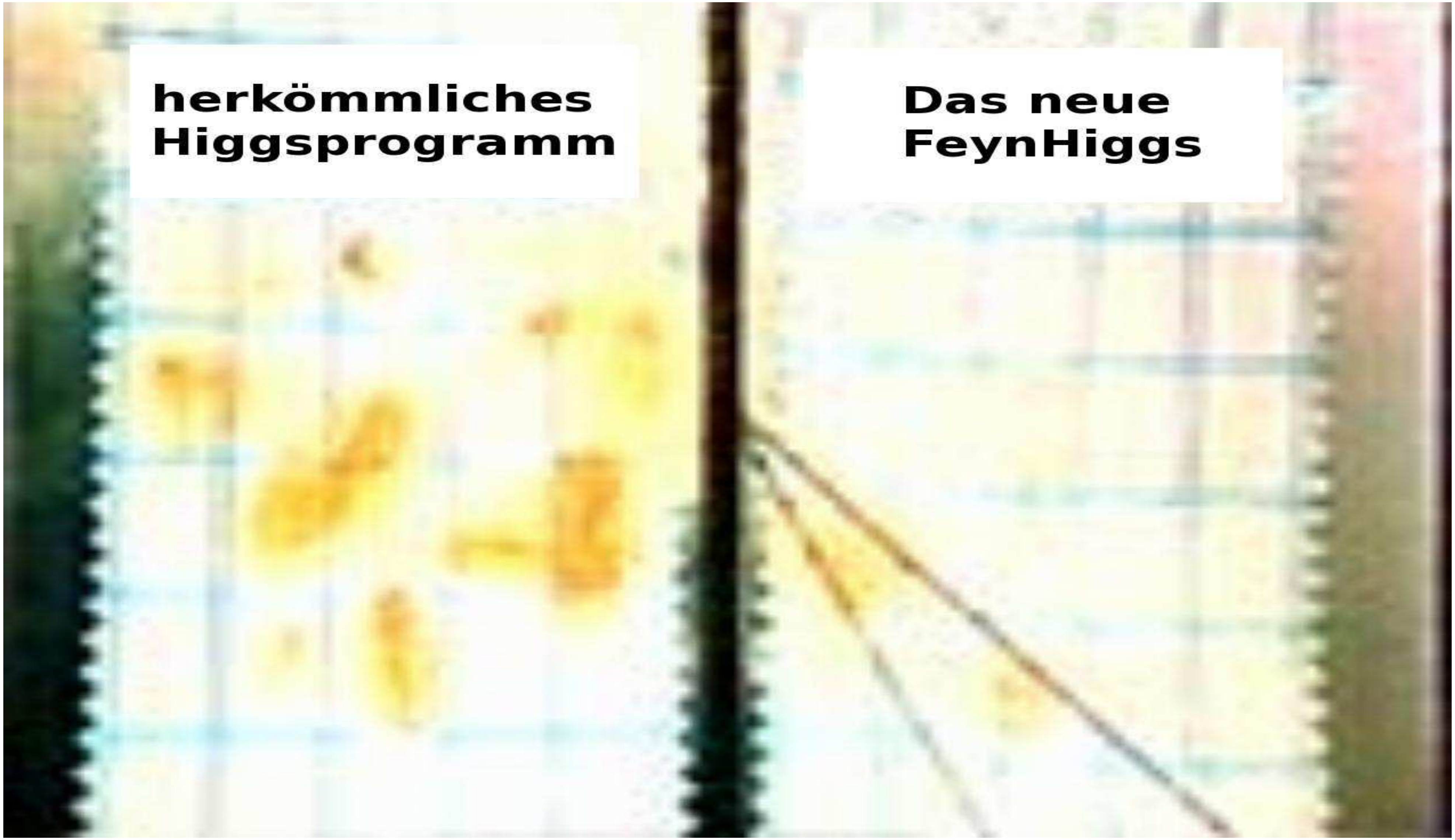

herkömmliches
Higgsprogramm
Das neue
FeynHiggs

Remaining WG1 (Higgs) discussions:

Monday, 23.02., 4.30pm:

– input from precision observables (LHC/ILC/GigaZ) to the Higgs sector
  Discussion leader: Wolfgang Hollik

– Higgs masses, couplings: what can measured? Where?
  How much model dependence enters?
  What are "optimal observables"?

Wednesday, 25.02., afternoon:

– What can we learn from the LHC with 200 pb^{-1}?
  Discussion leader: Andrey Korytov

Friday, 27.02., 10.00am:

– on: C/C' (extension of discussion on 18.02.):
  How exactly could we detect a deviation with 10 fb^{-1}?
  How does the deviation from the SM tell us where/how to search
  at future colliders?

sites.google.com/site/lhc2fchiggs

The Higgs at Future Lepton Colliders: What do we learn from the increased precision?

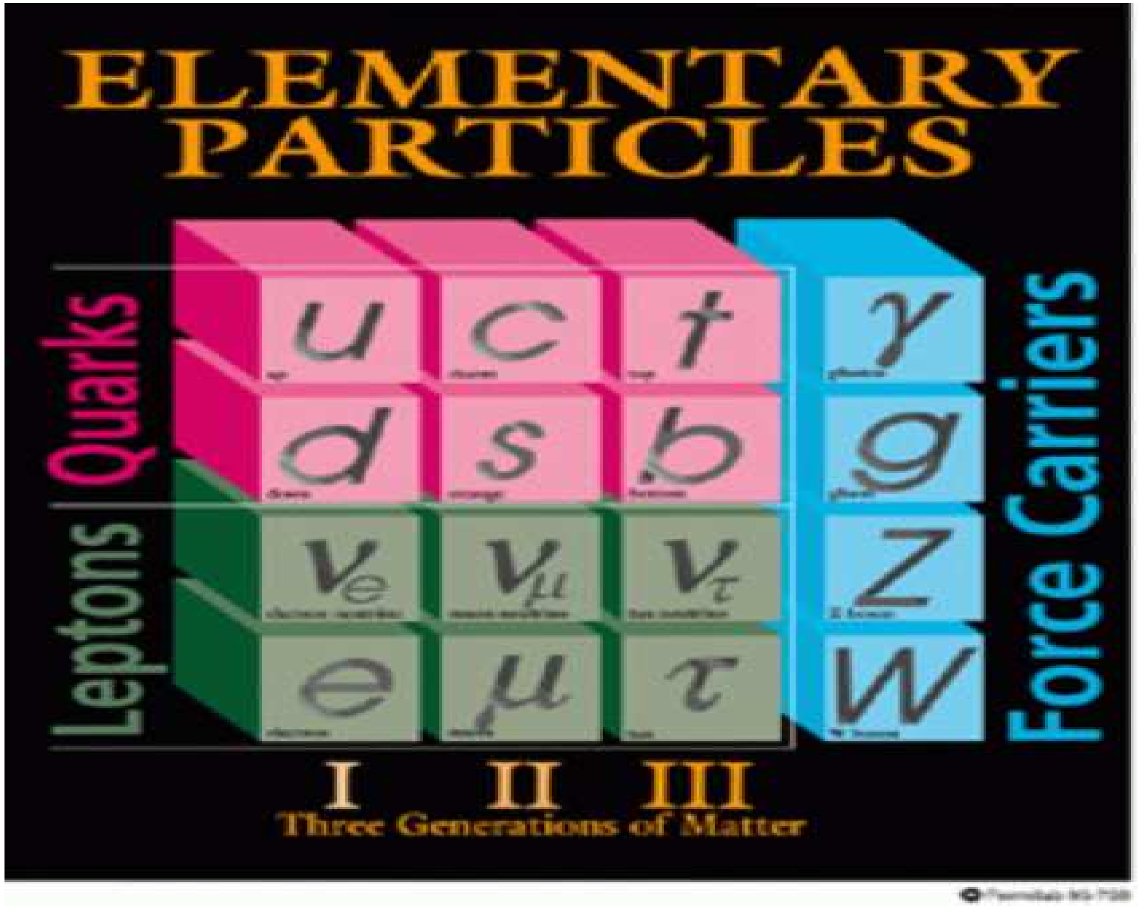
Sven Heinemeyer, IFCA (CSIC, Santander)

CERN, 02/2009

1. Introduction
2. Higgs couplings
3. The precision frontier
4. Left out topics
5. Conclusions

1. Introduction

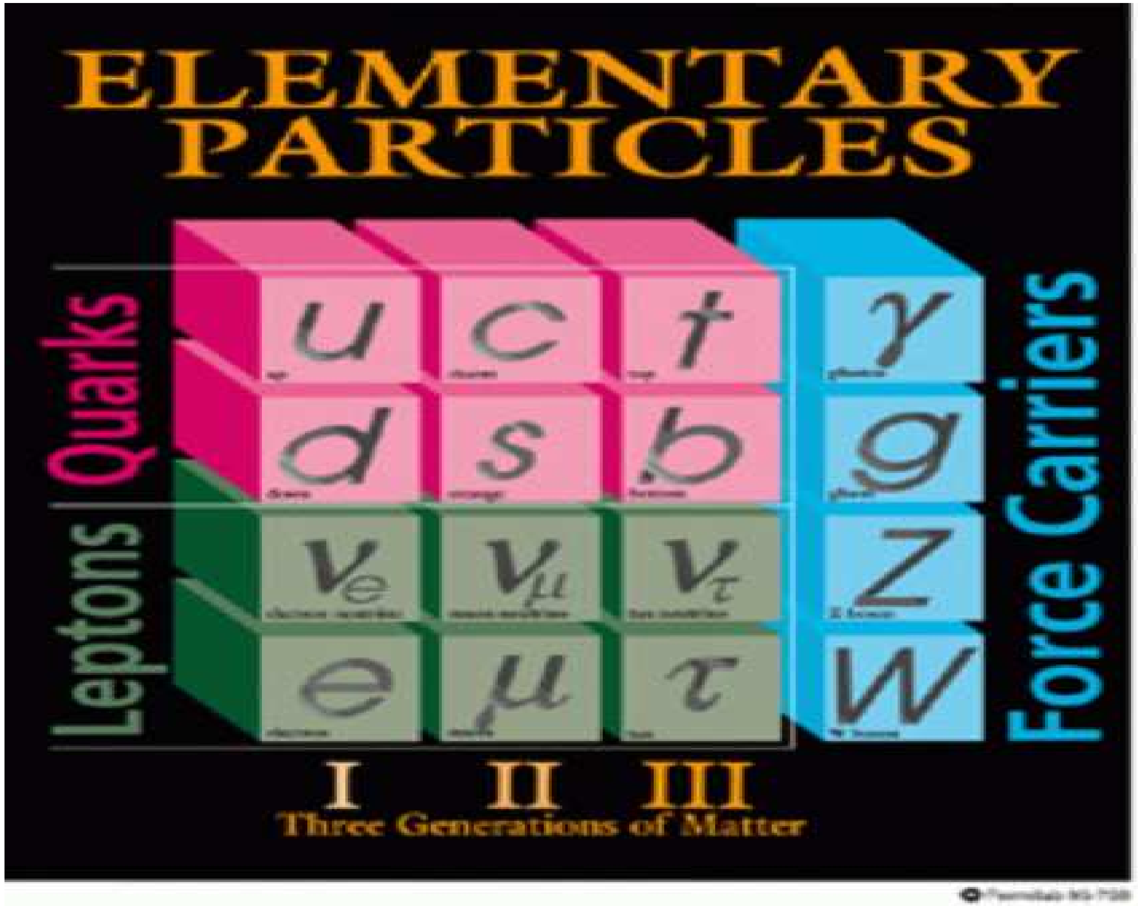
Current status of knowledge: the Standard Model (SM)



⇒ all particles experimentally seen

1. Introduction

Current status of knowledge: the Standard Model (SM)



⇒ all particles experimentally seen

⇒ but one particle is missing . . .

Problem:

Gauge fields Z, W^+, W^- are massive

explicite mass terms in the Lagrangian $\Leftrightarrow$ breaking of gauge invariance

Solution: Higgs mechanism

scalar field postulated, mass terms from coupling to Higgs field

Higgs sector in the Standard Model:

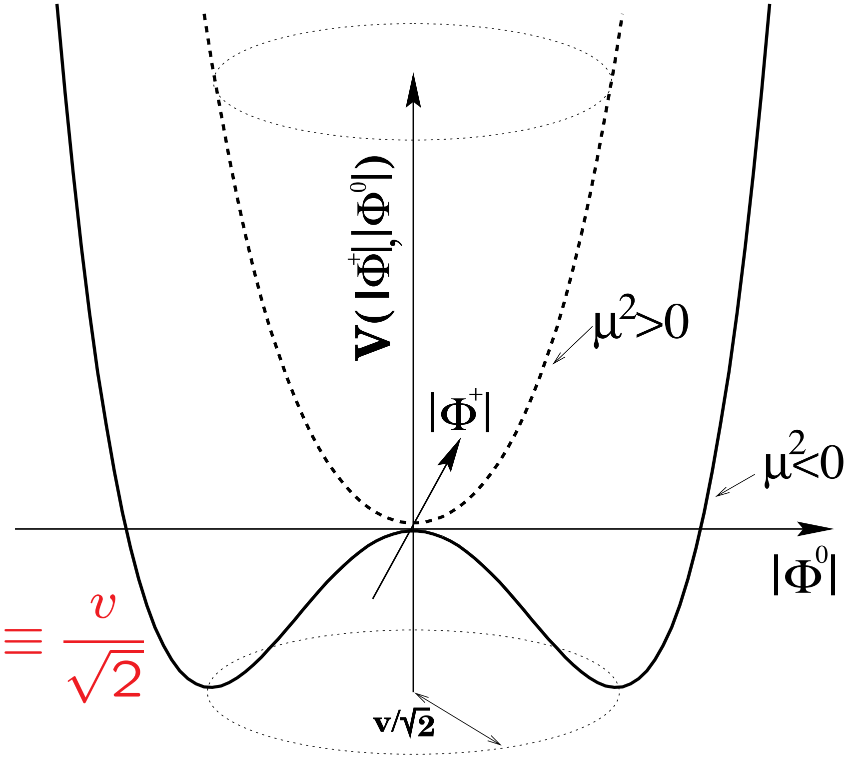
Scalar SU(2) doublet: $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$

Higgs potential:

$$V(\phi) = \mu^2 \left|\Phi^\dagger \Phi\right| + \lambda \left|\Phi^\dagger \Phi\right|^2, \quad \lambda > 0$$

$\mu^2 < 0$: Spontaneous symmetry breaking

minimum of potential at $|\langle \Phi_0 \rangle| = \sqrt{\frac{-\mu^2}{2\,\lambda}} \equiv \frac{v}{\sqrt{2}}$



$$\Phi = \begin{pmatrix} 0 \\ v + H \end{pmatrix} \quad \text{(unitary gauge)}$$

H: elementary scalar field, Higgs boson

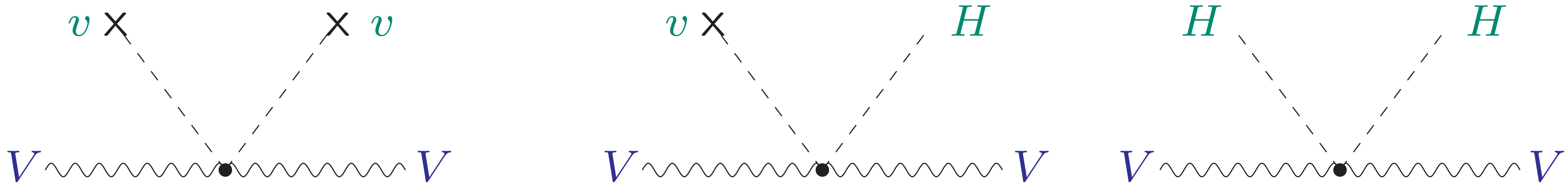
Lagrange density:

$$\mathcal{L}_{\text{Higgs}} = (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi)$$

Gauge invariant coupling to gauge fields

$\Rightarrow$ mass terms for gauge bosons and fermions

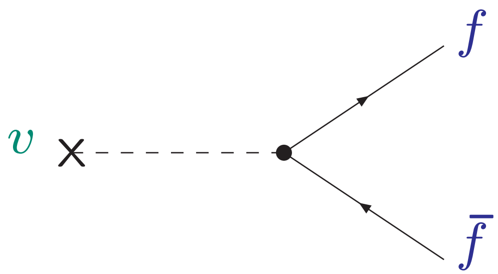
1.) $VV\Phi\Phi$ coupling:

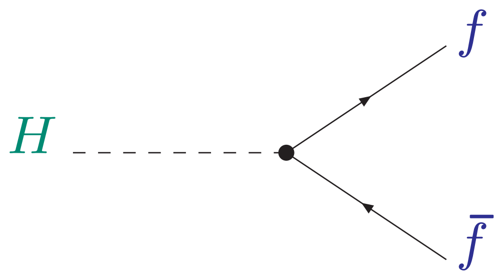


$\Rightarrow$ VV mass terms $\quad\quad$ $\Rightarrow$ triple/quartic couplings to gauge bosons

$g_2^2 v^2/2 \equiv M_W^2$, $(g_1^2 + g_2^2) v^2/2 \equiv M_Z^2$ $\Rightarrow$ coupling $\propto$ masses

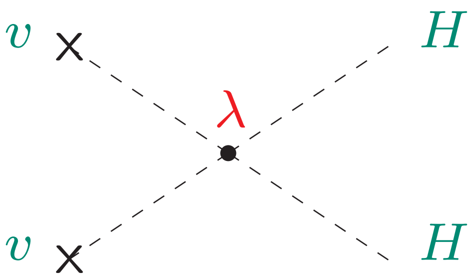
2.) fermion mass terms: Yukawa couplings





$m_f = v\, g_f \Rightarrow$ coupling $\propto$ masses

3.) mass of the Higgs boson: self coupling



. . .

$\lambda = M_H^2/v$

$M_H = v\sqrt{\lambda}$ free parameter

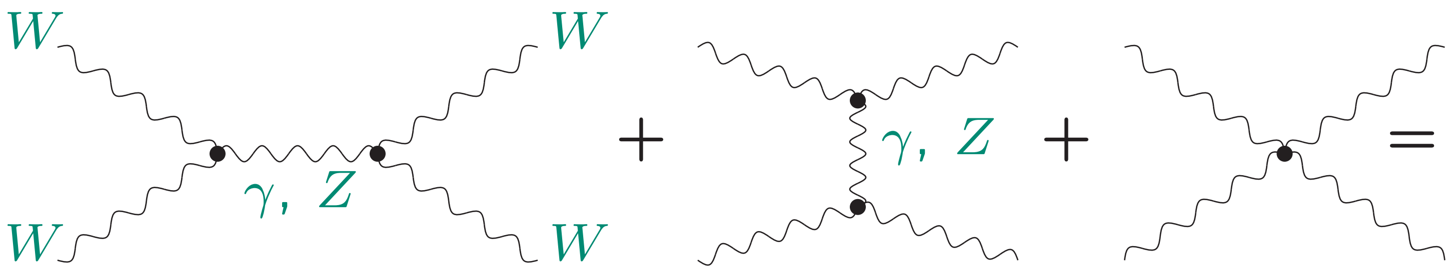
$\rightarrow$ last unknown parameter of the SM

$\Rightarrow$ establish Higgs mechanism $\equiv$ find the Higgs $\oplus$ measure its couplings

Another effect of the Higgs field:

Scattering of longitudinal W bosons: $W_L W_L \to W_L W_L$

$\mathcal{M}_V =$

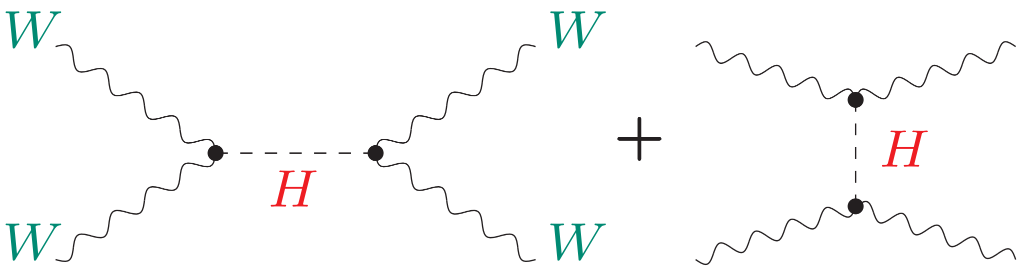


$= -g^2 \frac{E^2}{M_W^2} + \mathcal{O}(1)$ for $E \to \infty$

$\Rightarrow$ violation of unitarity

Contribution of a scalar particle with couplings prop. to the mass:

$\mathcal{M}_S =$



$= g_{WWH}^2 \frac{E^2}{M_W^4} + \mathcal{O}(1)$ for $E \to \infty$

$$\mathcal{M}_{\rm tot} = \mathcal{M}_V + \mathcal{M}_S = \frac{E^2}{M_W^4}\left(g_{WWH}^2 - g^2\, M_W^2\right) + \ldots$$

$\Rightarrow$ compensation of terms with bad high-energy behavior for

$$g_{WWH} = g\, M_W$$

Discovering the Higgs boson: what has to be done?

1. Find the new particle

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6. measure spin, . . .

Discovering the Higgs boson: what has to be done?

1. Find the new particle	T
2. measure its mass ($\Rightarrow$ ok?)	T
3. measure coupling to gauge bosons	
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5. measure self-couplings	
6. measure spin, . . .	

T = Tevatron,

Discovering the Higgs boson: what has to be done?

1. Find the new particle	T	L
2. measure its mass ($\Rightarrow$ ok?)	T	L
3. measure coupling to gauge bosons		L
4. measure couplings to fermions		L
5. measure self-couplings		
6. measure spin, . . .		

T = Tevatron, L = LHC,

Discovering the Higgs boson: what has to be done?

	T	L	I
1. Find the new particle	T	L	I
2. measure its mass (⇒ ok?)	T	L	I
3. measure coupling to gauge bosons		L	I
4. measure couplings to fermions		L	I
5. measure self-couplings		L	I
6. measure spin, . . .		L	I

T = Tevatron, L = LHC, I = ILC (or other Lepton Collider?)

We need the LHC and the ILC to find the Higgs
and to establish the Higgs mechanism!

The LHC can do a crucial part, but . . .

What is a coupling?

$\rightarrow$ parameter in the tree-level Lagrangian

$$\mathcal{L} = \ldots g_{HZZ} HZZ + \ldots g_{Hb\bar{b}} Hb\bar{b} + \ldots$$

$\Rightarrow$ these parameters show the symmetries expected from the Higgs mechanism, i.e.

coupling $\propto$ mass

$\Rightarrow$ factor out radiative corrections (depending on the model . . .)

What is a Lepton Collider?

1. ILC

   $\sqrt{s} = 500$ GeV ... 1000 GeV

   Options:
   - GigaZ
   - $\gamma\gamma$
   - $e\gamma$
   - $e^- e^-$

2. CLIC

   $\sqrt{s} = 1$ TeV ... 3 TeV
   $\rightarrow$ when I say "ILC" then "CLIC" is in principle included

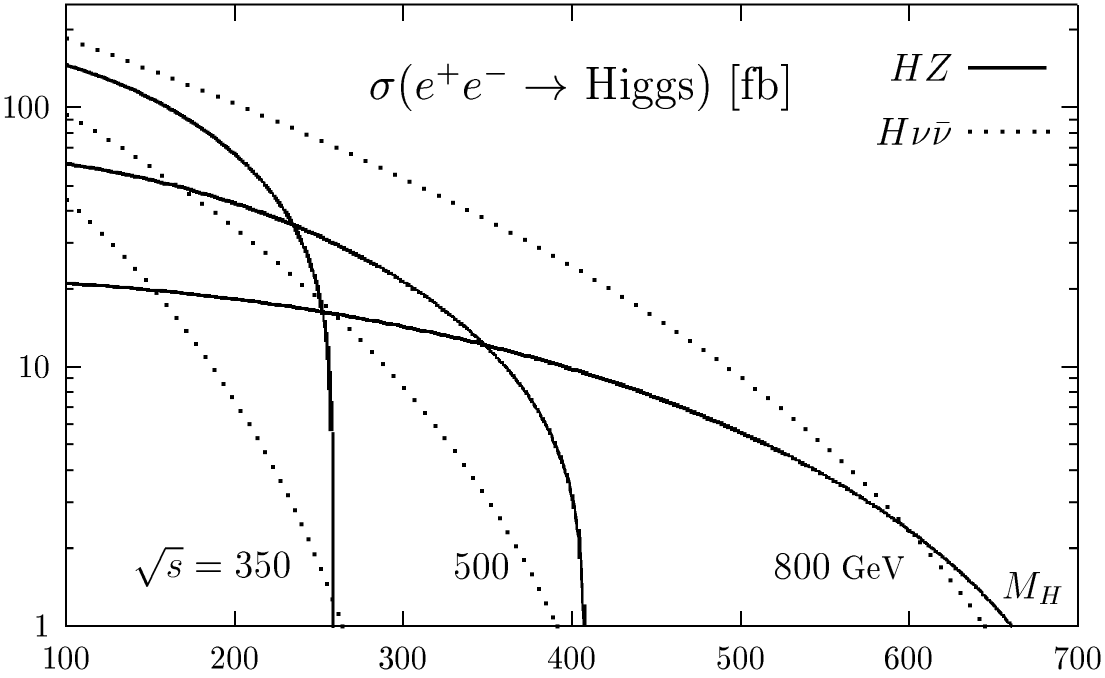
3. μC

4. NLSPC

For technical details check the talks by K. Moenig, K. Desch, B. Foster, M. Battaglia, P. Delahaye, A. Palmer, A. Blondel ...

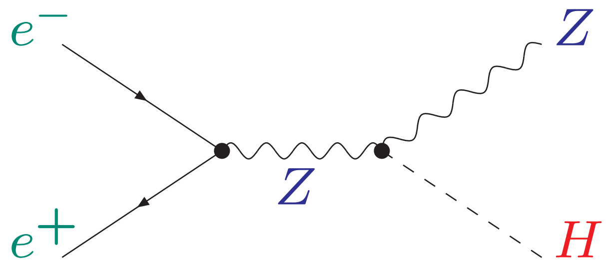
2. Higgs Couplings

Higgs production at the ILC:



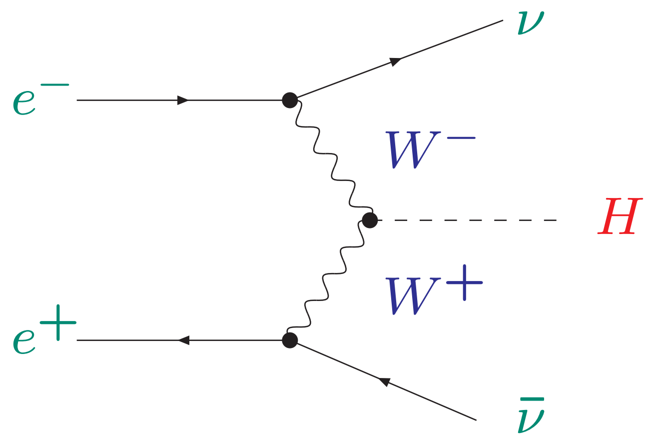
Higgs-strahlung:

$e^+e^- \to Z^* \to ZH$



weak boson fusion (WBF):

$e + e- \to \nu\bar{\nu}H$



⇒ Measurement of masses, couplings, . . . in per cent/per mille

Some ILC specifics:

recoil method: $e^+e^- \to ZH$, $Z \to e^+e^-, \mu^+\mu^-$

$\Rightarrow$ total measurement of Higgs production cross section

$\Rightarrow$ NO additional theoretical assumptions needed for absolute determination of partial widths

$\Rightarrow$ all observable channels can be measured with high accuracy

Some ILC results (500 fb^{-1}@$\sqrt{s} = 350$ GeV):

$\delta M_H \approx 50$ MeV
$\delta g_{ZZH} \approx 2.5\%$, $\delta g_{WWH} \approx 2 - 5\%$
$\delta g_{Hb\bar{b}} \approx 1 - 2\%$ (for $M_H \lesssim 150$ GeV)

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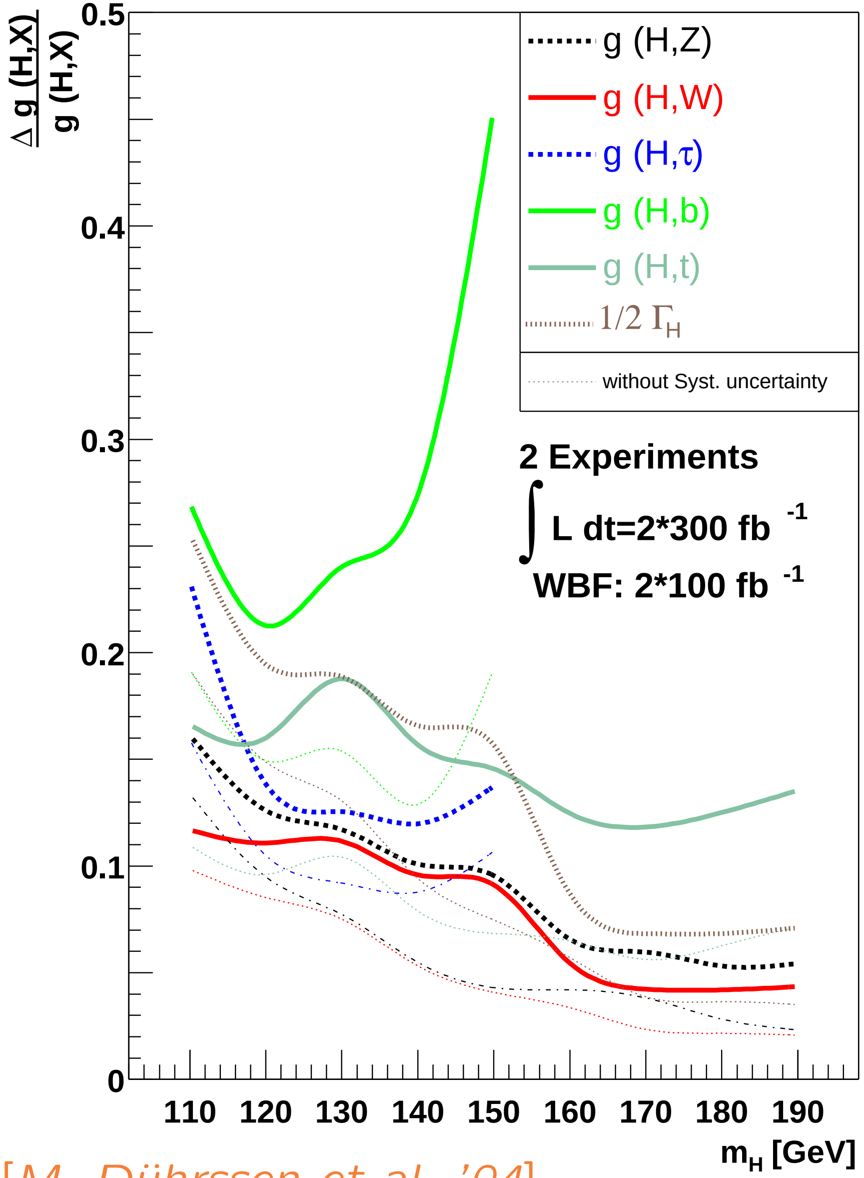
How does this compare to the LHC?

The LHC will find a Higgs and measure its characteristics:



[*M. Dührssen et al. '04*]

– mass: $\delta M_h \approx 200$ MeV

– couplings: $(2 * 300 + 2 * 100)$ fb^{-1} :

typical accuracies of 20-30%

for $m_H \leq 150$ GeV

10% accuracies for HVV couplings

above WW threshold

⇒ and this is still optimistic . . .

Assumption:

– $g^2_{HVV} \leq g^2_{HVV,\text{SM}} \times 1.05$

– SM rates for the Higgs

Problems:

– valid in weakly interacting models

– rates much lower than in SM ??

– physics can/will hide in 5% margin

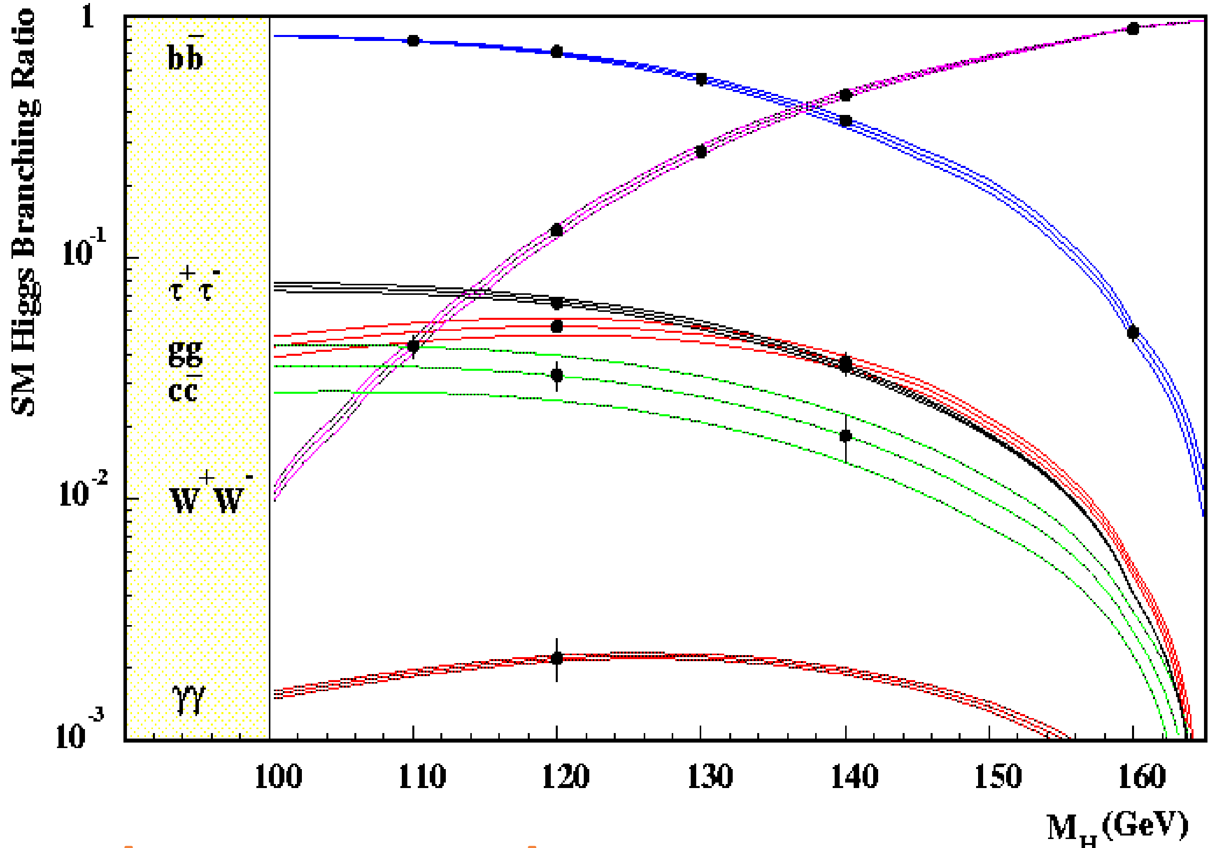
– self-couplings out of reach

⇒ ILC comes in

Compare to the ILC:

SM Higgs @ ILC:
Precise measurement of:

1. Higgs boson mass, $\delta M_H \approx$ 50 MeV
2. Higgs boson width (direct/indirect)
3. Higgs boson couplings, $\mathcal{O}$ (few%) $\Rightarrow$ $\Rightarrow$ model independent!
4. Higgs boson quantum numbers: spin, . . .



[*TESLA TDR '01*]

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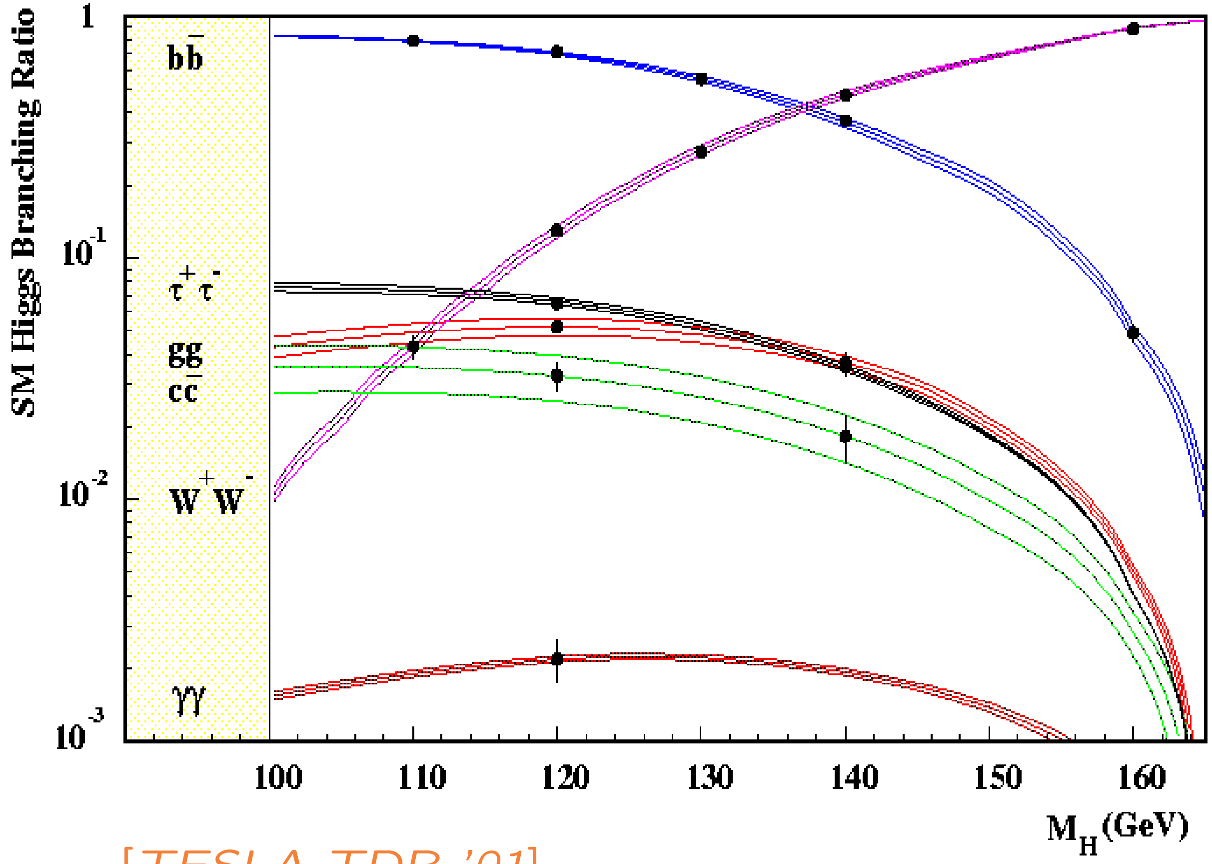

[*TESLA TDR '01*]

But do we need the ILC precision?

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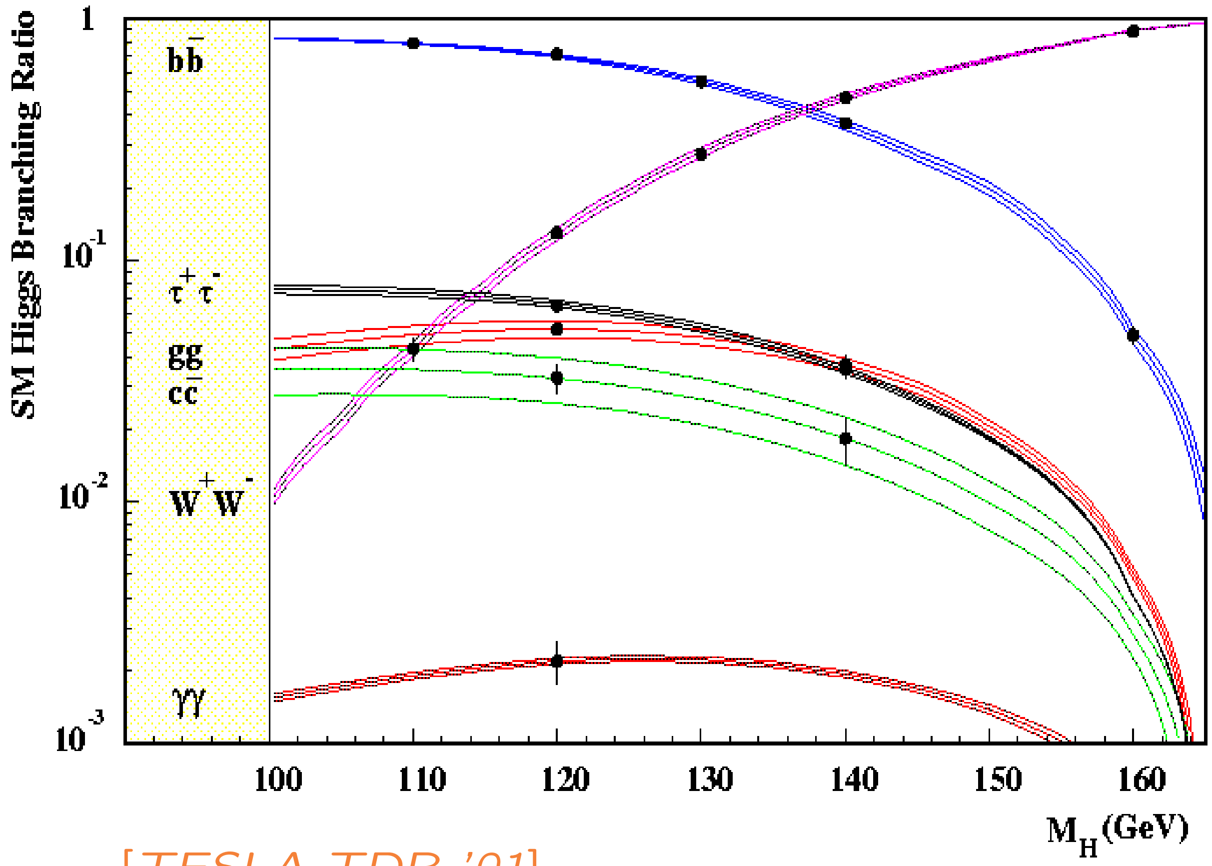
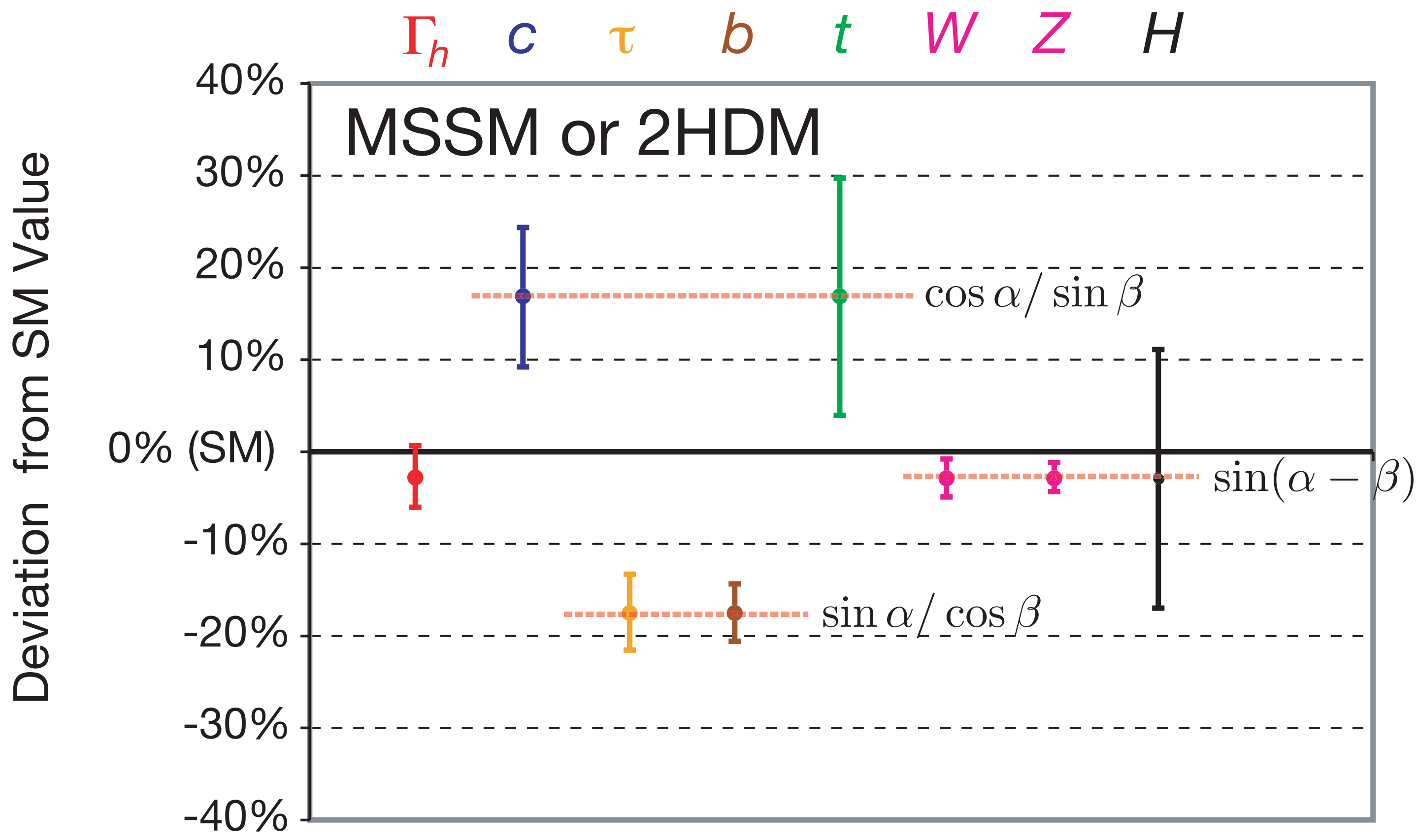


[TESLA TDR '01]

But do we need the ILC precision?
YES! To discriminate between the SM and extensions

Example I: Higgs couplings in the MSSM:

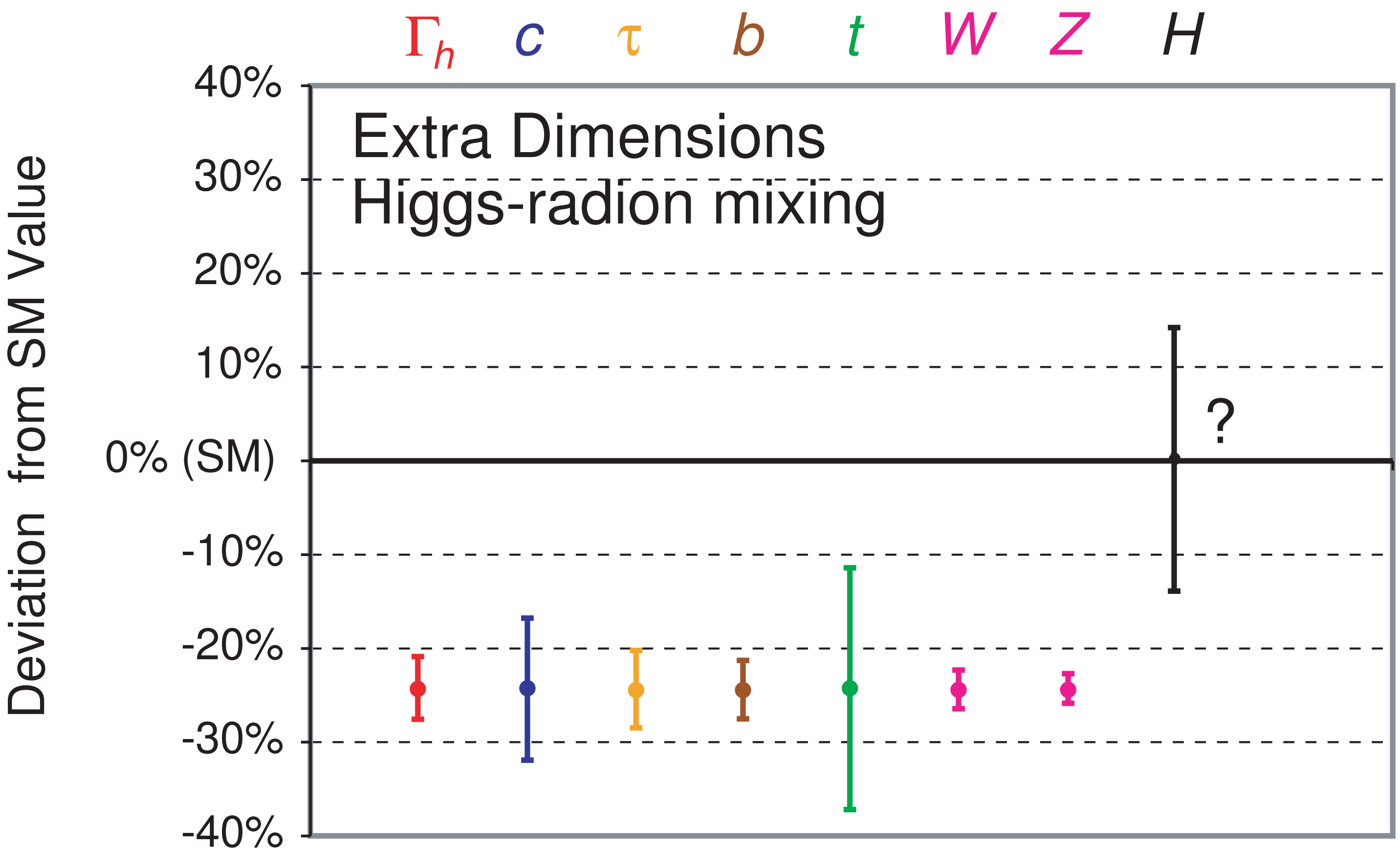
"Normal" MSSM scenario:



⇒ measurable deviations over large parts of the parameter space

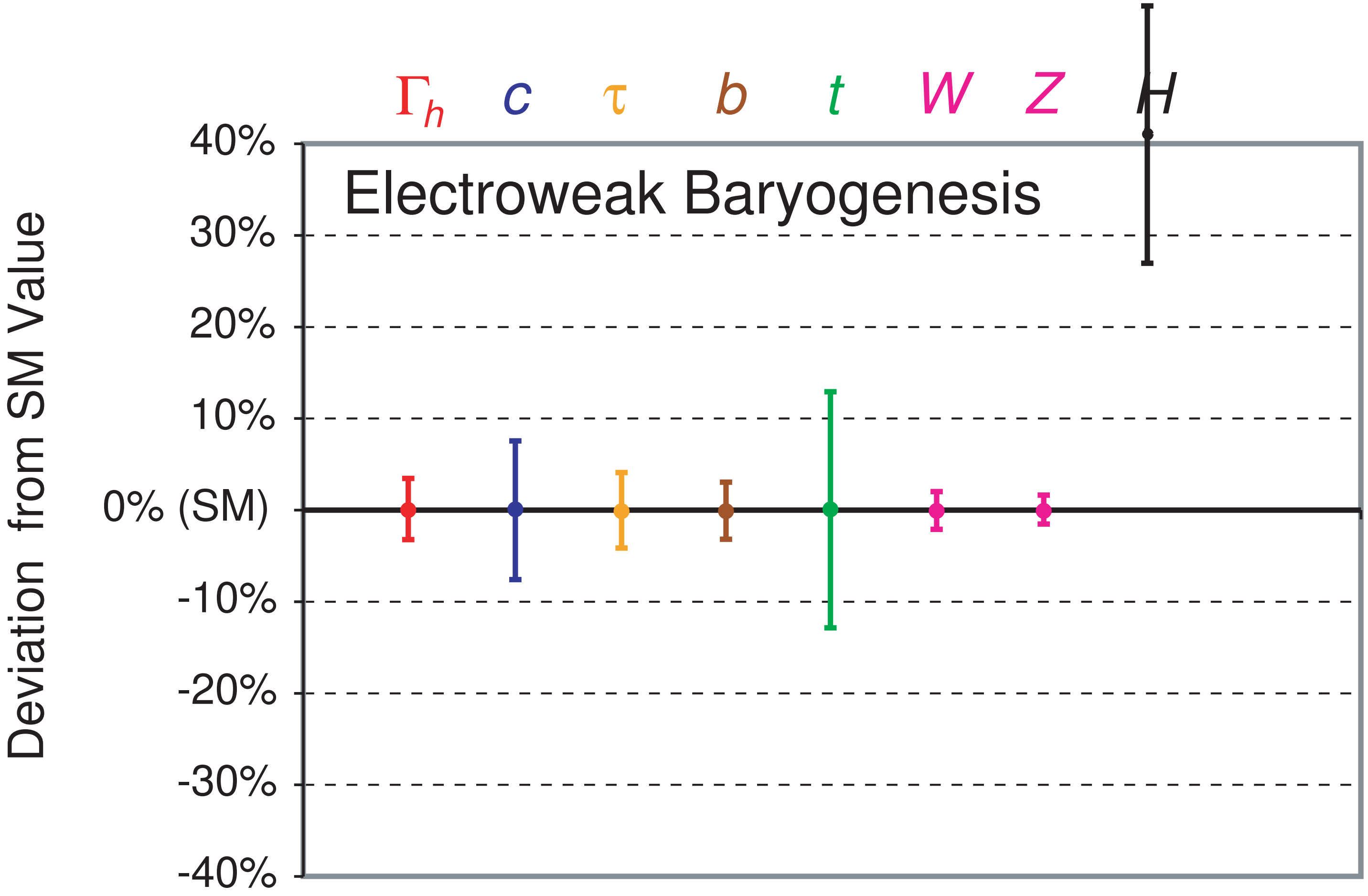
Example II: Higgs couplings in model with extra dimensions:

Effects of Kaluza Klein towers:



⇒ measurable deviations over large parts of the parameter space

Example III: Higgs couplings in a baryogenis motivated SM extension:



⇒ Only Higgs self coupling deviates, measurement possible!

Recent more general analysis:

[*V. Barger, H. Logan, G. Shaughnessy '09*]

Parameterization of deviations from the SM:

Model	Γ^h_W/Γ^{SM}_W	Γ^h_d/Γ^{SM}_d	Γ^h_u/Γ^{SM}_u	$\Gamma^h_\ell/\Gamma^{SM}_\ell$
SM	1	1	1	1
SM+S	$1-\delta^2$	$1-\delta^2$	$1-\delta^2$	$1-\delta^2$
2HDM-I	$1-\delta^2$	$1+2\delta/t_\beta$	$1+2\delta/t_\beta$	$1+2\delta/t_\beta$
2HDM-II	$1-\delta^2$	$1-2t_\beta\delta$	$1+2\delta/t_\beta$	$1-2t_\beta\delta$
2HDM-II+S	$1-\delta^2-\epsilon^2$	$1-2t_\beta\delta-\epsilon^2$	$1+2\delta/t_\beta-\epsilon^2$	$1-2t_\beta\delta-\epsilon^2$
2HDM-II+D	$1-\delta^2$	$1-2\delta(s_\gamma t_\beta/c_\Omega+c_\gamma t_\Omega)$	$1+2\delta(s_\gamma/c_\Omega t_\beta-c_\gamma t_\Omega)$	$1-2\delta(s_\gamma t_\beta/c_\Omega+c_\gamma t_\Omega)$
Flipped 2HDM	$1-\delta^2$	$1-2t_\beta\delta$	$1+2\delta/t_\beta$	$1+2\delta/t_\beta$
Lepton-specific 2HDM	$1-\delta^2$	$1+2\delta/t_\beta$	$1+2\delta/t_\beta$	$1-2t_\beta\delta$
MSSM	$1-\delta^2$	$1-2t'_\beta\delta$	$1+2\delta/t_\beta$	$1-2t_\beta\delta$
3HDM-D	$1-\delta^2$	$1-2\delta(s_\gamma t_\beta/c_\Omega+c_\gamma t_\Omega)$	$1+2\delta(s_\gamma/c_\Omega t_\beta-c_\gamma t_\Omega)$	$1+2\delta c_\gamma/t_\Omega$

Recent more general analysis:

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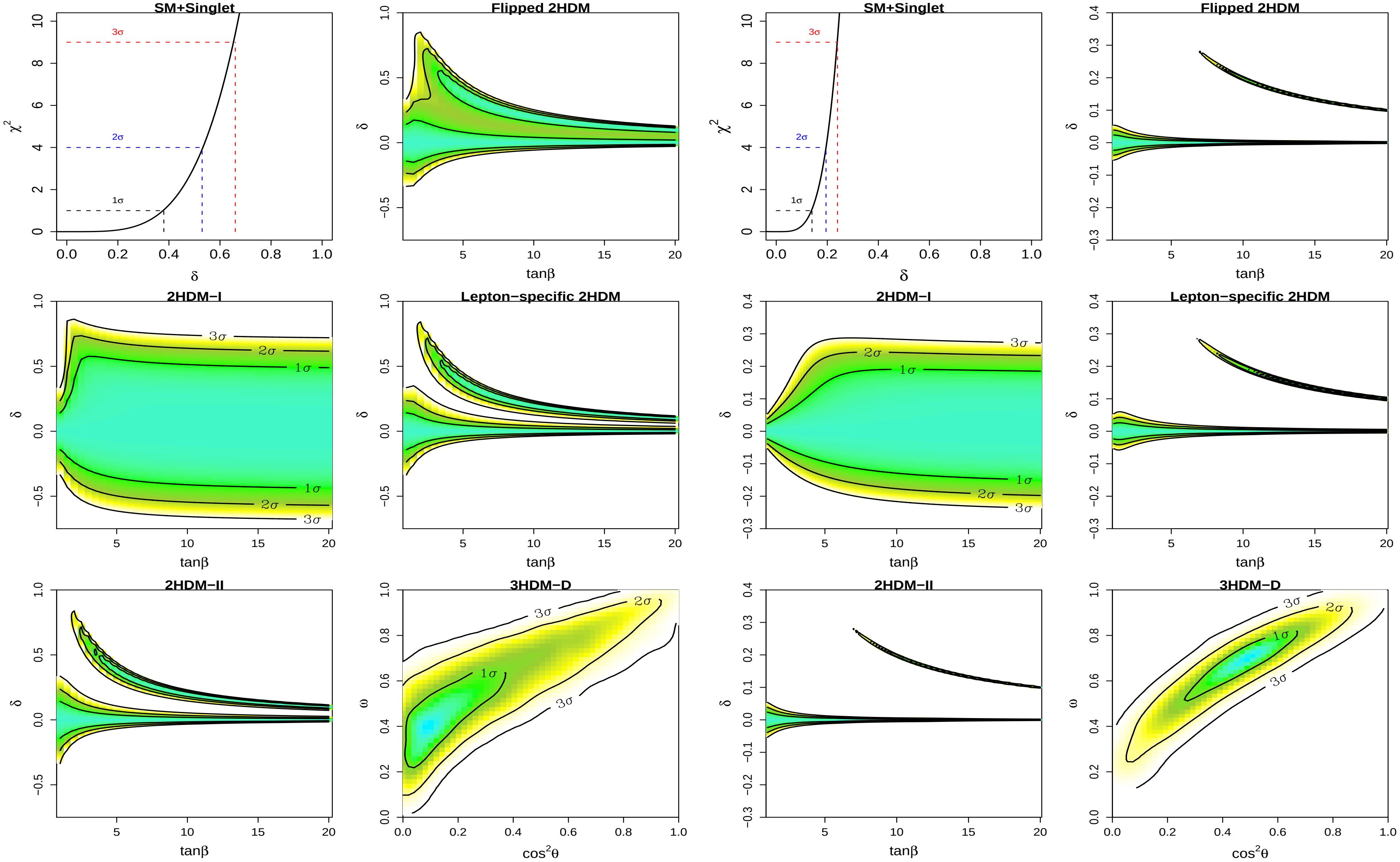
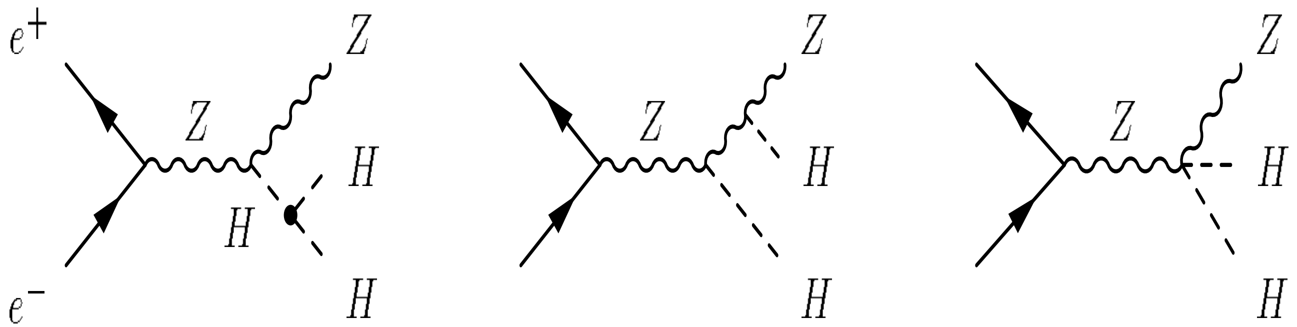
LHC ILC



Step 5: measurement of the Higgs boson self-coupling

$\Rightarrow$ only possible at the ILC



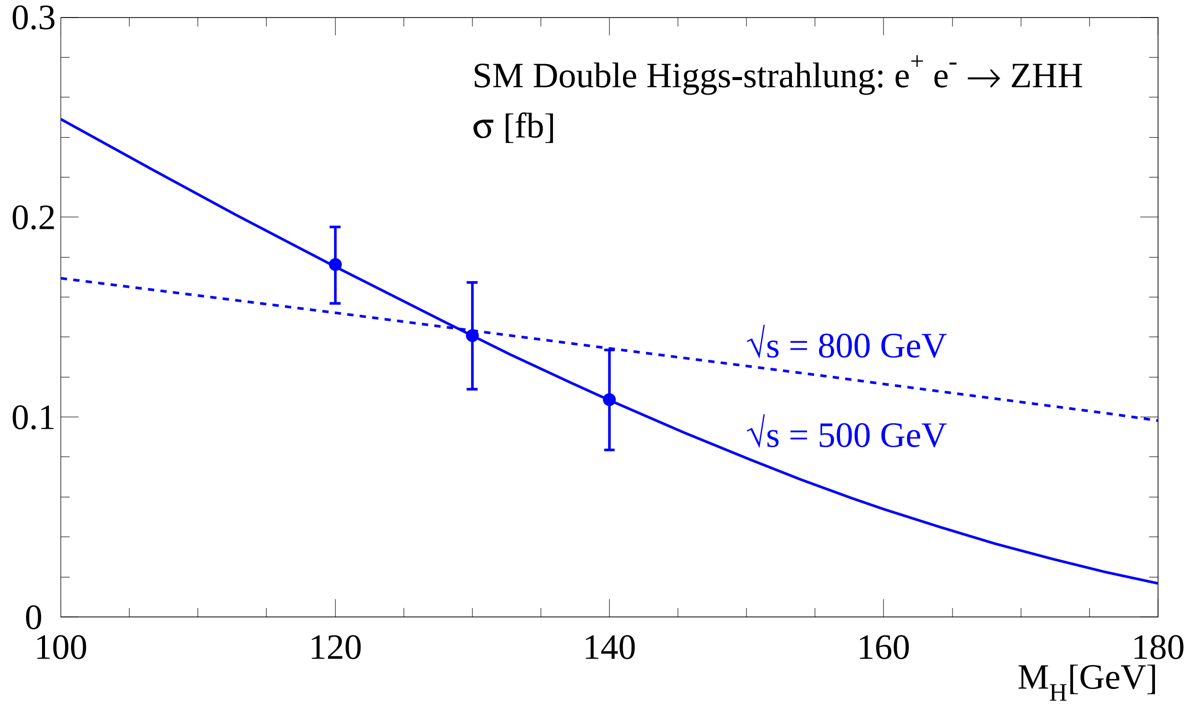
Parton-level study:

[*Djouadi, Kilian, Mühlleitner, Zerwas '99*]

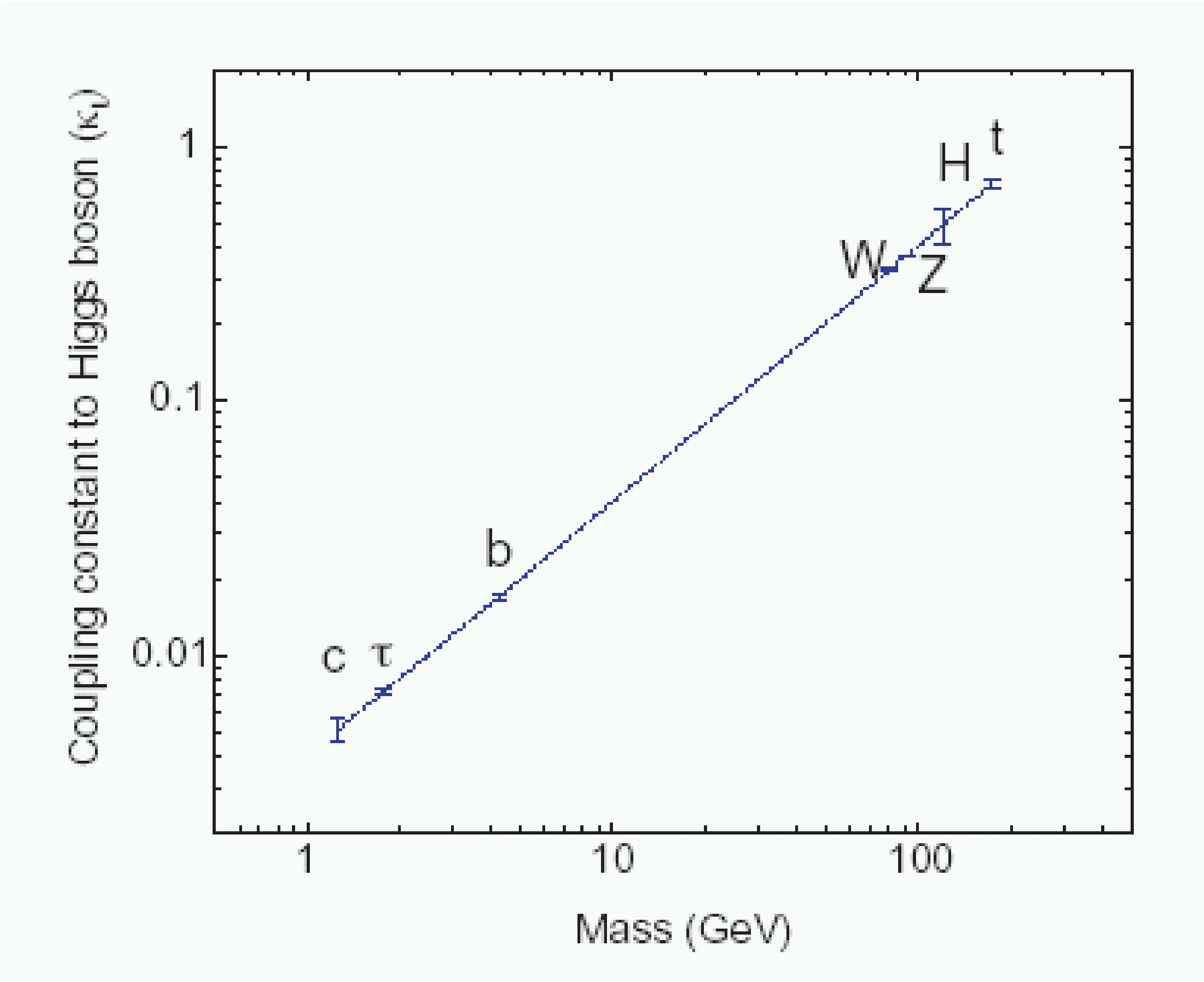
1 ab^{-1} $\Rightarrow$ 20–30% measurement of $\lambda = \lambda_{HHH}$

However:

$\lambda = \lambda_{HHHH}$ out of reach for all foreseeable colliders

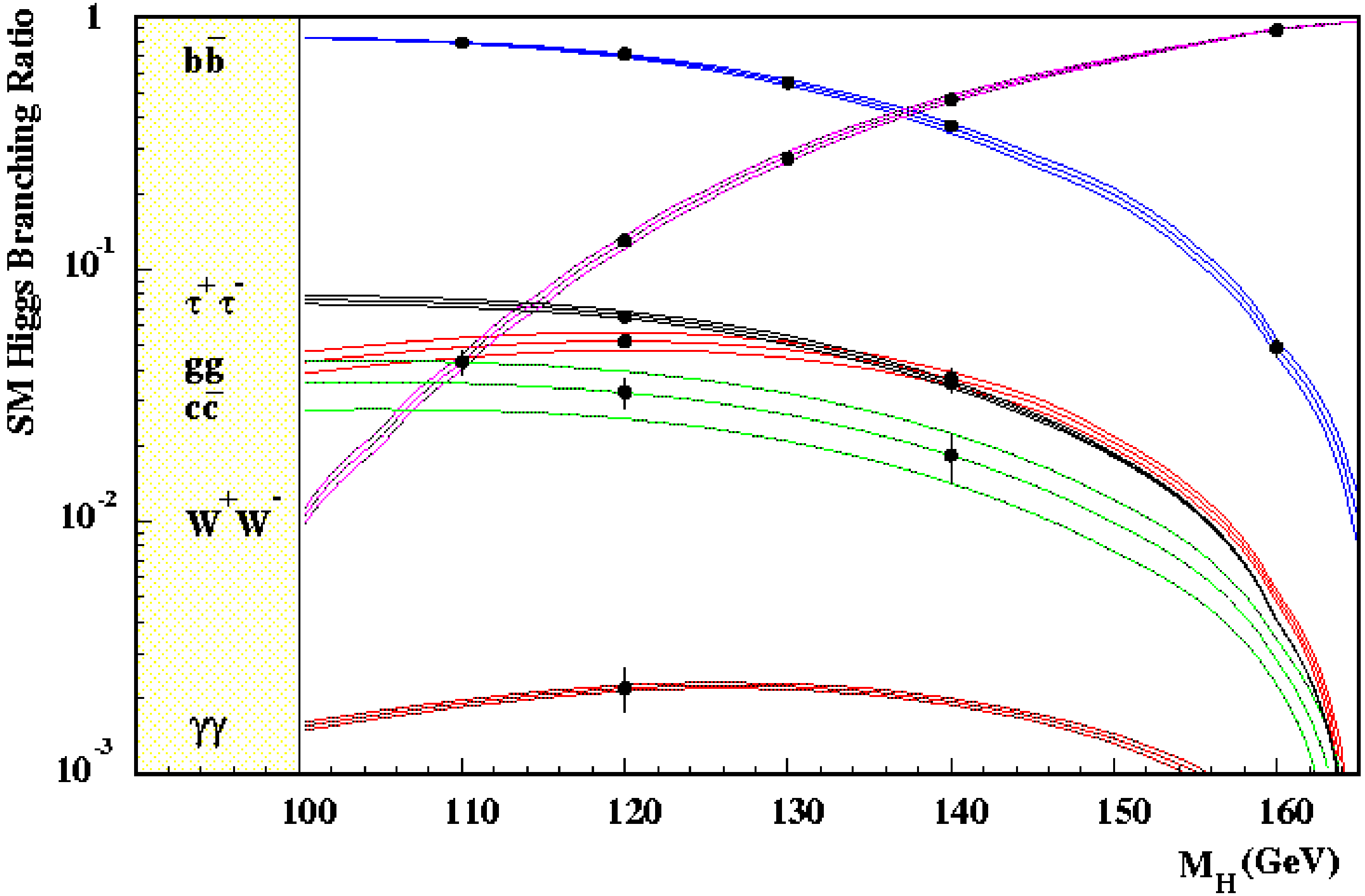


⇒ only Lepton Colliders can “verify” the Higgs mechanism



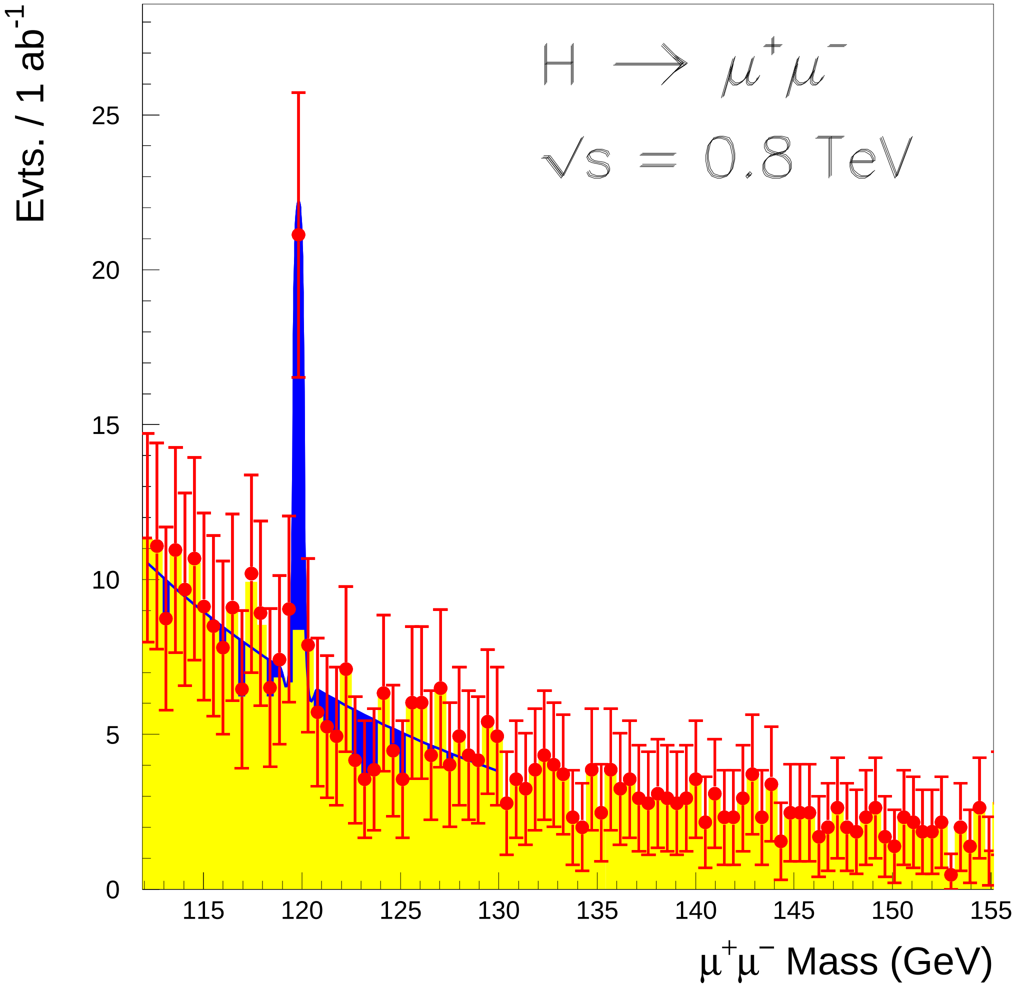
. . . including couplings to the second family!

⇒ coupling to the c quark:



. . . including couplings to the second family!

⇒ coupling to the muon:



($M_H = 120$ GeV, $\sqrt{s} = 800$ GeV, $\mathcal{L}_{\rm int} = 1$ ab^{-1})

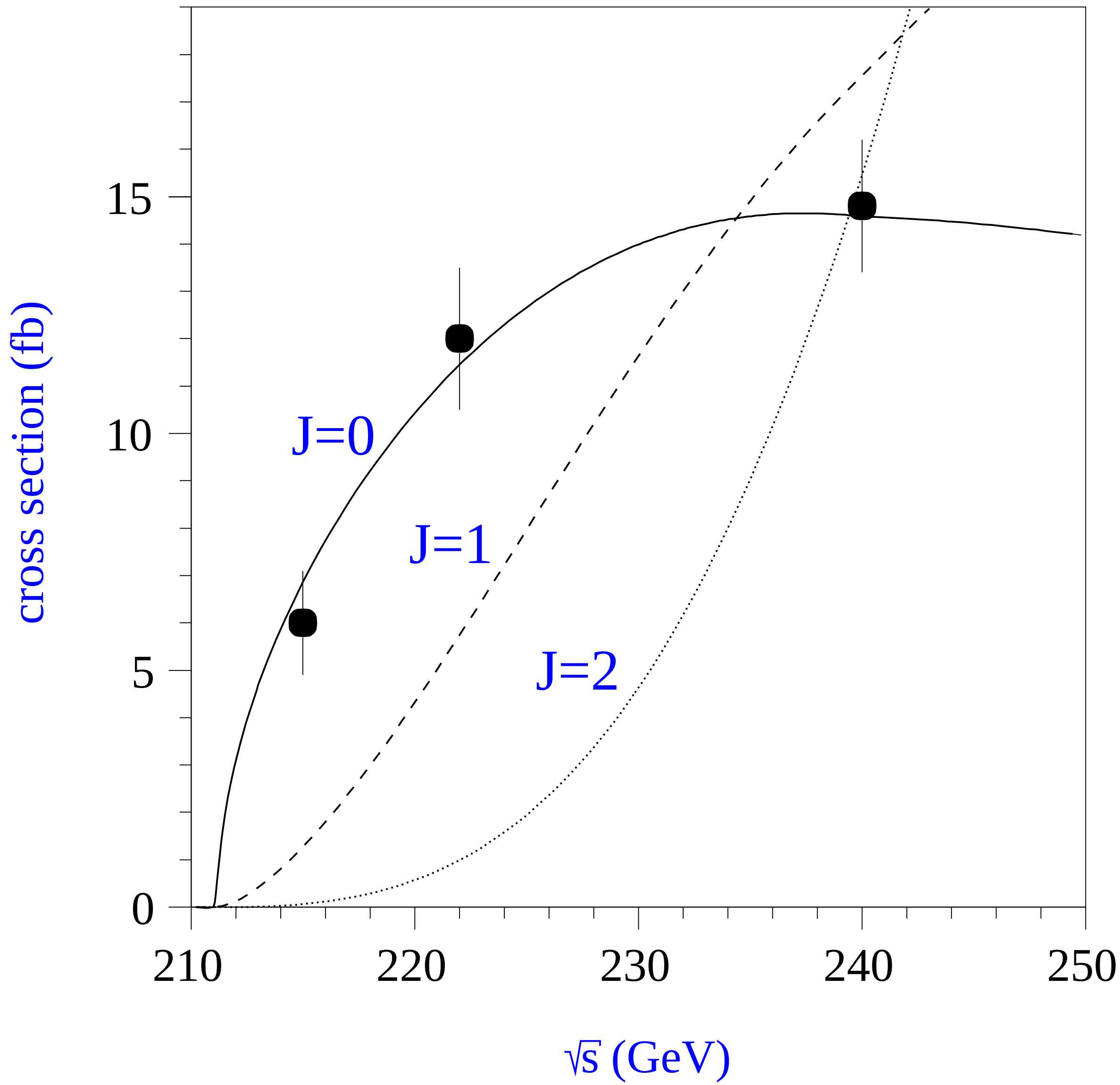
Step 6: measurement of the Higgs boson spin

$\Rightarrow$ easy at the ILC

Threshold scan for
$\sigma(e^+e^- \to ZX)$:

$X = H \Rightarrow \sigma \sim \beta$
(β from kinematics)

20 fb^{-1}
$\Rightarrow$ identification easy



Indirect determination of unknown Higgs sector parameters

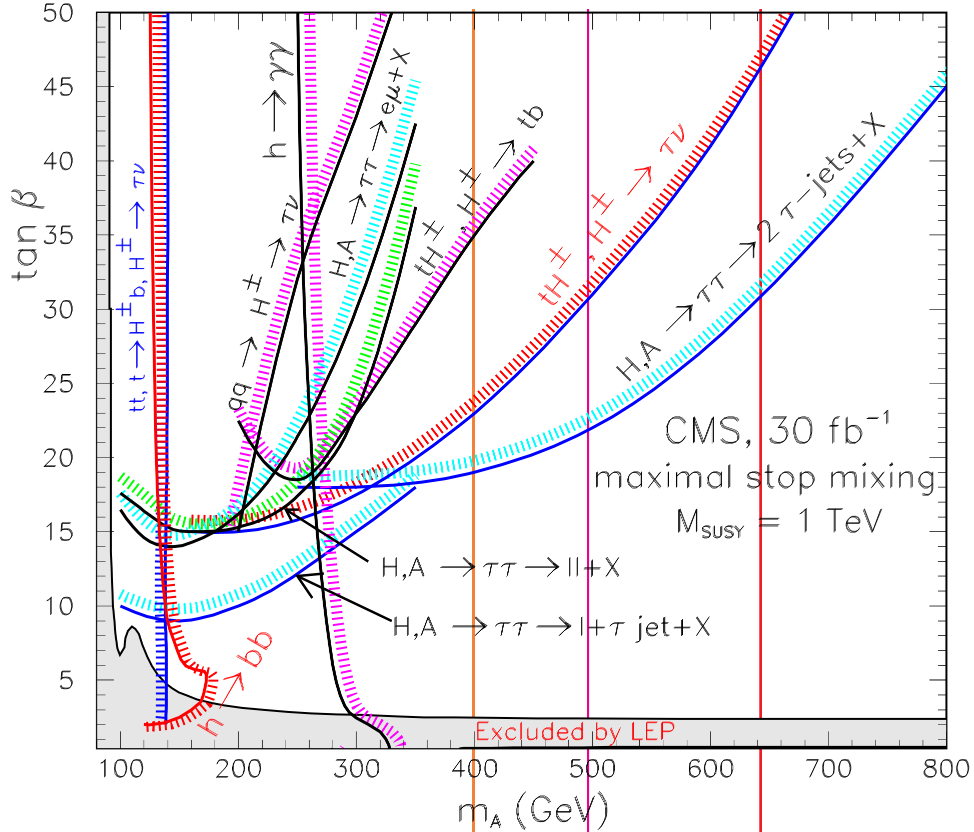
LHC/ILC reach for MSSM Higgs bosons:

LHC:

h : all $M_A - \tan\beta$ plane

H, A : unreachable parts

CMS, 30 fb^{-1}, $m_h^{\rm max}$ scenario: $\Rightarrow$



ILC:

kinematic limit: $M_A \lesssim \sqrt{s}/2$

$\rightarrow \sqrt{s} = 800$ GeV

$\rightarrow \sqrt{s} = 1000$ GeV

ILC: $\sqrt{s} = 800$ GeV
$\sqrt{s} = 1000$ GeV

$\gamma\gamma$:

kinematic limit: $M_A \lesssim 0.8\sqrt{s}$

$\gamma\gamma$: $\sqrt{s} = 800$ GeV

Q: Is it possible to extend the reach for heavy Higgs bosons ?

A: Yes, by direct and indirect measurements

$\Rightarrow$ indirect determination of M_A in LHC wedge

Existing LHC analyses neglect:

– MSSM intrinsic uncertainties
– parametric SM uncertainties
– anticipated parametric MSSM uncertainties

$\Rightarrow$ existing analyses unrealistic

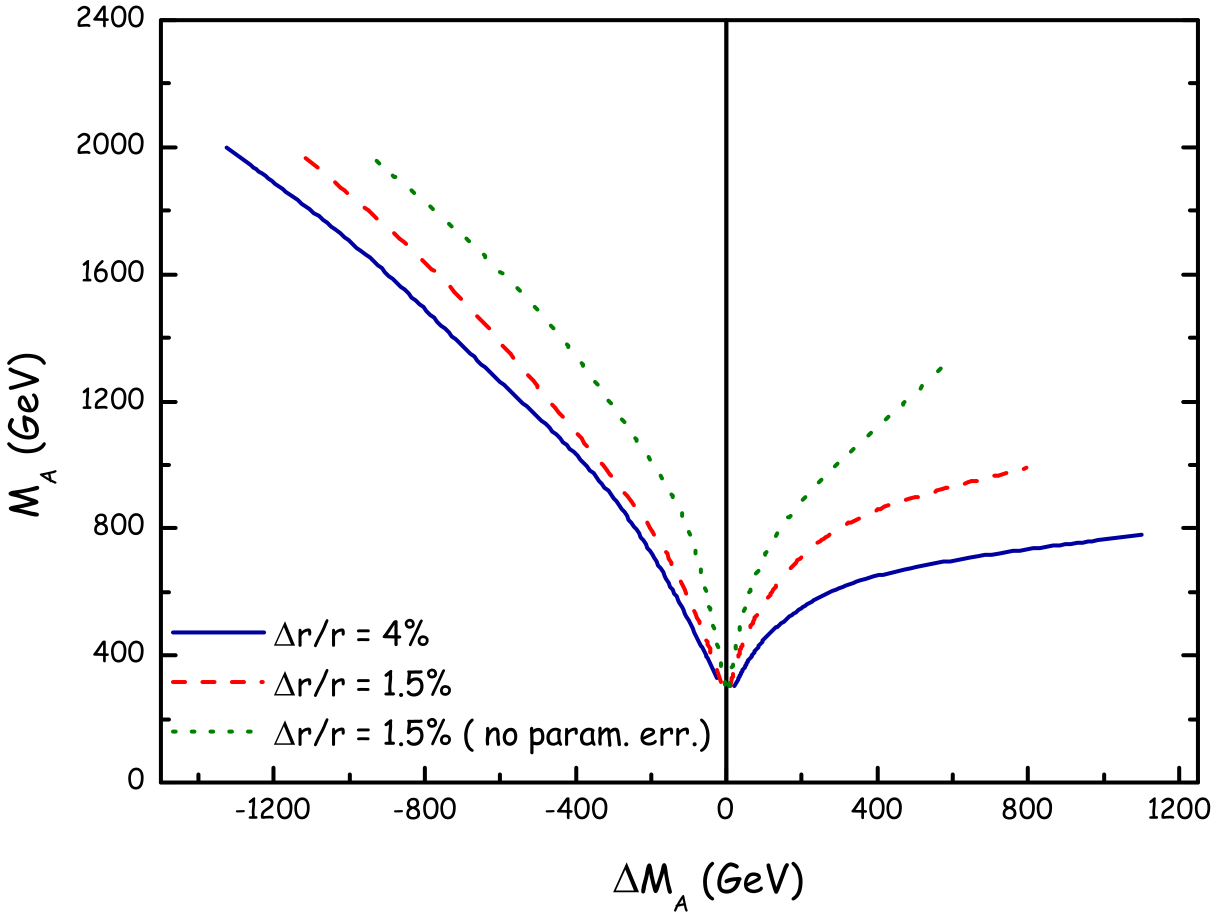
One analysis includes all uncertainties: [*K. Desch et al. '04*]

$\Rightarrow$ needs ILC uncertainty of

$$r \equiv \frac{\left[\mathrm{BR}(h \to b\bar{b})/\mathrm{BR}(h \to WW^*)\right]_{\mathrm{MSSM}}}{\left[\mathrm{BR}(h \to b\bar{b})/\mathrm{BR}(h \to WW^*)\right]_{\mathrm{SM}}}$$

+ input for masses, mixing angles from LHC $\oplus$ ILC

Analysis using r: [K. Desch et al. '04]



$\Delta r/r = 4\%$: upper limit on M_A up to $M_A \lesssim 800$ GeV

$\Delta r/r = 1.5\%$: $\Delta M_A/M_A = 20(30)\%$ for $M_A = 600(800)$ GeV

inclusion of parametric errors crucial for reliable bounds

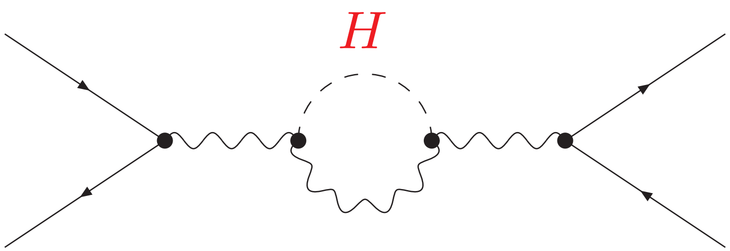
3. The precision frontier

Comparison of electro-weak precision observables with theory:

EW Precision data:		Theory:
$M_W, \sin^2\theta_{\rm eff}, a_\mu$	$\leftrightarrow$	SM, MSSM , . . .

$\Downarrow$

Test of theory at quantum level: Sensitivity to loop corrections, e.g. H



$\Downarrow$

SM: limits on M_H

Very high accuracy of measurements and theoretical predictions needed

Precision observables: M_W, $\sin^2\theta_{\rm eff}$, m_h, $(g-2)_\mu$, b physics, ...

– Theoretical prediction for M_W in terms of $M_Z, \alpha, G_\mu, \Delta r$:

$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right) = \frac{\pi\,\alpha}{\sqrt{2}\,G_\mu}(1+\Delta r)$$

$\Updownarrow$

loop corrections

Evaluate Δr from μ decay $\Rightarrow M_W$

– Theoretical prediction for the effective mixing angle:

$$\sin^2\theta_{\rm eff} = \frac{1}{4\,|Q_f|}\left(1-{\rm Re}\frac{g_V^f}{g_A^f}\right)$$

Higher order contributions:

$$g_V^f \to g_V^f + \Delta g_V^f, \quad g_A^f \to g_A^f + \Delta g_A^f$$

Precision observables: M_W, $\sin^2\theta_{\mathrm{eff}}$, m_h, $(g-2)_\mu$, b physics, ...

– Theoretical prediction for M_W in terms of $M_Z, \alpha, G_\mu, \Delta r$:

$$M_W^2 \left(1 - \frac{M_W^2}{M_Z^2}\right) = \frac{\pi\,\alpha}{\sqrt{2}\,G_\mu}(1 + \Delta r)$$

$$\Updownarrow$$

loop corrections

Evaluate Δr from μ decay $\Rightarrow M_W$

One-loop result for M_W in the SM:

[*A. Sirlin '80*] , [*W. Marciano, A. Sirlin '80*]

$$\Delta r_{1-\mathrm{loop}} = \quad \Delta\alpha \quad - \quad \frac{c_W^2}{s_W^2}\Delta\rho \quad + \quad \Delta r_{\mathrm{rem}}(M_H)$$

$$\sim \log\frac{M_Z}{m_f} \qquad \sim m_t^2 \qquad \log(M_H/M_W)$$

$$\sim 6\% \qquad \sim 3.3\% \qquad \sim 1\%$$

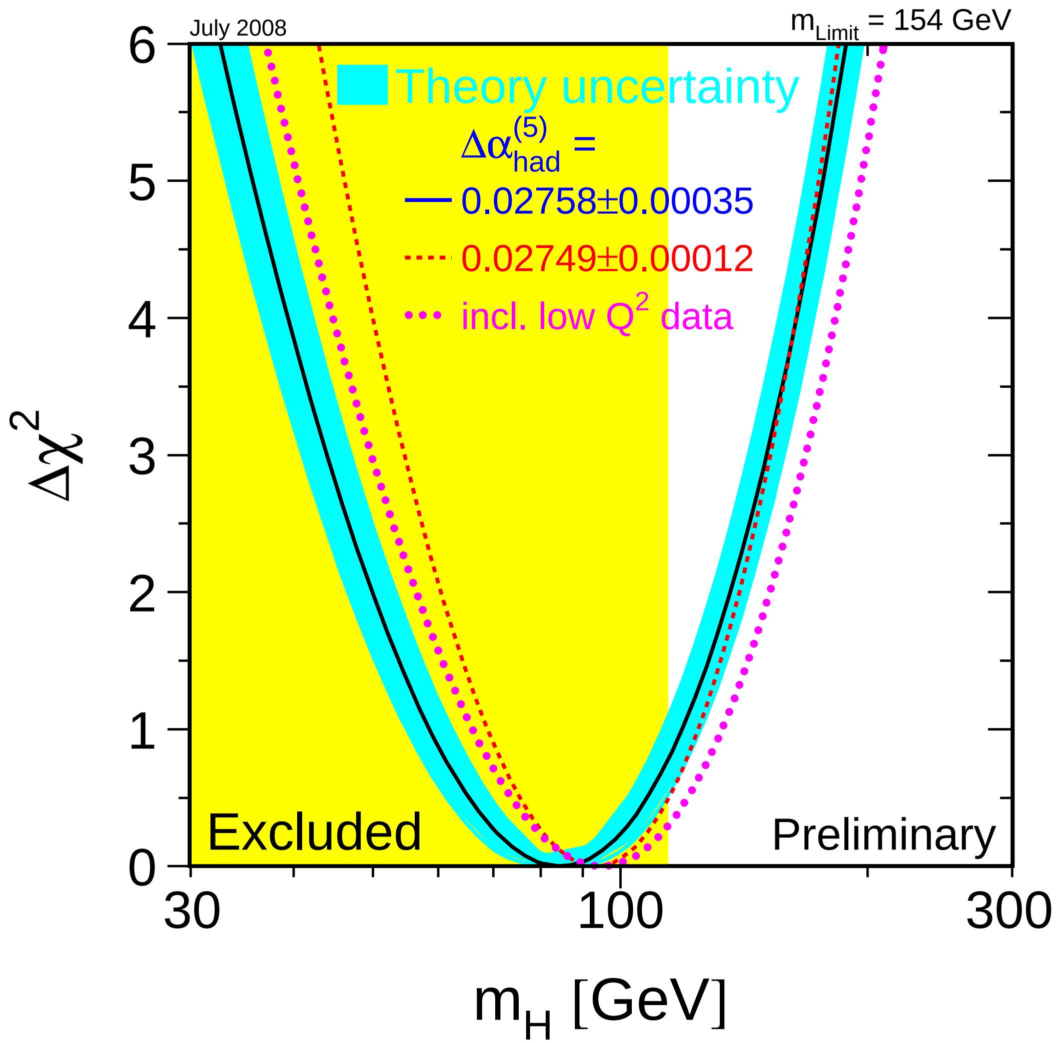
Current knowledge of $M_H^{\rm SM}$

Global fit to all SM data:

[*LEPEWWG '08*]

$\Rightarrow M_H = 84^{+34}_{-26}$ GeV

$M_H < 154$ GeV, 95% C.L.



Assumption for the fit:
SM incl. Higgs boson

$\Rightarrow$ no confirmation of Higgs mechanism

$\Rightarrow$ Higgs boson seems to be light, $M_H \lesssim 150$ GeV

Experimental errors of the precision observables:

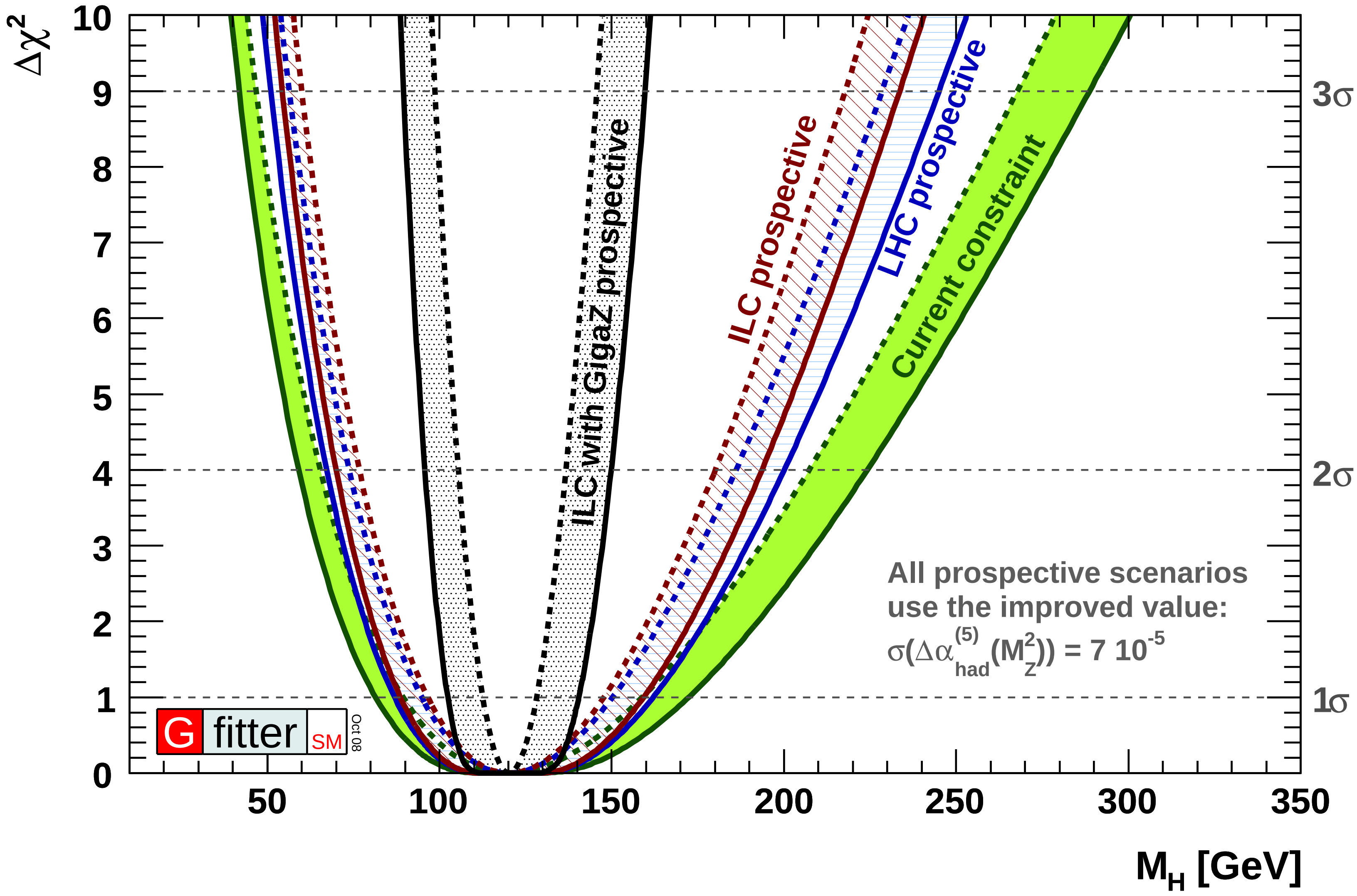
	today	Tev./LHC	ILC	GigaZ
$\delta \sin^2\theta_{\text{eff}} (\times 10^5)$	16	16	–	1.3
δM_W [MeV]	25	15	10	7
δm_t [GeV]	1.2	1-2	0.2	0.1

Relevant SM parametric errors: $\delta(\Delta\alpha_{\text{had}}) = 5 \times 10^{-5}$, $\delta M_Z = 2.1$ MeV

	$\delta m_t = 2$	$\delta m_t = 1$	$\delta m_t = 0.1$	$\delta(\Delta\alpha_{\text{had}})$	δM_Z
$\delta \sin^2\theta_{\text{eff}}$ [10^{-5}]	6	3	0.3	1.8	1.4
ΔM_W [MeV]	12	6	1	1	2.5

Improvement in the Blue Band plot:

[GFitter '09]



(note: artificially $M_H^{\text{SM}} = 120$ GeV)

So-called "tricky scenario":

The LHC finds only a SM-like Higgs and nothing else

Q: Do we still need the ILC?

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The LHC finds only a SM-like Higgs and nothing else

Q: Do we still need the ILC?

A: Of course! Or better: even more!

The ILC provides:

– precise Higgs coupling measurements

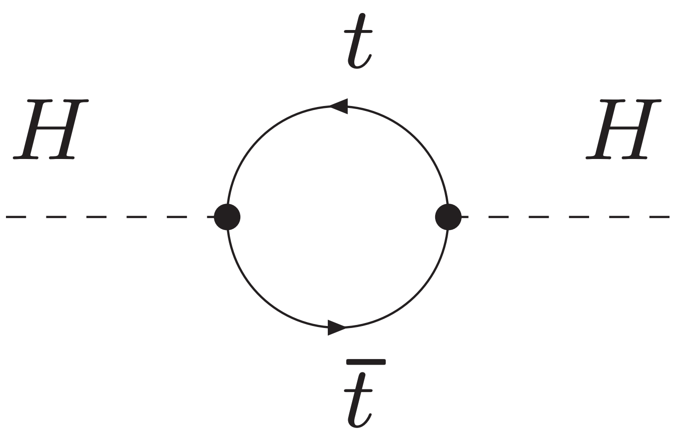
– precision observable measurements with the GigaZ option

⇒ Only the ILC can find deviations from the SM predictions via the various precision measurements

⇒ Only the ILC can point towards extensions of the SM

Going to extensions of the SM:

Nearly any model: large coupling of the Higgs to the top quark:



$\Rightarrow$ one-loop corrections $\Delta M_h^2 \sim G_\mu m_t^4$

$\Rightarrow$ M_H depends sensitively on m_t in all models where M_H can be predicted (SM: M_H is free parameter)

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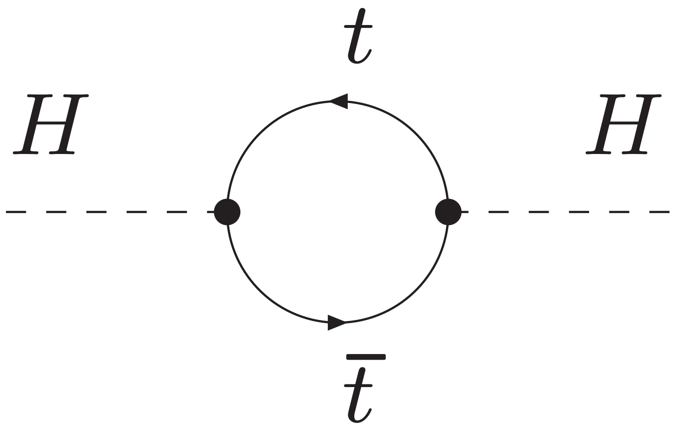

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$\Rightarrow$ Precision Higgs physics needs precision top physics

Contrary to the SM:

M_h is not a free parameter

MSSM tree-level bound: $M_h < M_Z$, excluded by LEP Higgs searches

Large radiative corrections:

Dominant one-loop corrections:

$$\Delta M_h^2 \sim G_\mu m_t^4 \log\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right)$$

The MSSM Higgs sector is connected to all other sector via loop corrections (especially to the scalar top sector)

Measurement of M_h, Higgs couplings $\Rightarrow$ test of the theory

LHC: $\Delta M_h \approx 0.2$ GeV

ILC: $\Delta M_h \approx 0.05$ GeV

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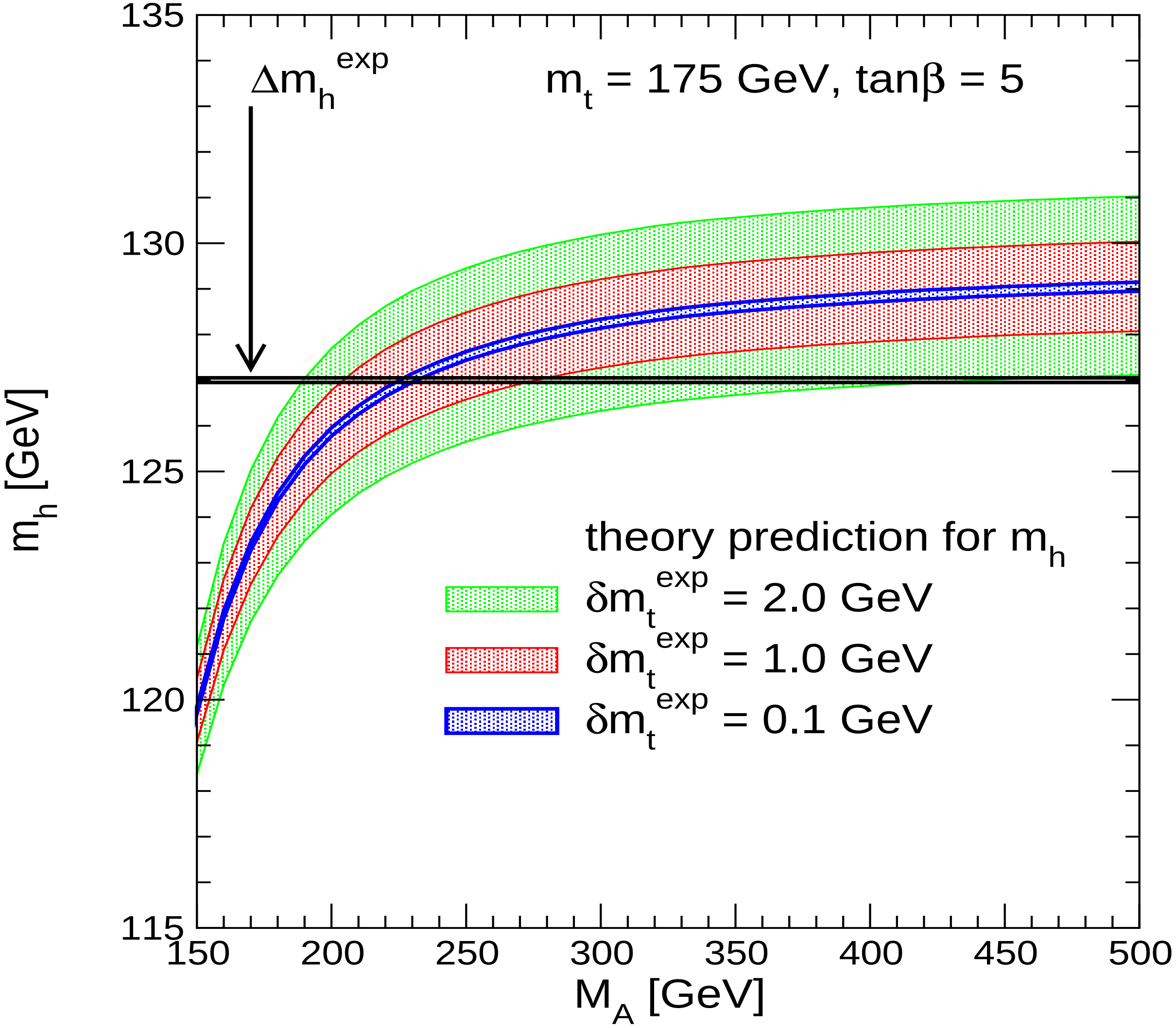
$\Rightarrow$ LHC precision of M_h requires ILC precision of m_t

Example: parametric uncertainty vs. experimental error:



m_h^{max} benchmark scenario (no experimental errors on SUSY parameters)

⇒ ILC precision on m_t needed to match experimental accuracy

4. Left out topics

1. The heavy MSSM Higgs bosons:
   possible to resolve M_A vs. M_H ?

2. $\tan\beta$:
   precise measurement of $\tan\beta$ (e.g. via $\gamma\gamma \to \tau\tau \to H$)

3. The cosmology connection:
   Funnel region: detailed knowledge of M_A, Γ_A, $g_{A\chi\chi}$ needed

4. MSSM vs. NMSSM
   possible to distinguish the NMSSM from the MSSM

5. μC: Higgs width
   direct measurement of Higgs width possible

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$\Rightarrow$ only precise knowledge of low-energy parameters will allow reconstruction of GUT scale physics

5. Conclusions

- Discovering the Higgs (mechanism):
  find the particle, measure its mass, all its couplings, quantum numbers

- Couplings: often LHC precision is not enough
  ILC/CLIC needed to discriminate models
  to determine unknown parameters indirectly
  to determine Higgs self-couplings (Higgs potential!)
  to determine quantum numbers . . .

- ILC/GigaZ: precision measurements of M_W, $\sin^2\theta_{\mathrm{eff}}$, m_t, . . .

  ⇒ most stringent consistency test of the SM
  ⇒ can point to scales beyond the SM
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Future Lepton Colliders are CRUCIAL to find the "ultimate theory"!

Remaining WG1 (Higgs) discussions:

Monday, 23.02., 4.30pm:

– input from precision observables (LHC/ILC/GigaZ) to the Higgs sector
  Discussion leader: Wolfgang Hollik

– Higgs masses, couplings: what can measured? Where?
  How much model dependence enters?
  What are "optimal observables"?

Wednesday, 25.02., afternoon:

– What can we learn from the LHC with 200 pb^{-1}?
  Discussion leader: Andrey Korytov

Friday, 27.02., 10.00am:

– on: C/C' (extension of discussion on 18.02.):
  How exactly could we detect a deviation with 10 fb^{-1}?
  How does the deviation from the SM tell us where/how to search
  at future colliders?

sites.google.com/site/lhc2fchiggs