What if the LHC finds only a Higgs?

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Vancouver Linear Collider Workshop 2006

The "Nightmare Scenario":

The Washington Post

An Anthem's Discordant Notes

Spanish Version of 'Star-Spangled Banner' Draws Strong Reactions

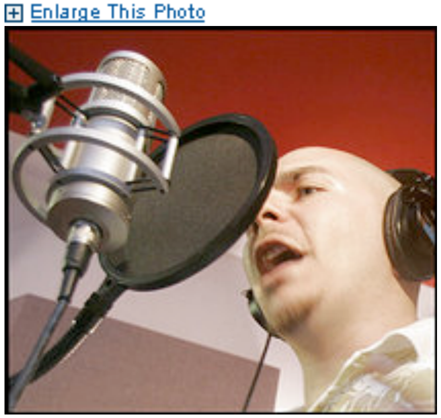
By David Montgomery
Washington Post Staff Writer
Friday, April 28, 2006; Page A01

Oh say can you see -- *a la luz de la aurora?*

The national anthem that once endured the radical transformation administered by Jimi Hendrix's fuzzed and frantic Stratocaster now faces an artistic dare at least as extreme: translation into Spanish.

The new take is scheduled to hit the airwaves today. It's called "Nuestro Himno" -- "Our Anthem" -- and it was recorded over the past week by Latin pop stars including Ivy Queen, Gloria Trevi, Carlos Ponce, Tito "El Bambino," Olga Tañon and the group

Enlarge This Photo



Pitbull, among the artists on the song. (By Wilfredo Lee -- Associated Press)

While critics sketch a nightmare scenario of a Canada-like land with an anthem sung in two languages, immigrant rights advocates say they agree learning English is essential. Studies of immigrant families suggest the process is inevitable: Eighty-two percent

The "Nightmare Scenario":

Tom LeCompte's version [Argonne Workshop on Collider Physics, May 2006]:

Why Are We Doing This Anyway?

- Find the Higgs
  - This will take years, unless both the following are true:
    - *We are lucky*
    - *Nature is kind*
  - A single scalar Higgs and nothing else would be a disaster
    - *Progress is made by having disagreements between expectations and measurements*
- Search for SUSY
  - No SUSY would irritate Carlos, which would have certain positive "quality of life" issues for me.
  - The party line is "Just look at the inclusive missing E_T distribution; you can't miss it" and occasionally, "The background to SUSY is SUSY"
- Some other surprise

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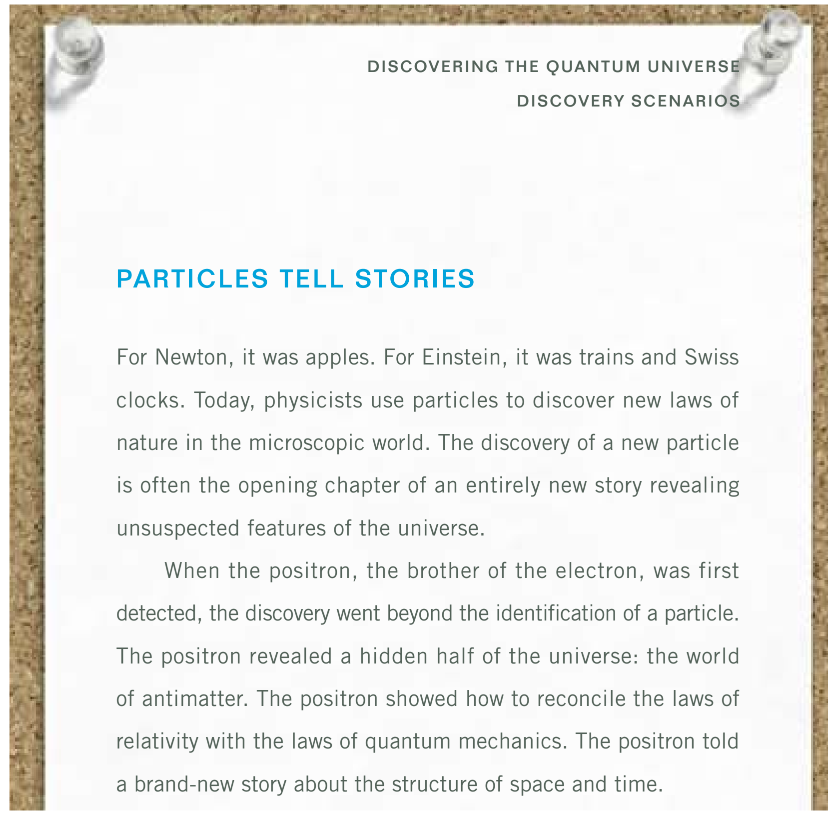
Why is it a nightmare scenario?

Reason #1:

Because “particles tell stories”.

We don’t just want to find the Higgs to fill in a few more numbers in the Particle Data Book.

We want to understand its story – the story that explains electroweak symmetry breaking and the hierarchy.


DISCOVERING THE QUANTUM UNIVERSE
DISCOVERY SCENARIOS

PARTICLES TELL STORIES

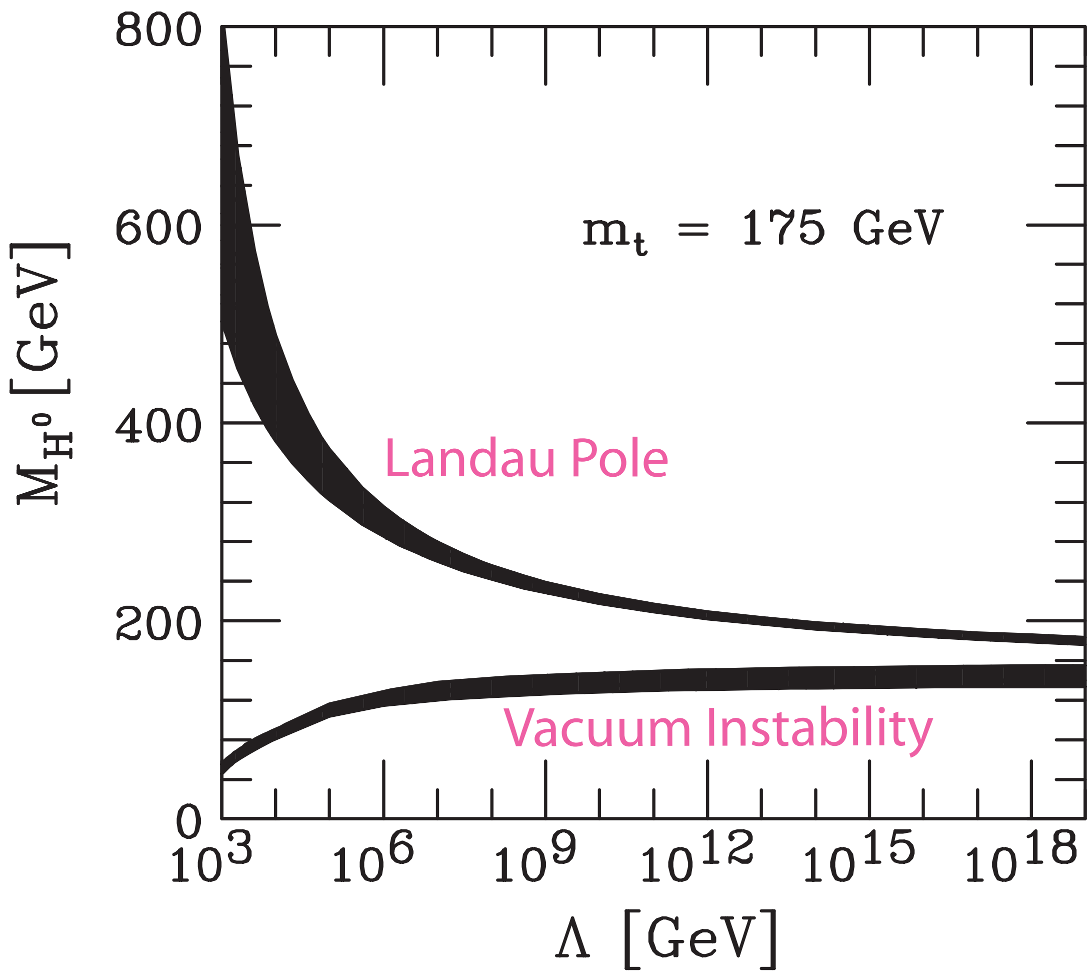
For Newton, it was apples. For Einstein, it was trains and Swiss clocks. Today, physicists use particles to discover new laws of nature in the microscopic world. The discovery of a new particle is often the opening chapter of an entirely new story revealing unsuspected features of the universe.

When the positron, the brother of the electron, was first detected, the discovery went beyond the identification of a particle. The positron revealed a hidden half of the universe: the world of antimatter. The positron showed how to reconcile the laws of relativity with the laws of quantum mechanics. The positron told a brand-new story about the structure of space and time.

Reason #2:

Can we get an ILC built with only the SM and a Higgs to study? This is a matter of politics...

The familiar picture:



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]

Real nightmare is a SM-like Higgs with mass ∼ 140–180 GeV.

SM Higgs sector is perturbative and stable (but terribly fine-tuned) all the way up to the Planck scale.

Is the familiar picture really correct?

Landau Pole:

Conventional wisdom holds that $\lambda\phi^4$ theory is trivial.

that is, λ runs down toward zero as the cutoff is taken to infinity.

This is supported by renormalization group eqns and nonperturbative finite-cutoff boundary conditions, but there is currently no rigorous proof (!).

Some recent discussion in lattice community about possible lattice discrepancies from RG predictions, but it seems inconclusive so far. $\longrightarrow$ Standard picture looks ok.

see e.g. Cea et al, hep-lat/0501013; Balog et al, hep-lat/0601016

Vacuum Instability:

Recent lattice and nonperturbative results $\rightarrow$ $V_{\rm eff}$ is always stable!

see e.g. Holland, hep-lat/0409112; Branchina & Faivre, hep-th/0503188

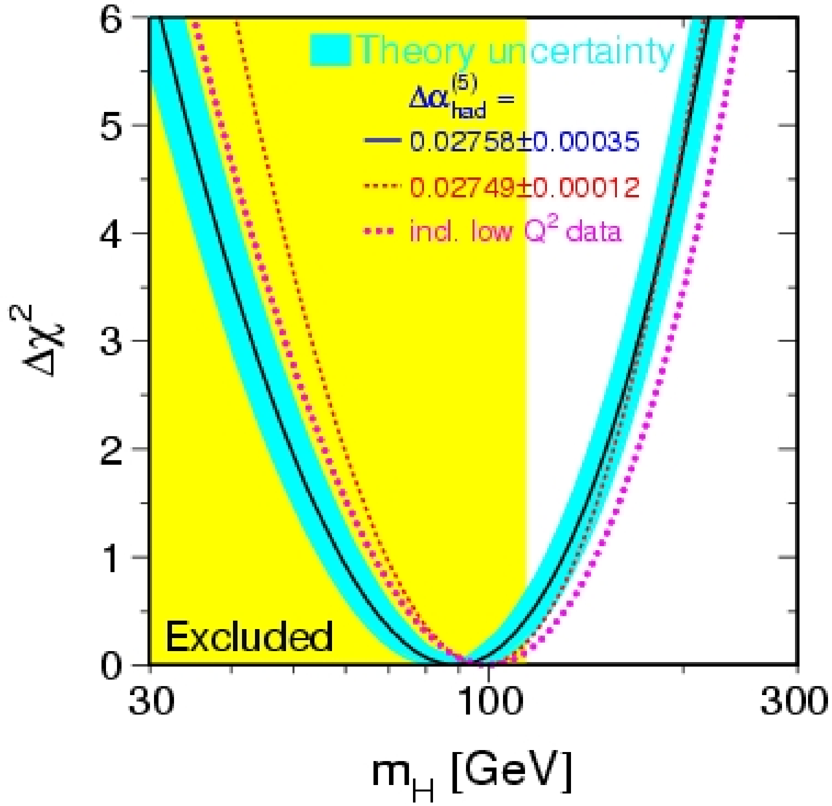
Lower bound on m_H comes from requiring bare $\lambda \geq 0$ at cutoff scale Λ [so that effective theory is valid].

Lower bound on m_H basically the same for large Λ:

$m_H \gtrsim 140$ GeV for $\Lambda \rightarrow M_{\rm Pl}$.

Lower bound ~ 10 GeV higher than old "vacuum instability" bound for $\Lambda \sim$ TeV.

To add to the misery, a Higgs mass in this range agrees nicely with expectations from precision electroweak data.



March 2006 update from LEP EWWG

One-sided 95% CL upper limit on m_H:

$m_H \leq 175$ GeV
(without LEP direct-search limit)

Renormalize probability for $m_H > 114$ GeV to 100%:

$m_H \leq 207$ GeV

No clues; SM looks totally consistent.

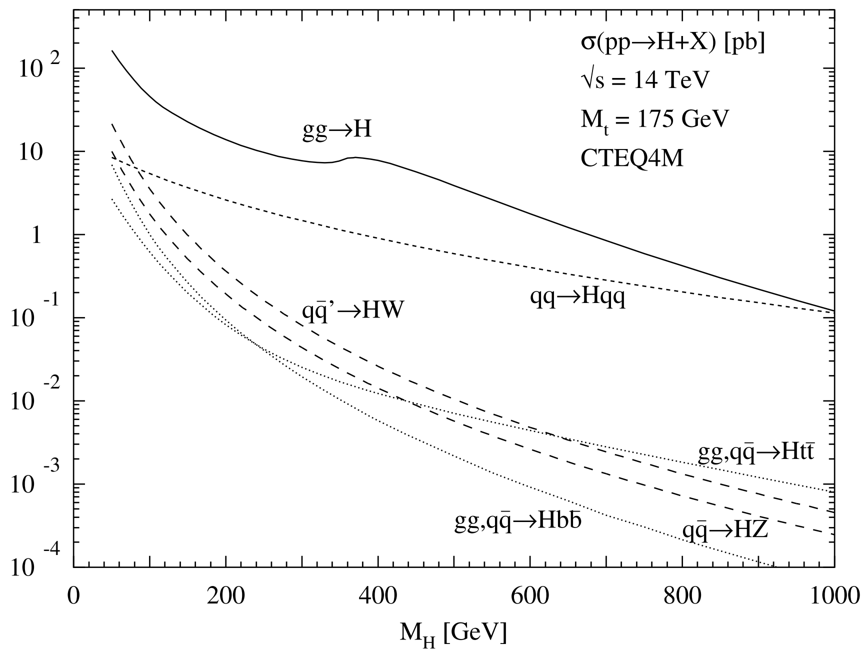
This particle has no story to tell! ;_;

What can we do if the nightmare comes true?

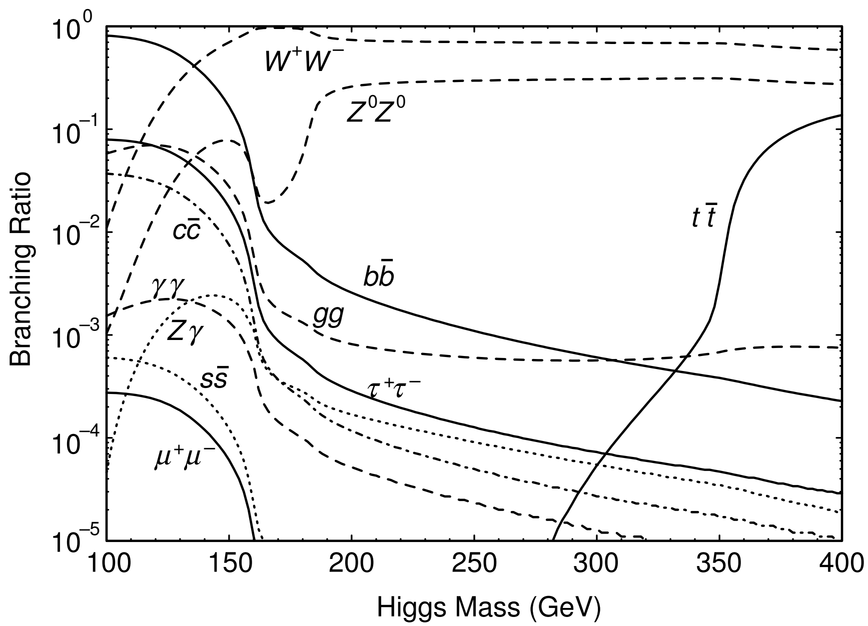
Measure everything we can at the LHC:
How Standard-Model–like is our Higgs?

Standard Model predictions depend only on m_H:

Production at LHC

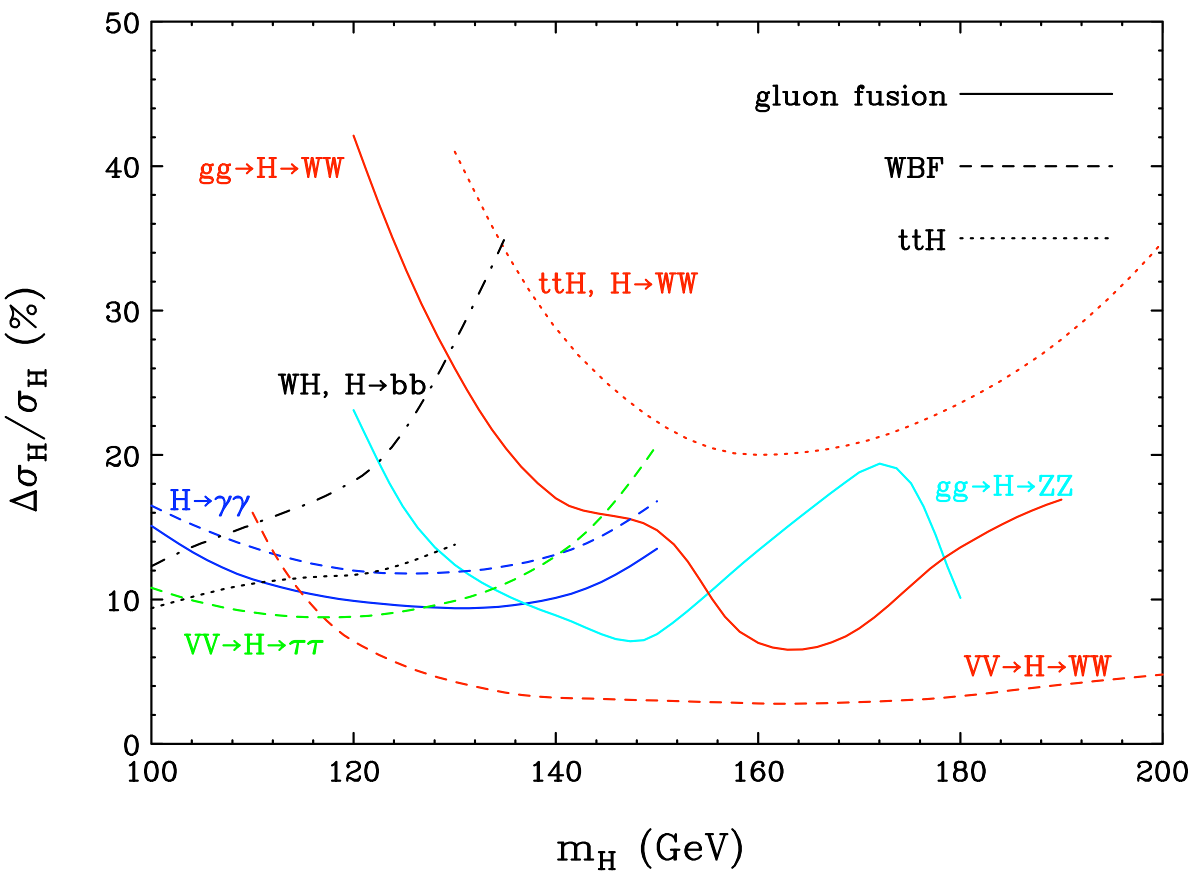


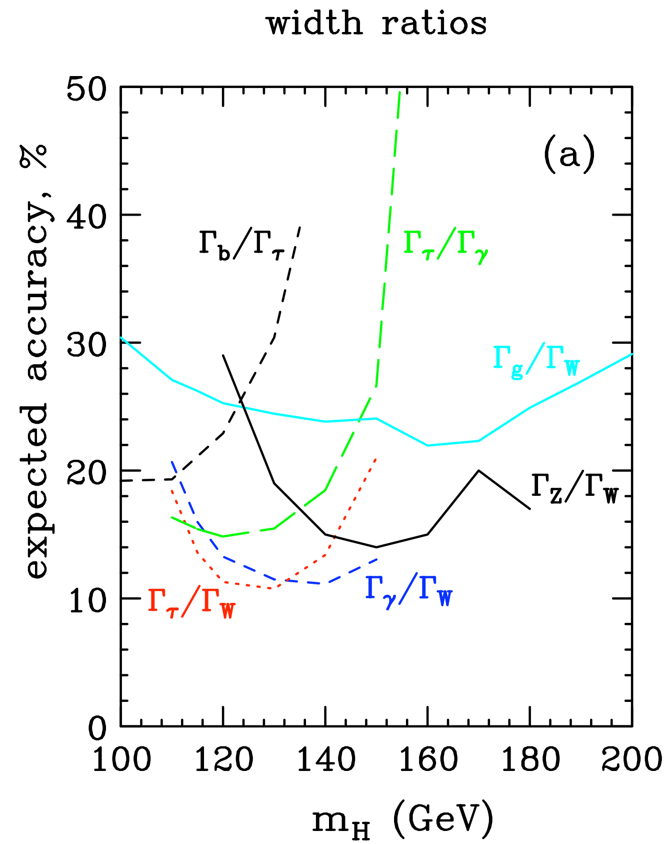
Decay



Measure Higgs production times decay rates;

take ratios to get ratios of partial widths.



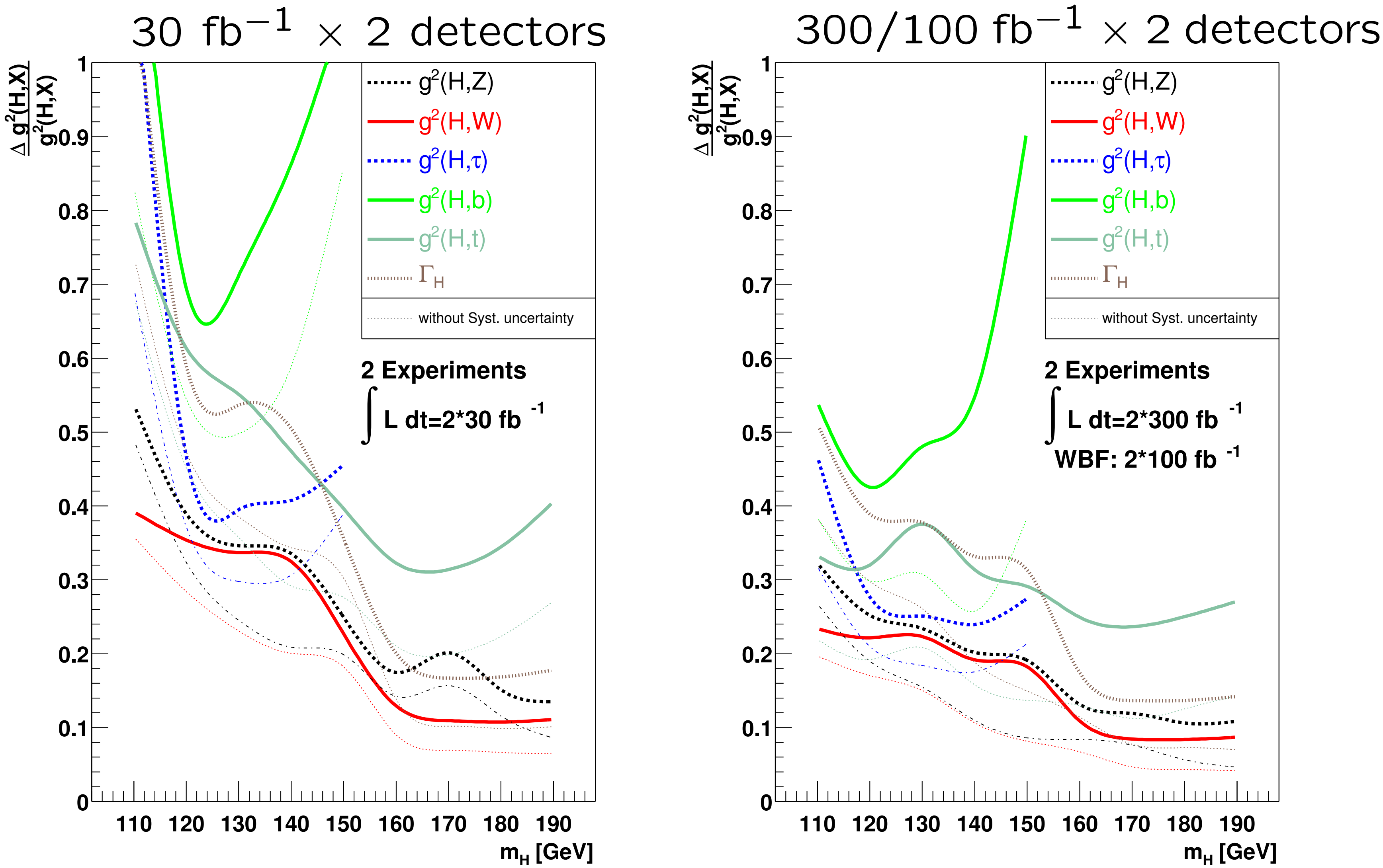


LHC, 200 fb^{-1} (except 300 fb^{-1} for $ttH, H \to bb$, $WH, H \to bb$)

from Zeppenfeld, hep-ph/0203123

Add a theory assumption: only Higgs doublet(s) and singlet(s)

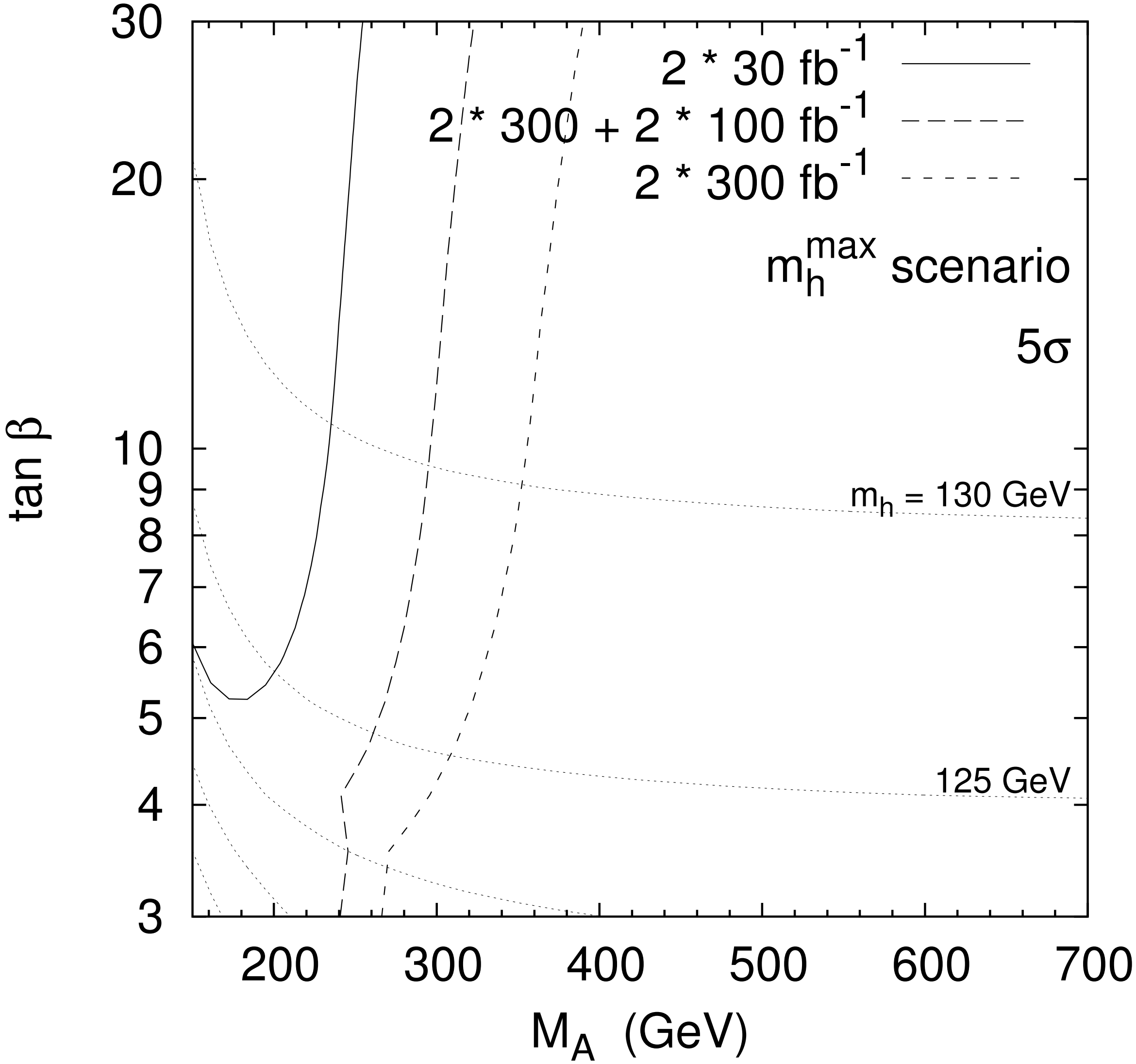
→ fit of Higgs couplings-squared from LHC data



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

Look for deviations from the Standard Model Higgs rates

Example: MSSM, $m_h^{\max}$ scenario

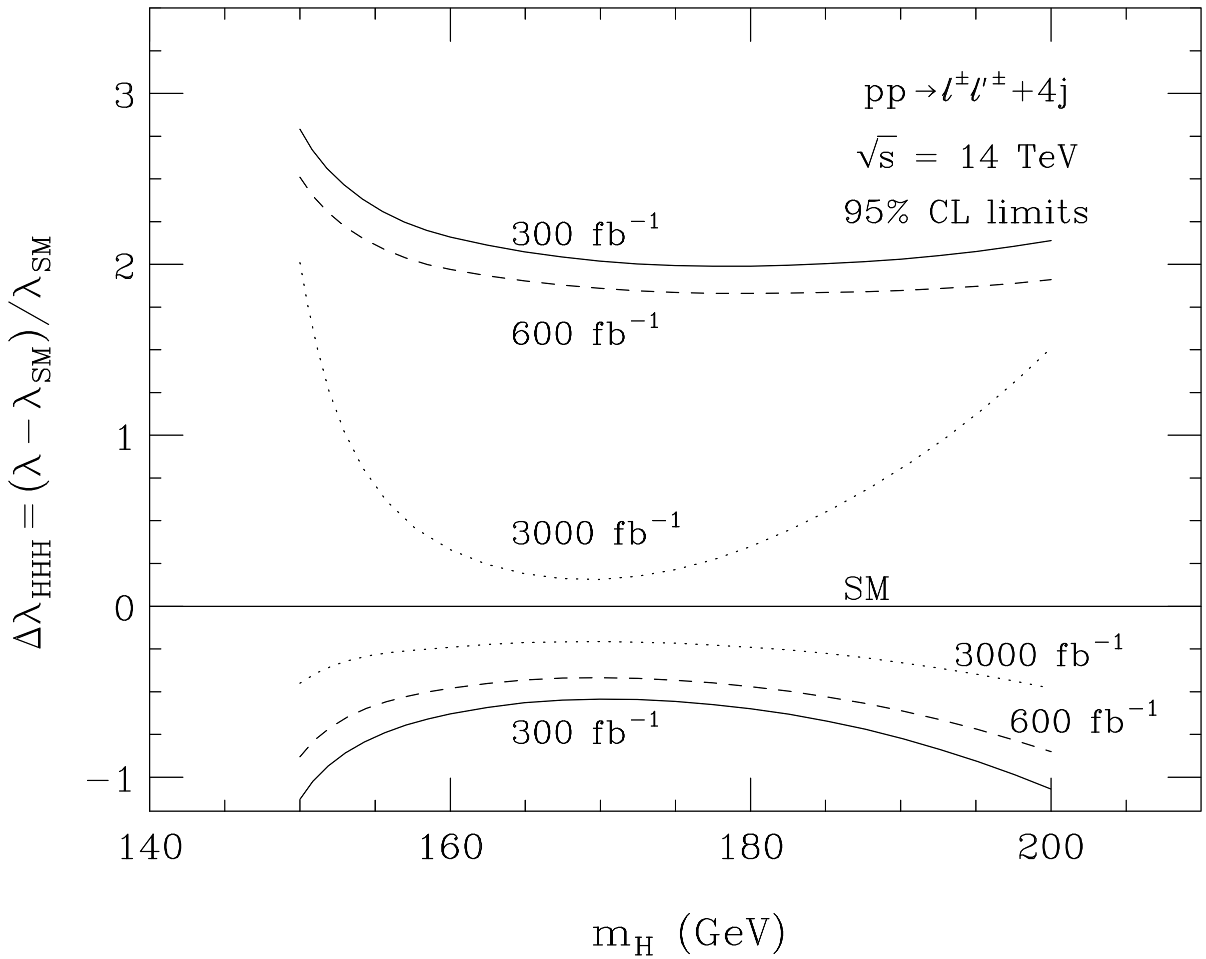


LHC sensitive to MSSM nature of h up to $m_A \lesssim 300$ GeV

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

Triple-Higgs coupling:

Use $gg \to HH \to WWWW$ process at LHC.



Determine λ_{hhh} to -30% to $+100\%$ (1σ) with 300 fb^{-1}

from Baur, Plehn & Rainwater, hep-ph/0211224

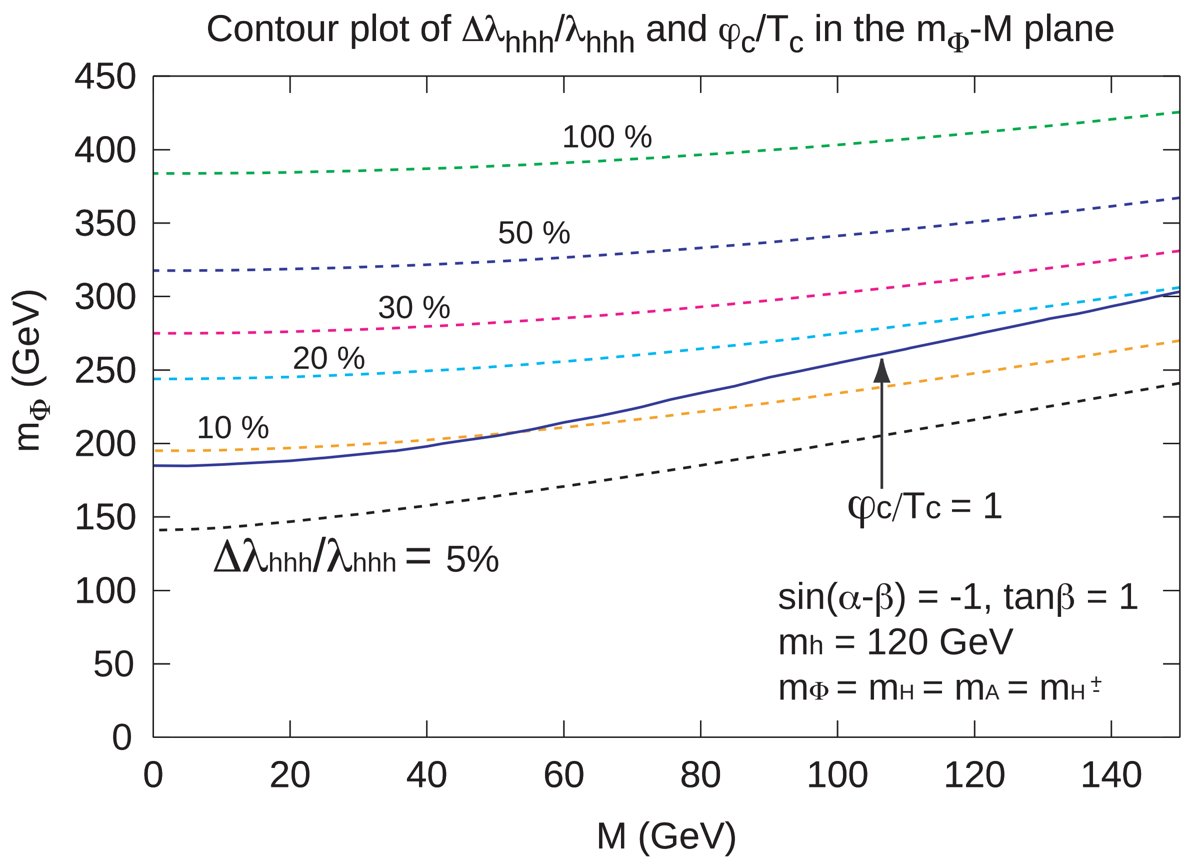
$gg \to HH \to b\bar{b}\gamma\gamma$ for $m_H \sim 120$ GeV – somewhat worse precision

Baur, Plehn & Rainwater, hep-ph/0310056

Triple-Higgs coupling could reveal electroweak baryogenesis

New scalars $\longrightarrow$ modification of effective potential to get strong enough phase transition

$\longrightarrow$ also modifies triple-Higgs coupling!



Two-Higgs-doublet model:

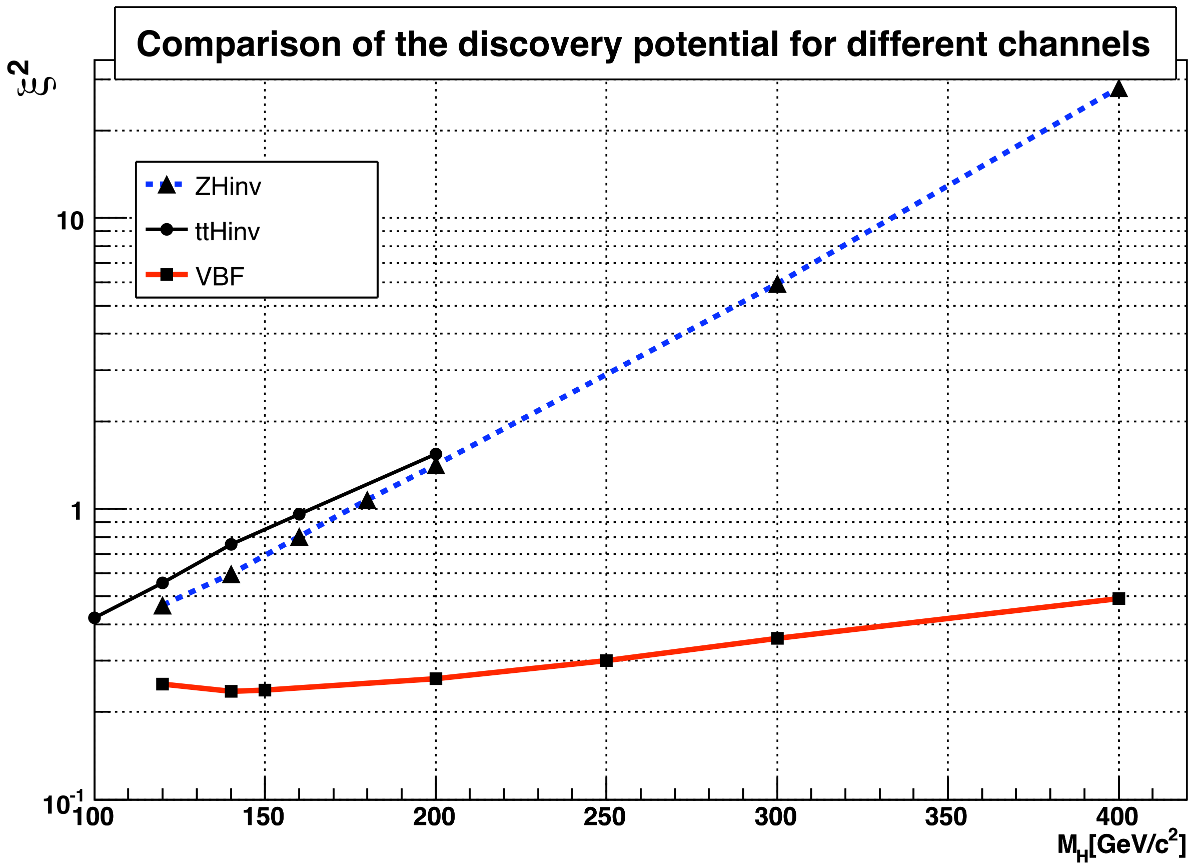
$\gtrsim$ 10% shift of triple-Higgs coupling

(LHC: would have to get lucky.)

from Kanemura, Okada & Senaha, hep-ph/0411354

Likewise MSSM: $\gtrsim$ 6% shift of λ_{hhh} from top-squark loops

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

Limits on exotic visible decay modes: e.g., $H \to \mu\mu$

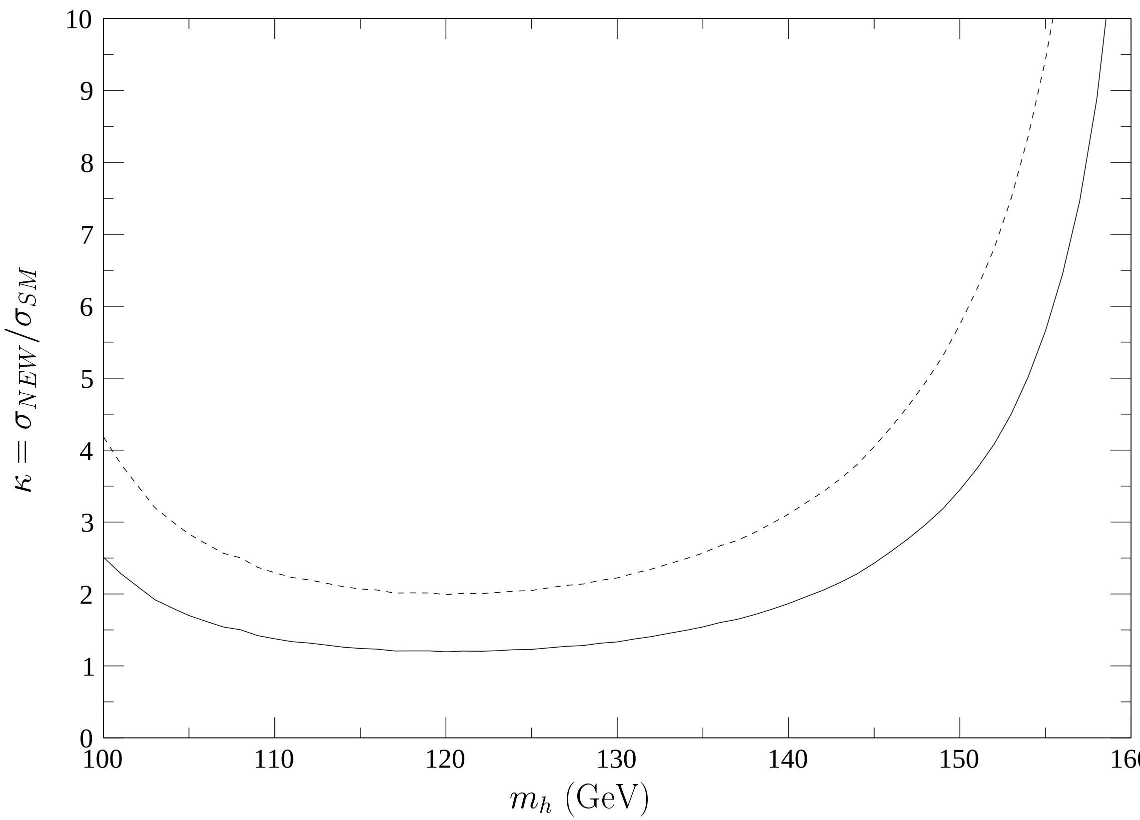
Do small fermion masses come from higher-dim operators?

$$\mathcal{L} = y \left(\frac{H^\dagger H}{\Lambda^2} \right)^n L H \mu_R \qquad \to \qquad y_\mu^{\text{eff}} = (2n+1) m_\mu / v$$

$gg \to H \to \mu\mu$

Scaling factor on SM rate to see 3σ, 5σ signal

Can probe $n = 1$!



Higgs mass [GeV]

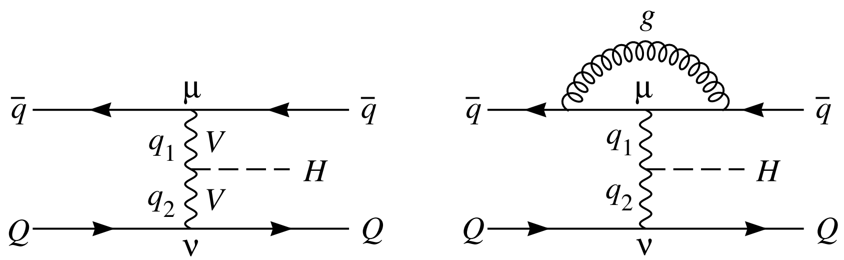
from Han & McElrath, hep-ph/0201023

Similar reach from VBF $\to H \to \mu\mu$ – Cranmer & Plehn, hep-ph/0605268

Tensor structure of the HVV coupling

Slide from D. Zeppenfeld, plenary talk at SUSY'06 conference

Most general HVV vertex $T^{\mu\nu}(q_1, q_2)$



(a) (b)

$$T^{\mu\nu} = a_1\, g^{\mu\nu} + a_2\, (q_1 \cdot q_2\, g^{\mu\nu} - q_1^\nu q_2^\mu) + a_3\, \varepsilon^{\mu\nu\rho\sigma}\, q_{1\rho} q_{2\sigma}$$

The $a_i = a_i(q_1, q_2)$ are scalar form factors

Physical interpretation of terms:

SM Higgs $\mathcal{L}_I \sim HV_\mu V^\mu \longrightarrow a_1$

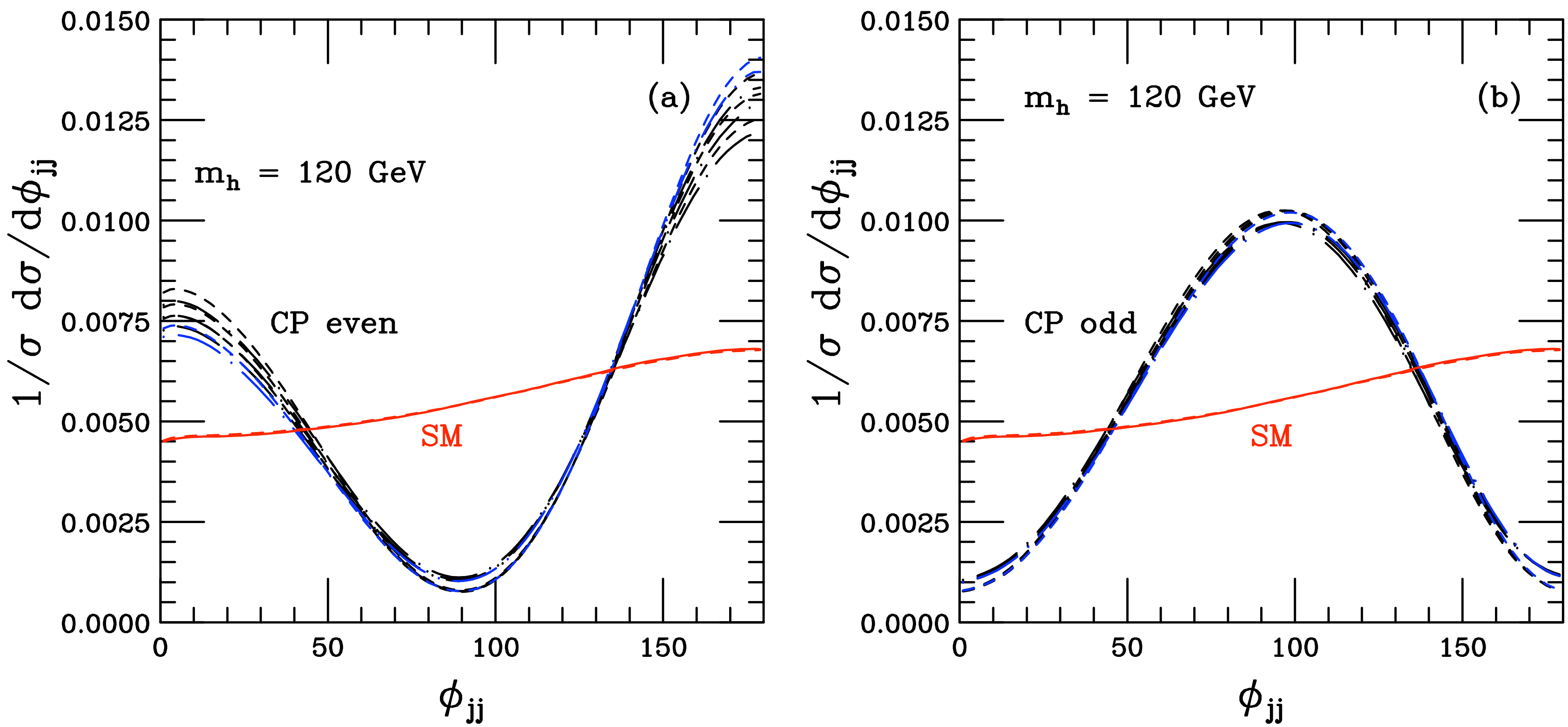
loop induced couplings for neutral scalar

CP even $\mathcal{L}_{eff} \sim HV_{\mu\nu} V^{\mu\nu} \longrightarrow a_2$

CP odd $\mathcal{L}_{eff} \sim HV_{\mu\nu} \tilde{V}^{\mu\nu} \longrightarrow a_3$

Must distinguish a_1, a_2, a_3 experimentally

Tell-tale signal for non-SM coupling is azimuthal angle between tagging jets



Dip structure at 90° (CP even) or 0/180° (CP odd) only depends on tensor structure of HVV vertex. Very little dependence on form factor, LO vs. NLO, Higgs mass etc.

[Figy & Zeppenfeld, hep-ph/0403297]

Dashed lines include LO vs NLO and formfactor effects for LHC

This is great if the HVV vertex is completely nonstandard!

... and just happens to give us the SM rates ...

But it doesn't help us much for a SM Higgs with a CP-odd admixture:

- SM $HV_\mu V^\mu$ coupling is tree-level

- CP-odd $HV_{\mu\nu}\widetilde{V}^{\mu\nu}$ coupling is loop-induced: gives only a tiny contribution to VBF rate.

Ideally, want to look at a process where the SM and CP-odd parts would come in at the same level, like Hgg or $H\gamma\gamma$ [both are loop induced]...

Tensor structure of the Hgg coupling (!) at LHC

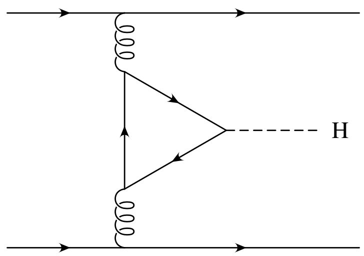
Slide from D. Zeppenfeld, plenary talk at SUSY'06 conference

Effective Hgg vertex is induced via top-quark loop

$$\text{CP}-\text{even}: \quad i\frac{m_t}{v} \quad \rightarrow \quad H\, G^a_{\mu\nu} G^{\mu\nu,a} \text{ coupling}$$

$$\text{CP}-\text{odd}: \quad \frac{m_t}{v}\gamma_5 \quad \rightarrow \quad H\, G^a_{\mu\nu} \tilde{G}^{\mu\nu,a} \text{ coupling}$$

Consider Hjj production via gluon fusion, e.g.



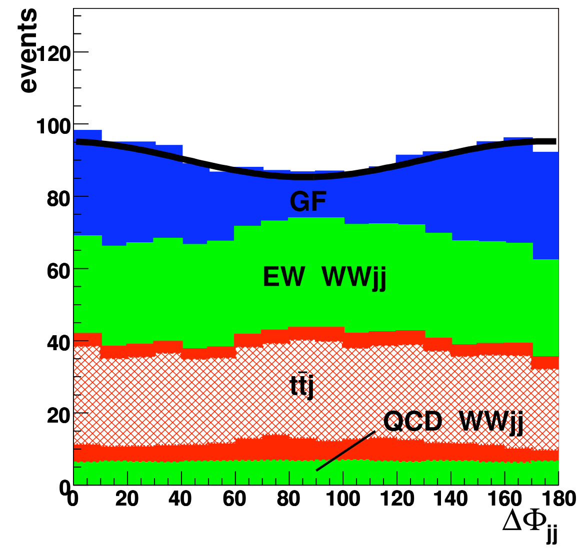
(a)

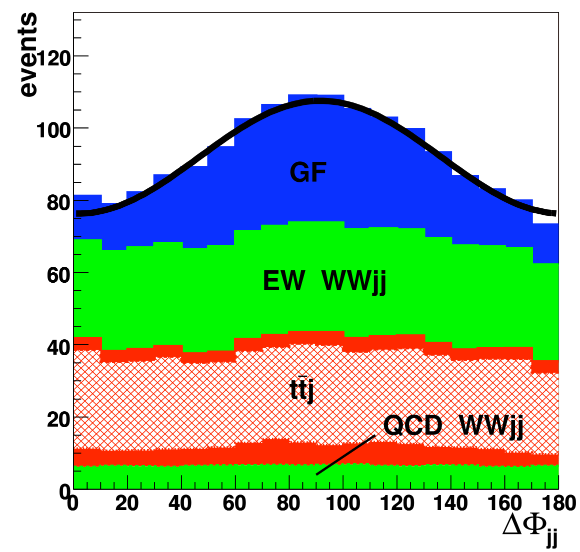
Parton level analysis with relevant backgrounds

(Hankele, Klämke, DZ, hep-ph/0605117)

$\Longrightarrow$ Difference visible in Hjj, $H \rightarrow WW \rightarrow l^+ l^- \not{p}_T$ events at $m_H \approx 160$ GeV with 30 fb^{-1} at 6σ level

Method can be generalized for any Higgs mass. Problem is lower signal rate for $h \rightarrow \tau\tau$ or $h \rightarrow \gamma\gamma$

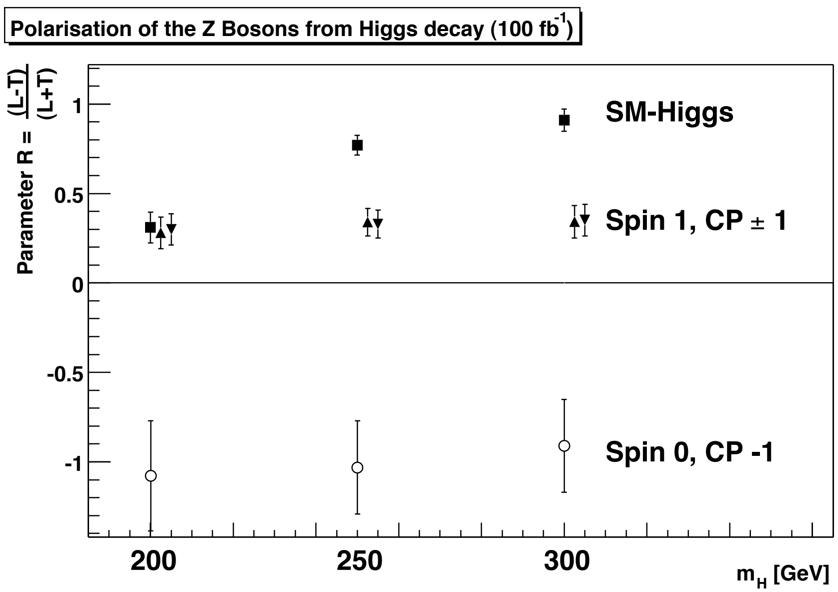




Spin and CP of the Higgs at LHC

$H \to ZZ \to 4\ell$: study angular correlations of the 4 leptons

Sensitive to longitudinal/transverse polarization of the Z bosons

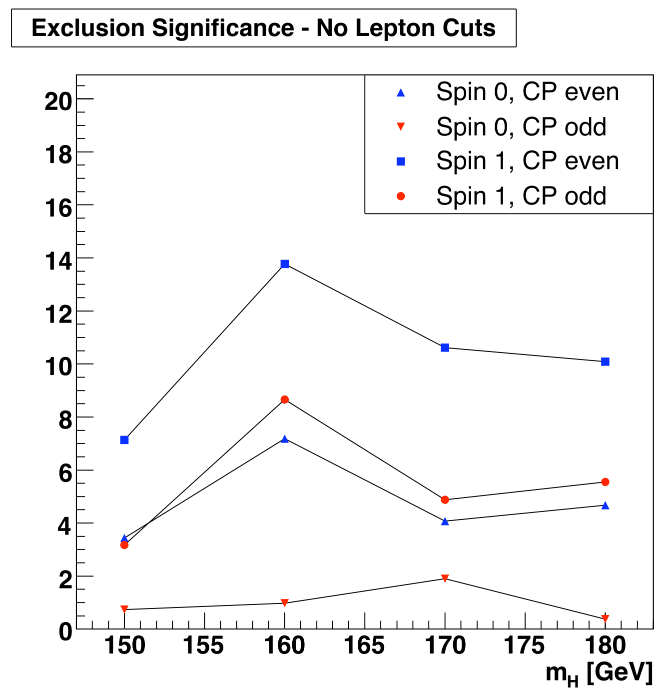


from Buszello, Fleck, Marquard & van der Bij, hep-ph/0212396

Works at higher Higgs masses

VBF $qqH \to qqWW \to qq\ell\nu\ell\nu$: Study angle between two forward jets and invar. mass of 2 leptons

Sensitive to structure of HWW vertices



30 fb^{-1}

from Buszello & Marquard, hep-ph/0603209

Works at lower Higgs masses

We've had the nightmare; now let's dream a little...

The ILC will be fantastic for Higgs measurements!

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 (%)								
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)								
$Z\gamma$		27.0 (c)							

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

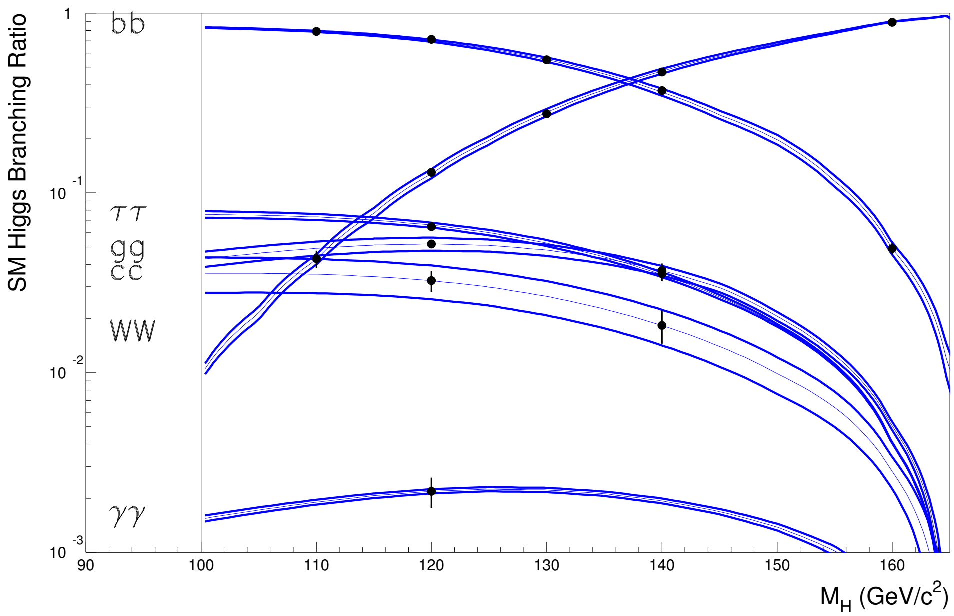
With a 1 TeV ILC one does even better (statistics):

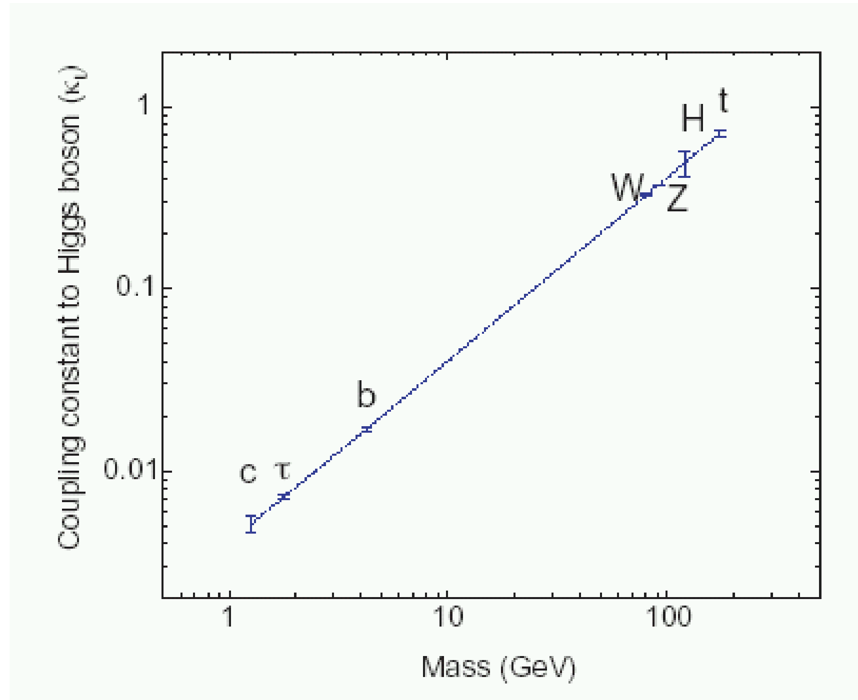
	Higgs Mass (GeV)				
	115	120	140	160	200
$\Delta(\sigma \cdot B_{bb})/(\sigma \cdot B_{bb})$	± 0.003	± 0.004	± 0.005	± 0.018	± 0.090
$\Delta(\sigma \cdot B_{WW})/(\sigma \cdot B_{WW})$	± 0.021	± 0.013	± 0.005	± 0.004	± 0.005
$\Delta(\sigma \cdot B_{gg})/(\sigma \cdot B_{gg})$	± 0.014	± 0.015	± 0.025	± 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-1000, 1 ab^{-1}, -80% e^- pol, $+50\%$ e^+ pol

Check for deviations from the Standard Model predictions:



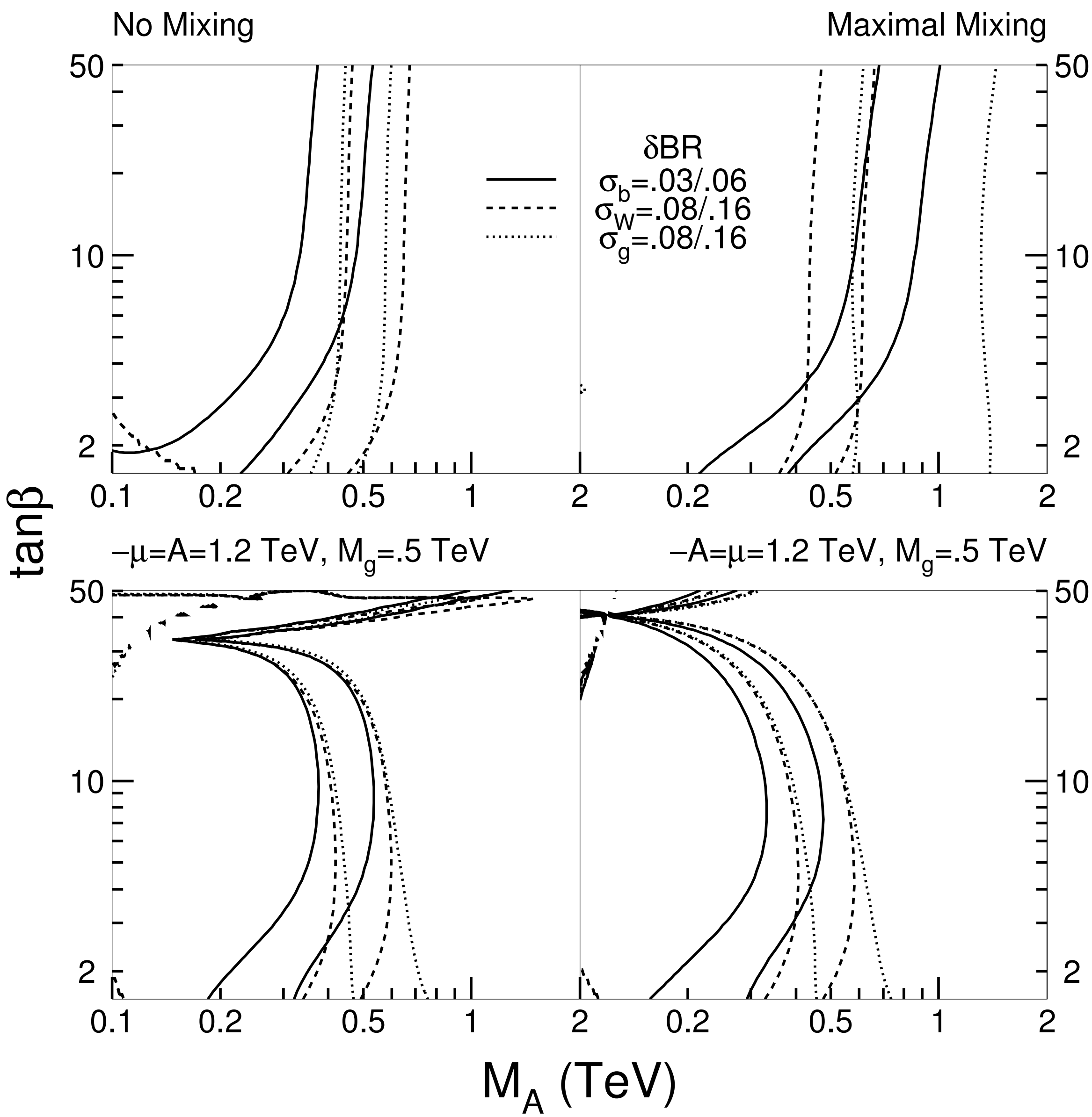


Battaglia & Desch, hep-ph/0101165

ACFA WG

ILC measurements are model-independent!

Constrain non-SM possibilities with ILC precision:



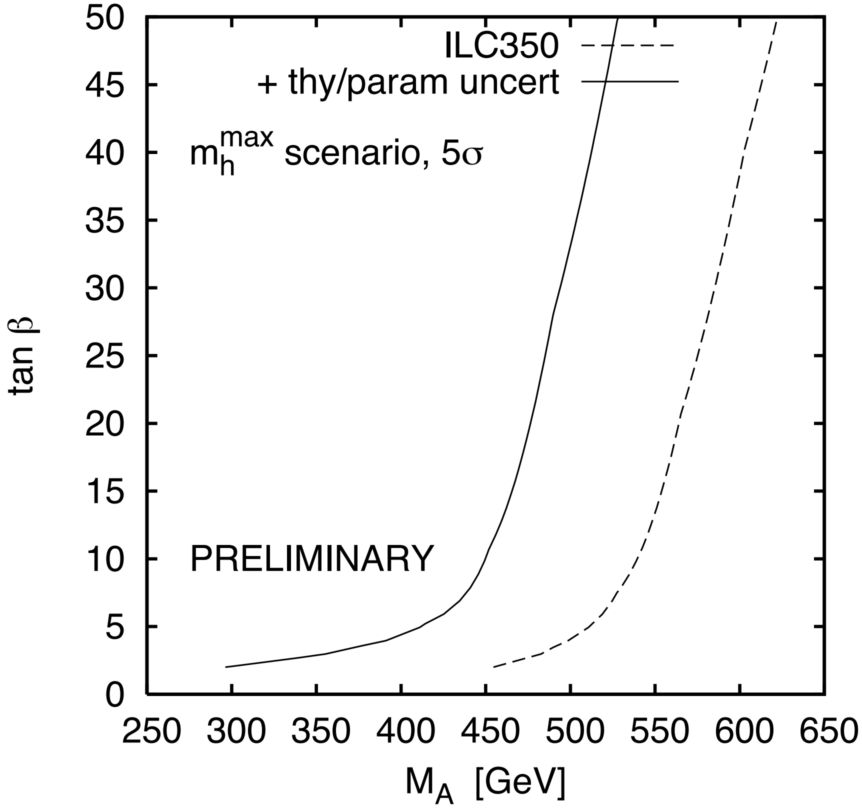
Example:
MSSM benchmark scenarios

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

Carena, Haber, H.L., Mrenna, hep-ph/0106116

ILC precision is so good that theory uncertainties start to matter!

"Distinguishing power" of SM Higgs vs MSSM h



ILC-350, 500 fb^{-1}

Parametric uncertainties

$\overline{m_b}(M_b) = 4.17 \pm 0.05$ GeV (1.2%)
$\alpha_s(M_Z) = 0.1185 \pm 0.002$ (1.7%)
$\overline{m_c}(M_c) = 1.23 \pm 0.09$ GeV (7.3%)

Theoretical uncertainties

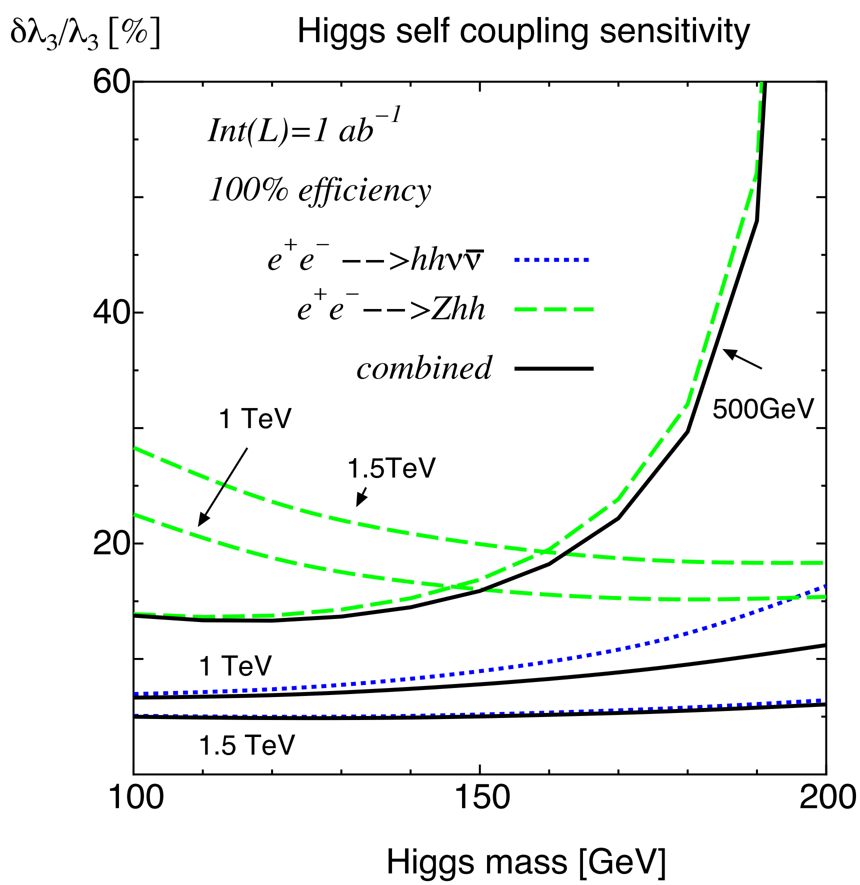
$\Gamma_{b\bar{b}}, \Gamma_{c\bar{c}} \sim 1\%$
$\Gamma_{gg} \sim 3\%$ N^{3}LO hep-ph/0604194

A. Droll & H.L. preliminary!

"Reach" in M_A: $\Delta\chi^2 = (5)^2$ away from SM

500–600 GeV with experimental uncertainties only
400–500 GeV including parametric & theory uncertainties
compare LHC 250–300 GeV

Measure the triple-Higgs coupling:



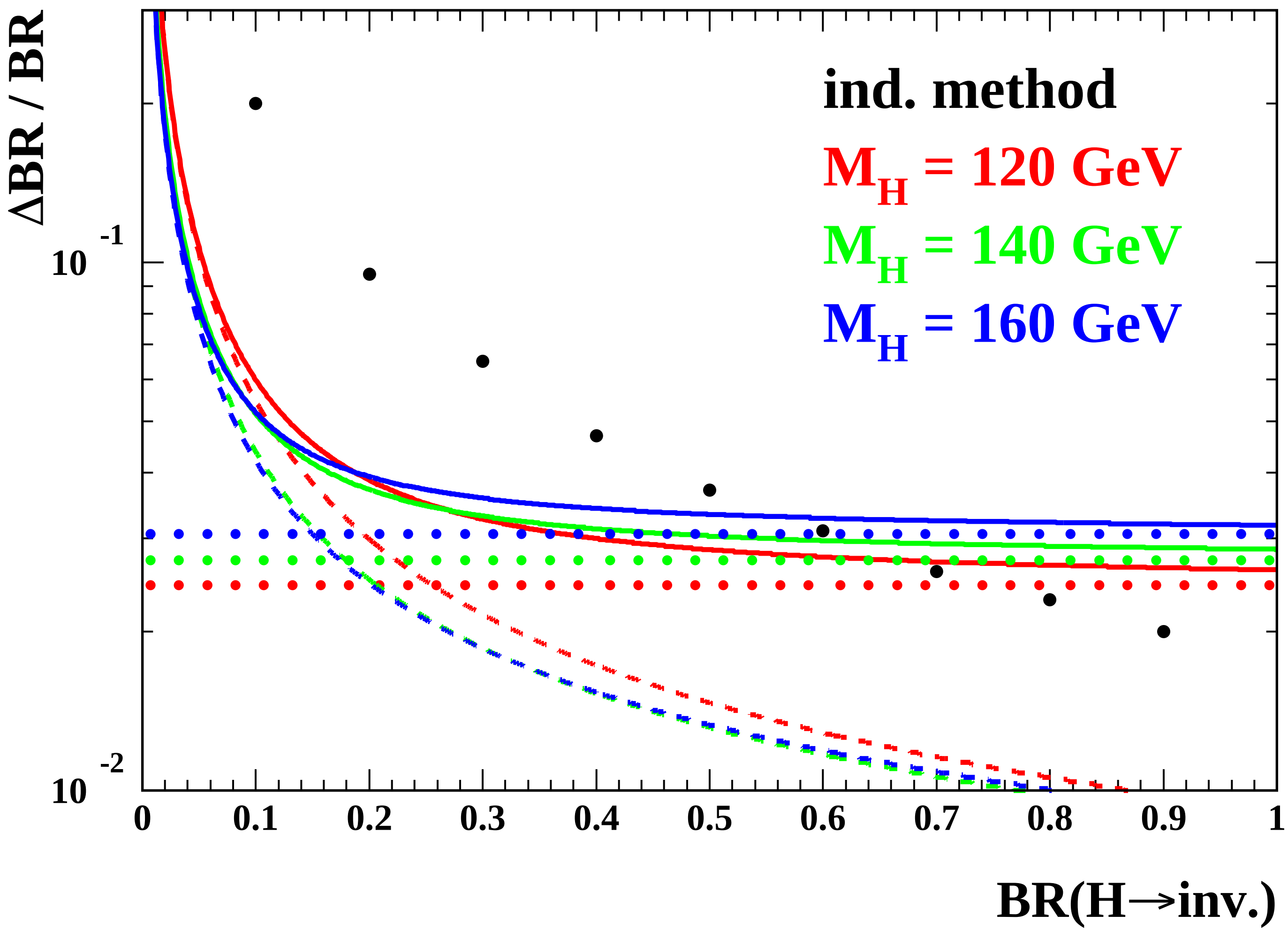
from Snowmass 2005 Higgs report, hep-ph/0511332

Precision $\sim 15\% \to 7\% \to 5\%$
with 500 GeV $\to$ 1000 GeV $\to$ 1500 GeV machine

Recall EW Baryogenesis: $\Delta\lambda_{hhh} \gtrsim$ 5–10%

Look for invisible Higgs decays at ILC:

↓ 5σ exclusion at BR $\sim$ 2%

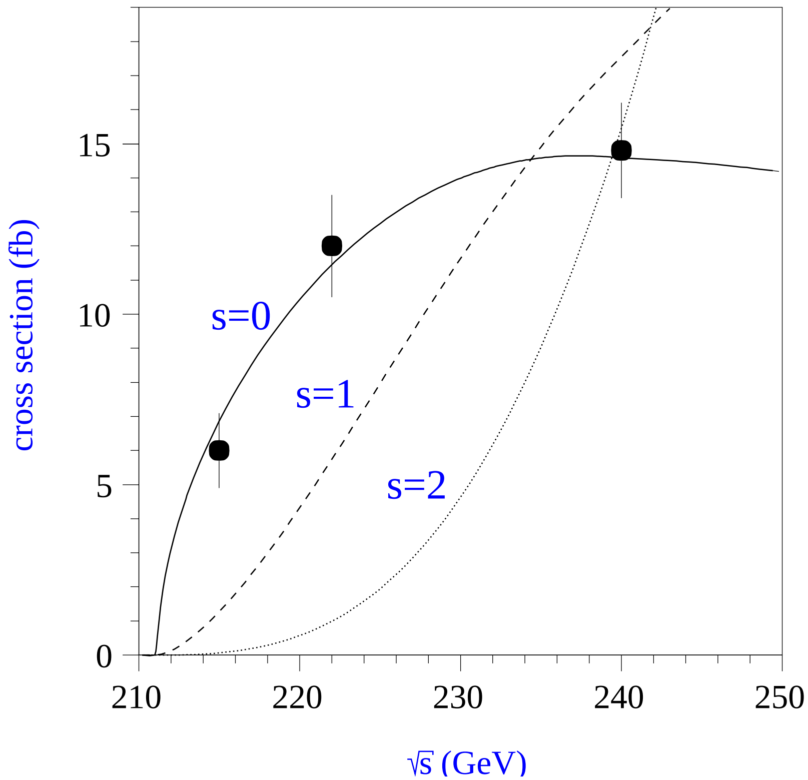


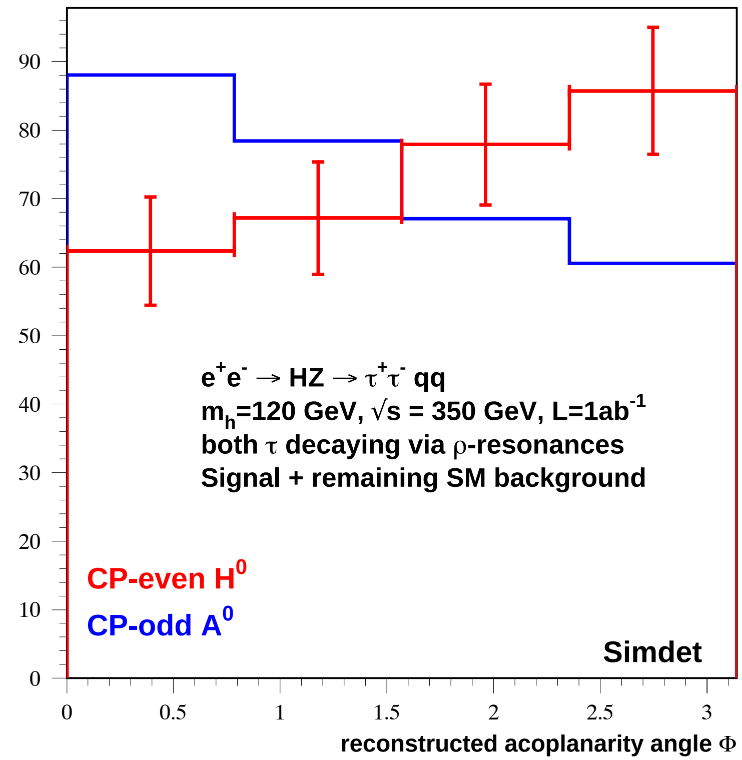
$\sim$ 3% meas
for large BR

500 fb^{-1} at 350 GeV. dashes - invisible rate; dots - Higgsstrahlung xsec

M. Schumacher, LC-PHSM-2003-096

Measure the Higgs spin... ...and CP





from Dova, Garcia-Abia & Lohmann, hep-ph/0302113

from Snowmass 2005 Higgs report, hep-ph/0511332

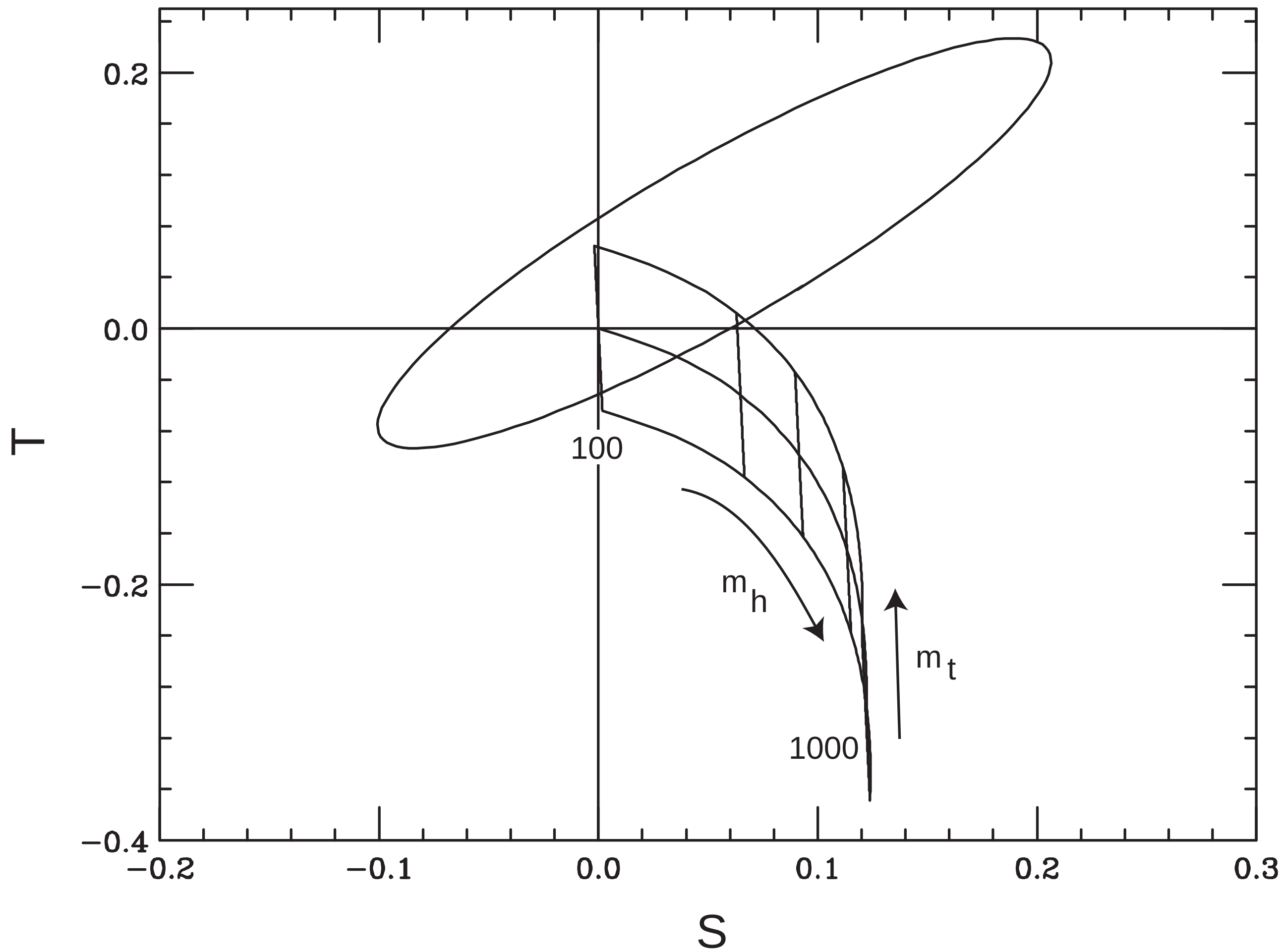
Dependence of threshold turn-on shape on Higgs spin

τ polarization in $H \to \tau\tau$, measured in relative τ decay angular distributions

Finally, look again for discrepancies from the SM:

Electroweak precision test

Does m_H agree with electroweak precision expectations?



from Peskin & Wells, hep-ph/0101342

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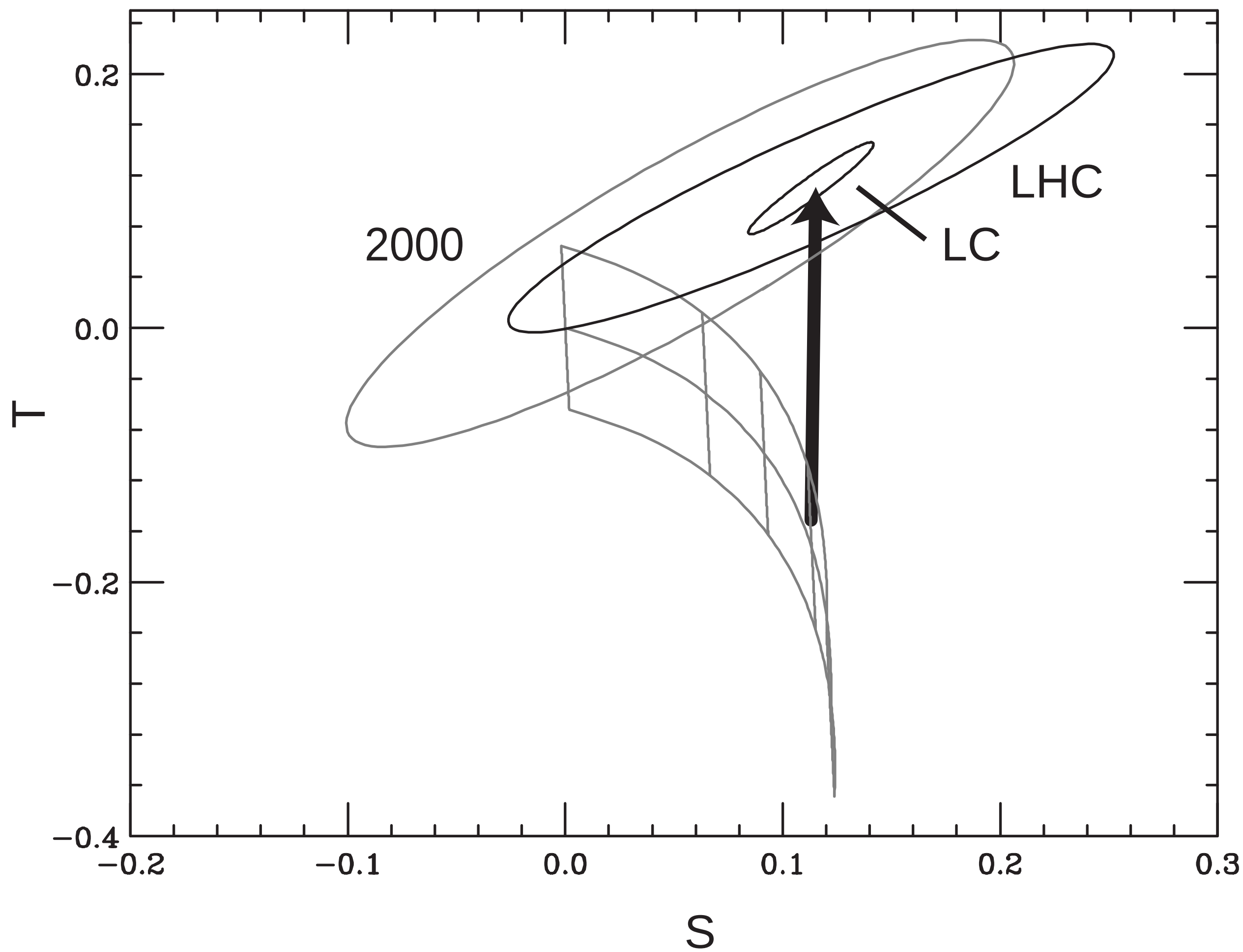


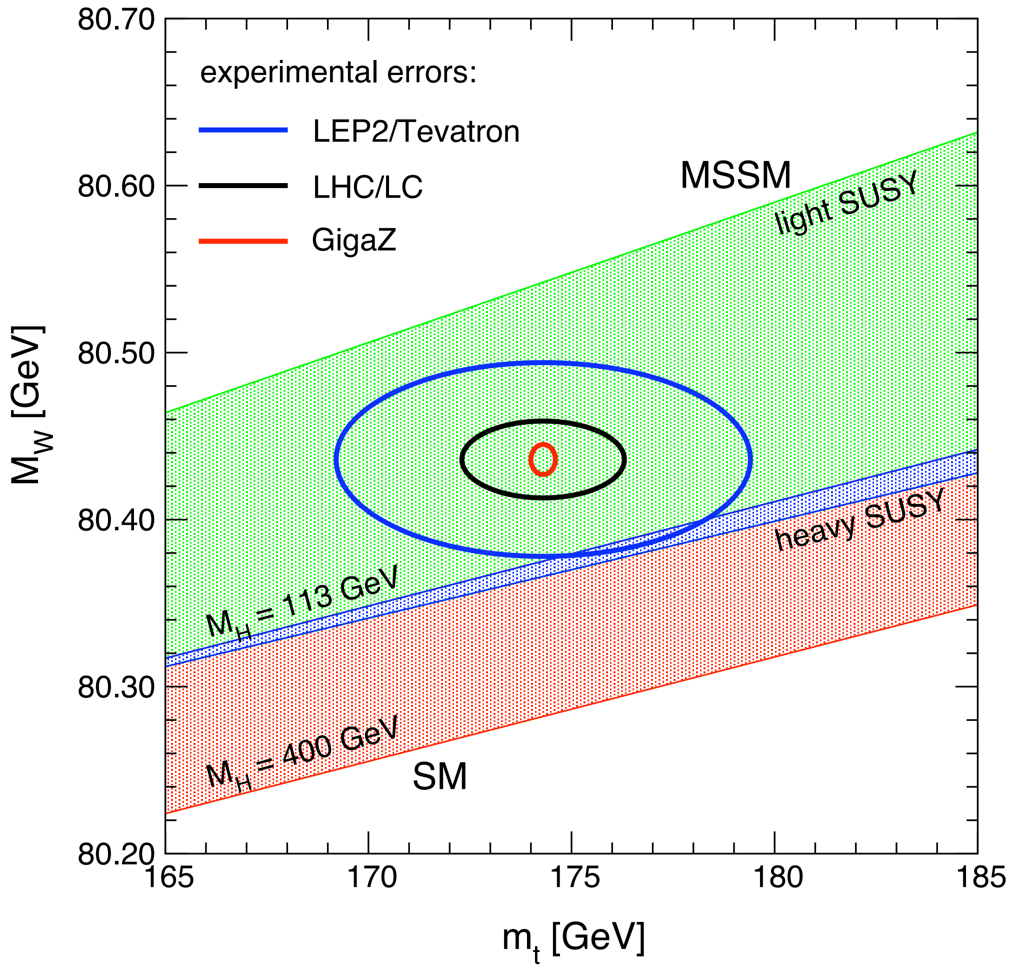
More stringent test of SM.

Gain clues to New Physics if there's a discrepancy

from Peskin & Wells, hep-ph/0101342

ILC GigaZ option:

Opportunity to take electroweak precision a level further and probe the SM at the quantum level



LEP:
constrains tree-level dim-6 ops as high as 10 TeV

GigaZ:
take it to 30 TeV??

LEP's "little hierarchy" becomes that much bigger.

from Heinemeyer & Weiglein, hep-ph/0012364

Conclusions, 1/3

Nightmares force us to think about our fears.

So, what if the LHC finds only a Higgs?

- First, get everything out of the LHC that we can.

LHC can measure:

- the Higgs mass
- ratios of couplings
- individual couplings [with some theory assumptions]
- sensitive to MSSM-like Higgs sector for $m_A \lesssim 300$ GeV
- can search for nonstandard decay modes: invisible; $\mu\mu$
- tensor structure of HWW, Hgg couplings

What else can we come up with?

Conclusions, 2/3

- Second, what "story(ies)" would this scenario tell us?

  - Nature doesn't care about fine-tuning?

    Landscape? What about $\theta_{\rm QCD}$?
  - Hierarchy is stabilized by something LHC can't see?

    "Twin Higgs" with mirror-world? LHC signatures??
  - Dark matter isn't a WIMP?

    Axion dark matter? WimpZillas?
  - Dark matter is a scalar singlet heavier than $m_H/2$?

    Direct detection?
  - [your model here]

  How can we test any of these?

  What are the next experimental steps?

Conclusions, 3/3

- Third, if the LHC finds only a Higgs, do we still want the ILC?

  - High-precision Higgs coupling measurements
    extend the sensitivity to deviations
  - Higgs triple coupling
    Insight to electroweak baryogenesis?
  - GigaZ precision electroweak
    Is m_H still consistent with pure SM?
  - Top threshold
    The SM isn't just the Higgs!
  - New Physics missed by the LHC but discoverable at ILC?
    Maybe a fishing expedition...

If so, then we'd better make the case!

... even in this worst of all possible scenarios.