Direct searches of additional Higgs bosons in the 2HDM at the LHC and ILC

Hiroshi Yokoya (U. of Toyama)

Collaborators: Shinya Kanemura (U. of Toyama),
Ya-Juan Zheng (NTU)

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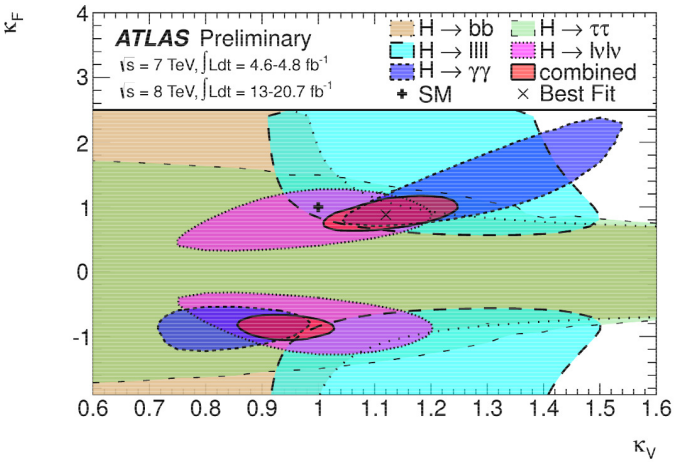
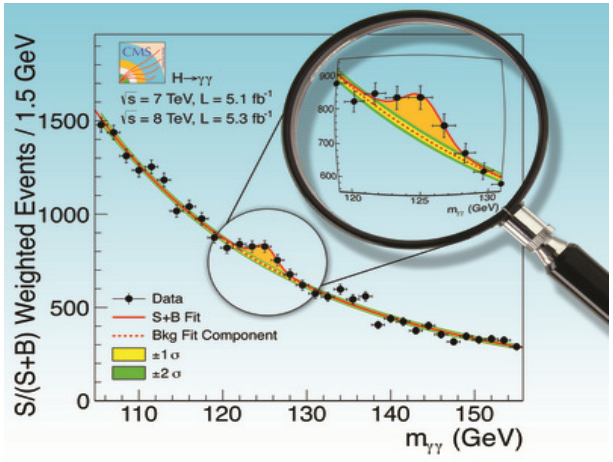
Introduction :

A Higgs boson was found at the LHC,
which seems mostly the SM one.





- But, we don't know whether this is the only one or there are more.
- Extended Higgs sectors are often introduced in the physics beyond the SM, to explain unsolved problems, such as dark matter, neutrino mass, baryon asymmetries ,,

Searches for extended Higgs sectors

Direct Searches

Find a peak/excess from the SM background.
Clear evidence with less ambiguity.
Mass reach is limited by collider energy.

Indirect Searches

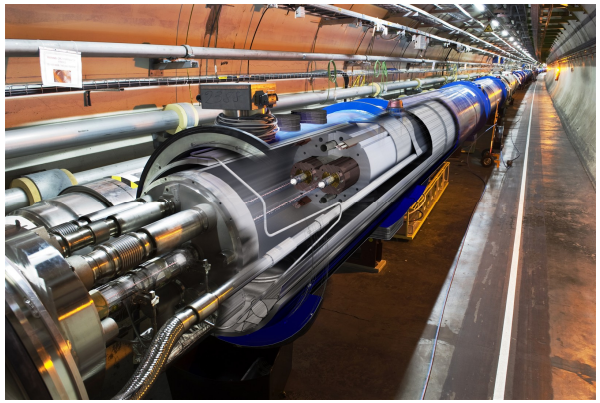
Check the SM couplings carefully including loop corrections, and find (small) deviations from the SM.
Mass reach can be very high due to loop effects.

Direct searches at future colliders

LHC $\sqrt{s}$ = 13-14TeV

$L = 300fb^{-1}$ 2015 - 2022

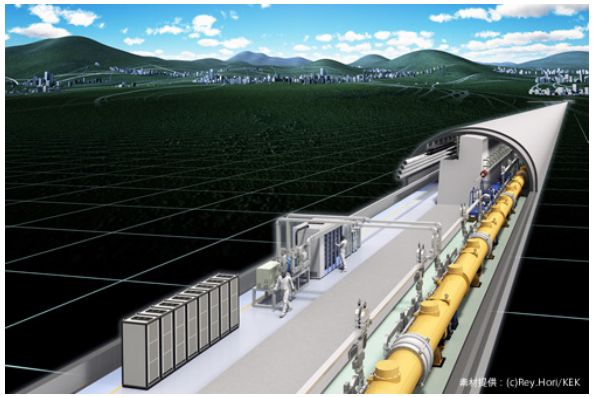
$3000fb^{-1}$ (HL-LHC) 2025(?) ~



ILC

$\sqrt{s}$ = 250GeV, 2025(?) ~

(~350GeV), 500GeV, 1TeV



For the direct searches, basically the LHC is better than the ILC.

But, there are still possibilities that the LHC cannot find/identify new Higgs bosons.

If their masses are within the ILC reaches, the ILC can help to explore them.

We study the complementarity of the direct searches of additional Higgs bosons at the LHC and ILC, in the context of the 2HDM with discrete symmetry.

Two Higgs Doublet Model (2HDM):

$$\Phi_1 + \Phi_2 \qquad \Phi_i = \begin{pmatrix} \omega_i^+ \\ \frac{1}{\sqrt{2}}(v_i + h_i + i\, z_i) \end{pmatrix}_{\text{i=1,2}}$$

- ρ = 1 at tree-level
- In general, FCNCs occur → discrete symmetry, aligned Yukawa,,,
- New sources of CP phases (assumed to be zero in this talk)

8 – 3 = 5 physical states:

$$h,\ H,\ A,\ H^{\pm}$$

VEVs: $v = \sqrt{v_1^2 + v_2^2} \simeq 246\ \text{GeV}$

$\tan\beta = v_1/v_2$

Mixing angles:

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} c_\alpha & -s_\alpha \\ s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}$$

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

Softly-broken discrete symmetry

- To avoid FCNCs, we consider models with a discrete symmetry

Glashow,Weinberg ('77)

$$\Phi_1 \to \Phi_1,\ \Phi_2 \to -\Phi_2$$

so that each fermion has Yukawa couplings to one Higgs bosons:

$$\mathcal{L} = \overline{L}\,(Y_{\ell 1}\Phi_1 + \times)\,\ell_R + \mathrm{H.c.}$$

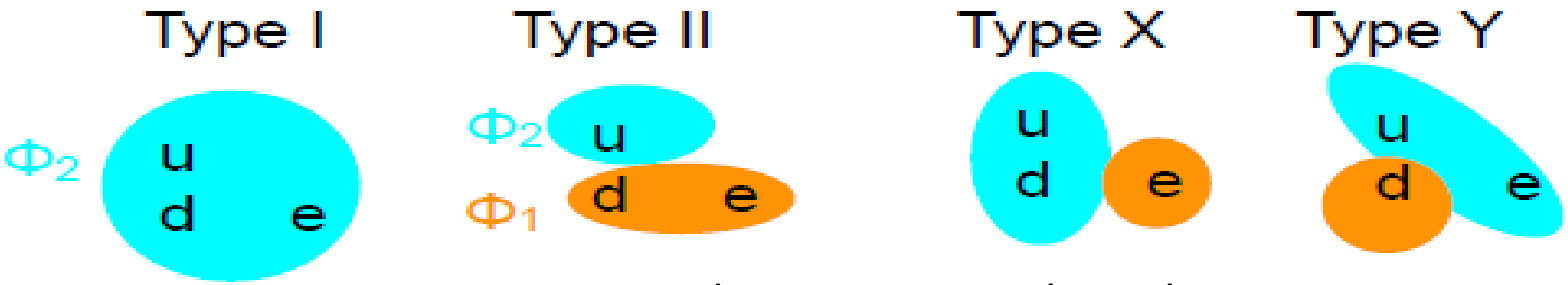
or vice versa

- Parity assignment to fermions :

V.Barger et.al. ('90),Y.Grossman ('94), A.Akeroyd,W.Stirling ('95),,,

Aoki,Kanemura,Tsumura,Yagyu ('09)

Four types of Yukawa models



all fermion couples to one Higgs boson

up v.s. down (MSSM)

quark v.s. lepton

flipped

SM-like limit [sin(β-α)→1] $\kappa_V^h \to 1,\ \kappa_V^H \to 0$

- In the SM-like limit, all the couplings of h(125GeV) become the same as those in the SM.
- For the additional bosons (H,A $H^{\pm}$), couplings to gauge bosons(φVV) vanish, while Yukawa couplings remain.

Therefore, searches of additional Higgs bosons by using Yukawa couplings are still possible in the SM-like limit.

(Fingerprinting of SM Higgs couplings is irrelevant in this limit.)

Direct searches at the LHC

- There exist many extensive studies for the searches of the MSSM Higgs bosons. e.g. ATLAS TDR
- We interpret there results to the general 2HDMs

ILC Higgs White paper (13),
Kanemura,Tsumura,Yagyu,HY

- H, A : $gg \to H/A$, $gg(q\bar{q}) \to Q\bar{Q}H/A$ $\Big\}$ $H/A \to b\bar{b}$ or $\tau^+\tau^-$
- $H^\pm$: $gb \to tH^-,\ H^- \to \bar{t}b$

- In the case where only couplings to lepton are large (Type-X in large tanβ) :

$$q\bar{q} \to HA \quad q\bar{q}' \to HH^\pm, AH^\pm$$
$$H/A \to \tau^+\tau^-,\ H^\pm \to \tau^\pm\nu$$

Aoki,Kanemura,Tsumura,
Yagyu('09),
Kanemura,Tsumura,HY('11)

Direct searches at the LHC

ILC Higgs White paper (13),
Kanemura,Tsumura,Yagyu,HY

Reaches of direct searches for additional Higgs boson(95% CL), interpreted from the ATLAS TDR.

Kanemura,HY,Zheng ('14)

solid:300fb^{-1}, dashed:3000fb^{-1}

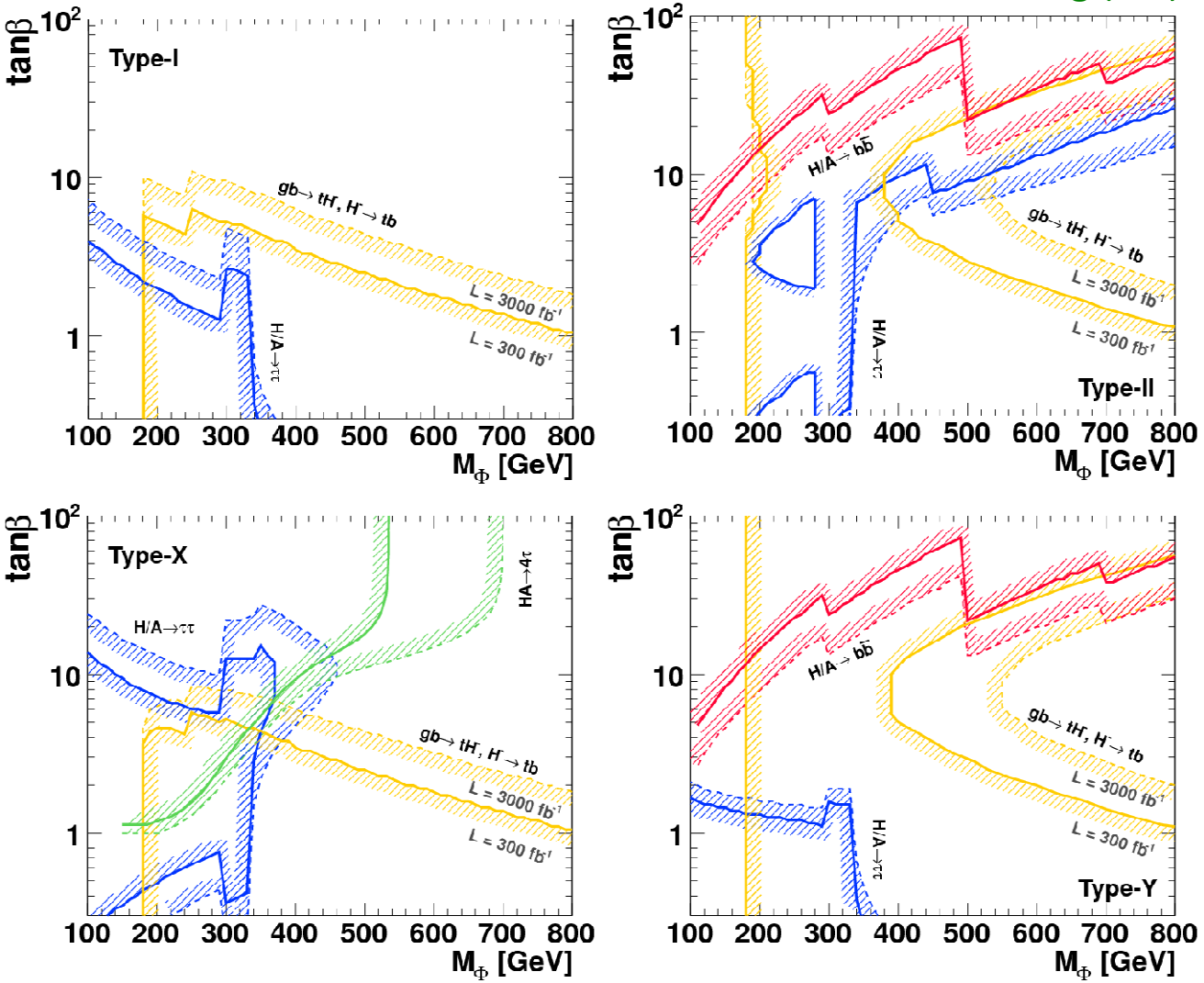
$(b\bar{b}+)H/A \to \tau^+\tau^-$

$b\bar{b} + H/A \to b\bar{b}b\bar{b}$

$gb \to tH^-; H^- \to \bar{t}b$

$q\bar{q} \to HA \to 4\tau$

Extensive regions are covered up to M_Φ~600GeV.



Direct searches at the ILC

Pair and single productions
of additional Higgs bosons

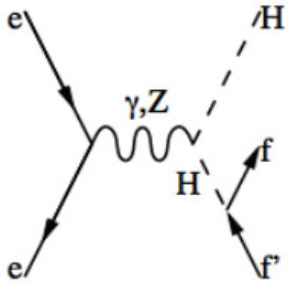
Kanemura,Moretti,Odagiri(01),
Kiyoura et al. (06),,,
Kanemura,HY,Zheng ('14)

At lepton colliders, heavy particle production is limited by the collision energy.

Pair production needs /s > 2m, while single production needs /s > m.

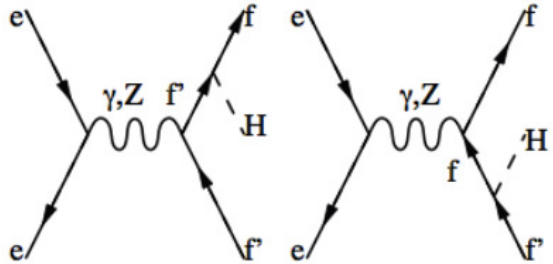
- /s > $m_H + m_A$ or $2m_{H+}$

$$e^+e^- \to HA$$
$$e^+e^- \to H^+H^-$$



- /s < $m_H + m_A$ or $2m_{H+}$

$$e^+e^- \to f\bar{f}H/A$$
$$e^+e^- \to f\bar{f}'H^\pm$$



- Single production can be enhanced by large Yukawa couplings,
  and extend the mass reach at lepton collider (a bit).

Direct searches at the ILC

Production cross sections at the ILC :

Pair production : O(1) ~ O(10) [fb]

Single production : up to O(0.1) ~ O(1) [fb] at extremely large/small tanβ

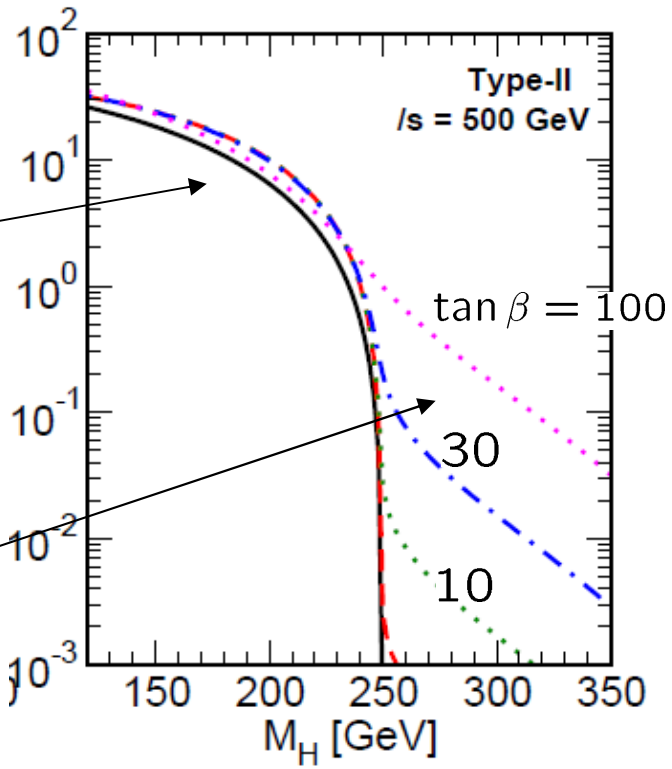
pair production

$\sigma_{bbH} = \sigma_{HA} \times \mathcal{B}r(A \to bb)$

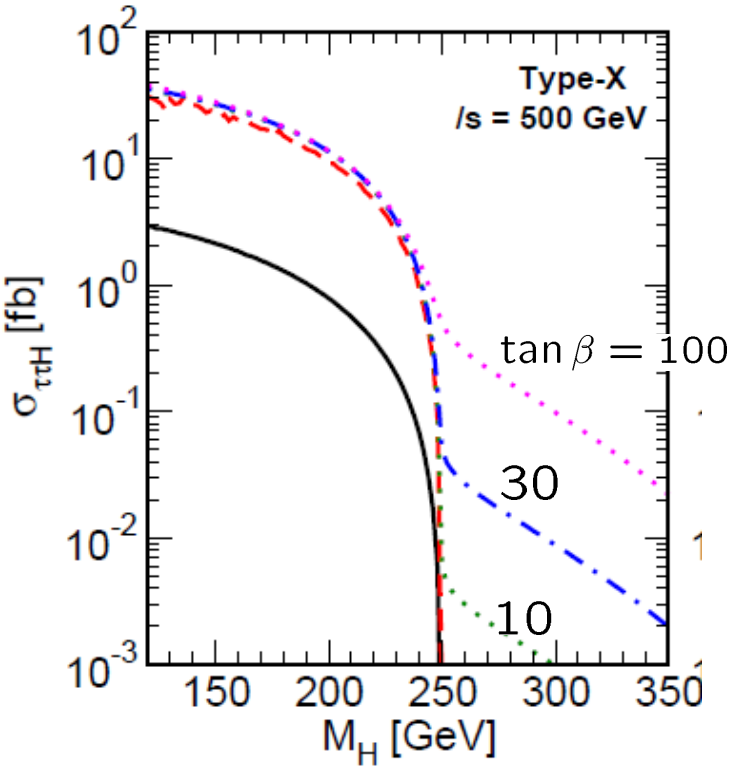
single production

$\sigma_{bbH} \propto (y_b^H)^2$

σ_{bbH} [fb] (Type-II)



$\sigma_{\tau\tau H}$ [fb] (Type-X)



Direct searches at the ILC

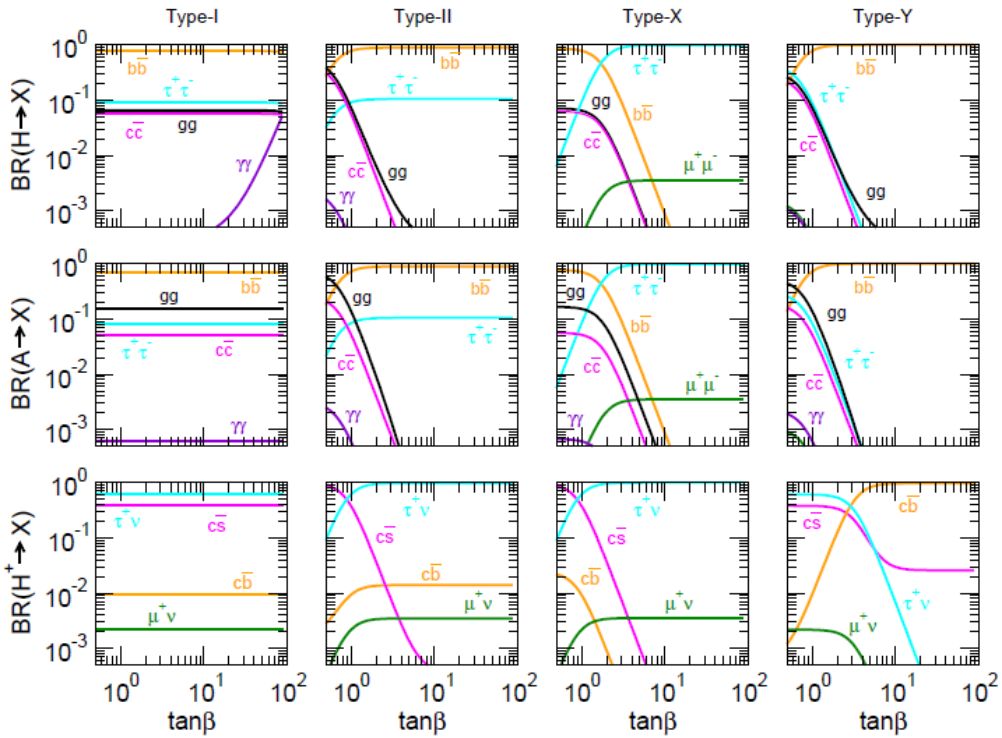
- Catalog of the signatures at the ILC,
  through the pair and single productions of additional Higgs bosons.

Our set-up
- general 2HDMs with Z_2 symmetry (four types of Yukawa)
- SM-like limit [$\sin(\beta-\alpha)=1$]

Productions (pair and single):

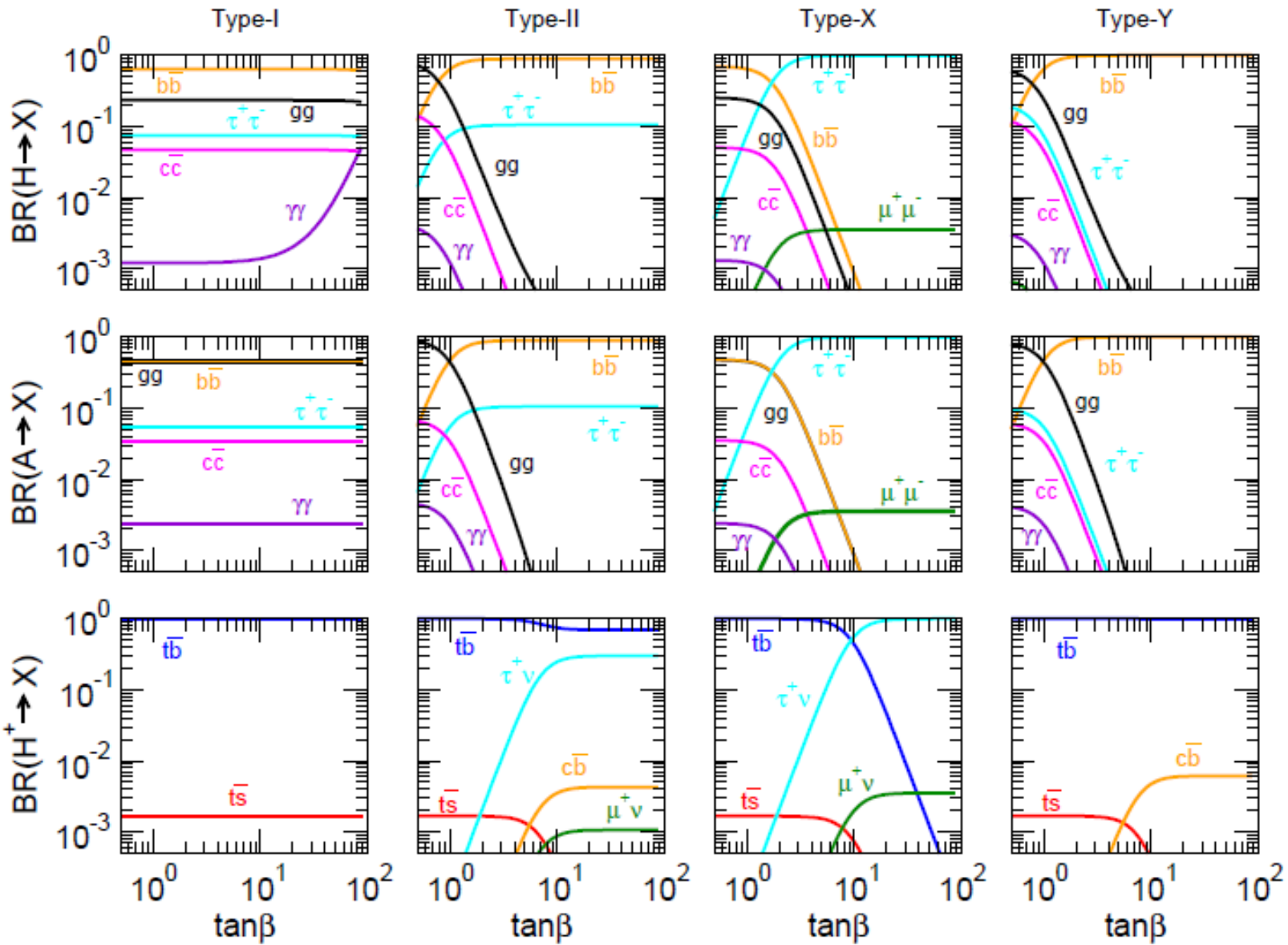
$$e^+e^- \to b\bar{b}H/A,$$
$$e^+e^- \to \tau^+\tau^- H/A,$$
$$e^+e^- \to t\bar{t}H/A,$$
$$e^+e^- \to \tau^+\nu H^\pm,$$
$$e^+e^- \to t\bar{b}H^\pm$$

Decays:



Decay Branching ratios

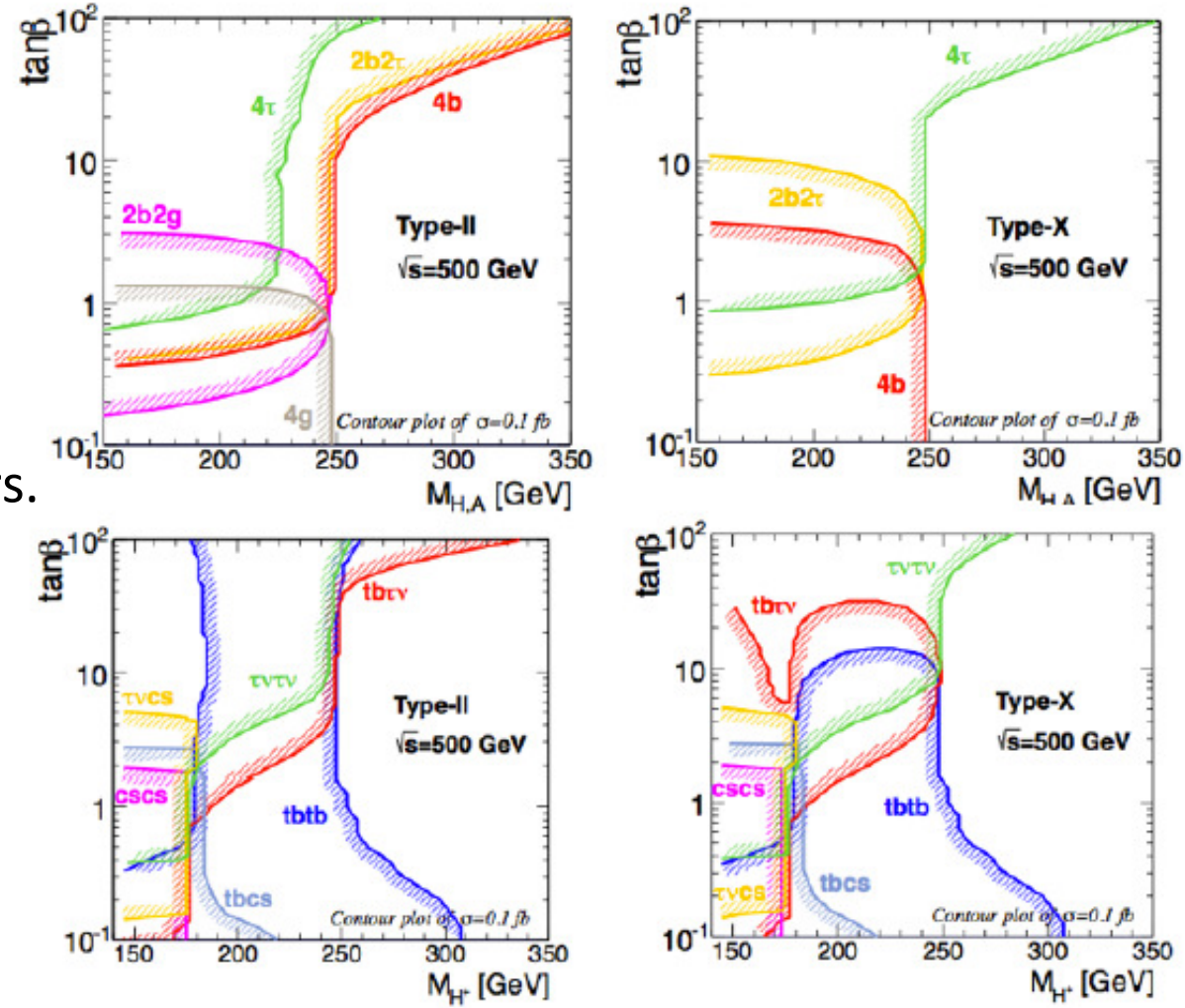
$m_H=m_A=m_{H^+}=250$ GeV, $\sin(\beta-\alpha)=1$



Direct searches at the ILC

Contour plot at σ = 0.1 fb (as a typical order of cross-sections Efficiency for each channel is not considered)

/s = 500 GeV Type-II & X



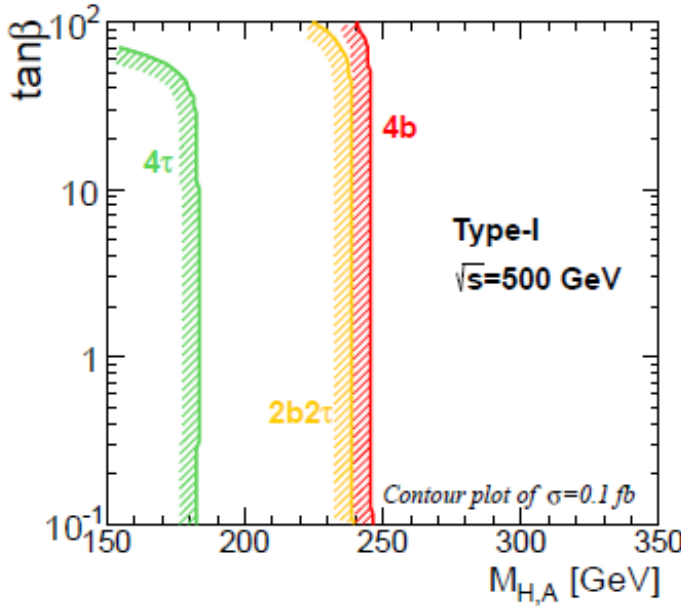
- In the pair production regions, we expect at least one kind of signature for any types/parameters.

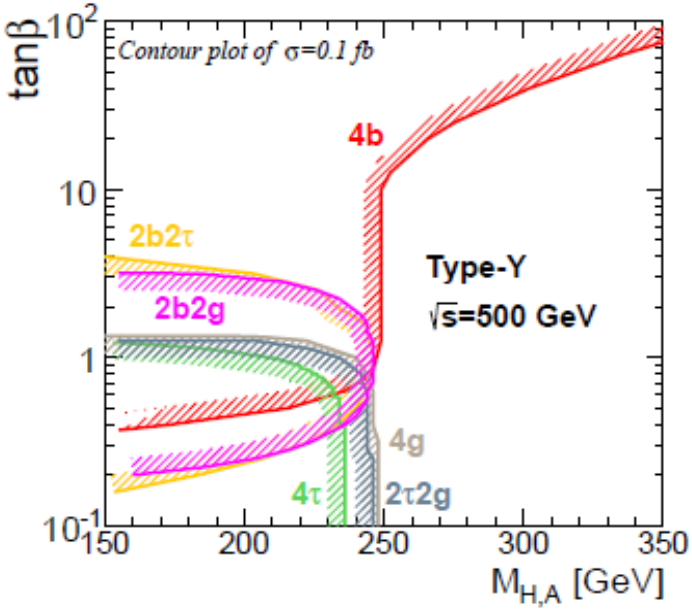
- For most of the cases, by the combination of the signatures, the type of Yukawa can be distinguished.

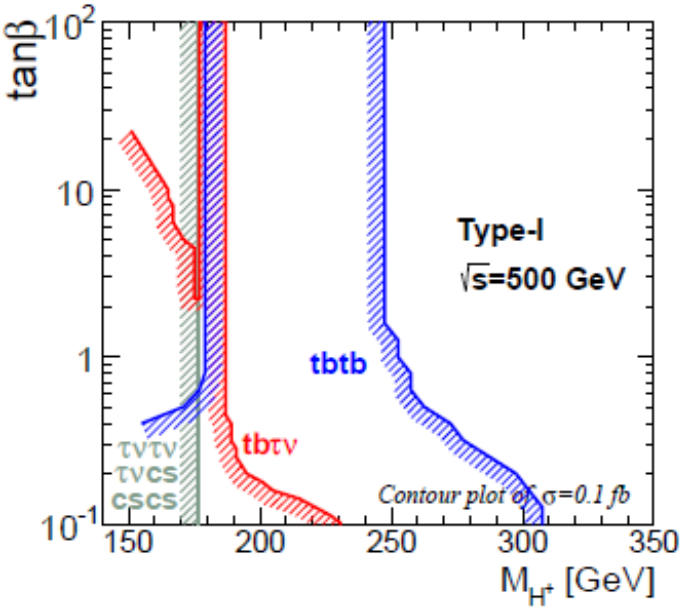
Direct searches at the ILC

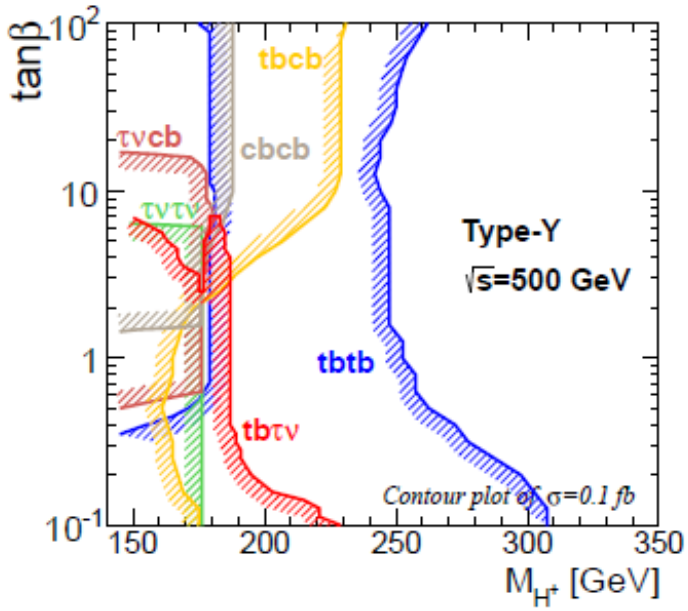
/s = 500 GeV

Type-I and Type-Y



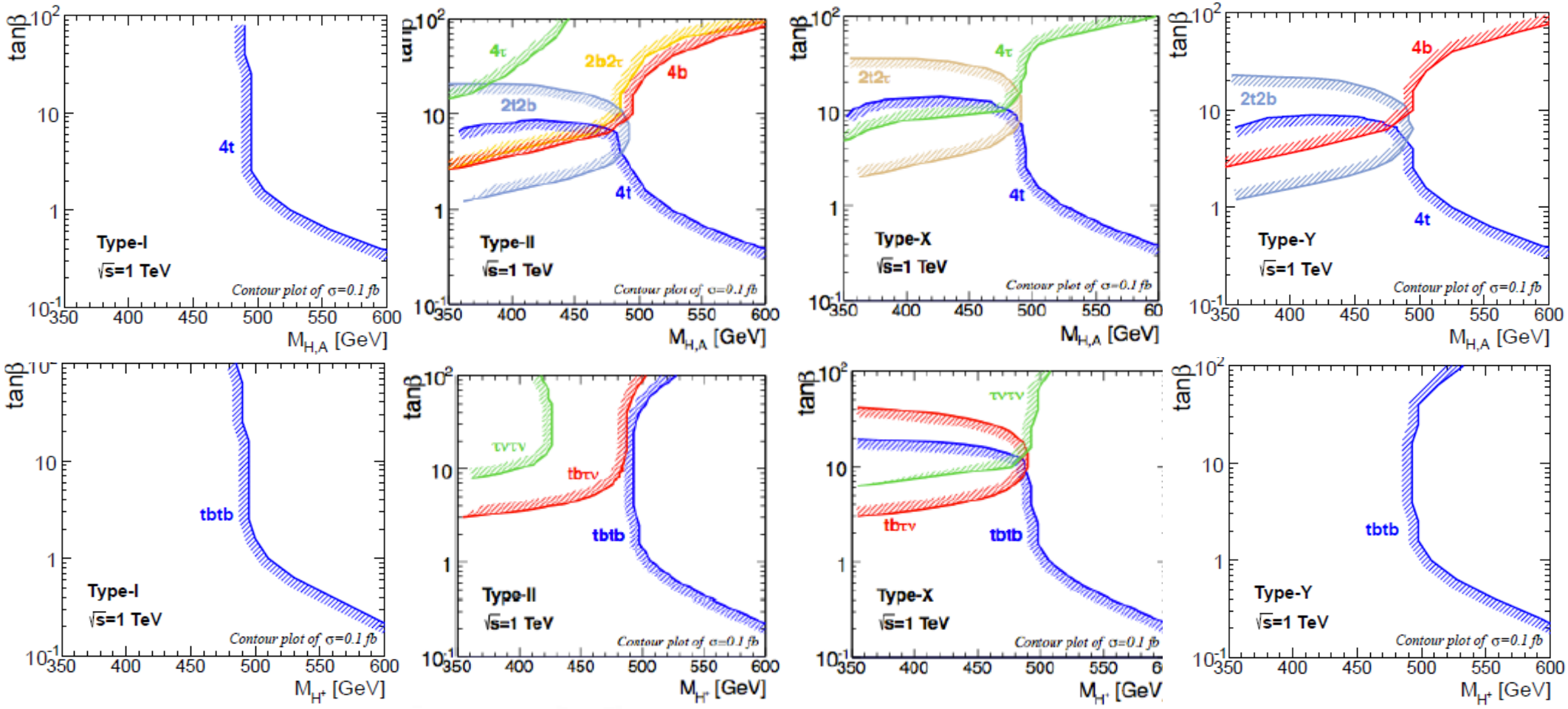






Direct searches at the ILC

/s = 1 TeV tt, tb decay modes are dominant → tttt, tbtb signatures.



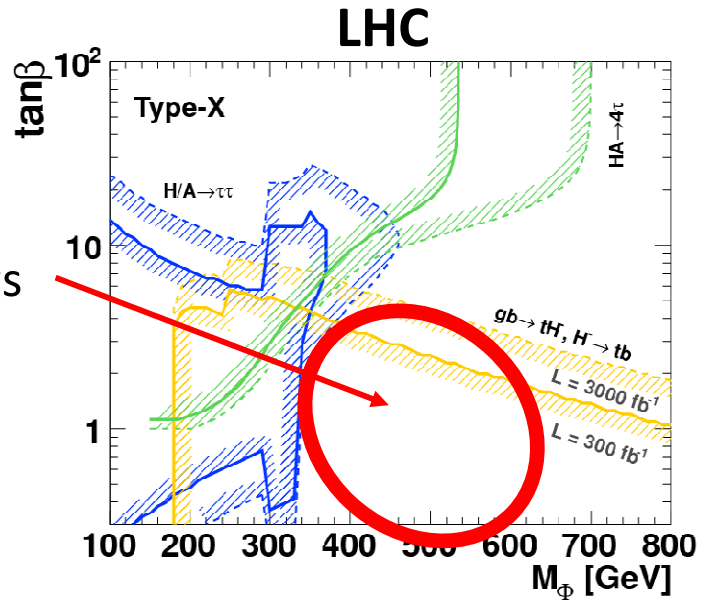
Complementarity of the LHC and ILC

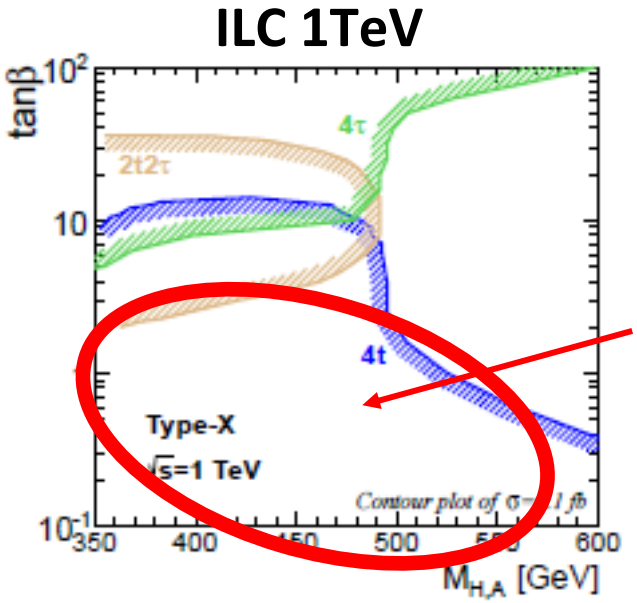
Scenarios in which the ILC is useful for the direct searches

① LHC cannot find new Higgs, but ILC can find it.

② LHC can find new Higgs, but models/types cannot be distinguished.
ILC then distinguish the models, determine the parameters.

Neutral Higgs cannot be discovered





ILC can find it !

Expected signatures at the LHC and ILC (benchmark points with M=220 GeV)

$(M, \tan\beta)$		Type-I		Type-II		Type-X		Type-Y	
		H, A	$H^\pm$	H, A	$H^\pm$	H, A	$H^\pm$	H, A	$H^\pm$
(220 GeV, 20)	LHC300	-	-	$\tau\tau$, bb	tb	4τ	-	bb	tb
	LHC3000	-	-	$\tau\tau$, bb	tb	4τ	-	bb	tb
	ILC500	$4b, 2b2\tau$	$tbtb$	$4b, 2b2\tau$, 4τ	$tbtb, tb\tau\nu$, $\tau\nu\tau\nu$	4τ	$tb\tau\nu$, $\tau\nu\tau\nu$	$4b$	$tbtb, tbcb$
(220 GeV, 7)	LHC300	-	-	$\tau\tau$	tb	4τ	-	-	tb
	LHC3000	-	tb	$\tau\tau$	tb	$\tau\tau, 4\tau$	-	-	tb
	ILC500	$4b, 2b2\tau$	$tbtb$	$4b, 2b2\tau$, 4τ	$tbtb, tb\tau\nu$, $\tau\nu\tau\nu$	$2b2\tau, 4\tau$	$tbtb, tb\tau\nu$, $\tau\nu\tau\nu$	$4b$	$tbtb, tbcb$
(220 GeV, 2)	LHC300	-	tb	$\tau\tau$	tb	$\tau\tau, 4\tau$	tb	-	tb
	LHC3000	$\tau\tau$	tb	$\tau\tau$	tb	$\tau\tau, 4\tau$	tb	-	tb
	ILC500	$4b, 2b2\tau$	$tbtb$	$4b, 2b2\tau$, $4\tau, 2b2g$	$tbtb$, $tb\tau\nu$	$4b, 2b2\tau$, 4τ	$tbtb$, $tb\tau\nu$	$4b, 2b2\tau$, $2b2g$	$tbtb$

Expected signatures at the LHC and ILC (benchmark points with M=400 GeV)

$(M, \tan\beta)$		Type-I		Type-II		Type-X		Type-Y	
		H, A	$H^\pm$	H, A	$H^\pm$	H, A	$H^\pm$	H, A	$H^\pm$
(400 GeV, 20)	LHC300	-	-	$\tau\tau$	tb	4τ	-	-	tb
	LHC3000	-	-	$\tau\tau$	tb	$\tau\tau, 4\tau$	-	-	tb
	ILC1TeV	$4t$	$tbtb$	$4b, 2b2\tau, 2t2b$	$tbtb, tb\tau\nu, \tau\nu\tau\nu$	$4\tau, 2t2\tau$	$tb\tau\nu, \tau\nu\tau\nu$	$4b, 2t2b$	$tbtb$
(400 GeV, 7)	LHC300	-	-	-	-	-	-	-	-
	LHC3000	-	-	$\tau\tau$	tb	$\tau\tau, 4\tau$	-	-	tb
	ILC1TeV	$4t$	$tbtb$	$4b, 2b2\tau, 2t2b, 4t$	$tbtb, tb\tau\nu$	$4t, 2t2\tau$	$tbtb, tb\tau\nu$	$4b, 2t2b, 4t$	$tbtb$
(400 GeV, 2)	LHC300	-	tb	-	tb	-	tb	-	tb
	LHC3000	-	tb	-	tb	-	tb	-	tb
	ILC1TeV	$4t$	$tbtb$	$4t, 2t2b$	$tbtb$	$4t$	$tbtb$	$4t, 2t2b$	$tbtb$

Summary

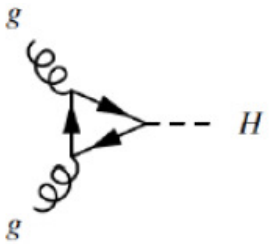
- We discussed the discovery potential of additional Higgs bosons in the 2HDM with discrete symmetry at the LHC and the ILC.
- Taking account of the pair and single production of additional Higgs bosons and the decay branching ratios of them, we list the expected signatures of additional Higgs bosons as a function of their masses and tanβ for all types of Yukawa models.
- We find that basically the LHC discovery reaches are higher than ILC, however, depending on the model or parameters, the direct searches at the ILC can be still useful for the discovery of additional Higgs bosons or to distinguish the model of Yukawa/determine the parameters such as their masses or tanβ.

Future task:
- Studies for the case with $\sin(\beta-\alpha)<1$
- Realistic detection efficiency at the ILC and BG contributions (especially, signals with top's; tttt, tbtb)

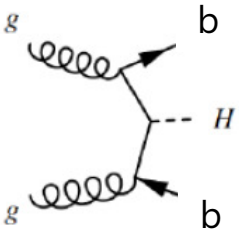
Golden channels: a la SUSY Higgs searches

$$pp \to H/A(b) \to \tau^+\tau^-(b)$$

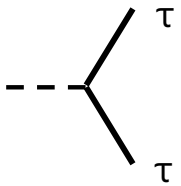
type-II



$\kappa_g \propto \tan\beta$ in large tanβ by bottom-loop



$\kappa_b \simeq \tan\beta$

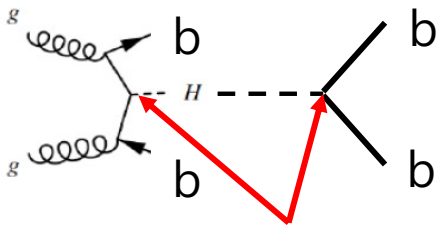


$\kappa_\tau \simeq \tan\beta$

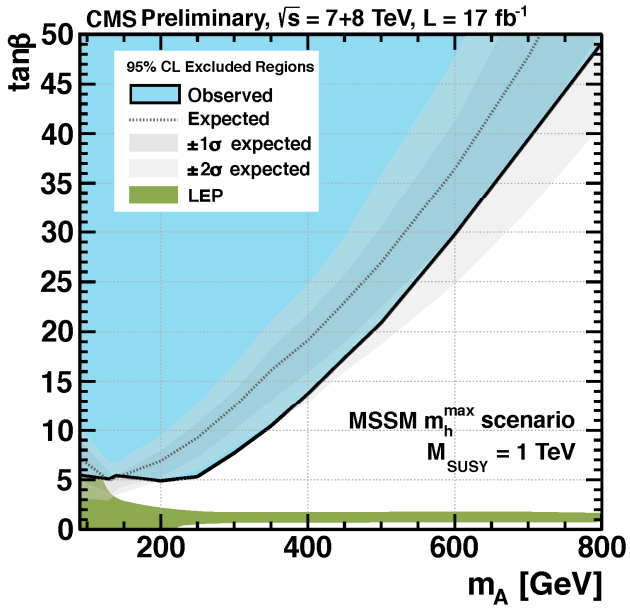
$(\mathcal{B}(\tau\tau) \sim 10\%)$

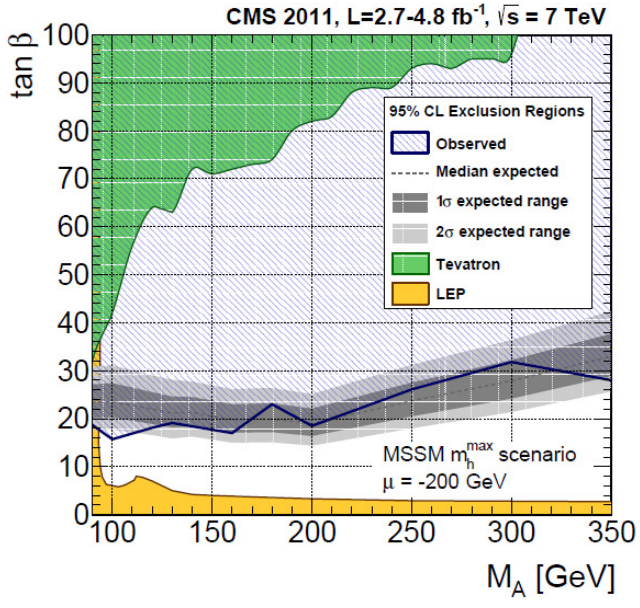
$$pp \to bH/A; H/A \to b\bar{b}$$

type-II, Y



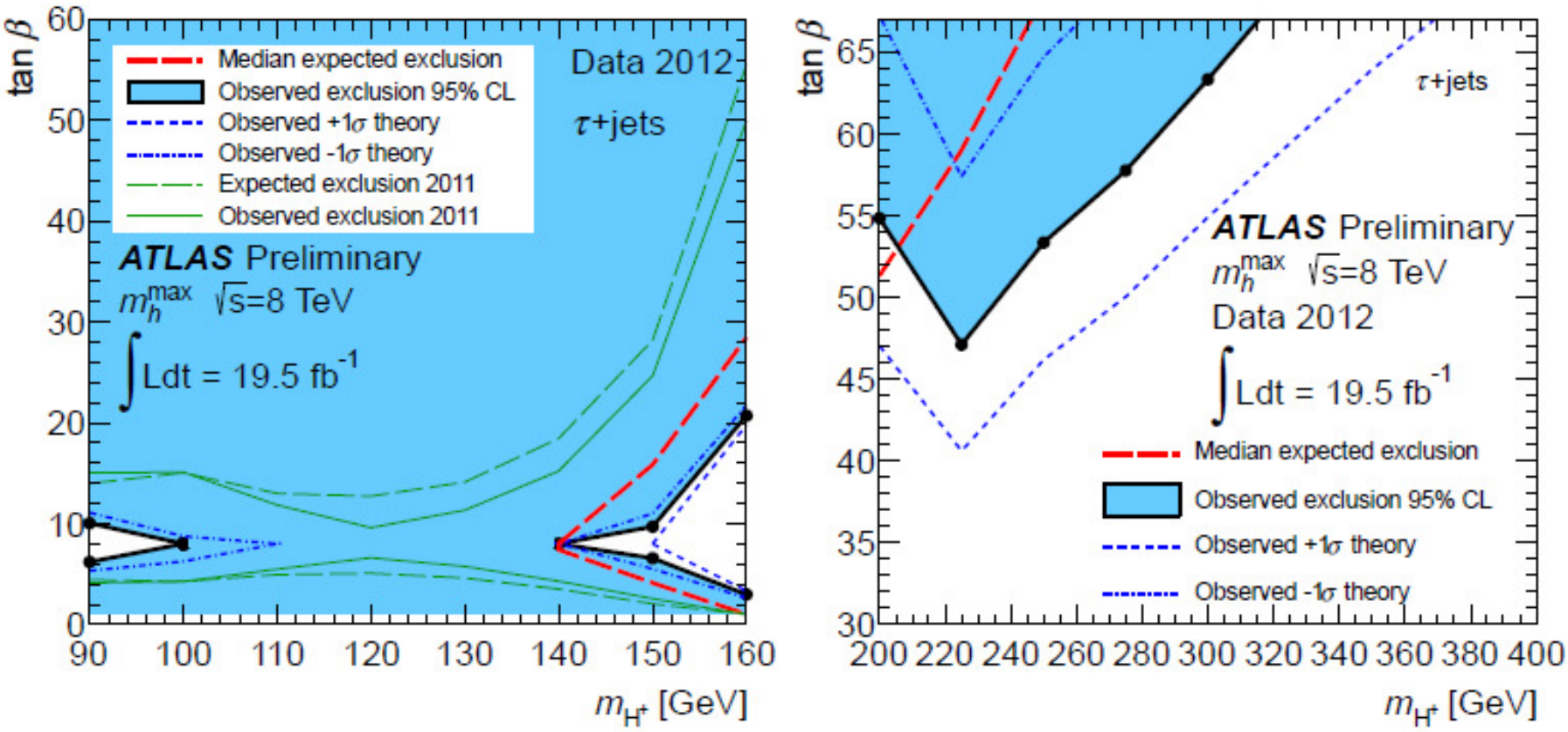
$\kappa_b \simeq \tan\beta$



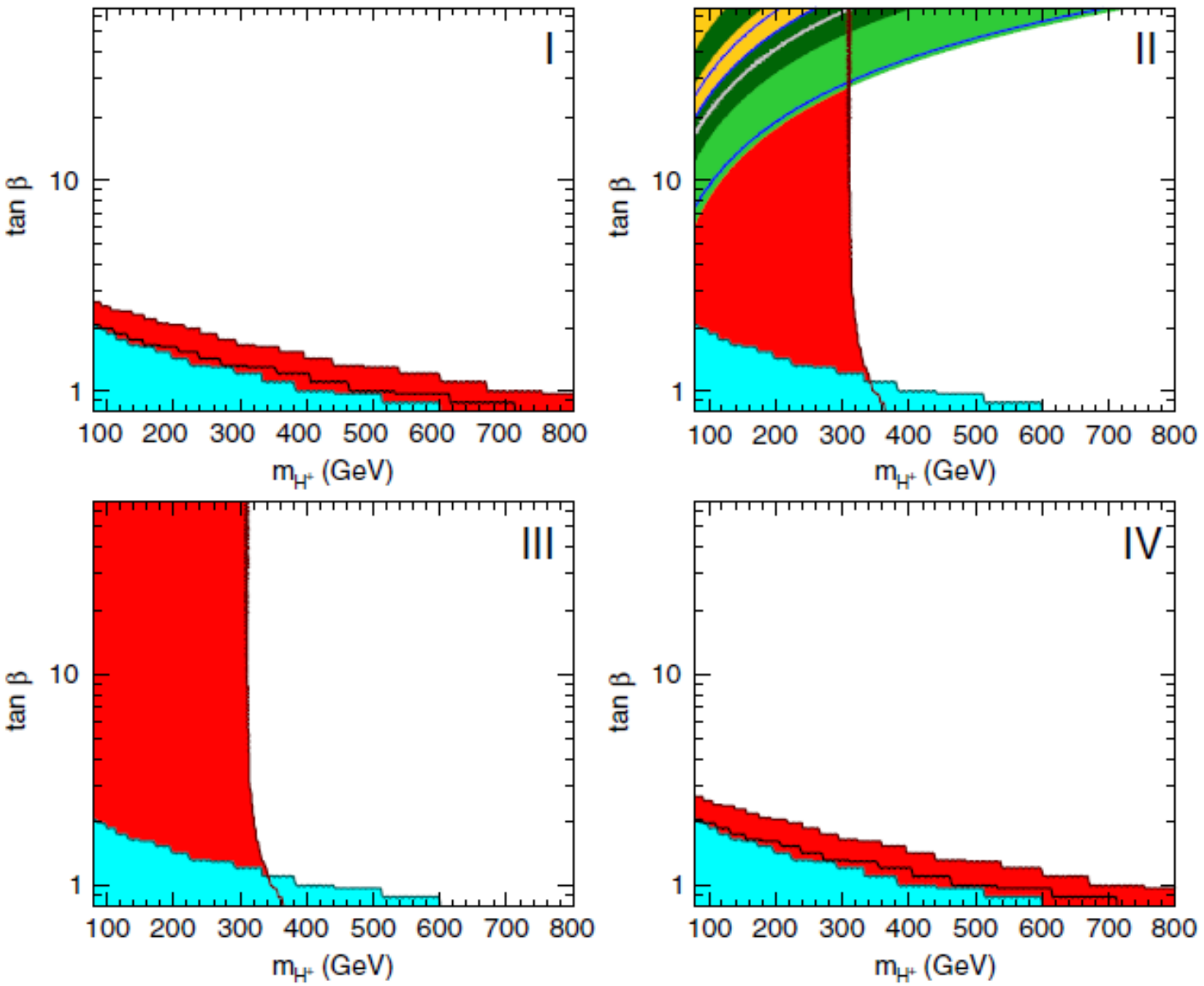


Charged Higgs search in the top quark decay :

$$t \to bH^+ \to b\tau^+\nu$$



Mahmoudi, Stal (10)



red : b->sγ

cyan : B-Bbar mixing

green : D_s->τν

(LHCデータも制限をつけ始めている。) **要チェック**