# Higgs and Physics beyond the Standard Model (3)

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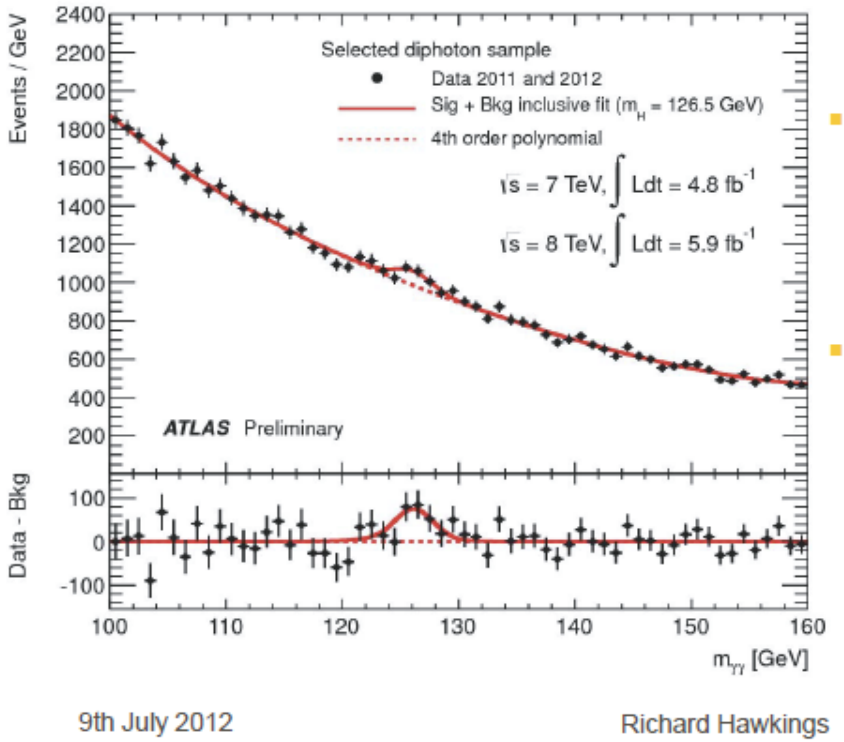
京都大学理学研究科特別講義

2012年8月27日 ー29日

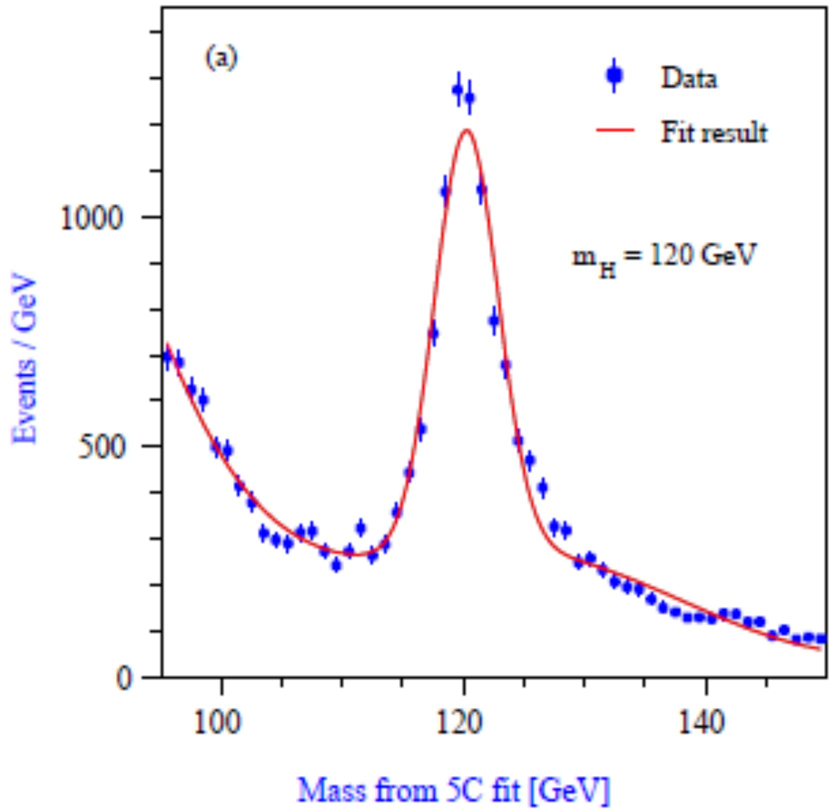
# Higgs physics at ILC

ATLAS (H->γγ) on July 2012




ILC Reference Design Report

$$e^+e^- \to ZH \to b\bar{b}q\bar{q}$$

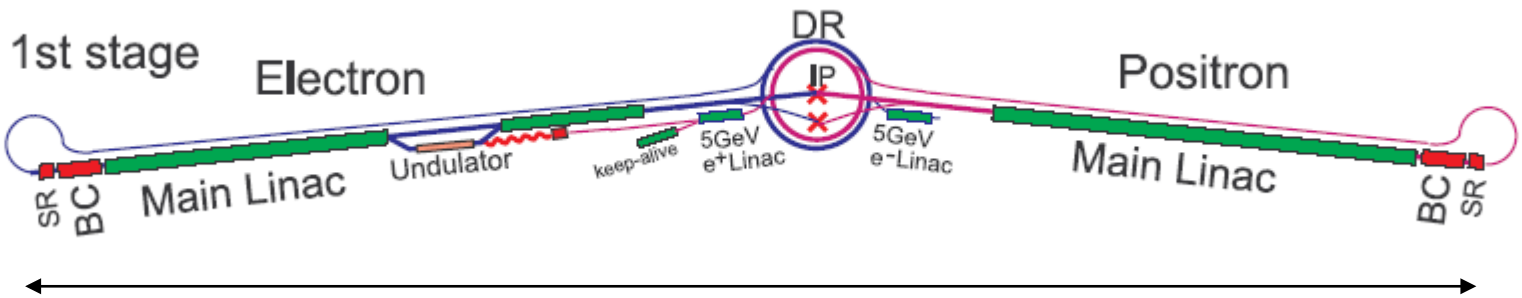



ILC is an ideal place for studying the Higgs boson

# International Linear Collider (ILC)

$e^+e^-$ linear collider
The design work is under way in the international framework (Global Design Effort)
Reference Design Report (2007)
Technical Design Report will be completed in 2012

- 1st stage: CM energy up to 500 GeV
- 2nd stage: go to 1 TeV range




~30km

# Hadron machines vs. lepton colliders

- Advantage of lepton colliders:

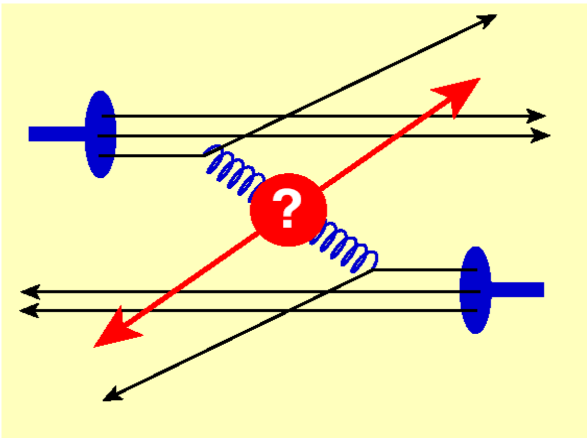
  $e^+$ and $e^-$ are elementary particle
  (well-defined kinematics).

  Less background than LHC experiments.

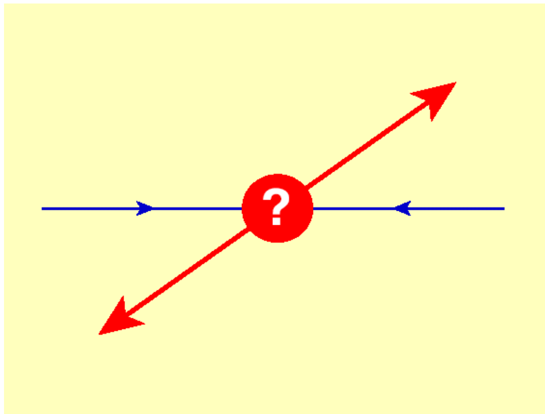
  Beam polarization, energy scan.

  $\gamma$ - $\gamma$, e- $\gamma$, e- e- options, Z pole option.

Hadron machines

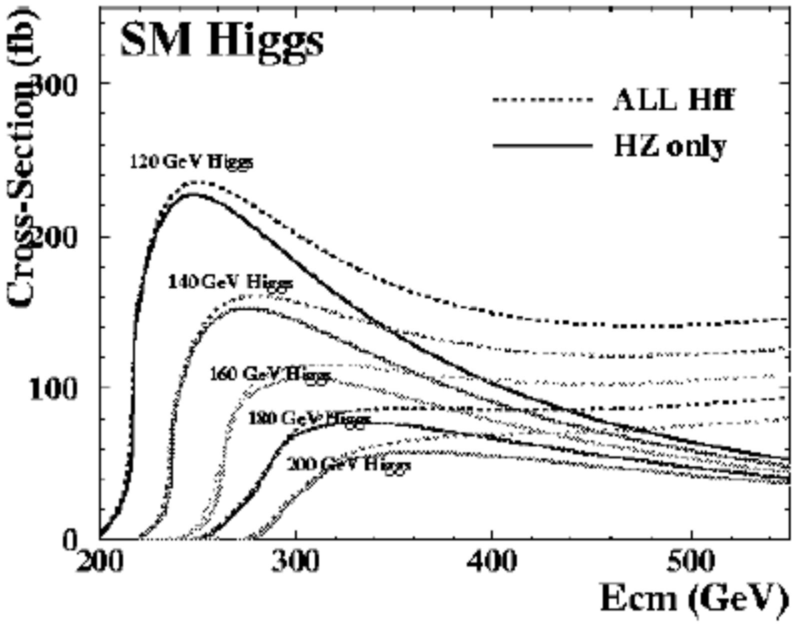


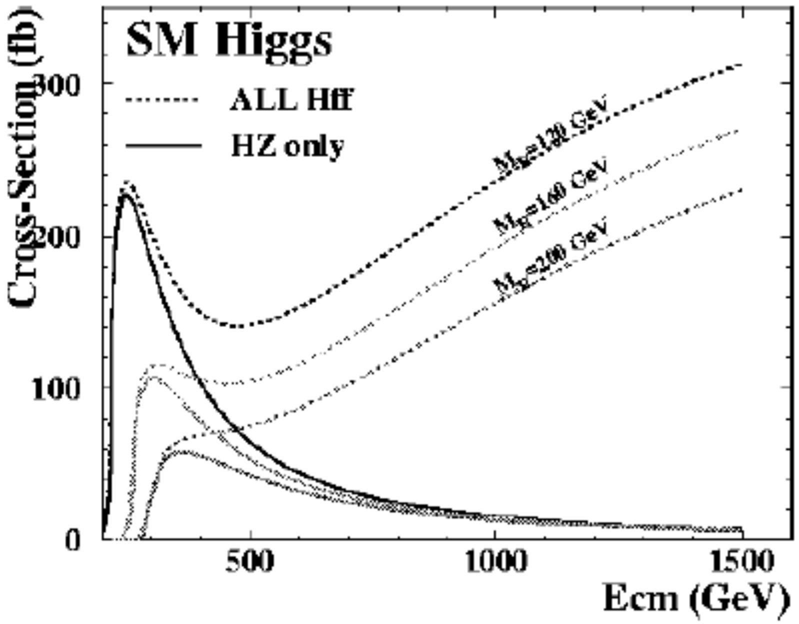

Lepton colliders

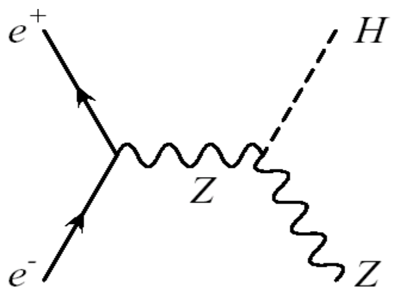


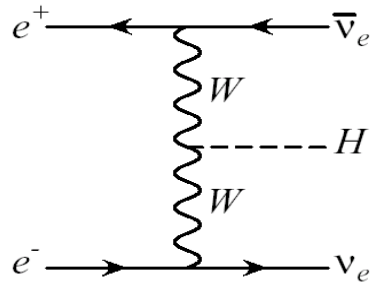
# Studies on the Higgs properties at ILC

Production cross section of the SM Higgs boson



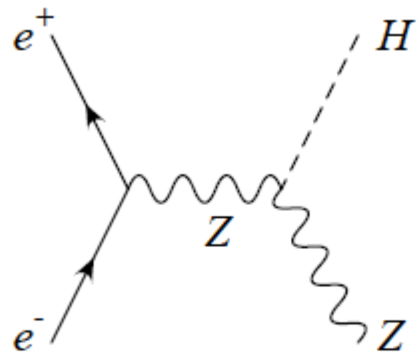




$10^5$ Higgs bosons are produced with $500fb^{-1}$ .

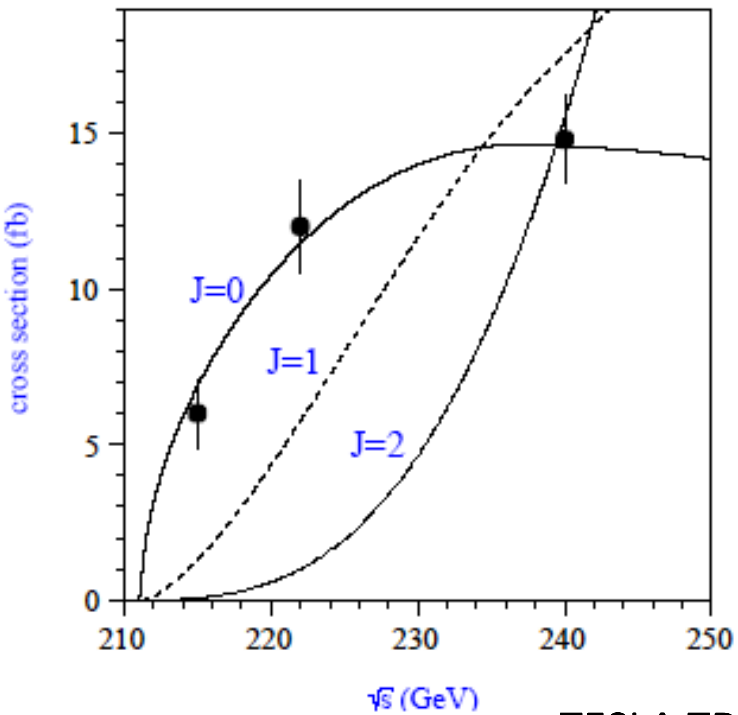
$e^+e^-$->HZ process

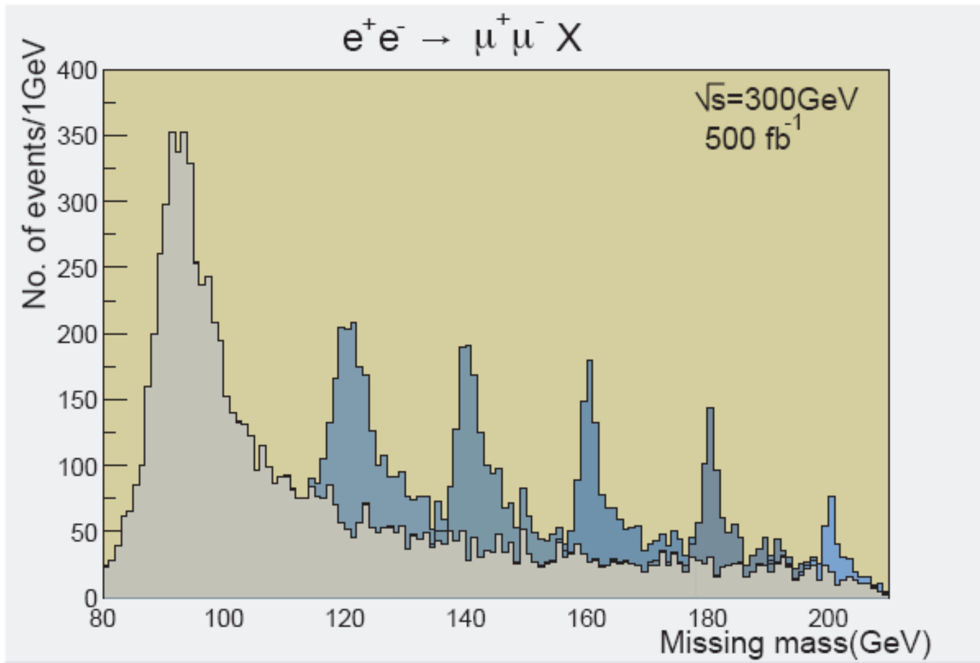



Recoil mass distribution
Higgs mass peak is observed even the Higgs boson decay into invisible particles

$$p_H^2 = (p_{e^+} + p_{e^-} - p_Z)^2$$

Spin determination of Higgs boson




TESLA TDR

GLC report

# Higgs coupling determination

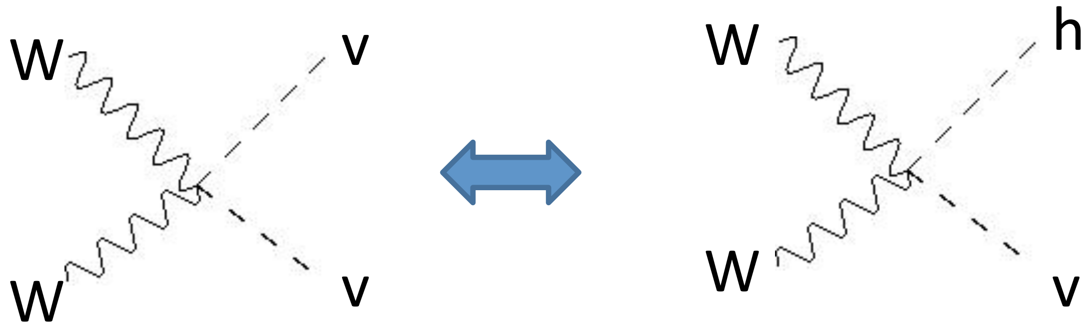
The Higgs particle  couple to heavier particles more strongly.
This is characteristic  feature of the Higgs interaction contrasted  to gauge interaction.

In the SM, the Higgs interaction can be obtained by replacement of v-> v+H.

$$L = m_W^2\left(1+\frac{H}{v}\right)^2 W^{+\mu}W^-_\mu + \frac{m_Z^2}{2}\left(1+\frac{H}{v}\right)^2 Z^\mu Z_\mu - \sum m_f\left(1+\frac{H}{v}\right)\bar{\psi}_f\psi_f$$

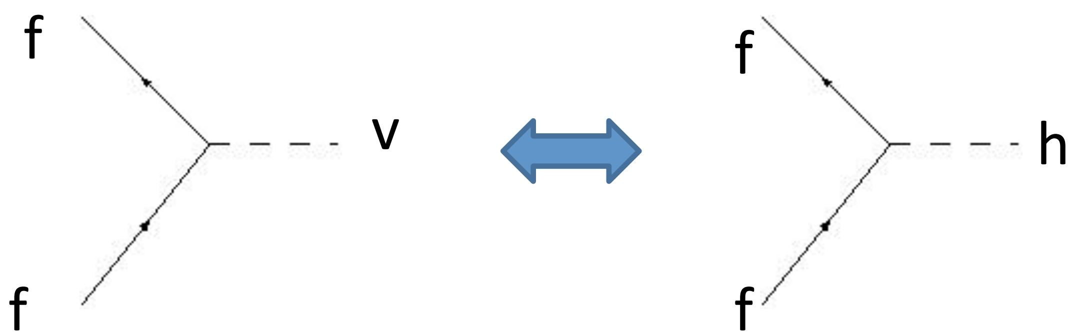
Gauge boson mass term

Gauge boson –Higgs coupling



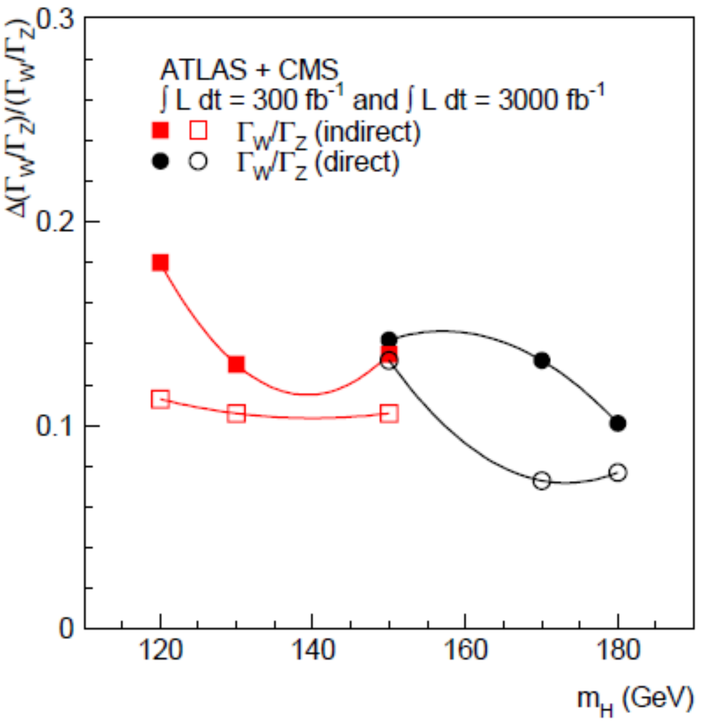

Fermion mass term

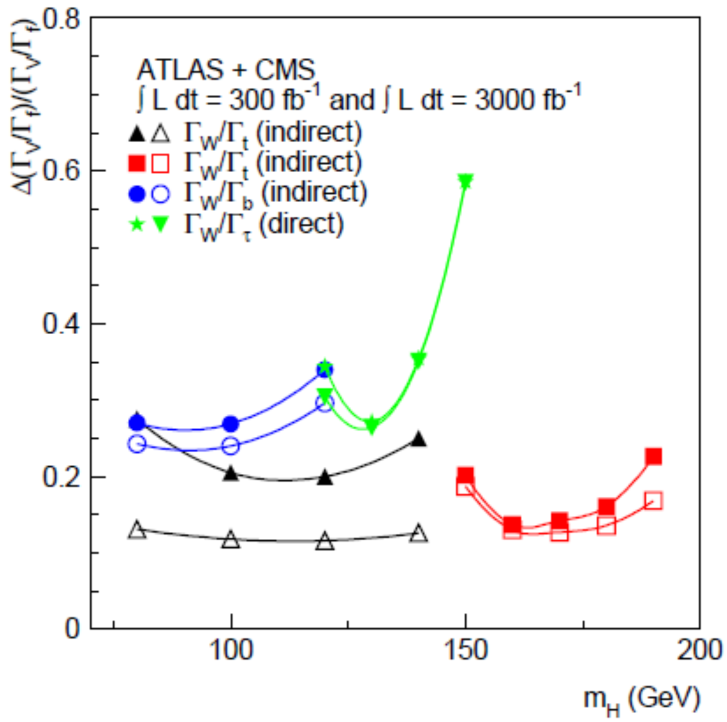
Fermion-Higgs coupling



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

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




Indirect
$\Gamma_W$ from H->γγ

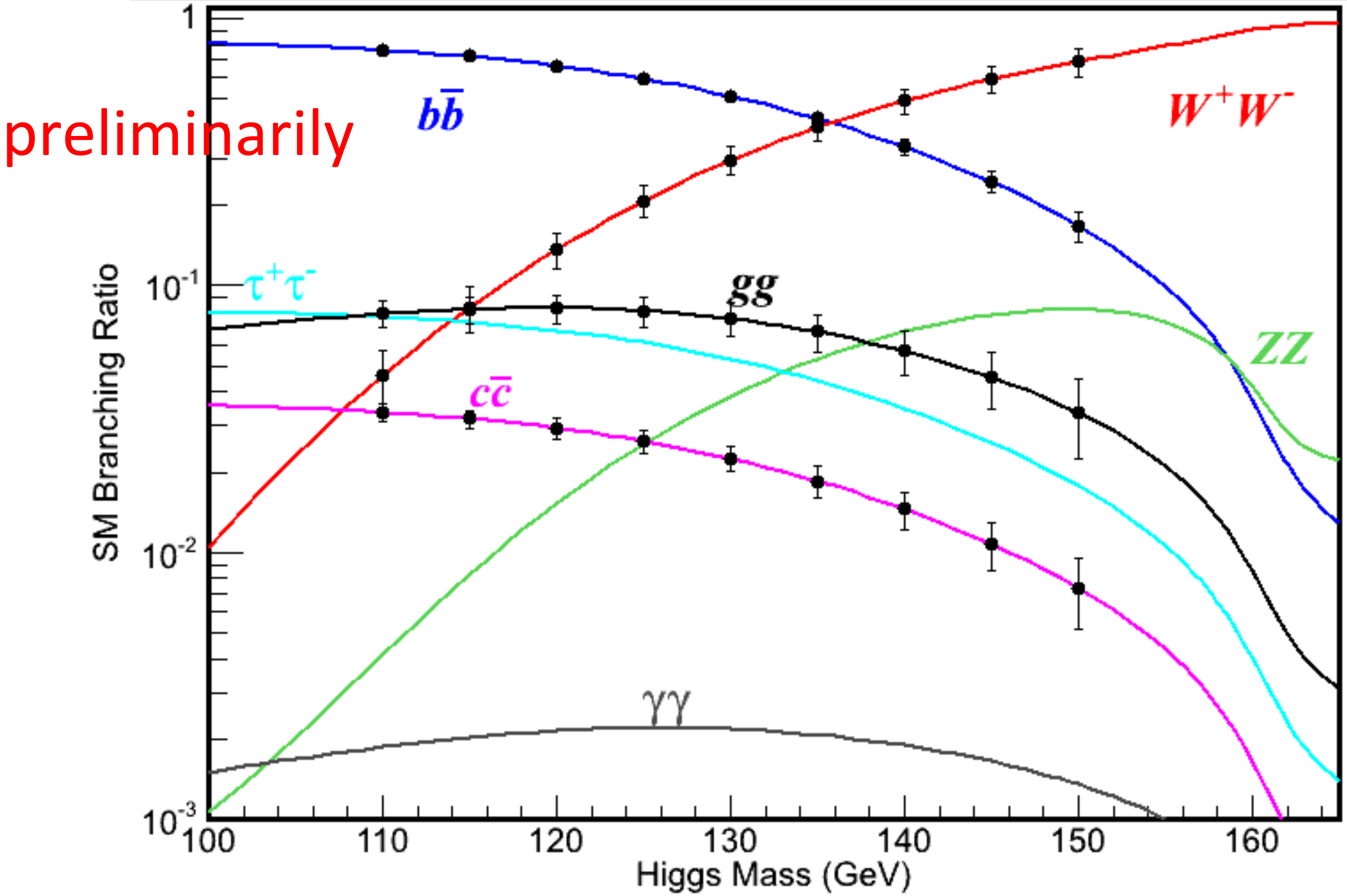
Indirect (W/t):WH and gg->H
Indirect (W/b): ttH (->γγ) and ttH(->bb)

Determination of coupling ratios at O(10) % level

hep-ph/0204087

# Branching ratio accuracy at ILC

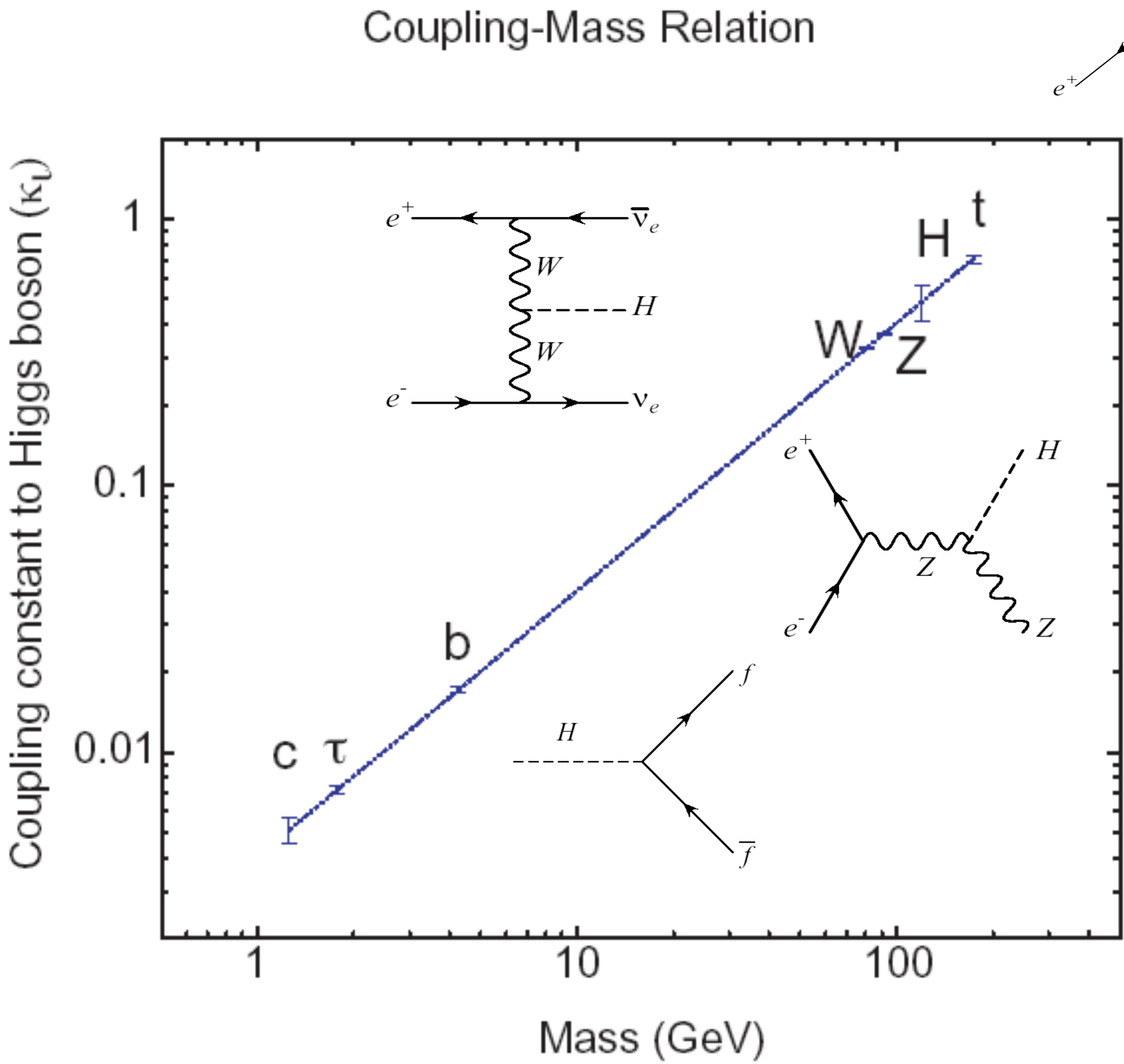
Ecm=250 GeV, L=250 fb$^{-1}$, Beam pol($e^+$,$e^-$)=(+30%, -80%)

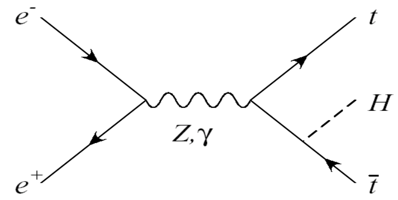


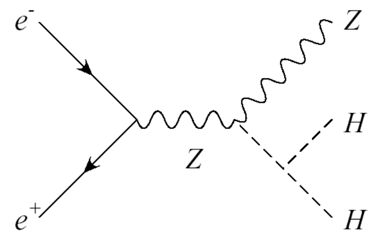

H. Ono
LCWS2011

Measurement accuracies are extrapolated from Mh=120 GeV

# Higgs coupling measurements at ILC




Mh=120 GeV

GLC Project

# Comparison of LHC and ILC Capabilities for Higgs Boson Coupling Measurements

MICHAEL E. PESKIN[1]

arXive: 1207.2516

$g(hAA)/g(hAA)|_{SM}-1$ LHC/HLC/ILC/ILCTeV

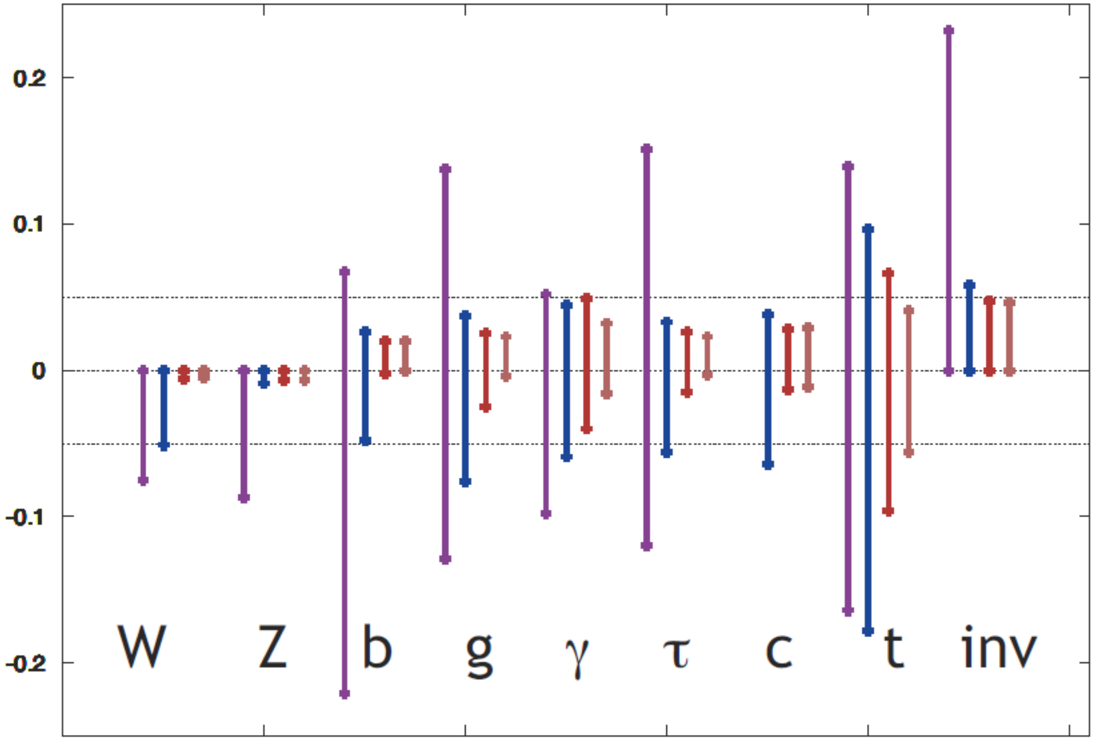



Figure 2: Comparison of the capabilities of LHC and ILC for model-independent measurements of Higgs boson couplings. The plot shows (from left to right in each set of error bars) 1 $\sigma$ confidence intervals for LHC at 14 TeV with 300 $fb^{-1}$, for ILC at 250 GeV and 250 $fb^{-1}$ ('HLC'), for the full ILC program up to 500 GeV with 500 $fb^{-1}$ ('ILC'), and for a program with 1000 $fb^{-1}$ for an upgraded ILC at 1 TeV ('ILCTeV'). The marked horizontal band represents a 5% deviation from the Standard Model prediction for the coupling.

# Implication of the branching ratio measurements for MSSM

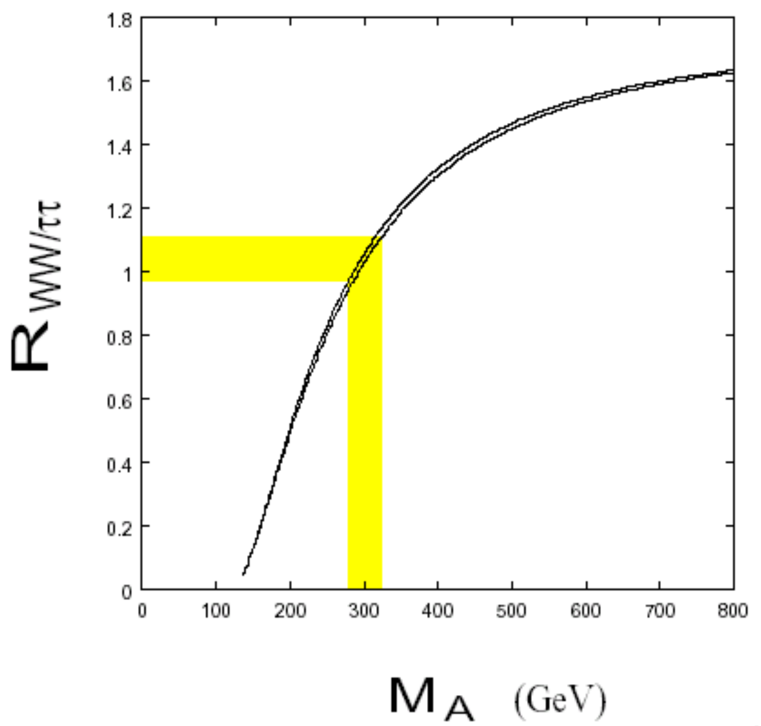
In the MSSM, the ratio of the branching ratios like B(h->cc)/B(h->bb) is useful to constrain the SUSY parameter, especially the heavy Higgs boson mass.
(Kamoshita-Okada-Tanaka, 1995)

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

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

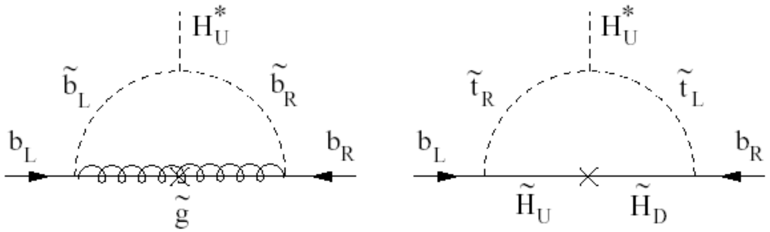
ACFA report 2001

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

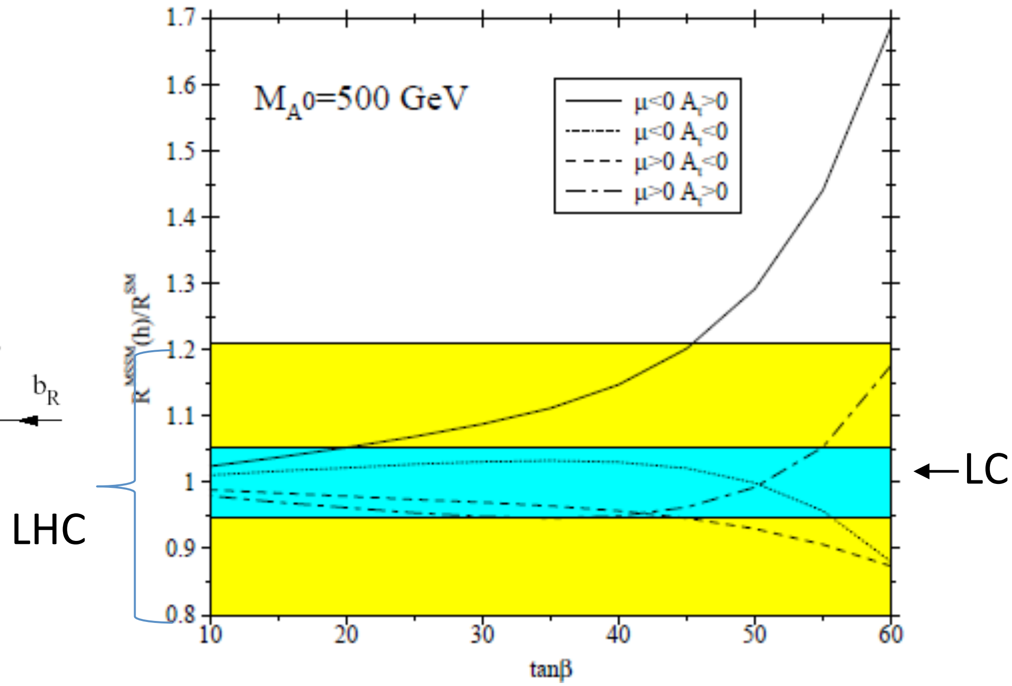


# SUSY loop contributions to the hbb Yukawa coupling

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



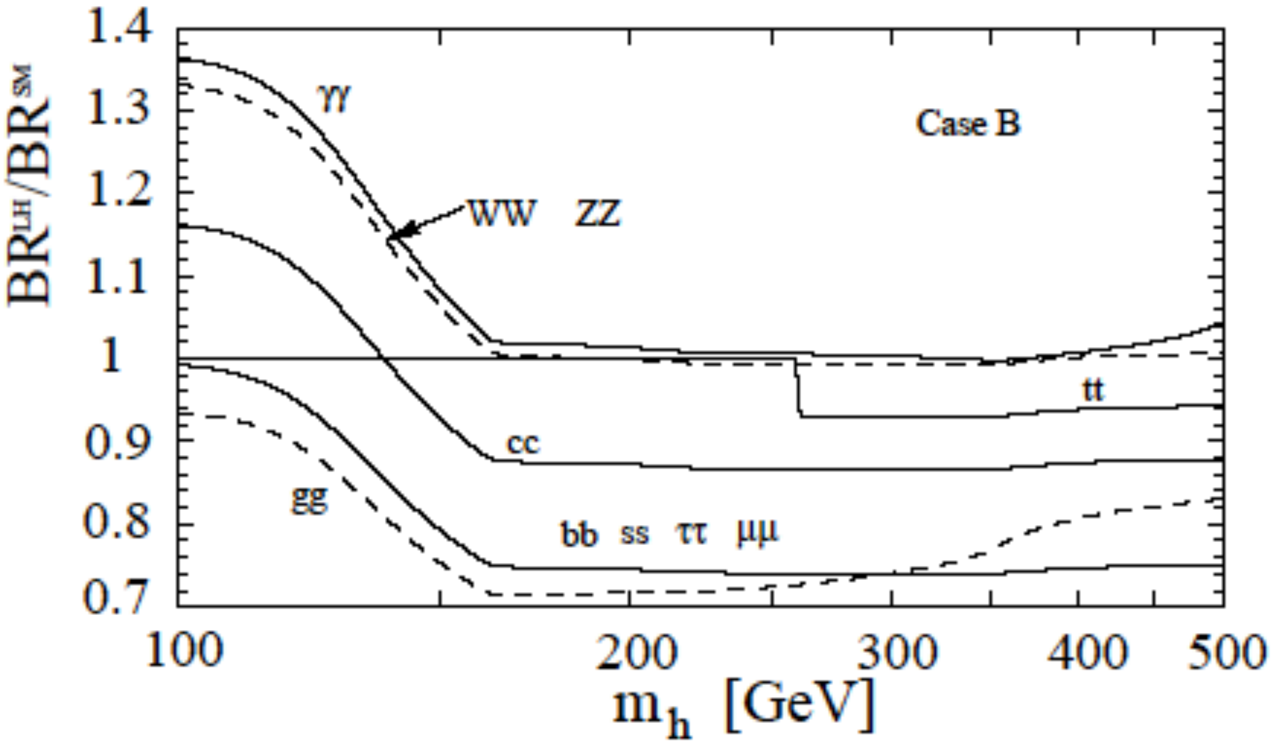

B(h->bb)/B(h->ττ) normalized by SM value




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

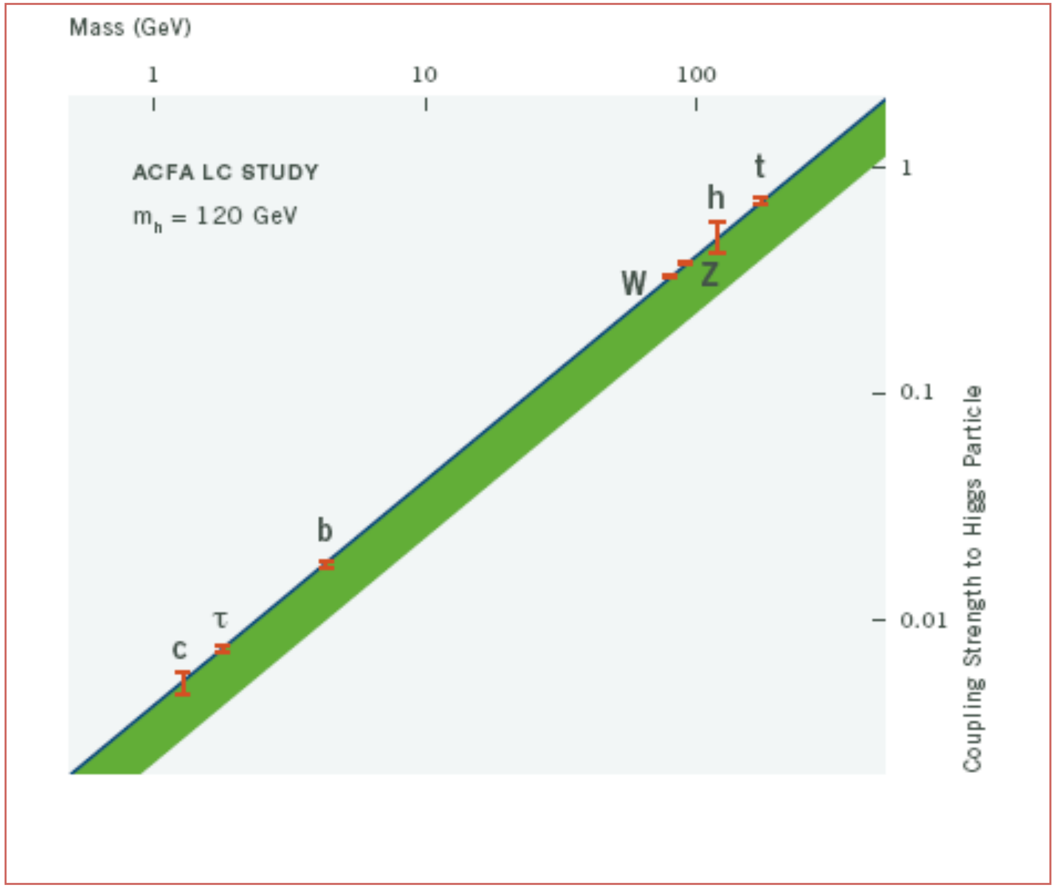
J.Guasch, W.Hollik,S.Penaranda 2001

Little Higgs model with T parity




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

# Radion-Higgs mixing in extra-dim model

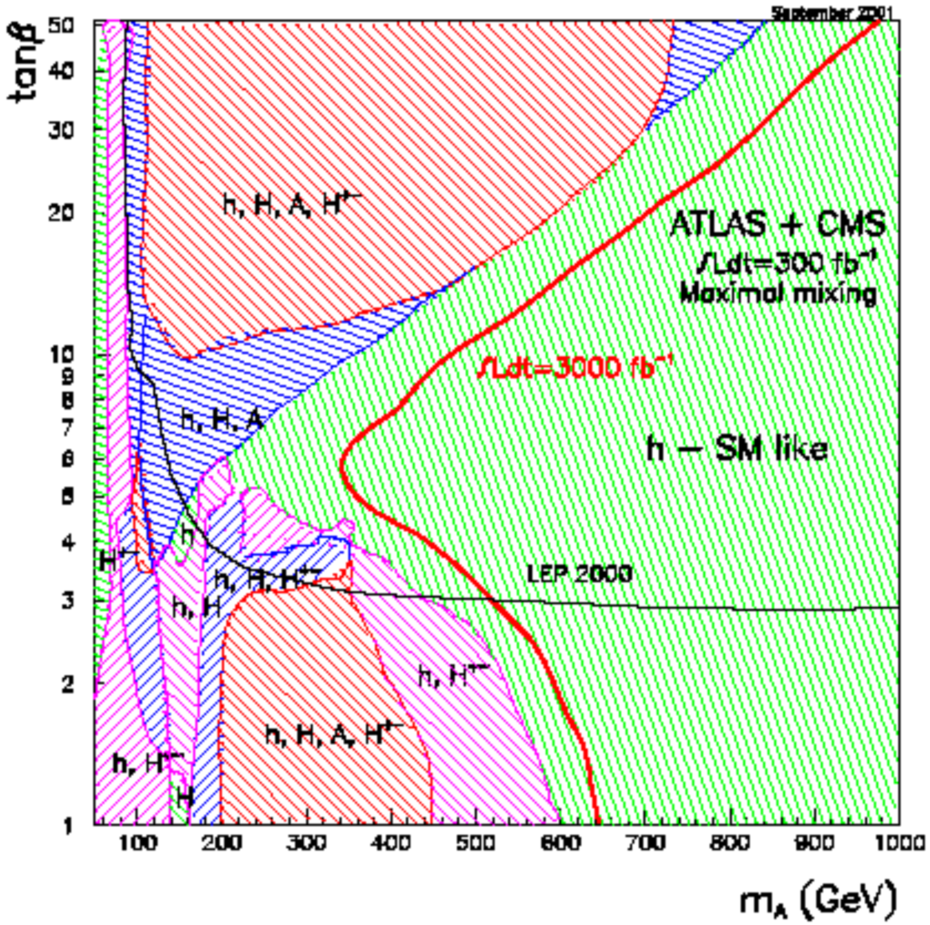



HEPAP report

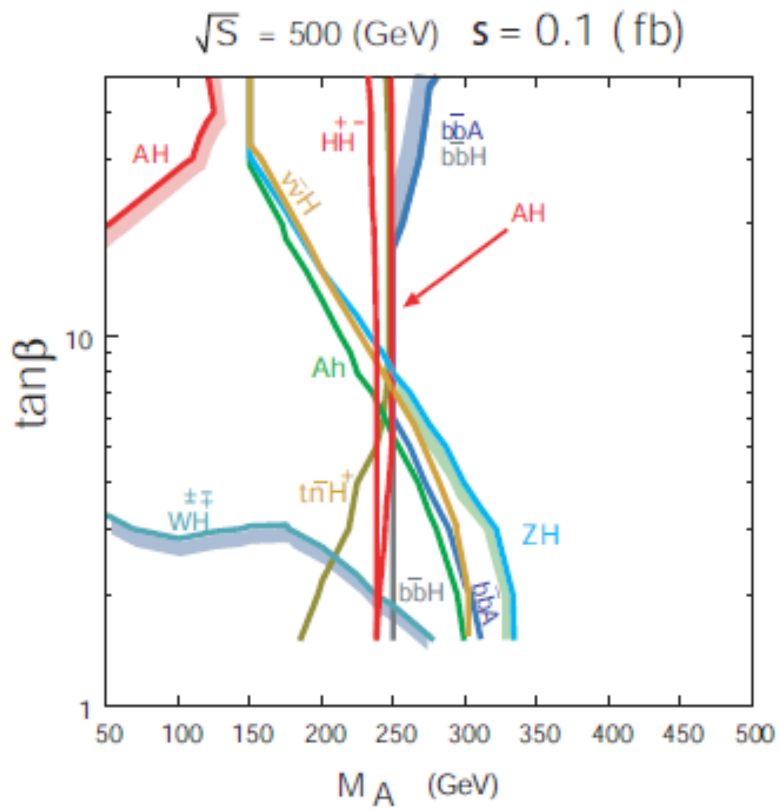
# SUSY heavy Higgs search

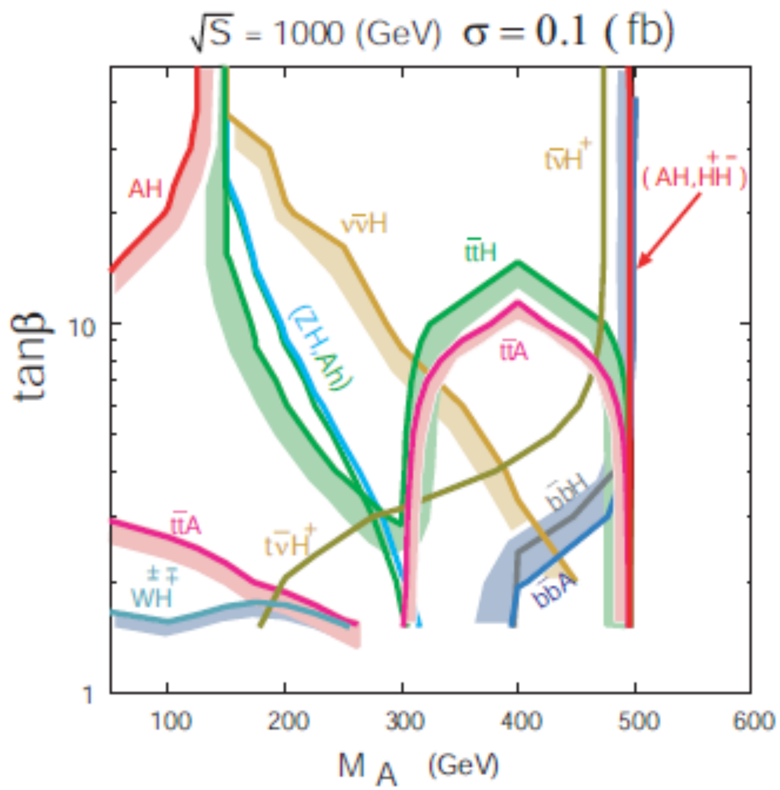
LHC covering

There is a “wedge”
where only one Higgs boson
can be found.



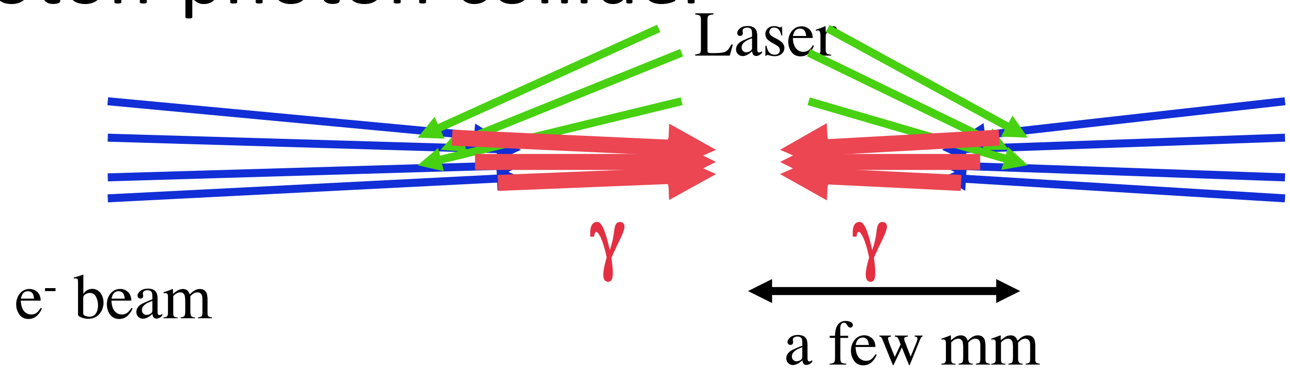
Heavy Higgs production processes for 500 GeV and 1TeV ILC

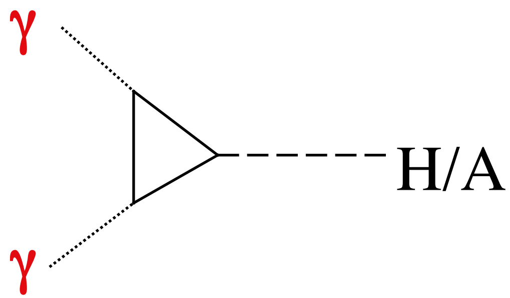


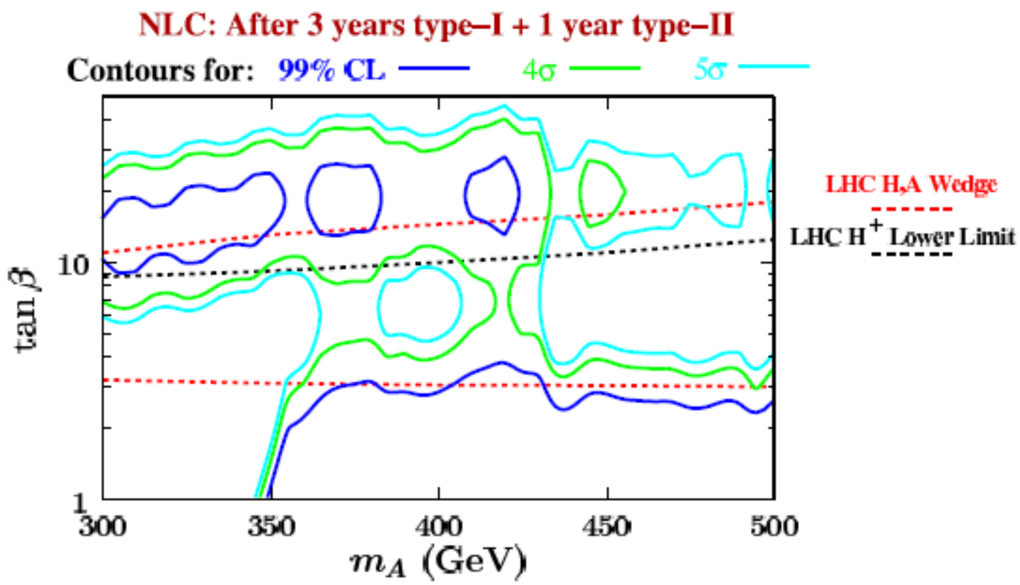

GLC report

# 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.




From ILC RDR

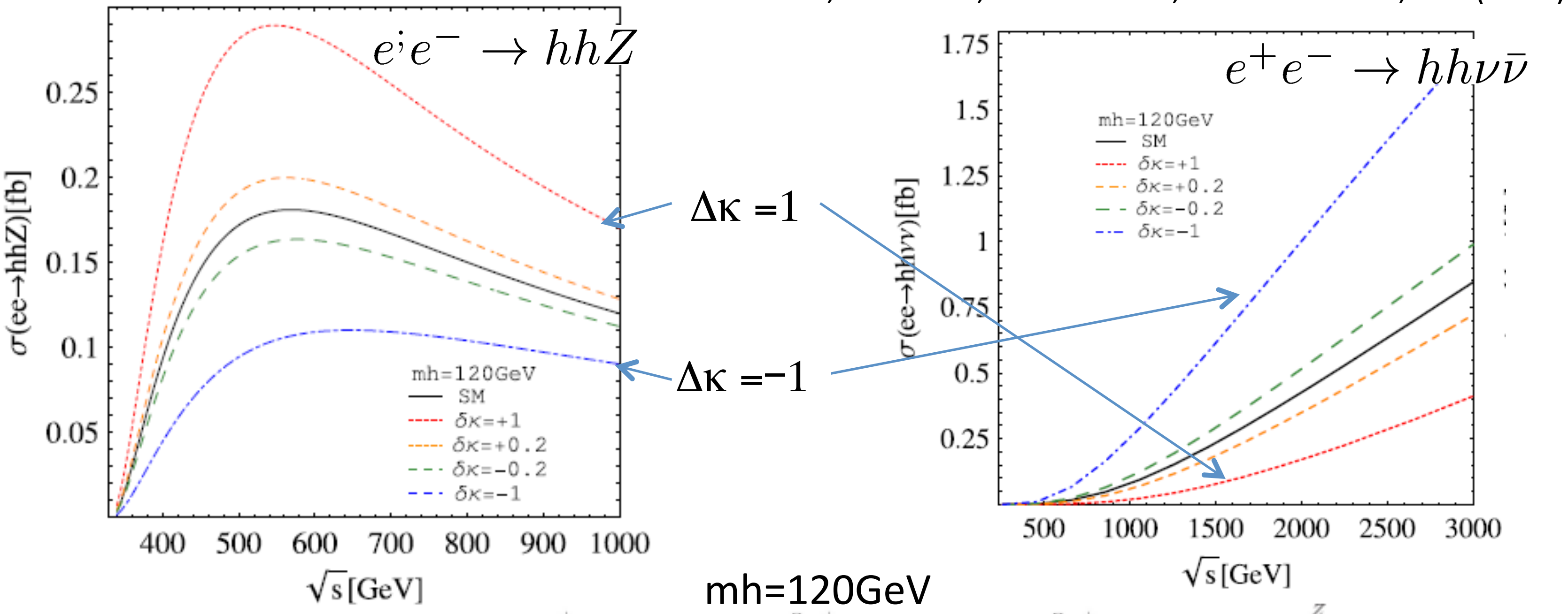
# Higgs self-coupling constant

- 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.

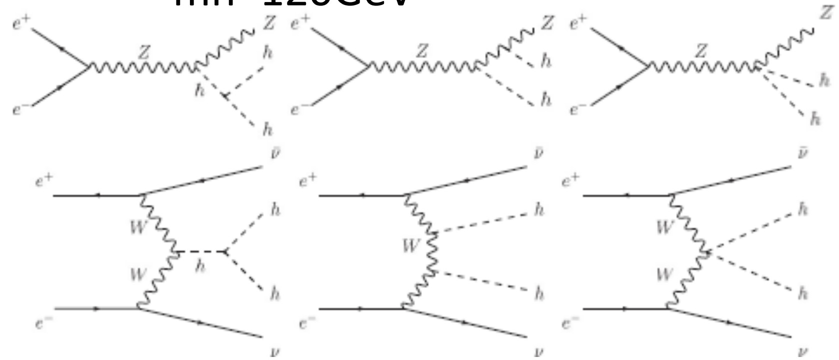
# Higgs self-coupling constant and Higgs potential

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)

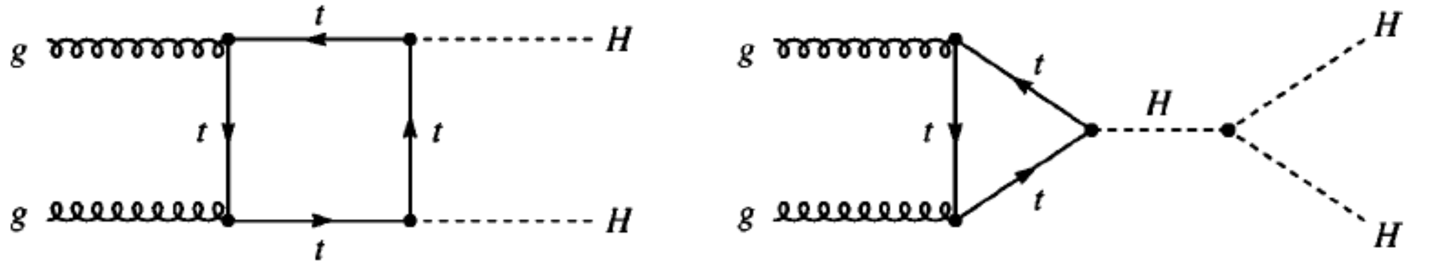


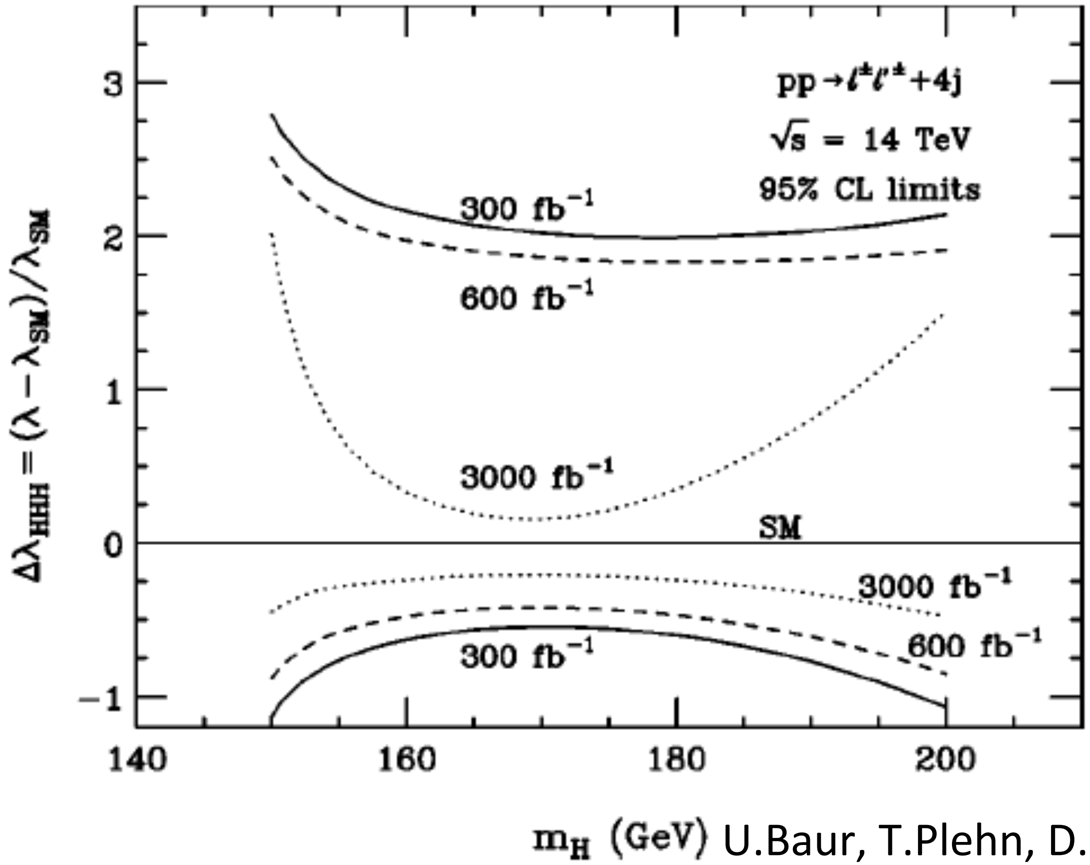

mh=120GeV



O(10)% measurement
 at ILC with a few $ab^{-1}$
Difficult at LHC with
mh~120GeV

Triple Higgs coupling measurement at LHC

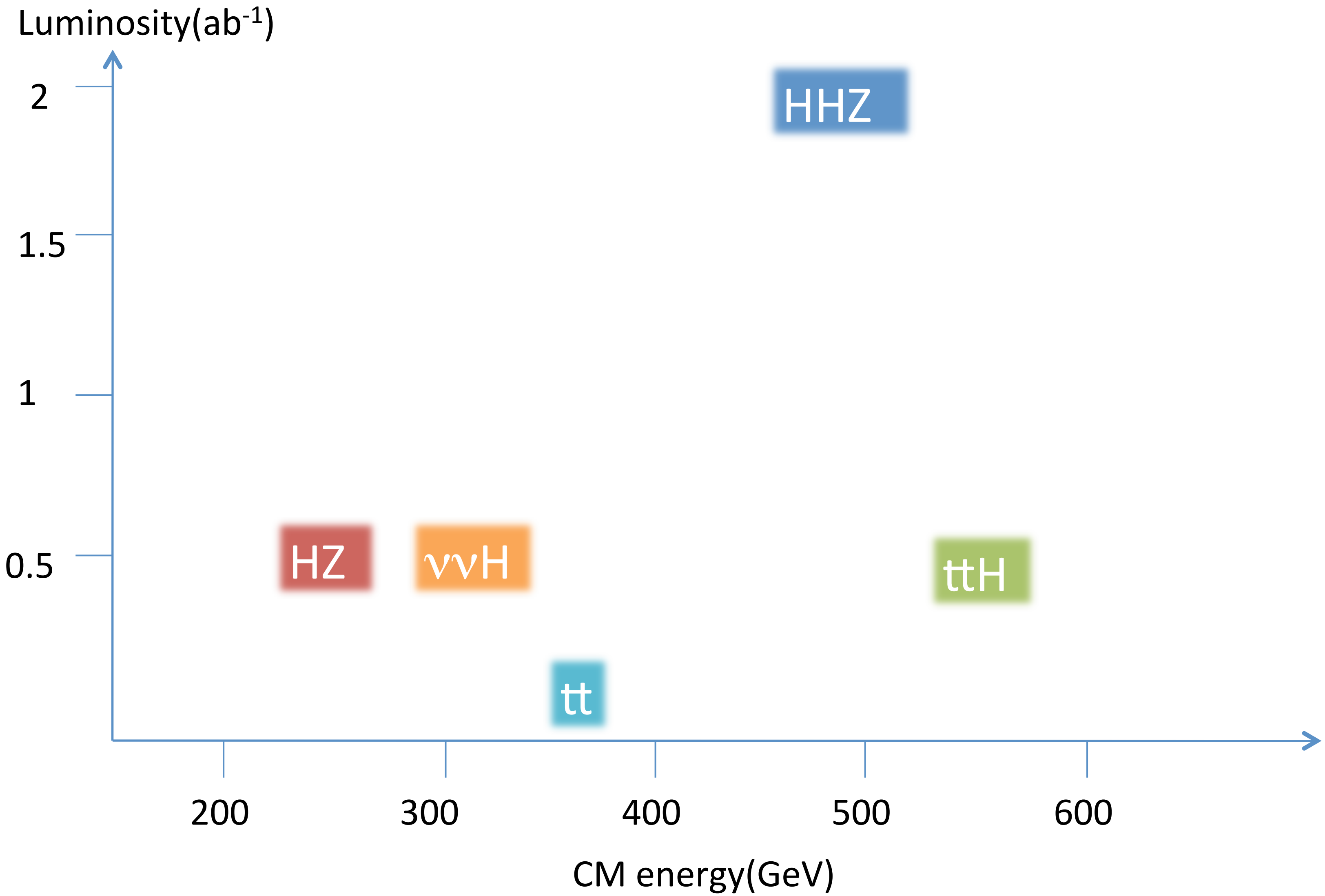



U.Baur, T.Plehn, D.Rainwater,2003

It seems that
the measurement
is feasible only for
the Higgs boson mass
of 150-200 GeV at the
HL-LHC.

# Higgs and Top programs at ILC



# Radiative correction to the triple Higgs coupling in the SM

In the SM, the triple Higgs coupling receive $O(m_t^4)$ correction from top loop diagram.

Very simple calculation shows:

$$V_{eff}(\phi) = -\frac{\mu^2}{2}\phi^2 + \frac{\lambda}{4}\phi^4 - \frac{3}{16\pi^2}m_t^4(\phi)(\ln\frac{m_t^2(\phi)}{Q^2} - \frac{3}{2})$$

$$(\phi = v + h)$$

$$= const + \frac{1}{2}m_h^2h^2 + \frac{1}{6}\lambda_{hhh}h^3 + ....$$

$$\left.\frac{\partial V_{eff}(\phi)}{\partial\phi}\right|_v = 0$$

$$m_h^2 \equiv \left.\frac{\partial^2 V_{eff}(\phi)}{\partial^2\phi}\right|_v$$

$$\lambda_{hhh} \equiv \left.\frac{\partial^3 V_{eff}(\phi)}{\partial^3\phi}\right|_v = \frac{3m_h^2}{v} - \frac{3m_t^4}{\pi^2v^3}$$

About 10% effect.
Non-decoupling in the large mt limit.
No O(mt^4) term in hVV couplings.

This measures the deformation of the Higgs potential by the top quark loop.

# Self-coupling correction in two Higgs doublet model

We calculate the radiative correction to the triple Higgs coupling in the two Higgs doublet model.

$$V_{2\mathrm{HDM}} = m_1^2 \left|\varphi_1\right|^2 + m_2^2 \left|\varphi_2\right|^2 - m_3^2 \left(\varphi_1^\dagger \varphi_2 + \varphi_2^\dagger \varphi_1\right) + \frac{\lambda_1}{2} \left|\varphi_1\right|^4 + \frac{\lambda_2}{2} \left|\varphi_2\right|^4$$
$$+\lambda_3 \left|\varphi_1\right|^2 \left|\varphi_2\right|^2 + \lambda_4 \left|\varphi_1^\dagger \varphi_2\right|^2 + \frac{\lambda_5}{2} \left\{\left(\varphi_1^\dagger \varphi_2\right)^2 + \left(\varphi_2^\dagger \varphi_1\right)^2\right\},$$

Two cases for heavy Higgs masses

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

$$M = m_3 / \sqrt{\cos\beta \sin\beta}$$

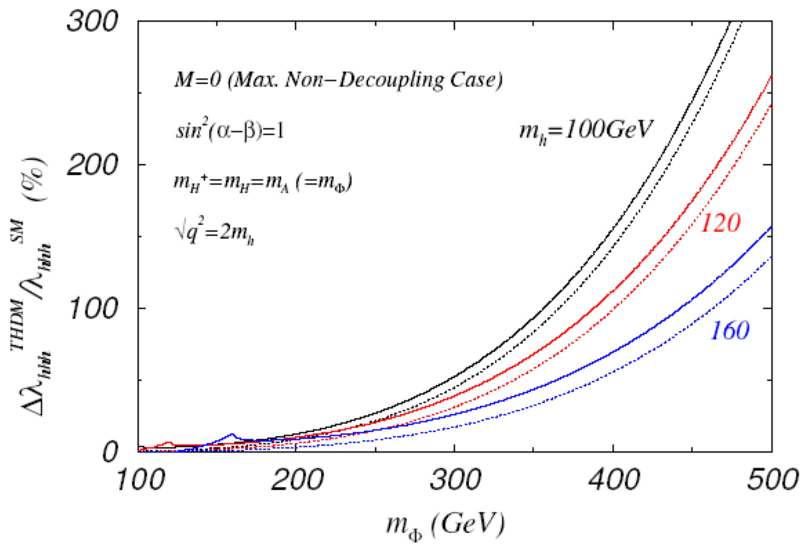
$$\tan\beta = <\phi_2> / <\phi_1>$$

Non-decoupling case: M, small.
Decoupling case: M, large.

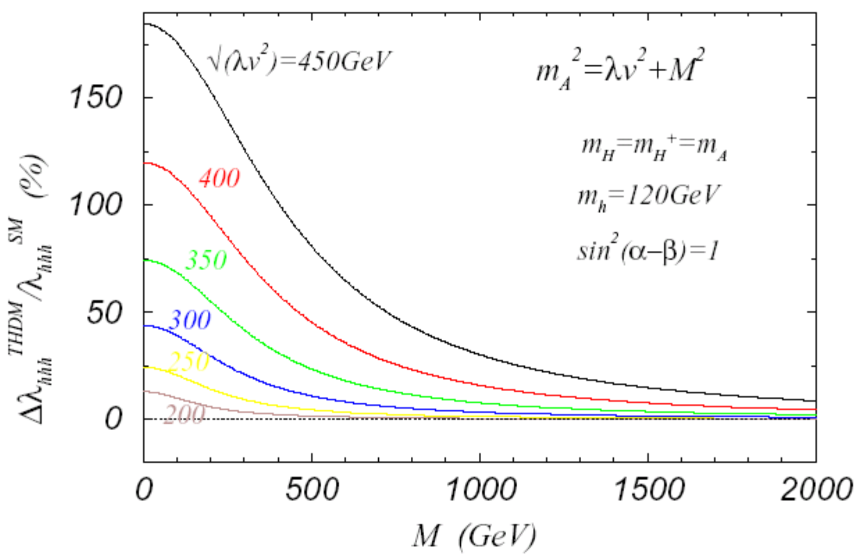
We consider the case:
the h-V-V coupling is found to be consistent with the SM at O(1)% level ,
and the $\rho$ parameter constraint is satisfied by degeneracy of heavy Higgs bosons.

$$\lambda_{hhh}^{eff}(THDM) = \frac{3m_h^2}{v}\left\{1+\frac{m_H^4}{12\pi^2 m_h^2 v^2}\left(1-\frac{M^2}{m_H^2}\right)^3 + \frac{m_A^4}{12\pi^2 m_h^2 v^2}\left(1-\frac{M^2}{m_A^2}\right)^3 + \frac{m_{H^\pm}^4}{6\pi^2 m_h^2 v^2}\left(1-\frac{M^2}{m_{H^\pm}^2}\right)^3 - \frac{N_{c_t} m_t^4}{3\pi^2 m_h^2 v^2} + \ldots\right\}$$

$(g_{VVH} \sim g_{VVH(SM)})$




The decoupling behavior of $\Delta\lambda_{hhh}^{THDM}$




Correction can be O(100)% in the non-decoupling case.

S.Kanemura, S.Kiyoura,Y.Okada, E.Senaha,and C.P. Yuan, 2002

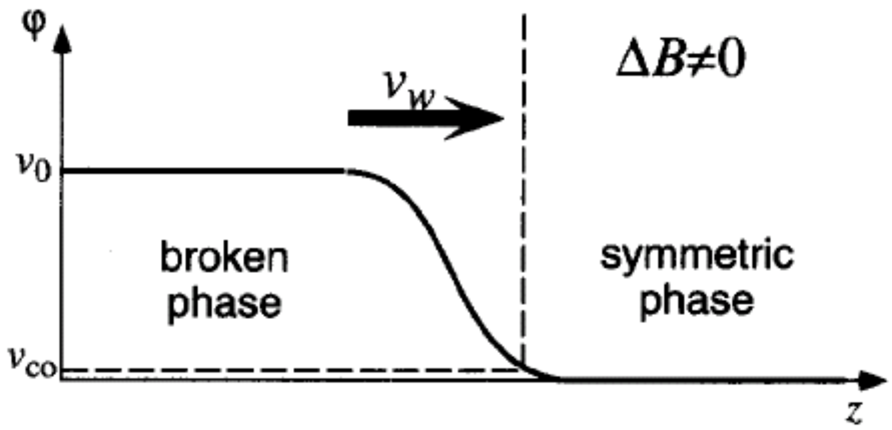
# Electroweak baryogenesis

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.

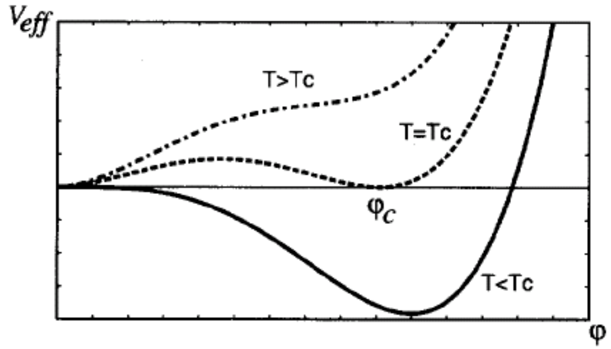
A strong first order phase transition is a necessary condition.




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.



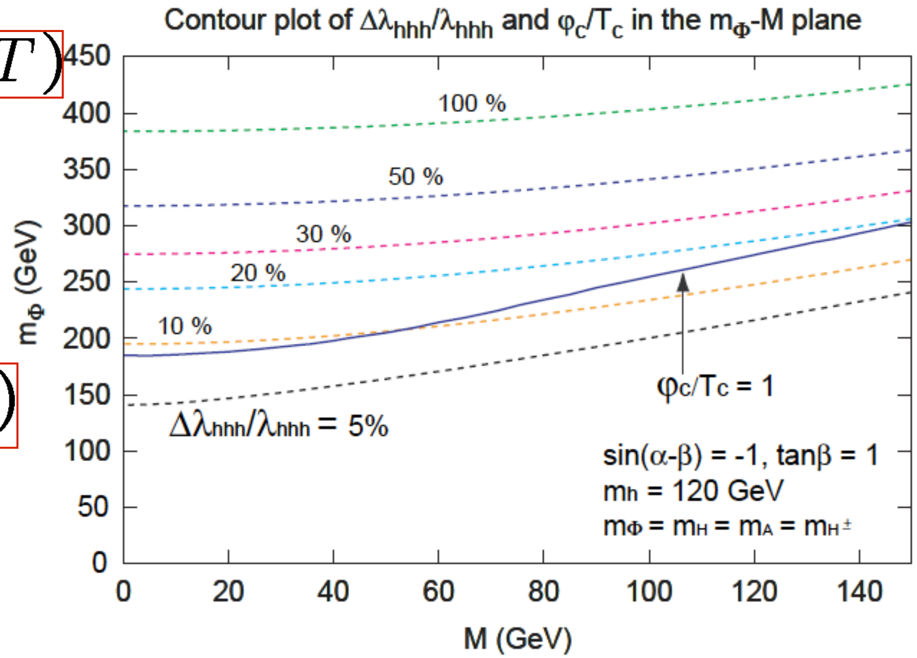

Successful electroweak baryogenesis :
Strong first order phase transition due to heavy Higgs boson loops.

$$V_T(\phi, T)$$

↕

Large radiative corrections to the zero temperature effective potential.
A large correction to the triple Higgs coupling constant

$$V_{eff}(\phi)$$




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