Indirect discovery reach of the additional MSSM Higgs bosons by precision measurements at future lepton colliders

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- In collaboration with
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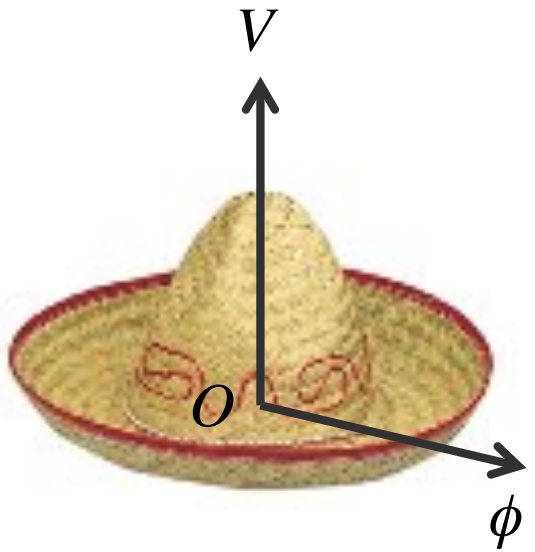
  and Hiroshi Yokoya (KIAS)
- Ref.: arXiv:1505.03761, to appear in IJMPA

Motivation

- Discovery of the 125 GeV Higgs boson at the CERN LHC
  - The Standard Model (SM) has been established as a low-energy effective theory below $O(100)$ GeV

This is not the end of the story



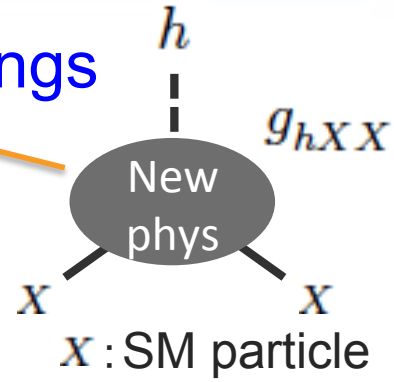
- Unsolved questions include:
  - Hierarchy problem
  - Is the Higgs boson elementary or composite?
  - Dynamics behind the EW sym. breaking?
  - Origin of the Higgs coupling?
  - Is the Higgs boson solitary?
- Higgs boson = Window to New Physics
  - An SM-like Higgs boson $\neq$ The SM Higgs boson

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

Strategy

- New physics effects are in the Higgs boson couplings

  Fingerprinting of the Higgs couplings: $\kappa_X = \dfrac{g_{hXX}}{g_{hXX}|_{\rm SM}}$



  - New physics scale can be determined
  - New models can be distinguished

  Future lepton collider accuracy of κ_X : percent level [ILC Higgs White Paper]

  → Precise prediction of the Higgs boson couplings is important [See Ms. Kikuchi's talk for fingerprinting]

- This talk:
  - In the Minimal Supersymmetric Standard Model (MSSM) , we evaluate Higgs boson branching ratios at the 1-loop level
  - The ratio of the branching ratios $\mathrm{Br}(h \to b\bar{b})/\mathrm{Br}(h \to WW)$ is sensitive to the heavy Higgs boson mass at lepton colliders
  - The indirect discovery reach of the heavy Higgs bosons expected at the ILC programs are shown [See Prof. Kanemura's talk for unitarity bound on the 2nd Higgs boson]

Loop corrections to the MSSM Bottom Yukawa coupling

- MSSM Higgs sector:

	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
H_1	1	2	$-1/2$
H_2	1	2	$+1/2$

h : SM-like Higgs boson $m_h = 125GeV$

$H, A, H^{\pm}$: MSSM heavy Higgs bosons

$m_H \cong m_A \cong m_{H^{\pm}}$

- Bottom Yukawa interaction:

[ILC Technical Design Report; ILC Higgs White Paper]

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

- SUSY breaking ⇒ "Wrong Higgs coupling"

[Hall,Rattazzi,Sarid(1994);Hempfling(1994); Eberl,Hidaka,Kraml,Majerotto,Yamada(2000); Haber,Mason(2008);Endo,Moroi,Nojiri(2015), ...]

- Bottom quark mass:

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

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

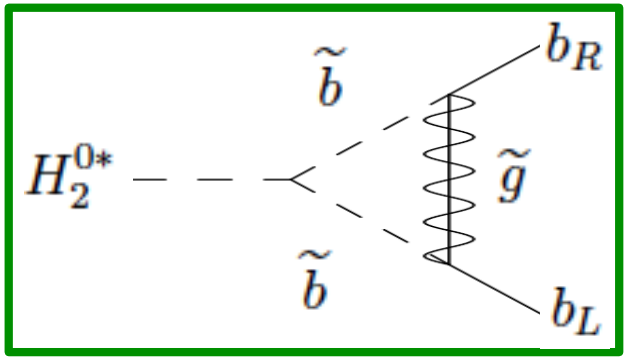
$$g^0_{hb\bar{b}} = \frac{g m_b}{\sqrt{2} m_W} \frac{\sin\alpha}{\cos\beta} \quad \Rightarrow \quad g_{hb\bar{b}} = \frac{g m_b}{\sqrt{2} m_W} \frac{\sin\alpha}{\cos\beta} \left[1 + \frac{1}{1+\Delta_b}\left(\frac{\delta\lambda_b}{\lambda_b} - \Delta_b\right)(1 + \cot\alpha\cot\beta)\right]$$

Properties of the Bottom Yukawa coupling

- There are two new mass scales in the MSSM: $m_{\rm SUSY}, m_A$
  - In the limit of large $\mu \sim M_3 \sim A_t \sim m_{\rm SUSY}$ with m_A fixed

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

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



- 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)

  - 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

- FeynHiggs2.10.3 is used [www.feynhiggs.de: Hahn,Heinemeyer,Hollik, Rzehak,Weiglein,Williams]
  - 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
  - 1st Neutralino is the lightest supersymmetric particle
- Simplifying assumptions:
  - Mass universality for the 1st and 2nd generation sfermions
  - Universal A-parameters: $A_f = \lambda_f A_0, \quad (f = t, b, \tau, \cdots)$

MSSM Parameters and Constraints

- Input parameters:
  - Reference point:

Parameter	Value	
$\widetilde{m}_{L,E_{1,2}}$	1000 GeV	(Common)
$\widetilde{m}_{Q,U,D_{1,2}}$	4000 GeV	(Common)

  - Scanned parameters:

Parameter	Scan bounds
M_A	[200 GeV, 3000 GeV]
$\tan\beta$	[1, 60]
$\widetilde{m}_{L,E_3}$	[100 GeV, 1000 GeV]
$\widetilde{m}_{Q,U,D_3}$	[500 GeV, 4000 GeV]
$\lvert A_0\rvert$	[0 GeV, $3(\widetilde{m}_{Q_3}\widetilde{m}_{U_3})^{1/2}$]
$\lvert\mu\rvert$	[100 GeV, 1000 GeV]
$\lvert M_1\rvert$	[100 GeV, 1000 GeV]
$\lvert M_2\rvert$	[100 GeV, 1000 GeV]
M_3	[1400 GeV, 4000 GeV]

- Constraints on masses:

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

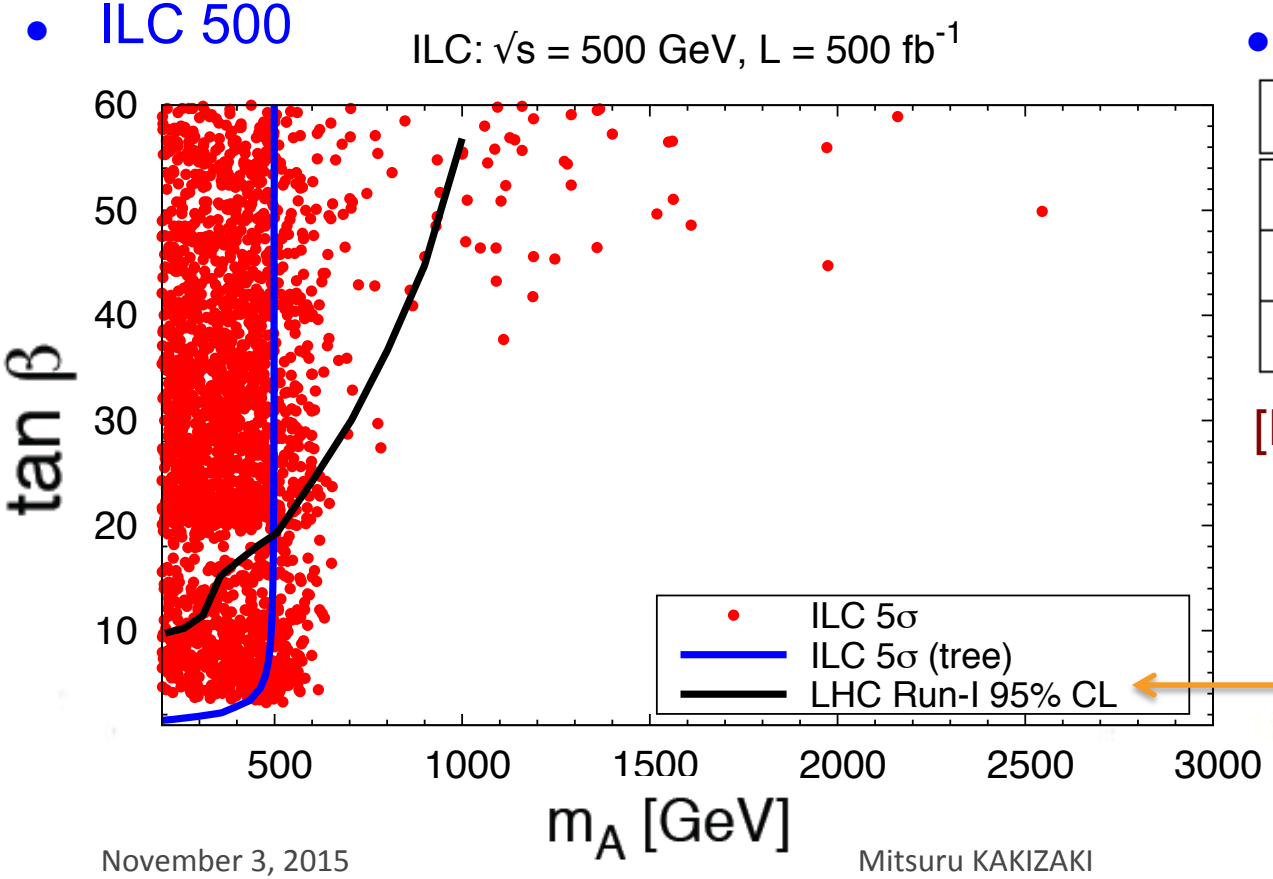
Heavy MSSM Higgs Mass Reach at ILC 500

- To cancel uncertainties of the production and total decay rate, we take the ratio of branching fractions from the same mode

$e^+e^- \to \nu\bar{\nu}h$:

$$R = \left.\frac{\mathrm{Br}(h \to WW)}{\mathrm{Br}(h \to b\bar{b})}\right|_{\mathrm{MSSM}} \Big/ \left.\frac{\mathrm{Br}(h \to WW)}{\mathrm{Br}(h \to b\bar{b})}\right|_{\mathrm{SM}}$$

- ILC 500



[ATLAS (2014)]

- ILC sensitivity:

R	95%CL	5σ
ILC500	0.050	0.125
ILC500 LumiUp	0.027	0.068
ILC1000 LumiUp	0.021	0.052

[ILC Higgs White Paper(2013)]

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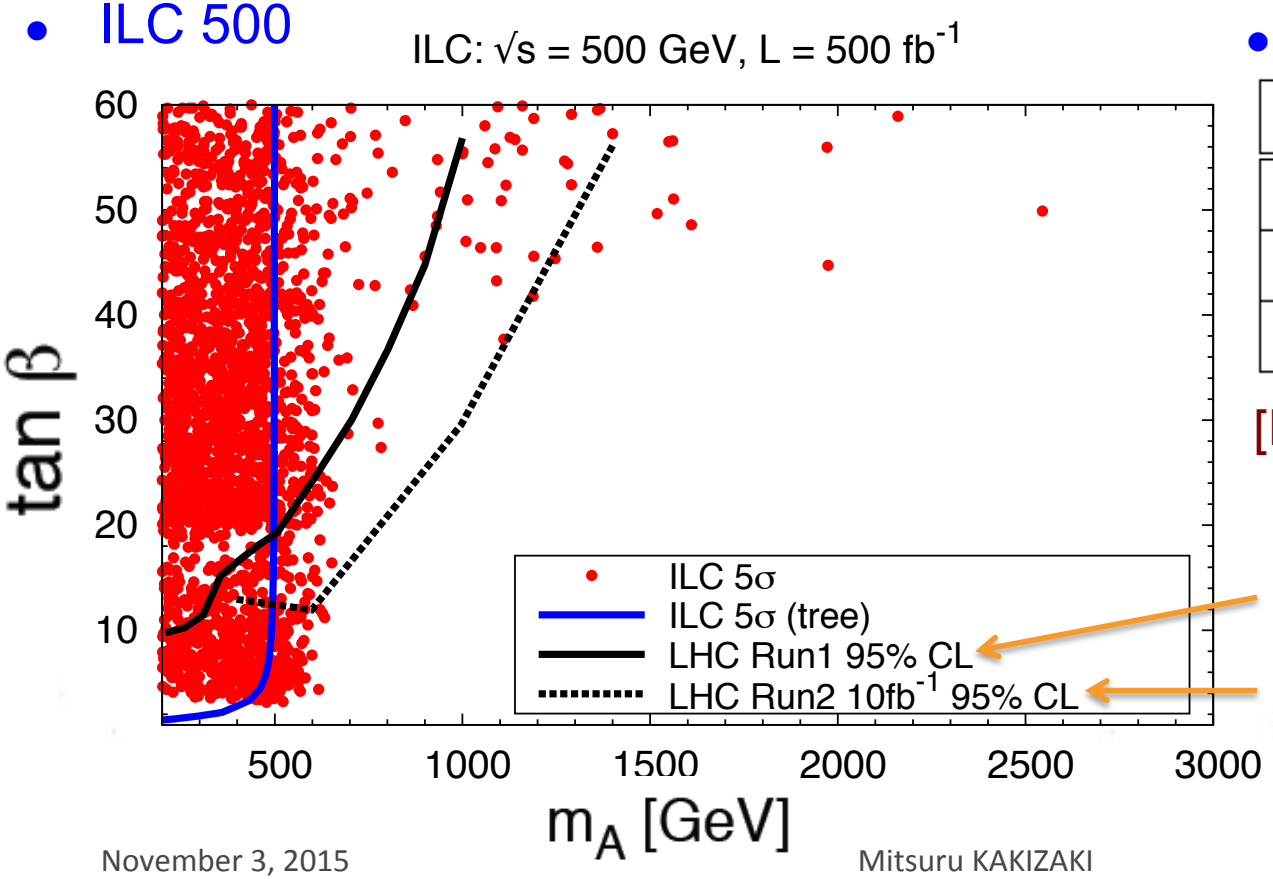

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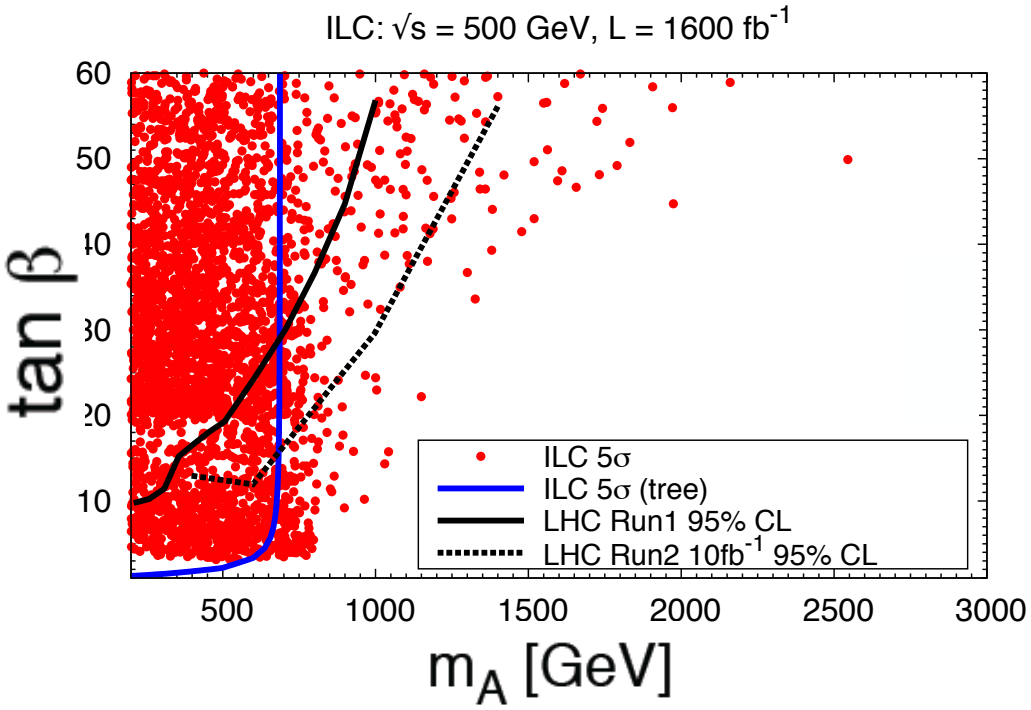
[ILC Higgs White Paper(2013)]

[ATLAS (2014)]

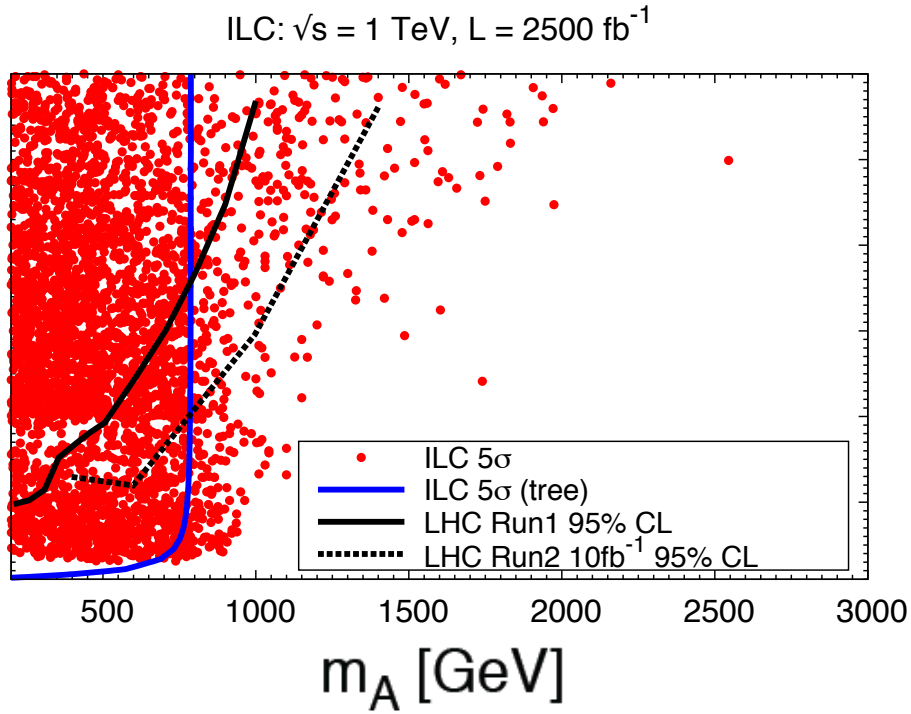
[Morinaga, JPS 70th Annual Meeting (2015)]

Heavy MSSM Higgs Mass Reach (Luminosity Upgrades)

- ILC 500 LumiUp:



- ILC 1000 LumiUp:



[ILC Higgs White Paper; ATLAS（2014）;Morinaga, JPS 70th Annual Meeting (2015]

- The indirect reach through the Higgs coupling measurements can be higher than the LHC direct observation limits
- ILC programs with luminosity upgrades are particularly useful in exploring the heavy MSSM Higgs bosons

Summary

- In the MSSM, the bottom Yukawa coupling of the discovered Higgs boson significantly deviates from the tree-level prediction due to the non-decoupling effects

- We point out the ratio of the Higgs boson branching ratios $\mathrm{Br}(h \to b\bar{b})/\mathrm{Br}(h \to WW)$ is a sensitive probe for indirect additional MSSM Higgs boson search

- Using the ratio, we have shown indirect 5σ discovery potential of the additional MSSM Higgs bosons at planned ILC stages

- Fingerprinting of Higgs boson couplings is a powerful tool to explore and distinguish models explaining dynamics of the EWSB (MSSM, NMSSM, Composite models, ...)

Backup slides

Determination of the Higgs Boson Branching ratios at the ILC

- Expected accuracies for cross section times branching ratio for the 125 GeV Higgs boson: $\Delta(\sigma \cdot BR)/(\sigma \cdot BR)$ (1σ)

$\sqrt{s}$ and $\mathcal{L}$ (P_{e-}, P_{e+})	250 fb^{-1} at 250 GeV (-0.8,+0.3)	1600 fb^{-1} at 500 GeV (-0.8,+0.3)	1600 fb^{-1} at 500 GeV (-0.8,+0.3)
	$\nu\bar{\nu}h$	$\nu\bar{\nu}h$	$\nu\bar{\nu}h$
$\Delta\sigma/\sigma$	-	-	
BR(invis.)	-	-	-
mode	$\Delta(\sigma \cdot BR)/(\sigma \cdot BR)$	$\Delta(\sigma \cdot BR)/(\sigma \cdot BR)$	
$h \to bb$	0.7%	0.4%	0.3%
$h \to c\bar{c}$	6.2%	3.5%	2.0%
$h \to gg$	4.1%	2.3%	1.4%
$h \to WW^*$	2.4%	1.3%	1.0%
$h \to \tau^+\tau^-$	9.0%	5.0%	2.0%
$h \to ZZ^*$	8.2%	4.6%	2.6%
$h \to \gamma\gamma$	23%	13%	5.4%
$h \to \mu^+\mu^-$	-	-	20%

[ILC Higgs White paper (2013)]

Determination of the Higgs Boson Couplings at the ILC

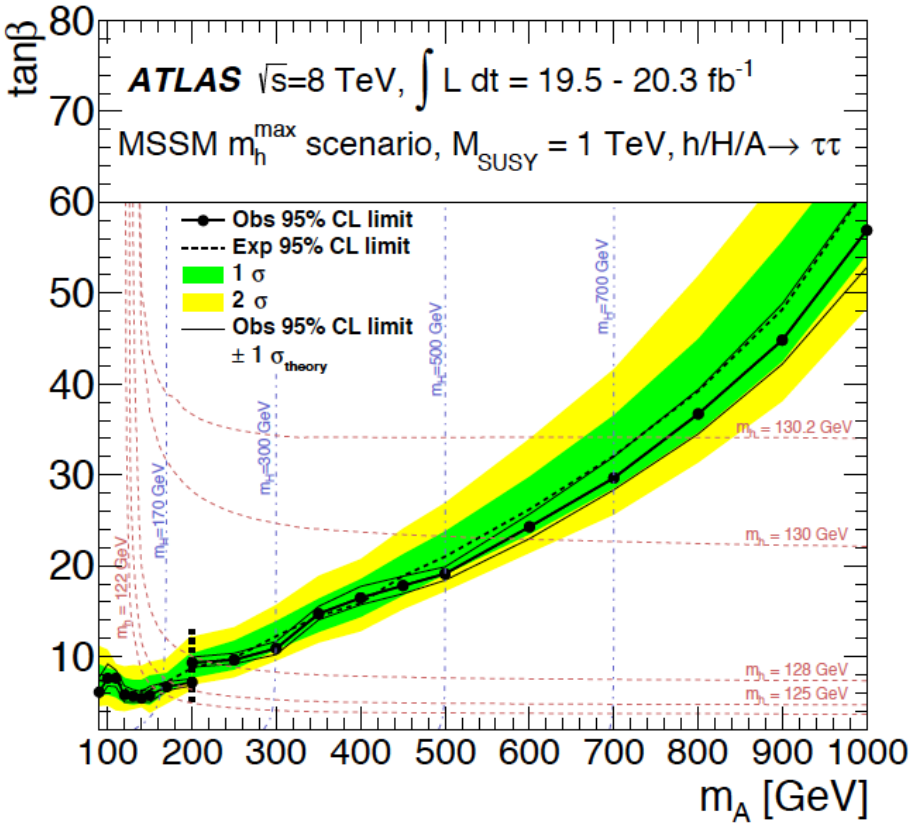
- Expected accuracies for model independent determination of the 125 GeV Higgs boson couplings: (1σ)

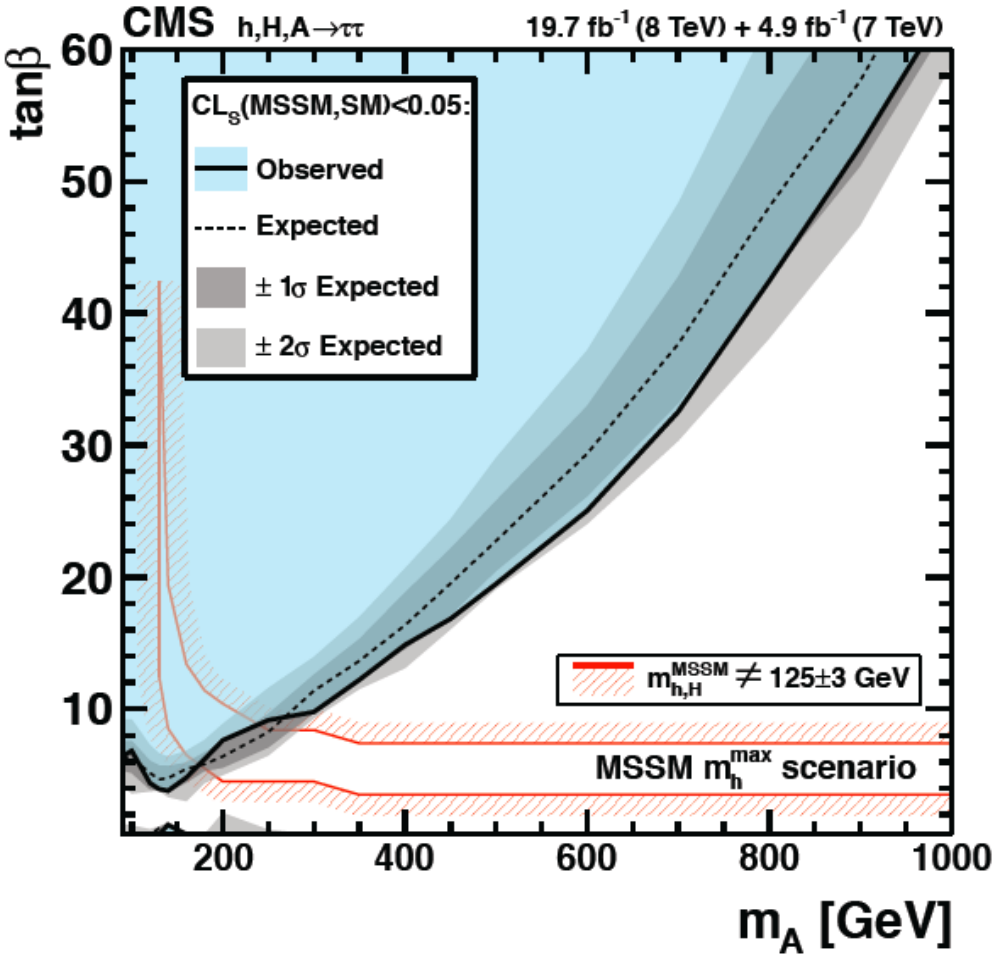
	ILC(250)	ILC(500)	ILC500(LumUp)	ILC(LumUp)
$\sqrt{s}$ (GeV)	250	250+500	250+500	250+500+1000
L (fb^{-1})	250	250+500	1150+1600	1150+1600+2500
$\gamma\gamma$	18 %	8.4 %	4.5 %	2.4 %
gg	6.4 %	2.3 %	1.2 %	0.9 %
WW	4.8 %	1.1 %	0.6 %	0.6 %
ZZ	1.3 %	1.0 %	0.5 %	0.5 %
$t\bar{t}$	–	14 %	7.8 %	1.9 %
bb	5.3 %	1.6 %	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 %
hhh	–	83 %	46 %	13 %
BR(invis.)	< 0.9 %	< 0.9 %	< 0.4 %	< 0.4 %

[ILC Higgs White paper (2013)]

Heavy MSSM Higgs boson search at the LHC

- Exclusion limit at the LHC through $A/H \to \tau^+\tau^-$





[arXiv:1409.6064]

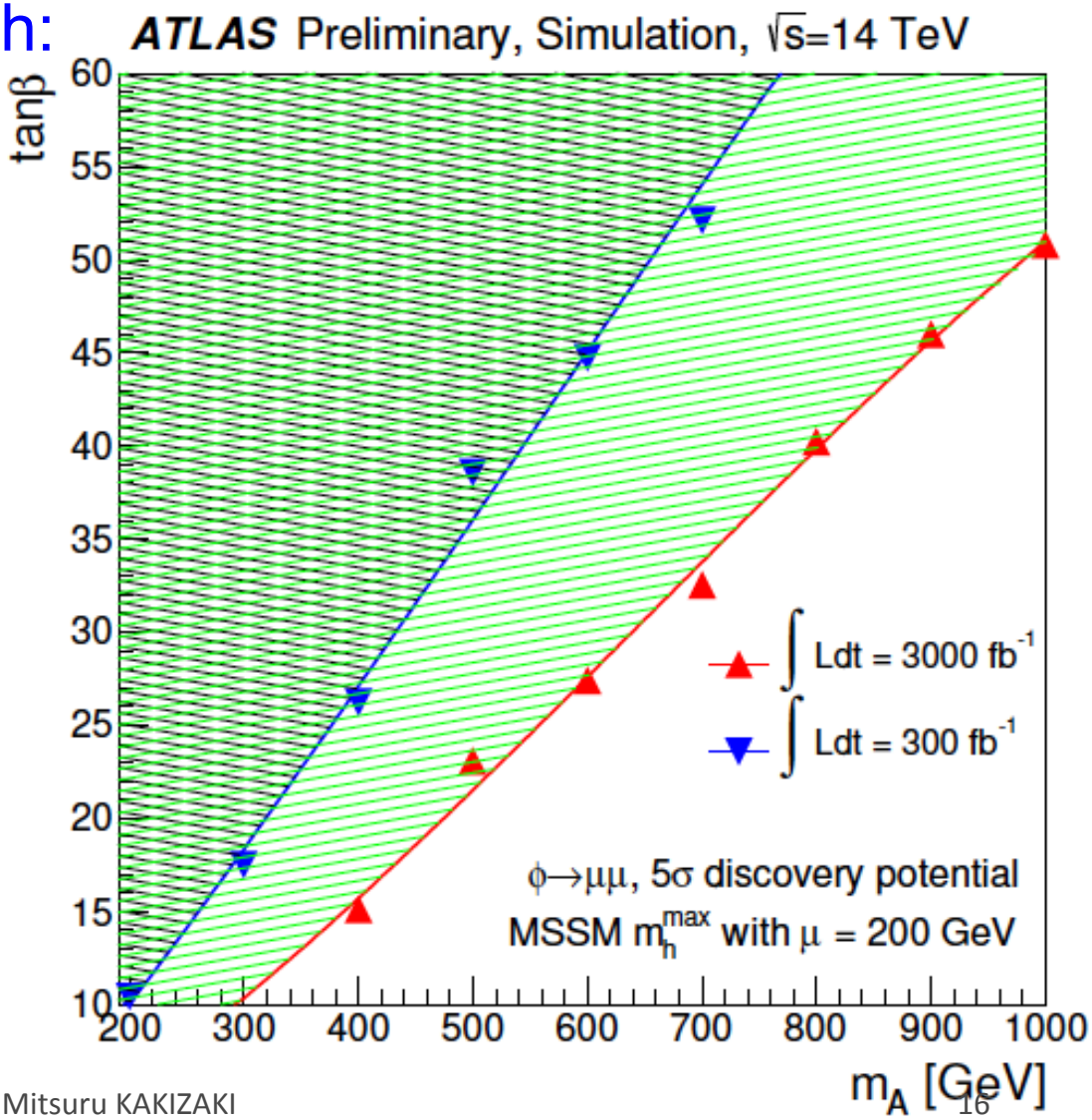
[arXiv:1408.3316]

Expected Heavy MSSM Higgs Boson Mass Reach at the LHC

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

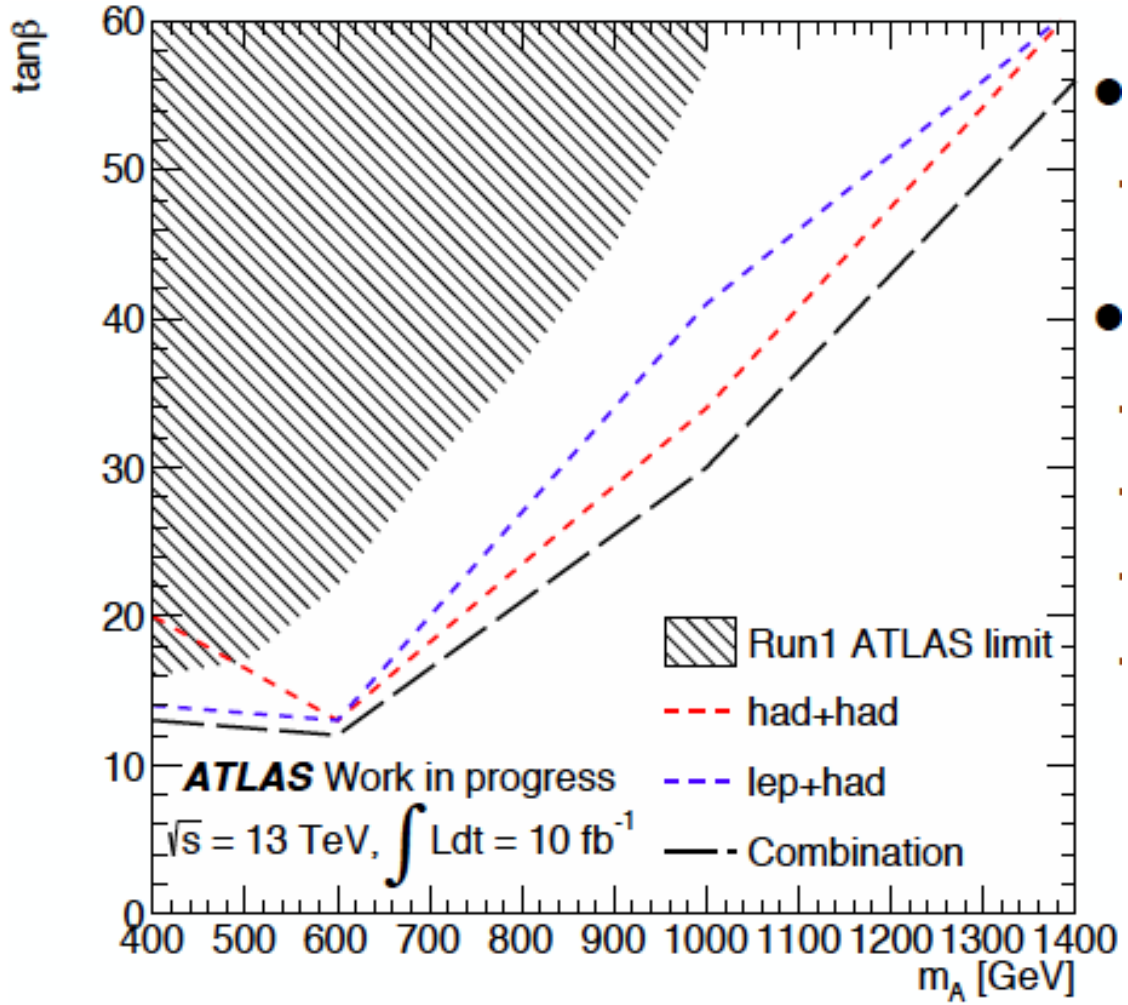
$$A/H \rightarrow \mu^+\mu^-$$

[ATLAS-PHYS-PUB-2013-016]



Expected Heavy MSSM Higgs Boson Mass Reach at the LHC

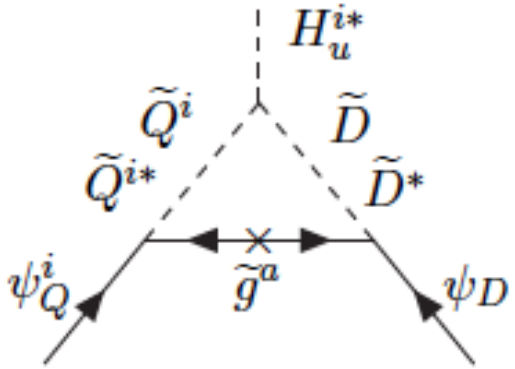
- Expected 95% CL exclusion limit at the LHC ATLAS

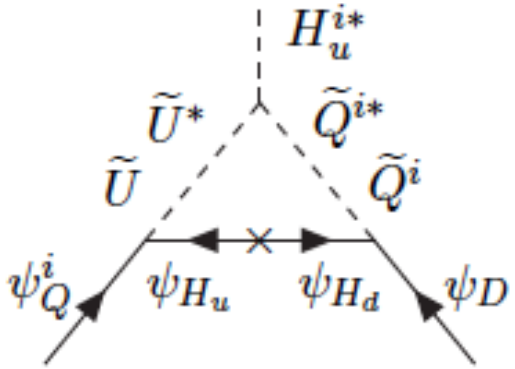


[From Morinaga, JPS 70th Annual Meeting (2015)]

Wrong-Higgs Yukawa interactions

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





- 3-point scalar interactions:

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

[Haber,Mason(2008)]

Yukawa couplings in the MSSM

- Radiative corrections to the bottom Yukawa coupling:

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

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

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

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