30 fb^{-1} (from CMS)

$\leftrightarrow 2.9\sigma$ exclusion contours with 10 fb^{-1} (2σ with 5 fb^{-1})

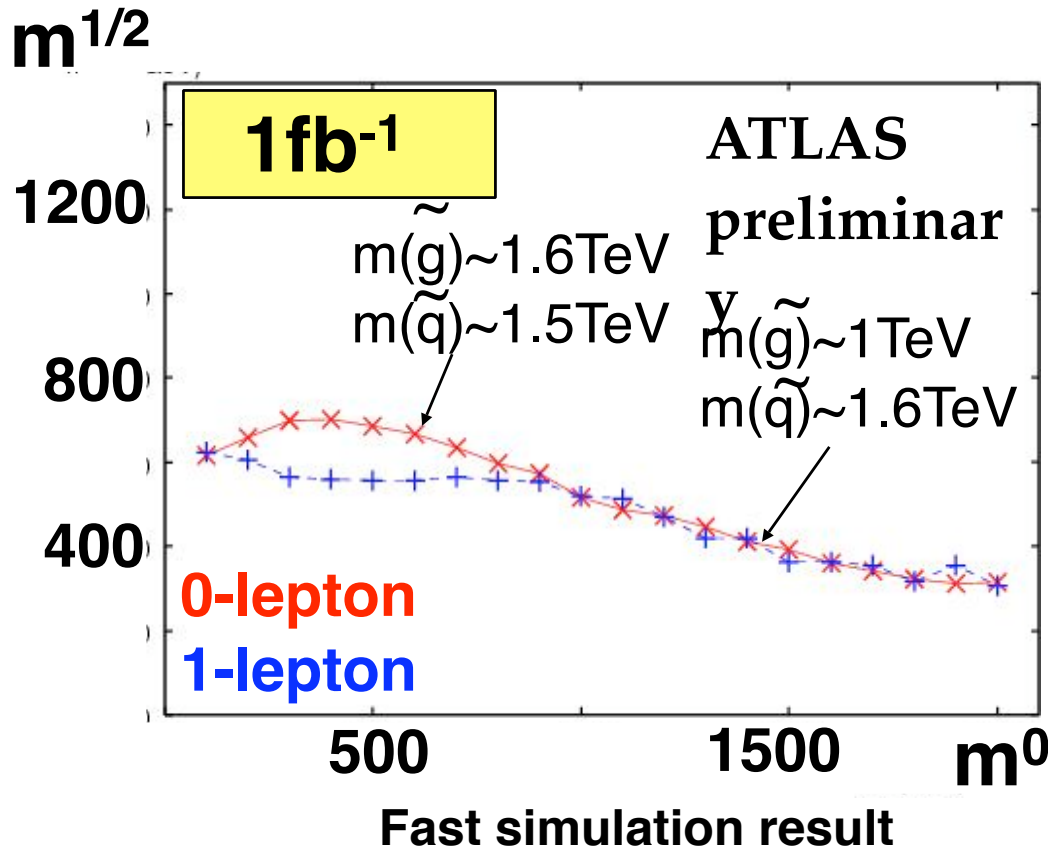


Carena, Heinemeyer, Wagner, Weiglein, hep-ph/0511023

Similar constraints on heavy Higgses in any model with two Higgs doublets and “Type II” fermion couplings.

Example: SUSY particles

MSUGRA 5σ discovery in 1 fb^{-1} :



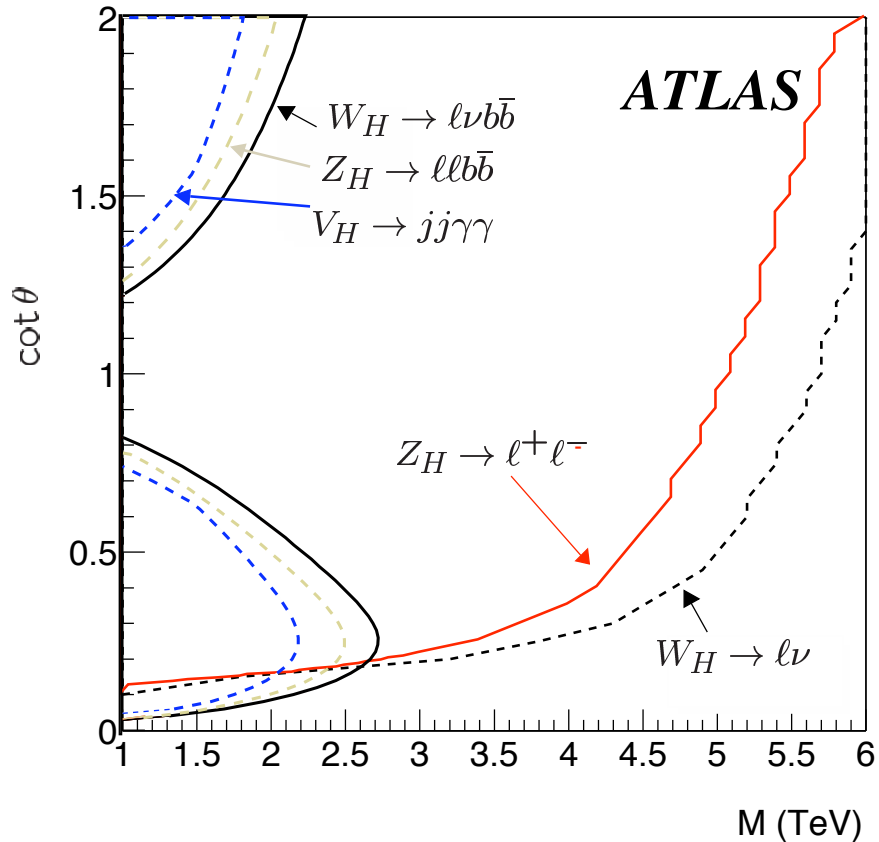
Nojiri, SUSY'06 talk

Have to push squarks & gluinos well above 1 TeV to not see them in the first 10 fb^{-1} .

Universal Extra Dimensions: similar constraints.

Example: Littlest Higgs model W_H, Z_H search

5σ discovery reach with 300 fb^{-1} :



Azuelos et al, [hep-ph/0402037](https://arxiv.org/abs/hep-ph/0402037)

Contours correspond to 95% CL exclusion with 50 fb^{-1} .
Need to scale down for Early-Phase exclusion limits.

More generic constraints

Higgs observation in SM mode(s) rules out overwhelming non-standard decay mode.

- $h \rightarrow aa$ in NMSSM
- $h \rightarrow$ jets (e.g., via very light sbottoms)
- Invisibly-decaying Higgs: $H \rightarrow SS$, $H \rightarrow$ Majorons, $H \rightarrow$ graviscalars, ...

5σ discovery \leftrightarrow 20% measurement of relevant rate

- Inclusive $H \rightarrow \gamma\gamma$ for 115–130 GeV [CMS]
- Inclusive $H \rightarrow ZZ$ for 130–160 and 180+ GeV
- Inclusive $H \rightarrow WW$ for 150–180 GeV
- WBF $\rightarrow H \rightarrow WW$ for 135–190 GeV [ATLAS]

Rate measurement: $\sigma \times BR$.

$BR \leq 1 \rightarrow$ lower bound on σ .

No upper bound on σ : can dial couplings to reproduce observed rates.

The “Higgs Questions”: Responsible for EWSB?

Does the new state give rise to the W , Z masses?

Tree-level HWW , HZZ couplings possible only if H carries a vev:

$$\text{SM: } \mathcal{L} = |\mathcal{D}_\mu H|^2 \longrightarrow (g^2/4)(h+v)^2 W^+ W^- + (g_Z^2/8)(h+v)^2 ZZ$$

HWW , HZZ couplings $\sim g^2 v$, times a possible group-theory coefficient from $SU(2)$ multiplets larger than doublets.

$$\mathcal{L} = |\mathcal{D}_\mu \Phi|^2 \longrightarrow (g^2/4)[2T(T+1) - Y^2/2](\phi+v)^2 W^+ W^- + (g_Z^2/8)Y^2(\phi+v)^2 ZZ$$

Constraints from ρ parameter can be evaded by monkeying around with representations and vevs. $Q = T^3 + Y/2$

$SU(2)$ doublets only: sum rule $\sum_{\phi_i} g_{\phi_i}^2 WW = g_{H_{\text{SM}}}^2 WW$
Larger multiplets: sum rule violated

Compared to SM HWW , HZZ :

- Can get enhancements from group-theory factors
- Can get suppressions by mixing angles

Constraints from early LHC data:

$WBF \rightarrow H \rightarrow WW$ for 135–190 GeV puts a lower bound on HWW coupling (from production rate – decay $BR \leq 100\%$)

Small overlap in Inclusive $H \rightarrow WW$ and Inclusive $H \rightarrow ZZ$ for 150–160 GeV: can measure ratio of rates
→ ratio of HWW and HZZ couplings-squared.

Higher mass: direct measurement of Higgs width bounds the inclusive production coupling: puts a (weak) lower bound on HZZ coupling.

$$\text{Rate} = \sigma(gg \rightarrow H)\Gamma(H \rightarrow ZZ)/\Gamma_{\text{tot}}; \quad \Gamma(H \rightarrow gg) \leq \Gamma_{\text{tot}}$$

Rates provide SM check.

But general models will not be very constrained.

The “Higgs Questions”: Responsible for fermion masses?

Tree-level fermion masses can come only from a Higgs doublet.

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

Only access to fermion couplings in early LHC data is from:

- nonobservation of fermionic decay modes
- nonobservation of associated production (e.g., bbH)
- observation of inclusive production.

Inclusive production must come from:

- gluon fusion
- $q\bar{q}$
- weak boson fusion
- associated production with W , Z , quark(s)

The latter two can be tagged.

Enhanced $q\bar{q} \rightarrow H$?

- Tevatron limits to constrain 1st-generation $q\bar{q}$ vs. gluon fusion?
- Above 130 GeV, $H \rightarrow WW, ZZ$ decays require H carries some vev: theoretically difficult to get huge enhancement of $q\bar{q}H$ coupling while maintaining tiny m_q .

Gluon fusion goes via loop of colored particles:

- quarks in SM: first window on $t\bar{t}H$
- extra contributions in BSM (e.g., squarks), constrained by direct new-particle searches

Can check ratio of Inclusive to WBF cross sections for 135–190 GeV – constrain Hgg vs. HWW couplings.

$H \rightarrow \gamma\gamma$ decay goes via loop of charged particles:

- SM: W loop dominant, t loop $\sim 30\%$
- Add possible loops of charged, color-neutral BSM particles
- Rest of amplitude is same as $gg \rightarrow H$, but with color factors replaced by charges.

Exception for loop-induced couplings: the Radion.

g_{55} in Randall-Sundrum models; mixes with the Higgs.

Couples to the trace of the stress-energy tensor T_{μ}^{μ} .

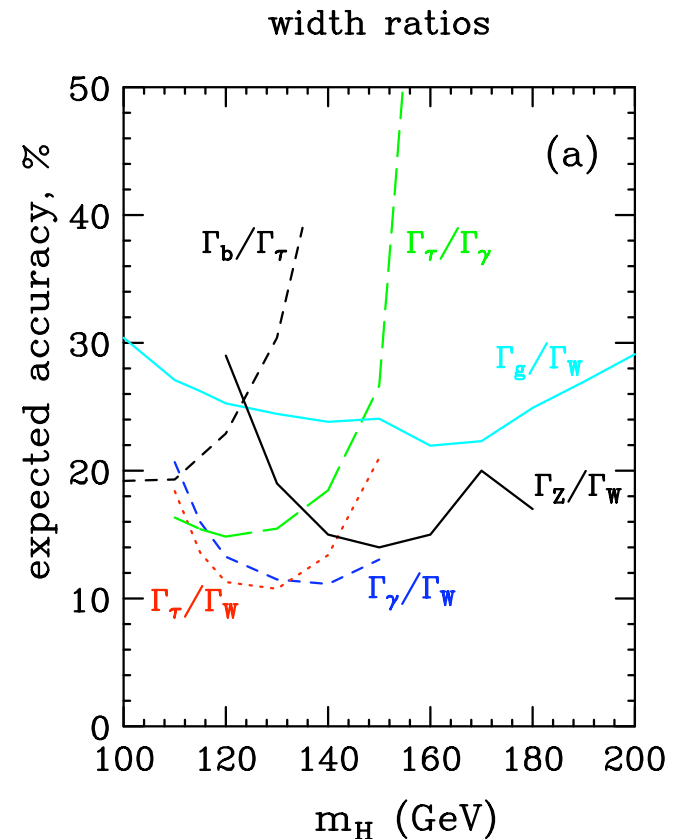
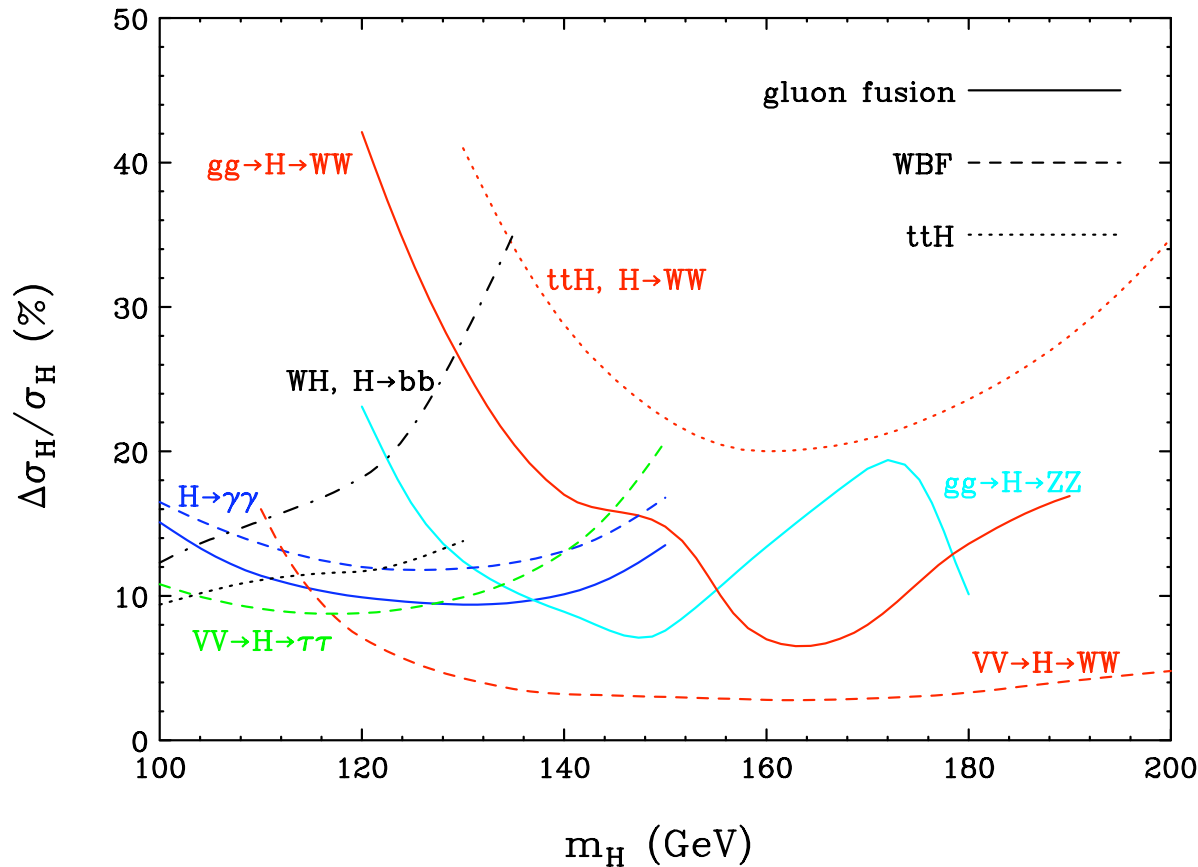
- Couples to fermions and gauge bosons the same way as the SM Higgs but with coupling strengths scaled down by $v/\sqrt{6}\Lambda_{\pi} \sim$ few percent.
- Couples to gg and $\gamma\gamma$ through the usual SM loop diagrams PLUS additional coupling through the **trace anomaly** – contributions to the coupling amplitude proportional to SU(3) and SU(2), U(1) beta-functions.

Not enough constraints in LHC Early Phase: can always tune parameters to reproduce SM rates in few observed channels.

With MORE DATA, can measure rates in more production and decay modes

Take ratios to get ratios of partial widths.

200 fb⁻¹, except 300 fb⁻¹ for $ttH, H \rightarrow bb, WH, H \rightarrow bb$

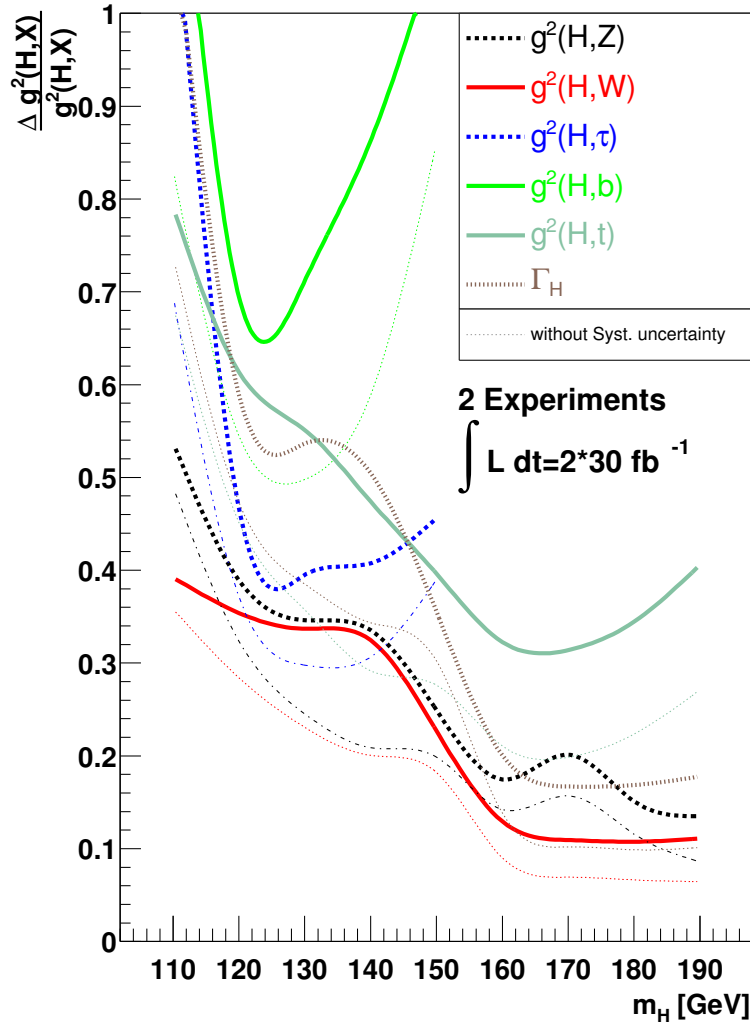


from Zeppenfeld, hep-ph/0203123

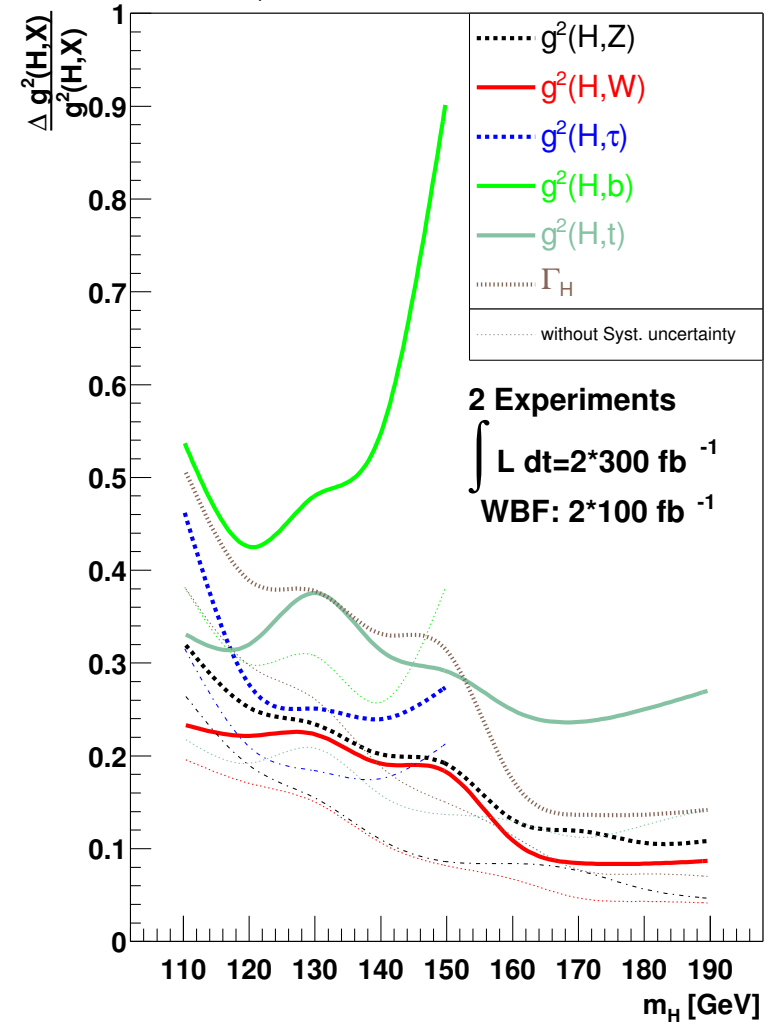
Still need a theory assumption to fit Higgs couplings-squared.

→ Assume only Higgs doublet(s) and singlet(s): $g_{\phi VV}^2 \leq g_{H_{SM} VV}^2$

30 fb⁻¹ × 2 detectors



300/100 fb⁻¹ × 2 detectors



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

For high-precision, model-independent Higgs coupling measurements, need ILC.

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).

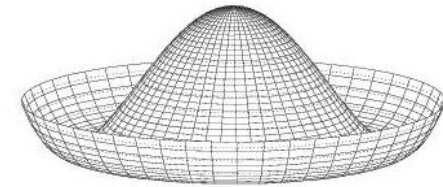
Mass(GeV)	120	140	160	180	200	220	240	280	320
Decay	Relative Precision (%)								
bb	2.4 (a) / 1.9 (e)	2.6 (a)	6.5 (a)	12.0 (d)	17.0 (d)	28.0 (d)			
$c\bar{c}$	8.3 (a) / 8.1 (e)	19.0 (a)							
$\tau\tau$	5.0 (a) / 7.1 (e)	8.0 (a)							
$\mu\mu$	30. (d)								
gg	5.5 (a) / 4.8 (e)	14.0 (a)							
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 γ		27.0 (c)							

review talk by K. Desch, [hep-ph/0311092](https://arxiv.org/abs/hep-ph/0311092)

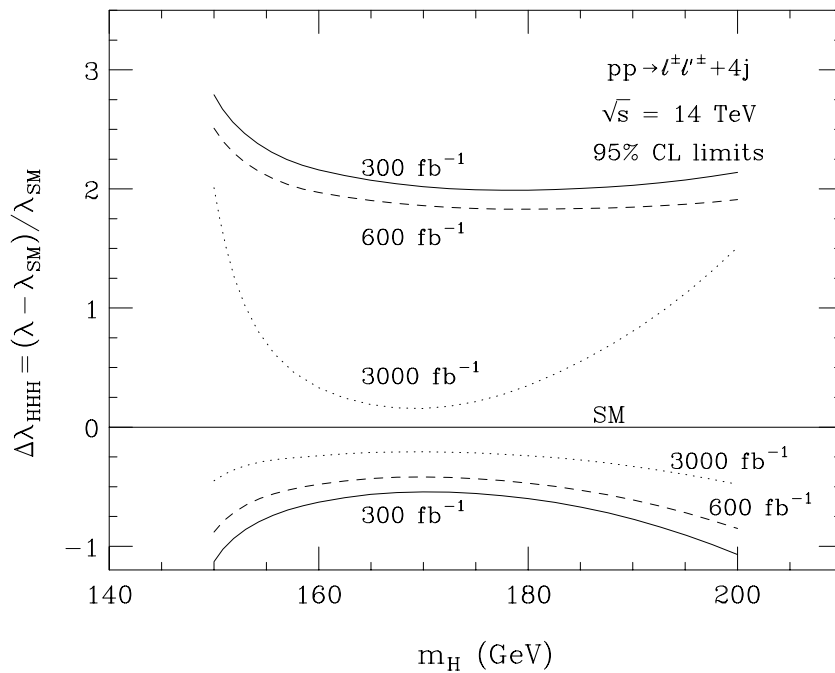
	Higgs Mass (GeV)				
	115	120	140	160	200
$\Delta(\sigma \cdot B_{bb})/(\sigma \cdot B_{bb})$	± 0.003	± 0.004	± 0.005	± 0.018	± 0.090
$\Delta(\sigma \cdot B_{WW})/(\sigma \cdot B_{WW})$	± 0.021	± 0.013	± 0.005	± 0.004	± 0.005
$\Delta(\sigma \cdot B_{gg})/(\sigma \cdot B_{gg})$	± 0.014	± 0.015	± 0.025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

1000 GeV, 1000 fb^{-1} , $-80\% e^- \text{ pol}$, $+50\% e^+ \text{ pol}$ from Barklow, [hep-ph/0312268](https://arxiv.org/abs/hep-ph/0312268)

Structure of the Higgs potential: Triple-Higgs coupling



$gg \rightarrow HH \rightarrow WWWW$ at LHC



Baur, Plehn, Rainwater, hep-ph/0211224

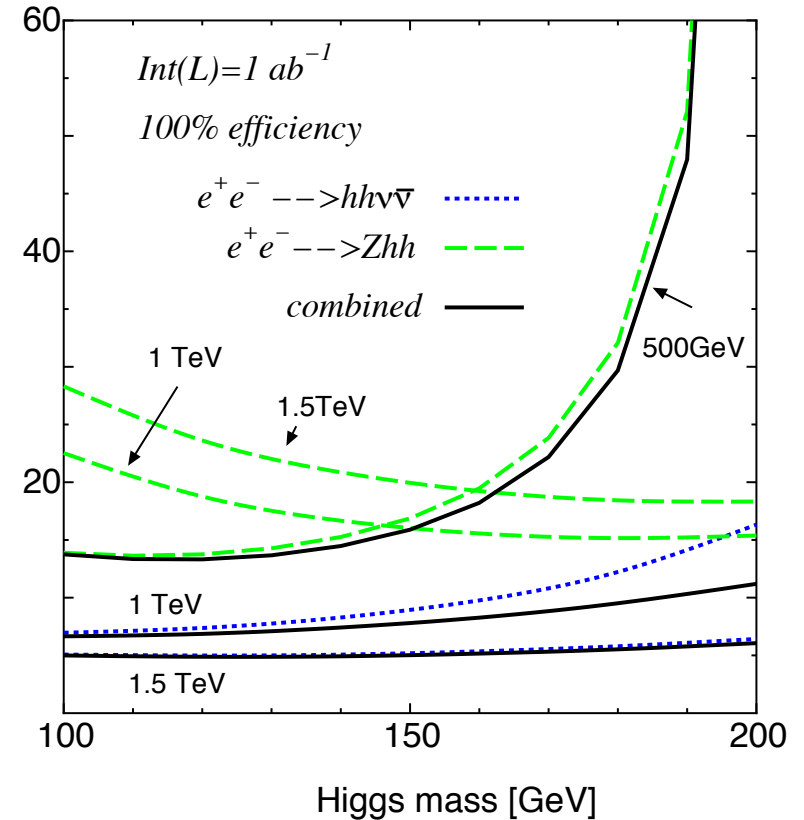
+100%
-30% w/ 300 fb^{-1}

Heather Logan

Higgs Theory

$\delta\lambda_3/\lambda_3$ [%]

Higgs self coupling sensitivity



Snowmass '05 Higgs WG, hep-ph/0511332

~ 15% → 7% → 5%

w/ 500 → 1000 → 1500 GeV

The LHC Early Phase for the ILC 2007-04-12

Questions: The LHC Early Phase for the ILC

Impact of early LHC results on choice of ultimate ILC energy range / upgrade path?

Any issues that need to be implemented in machine/detector design from the start?

Could there be cases that would change the consensus about the 500 GeV ILC physics case?

What are the prospects for LHC/ILC interplay based on early LHC data?

This scenario: Good case for studying the (discovered!) Higgs

$M_H \lesssim 180$ GeV: Standard 350–500 GeV ILC plan is ideal!

$M_H \sim 180$ –250 GeV: Standard ILC plan is good.
Need more studies of what ILC can do in such a scenario.

Heavier SM-like Higgs: Inconsistent with SM EW precision fit!
Signal for BSM. But need to consider our ILC options.

If we discover a 500 GeV SM-like Higgs and no other new physics in the LHC Early Phase, do we:

- go straight for a 1 TeV ILC to study the Higgs?
- build GigaZ first to study EW precision (and maybe follow with the $t\bar{t}$ threshold and W pair production)?
- wait for more LHC data before making a decision on ILC?

LHC data is coming very soon!

Let's go beyond the standard scenarios and consider implications for ILC plans.