



# Precise determination of the heavy MSSM Higgs boson mass scale by Higgs boson coupling measurements at future linear colliders

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- In collaboration with  
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- Work in progress

# 1. Motivation

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- Discovery of a Higgs boson at the CERN LHC
  - The Standard Model (SM) is established as a low-energy effective theory below  $O(100)$  GeV
- This is not the end of the story
- Unsolved questions include:
  - Hierarchy problem
  - Is the Higgs boson elementary or composite?
  - What is the dynamics behind the electroweak symmetry breaking?
  - Origin of the Higgs coupling?
  - Is the Higgs boson solitary?
- Higgs boson = Window to New Physics
  - An SM-like Higgs boson  $\neq$  The SM Higgs boson

Hints of new physics are obtained by investigating properties of the discovered Higgs boson

# Strategy

- Evidence of new physics is left in the Higgs boson couplings

Fingerprinting of deviation of the Higgs couplings:  $\kappa_X = \frac{g_{hXX}}{g_{hXX}|_{\text{SM}}}$

- The scale of new physics can be determined
- Models beyond the SM can be distinguished
  - To this end, precise prediction of the Higgs boson couplings at loop level is important

- This talk:
  - We focus on the Higgs boson couplings enhanced by non-decoupling effect in the Minimal Supersymmetric Standard Model (MSSM)
  - Higgs boson branching ratios are computed at 1-loop level
  - The indirect heavy Higgs boson mass reach can be significantly extended, compared to the tree-level results
    - For fingerprinting of BSM models, see S. Kanemura's talk
    - For fingerprinting of composite models, see N. Machida's talk

# Loop corrections to the MSSM Bottom Yukawa coupling

- The MSSM bottom Yukawa interaction is modified due to loop contributions: [For reviews, see ILC Technical Design Report; ILC Higgs White Paper]

- Bottom Yukawa interaction:

$$-\mathcal{L}_b = \lambda_b \bar{b}_R H_1 Q_L \quad \longrightarrow \quad -\mathcal{L}_b = (\lambda_b + \delta\lambda_b) \bar{b}_R H_1 Q_L + \underline{\Delta\lambda_b \bar{b}_R Q_L H_2^*}$$

- Wrong Higgs coupling is induced due to SUSY breaking

[Hall,Rattazzi,Sarid(1994);Hempfling(1994);  
Eberl,Hidaka,Kraml,Majerotto,Yamada(2000);Haber,Mason(2008); ....]

- Bottom mass:

$$m_b = \frac{\lambda_b v}{\sqrt{2}} \cos \beta \quad \longrightarrow \quad m_b = \frac{\lambda_b v}{\sqrt{2}} \cos \beta (1 + \Delta_b) \quad \Delta_b \equiv \frac{\delta\lambda_b}{\lambda_b} + \frac{\Delta\lambda_b}{\lambda_b} \tan \beta$$

- Bottom Yukawa coupling to the SM-like Higgs boson:

$$g_{hbb}^0 = \frac{gm_b}{\sqrt{2}m_W} \frac{\sin \alpha}{\cos \beta}$$
$$\longrightarrow g_{hbb} = \frac{gm_b}{\sqrt{2}m_W} \frac{\sin \alpha}{\cos \beta} \left[ 1 + \frac{1}{1 + \Delta_b} \left( \frac{\delta\lambda_b}{\lambda_b} - \Delta_b \right) (1 + \cot \alpha \cot \beta) \right]$$

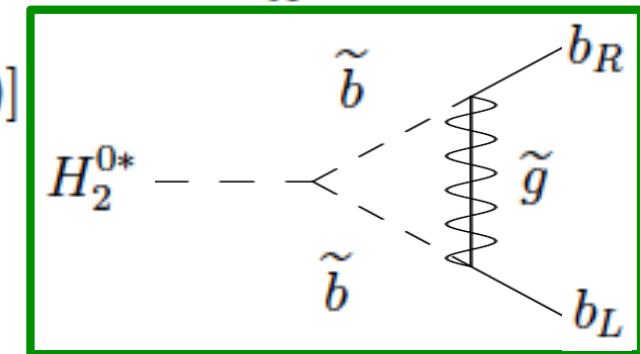
# Properties of the Bottom Yukawa coupling

- There are two new mass scales:  $m_{\text{SUSY}}, m_A$

- In the limit of large  $\mu \sim M_3 \sim A_t \sim m_{\text{SUSY}}$  with  $m_A$  fixed

$$g_{h b \bar{b}} \simeq \frac{g m_b}{\sqrt{2} m_W \cos \beta} \frac{\sin \alpha}{\cos \beta} [1 - \Delta_b (1 + \cot \alpha \cot \beta)]$$

$$\Delta_b \simeq \left( \frac{2\alpha_s}{3\pi} \frac{\mu M_3}{m_{\text{SUSY}}^2} + \frac{\lambda_t^2}{16\pi^2} \frac{\mu A_t}{m_{\text{SUSY}}^2} \right) \tan \beta$$



- SUSY loop corrections do not decouple for small  $m_A$  and are enhanced for large  $\tan \beta$ , in sharp contrast to the type-II two-Higgs-doublet model

- For the cases of the two-Higgs-doublet models, see S. Kanemura's talk

- In the limit of a large heavy Higgs boson mass  $m_A$

$$1 + \cot \alpha \cot \beta = -\frac{2m_Z^2}{m_A^2} \cos 2\beta + \mathcal{O}\left(\frac{m_Z^4}{m_A^4}\right)$$

- SUSY radiative corrections decouple

# Numerical Analysis

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- FeynHiggs2.10.2 is used [www.feynhiggs.de,  
Hahn,Heinemeyer,Hollik,Rzehak,Weiglein]
- The Higgs boson masses and mixing angle are computed at 2-loop level in the on-shell scheme
- Higgs boson decay rates are computed at 1-loop level [Williams,Weiglein(2008)]
- Imposed conditions:
  - CP conservation; No color or charge breaking
  - No negative sfermion mass squared
  - Superparticle mass bounds obtained at the LHC
  - 1<sup>st</sup> Neutralino is the lightest supersymmetric particle
- Simplifying assumptions:
  - Mass universality for the 1<sup>st</sup> and 2<sup>nd</sup> generation sfermions
  - Universal A-parameters:  $A_f = \lambda_f A_0$ , ( $f = t, b, \tau, \dots$ )

# Parameters and Constraints

- Input parameters:

- Reference point:

Parameter	Value
$\tilde{m}_{L,E_{1,2}}$	1000 GeV
$\tilde{m}_{Q,U,D_{1,2}}$	4000 GeV

(Common)  
(Common)

- Scanned parameters:

Parameter	Scan bounds
$M_A$	[200 GeV, 2000 GeV]
$\tan \beta$	[1, 60]
$\tilde{m}_{L,E_3}$	[100 GeV, 1000 GeV]
$\tilde{m}_{Q,U,D_3}$	[500 GeV, 4000 GeV]
$ A_0 $	[0 GeV, $3(\tilde{m}_{Q_3}\tilde{m}_{U_3})^{1/2}$ ]
$ \mu $	[100 GeV, 1000 GeV]
$ M_1 $	[100 GeV, 1000 GeV]
$ M_2 $	[100 GeV, 1000 GeV]
$ M_3 $	[1400 GeV, 4000 GeV]

- Constraints:

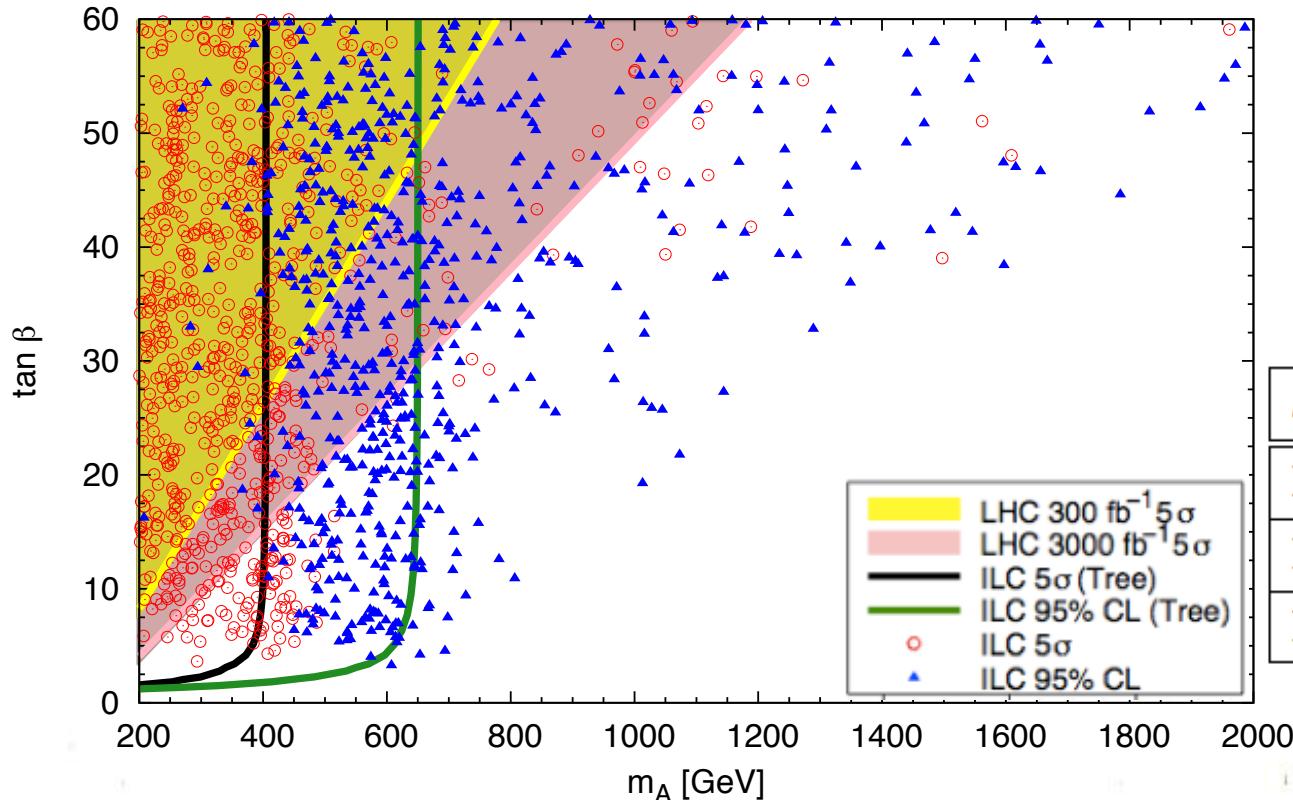
Observables	Constraints
$m_h$	[122 GeV, 128 GeV]
$m_{\tilde{g}}$	$> 1400$ GeV
$m_{\tilde{\chi}_1^0}$	$> 90$ GeV
$m_{\tilde{\chi}_1^\pm}$	$> \max(400 \text{ GeV}, m_{\tilde{\chi}_1^0})$
$m_{\tilde{t}_1}$	$> \max(640 \text{ GeV}, m_{\tilde{\chi}_1^0})$
$m_{\tilde{b}_1}$	$> \max(620 \text{ GeV}, m_{\tilde{\chi}_1^0})$
$m_{\tilde{\tau}_1}$	$> m_{\tilde{\chi}_1^0}$

# Heavy Higgs Mass Reach

- Indirect heavy Higgs mass reach by coupling measurements of

$$\kappa_W/\kappa_b = \left( \frac{\text{Br}(h \rightarrow WW)}{\text{Br}(h \rightarrow b\bar{b})} \Big|_{\text{MSSM}} \Big/ \frac{\text{Br}(h \rightarrow WW)}{\text{Br}(h \rightarrow b\bar{b})} \Big|_{\text{SM}} \right)^{1/2}$$

- ILC 500 ILC [250 GeV, 250 fb<sup>-1</sup> ⊕ 500 GeV, 500 fb<sup>-1</sup>]



- NB:  $m_h < m_Z$  at tree-level
- ILC Sensitivity:

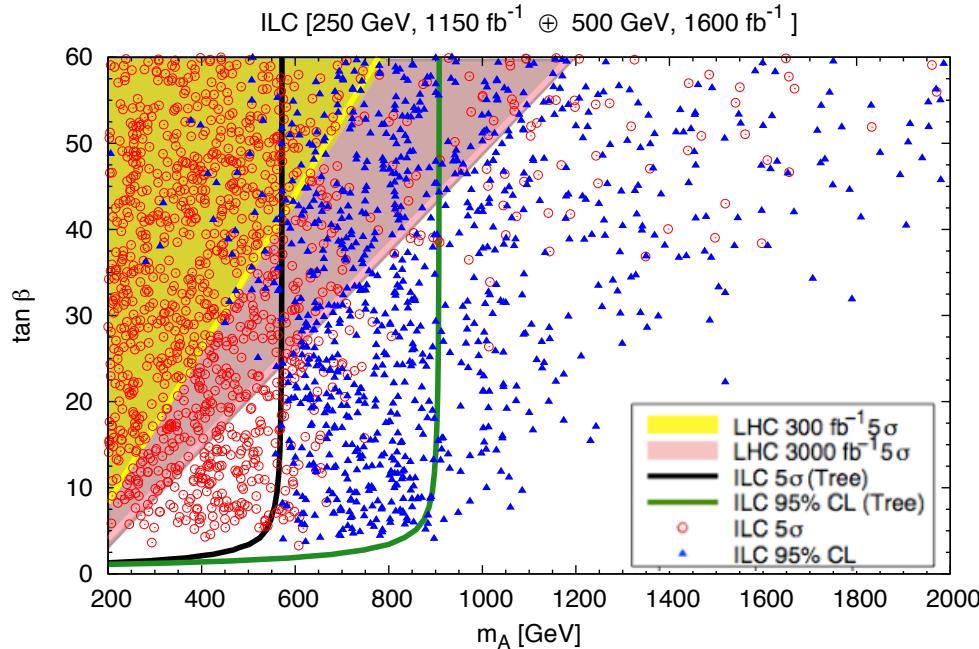
$\kappa_W/\kappa_b$	$2\sigma$	$5\sigma$
ILC500	0.962	0.903
ILC500 (LumiUp)	0.980	0.950
ILC1000 (LumiUp)	0.982	0.954

[Refs.: ILC Higgs White Paper; ATLAS-PHYS-PUB-2013-016]

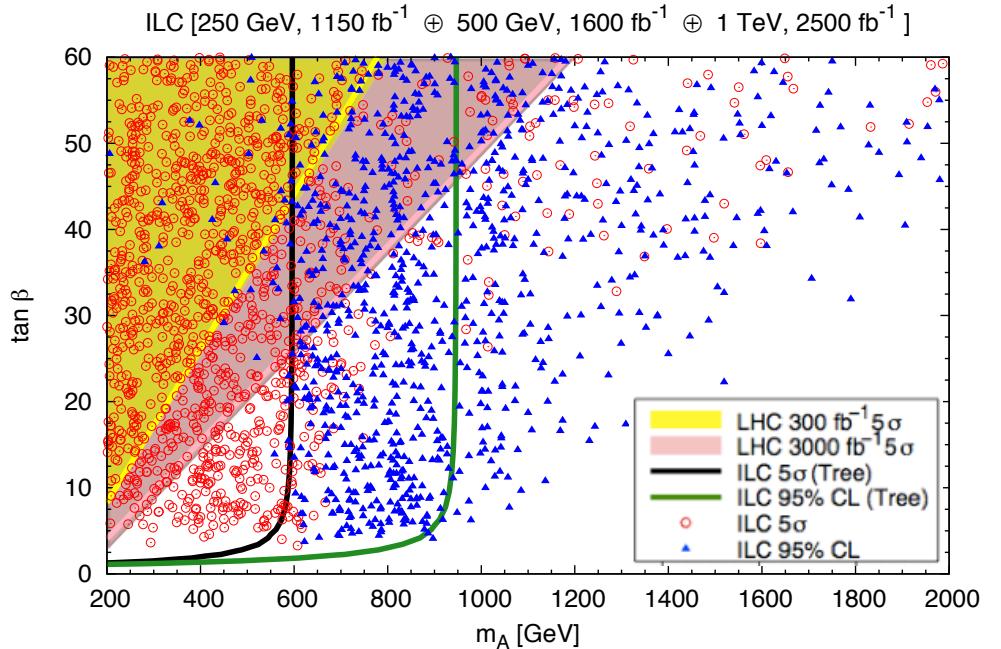
- For direct heavy Higgs boson searches, see H. Yokoya's talk

# Heavy Higgs Mass Reach (Luminosity Upgrades)

- ILC 500 LumiUp:



- ILC 1000 LumiUp:



[Refs.: ILC Higgs White Paper; ATLAS-PHYS-PUB-2013-016]

- The indirect reach through the Higgs coupling measurements can be higher than the LHC direct observation limits
- The indirect reach of the MSSM heavy Higgs boson mass can be significantly extended, compared to the tree-level results

## 5. Summary

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- We have evaluated to what extent the Higgs boson couplings can be modified due to loop corrections
- Due to the non-decoupling effects, very heavy supaprarticles contribute to the deviation of the couplings
- The indirect reach of the MSSM heavy Higgs boson mass can be significantly extended, compared to the tree-level results
- The indirect heavy Higgs mass reach through the Higgs coupling measurements can be higher than the LHC direct observation limit
- Fingerprinting of Higgs boson couplings is a powerful tool to explore and distinguish models explaining dynamics of the EWSB (MSSM, NMSSM, Composite models, ...) and should be encouraged

# Backup slides

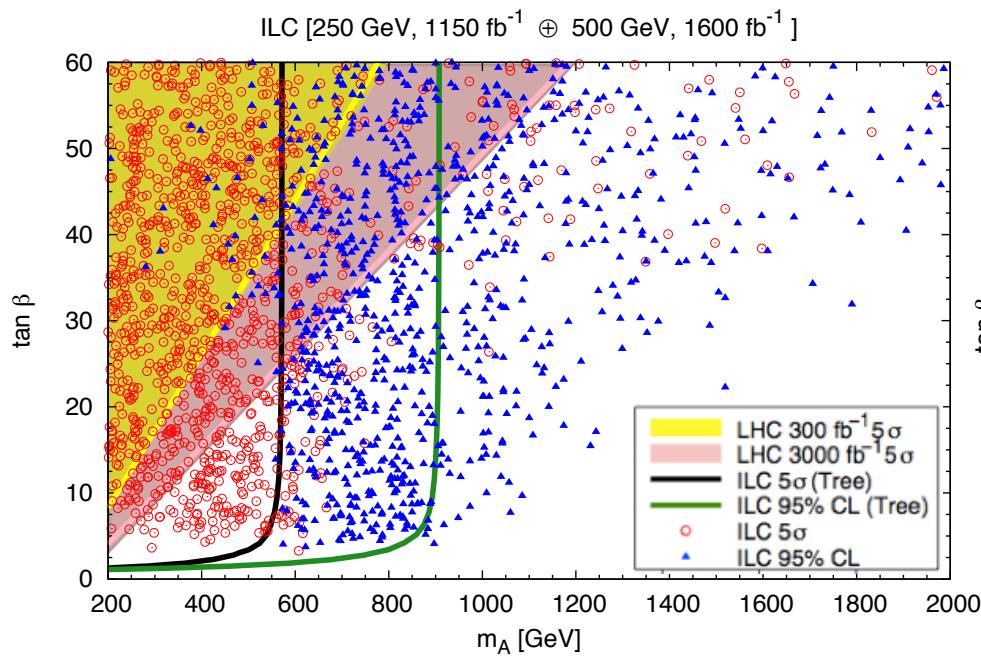
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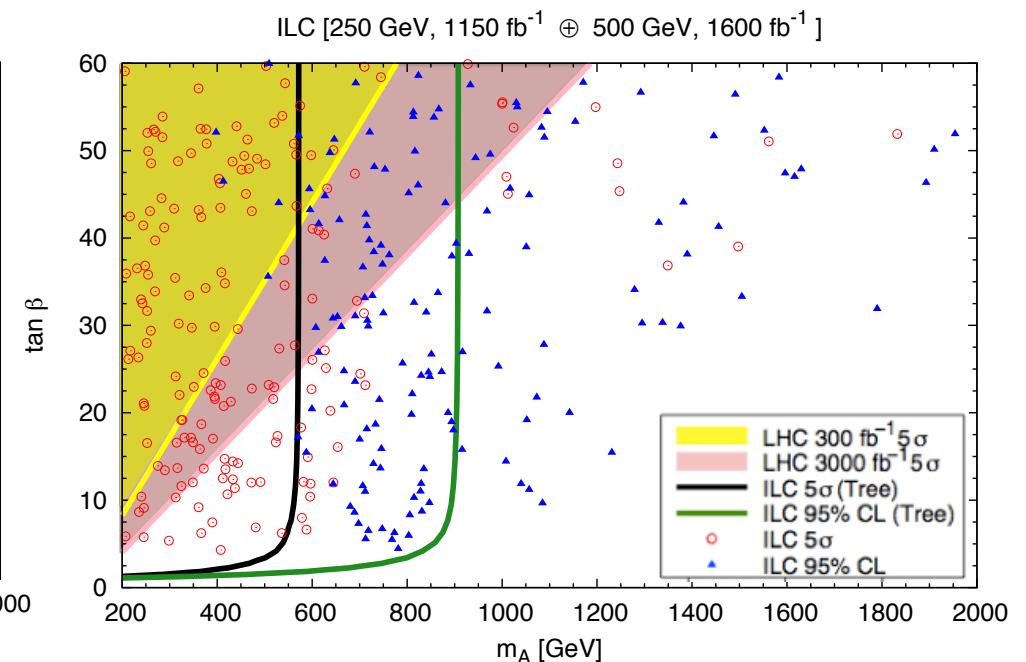
# Influence of the precise Higgs boson mass measurement

- ILC 500 LumiUp:

$$122\text{GeV} < M_h < 128\text{GeV}$$



$$125\text{GeV} < M_h < 126\text{GeV}$$



[Refs.: ILC Higgs White Paper; ATLAS-PHYS-PUB-2013-016]

- The parameter space of the MSSM is narrowed down through precise Higgs boson mass measurements

# Determination of the Higgs Boson Couplings at the ILC

- Expected accuracies for model independent determination of the Higgs boson couplings:  $(1\sigma)$

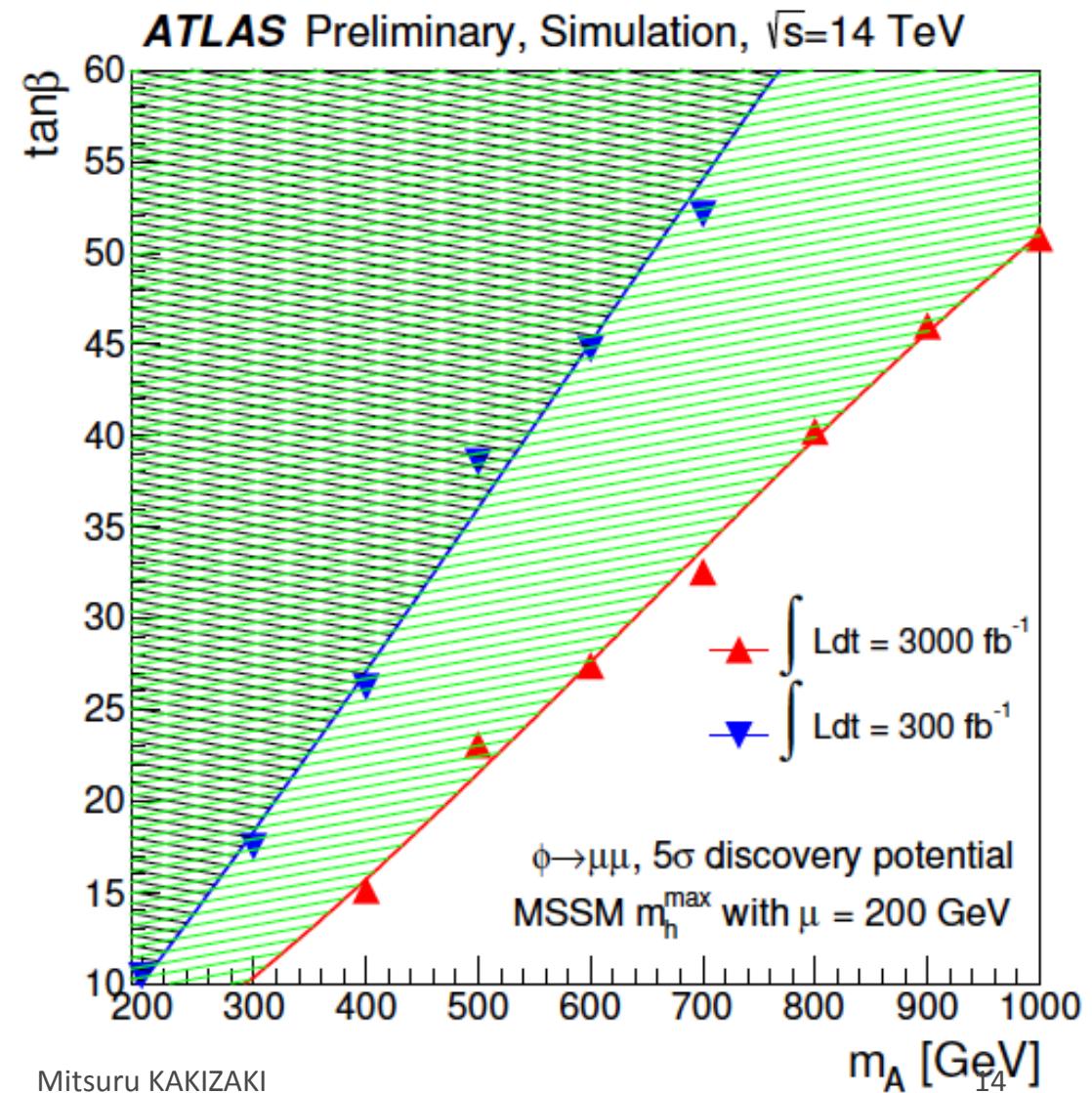
	ILC(250)	ILC(500)	ILC500(LumUp)	ILC(LumUp)
$\sqrt{s}$ (GeV)	250	250+500	250+500	250+500+1000
$L$ ( $\text{fb}^{-1}$ )	250	250+500	1150+1600	1150+1600+2500
$\gamma\gamma$	18 %	8.4 %	4.5 %	2.4 %
$qq$	6.4 %	2.3 %	1.2 %	0.9 %
$WW$	4.8 %	1.1 %	0.6 %	0.6 %
$ZZ$	1.3 %	1.0 %	0.5 %	0.5 %
$t\bar{t}$	–	14 %	7.8 %	1.9 %
$bb$	5.3 %	1.6 %	0.8 %	0.7 %
$\tau^+\tau^-$	5.7 %	2.3 %	1.2 %	0.9 %
$c\bar{c}$	6.8 %	2.8 %	1.5 %	1.0 %
$\mu^+\mu^-$	91 %	91 %	42 %	10 %
$\Gamma_T(h)$	12 %	4.9 %	2.5 %	2.3 %
$hh$	–	83 %	46 %	13 %
BR(invis.)	< 0.9 %	< 0.9 %	< 0.4 %	< 0.4 %

[ILC Higgs White paper (2013)]

# MSSM Heavy Higgs Mass Reach at the LHC

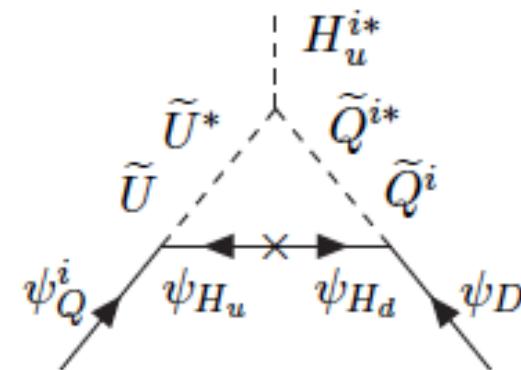
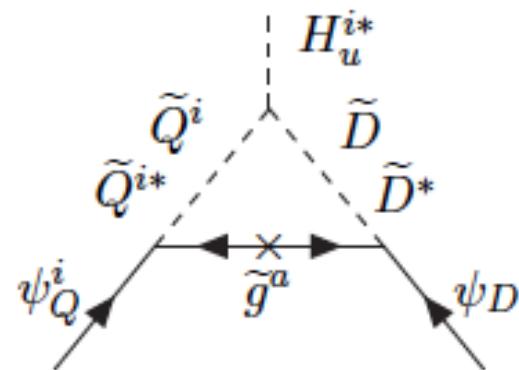
- 5 sigma direct discovery potential of the MSSM heavy Higgs bosons at the LHC:

[ATLAS-PHYS-PUB-2013-016]



# Wrong-Higgs Yukawa interactions

- 1-loop diagrams contributing to the wrong-Higgs Yukawa interactions:



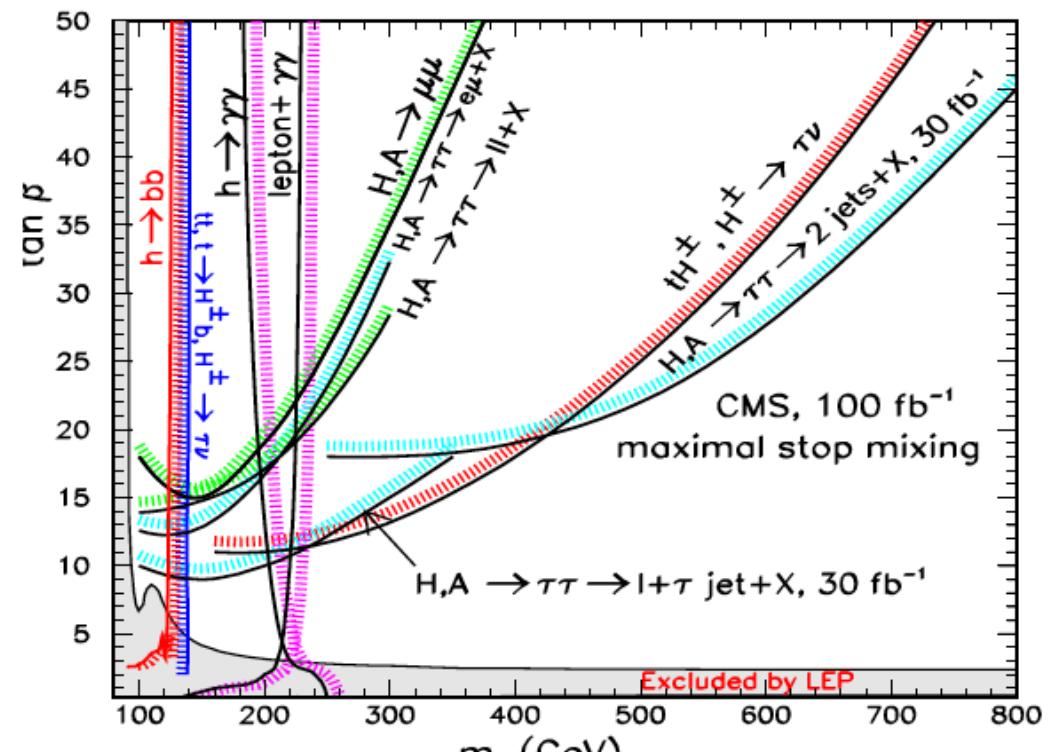
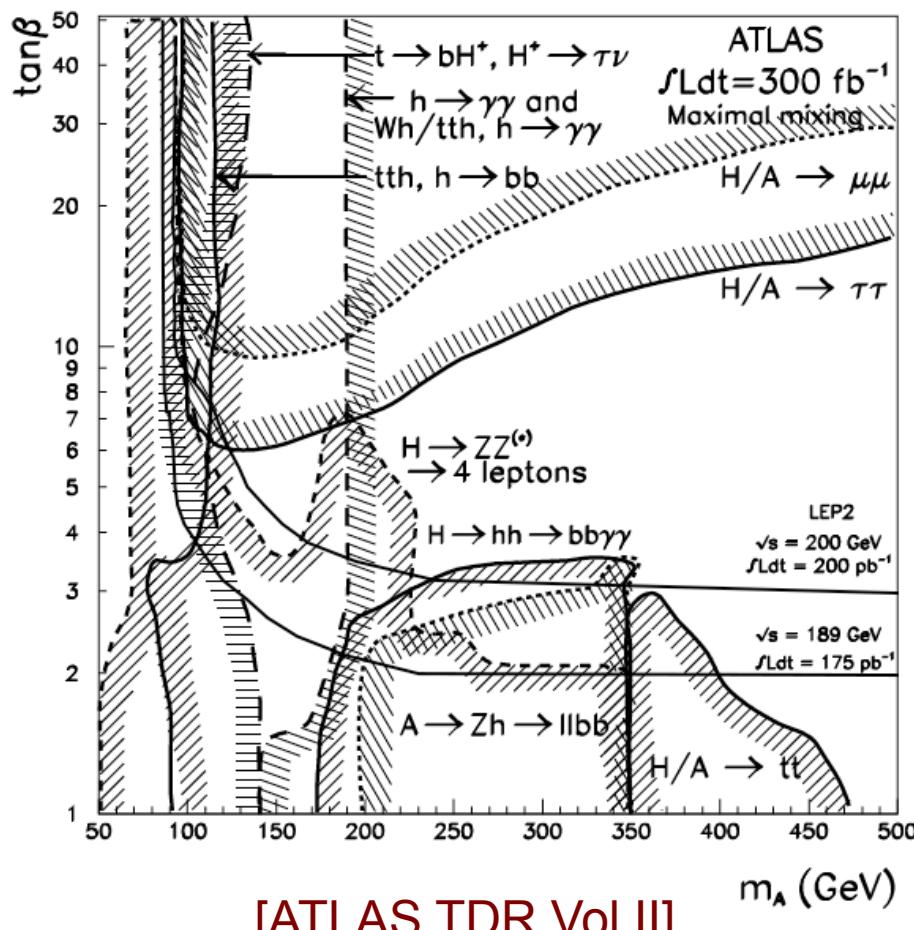
- 3-point scalar interactions:

$$\mathcal{L}_{\text{int}} = \mu h_t H_d^i \tilde{Q}^{i*} \tilde{U}^* + \mu h_b H_u^i \tilde{Q}^{i*} \tilde{D}^* - \epsilon_{ij} [h_b A_b H_d^i \tilde{Q}^j \tilde{D} - h_t A_t H_u^i \tilde{Q}^j \tilde{U}] + \text{h.c.}$$

[Haber,Mason(2008)]

# MSSM Heavy Higgs Mass Reach at the LHC

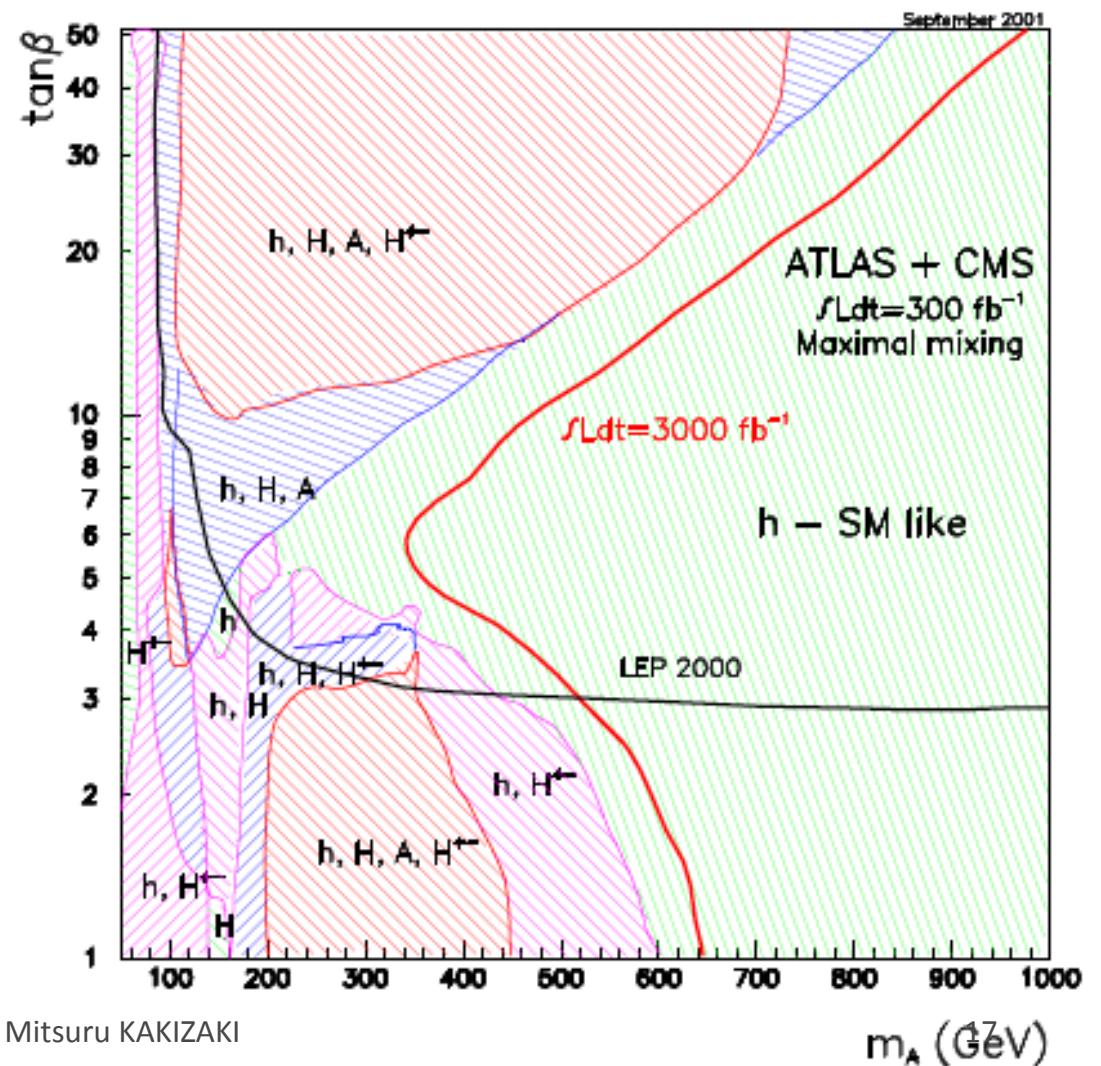
- Direct discovery potential of the MSSM heavy Higgs bosons at the LHC:



# MSSM Heavy Higgs Mass Reach at the HL-LHC

- Direct discovery potential of the MSSM heavy Higgs bosons at the High Luminosity LHC:

[hep-ph/0204087]



# Yukawa couplings in the MSSM

- Radiative corrections to the bottom Yukawa coupling:

$$g_{h^0 b\bar{b}} = -\frac{gm_b}{2m_W} \frac{\sin\alpha}{\cos\beta} \left[ 1 + \frac{1}{1+\Delta_b} \left( \frac{\delta h_b}{h_b} - \Delta_b \right) (1 + \cot\alpha \cot\beta) \right]$$

$$\Delta_b \simeq \frac{\Delta h_b}{h_b} \tan\beta$$

$$\Delta h_b \simeq h_b \left[ \frac{2\alpha_s}{3\pi} \mu M_3 \mathcal{I}(M_{\tilde{b}_1}, M_{\tilde{b}_2}, M_g) + \frac{h_t^2}{16\pi^2} \mu A_t \mathcal{I}(M_{\tilde{t}_1}, M_{\tilde{t}_2}, \mu) \right]$$

$$\mathcal{I}(a, b, c) = \frac{a^2 b^2 \ln(a^2/b^2) + b^2 c^2 \ln(b^2/c^2) + c^2 a^2 \ln(c^2/a^2)}{(a^2 - b^2)(b^2 - c^2)(a^2 - c^2)} \sim 1/\max(a^2, b^2, c^2)$$