Higgs Physics

Yasuhiro Okada (KEK)

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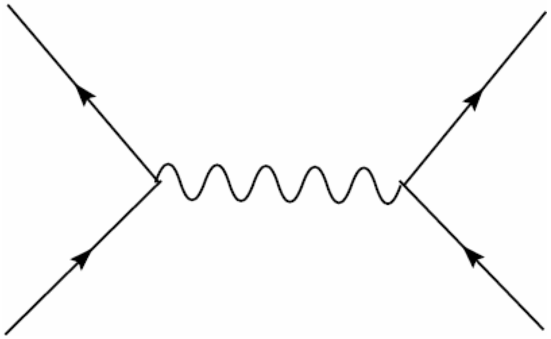
Higgs mechanism

- One of two principles of the Standard Model.

  “Gauge invariance” and “Higgs mechanism”
- Origin of the weak scale.

  “Why is the weak interaction so weak?”

$$G_F = \frac{1}{\sqrt{2}v^2}$$



Goals of Higgs physics

- Find Higgs bosons and establish the mass generation mechanism of quarks, leptons and the gauge bosons.

  Coupling constant measurements

- Clarify physics behind the electroweak symmetry breaking.

  “What is the Higgs particle?”

  Elementary or composite?

  A window to the physics beyond the Standard Model.

Higgs boson mass

- Higgs mass -> Strength of the dynamics responsible for the electroweak symmetry breaking.
- In the SM,

$$m_h = \sqrt{2\lambda} v \qquad V = -\mu^2 |\phi|^2 + \lambda |\phi|^4$$

- In general,

a light Higgs boson is consistent with weakly interacting scenario (GUT/SUSY/String unification ?),

a heavy Higgs boson implies strongly interacting scenario.

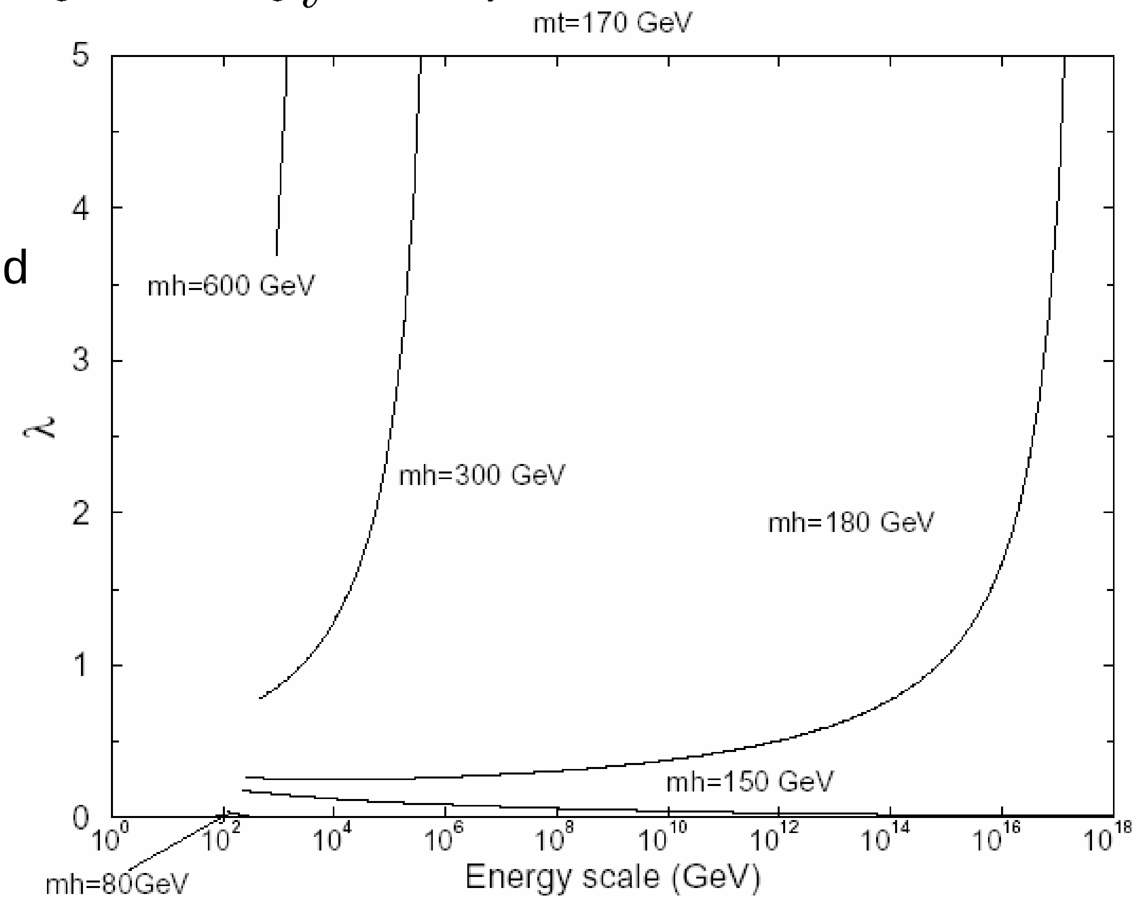
Theoretical bounds on the Higgs boson mass in the SM

RGE for the Higgs self-coupling constant in the SM

$$\mu\frac{d}{d\mu}\lambda = \frac{1}{16\pi^2}(24\lambda^2 + 12y_t\lambda - 6y_t^2 + ...)$$

If we require that the SM is valid up to 10^19 GeV,

$$130\text{GeV} \leq m_h \leq 180 \text{ GeV}$$



Higgs mass in SUSY models

- SUSY models include at least two Higgs doublets.
- In the minimal SUSY Standard Model (MSSM), the lightest CP-even Higgs boson mass has theoretical upper bound.

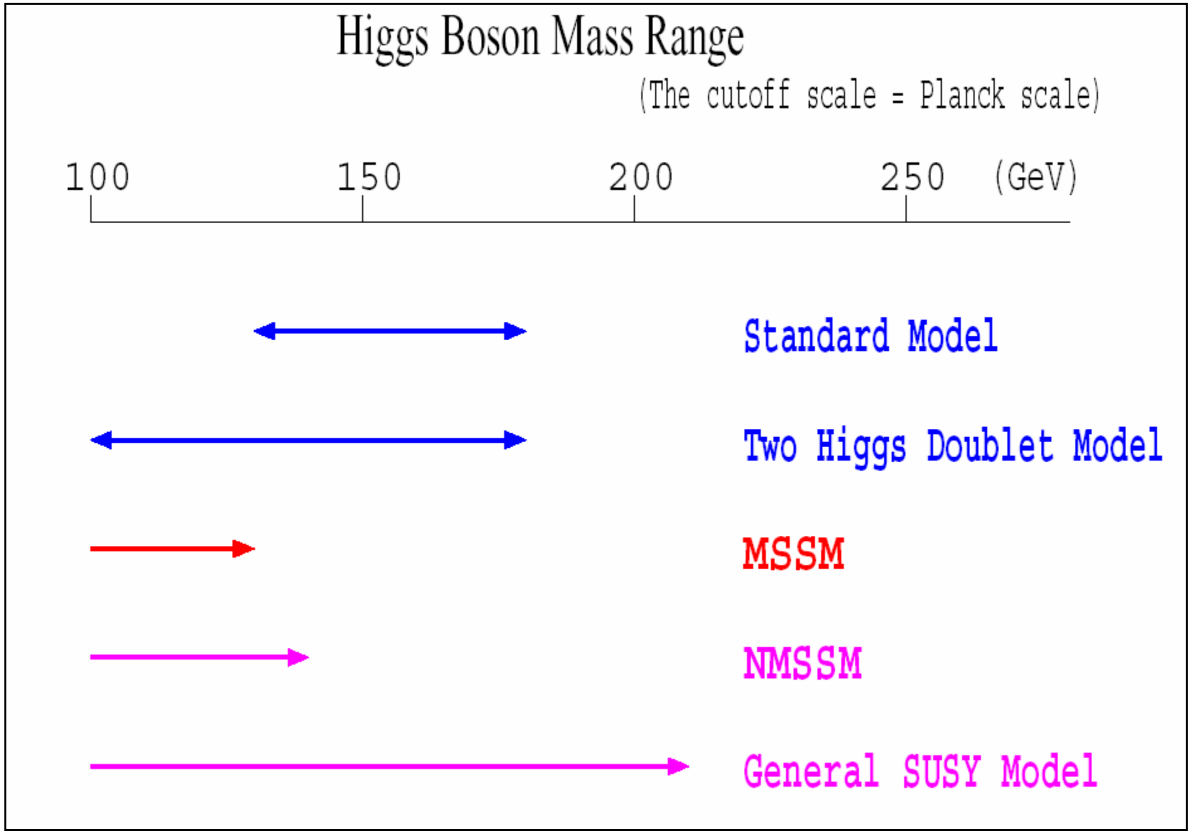
$$V_{Higgs} = m_1^2|H_1|^2 + m_2^2|H_2|^2 - m_3^2(H_1 \cdot H_2 + \bar{H}_1 \cdot \bar{H}_2) + \frac{g_2^2}{8}(\bar{H}_1\tau^a H_1 + \bar{H}_2\tau^a H_2)^2 + \frac{g_1^2}{8}(|H_1|^2 - |H_2|^2)^2 + \Delta V.$$

$$m_h^2 \le m_Z^2 \cos^2 2\beta + \frac{6}{(2\pi)^2}\frac{m_t^4}{v^2}\ln\frac{m_{stop}^2}{m_t^2}, \qquad \left(\tan\beta = \frac{<H_2^0>}{<H_1^0>}\right)$$

$$m_h < 135\text{GeV}$$

Possible vacuum instability is saved by supersymmetry.

Possible range of the lightest Higgs boson mass for the Planck scale cutoff

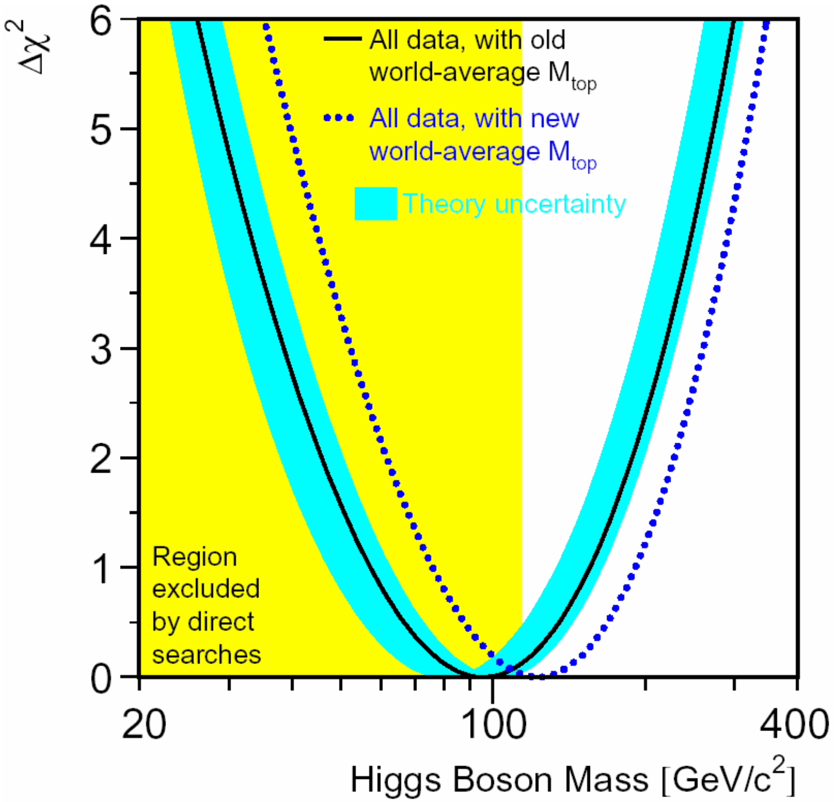


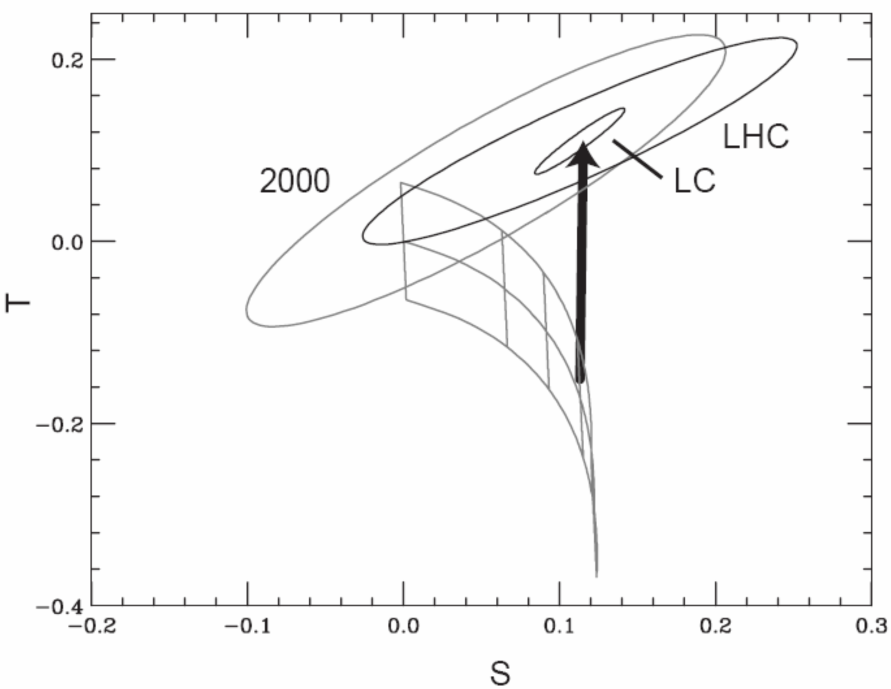
As long as theory behaves weakly-coupled up to the Planck scale, the Higgs bosom mass is les than ~200 geV.

Precision EW test and the Higgs Mass

In the SM, the global fit suggests a light Higgs boson.

M.Peskin and J.Wells





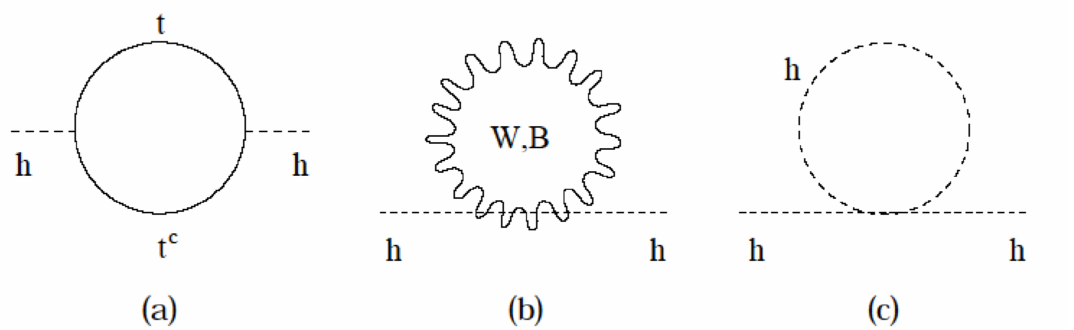
$$m_h < 251 \text{ GeV } (95\%\text{CL})$$

mt=174.3+-5.1GeV
mh=100,200,300,500,1000 GeV

Additional new physics is needed to accommodate a heavy Higgs boson.

Hierarchy problem

- If the cutoff scale is very high, fine tuning of the Higgs boson mass is serious problem.

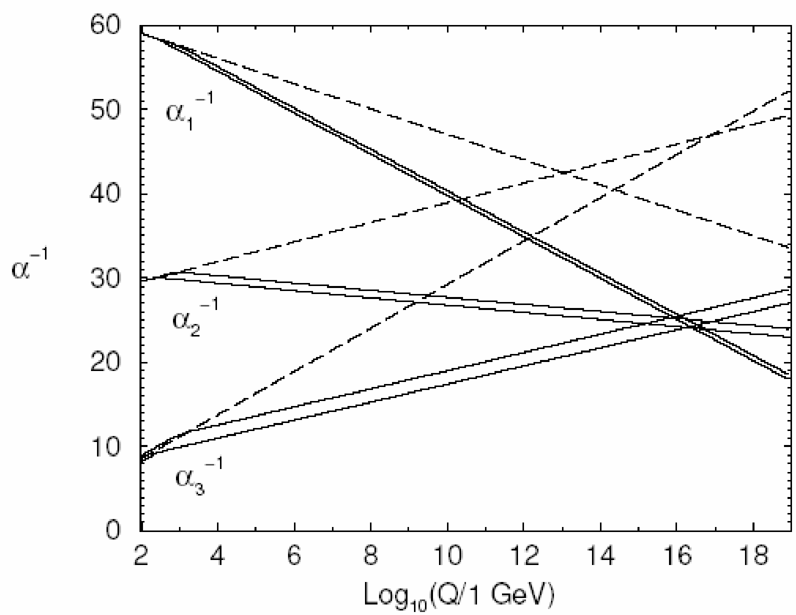


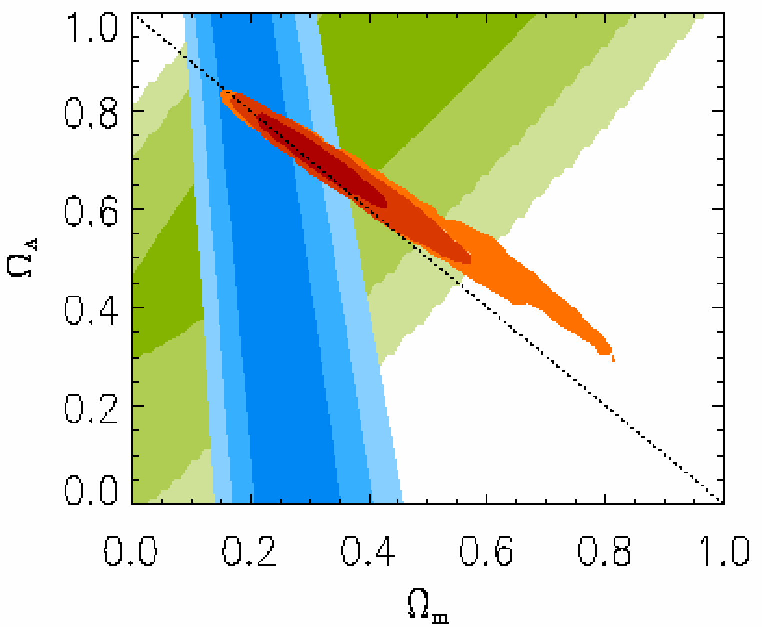
$$m_{phys}^2 = m_0^2 + g^2 \Lambda_{cutoff}^2$$

We need to find a reason to keep the Higgs boson mass light.

Supersymmetry

- Extend relativity.
- Introduce SUSY partners
- No quadratic divergence in scalar masse renormalization in SUSY theory.
- Justification of elementary scalar fields up to the Planck scale.
- Gauge coupling unification, dark matter candidate.





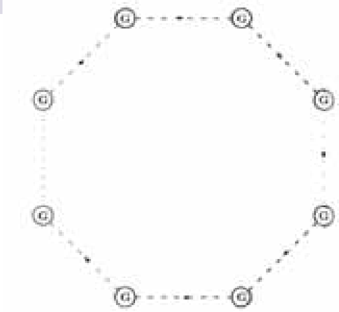
Compositeness

- The Higgs boson is a composite state of some strong interaction.
- This scenario is usually severely constrained by the precision EW measurements.
- New ideas are proposed.

  Deconstruction, Little Higgs model, Higgsless model, etc.

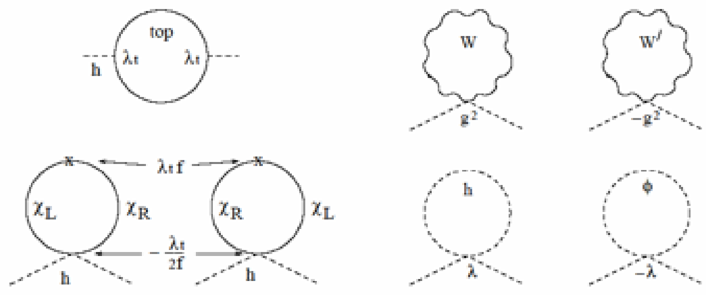
- Deconstruction.

Gauge theory with a discretized fifth dimension.



- Little Higgs model.

Higgs as a pseudo NG boson. No quadratic divergence at one-loop.

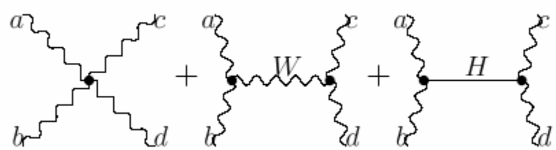


- Higgsless Model .

5dim model without a Higgs boson. Unitarity is saved by KK modes of gauge bosons

$W_L W_L$ scattering amplitude in the SM

$$i\mathcal{M}(W_L^a W_L^b \to W_L^c W_L^d) =$$



+crossed.

Common feature
New states at ~1TeV
Cutoff scale > 10 TeV
Severe constraints from EW precision tests

Summary 1

- Higgs physics : Understanding the weak scale.
- What is the Higgs particle?

  Elementary (like gravity) or composite (like pion)?

  Very important implications for particle physics and cosmology.
- How is the hierarchy problem solved?

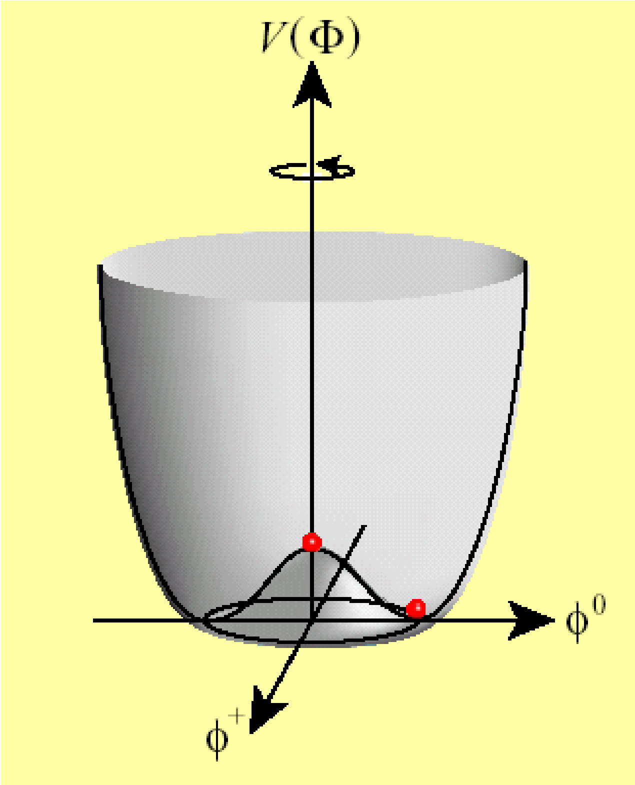
  SUSY?
- Higgs physics is a central issue in and beyond the SM.

Phenomenology of Higgs bosons

- In order to establish the mass generation mechanism of elementary particles, various Higgs boson couplings have to be determined.
- A Higgs boson will be discovered at LHC, but we need ILC to establish the Higgs mechanism.

Higgs potential in the SM

$$V = -\mu^2|\phi|^2 + \lambda|\phi|^4$$



Mass formulas of elementary particles in the SM

Higgs particle $$m_h = \sqrt{2\lambda}v$$

Top quark $$m_t = \frac{y_t}{\sqrt{2}}v$$

W boson $$m_W = \frac{g_2}{2}v$$

Z boson $$m_Z = \frac{\sqrt{g_1^2+g_2^2}}{2}v$$

VEV of the Higgs field

$$<\phi^0> = v/\sqrt{2}$$

Higgs search at LHC

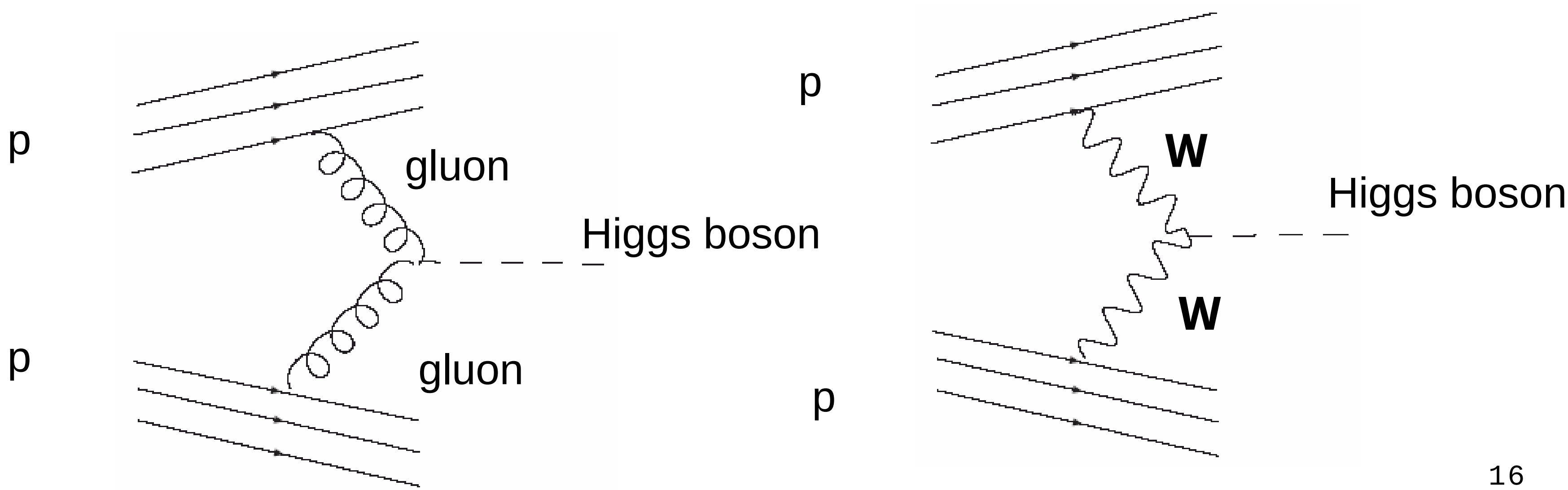
LHC: 2007 14 TeV pp collider

Discovery of the Higgs boson is a main target.

Higgs boson search depends on the Higgs boson mass

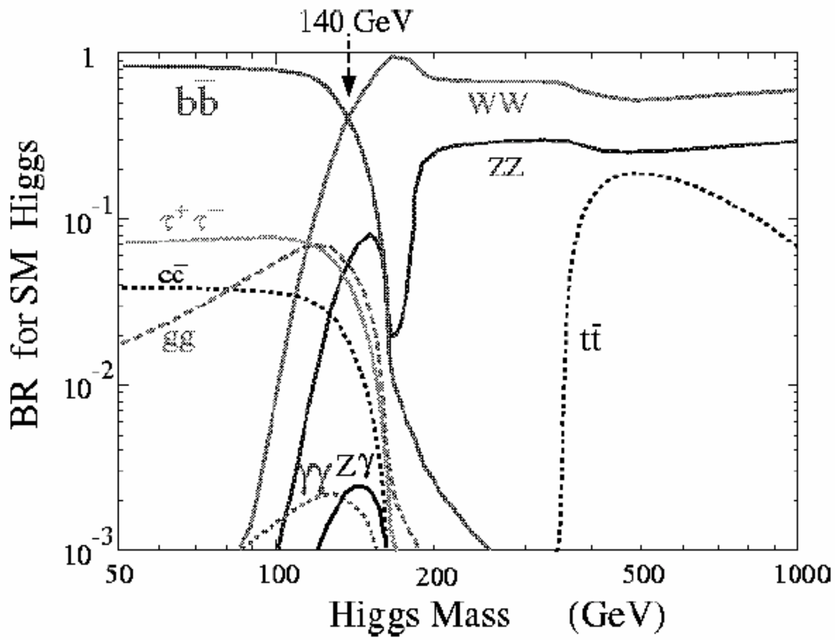
Production: gluon fusion, WW fusion

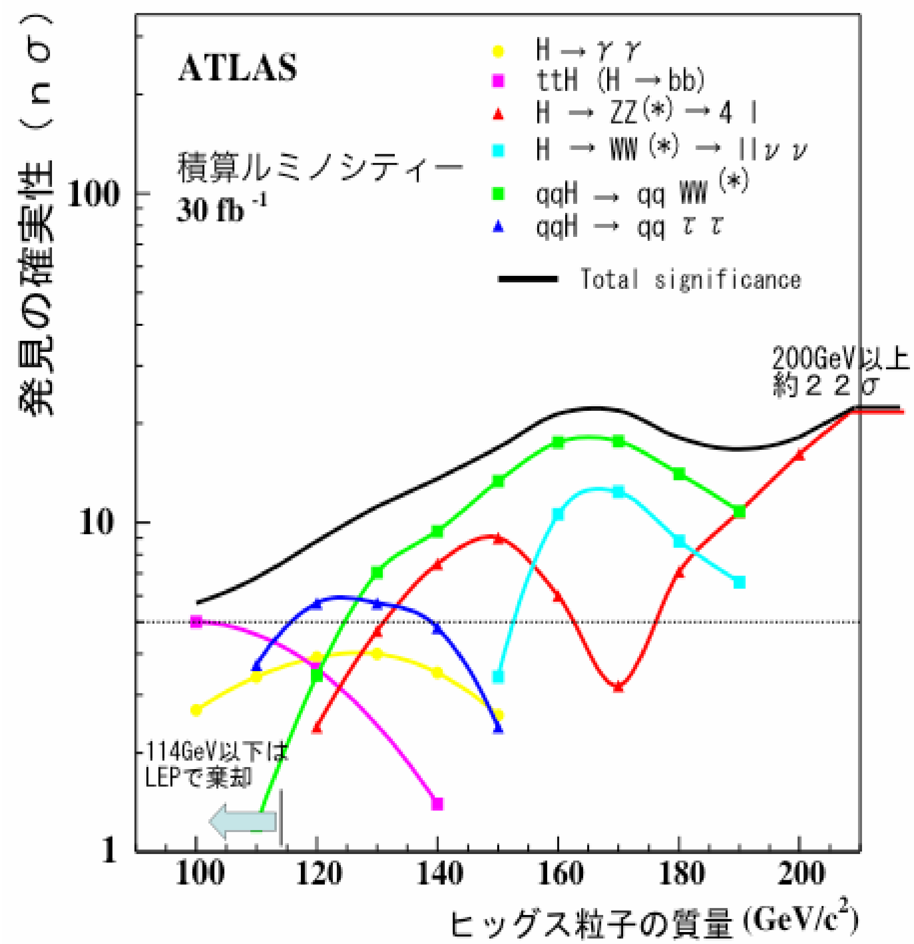
Decay: decay to heavier particles if kinematically allowed.



SM Higgs boson decay branching ratios

Higgs discovery at ATLAS

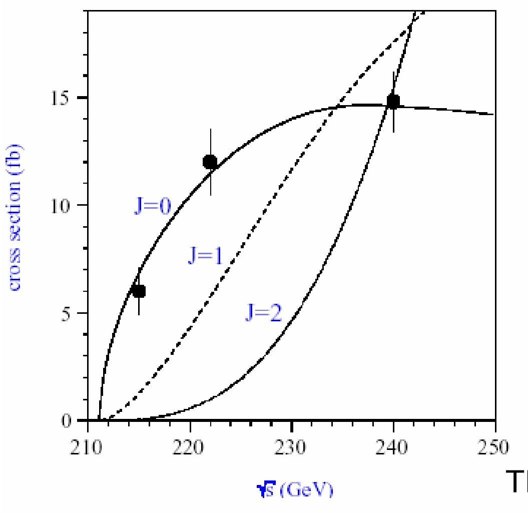




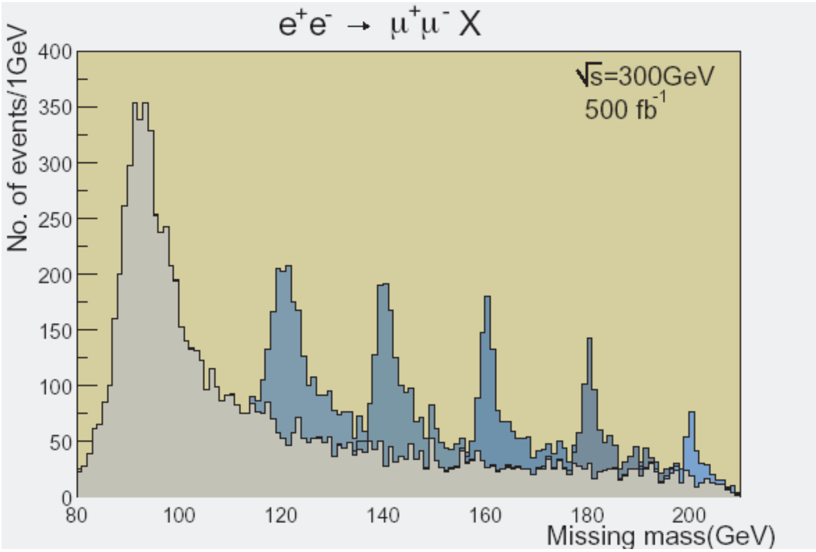
At LHC, a SM-like Higgs boson can be discovered independent of its mass.

Higgs physics at LC

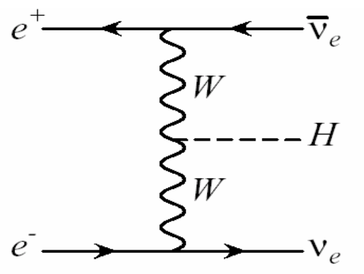
- Determination of spin and parity.
- Precise mass determination .
  ($\delta m_H \sim 40$ MeV for $m_H = 120$ GeV)
- Detection of the Higgs boson independent of its decay property. (Recoil mass distribution in the HZ mode)
- Coupling measurement
  -> Mass generation mechanism of elementary particles.

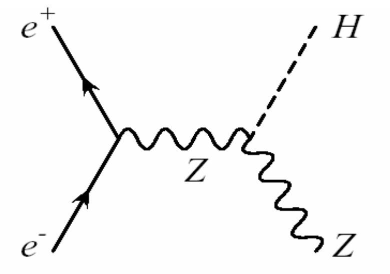


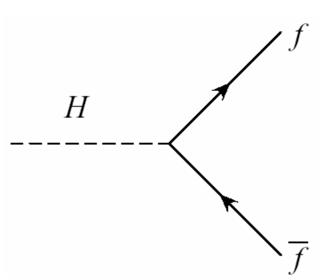
TESLA TDR

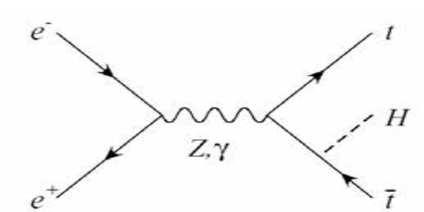


GLC report







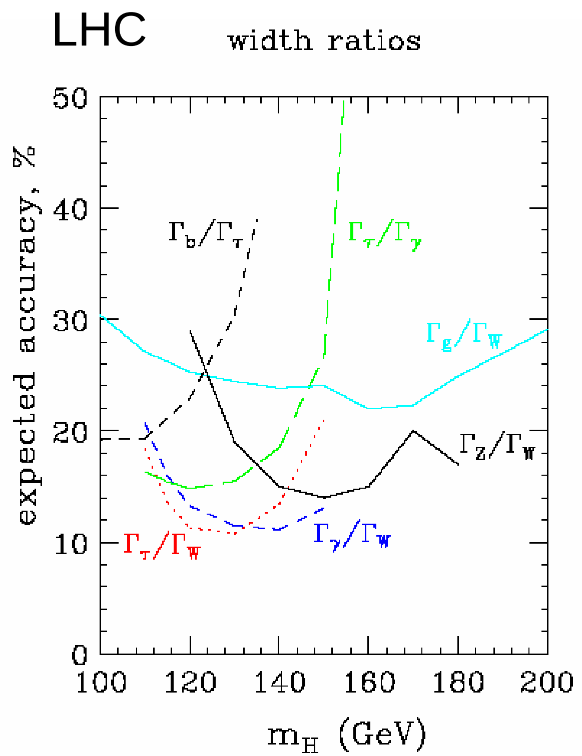


Higgs coupling measurement

LHC: O(10%) measurements for some ratios of coupling constants.
LC: O(1%) determination for various coupling constants.

LC

Precision of coupling determination
mH=120 GeV, 500/fb



$\sqrt{s}$	300 GeV	400 GeV	500 GeV
Δm_h (lepton-only)	80 MeV	—	—
Δm_h	40 MeV	—	—
$\Delta\sigma/\sigma$ (lepton-only)	2.1%	2.5%	2.9%
$\Delta\sigma/\sigma$	1.3%	—	—
$\Delta(\sigma_h \cdot Br(b\bar{b}))$	2.0%	—	—
ZZH-coupling ΔZZH/ZZH	1.1%	1.3%	1.5%
WWH-coupling ΔWWH/WWH	1.6%	—	—
$\Delta\Gamma_{h^0}/\Gamma_{h^0}$	5.5%	12%	16%
Yukawa coupling $\Delta\lambda/\lambda$			
λ_b	2.8%	6.1%	8.1%
λ_τ	3.5%	—	—
λ_c	11.3%	13%	15%
λ_b/λ_τ	2.3%	—	—
λ_b/λ_c	11%	12%	14%
$\lambda_{up-type}$	4.1%	—	—
$\lambda_{down-type}/\lambda_{up-type}$	3.2%	—	—
$\Delta(\sigma \cdot Br)/(\sigma \cdot Br)$			
$h^0 \to b\bar{b}$	1.1%	1.3%	1.7%
$h^0 \to W^+W^-$	5.1%	12%	16%
$h^0 \to \tau^+\tau^-$	4.4%	—	—
$h^0 \to c\bar{c}+gg$	6.3%	—	—
$h^0 \to c\bar{c}$	22%	23%	27%
$h^0 \to gg$	10%	11%	13%
$h^0 \to \gamma\gamma$	—	—	—
$h^0 \to Z^0\gamma$	—	—	—

The Precision Higgs WG of Smowmass 2001

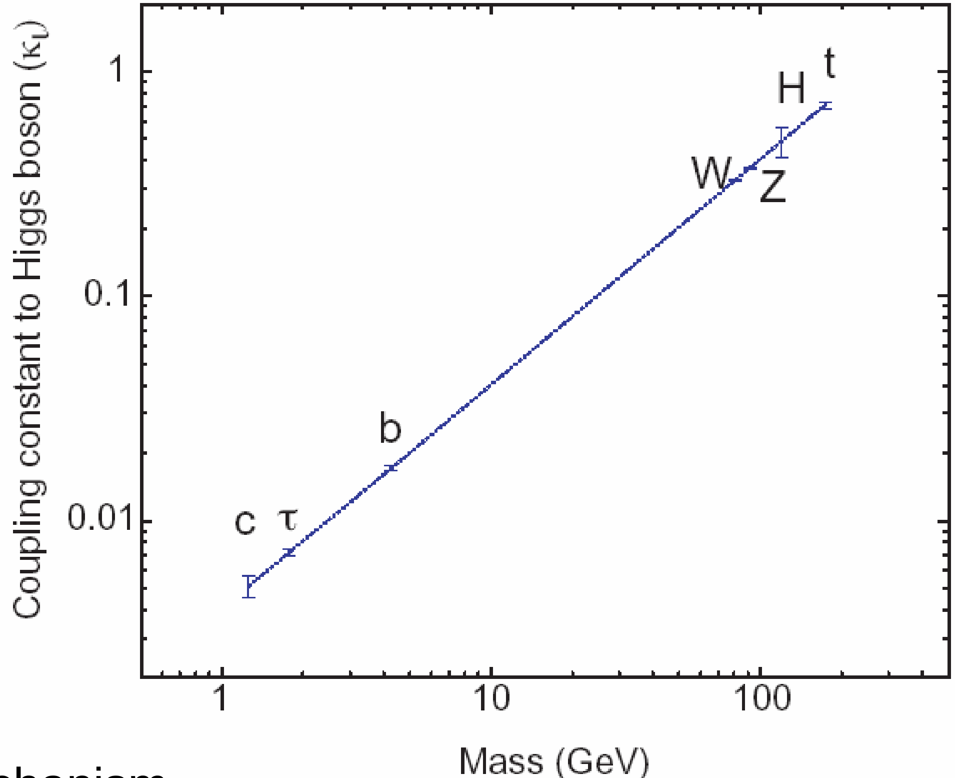
ACFA report

Coupling Mass relation

Particle mass

$$m_i = v \times \kappa_i$$

Higgs coupling constant



Establish the mass generation mechanism

LC:300 – 700 GeV

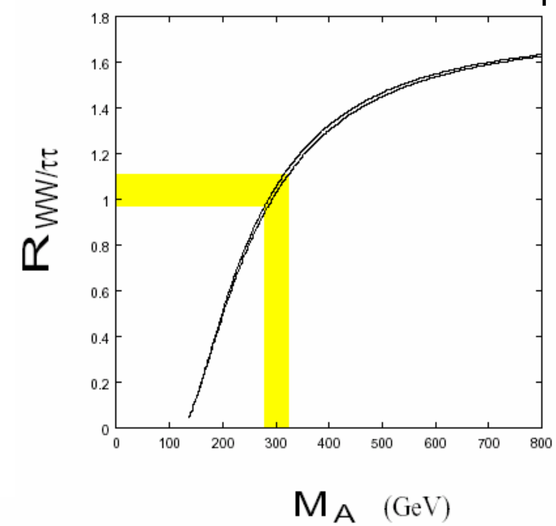
Implication of the branching ratio measurements for MSSM

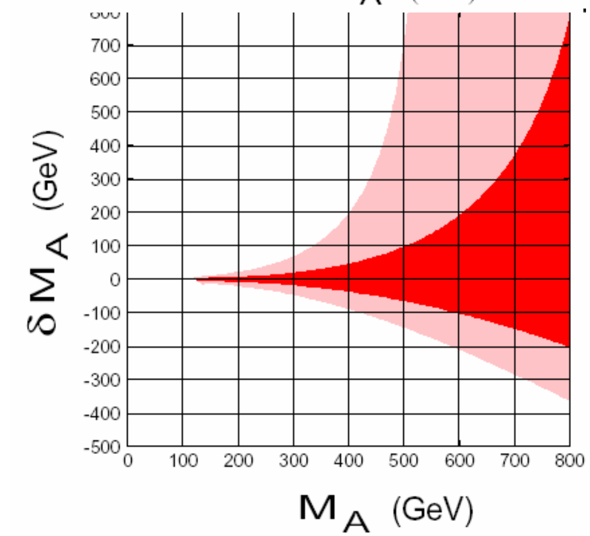
ACFA report 2001

In the MSSM, the ratio of the branching ratios like B(h->cc)/B(h->bb) is useful to constrain the SUSY parameter, especially the heavy Higgs boson mass.
(Kamoshita-Okada-Tanaka, 1995)

$$
\begin{aligned}
R_{cc+gg/\tau\tau} &\equiv \frac{(B(h\to c\bar{c}) + B(h\to gg))}{B(h\to \tau\bar{\tau})} \\
&\simeq \left(\frac{m_A^2 - m_h^2}{m_A^2 + m_Z^2}\right)^2 R_{cc+gg/\tau\tau}(SM) \\
R_{WW/\tau\tau} &\equiv B(h\to W^{(*)}W^{(*)})/B(h\to \tau\bar{\tau}) \\
&\simeq \left(\frac{m_A^2 - m_h^2}{m_A^2 + m_Z^2}\right)^2 R_{WW/\tau\tau}(SM)
\end{aligned}
$$

This is particularly important when LHC and the first stage of LC find the only one Light SUSY Higgs boson.

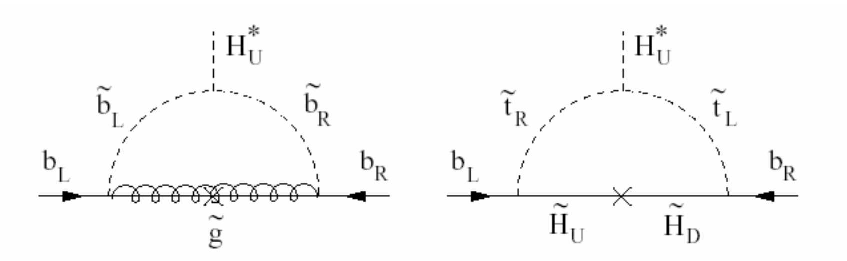




Dark region = LC
Light region = LHC

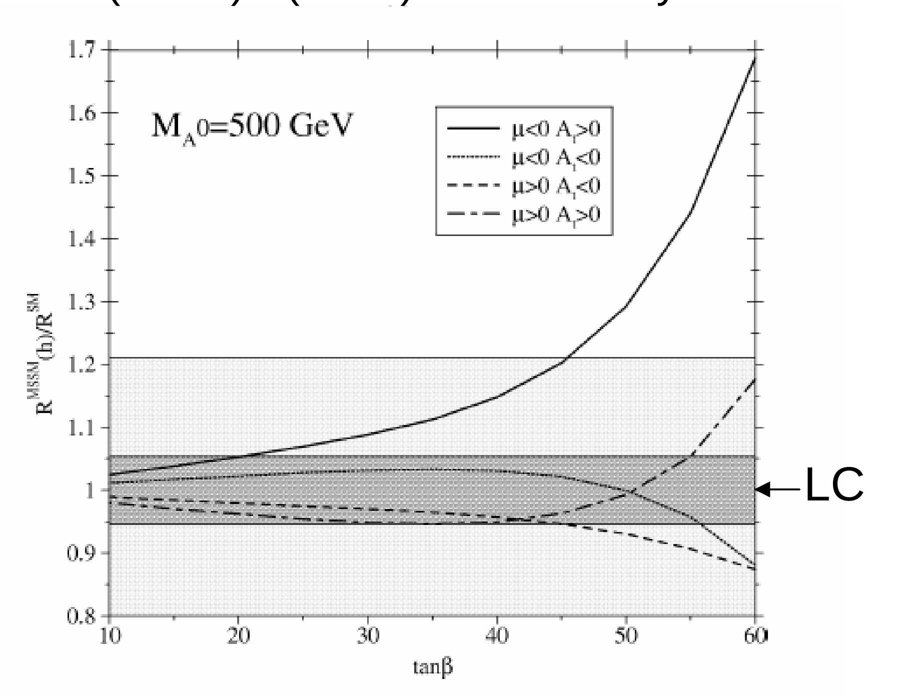
SUSY loop contributions to the hbb Yukawa coupling

B(h->bb)/B(h->ττ) is sensitive to the SUSY loop correction to the bottom Yukawa coupling for a large tanβ region.



K.S.Babu, C.Kolda:
M.Carena, D.Garcia, U.Nierste, C.E.M.Wagner

B(h->bb)/B(h->ττ) nomalized by SM value



$$M_{\tilde{g}} = M_{\tilde{b}_1} = M_{\tilde{t}_1} = M_{\tilde{\tau}_1} = M_2 = |\mu| = A_b$$
$$= A_\tau = |A_t| = 1.5\ \mathrm{TeV},$$

J.Guasch, W.Hollik,S.Penaranda

SUSY Higgs sector

Two Higgs doublet model

$\tan\beta$ (vacuum angle)

$$m_h = f(m_A, \tan\beta, m_t, m_{\tilde{t}}, \ldots)$$

Determination of tan β from:
mass formula,
heavy Higgs decay branching,
stau decay,
chargino-neutralino sector…

↔

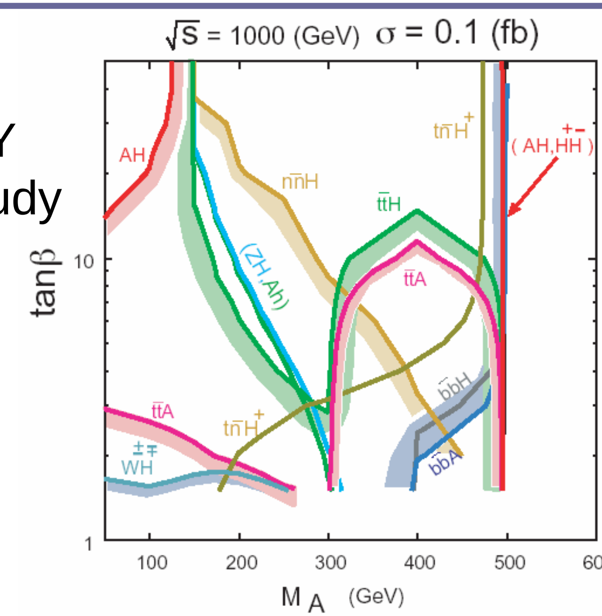
EW gauge interaction

$\sin\theta_W$ (gauge boson mixing angle)

ρ -parameter

Determination of sin θw from various EW processes (LEP, SLC).

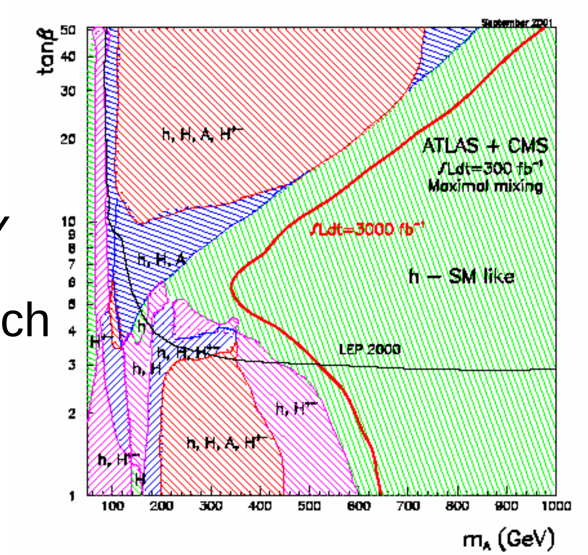
LC SUSY Higgs study



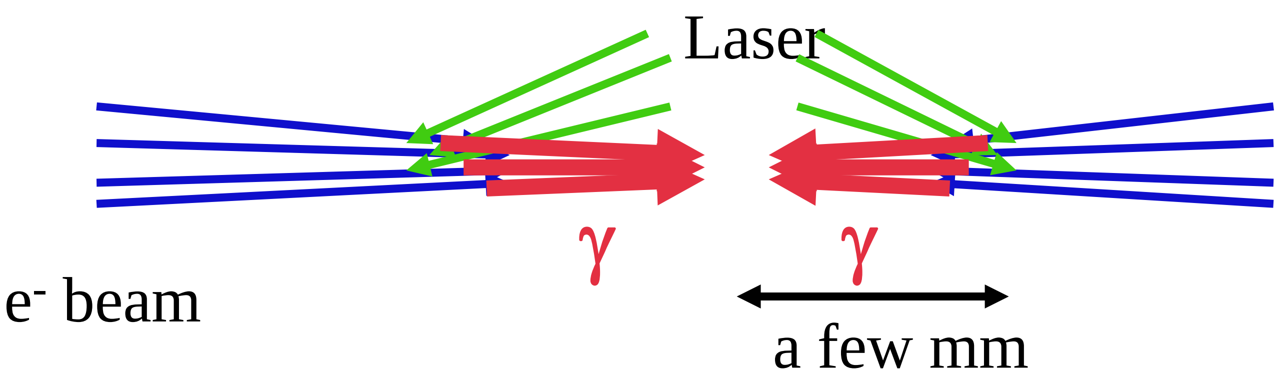
S.Kiyoura et al, GLC report

LHC SUSY

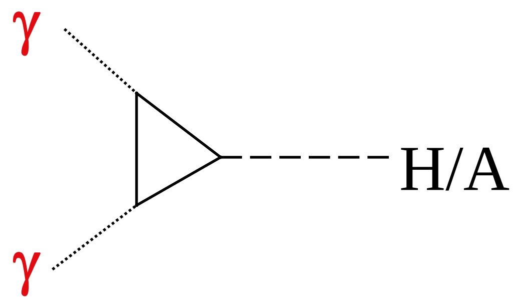
Higgs search



Photon-photon collider



- ILC can have an additional interaction point with photon-photon collisions.
- The heavy Higgs boson can be produced up to 400 GeV for 500 GeV LC.
- CP properties of the heavy Higgs boson can be studied.

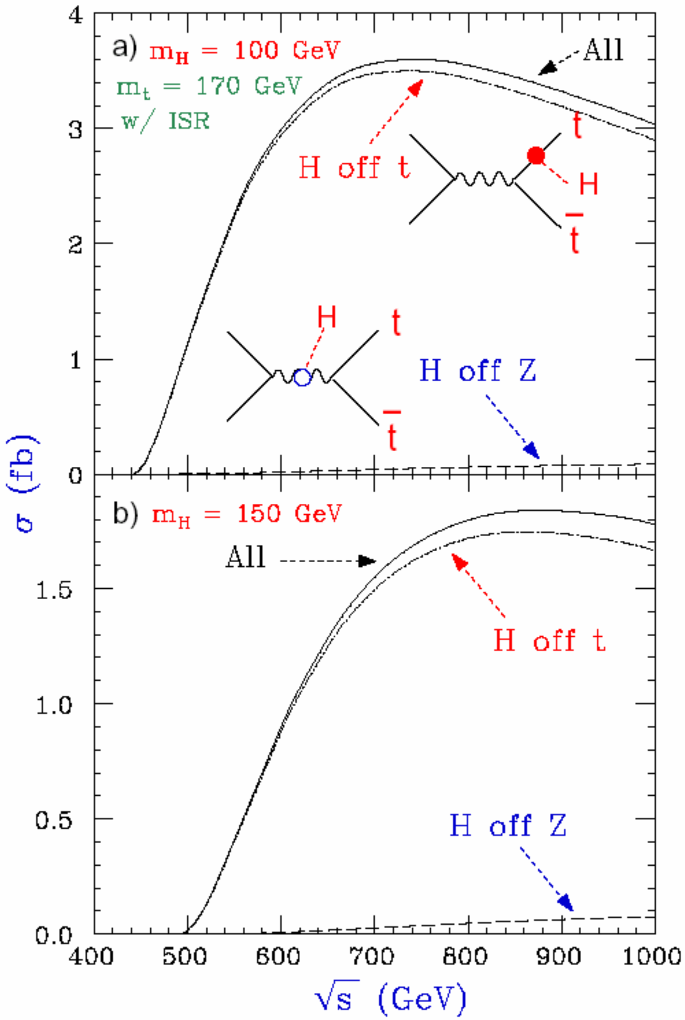


Top Yukawa coupling

Determination of the top Yukawa coupling constants requires a higher energy. (Ecm > 700 GeV)

The top Yukawa coupling is determined at 4-5% accuracy for mh=120 GeV and Lint=500/fb at Ecm= 700 GeV

-> Energy upgrade of LC



ACFA report, 2001

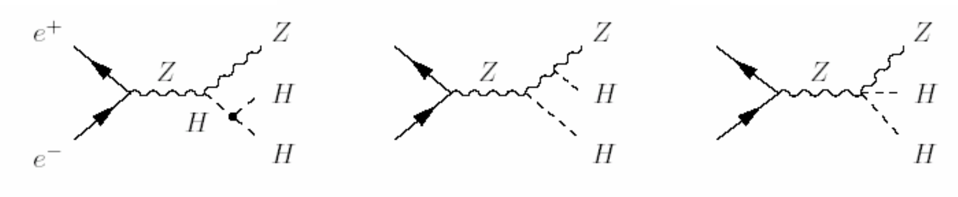
Higgs self-coupling constant

- Determination of the Higgs potential is one of the most fundamental issues. Origin of the electroweak symmetry breaking.
- Double Higgs boson production at LC will be the first access to the Higgs potential.
- New physics effects may appear in the Higgs self-coupling constant.

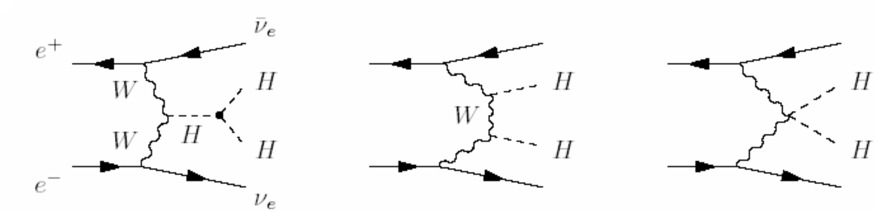
Higgs self-coupling measurement at LC

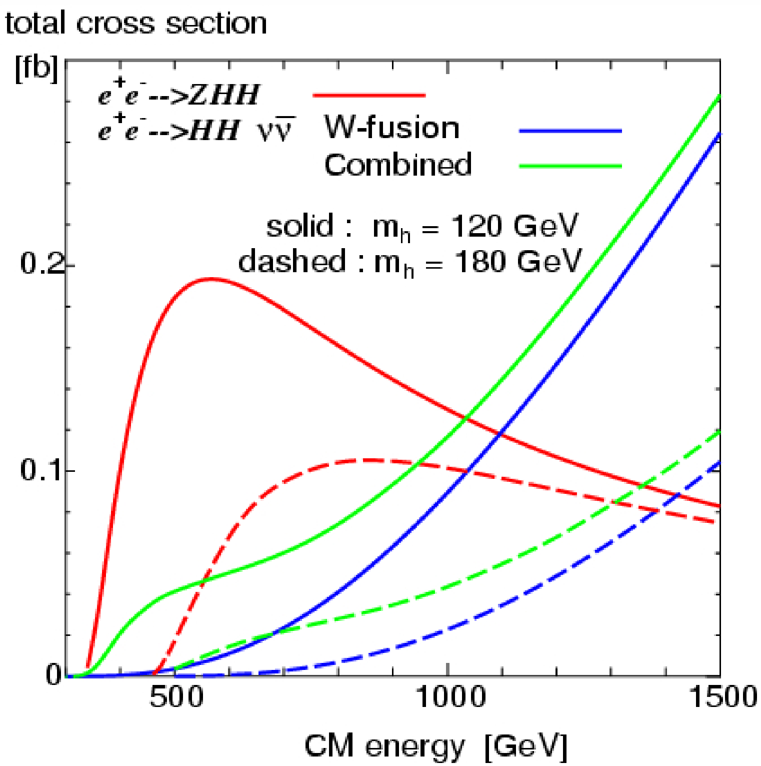
Two production processes. The WW fusion process is more important for a higher energy.

$e^+e^- \to ZHH$



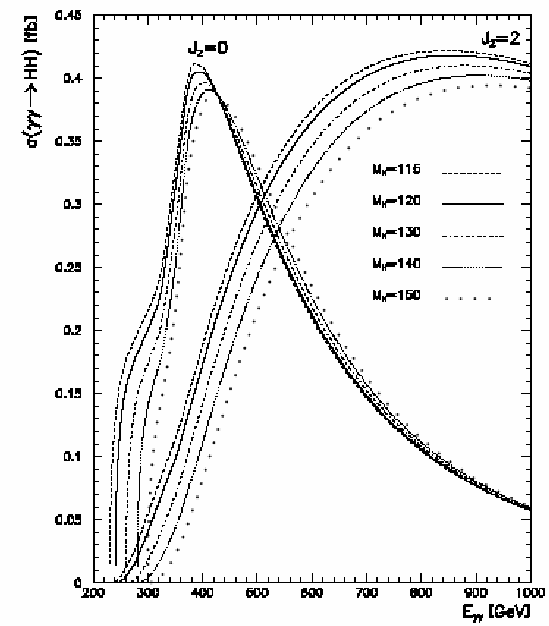
$e^+e^- \to \nu\bar{\nu}HH$





ACFA Higgs WG, Y.Yasui, et.al.

γγ->HH



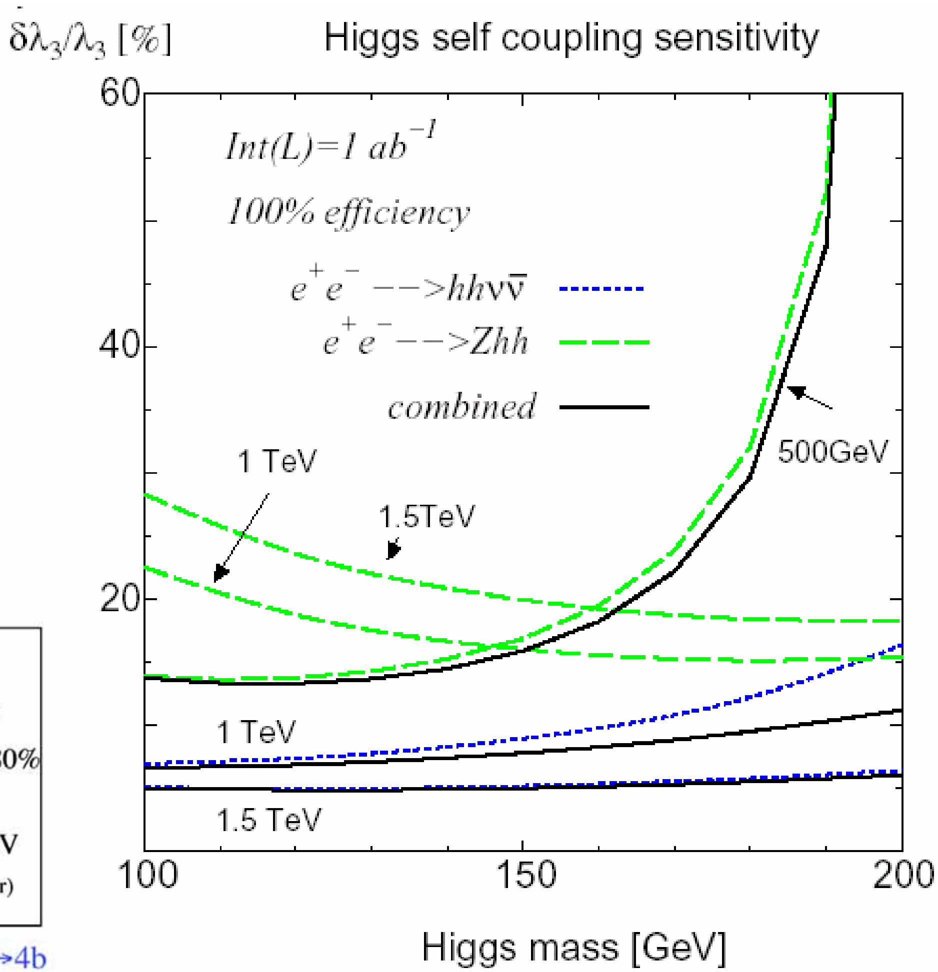
R. Belusevic and G.Jikia

- Meaningful measurement of the self-coupling at 500 GeV from the Zhh process (and $\gamma\gamma$ collider option).
- For precise determination, the collider energy should be 1 TeV and more.

->Energy upgrade of LC.

~20 % determination with 1/fab at Ecm=500 GeV for mh=120 GeV,

~10% with 1/ab at 1TeV



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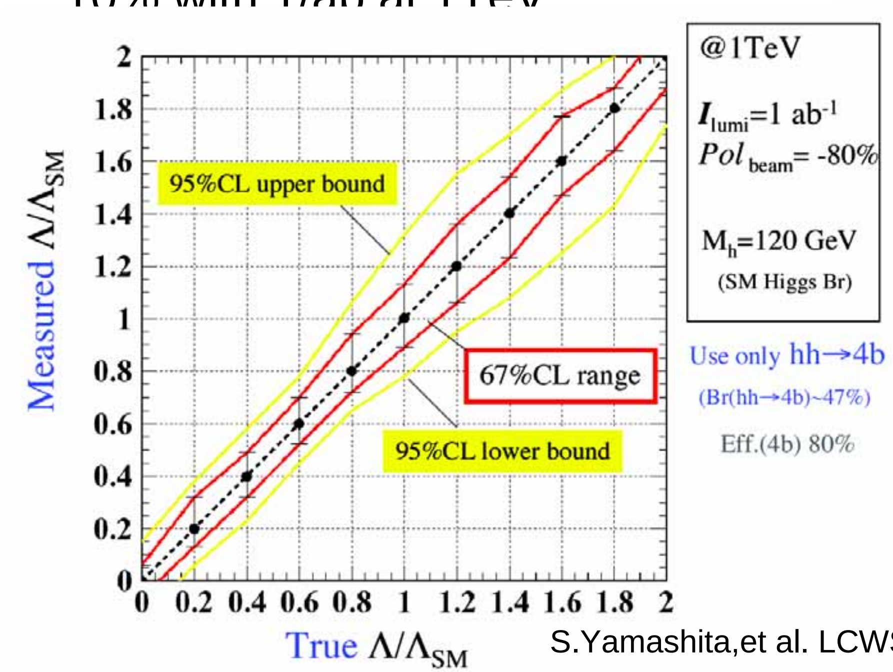


S.Yamashita,et al. LCWS 2004

Electroweak baryogenesis and quantum corrections to the hhh coupling in 2HDM

- Baryogenesis: Explain baryon-to-photon ratio from zero baryon number. $n_B/s \sim 10^{-10}$
- A basic fact: B+L violation at high temperature n the SM.
- Two scenarios:

  (1) B-L generation above the EW phase transition (leptogenesis, etc).

  (2) Baryogenesis at the EW phase transition.
- EW baryogenesis is difficult in the minimal SM.
- 2HDM is a simple viable model. A.Nelson, D.B.Kaplan, A.G.Cohen, 91, M.Joyce, T.Prokopec,and N.Turok 91; J.M.Cline,K.Kainulainen,A.P.Vischer,96

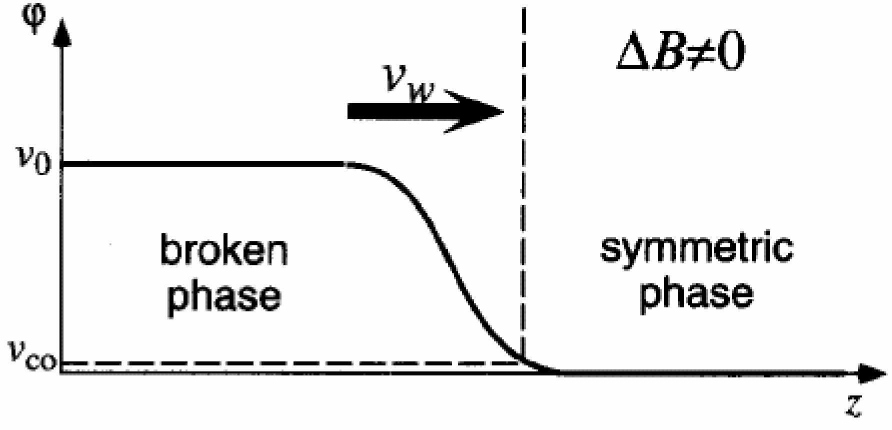
Connection between collider physics and cosmology

$$V_{eff}(\phi) \leftrightarrow V_T(\phi, T)$$

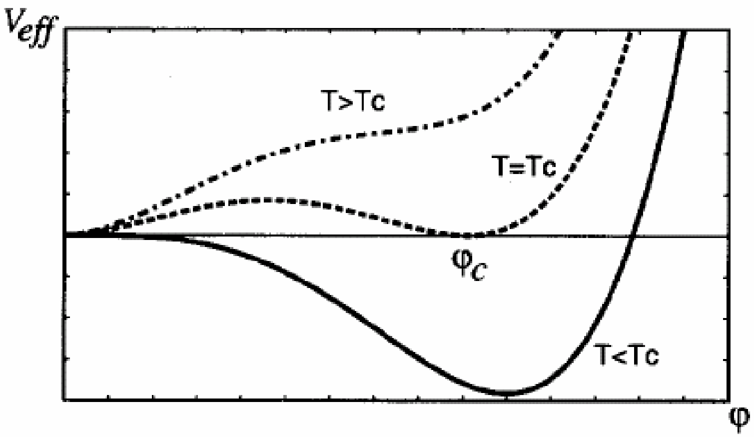
Baryon number generation at the electroweak phase transition

- Strong first order phase transition.
- Expansion of a bubble wall.
- Charge flow of fermions due to CP violation at the wall.
- Baryon number violation in the symmetric phase.

In the minimal SM, the phase the phase transition is not strong first order, and CP violation from the Kobayashi-Maskawa phase is too small.



Conditions for successful baryogenesis



Strong first order phase transition.

Not to erase the baryon number after transition by sphaleron process.

$$\phi_c/T_c > 1$$

In the high temperature expansion (M=0),

$$V_T(\phi,T) = D(T^2 - T_0^2)\phi^2 - ET\phi^3 + \frac{\lambda_T}{4}\phi^4 + ...$$

$$E = \frac{1}{12\pi v^3}(6m_W^3 + 3m_Z^3 + m_h^3 + m_H^3 + m_A^3 + 2m_{H\pm}^3)$$

$$\phi_c/T_c = 2E/\lambda_{T_c}$$

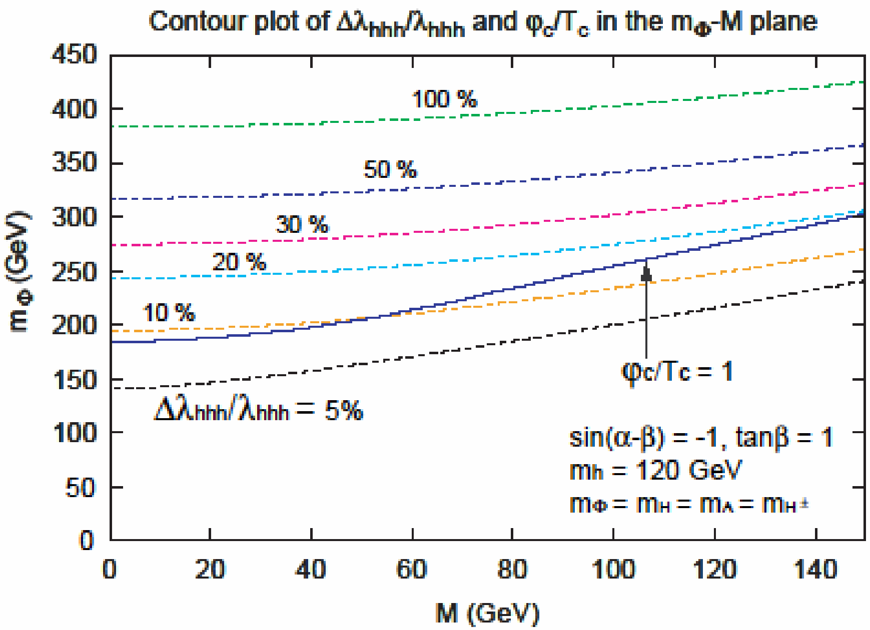
Strong first order phase transition
<-> "Non-decoupling" effects of heavy Higgs bosons
<-> Correlation with a large corrections to the hhh coupling at zero temperature

Numerical calculation

S.Kanemura, Y.Okada, E.Senaha

We calculate the finite temperature effective potential without the high temperature expansion for M>0.

We also study the loop correction to the hhh coupling constant.



$$m_\Phi^2 \simeq M^2 + \lambda_i v^2$$

$$\Delta\lambda_{hhh}/\lambda_{hhh} \gtrsim 10\%$$

for successful electroweak baryogenesis

Correlation between zero temperature and finite temperature potential.

Connection between cosmology and collider signals.

Summary 2

- The coupling measurement is essential for establishing the Higgs mechanism. ILC is necessary for this purpose.
- Coupling determination can also provide information on physics beyond the SM.
- Information on the Higgs potential will be obtained by the double Higgs boson production at ILC. We may be able to know physics at the electroweak phase transition.