# Theoretical review on Higgs and related issues

Yasuhiro Okada (KEK/Sokendai)

ISMD2011

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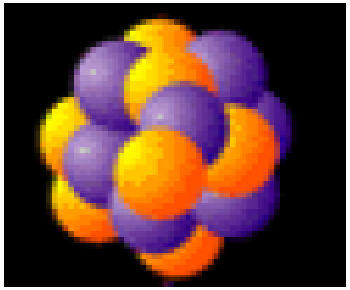
# Entering TeV scale physics

MeV



~1930: Discovery of neutrons
Two new forces (strong, weak) are introduced

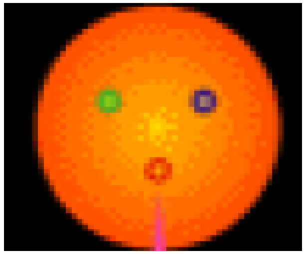
The Fermi constant

The Higgs VEV

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

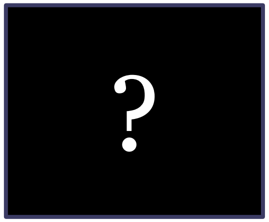
Nambu's Symmetry Breaking

GeV



~1970: Theory of three interactions based on one additional unknown force (electroweak symmetry breaking)

TeV




~2010: What is the unknown force?

# A Higgs boson

## No lose theorem

There must be a Higgs boson(s) or some alternative signals below
a TeV energy scale related to the dynamics of electroweak symmetry breaking.

## A Higgs boson is a tool to probe the TeV physics

It is likely to find a Standard Model (SM) -like Higgs boson near future.
May new physics models predict a SM-like Higgs boson as the first signal to physics behind the electroweak symmetry breaking.

A Higgs boson may play a similar role of the pion for strong interaction in understanding the weak interaction.

The pion is the Yukawa meson and the Nambu-Goldstone boson associated with chiral symmetry breaking in strong interaction.

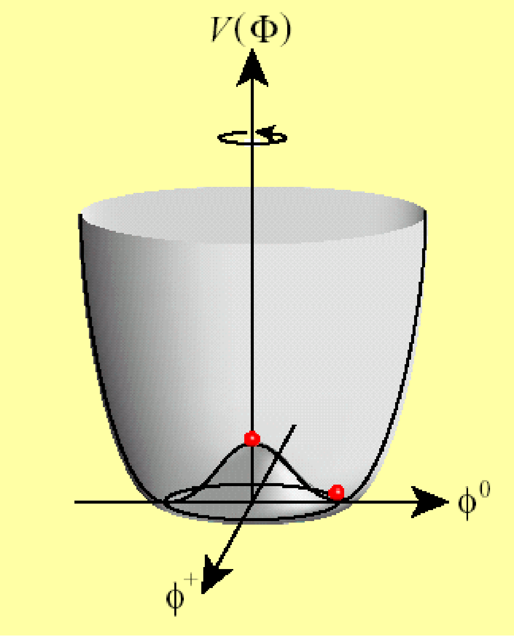
# The SM Higgs Lagrangian

$$L = |D_\mu \Phi|^2 - (-\mu^2|\Phi|^2 + \lambda|\Phi|^4)$$

$$\Phi = \begin{pmatrix} \phi^+(x) \\ \frac{v+h(x)}{\sqrt{2}} + i\frac{\eta(x)}{\sqrt{2}} \end{pmatrix}$$

v~246 GeV

h(x): physical Higgs boson




## Very simple!

Only one free parameter determined by the Higgs boson mass

$$\boxed{m_h = \sqrt{2\lambda}v}$$

But this is supposed to be an effective theory below some cutoff scale.

## Fundamental questions are:

Where is the cutoff ?
How does the Higgs field arise?
What determines the Higgs potential?

# Example 1. Minimal Supersymmetric Standard Model (MSSM)

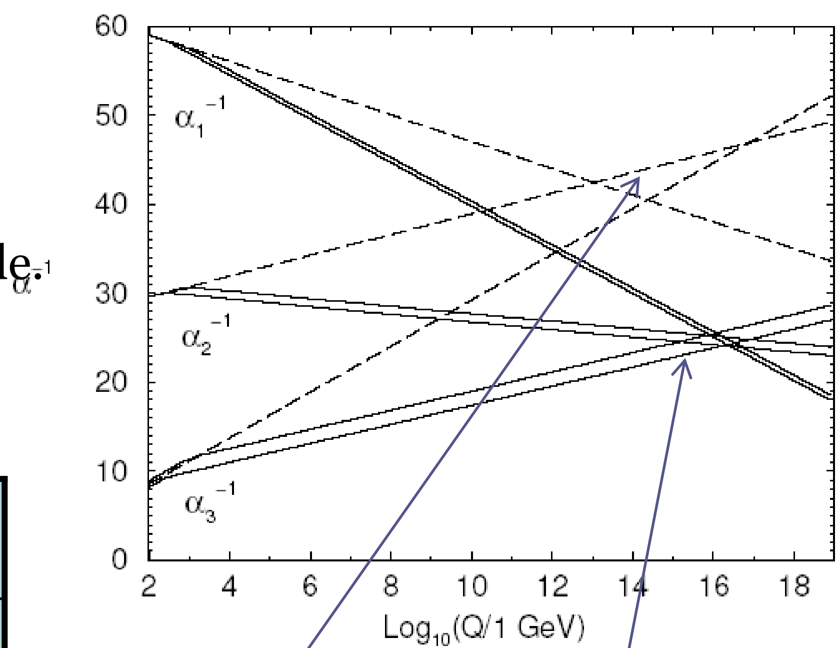
Supersymmetry (SUSY) is an extension of relativity
Consistent with unification of three gauge interactions

The cutoff scale is essentially the Planck scale.
$-\mu^2$ is determined by SUSY breaking
$\lambda$ is essentially determined by SU(2) xU(1) gauge coupling constants

| | |
|---|---|
| quark | $(q)$ |
| lepton | $(l)$ |
| gluon | $(g)$ |
| W,Z,γ,H | |

| | |
|---|---|
| squark | $(\tilde{q})$ |
| slepton | $(\tilde{l})$ |
| gluino | $(\tilde{g})$ |
| neutralino, chargino | $(\tilde{\chi})$ |

SUSY GUT coupling unification




Without SUSY particles

With SUSY particles

The Higgs sector in the MSSM is Two Higgs Doublet Model (2HDM)

Physical Higgs bosons: $h, H$ (CP-even), $A$ (CP-odd), $H^{\pm}$ (Charged Higgs)

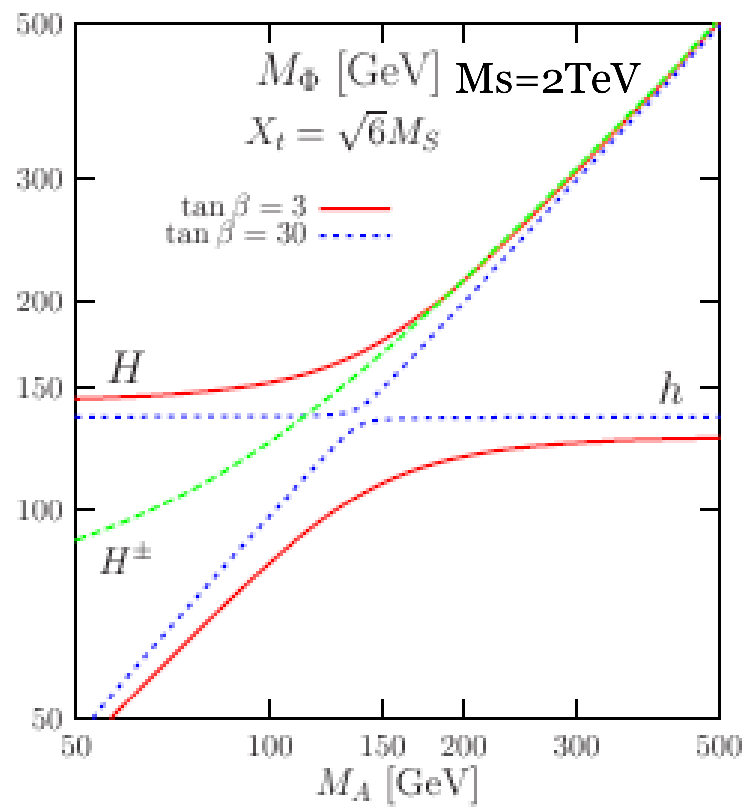
$$V_{Higgs} = m_1^2|H_1|^2 + m_2^2|H_2|^2 - m_3^2(H_1 \cdot H_2 + \bar{H}_1 \cdot \bar{H}_2)$$
$$+\frac{g_2^2}{8}(\bar{H}_1\tau^a H_1 + \bar{H}_2\tau^a H_2)^2 + \frac{g_1^2}{8}(|H_1|^2 - |H_2|^2)^2$$
$$+\Delta V,$$

Radiative corrections

The lightest Higgs boson mass is lighter than ~130 GeV.
Four other Higgs bosons can be nearly degenerate.

The first particle to be discovered may be a SM-like Higgs boson.

Y.Okada, M.Yamaguchi, T.Yanagida;
J.Ellis, G.Ridorfi, F.Zwirner;
H.Haber, R.Hempfling, 1991



# Example 2. Little Higgs Models

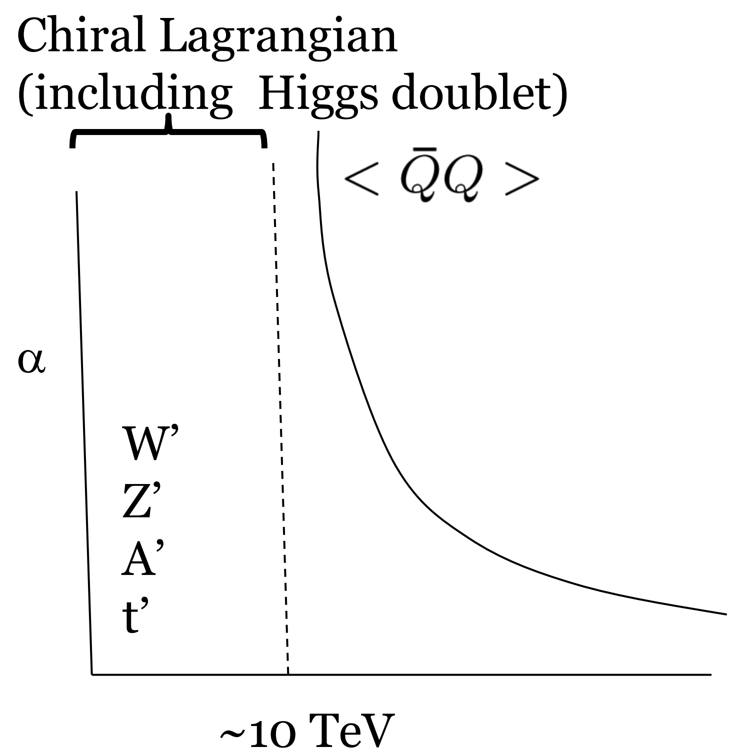
N.Arkani-Hamed,A.G.Cohen, E.Katz
and A.E.Nelson, T.Gregoire, ans J.G.Wacker;
N.Arkani-Hamed,A.G.Cohen, E.Katz
and A.E.Nelson, 2002

The Higgs doublet field is embedded in pseudo Nambu-Goldstone mode of some strong dynamics confined at ~10 TeV.

The Higgs potential is determined by symmetry breaking effects (gauge and Yukawa couplings)

A light Higgs boson is stable against radiative corrections thanks to carefully chosen global and local symmetries.

The first particle to be discovered may be a SM-like Higgs boson, although there should be heavy partners of gauge bosons and top quarks around a TeV.

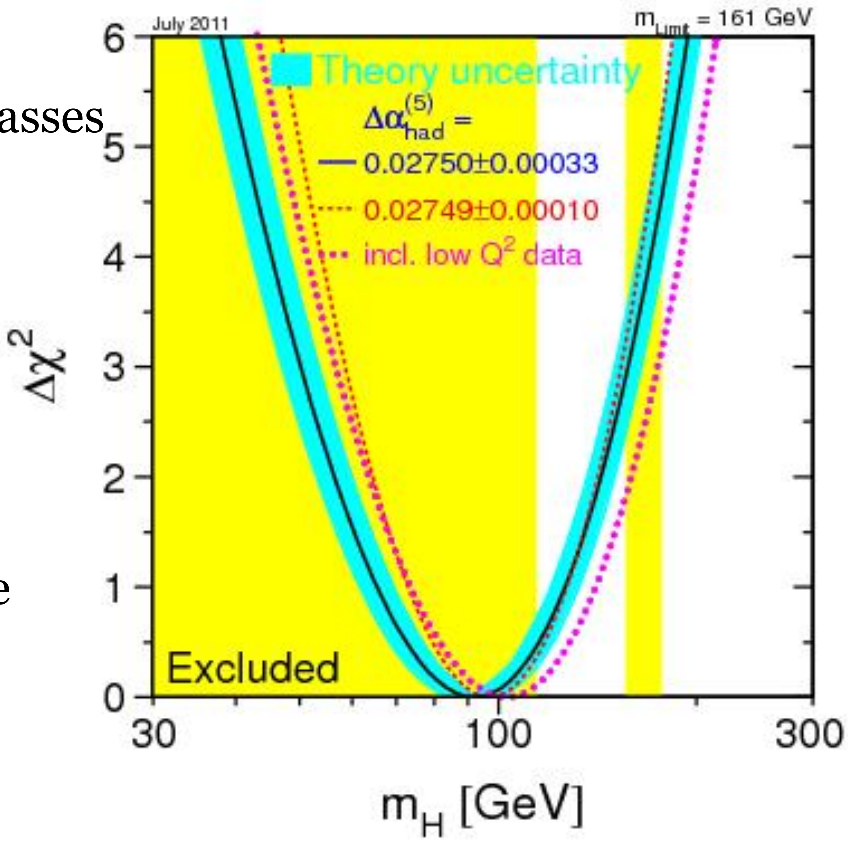



Example:
SU(5)/SO(5) (The littlest Higgs model)

# The Higgs boson is likely to be light

Electroweak precision measurements combined with the top and W boson masses indicate a light Higgs boson in the SM.

$$m_h < 161 \text{ GeV (95\%CL)}$$



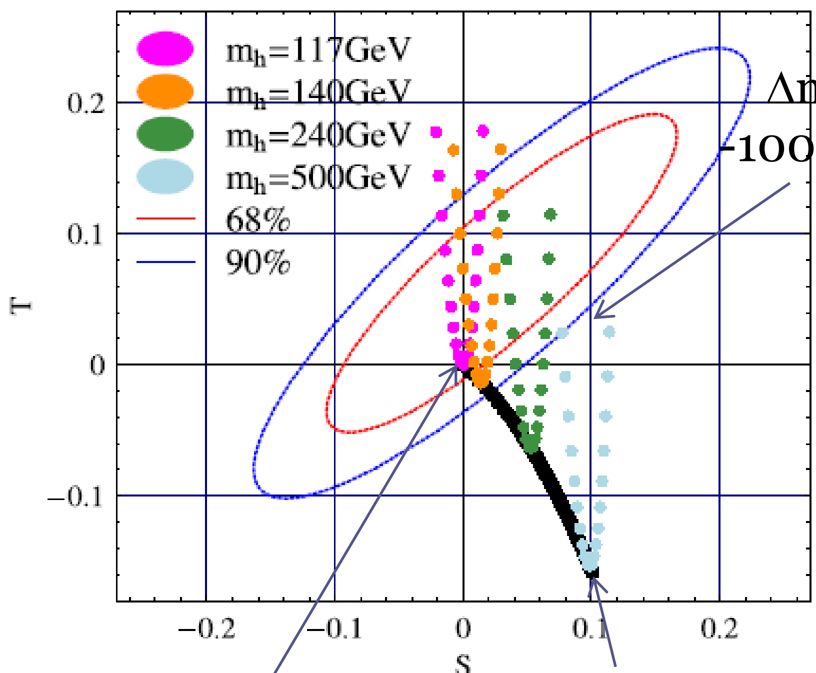

If a heaver Higgs boson is found, there should be something more than one Higgs boson.

# Example: Two Higgs Doublet Model (2HDM)

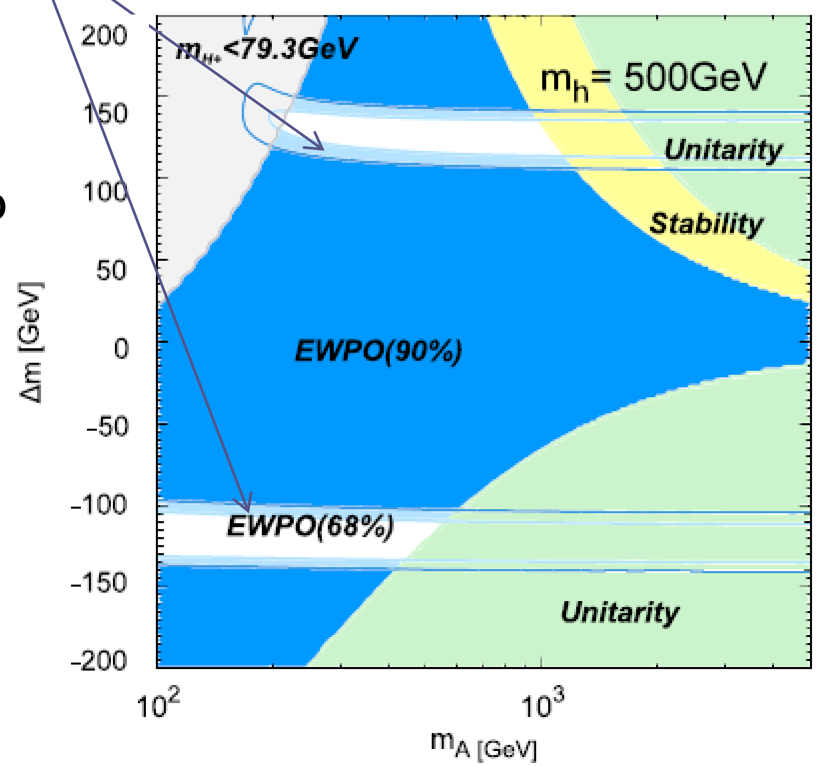
Constraints from electroweak precision measurements

allowed regions

$\Delta m = m_A - m_{H^\pm}$ mh=500GeV




Δm= -100=>100

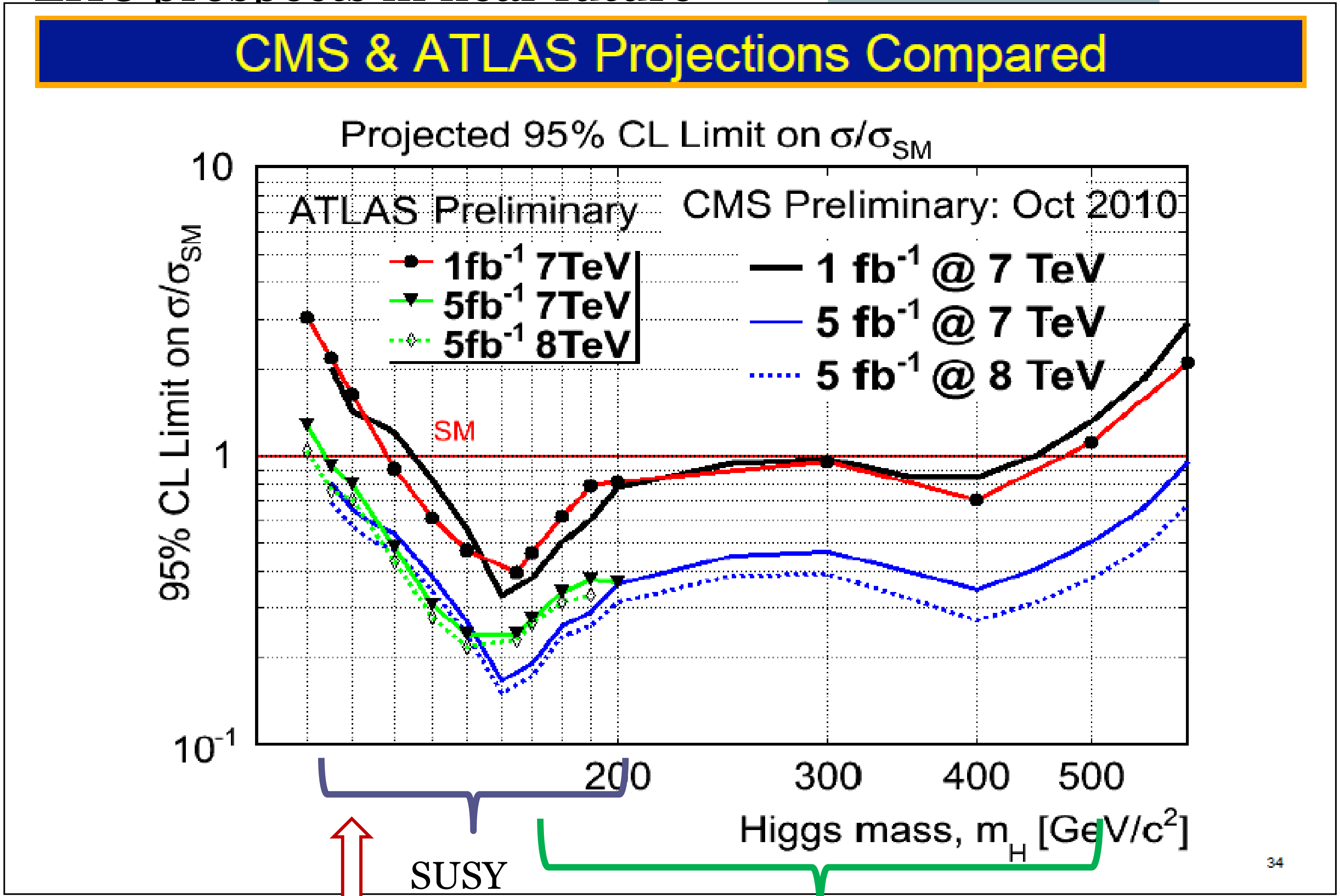



mh=117 mh=500

If a SM-like Higgs boson is 500 GeV, there must exist heavy Higgs bosons below 1 TeV in the THDM.

S.Kanemura, Y.O. H.Taniguchi , K.Tsumura, PLB (2011)

# LHC prospects in near future




MSSM favored

SUSY possible

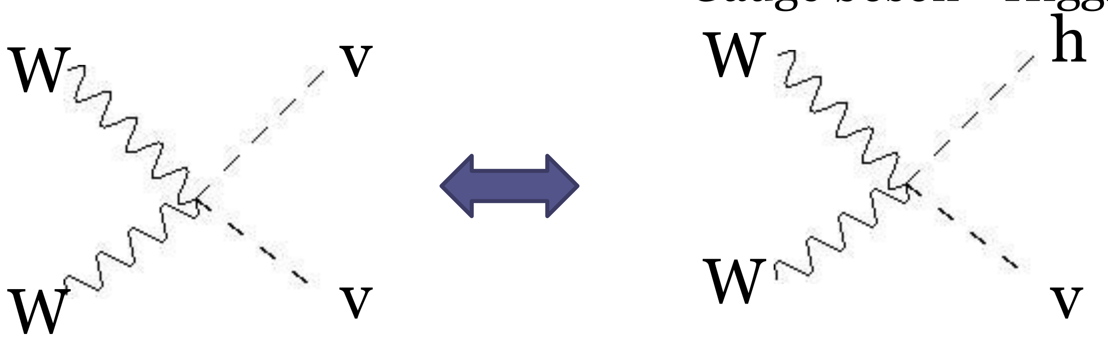
Need something more than a Higgs boson.

# After a Higgs boson is found,

Fundamental measurements are determination of the Higgs boson coupling constants to other elementary particles.

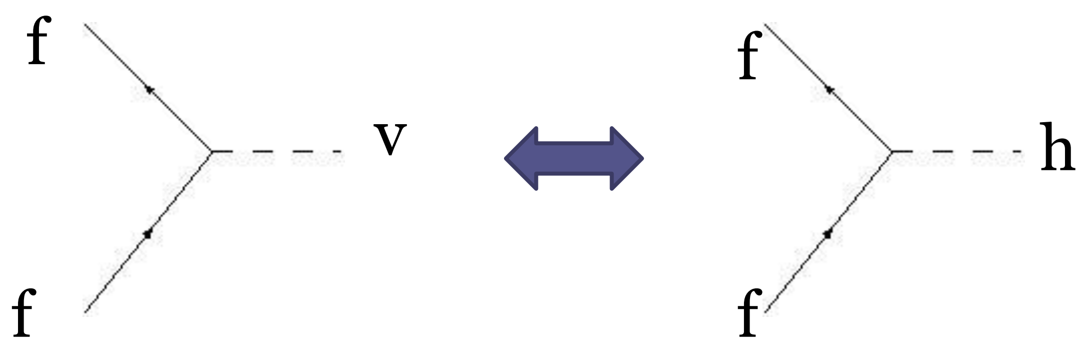
Gauge boson mass term

Gauge boson –Higgs coupling



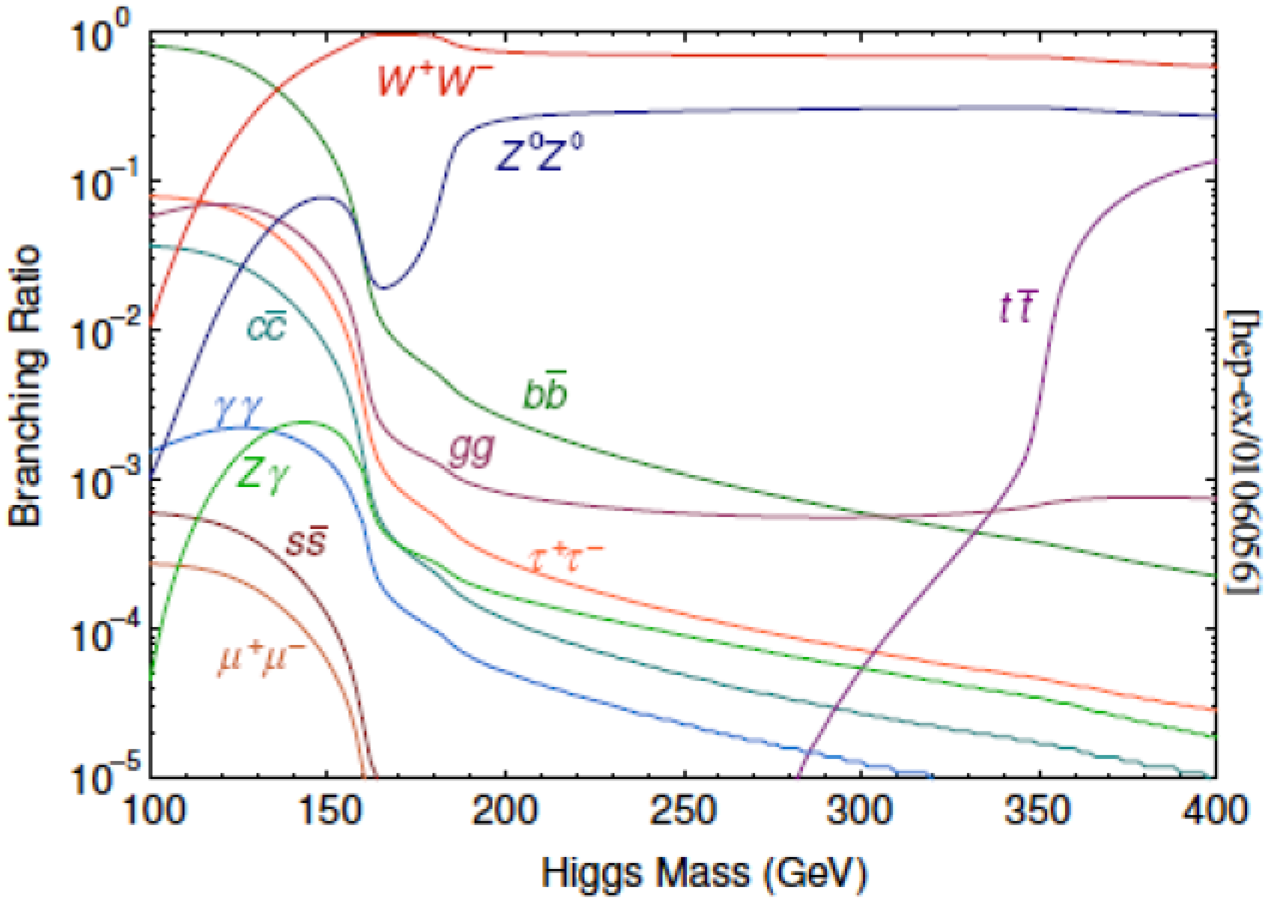

Fermion mass term

Fermion-Higgs coupling




Important measurements at LHC and ILC

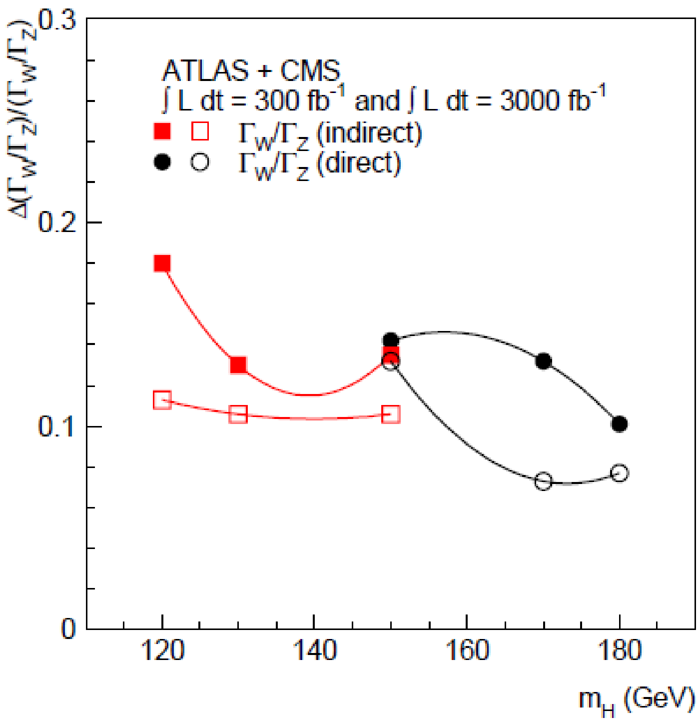
# Higgs boson branching ratio

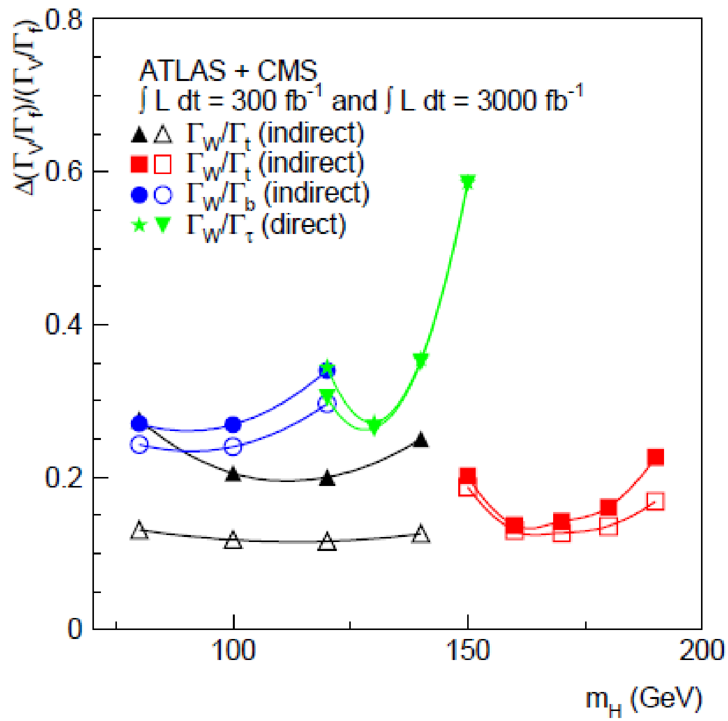



Higgs bosons tend to decay heaviest possible particles.

# Higgs coupling measurements at LHC and High Luminosity (HL)-LHC

LHC 300fb$^{-1}$, HL-LHC 3000fb$^{-1}$




Indirect
$\Gamma_W$ from H->$\gamma\gamma$

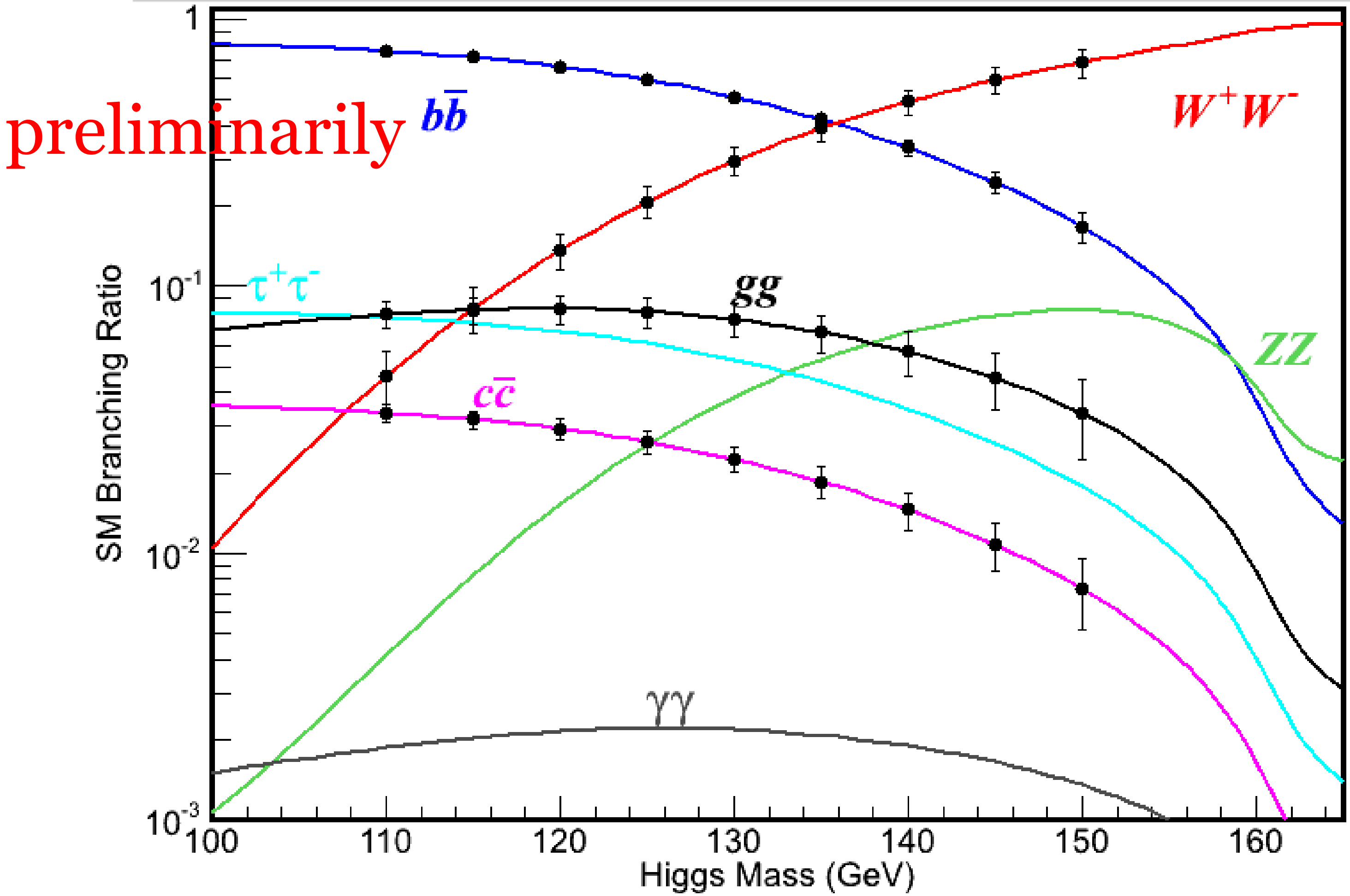
Indirect (W/t):WH and gg->H
Indirect (W/b): ttH (->$\gamma\gamma$) and ttH(->bb)

Determination of coupling ratios at O(10) % level

hep-ph/0204087

# Branching ratio accuracy at ILC

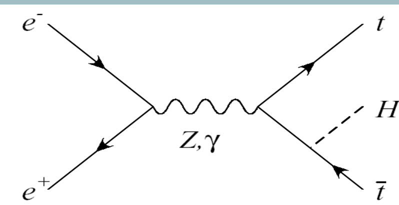
Ecm=250 GeV, L=250 fb$^{-1}$, Beam pol($e^+$,$e^-$)=(+30%, -80%)

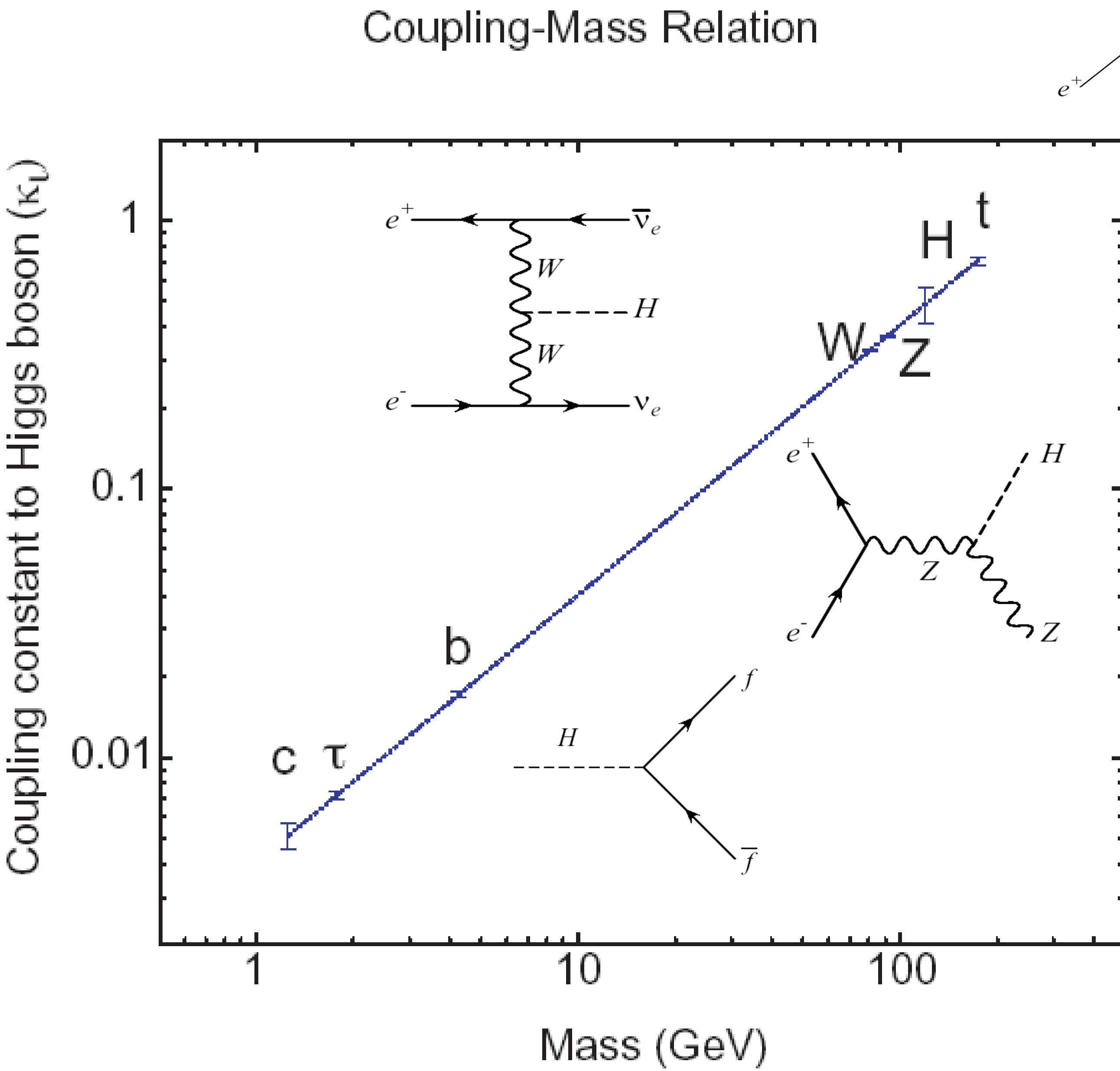


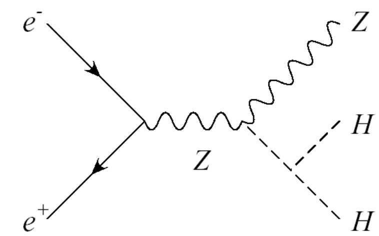

H. Ono
LCWS2011

Measurement accuracies are extrapolated from Mh=120 GeV

# Higgs coupling measurements at ILC




Mh=120 GeV

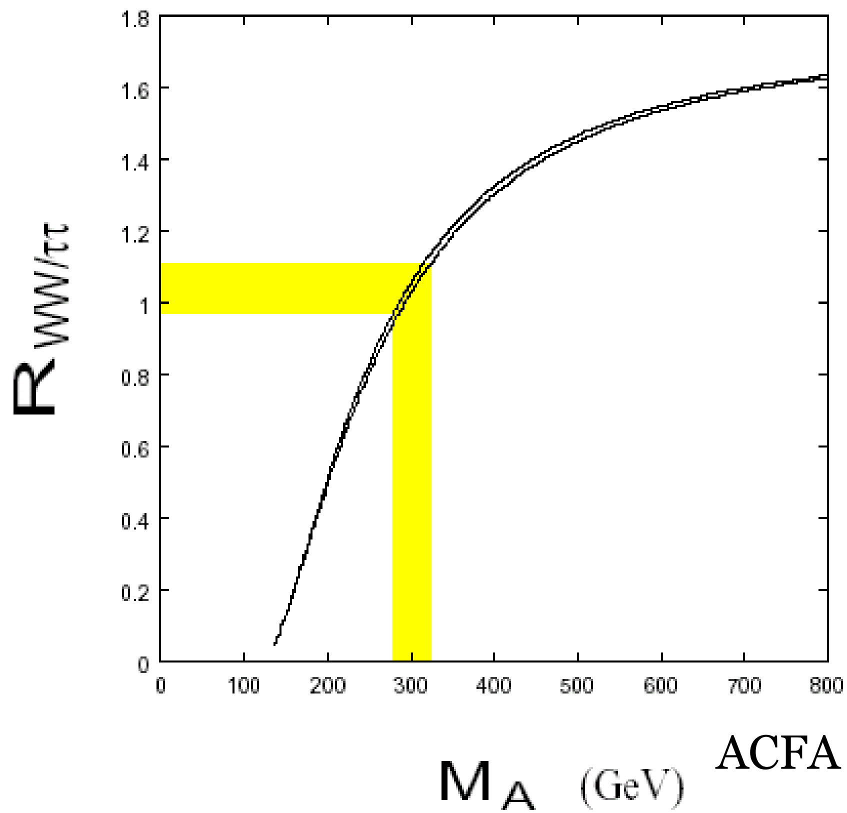
GLC Project

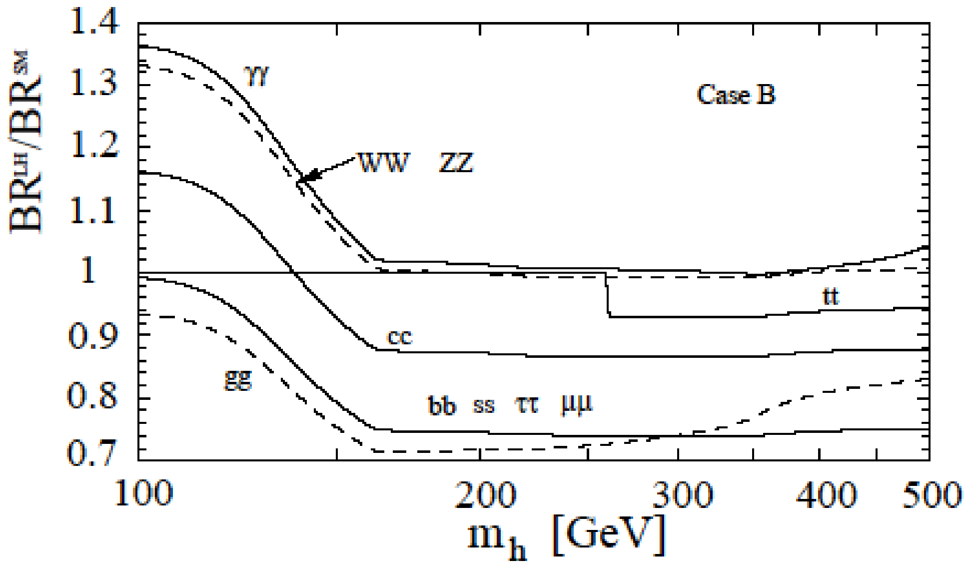
# New physics from Higgs branching measurements

Minimal SUSY SM (MSSM)

Little Higgs with T-parity

$B(h \to WW)/B(h \to \tau\tau)$




R.-C.Chen K.Tobe, C.-P. Yuan ,2006

ACFA report

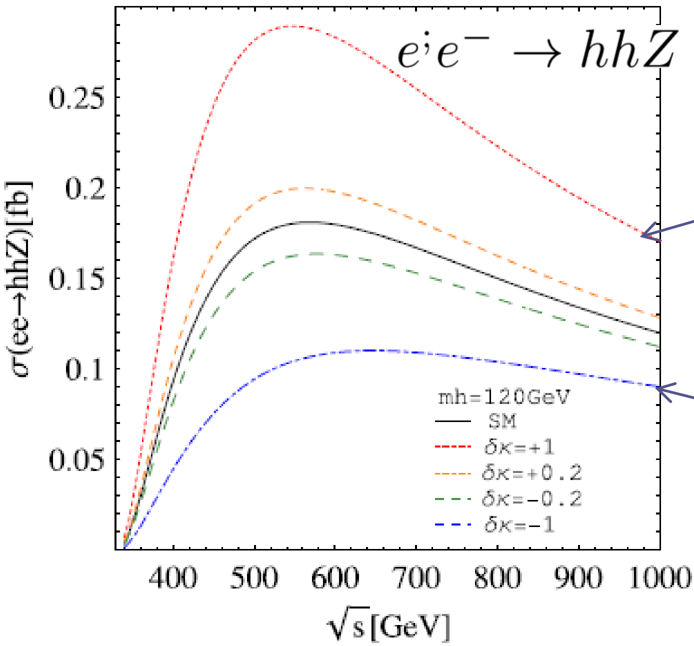
Heavy Higgs boson mass from the light Higgs branching ratio

Higgs branching ratios change due to heavy fermion loop

# Higgs self-coupling constant and Higgs potential

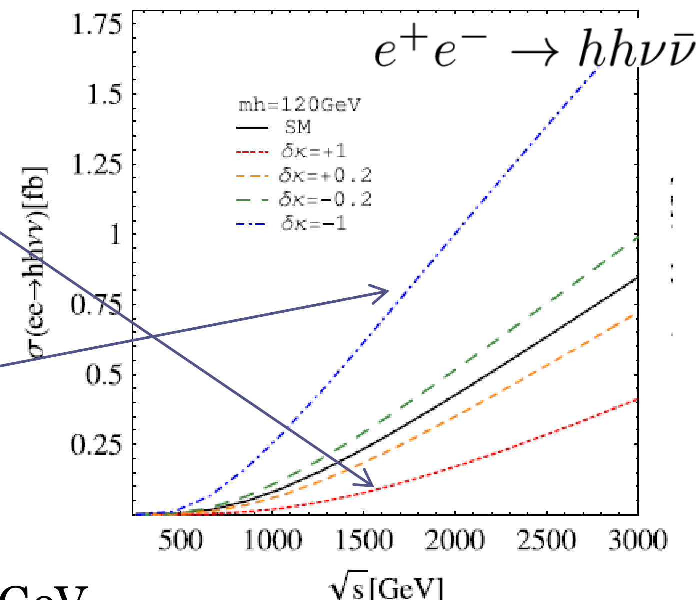
Higgs boson pair production process provide the first information on Higgs self-coupling constant. $\lambda_{hhh} = \lambda_{hhh}^{\rm SM}(1 + \Delta\kappa)$

E.Asakawa, D.Harada, S.Kanamura ,Y.O. K.Tsumura, PRD(2010)

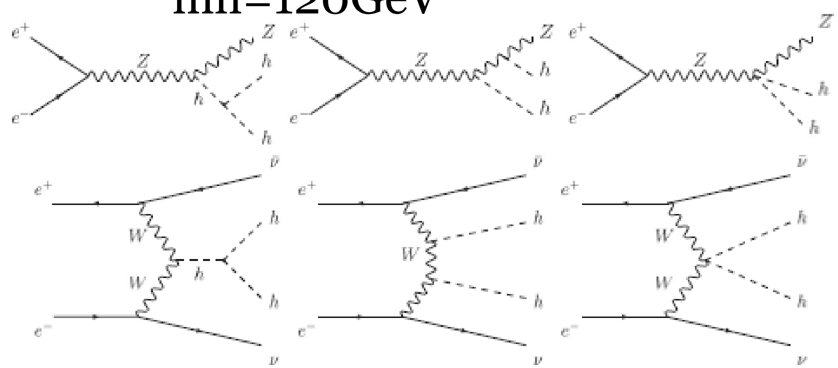



Δκ =1

Δκ =−1




mh=120GeV



O(10)% measurement at ILC with a few ab$^{-1}$

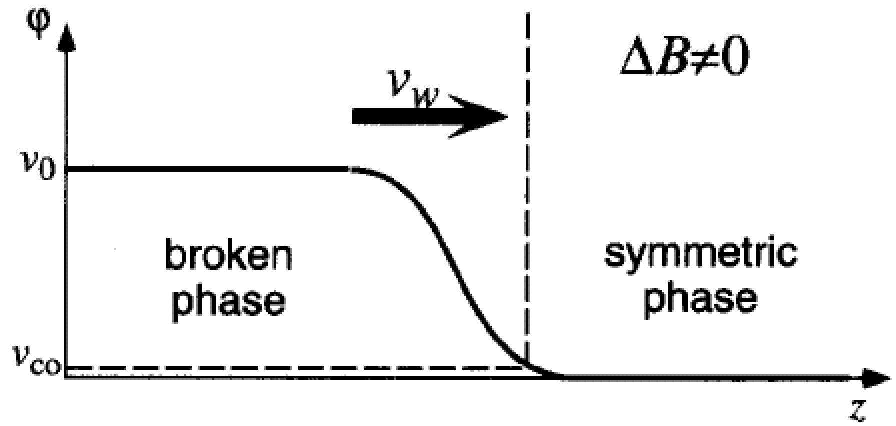
# Electroweak baryogenesis

Baryon number of the Universe $n_B/s \sim 10^{-10}$

One possible scenario is generation of the baryon asymmetry at the electroweak phase transition.

This scenario involves the formation and expansion of bubbles at the electroweak phase transition.

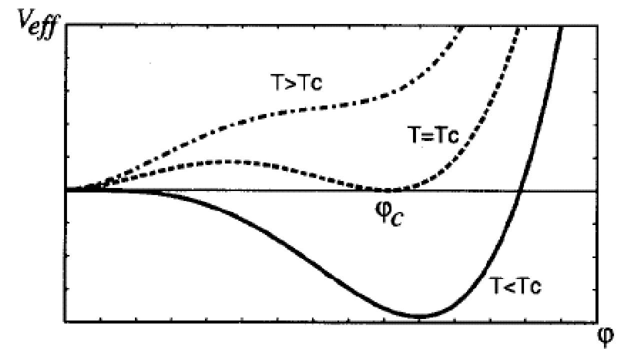
A strong first order phase transition is a necessary condition.




Extension of the Higgs sector is necessary.

# Electroweak baryogenesis and the radiative correction to the Higgs self coupling constant in 2HDM

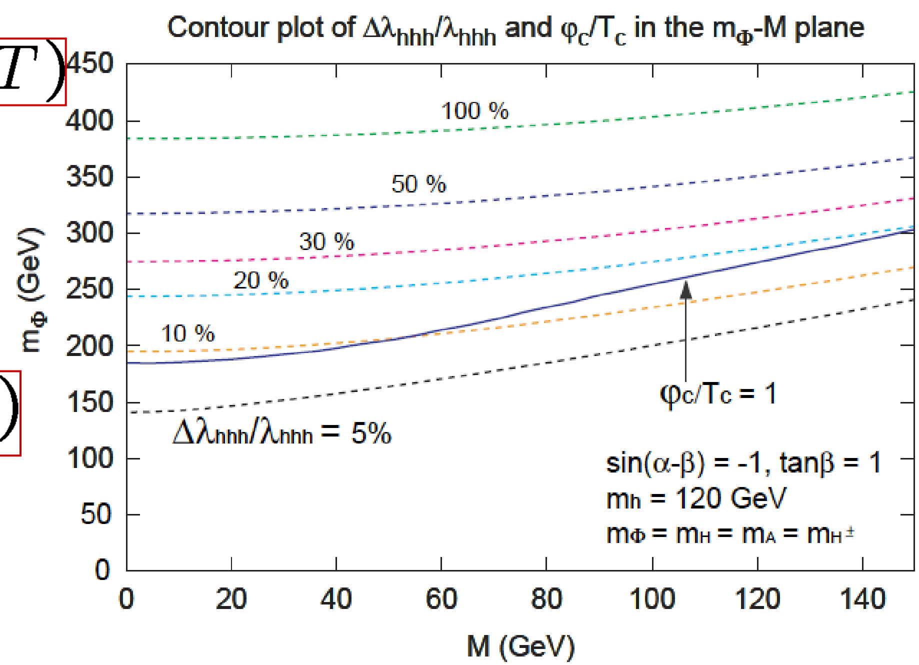
The loop correction to the triple Higgs coupling constant becomes large, if the electroweak baryogenesis is realized in 2HDM.




Successful electroweak baryogenesis：
Strong first order phase transition due to heavy Higgs boson loops. $\boxed{V_T(\phi, T)}$

↕

Large radiative corrections to the zero temperature effective potential.
A large correction to the triple Higgs coupling constant $\boxed{V_{eff}(\phi)}$




S.Kanemura, Y.O. E.Senaha, PLB (2005)

# Summary

- A Higgs boson is likely to be discovered soon.
- Once a Higgs boson is found, we need to study its properties precisely,

  - to test the mass generation mechanism of elementary particles,

  - to provide a window to physics behind the electroweak symmetry breaking.
- This could lead to understanding of the electroweak phase transition.