Search for extra Higgs bosons at ILC after LHC

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Outline

- Motivation
- Extra Higgs bosons within two Higgs doublet models (2HDM)
- Hadron collider reach for 2HDM particles
- Complementary discovery reach of extra Higgs bosons at ILC
- Summary and discussions

Motivation

- If the standard model(SM) electroweak theory is non-minimal, it is natural to consider extensions of Higgs sector.
- LHC discovery potential for extra Higgs bosons is limited in the small tanb region.
- ILC may provide interesting signatures as a complementary machine of LHC

2HDM particle content

Two Higgs doublet fields:

$$\Phi_i = \begin{pmatrix} H_i^+ \\ (H_i^0 + iA_i^0)/\sqrt{2} \end{pmatrix}, \quad i = 1, 2.$$

General Higgs potential:

$$V_{\rm 2HDM} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \right]$$

Gunion & Haber (2003)

$$+ \frac{1}{2}\lambda_1 \left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{1}{2}\lambda_2 \left(\Phi_2^\dagger \Phi_2\right)^2 + \lambda_3 \left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) + \lambda_4 \left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right)$$

hypercharge Y=1

$$+ \left\{ \frac{1}{2}\lambda_5 \left(\Phi_1^\dagger \Phi_2\right)^2 + \left[\lambda_6 \left(\Phi_1^\dagger \Phi_1\right) + \lambda_7 \left(\Phi_2^\dagger \Phi_2\right) \right] \left(\Phi_1^\dagger \Phi_2\right) + \text{h.c.} \right\}.$$

After SSB: 5 physical Higgs scalar left:

2 CP-even	1 CP-odd	2 Charged
h,H	A	$H^\pm$

Flavor changing neutral current (FCNC):

- SM: suppressed by electromagnetic gauge symmetry and GIM
- 2HDM: imposing discrete Z2 symmetry

2HDM Yukawa interactions

$$\mathcal{L}_{\rm yukawa}^{\rm THDM} = -\sum_{f=u,d,\ell}\left(\frac{m_f}{v}\xi_h^f\bar{f}fh + \frac{m_f}{v}\xi_H^f\bar{f}fH - i\frac{m_f}{v}\xi_A^f\bar{f}\gamma_5 fA\right)$$

neutral Higgs

$$-\left\{\frac{\sqrt{2}V_{ud}}{v}\bar{u}\left(m_u\xi_A^u P_L + m_d\xi_A^d P_R\right)dH^+ + \frac{\sqrt{2}m_\ell\xi_A^\ell}{v}\bar{\nu_L}\ell_R H^+ + \text{H.c.}\right\}$$

charged Higgs

4 types with softly broken Z_2 symmetry

mixing factors:

	ξ_h^u	ξ_h^d	ξ_h^ℓ	ξ_H^u	ξ_H^d	ξ_H^ℓ	ξ_A^u	ξ_A^d	ξ_A^ℓ
Type-I	c_α/s_β	c_α/s_β	c_α/s_β	s_α/s_β	s_α/s_β	s_α/s_β	$\cot\beta$	$-\cot\beta$	$-\cot\beta$
Type-II	c_α/s_β	$-s_\alpha/c_\beta$	$-s_\alpha/c_\beta$	s_α/s_β	c_α/c_β	c_α/c_β	$\cot\beta$	$\tan\beta$	$\tan\beta$
Type-X	c_α/s_β	c_α/s_β	$-s_\alpha/c_\beta$	s_α/s_β	s_α/s_β	c_α/c_β	$\cot\beta$	$-\cot\beta$	$\tan\beta$
Type-Y	c_α/s_β	$-s_\alpha/c_\beta$	c_α/s_β	s_α/s_β	c_α/c_β	s_α/s_β	$\cot\beta$	$\tan\beta$	$-\cot\beta$

fermionphobic

MSSM

leptonphobic (small tanb)

completeness

leptonphilic (large tanb)

c_α ~cos

s_β ~sin

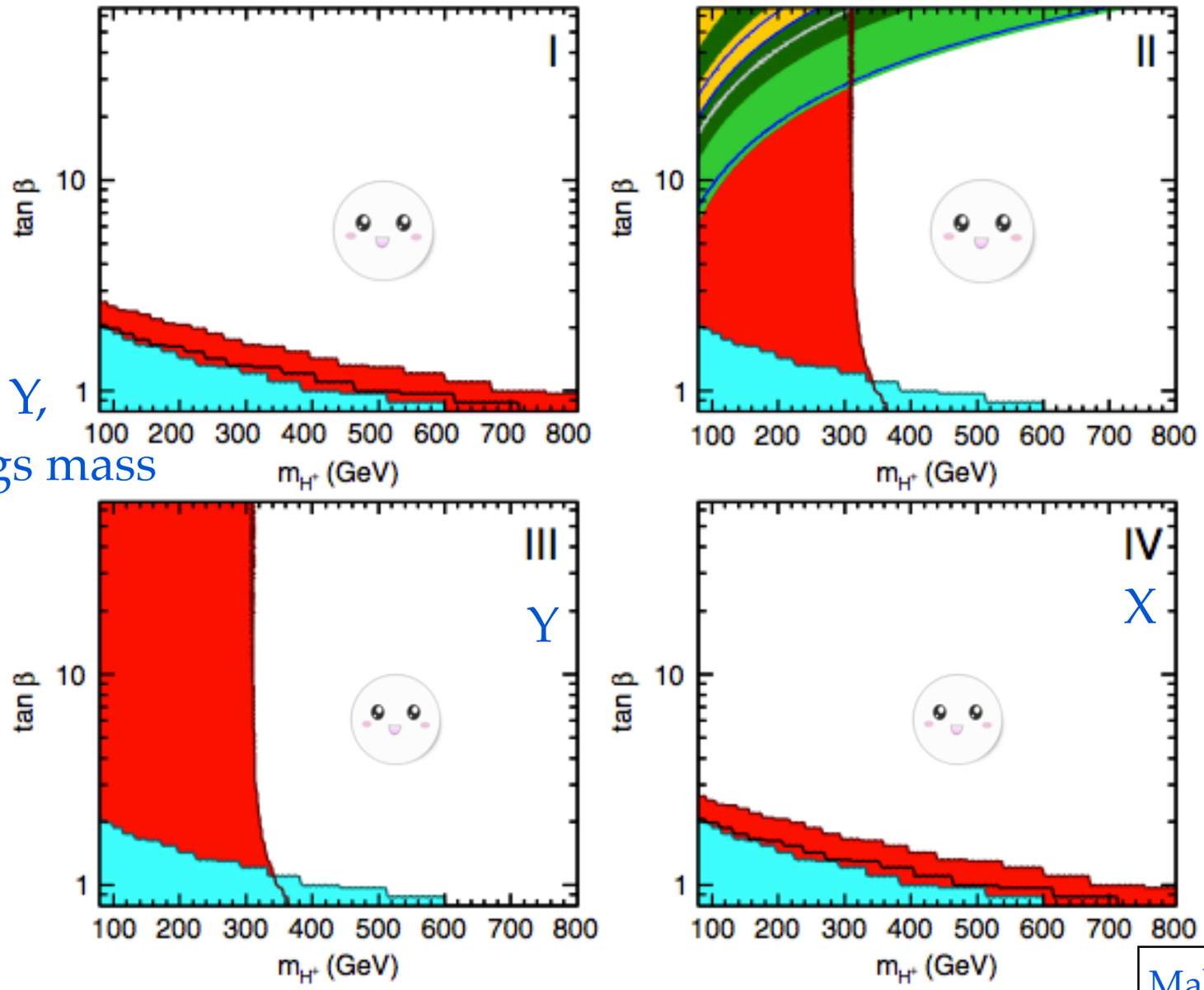
$$v = \sqrt{v_1^2 + v_2^2} \simeq 246\ \text{GeV} \qquad \tan\beta = v_2/v_1$$

when $\sin(\beta-\alpha) = 1.$ h is SM Higgs

Aoki et.al (2009)

Flavor constaints on charged Higgs boson

In type II and type Y,
still room for large Higgs mass



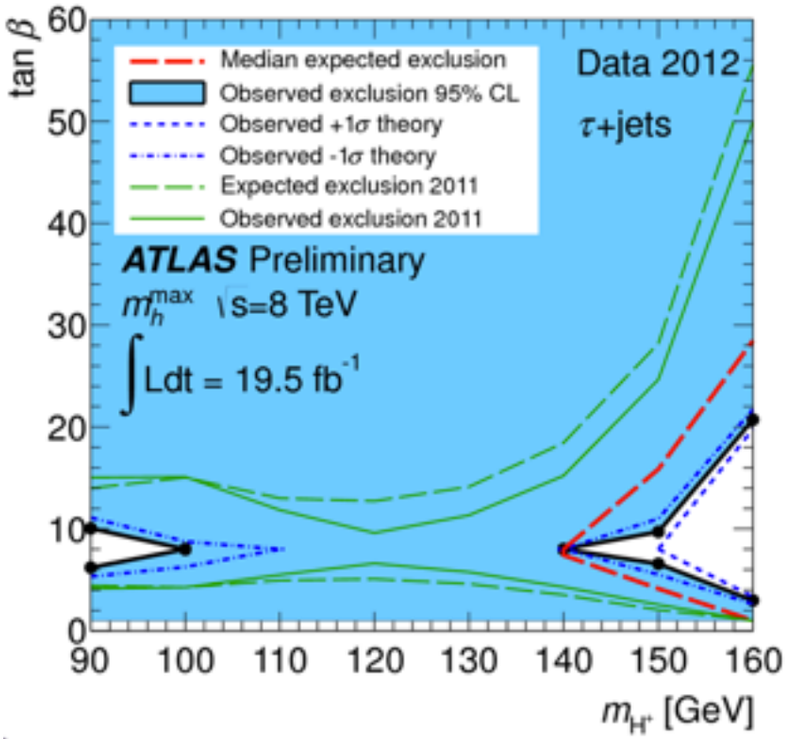
most constrained

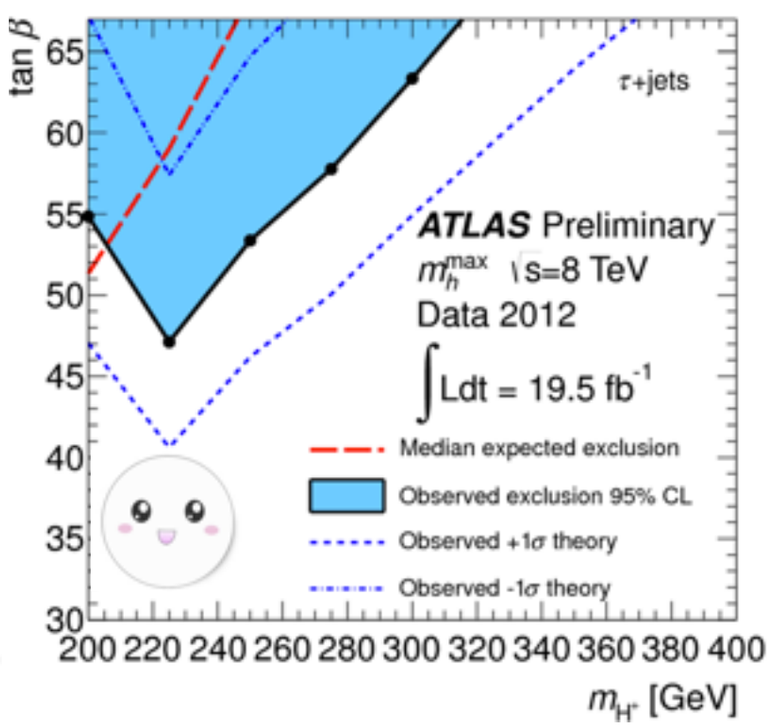
Mahmoudi & Stal (2010)

FIG. 10 (color online). Excluded regions of the $(m_{H^+}, \tan\beta)$ parameter space for Z_2-symmetric 2HDM types. The color coding is as follows: BR$(B \to X_s\gamma)$ (red), Δ_{0-} (black contour), ΔM_{B_d} (cyan), $B_u \to \tau\nu_\tau$ (blue), $B \to D\tau\nu_\tau$ (yellow), $K \to \mu\nu_\mu$ (gray contour), $D_s \to \tau\nu_\tau$ (light green), and $D_s \to \mu\nu_\mu$ (dark green). The white region is not excluded by any of these constraints.

Collider constaints on Higgs bosons

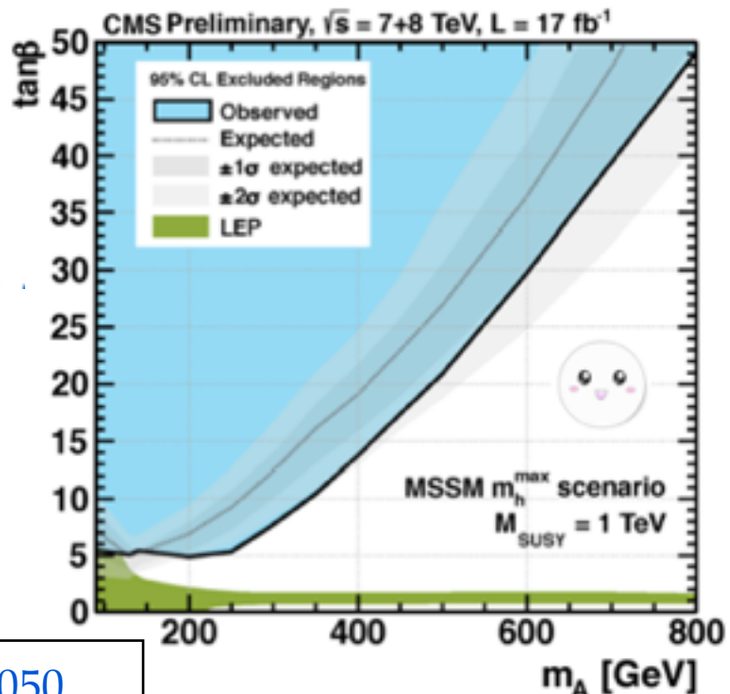
MSSM type





ATLAS-CONF-2013-090

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



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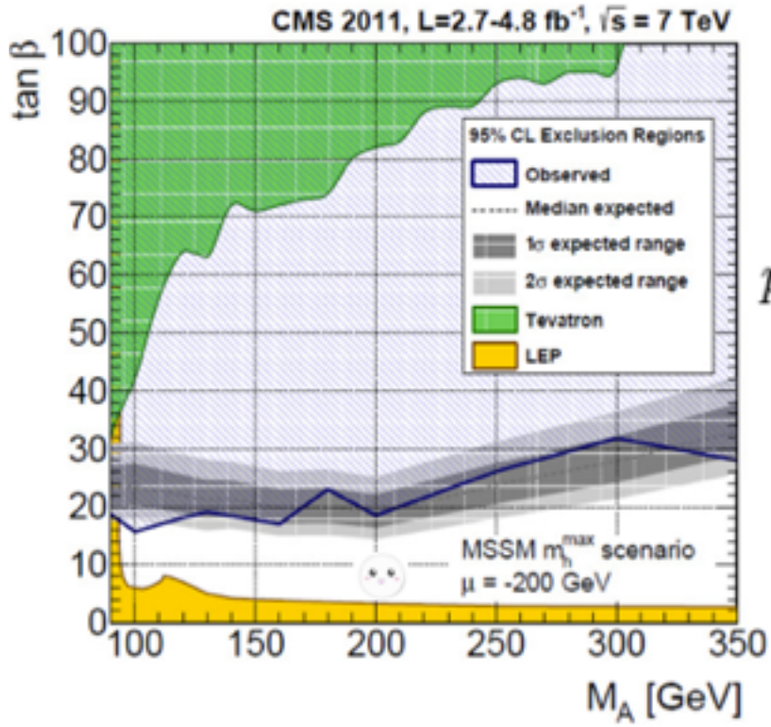


$pp \to bH/A; H/A \to b\bar{b}$

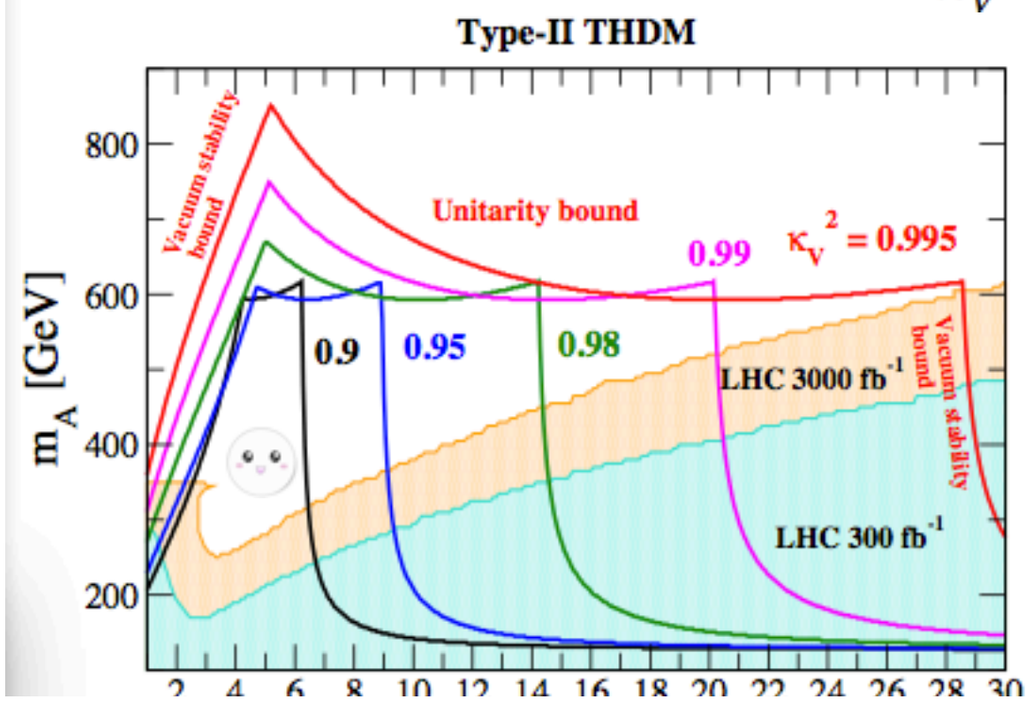
HIG-12-033

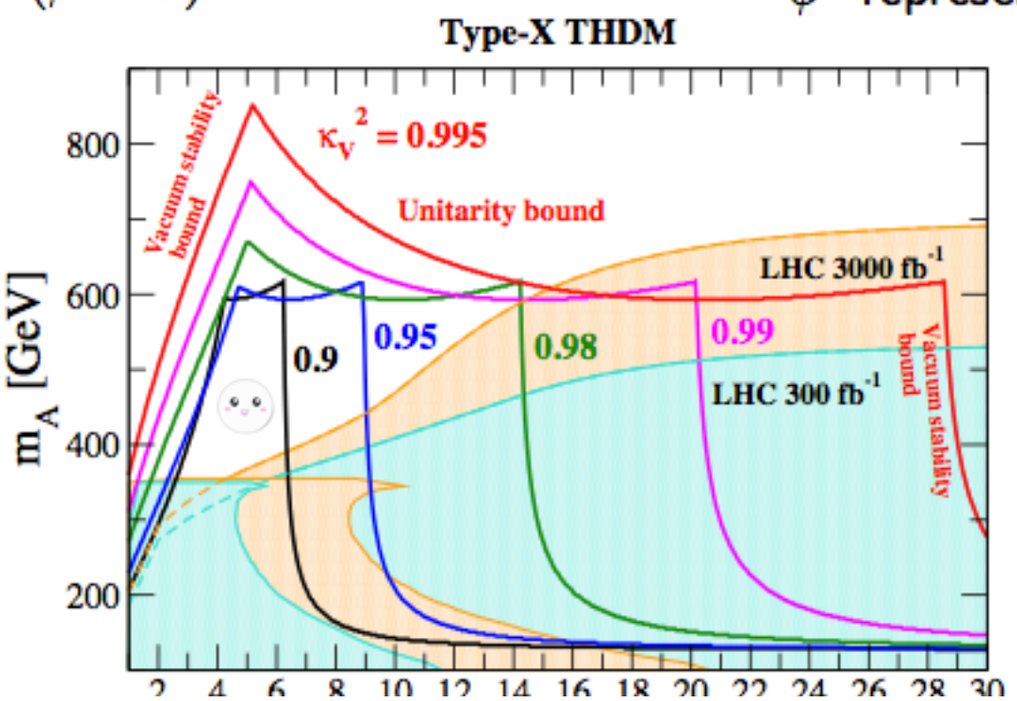
Search for extra Higgs bosons at ILC after LHC

LHC v.s. ILC

$$gg \to \phi^0 \to \tau^+\tau^-,$$
$$gg \to b\bar{b}\phi^0 \to b\bar{b}\tau^+\tau^-,$$
$$q\bar{q} \to \tau^+\tau^-\phi^0 \to \tau^+\tau^-\tau^+\tau^-,$$
ϕ^0 represents H or A

$$\kappa_V^2 = \sin^2(\beta - \alpha)$$





14TeV
LHC

Figure 1.20. Regions below the curves are allowed by the constraints from unitarity and vacuum stability on the $\tan\beta$-m_A plane for each fixed value of κ_V^2 for $M = m_A = m_H = m_{H^+}$ in the Type II and Type X 2HDMs. Expected excluded parameter spaces are also shown by blue (orange) shaded regions from the gluon fusion production and associate production of A and H with bottom quarks and tau leptons at the LHC with the collision energy to be 14 TeV with the integrated luminosity to be 300 fb^{-1} (3000 fb^{-1}).

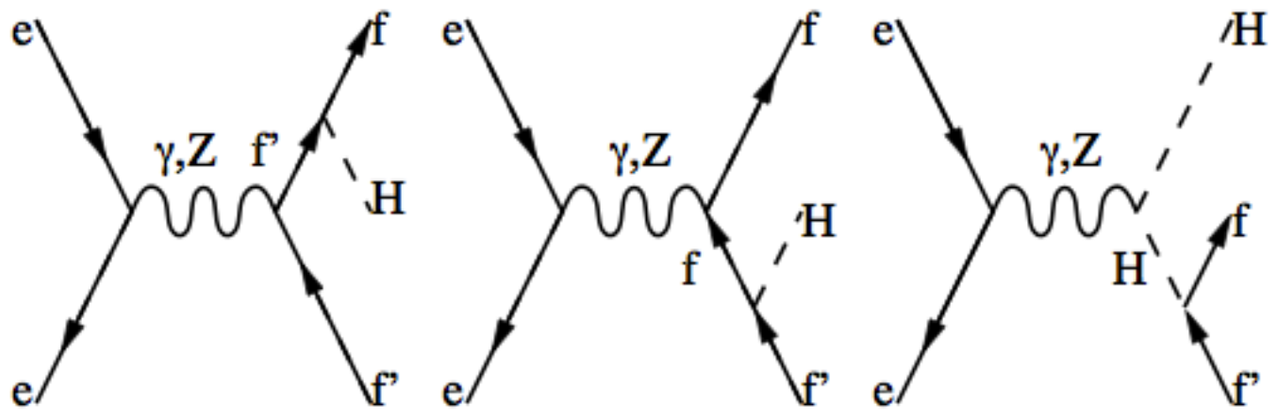
ILC has advantages in small tanbeta region 500 GeV (pair)
single production process contribute for larger mass region

Asner et.al (1310.0763)

Higgs Production process at ILC

$e^-e^+ \to \tau^-\bar{\nu}_\tau H^+, \tau^+\nu_\tau H^-$
$e^-e^+ \to \bar{t}bH^+, t\bar{b}H^-$

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



type II 2HDM study : Kanemura et.al, (2001), Moretti(2002)

thorough study on Higgs production with all types of Yukawa interactions at LO

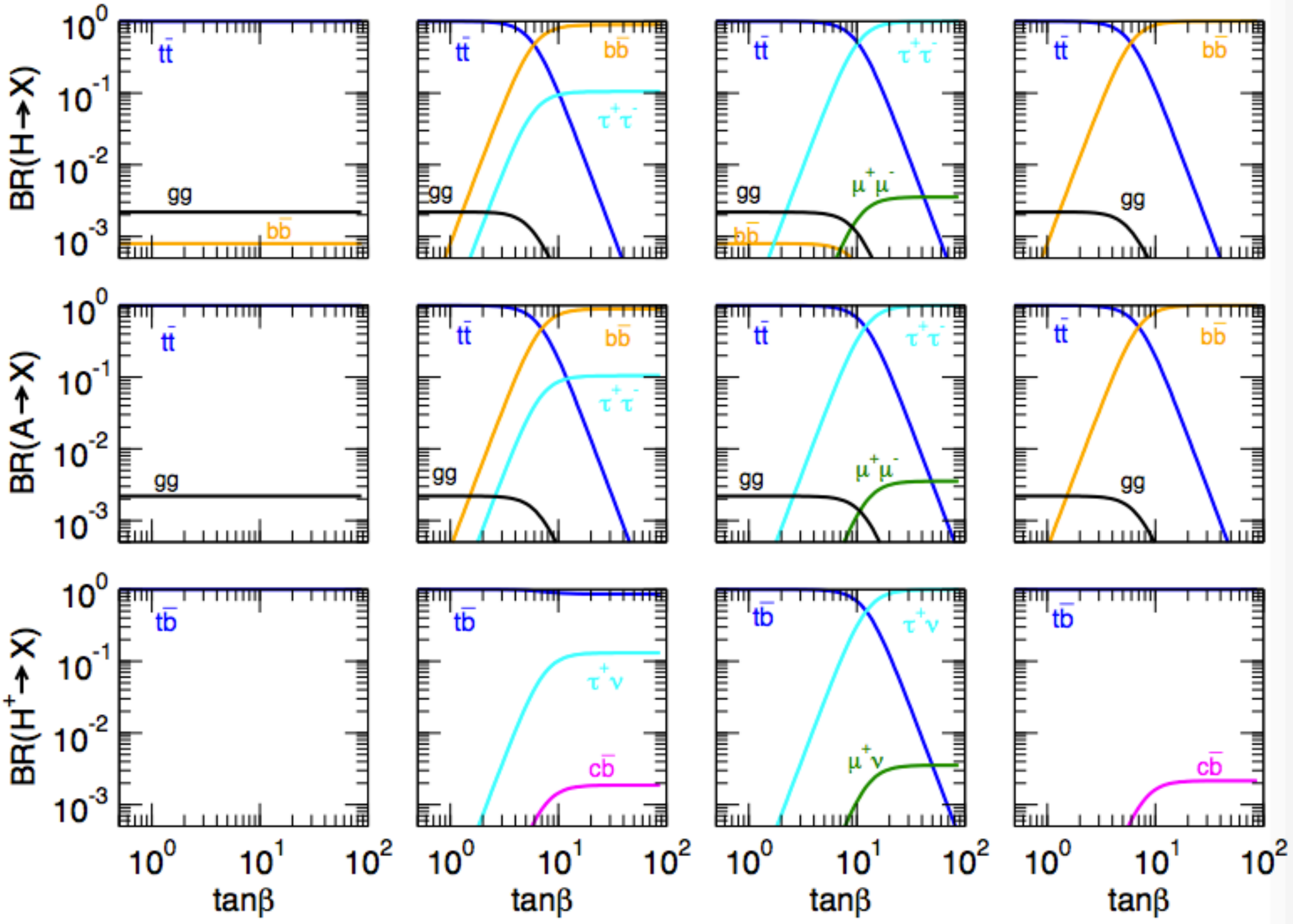
Search for extra Higgs bosons at ILC after LHC

Higgs decay branching ratio

500 GeV Higgs

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

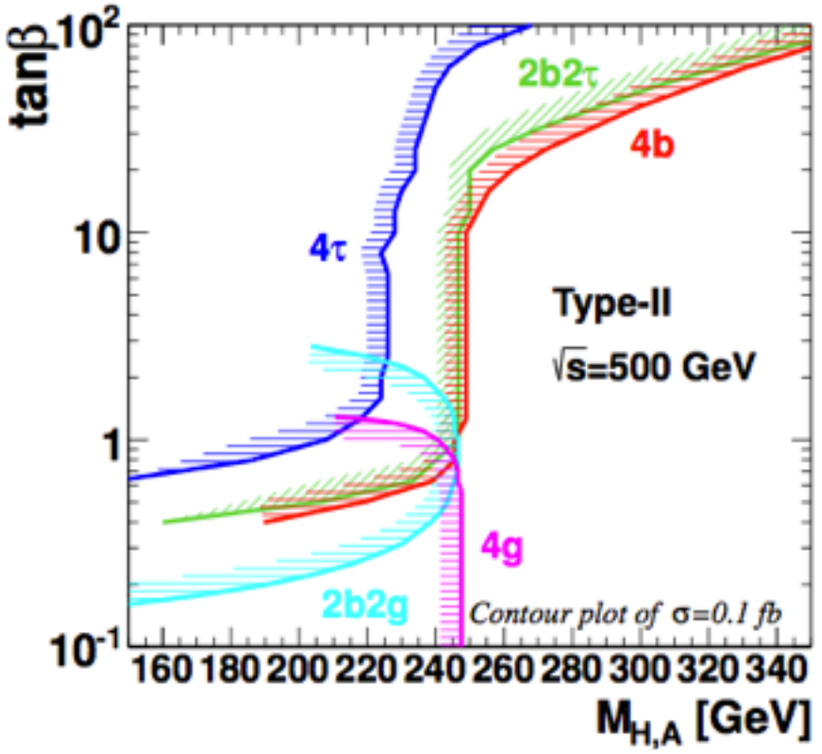
go beyond the threshold of pair production and we can study the single production with different decay channels

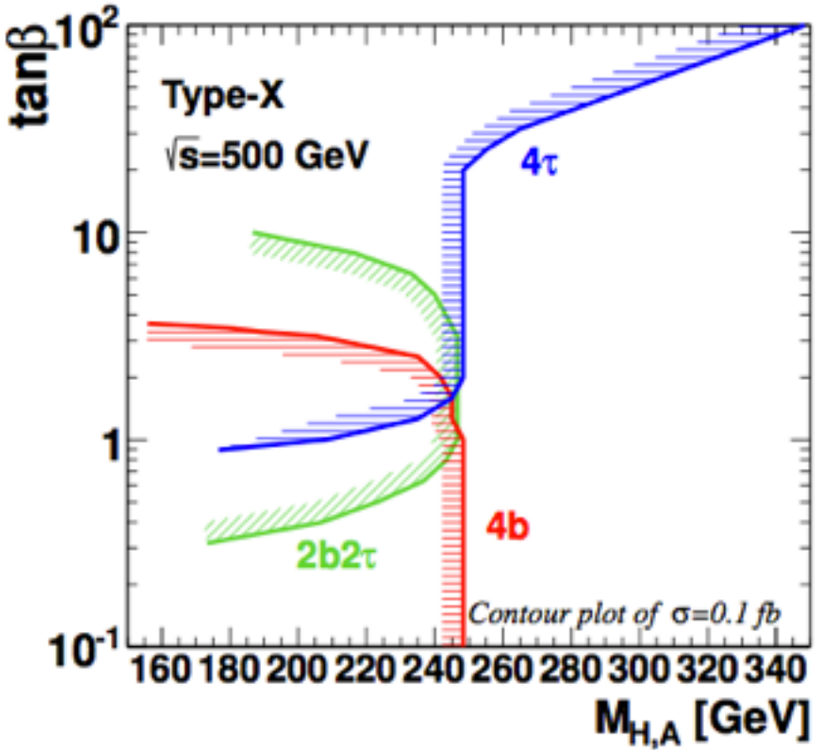


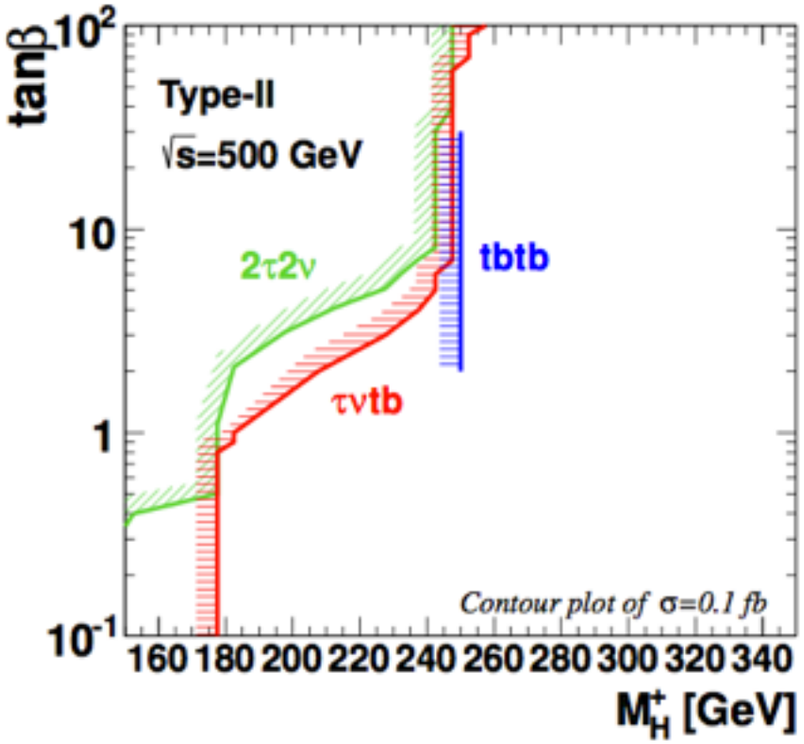
Search for extra Higgs bosons at ILC after LHC

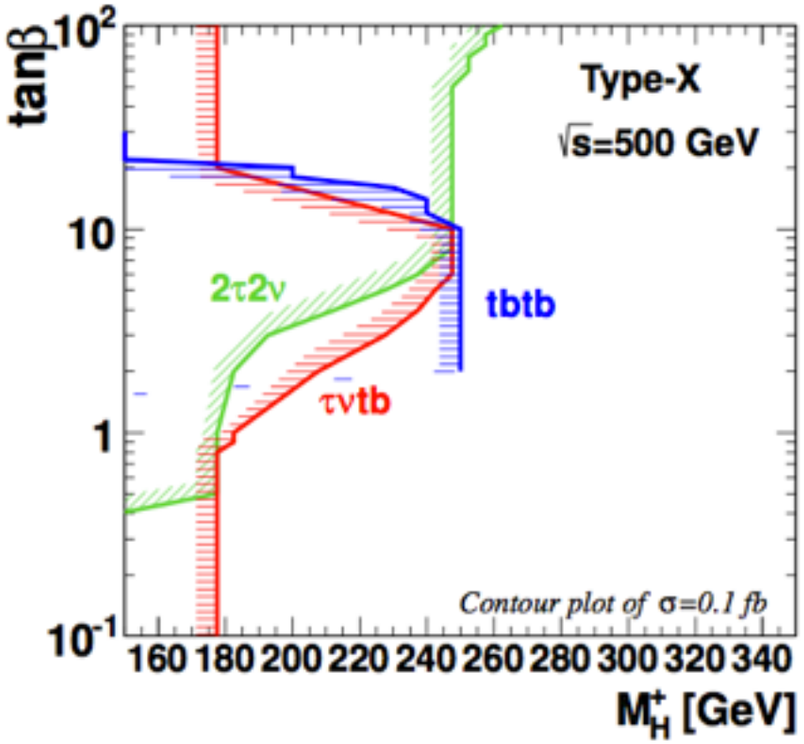
contour plot for cross section 0.1fb

500GeV

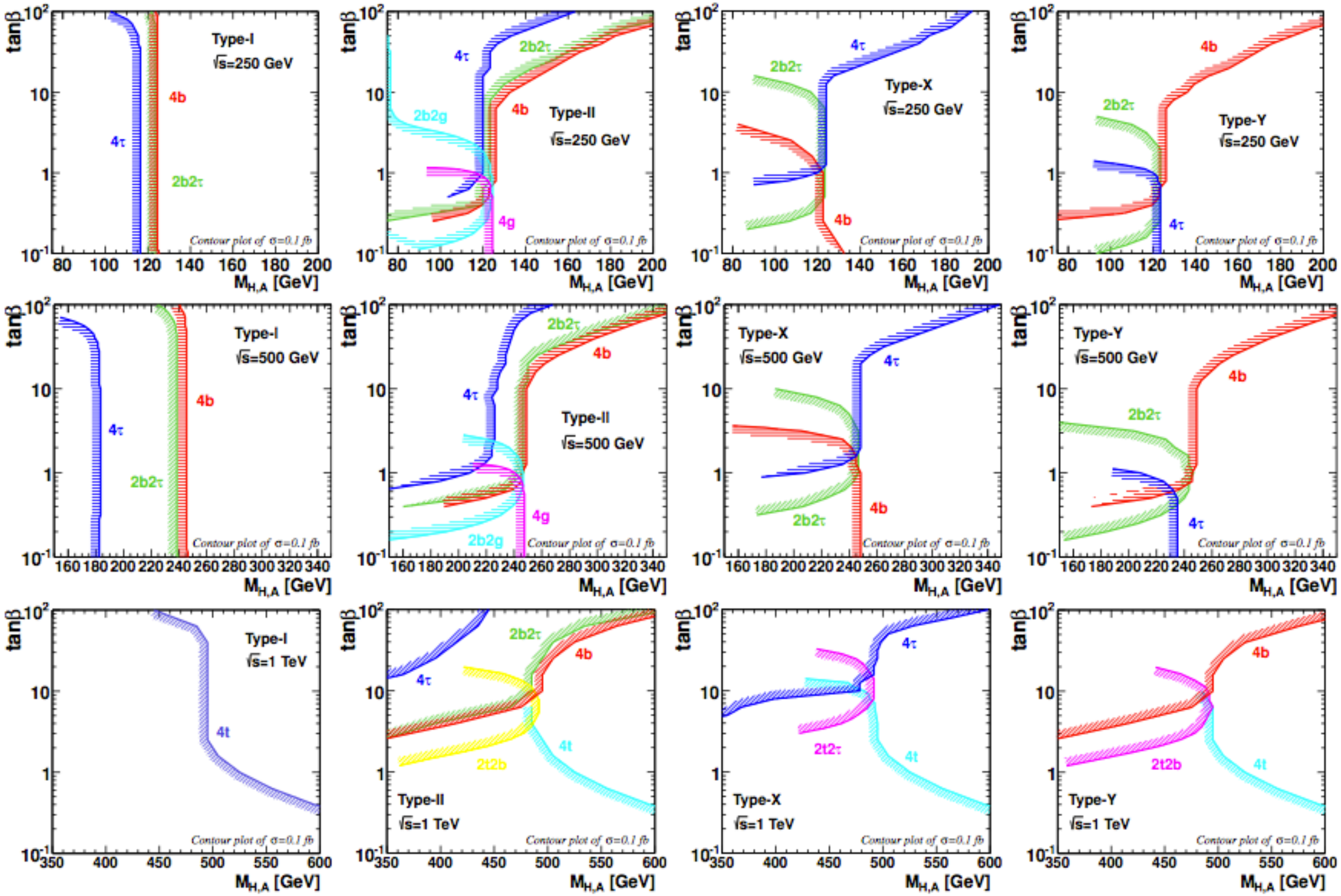








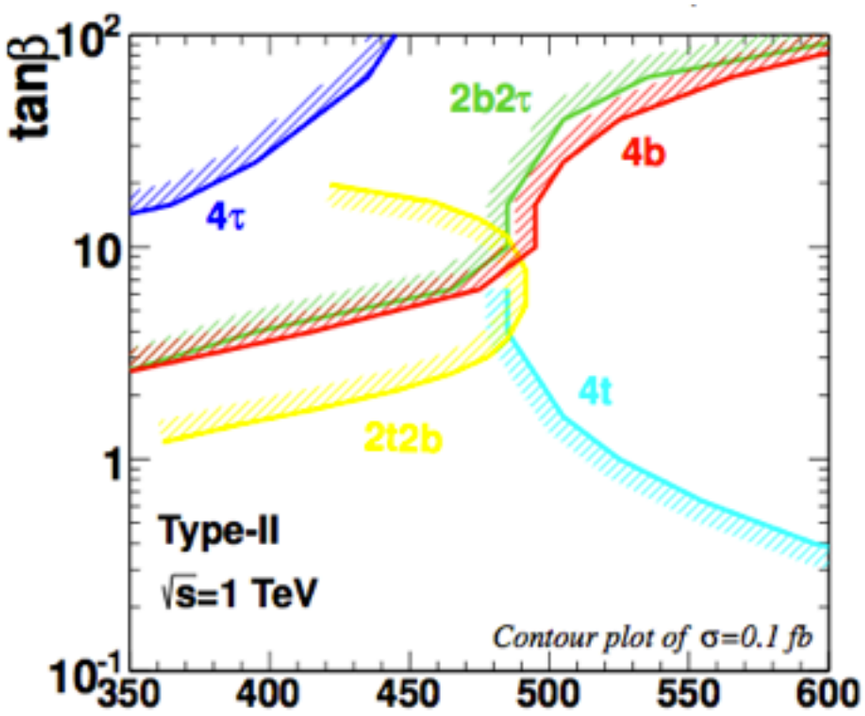
Production of extra Higgs bosons at the International Linear Collider

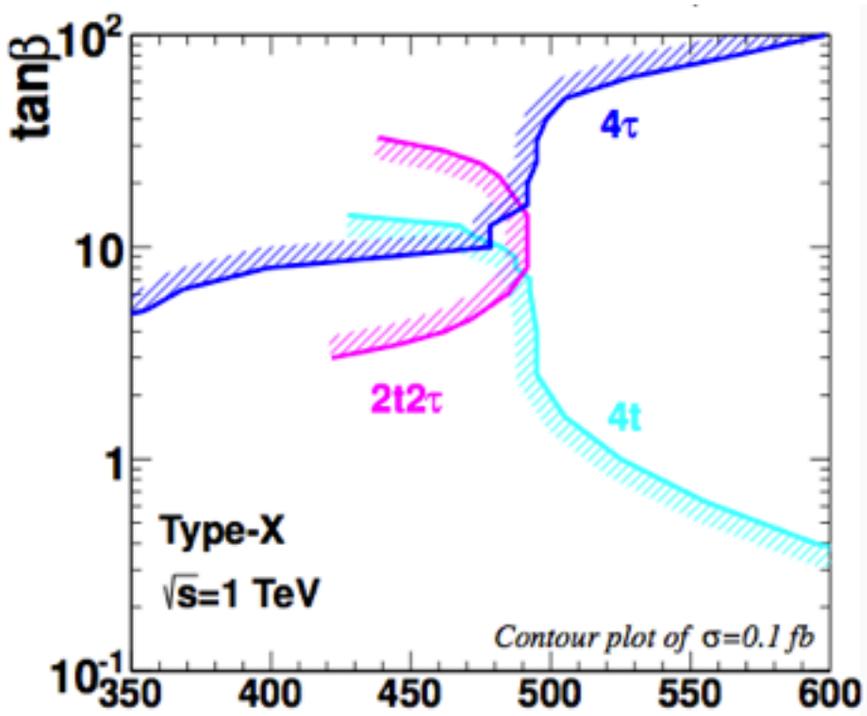


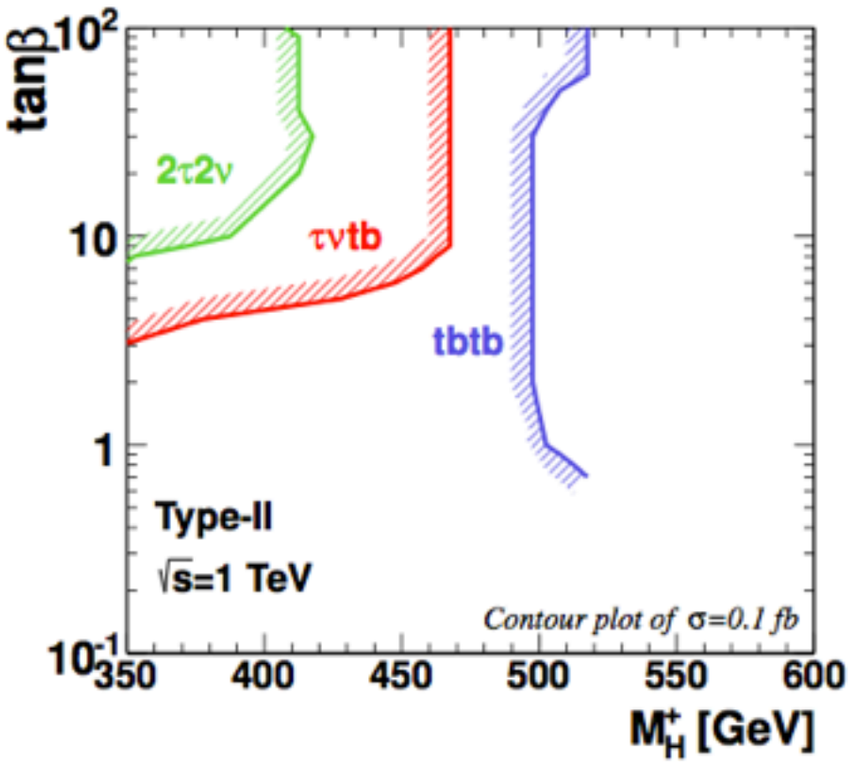
sensitive to different types

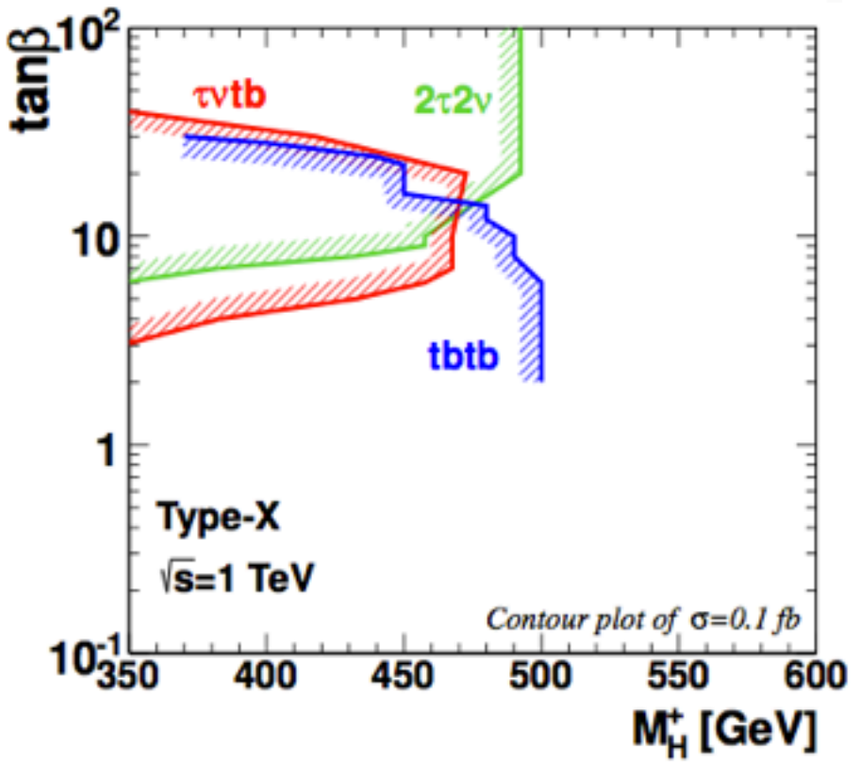
Search for extra Higgs bosons at ILC after LHC

0.1fb contour plot @1TeV ILC







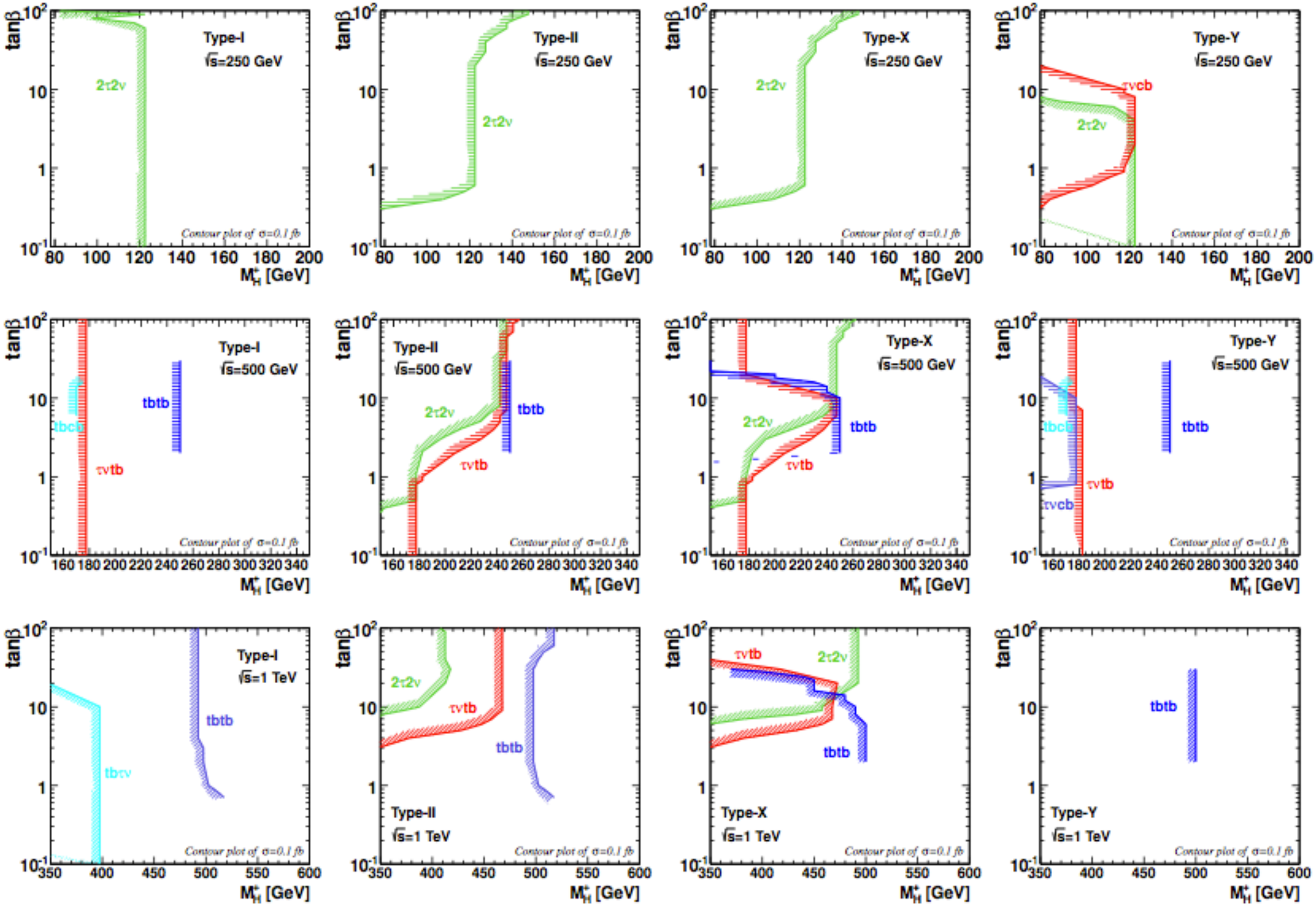


1TeV

4t/tbtb discovery channel

tanb <10 larger mH

Search for extra Higgs bosons at ILC after LHC



SM background

Signature	$\sqrt{s} = 250$ GeV	$\sqrt{s} = 500$ GeV	$\sqrt{s} = 1$ TeV
4τ	2.1 fb/	0.7 fb/	0.2 fb/
$2\tau 2b$	23 fb/	7.2 fb/	1.8 fb/
$4b$	18 fb/	7.2 fb/	2.9 fb/
$2t2b$		1.7 fb/	5.1 fb/
$2t2\tau$		0.07 fb/	0.26 fb/
$4t$ (QCD)			1.4×10^{-3} fb/
$4t$ (QED)			7.9×10^{-4} fb/

without kinematic cuts

Summary

- We made a complementary study on Higgs bosons in all types of 2HDMs at ILC and emphasize on the parameter region beyond LHC reach.
- Extra Higgs boson production and decay final states provides discriminative signatures from different types of Yukawa interactions within 2HDM.
- Single Higgs production above mass threshold is included and shows distinct signatures as discovery channel.

Thanks for your attention!