Tanβ determination from the Higgs boson decay at the International Linear Collider

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Outline

- Introduction: a general Two Higgs Doublet Model
- Tanβ measurement in a general 2HDM at the ILC
  1. HA production and decay
     - 1.a Branching ratio of H/A
     - 1.b Total decay width
  2. SM-like Higgs boson precision measurement
- Summary

Introduction

- A Higgs boson was discovered at the LHC last year.
  Couplings are consistent with the SM, so far.

- However, the whole structure of the Higgs sector is unknown,
  because the extended Higgs sector is not excluded.

- Extended Higgs sector is often introduced in the model beyond the SM to solve the unresolved problems in the SM; dark matter, neutrino mass, and the baryon asymmetry of the universe etc.

- **Two Higgs Doublet Model (2HDM)** is one of the simplest extended Higgs model.

  ✓ SU(2)-doublet Y=1/2 scalars Φ_1 & Φ_2

  ✓ EW rho parameter; $\rho=1$ at tree level

  ✓ FCNC can be avoided by imposing Z_2 symmetry

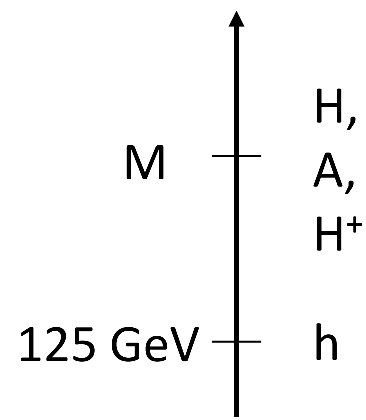
Two Higgs Doublet Model

- Five physical scalars (CP-even, odd, charged) : $h, H, A, H^{\pm}$

Masses : $m_h \simeq \sqrt{\lambda v^2} = 125\ \mathrm{GeV}$

$$m_H,\ m_A,\ m_{H^+} \simeq \sqrt{M^2 + \lambda_i v^2}$$

where $M^2 = m_3^2/(\sin\beta\cos\beta)$



Mixing angles α and β :

$$\begin{pmatrix} z_1 \\ z_2 \end{pmatrix} = \begin{pmatrix} c_\beta & -s_\beta \\ s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} z \\ A \end{pmatrix}$$

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} c_\alpha & -s_\alpha \\ s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix} \qquad \begin{pmatrix} \omega_1^+ \\ \omega_2^+ \end{pmatrix} = \begin{pmatrix} c_\beta & -s_\beta \\ s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} \omega^+ \\ H^+ \end{pmatrix}$$

$$\alpha = \cdots \qquad \tan\beta = \langle\Phi_2\rangle/\langle\Phi_1\rangle$$

Two Higgs Doublet Model

- Yukawa couplings in the 2HDM

To avoid FCNC, softly-broken Z_2 symmetry is imposed.

Glashow,Weinberg (77)

$$\Phi_1 \to \Phi_1 \qquad \Phi_2 \to -\Phi_2$$

Depending on the Z_2 charge assignment onto Fermions,
there are four types of Yukawa interactions

Type-II: Higgs sector in the MSSM

Type-X: lepton-specific, model for neutrinos

Type-I: fermiphobic, **Type-Y**: flipped

	Φ_1	Φ_2	u_R	d_R	ℓ_R	Q, L
Type-I	+	-	-	-	-	+
Type-II	+	-	-	+	+	+
Type-X	+	-	-	-	+	+
Type-Y	+	-	-	+	-	+

Aoki,Kanemura,Tsumura,Yagyu(09)

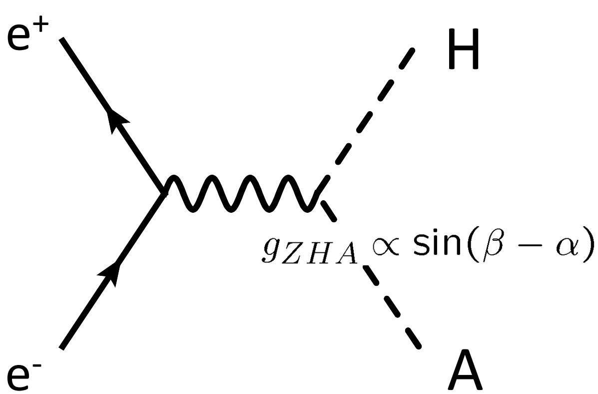
$\tan\beta = \langle \Phi_2 \rangle / \langle \Phi_1 \rangle$

- Our theme: **tanβ measurement at the ILC**

Earlier studies by Berger,Han,Jiang (01), Gunion,Han,Jiang,Sopczak (03)

tanβ measurement by using H/A production and their decay within the MSSM scenario

direct measurements by using extra Higgs bosons production (possible only if kinematically accessible)



- HA production is independent of tanβ
- tanβ dependence exists in the decay of H/A.

$$\Gamma_{H/A} \ \& \ \mathcal{B}_{H/A}$$

$\tan\beta = \langle\Phi_2\rangle/\langle\Phi_1\rangle$

Kanemura,Tsumura,HY (13)

- We study methods and the accuracy of tanβ measurement **in a general 2HDM** **at the ILC**.

$(\sqrt{s} = 250\ \text{GeV}\ \&\ \mathcal{L} = 250\ \text{fb}^{-1})$

In general 2HDM, sin(β-α) can deviate from 1,
as long as perturbative unitarity is satisfied.

Kanemura,Kubota,Takazugi(93)

$$\sin(\beta-\alpha) \simeq 1 - \frac{2m_Z^4}{m_A^4 \tan^2\beta}$$

If sin(β-α)<1,

tanβ dependence appears in the SM-like Higgs couplings.

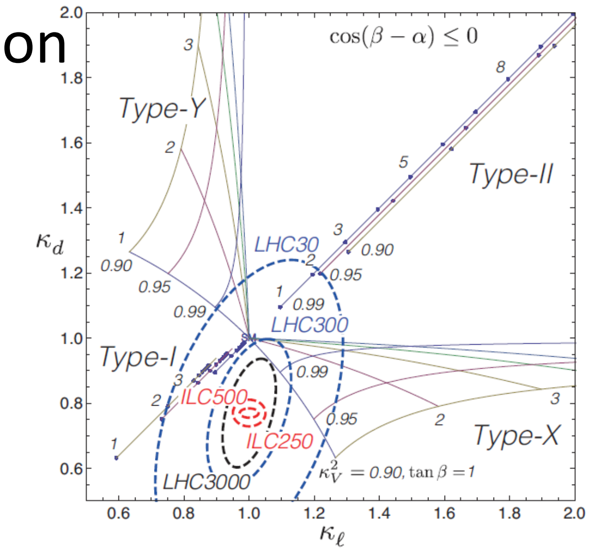
Our new proposal (in addition to the previous method):
use the precision measurements of the SM-like Higgs couplings

Indirect measurement and fingerprinting

- Indirect measurement through the small deviation in the SM-like Higgs couplings → fingerprinting

  discriminate models by the pattern of deviations in various couplings

  → K.Tsumura, M.Kikuchi's talks

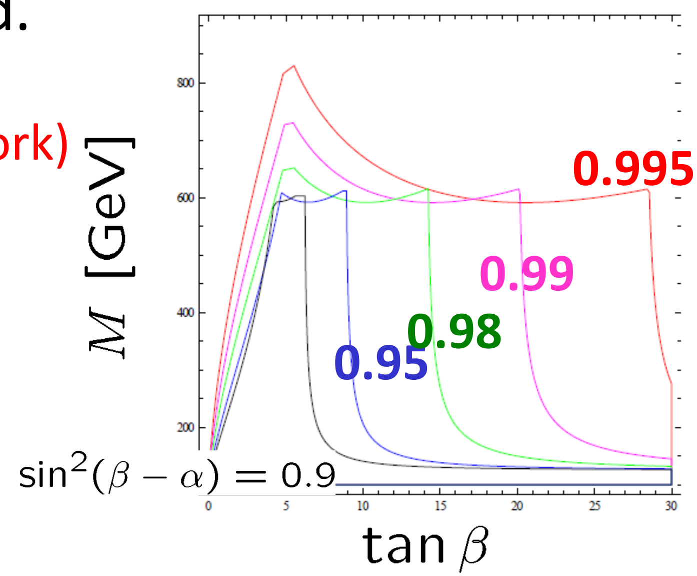


- By measuring the magnitude of deviations, parameters in the model can be determined.

  e.g. tanβ determination in the 2HDM (our work)

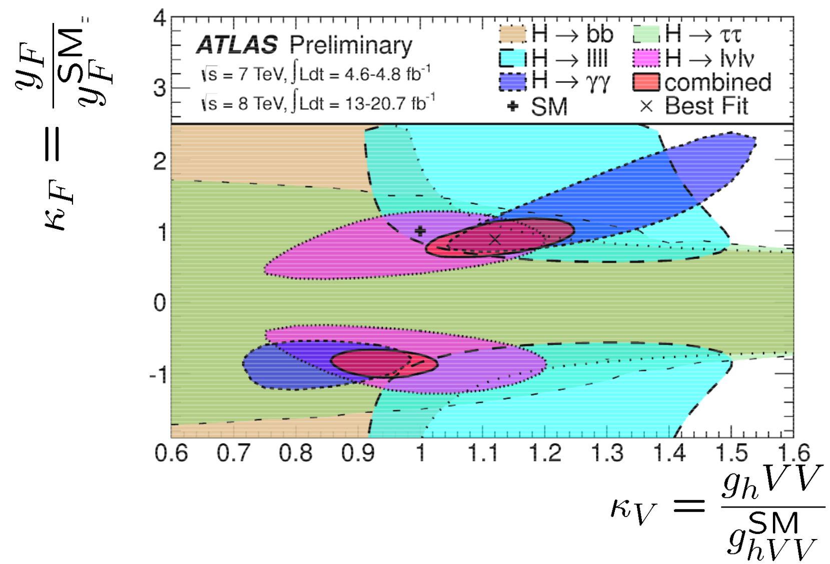
- Feedback to direct searches: prediction of masses, detailed signatures, etc.

  e.g. upper bound on the mass by perturbative unitarity.



Measurement of sin(β-α)

$$\kappa_V = \frac{g_{hVV}}{g_{hVV}^{\text{SM}}} = \sin(\beta - \alpha)$$

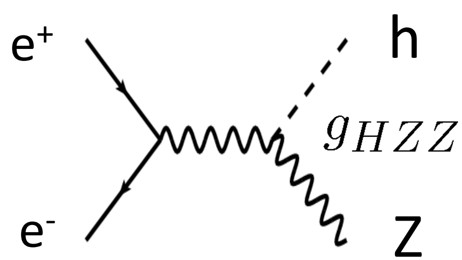


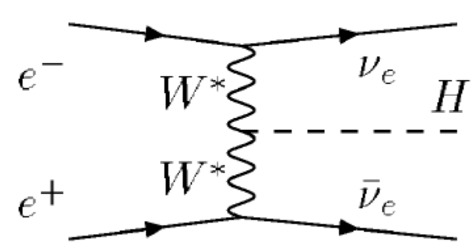
- At the LHC, hVV coupling is constrained by the global fit.

  ~2-5% @ 14TeV, 3000 fb^{-1}

- At the ILC, sin(β-α) can be directly measured by σ(hZ) or σ(hνν)

  ~0.5% @ 500GeV, 500fb^{-1}





- Introduction : General Two Higgs Doublet Model

- Tanβ measurement in general 2HDM at the ILC

    1. HA production and their decay

        1.a Branching ratio of H/A

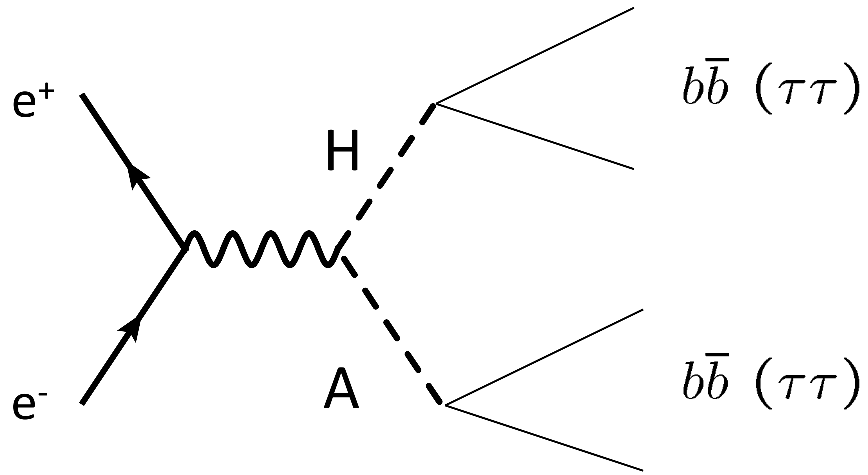
        1.b Total decay width

    2. SM-like Higgs boson precision measurement

- Summary

(1.a) Branching ratio methods

Gunion,Han,Jiang,Sopczak (03)
Kanemura,Tsumura,HY (13)

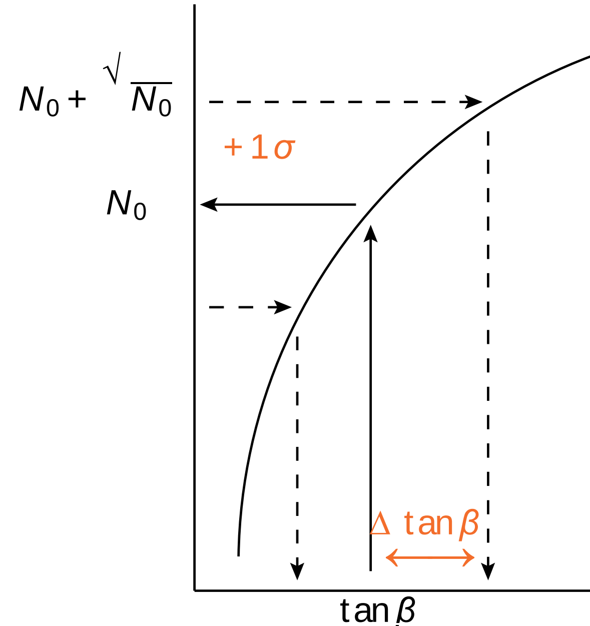


- Branching ratio can be measured by counting the number of 4b (4τ) events, since the production part is independent of of tanβ

$$N[4b(4\tau)] = \sigma_{HA} \cdot \mathcal{B}_H \cdot \mathcal{B}_A \cdot \mathcal{L}$$

- Accuracy of the measurement can be estimated by

$$N(\tan\beta \pm \Delta\tan\beta) = N_{obs} \pm \sqrt{N_{obs}}$$



(1.a) Branching ratio methods

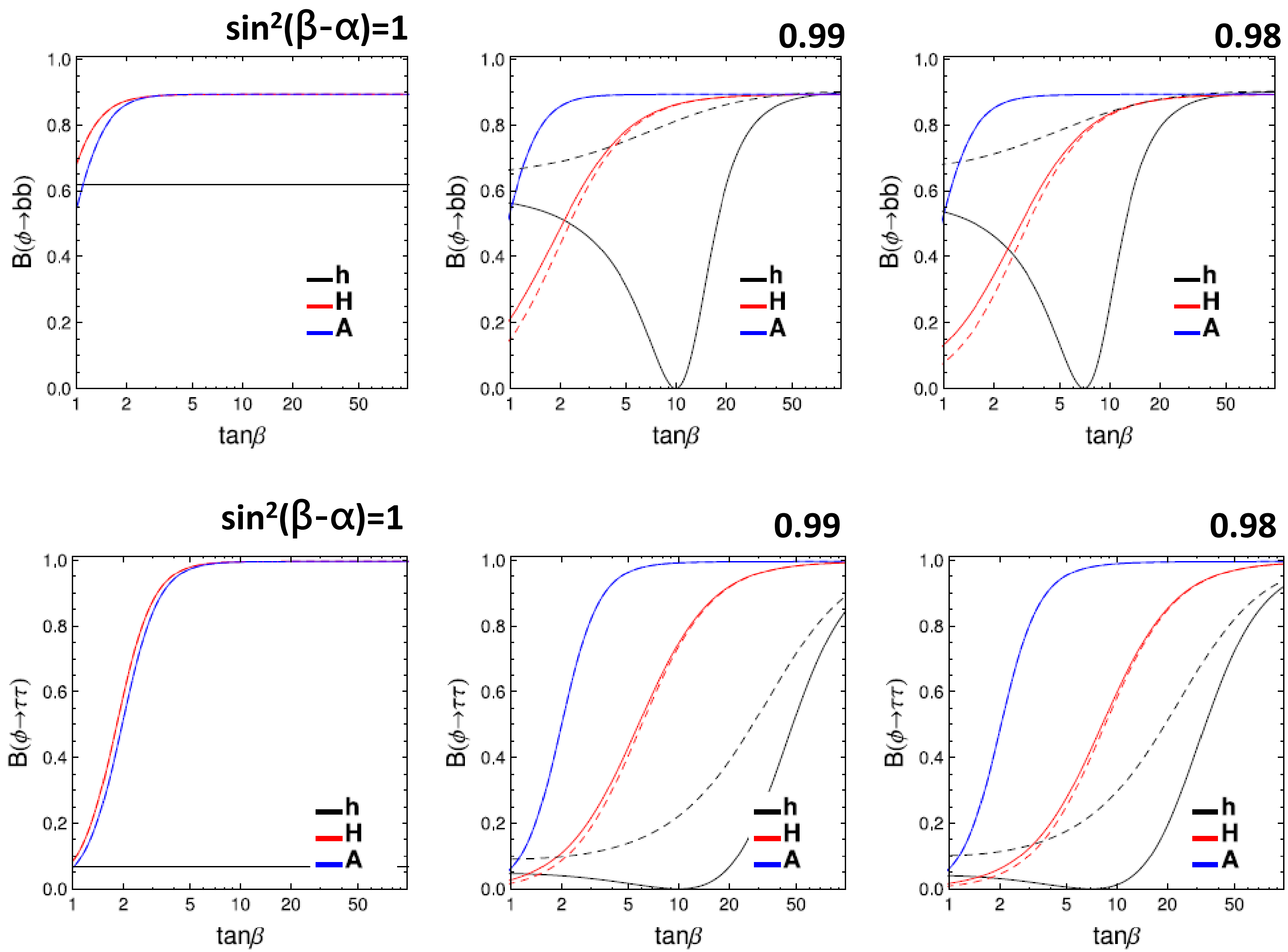
$m_{H/A} = 200$ GeV   solid(dashed) : cos(β-α) >0 (<0)

Br(ϕ→bb)

in type-II

Br(ϕ→ττ)

in type-X



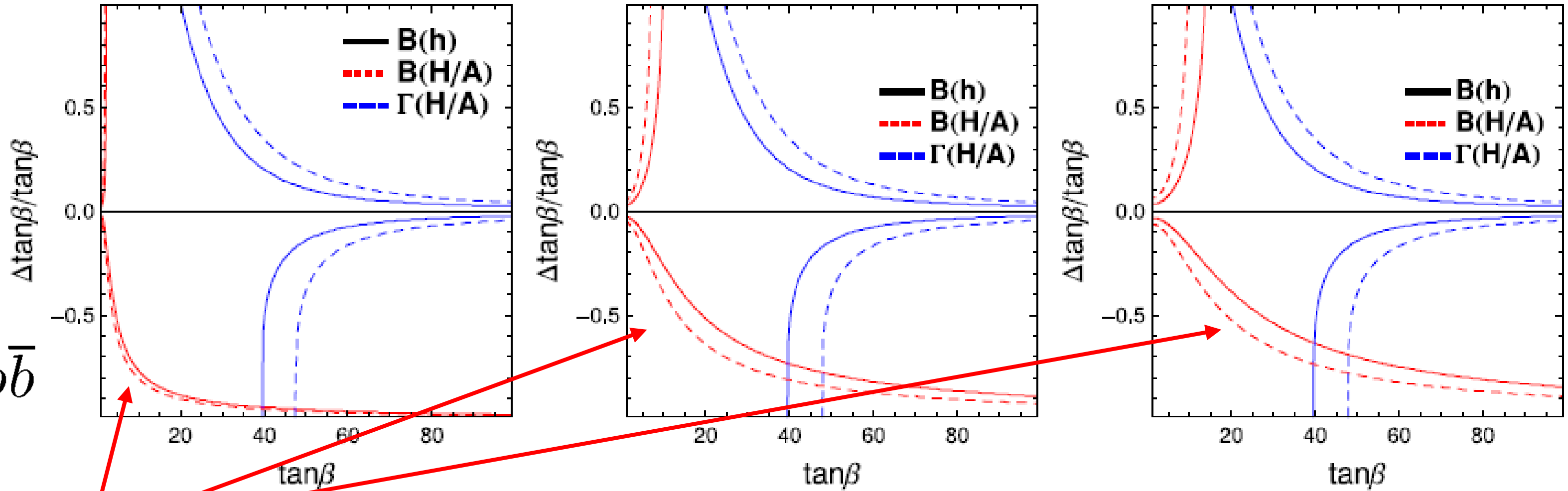
Results (part 1.a)

$m_{H/A} = 200$ GeV $\cos(\beta-\alpha) < 0$

$\sin^2(\beta-\alpha)=1$ **0.99** **0.98**

Type-II:

$HA \to b\bar{b}b\bar{b}$

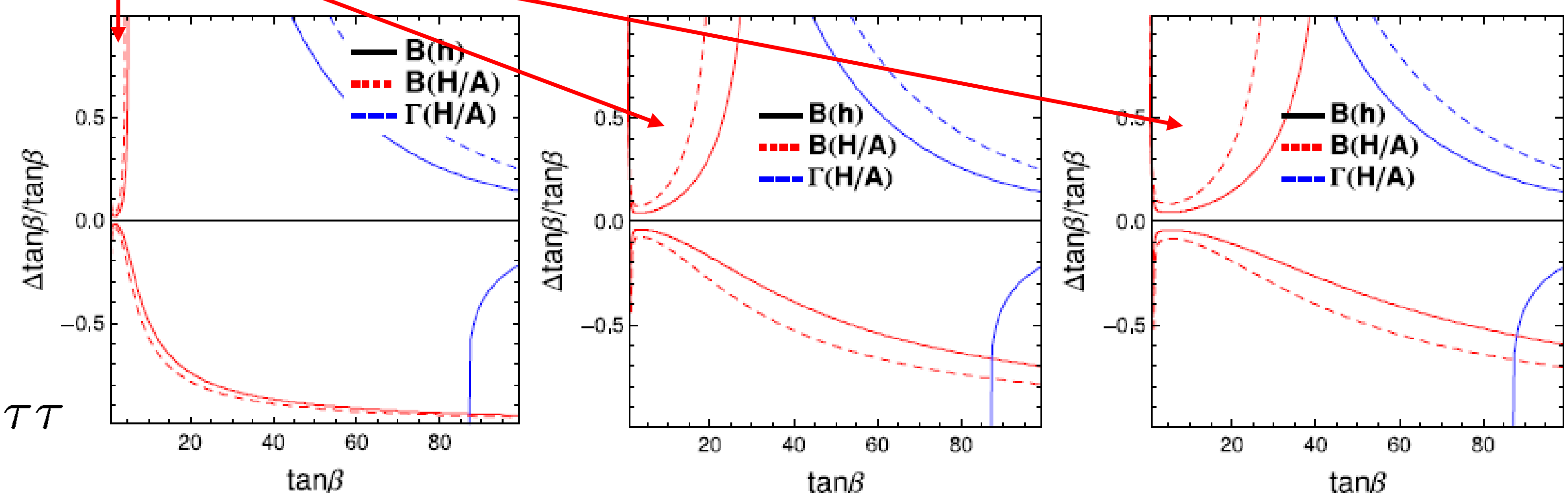


solid(dashed)=1σ (2σ)

Branching ratio method : sensitive in smaller tanβ region (before the Br saturates.)

Type-X:

$HA \to \tau\tau\tau\tau$

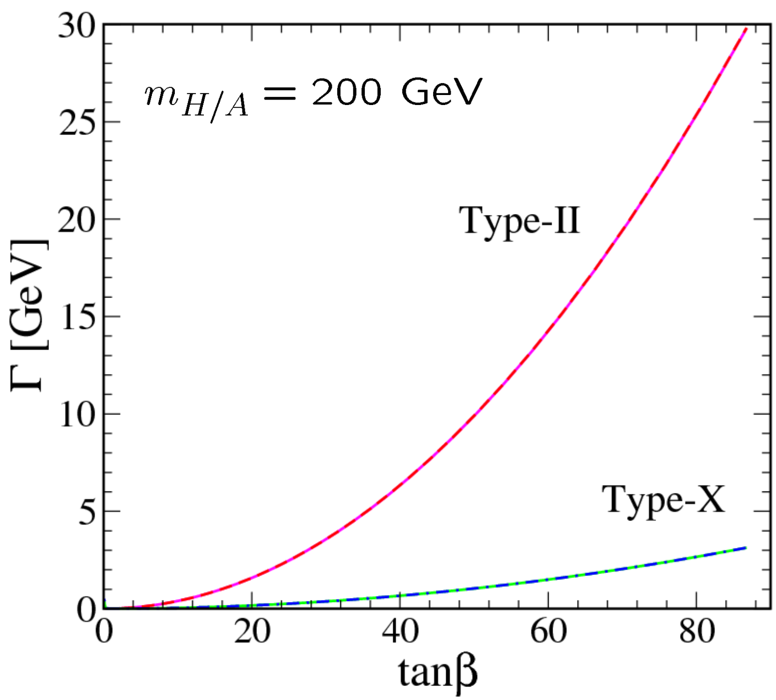


$\sin^2(\beta-\alpha)=1$ **0.99** **0.98**

(1.b) Total decay width method

Gunion,Han,Jiang,Sopczak (03)
Kanemura,Tsumura,HY (13)

- The total decay width is proportional to $(\tan\beta)^2$.
- It can be measured from the shape of Breit-Wigner distribution, if the experimental resolution is better than the decay width.
- The experimental resolution is determined by the detector performance.



width from the Breit-Wigner distribution

$$\Gamma_R = \sqrt{\Gamma_{H/A}^2 + \Gamma_{res}^2}$$

particle width — **resolution of measurement**

accuracy :

$$\Delta\Gamma_{H/A} = \sqrt{(\Gamma_R/\sqrt{2N})^2 + (\Delta\Gamma_{res})^2}$$

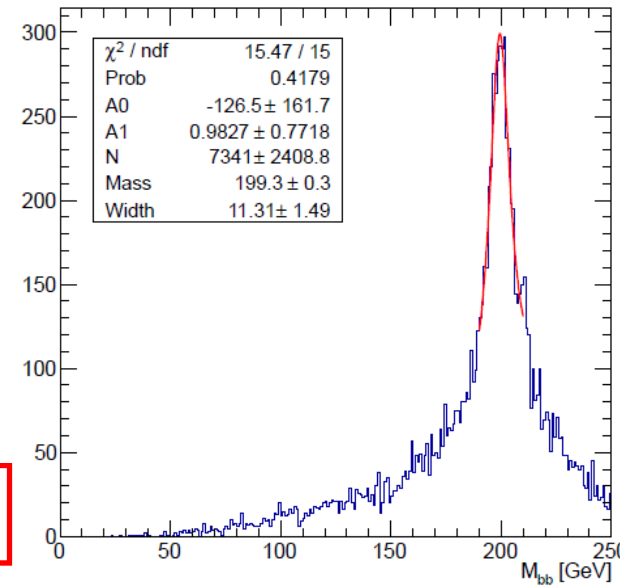
(1.b) Total decay width method

PYTHIA simulation :

- Type-II : $e^+e^- \to HA \to (b\bar{b})(b\bar{b})$

  Jet energy scales can be resolved event-by-event in e^+e^- collision.

with $\frac{\Delta E_J}{E_J} = \frac{0.3}{\sqrt{E[\mathrm{GeV}]}}$, we get $\Gamma^{bb}_{res} \simeq 11\ \mathrm{GeV}$



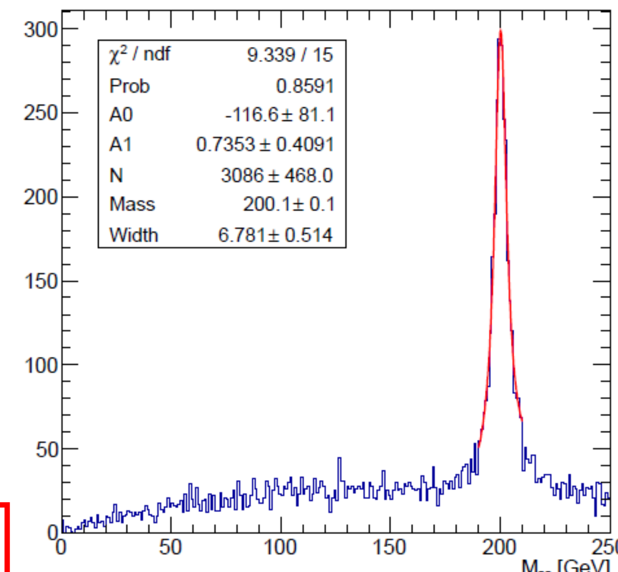
- Type-X : $e^+e^- \to HA \to (\tau^+\tau^-)(\tau^+\tau^-)$

  Charged track momenta can be measured very accurately.

  4τ momenta can be reconstructed by collinear approximation (rescaling).

  Resolution dominantly comes from the validity of this collinear approximation.

$\Gamma^{\tau\tau}_{res} \simeq 7\ \mathrm{GeV}$



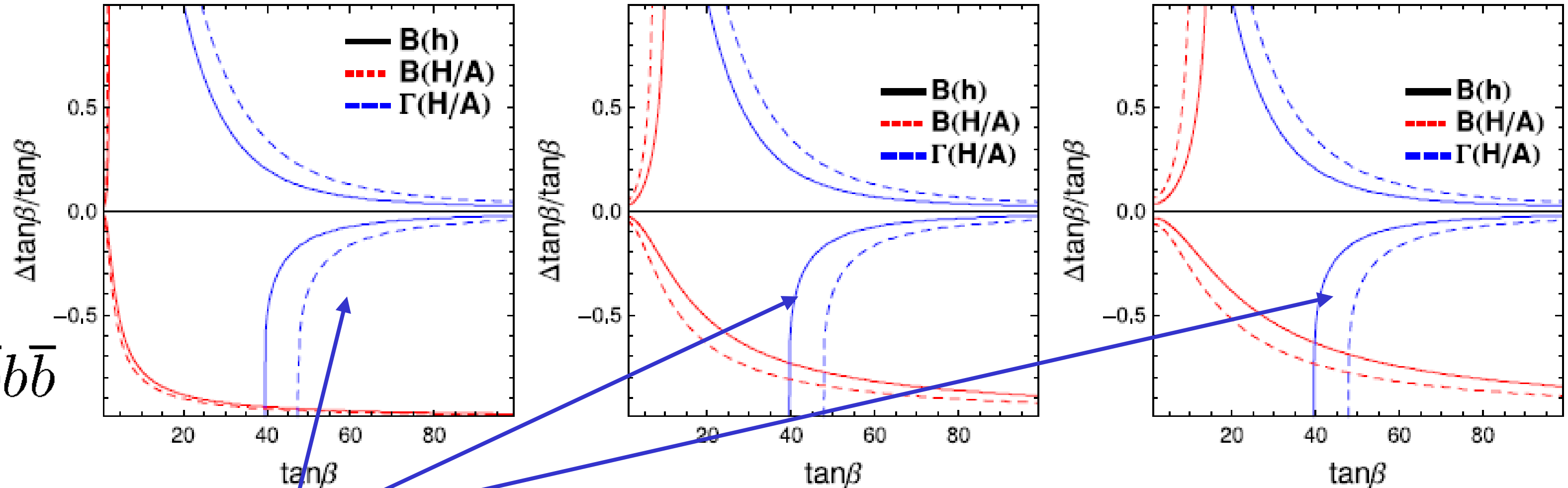
Results (part 1.b)

$m_{H/A} = 200$ GeV $\quad \cos(\beta-\alpha) < 0$

$\sin^2(\beta-\alpha)=1$ **0.99** **0.98**

Type-II:

$HA \to b\bar{b}b\bar{b}$

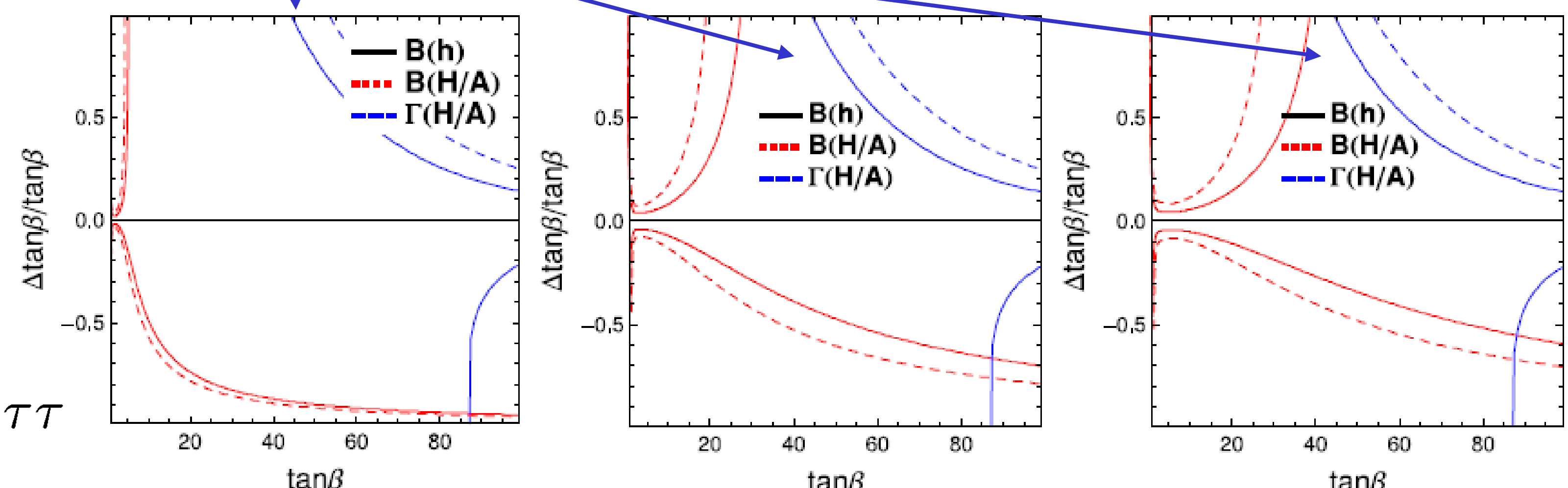


solid(dashed)=1σ (2σ)

Total decay width method : sensitive in larger tanβ region (large decay width)

Type-X:

$HA \to \tau\tau\tau\tau$



$\sin^2(\beta-\alpha)=1$ **0.99** **0.98**

2. Method by using the SM-like Higgs boson

Kanemura,Tsumura,HY (13)

- Couplings of the SM-like Higgs boson can be measured very precisely at the ILC.

$$\begin{cases} \Delta y_b^2/y_b^2 \simeq 2.9\%(1.5\%) \\ \Delta y_\tau^2/y_\tau^2 \simeq 4.9\%(2.5\%) \\ \Delta g_{hVV}^2/g_{hVV}^2 \simeq 2.6\%(1.3\%) \end{cases}$$

2σ (1σ)
at the ILC $\sqrt{s}$=250GeV, L=250 fb^{-1}

ILC white paper 1310.0763

- Yukawa couplings of SM-like Higgs depend on tanβ, if $\sin^2(\beta-\alpha)<1$

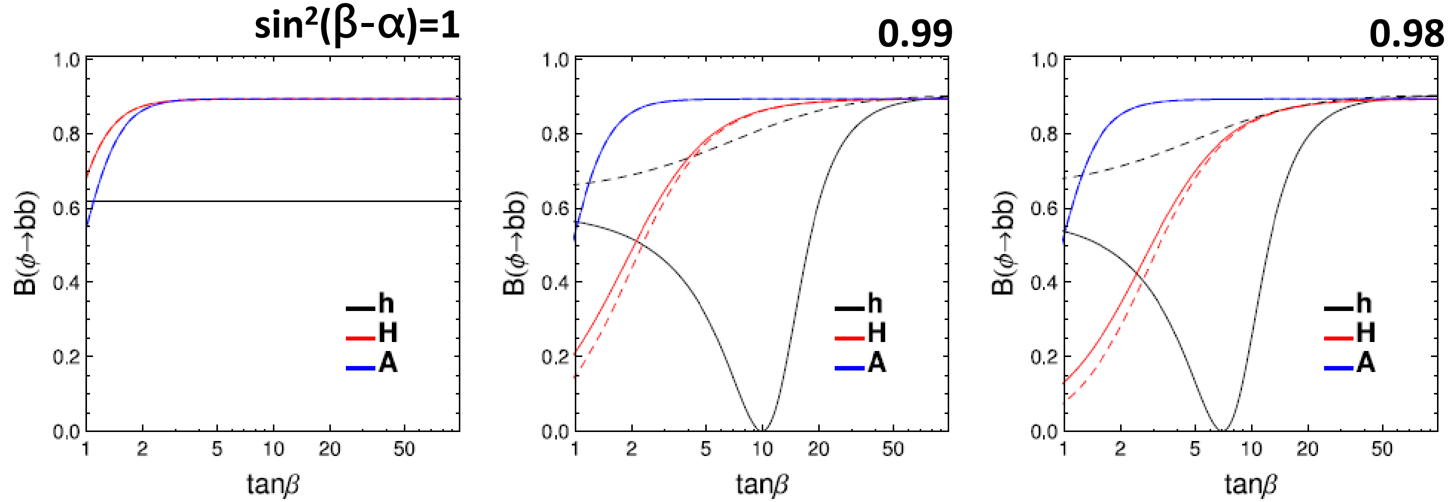
$$\begin{cases} \text{Type-II}: \quad y_{d,\ell}^h/y_{d,\ell}^{h,\text{SM}} = \sin(\beta-\alpha) - \tan\beta\cdot\cos(\beta-\alpha) \\ \text{Type-X}: \quad y_\ell^h/y_\ell^{h,\text{SM}} = \sin(\beta-\alpha) - \tan\beta\cdot\cos(\beta-\alpha) \end{cases}$$

→ Tanβ determination through the (small) deviation in the SM-like Higgs couplings!

2. Method by using the SM-like Higgs boson

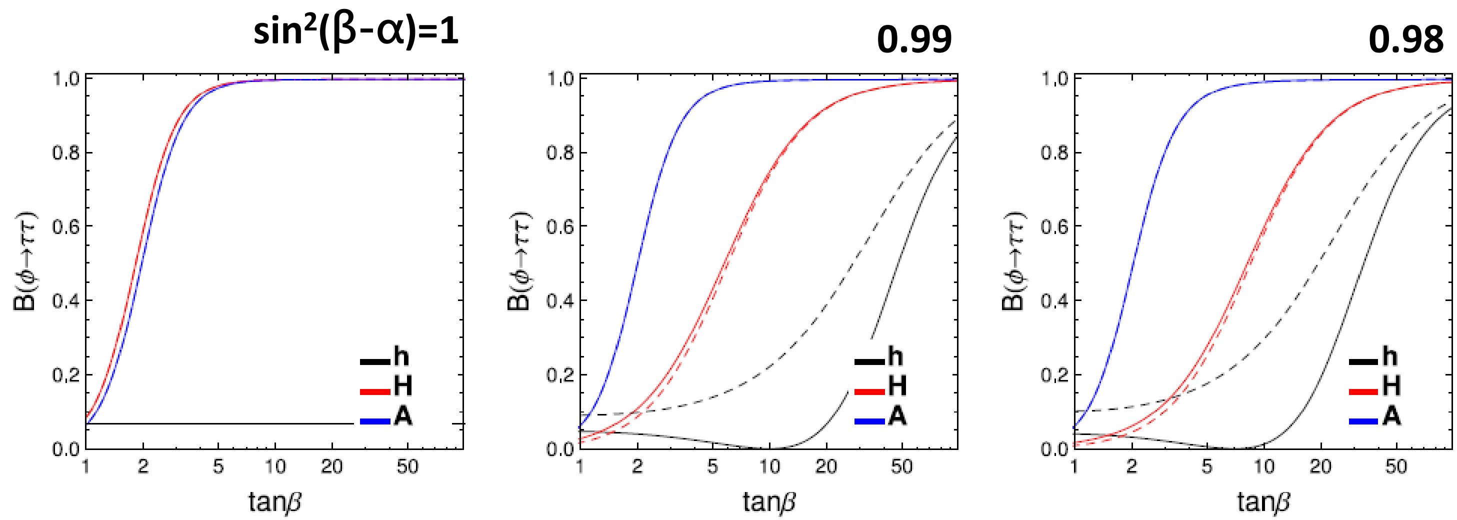
Br(bb)

in type-II:



Br(ττ)

in type-X:



solid(dashed) : cos(β-α) >0 (<0)

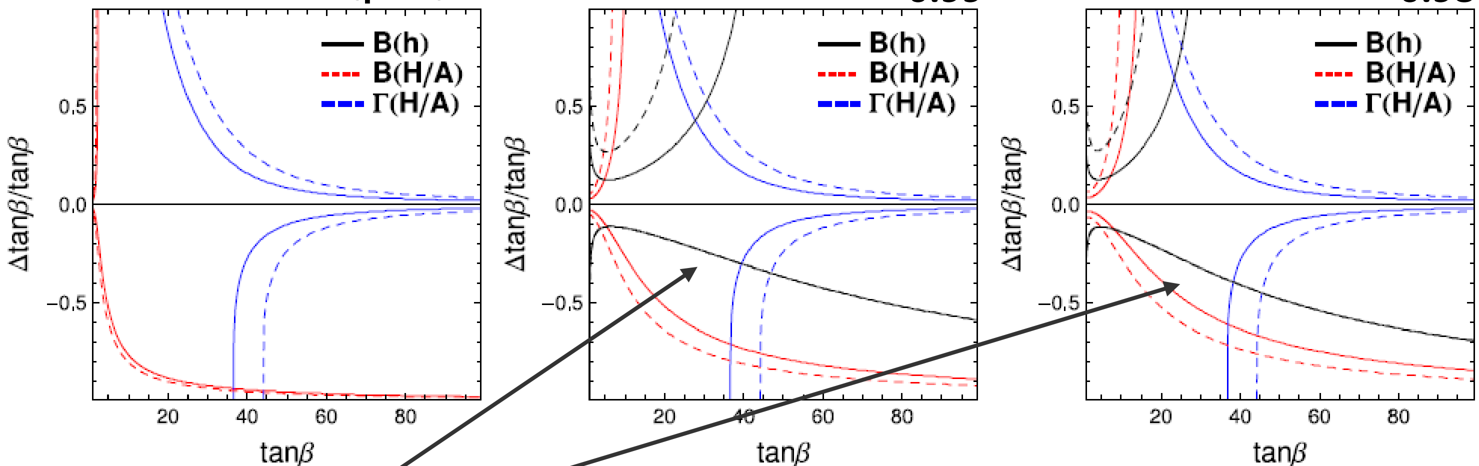
Results (part 2.)

$m_{H/A} = 200$ GeV $\cos(\beta - \alpha) < 0$

Type-II:

using Br(bb)

$\sin^2(\beta-\alpha)=1$ 0.99 0.98

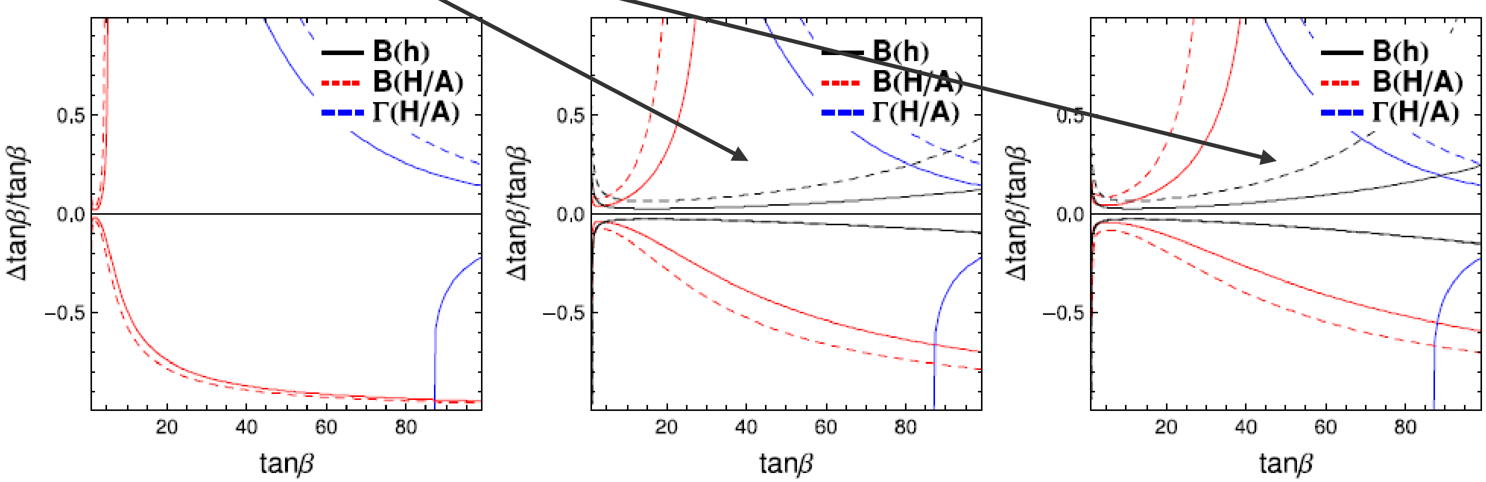


solid(dashed)=1σ (2σ)

SM-like Higgs coupling method : sensitive if $\sin^2(\beta-\alpha)<1$

Type-X:

using Br(ττ)



$\sin^2(\beta-\alpha)=1$ 0.99 0.98

IV. Summary

- In the general Two Higgs Doublet Model, sin(β-α) and tanβ are important fundamental parameters governing Higgs boson couplings.

- We studied the methods and the accuracy of determining tanβ in the general 2HDM at the ILC experiment.

- In addition to the previously proposed methods by using the direct production of extra bosons, H and A, we proposed a method by using the SM Higgs boson, which is effective if $\sin^2(\beta-\alpha)<1$.

- We found that our method gives the most precise determination for a wide region of tanβ, especially in the type-X 2HDM.

Comments on other types

- Type-Y: almost same as Type-II, when using the bb mode.
  tau mode can distinguish them.

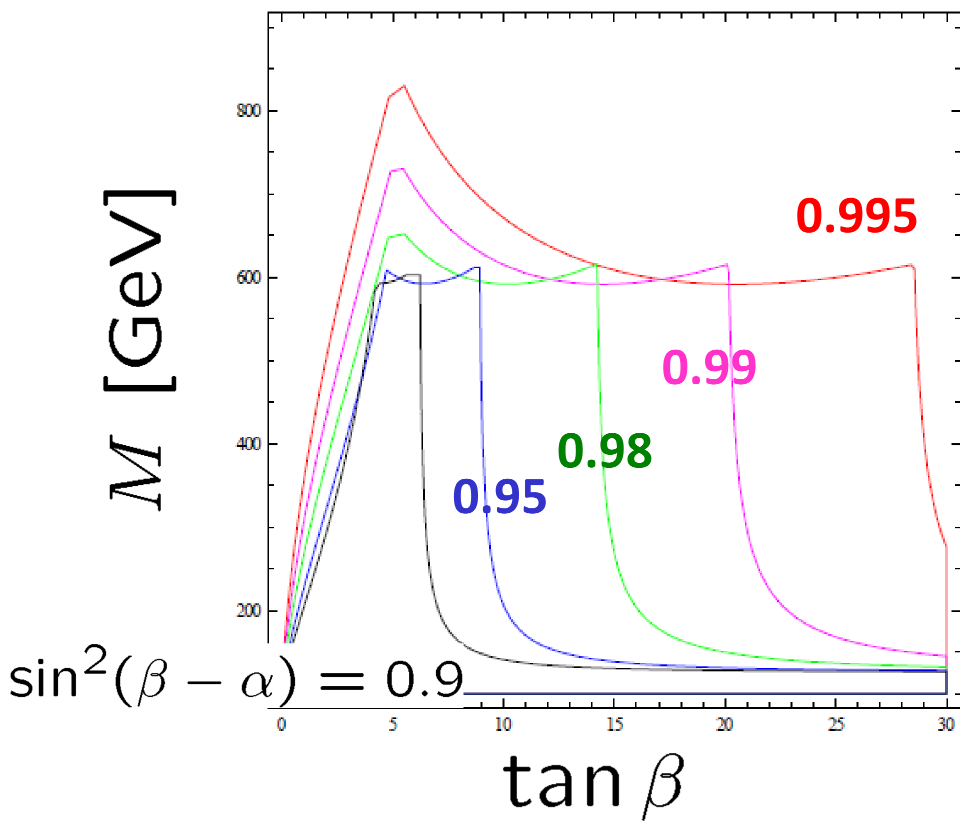
- Type-I: all the Yukawa couplings of extra bosons are suppressed by 1/tanβ. Only sin(β-α) deviation may be seen.

- What does the indirect measurement of tanβ [and sin(β-α)] imply?

- Perturbative unitarity condition gives the upper limit of the mass scale $M=m_H=m_A=m_{H\pm}$.

- Useful information (feedback) for the direct search

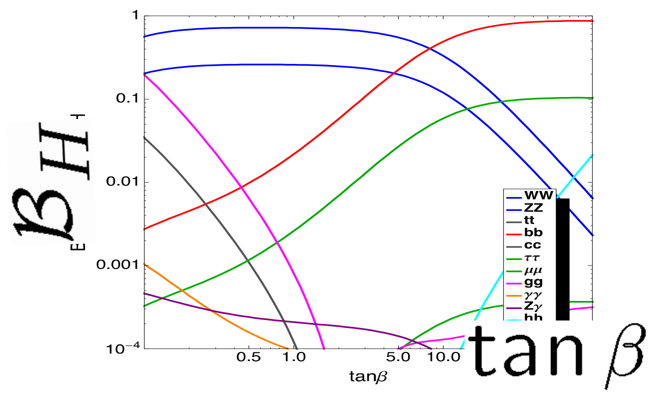
- Definite evidence of sin(β-α)<1 is crucial. (hVV vertex measurement)



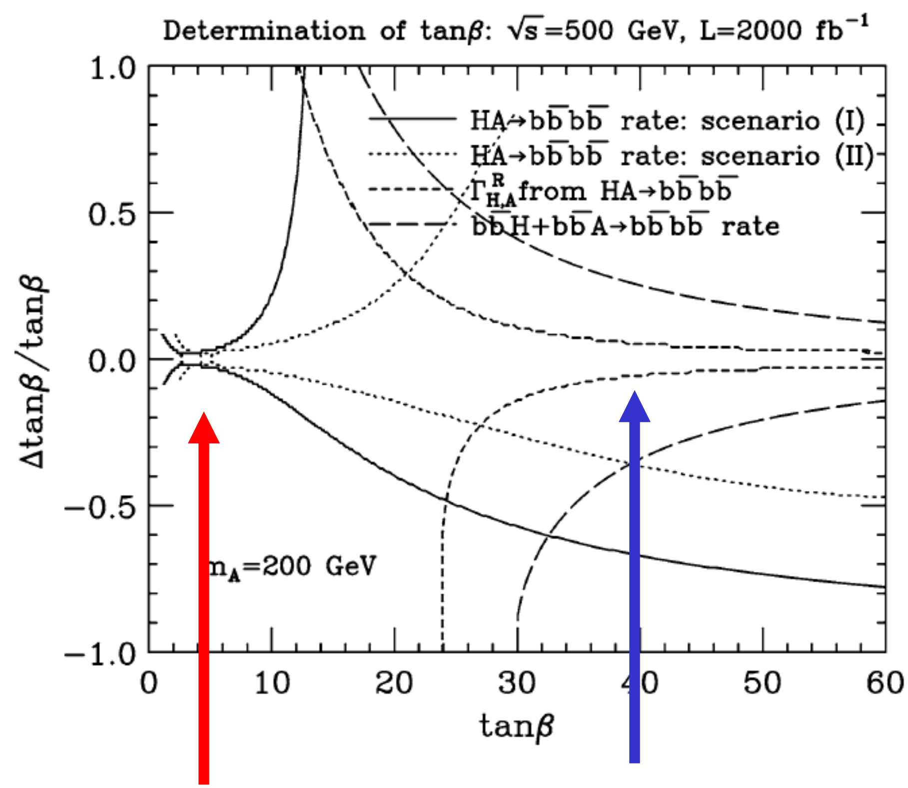
$\tan\beta = \langle \Phi_2 \rangle / \langle \Phi_1 \rangle$

- Branching ratio of H/A

Gunion,Han,Jiang,Sopczak (03)



The dominant branching ratio Br(bb) has tanβ sensitivity in smaller tanβ region (before saturated).



$\mathcal{B}(b\bar{b})$ $\Gamma_{H/A}$

- Total decay width of H/A

$$\Gamma_{H/A} \propto \tan^2\beta$$

Experimentally, the decay width can be measured when it is large. → useful for large tanβ

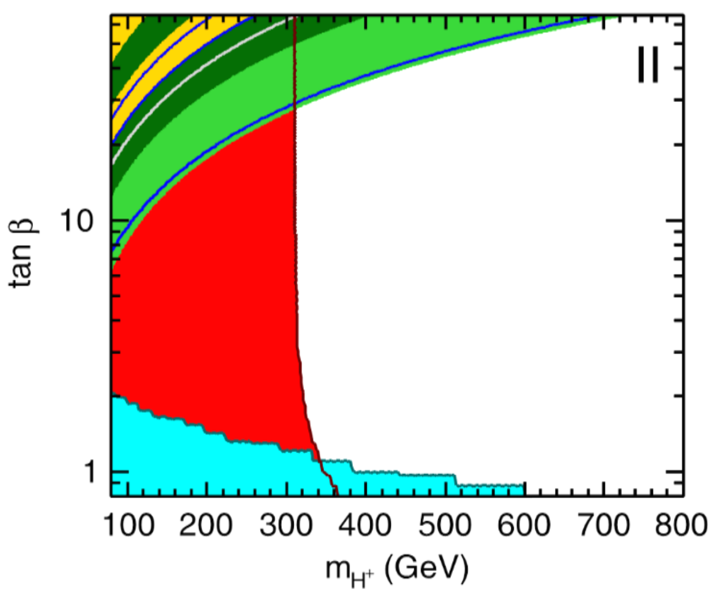
Higgs couplings in the 2HDM

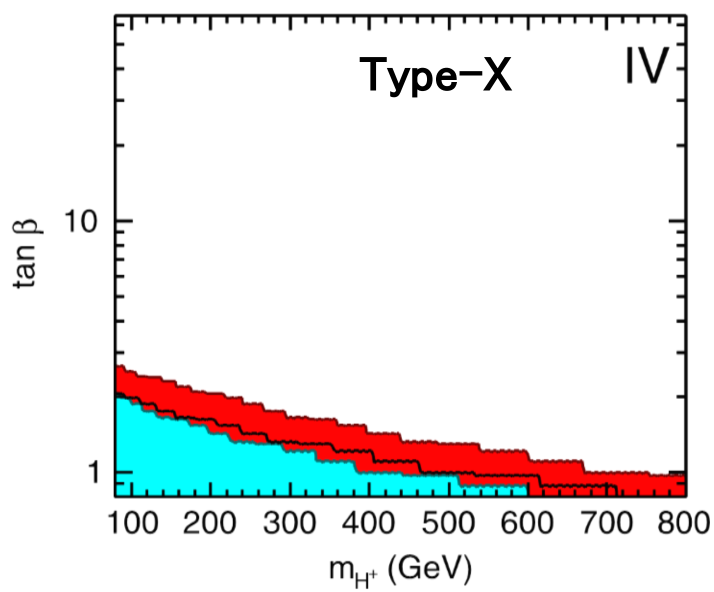
h	H	A ($H^\pm$)
Higgs-Gauge couplings:		
$\frac{g_{hVV}}{g_{hVV}^{\text{SM}}} = \sin(\beta-\alpha)$	$\frac{g_{HVV}}{g_{hVV}^{\text{SM}}} = \cos(\beta-\alpha)$	$\frac{g_{AVV}}{g_{hVV}^{\text{SM}}} = 0$
Yukawa couplings $(\xi_i^a = y_i^a / y_i^{h_{\text{SM}}})$		
Type-II :		
$\xi_u^h = \sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha)$	$\xi_u^H = \cos(\beta-\alpha) - \cot\beta\sin(\beta-\alpha)$	$\xi_u^A = \cot\beta$
$\xi_{d,\ell}^h = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)$	$\xi_{d,\ell}^H = \cos(\beta-\alpha) + \tan\beta\sin(\beta-\alpha)$	$\xi_{d,\ell}^A = \tan\beta$
Type-X :		
$\xi_{u,d}^h = \sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha)$	$\xi_{u,d}^H = \cos(\beta-\alpha) - \cot\beta\sin(\beta-\alpha)$	$\xi_{u,d}^A = \pm\cot\beta$
$\xi_\ell^h = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)$	$\xi_\ell^H = \cos(\beta-\alpha) + \tan\beta\sin(\beta-\alpha)$	$\xi_\ell^A = \tan\beta$

Experimental constraints on the 2HDM

- Flavor data and collider search can constrain parameters in 2HDM
  - Type-II : strong constraints by b→sγ, B-B mixing,,,
  - Type-X : only for small tanβ or m_H < 100GeV

Mahmoudi, Stal (2009)

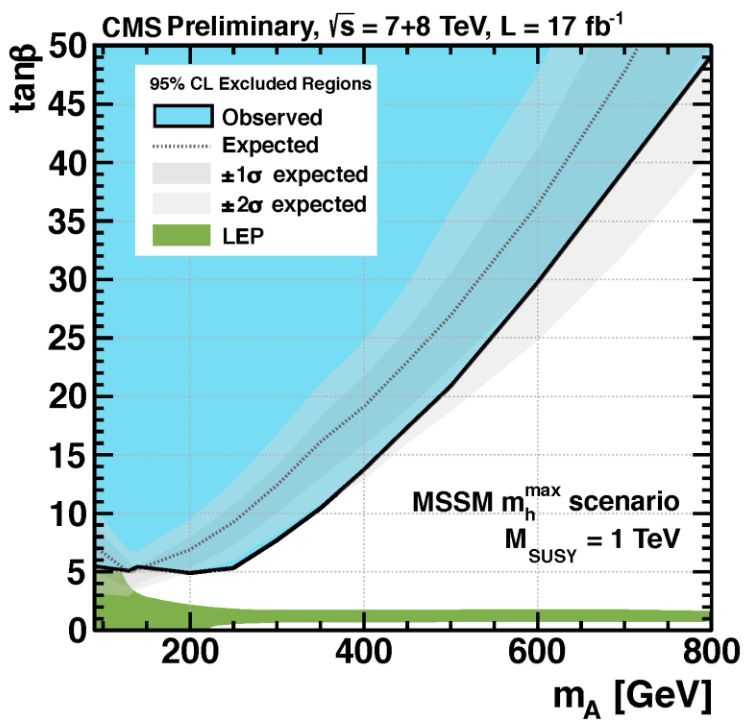




- LHC constraints on (SUSY) m_A and tanβ by H/A production

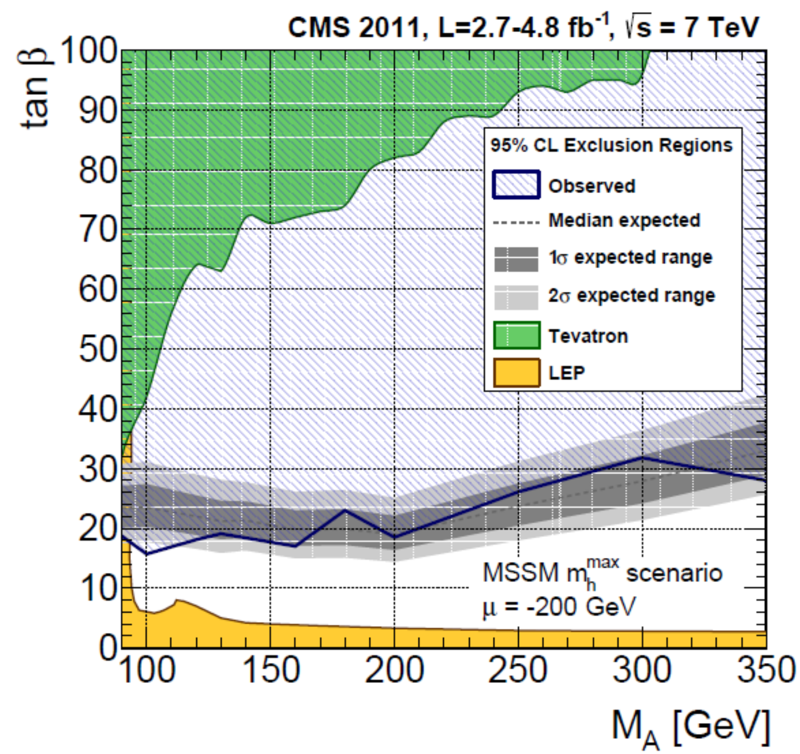
$$pp \to H/A \to \tau^+\tau^-$$

type-II



$$pp \to bH/A;\, H/A \to b\bar{b}$$

type-II, Y



- No constraint, so far, on type-I and X

Fingerprinting in Higgs sector

Kanemura,Tsumura,HY (13)

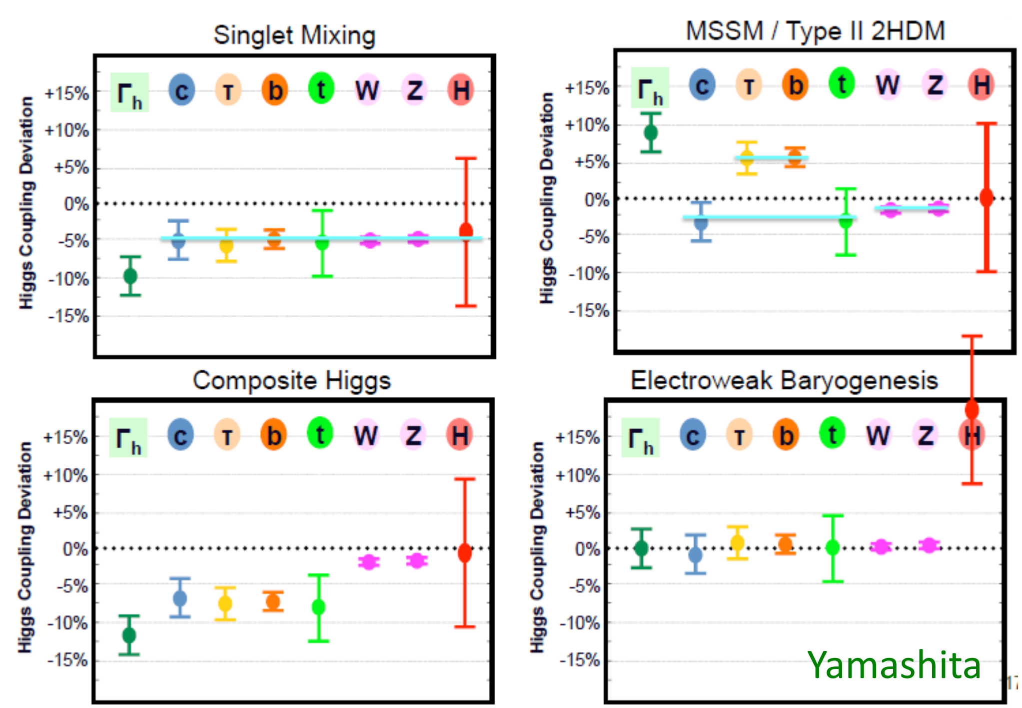
- Tanβ measurement by using precise measurements of SM-like Higgs(h) couplings

  indirect measurement, applicable even if H and A are heavy,
  useful only if $\sin^2(\beta-\alpha)<1$,
  needs model discrimination → **"Fingerprinting"**

Fingerprinting :

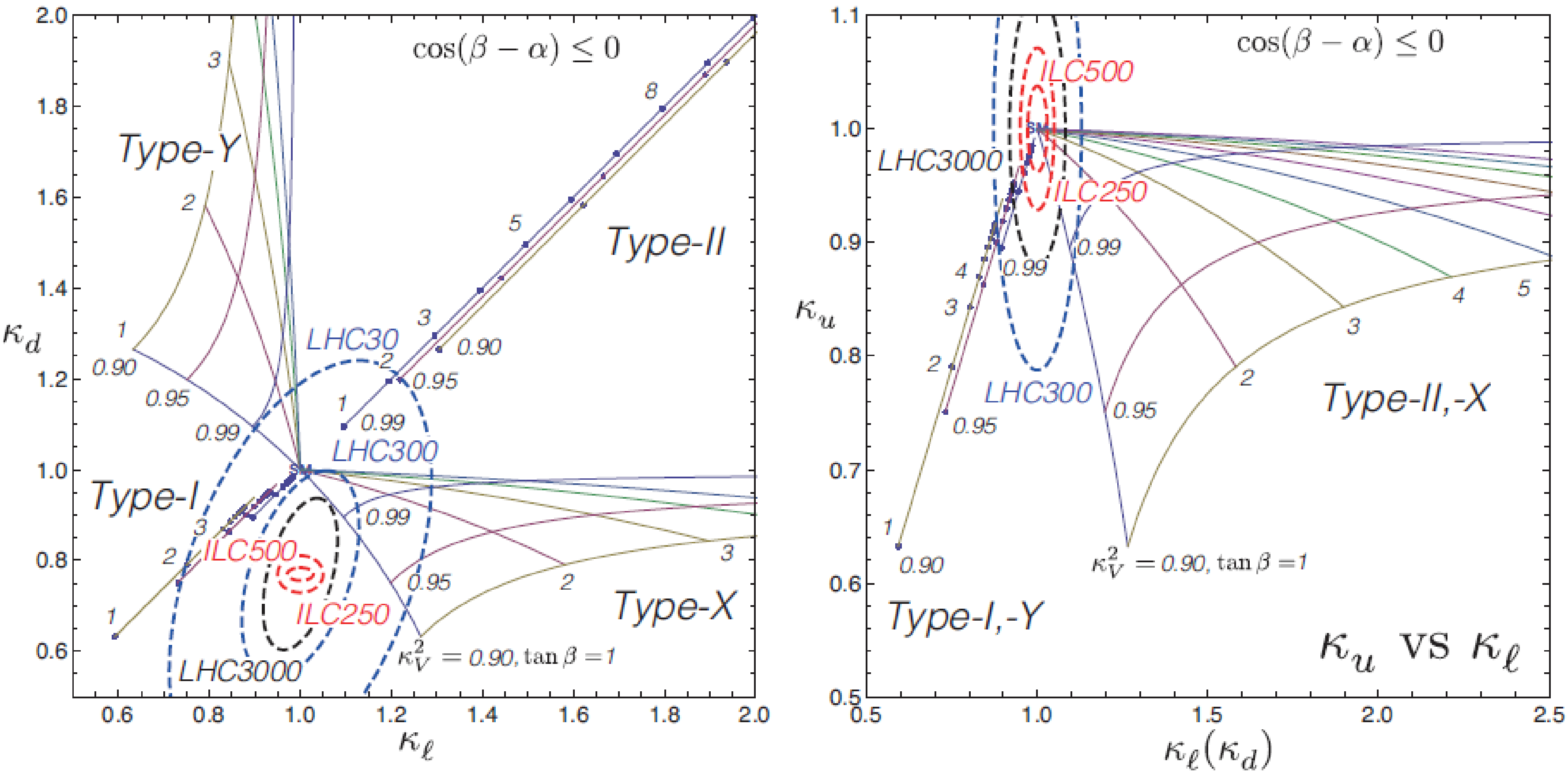
find (small) discrepancies in various channel of Higgs couplings etc, and check the pattern of deviations.

Models can be discriminated by finding the model which predicts the observe pattern of the deviations.



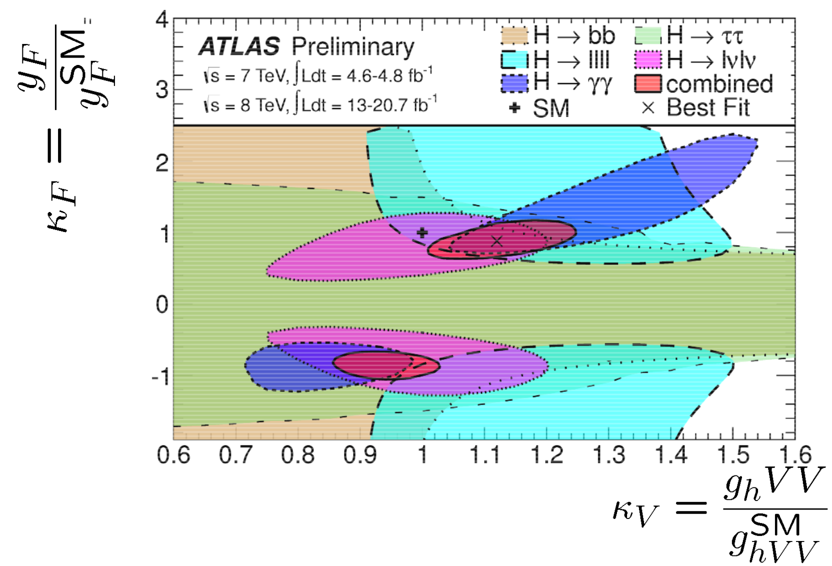
Fingerprinting (2HDM) : ILC White paper 1310.0763

$(\kappa_i^a = y_i^a / y_i^{h_{SM}})$



Measurement of sin(β-α)

$$\kappa_V = \frac{g_{hVV}}{g_{hVV}^{\mathrm{SM}}} = \sin(\beta - \alpha)$$

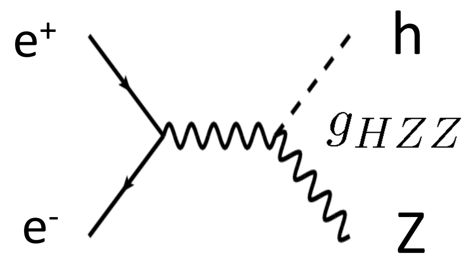


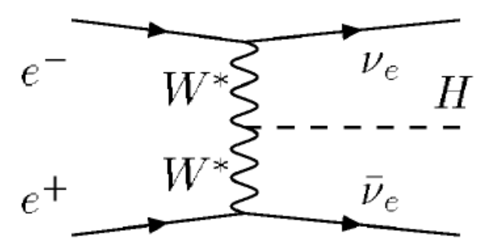
- At the LHC, hVV coupling is constrained by the global fit.

  ~2-5% @ 14TeV, 3000 fb^{-1}

- At the ILC, sin(β-α) can be directly measured by σ(hZ) or σ(hνν)

  ~0.5% @ 500GeV, 500fb^{-1}





Slide by H.Haber (Scalar 2013), 1310.0763

Summary of expected accuracies for the three cross sections and eight branching ratios obtained from an eleven parameter global fit of all available data.

	ILC(250)	ILC500	ILC(1000)	ILC(LumUp)
process	$\Delta\sigma/\sigma$			
$e^+e^- \to ZH$	2.6 %	2.0 %	2.0 %	1.0 %
$e^+e^- \to \nu\bar{\nu}H$	11 %	2.3 %	2.2 %	1.1 %
$e^+e^- \to t\bar{t}H$	-	28 %	6.3 %	3.8 %
mode	$\Delta Br/Br$			
$H \to ZZ$	19 %	7.5 %	4.2 %	2.4 %
$H \to WW$	6.9 %	3.1 %	2.5 %	1.3 %
$H \to b\bar{b}$	2.9 %	2.2 %	2.2 %	1.1 %
$H \to c\bar{c}$	8.7 %	5.1 %	3.4 %	1.9 %
$H \to gg$	7.5 %	4.0 %	2.9 %	1.6 %
$H \to \tau^+\tau^-$	4.9 %	3.7 %	3.0 %	1.6 %
$H \to \gamma\gamma$	34 %	17 %	7.9 %	4.7 %
$H \to \mu^+\mu^-$	100 %	100 %	31 %	20 %

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← hVV^2 (=$[\sin(\beta-\alpha)]^2$)

← [bottom Yukawa]^2

← [tau Yukawa]^2

- Sin(β-α) and tanβ are the important parameters in the 2HDM

sin(β-α) : Higgs-gauge couplings

tanβ = v_2/v_1 : Yukawa couplings (flavor- & type-dependent)

- SM-like limit : sin(β-α) → 1

sin(β-α) is a free parameter in general 2HDM, while in SUSY,

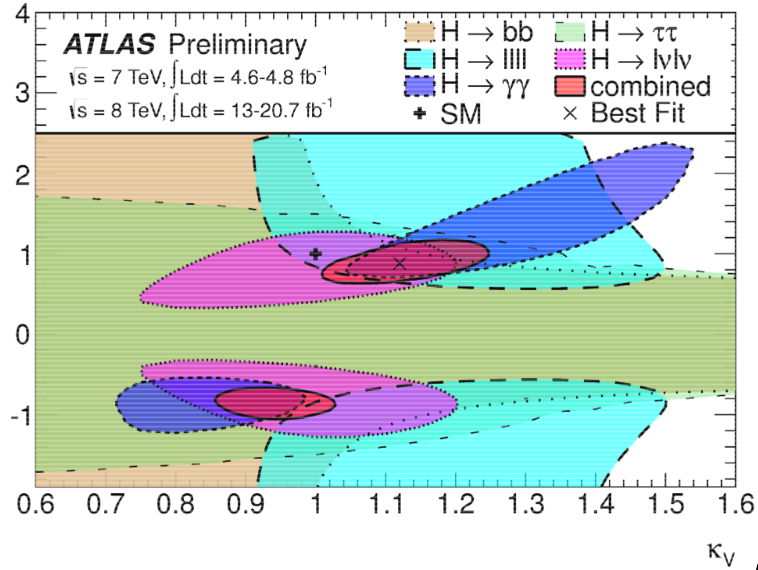
$$\sin(\beta-\alpha) \simeq 1 - \frac{2m_Z^4}{m_A^4 \tan^2\beta}$$

However, large deviation from unity is restricted by the pertrubative unitarity of the Higgs boson scattering amplitudes. Kanemura,Kubota,Takazugi(93)

Thus, even in the general 2HDM, sin(β-α) is assumed to be close to unity.

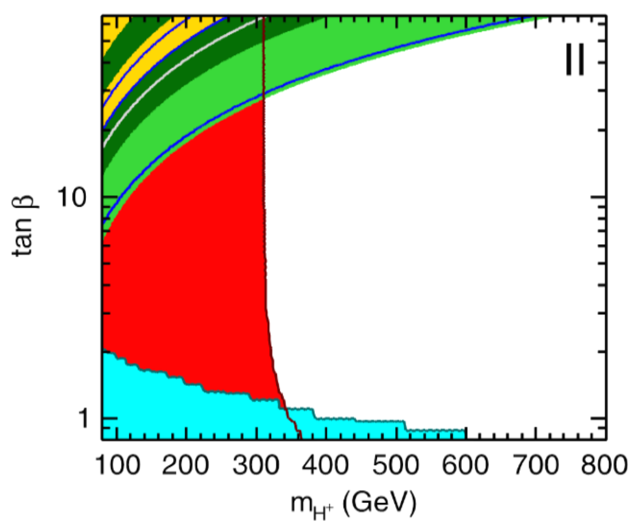
Measurement at the LHC :

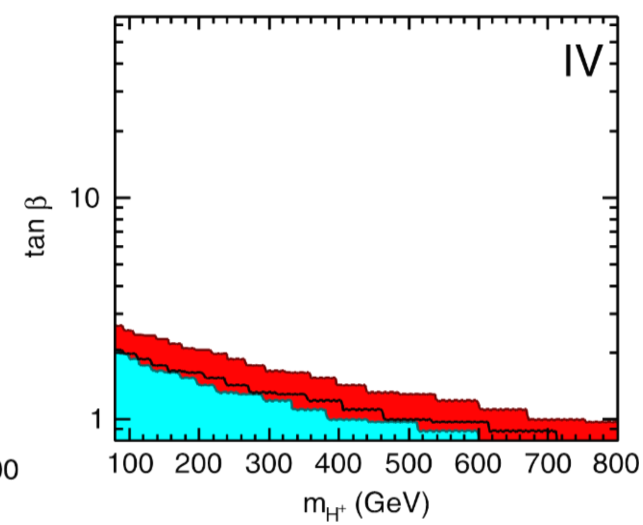
$$\kappa_F = \frac{y_F}{y_F^{\text{SM}}}$$



$$\kappa_V = \frac{g_{hVV}}{g_{hVV}^{\text{SM}}}$$

Constraints from flavor





Mahmoudi, Stal (2009)

Resolution of total width measurements

- The dominant partial decay width is proportional to $(\tan\beta)^2$.
- The total decay width can be measured by the shape of Breit-Wigner distribution, if the experimental resolution is better than the decay width.
- The experimental resolution is determined by the detector performance.

resolution of width : $\Gamma_{res} \simeq \Delta M \propto \Delta E$

thus, the width to be measured from the distribution is

$$\Gamma_R = \sqrt{\Gamma_{H/A}^2 + \Gamma_{res}^2}$$

Then, the accuracy of the particle width measurement can be estimated by

$$\Delta\Gamma_{H/A} = \sqrt{(\Gamma_R/\sqrt{2N})^2 + (\Delta\Gamma_{res})^2}$$