Search for extra Higgs bosons at ILC after LHC

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Based on Shinya Kanemura, Hiroshi Yokoya and YJZ, arXiv: 1404.5835

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

Motivation

Photo: A. Mahmoud
François Englert

Photo: A. Mahmoud
Peter W. Higgs

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

- 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 relatively small tanb region.
- ILC may provide interesting signatures as a complementary machine of LHC

2 Higgs doublet extensions of SM

Related History

- T.D. Lee, *A Theory of Spontaneous T Violation*, Phys. Rev. **D8**, 1226 (1973).

The first motivated 2HDM: an attempt to find a new source of CP-violation.

- S.L. Glashow and S. Weinberg, *Natural Conservation Laws For Neutral Currents*, Phys. Rev. **D15**, 1958 (1977).

To avoid neutral-Higgs-mediated tree-level flavor changing neutral currents (FCNCs), all fermions of a given electric charge can couple to at most one Higgs doublet (in a model with multiple scalar doublets).

- N.G. Deshpande and E. Ma, *Pattern Of Symmetry Breaking With Two Higgs Doublets*, Phys. Rev. **D18**, 2574 (1978).

Parameters of the Higgs potential had to lie in an appropriate region of parameter space to ensure that $U(1)_{\mathrm{EM}}$ is not broken.

- the axion as the CP-odd scalar of a 2HDM [the Peccei-Quinn mechanism].
- the requirement of a second Higgs doublet in the minimal supersymmetric extension of the Standard Model (MSSM).

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:

Gunion & Haber (2003)

hypercharge
Y=1

$$V_{\rm 2HDM} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \right]$$
$$+ \frac{1}{2}\lambda_1 \left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{1}{2}\lambda_2 \left(\Phi_2^\dagger \Phi_2\right)^2 + \lambda_3 \left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) + \lambda_4 \left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right)$$
$$+ \left\{ \frac{1}{2}\lambda_5 \left(\Phi_1^\dagger \Phi_2\right)^2 + \left[\lambda_6 \left(\Phi_1^\dagger \Phi_1\right) + \lambda_7 \left(\Phi_2^\dagger \Phi_2\right)\right] \left(\Phi_1^\dagger \Phi_2\right) + \text{h.c.} \right\}.$$

After SSB: 5 physical Higgs scalar left:

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

General 2HDM structure

different Higgs-fermion interactions

- Type I: one Higgs doublet couples to both up-type and down-type fermions, and the other Higgs doublet does not couple at all to the fermions.(Haber. Kane & Sterling (1979))
- Type II: one doublet couples only to down-type quarks and another doublet couples to the up-type quarks. (Donoghue&Li (1979))
- Type III: all possible Higgs-fermion couplings allowed. (Cheng & Sher (1987))
- Lepton-specific / flipped / neutrino-specific / inert...

Gunion, Haber, Kane & Dawson(2000);
Branco, Ferreira, Lavoura, Rebelo, Sher & Silva (2011)

basic experimental constraints on 2HDM

rho paremter ~1: The experimental value of the rho parameter is quite close to unity

$$\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = \frac{\sum_i \left[T_i(T_i+1) - Y_i^2\right] v_i^2}{\sum_i 2Y_i^2 v_i^2}$$

Y_i : hypercharge
T_i : isospin
v_i : VEV

EW sector of the model would approximately have a global SU(2) symmetry (the custodial symmetry) to guarantee rho=1 at tree level

Custodial SU(2) symmery exists in the kinetic term

- Standard Model
- Models with multi-doublet fields (with singlets)

Flavor changing neutral current (FCNC):

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

2HDM Yukawa interactions

with softly broken Z_2 symmetry

$$\mathcal{L}_{\text{yukawa}}^{\text{THDM}} = -\sum_{f=u,d,\ell} \left(\frac{m_f}{v} \xi_h^f \overline{f} f h + \frac{m_f}{v} \xi_H^f \overline{f} f H - i \frac{m_f}{v} \xi_A^f \overline{f} \gamma_5 f A \right)$$

neutral Higgs

$$- \left\{ \frac{\sqrt{2} V_{ud}}{v} \overline{u} \left(m_u \xi_A^u \mathrm{P}_L + m_d \xi_A^d \mathrm{P}_R \right) d H^+ + \frac{\sqrt{2} m_\ell \xi_A^\ell}{v} \overline{\nu_L} \ell_R H^+ + \mathrm{H.c.} \right\}$$

charged Higgs

	Φ_1	Φ_2	u_R	d_R	ℓ_R	Q_L	L_L
Type-I	+	−	−	−	−	+	+
Type-II	+	−	−	+	+	+	+
Type-X	+	−	−	−	+	+	+
Type-Y	+	−	−	+	−	+	+

mixing factors:

4 types	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

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

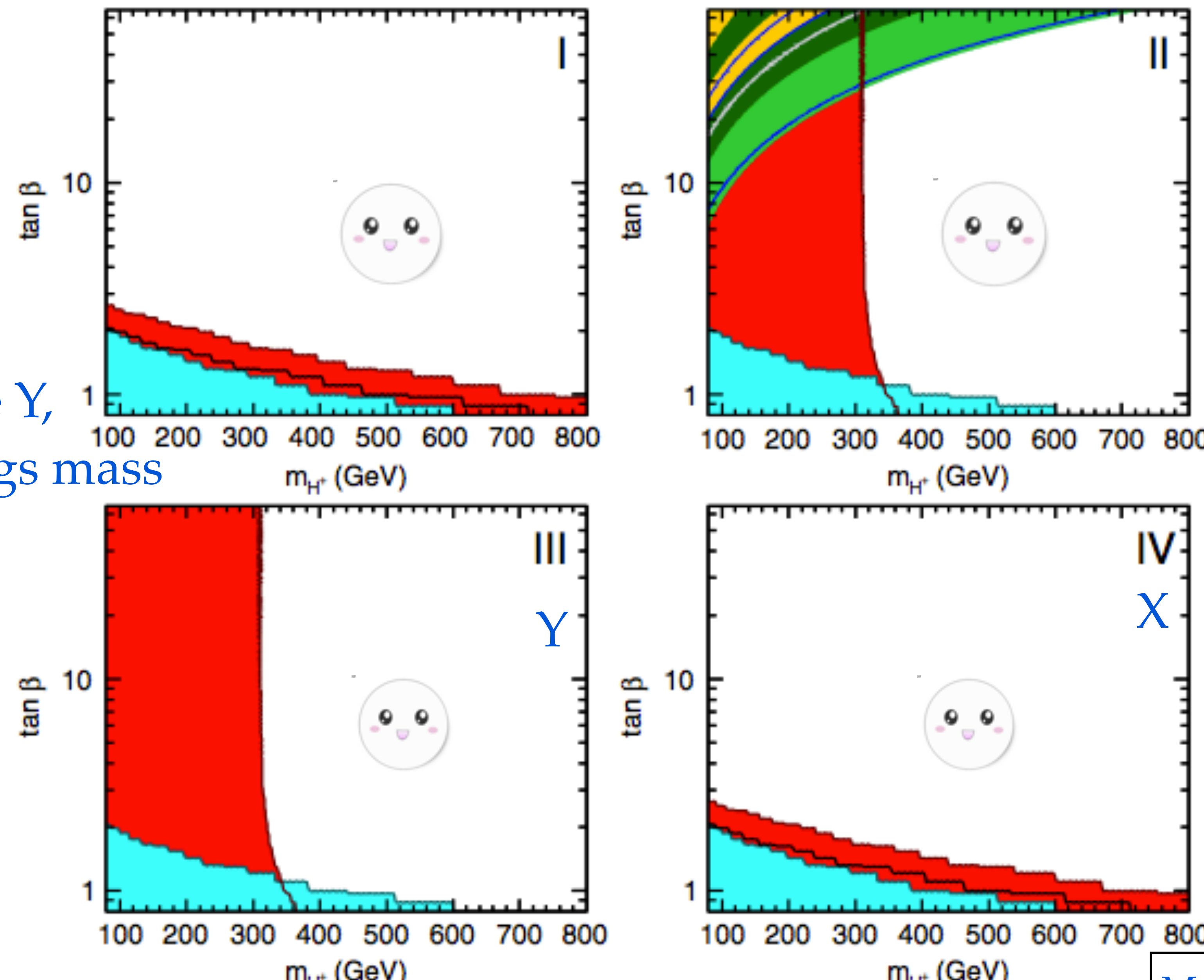
when $\sin(\beta - \alpha) = 1.$ h is SM Higgs

Aoki, Kanemura, Tsumura and Yagyu, 2009

Flavor constaints on charged Higgs boson

most constrained

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



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.

Search for extra Higgs bosons at ILC after LHC

BABAR observes a 3.4 sigma deviation in B-> D-tau-nu/D*-tau-nu.
However, this data is inconsistent with the type II 2HDM at the 99.8% C.L.

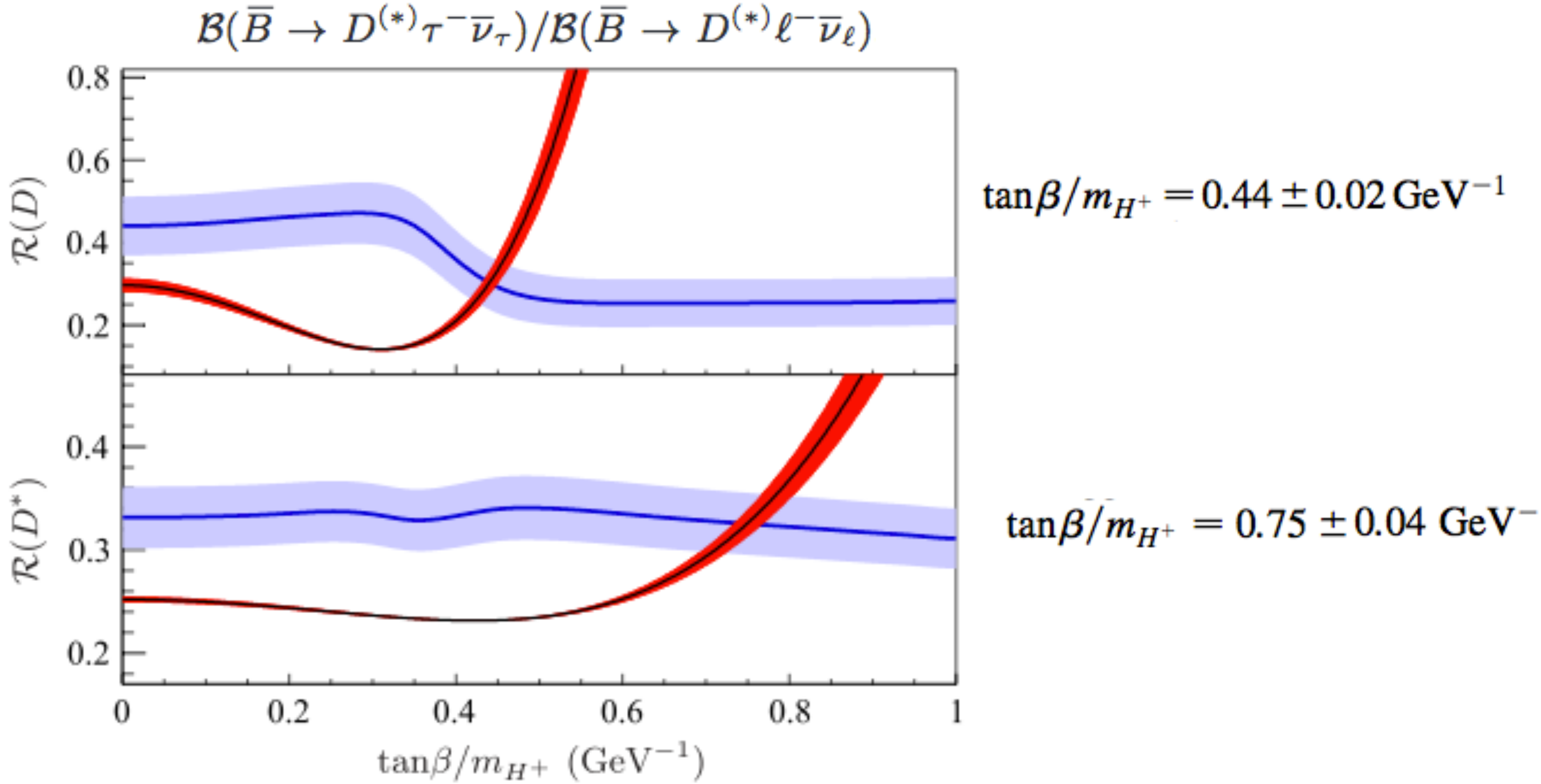


FIG. 2 (color online). Comparison of the results of this analysis (light gray, blue) with predictions that include a charged Higgs boson of type II 2HDM (dark gray, red). The SM corresponds to $\tan\beta/m_{H^+} = 0$.

J.P.Lees et al. [BaBar collaboration], Evidence for an excess of B -> D(*)-tau-nu decays, PRL.109,101802

Extra Higgs boson production at the LHC

Neutral Higgs bosons production at the LHC

$$\bullet\ \textbf{H, A:}\quad \left.\begin{array}{l} gg \to H/A \\ gg(q\bar{q}) \to Q\bar{Q}H/A \end{array}\right\} H/A \to b\bar{b} \text{ or } \tau^+\tau^-$$

Charged Higgs bosons production at the LHC

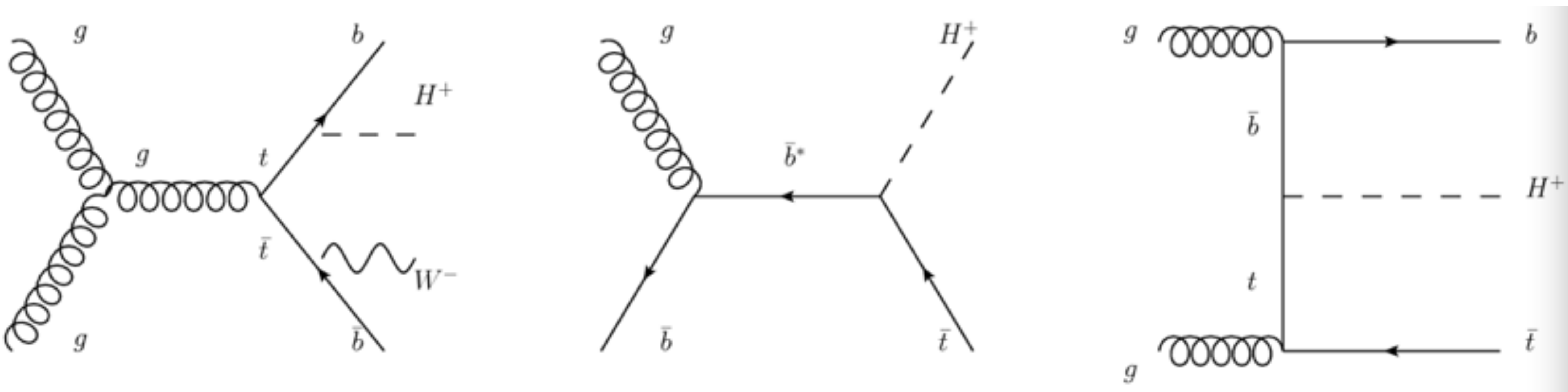
$$M \le m_t - m_b \qquad gg(q\bar{q}) \to H^- t\bar{b}$$

$$\boxed{M > m_t + m_b \qquad gb \to tH^-}$$

Kunszt et.al 1992

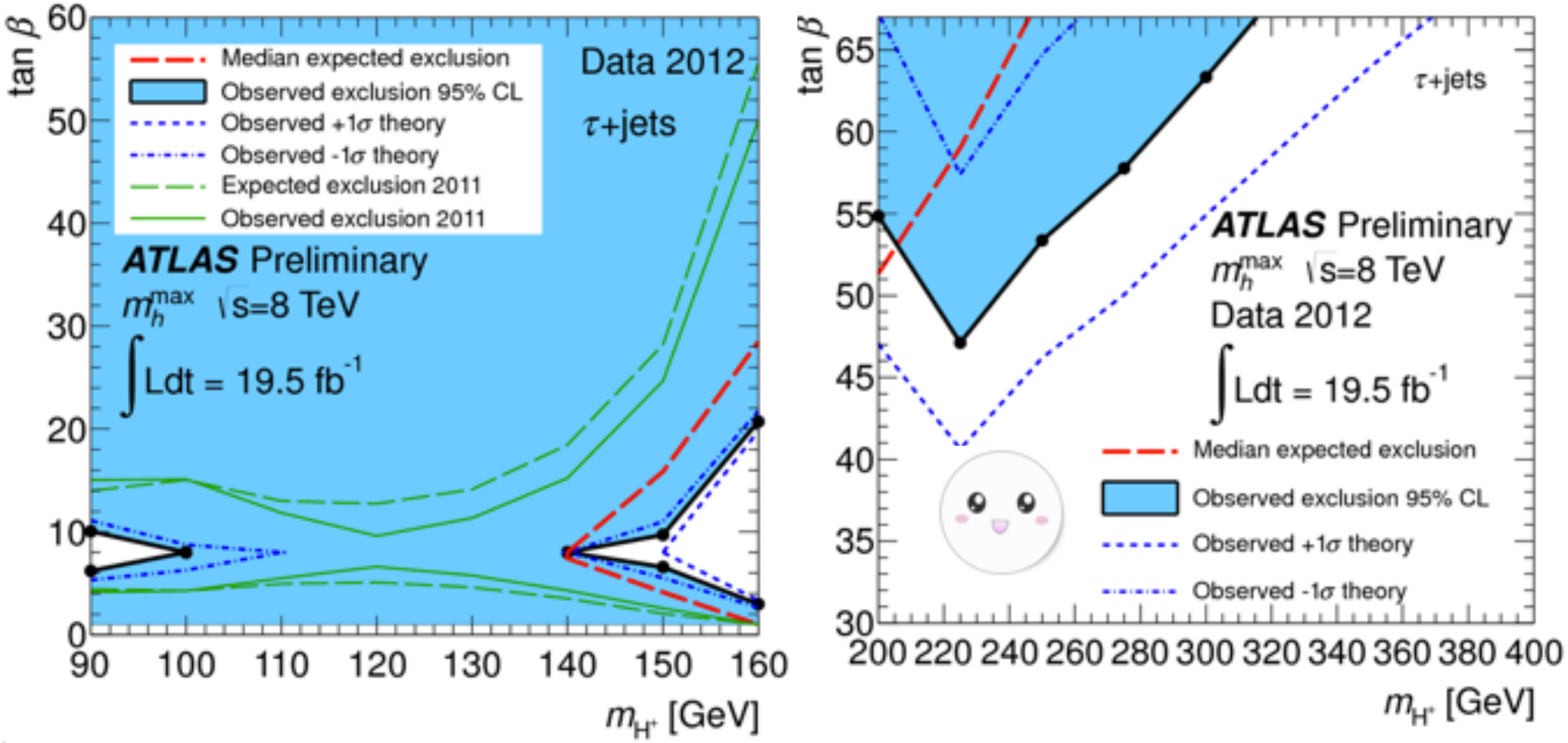
Gunion et.al(1987), Barnett et.al (1988), Barger et.al (1994), Miller et.al (2000)...

Collider constraints on charged Higgs boson



H>tau-nu

tau jets final states



ATLAS-CONF-2013-090

CMS: light Higgs region

Collider constraints on neutral Higgs boson

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

type-II

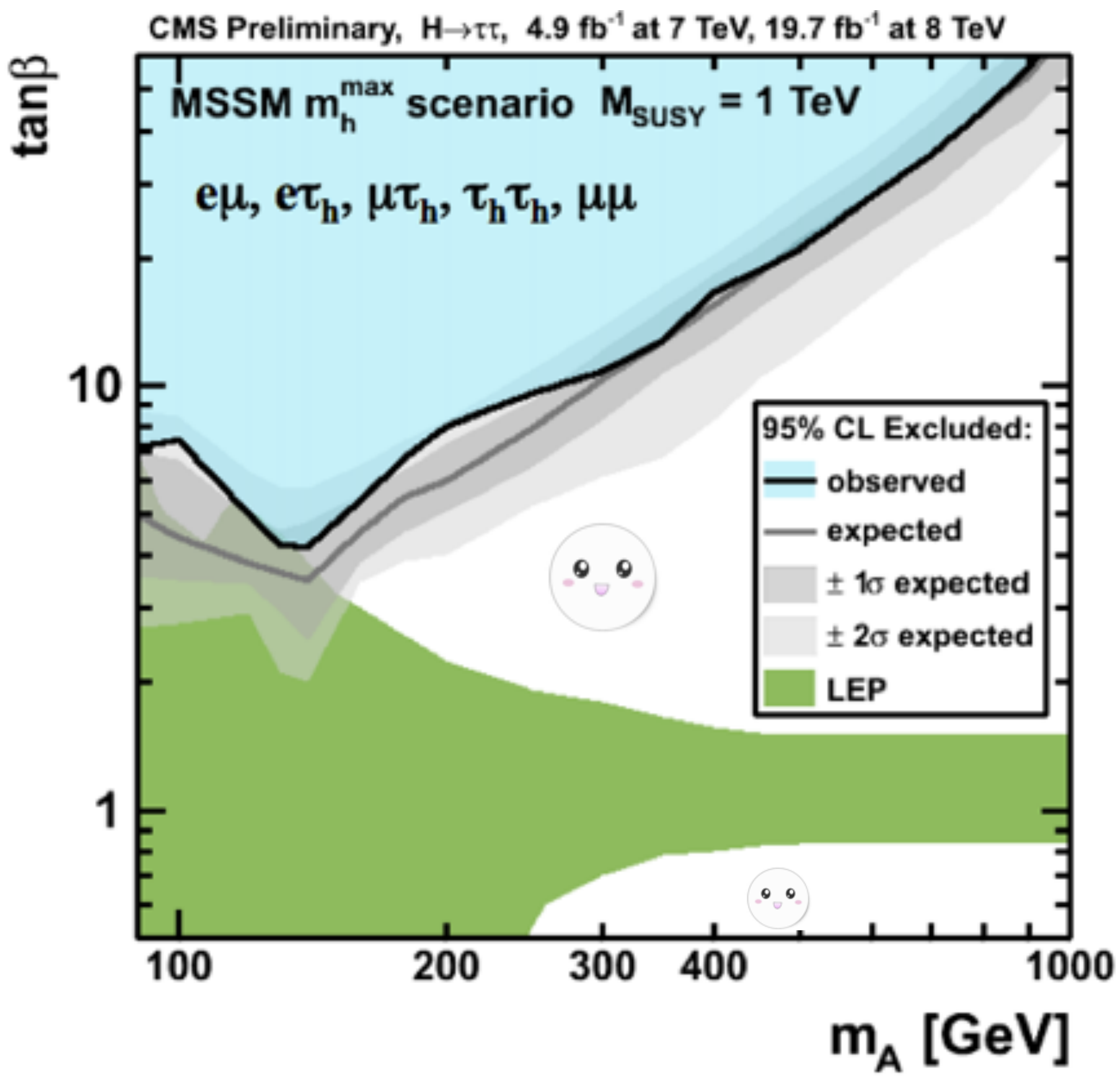
gg(t/b) --> H/A

	Φ_1	Φ_2	u_R	d_R	ℓ_R	Q_L	L_L
Type-I	+	−	−	−	−	+	+
Type-II	+	−	−	+	+	+	+
Type-X	+	−	−	−	+	+	+
Type-Y	+	−	−	+	−	+	+

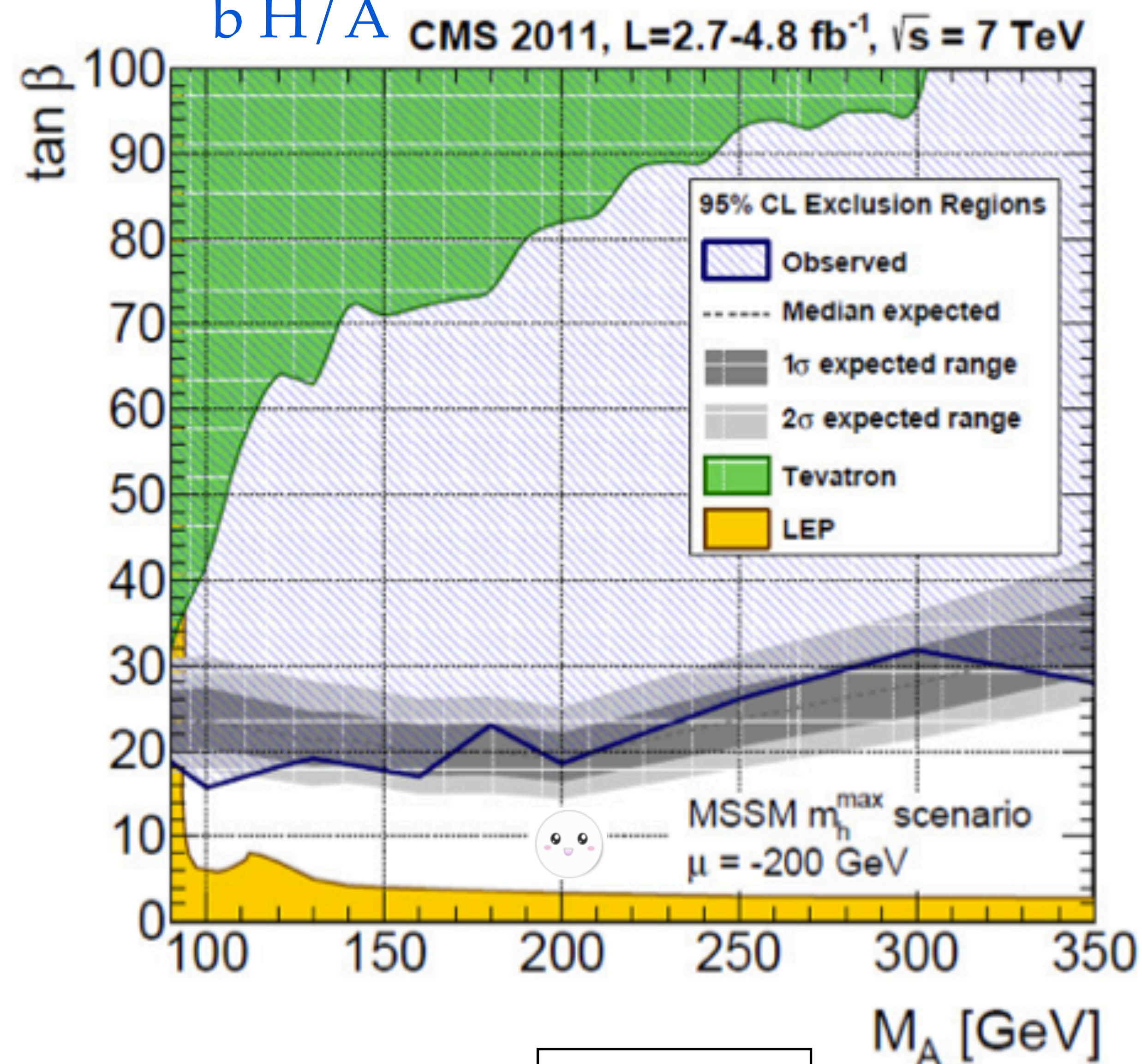
$$pp \to bH/A;\, H/A \to b\bar{b}$$

bg fusion--> b H/A

type-II, Y



HIG-13-021



HIG-12-033

No constraint so far on Type I and Type X

Higgs Decay

partial decay width:

$$\Gamma(\varphi \to q\bar{q}) = N_C \frac{G_F m_\varphi m_q^2}{4\sqrt{2}\pi} \xi_\varphi^{q\,2} \times \begin{cases} \beta_q^3 \text{ for } \varphi = h, H \\ \beta_q \text{ for } \varphi = A \end{cases},$$

$$\Gamma(\varphi \to \ell^+\ell^-) = \frac{G_F m_\varphi m_\ell^2}{4\sqrt{2}\pi} \xi_\varphi^{\ell\,2} \times \begin{cases} \beta_\ell^3 \text{ for } \varphi = h, H \\ \beta_\ell \text{ for } \varphi = A \end{cases},$$

$$\Gamma(H^+ \to u\bar{d}) = N_C \frac{G_F m_{H^\pm} |V_{ud}|^2}{4\sqrt{2}\pi} \beta_{ud} \left\{ \left(m_u^2 \xi_A^{u\,2} + m_d^2 \xi_A^{d\,2} \right) \left(1 - \frac{m_u^2 + m_d^2}{m_{H^\pm}^2} \right) - \frac{4 m_u^2 m_d^2 \xi_A^u \xi_A^d}{m_{H^\pm}^2} \right\},$$

$$\Gamma(H^+ \to \ell^+\nu) = \frac{G_F m_{H^\pm} m_\ell^2}{4\sqrt{2}\pi} \xi_A^{\ell\,2} \left(1 - \frac{m_\ell^2}{m_{H^\pm}^2} \right)^2,$$

$$\lambda(x, y) = 1 + x^2 + y^2 - 2x - 2y - 2xy,$$

$$q = u, d, s, c, t, b;\ \ell = e, \mu, \tau;$$

$$\beta_X = \lambda^{1/2}\left(\frac{m_X^2}{m_\varphi^2}, \frac{m_X^2}{m_\varphi^2} \right) = \sqrt{1 - \frac{4 m_X^2}{m_\varphi^2}},$$

$$\beta_{XY} = \lambda^{1/2}\left(\frac{m_X^2}{m_\varphi^2}, \frac{m_Y^2}{m_\varphi^2} \right).$$

Nc=3 is color factor; Vud: KM matrix

Higgs decay

partial decay width:

$$\Gamma(\varphi \to gg) = \frac{G_F \alpha_S^2 m_\varphi^3}{64\sqrt{2}\pi^3} \left| \sum_{f=q} I_f^\varphi(m_f, 1) \right|^2$$

$$\Gamma(\varphi \to \gamma\gamma) = \frac{G_F \alpha_{\rm EM}^2 m_\varphi^3}{128\sqrt{2}\pi^3} \left| \sum_f Q_f^2 I_f^\varphi(m_f, N_C) + I_W^\varphi + I_{H^\pm}^\varphi \right|^2$$

where fermionic loop functions are given by

$$I_f^\varphi(m_f, N_C) = \xi_\varphi^f \times \begin{cases} -N_C \frac{4m_f^2}{m_\varphi^2} \left[2 - \beta_f^2 m_\varphi^2 C_0(0, 0, m_\varphi^2, m_f^2, m_f^2, m_f^2)\right] & \text{for } \varphi = h, H \\ +4N_C m_f^2 C_0(0, 0, m_\varphi^2, m_f^2, m_f^2, m_f^2) & \text{for } \varphi = A \end{cases}$$

Passarino-Veltman functions:

$$C_0(0, 0, m_\varphi^2, m^2, m^2, m^2) = \frac{-2}{m_\varphi^2} f\left(\frac{4m^2}{m_\varphi^2}\right)$$

$$f(x) = \begin{cases} \left[\arcsin\left(\sqrt{1/x}\right)\right]^2 & \text{for } x \geq 1 \\ -\frac{1}{4}\left[\ln\left(\frac{1+\sqrt{1-x}}{1-\sqrt{1-x}}\right) - i\pi\right]^2 & \text{for } x < 1 \end{cases}$$

Aoki, Kanemura, Tsumura and Yagyu, 2009

Gunion, Haber, Kane and Dawson , 1990

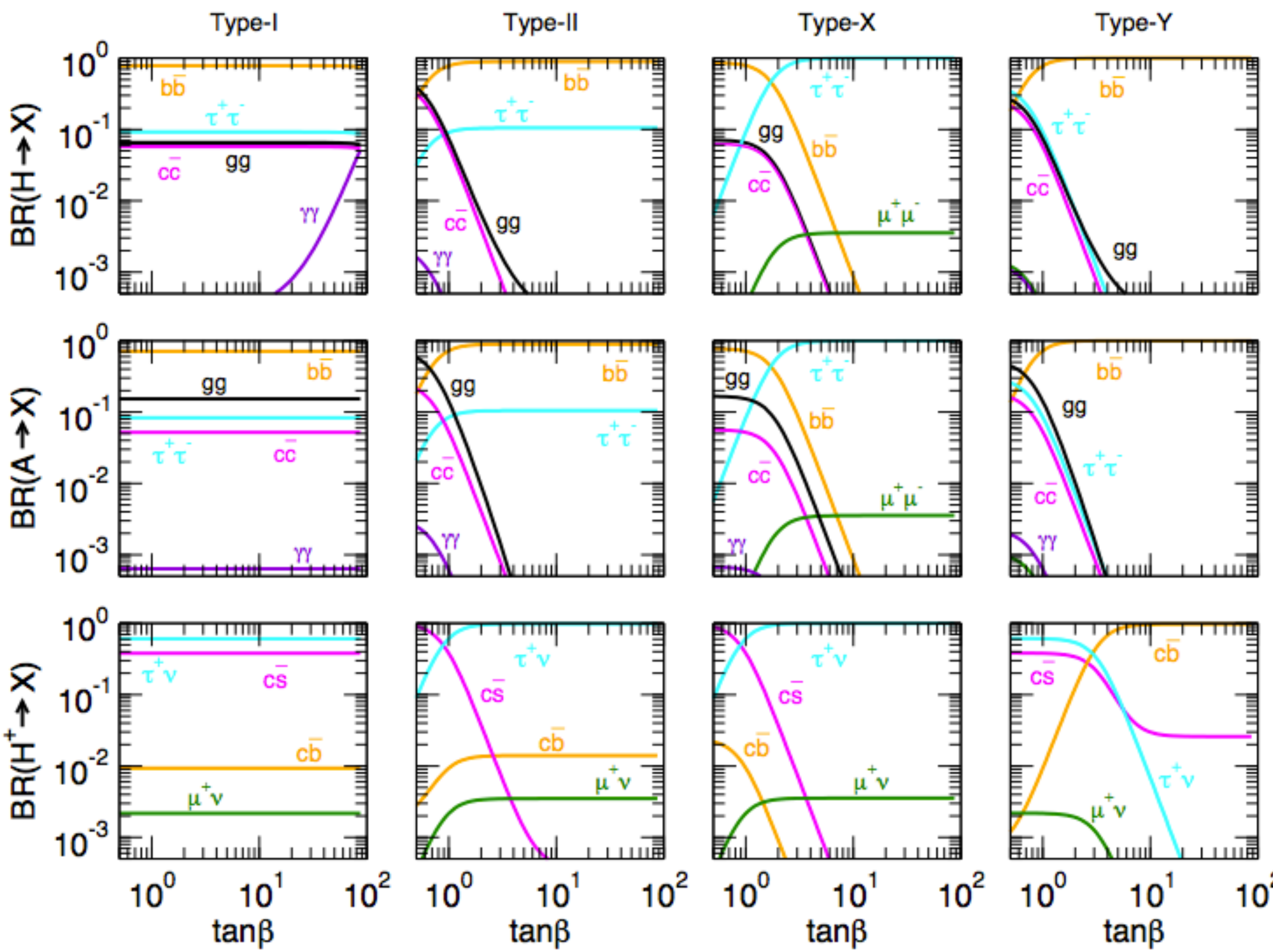
Djouadi, Phys. Rept. 2008

Higgs decay branching ratio

125 GeV Higgs
SM-like limit

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

$\sin(\beta - \alpha) = 1$



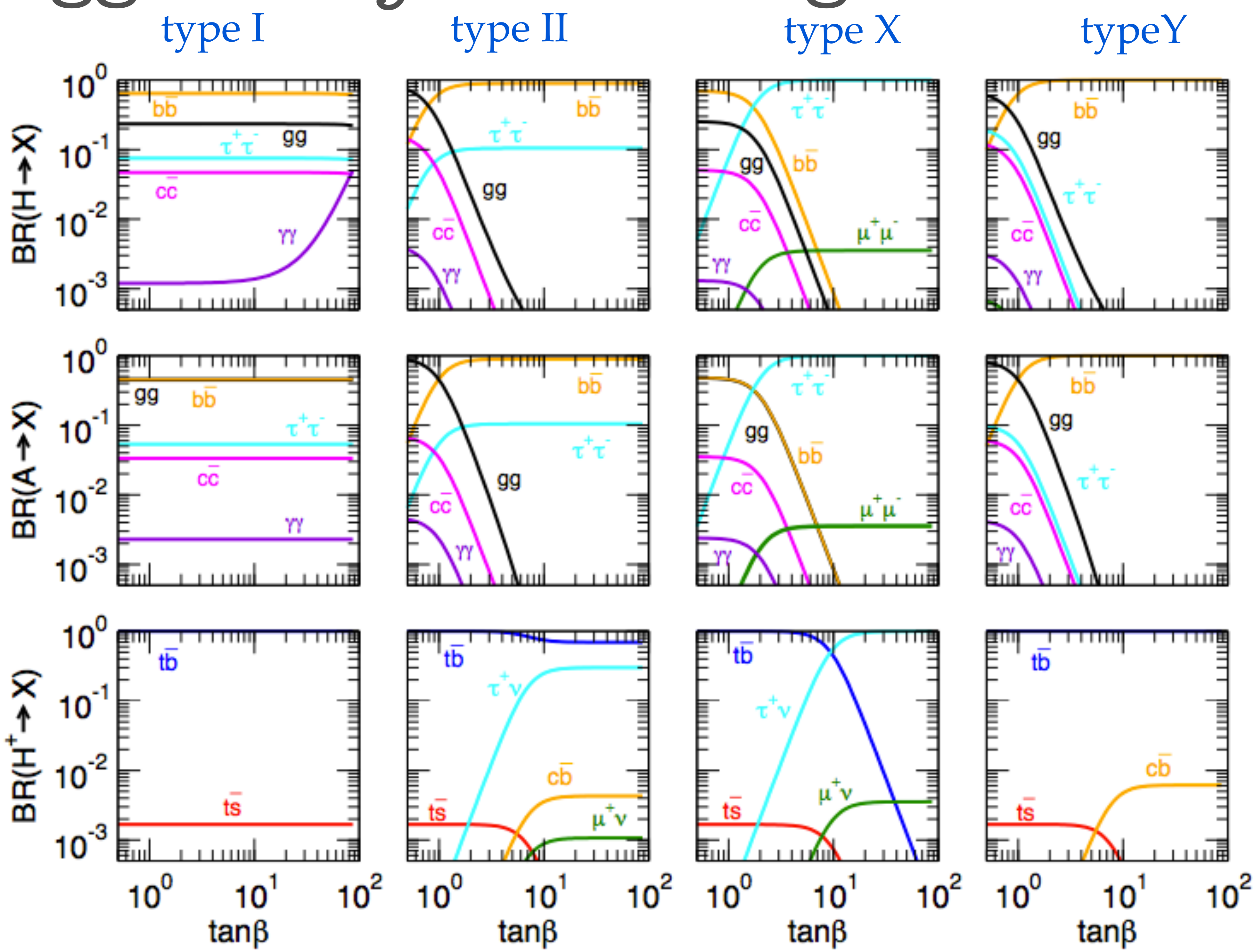
Higgs decay branching ratio

250 GeV Higgs
SM-like limit

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

$\sin(\beta - \alpha) = 1$

H to top decay open

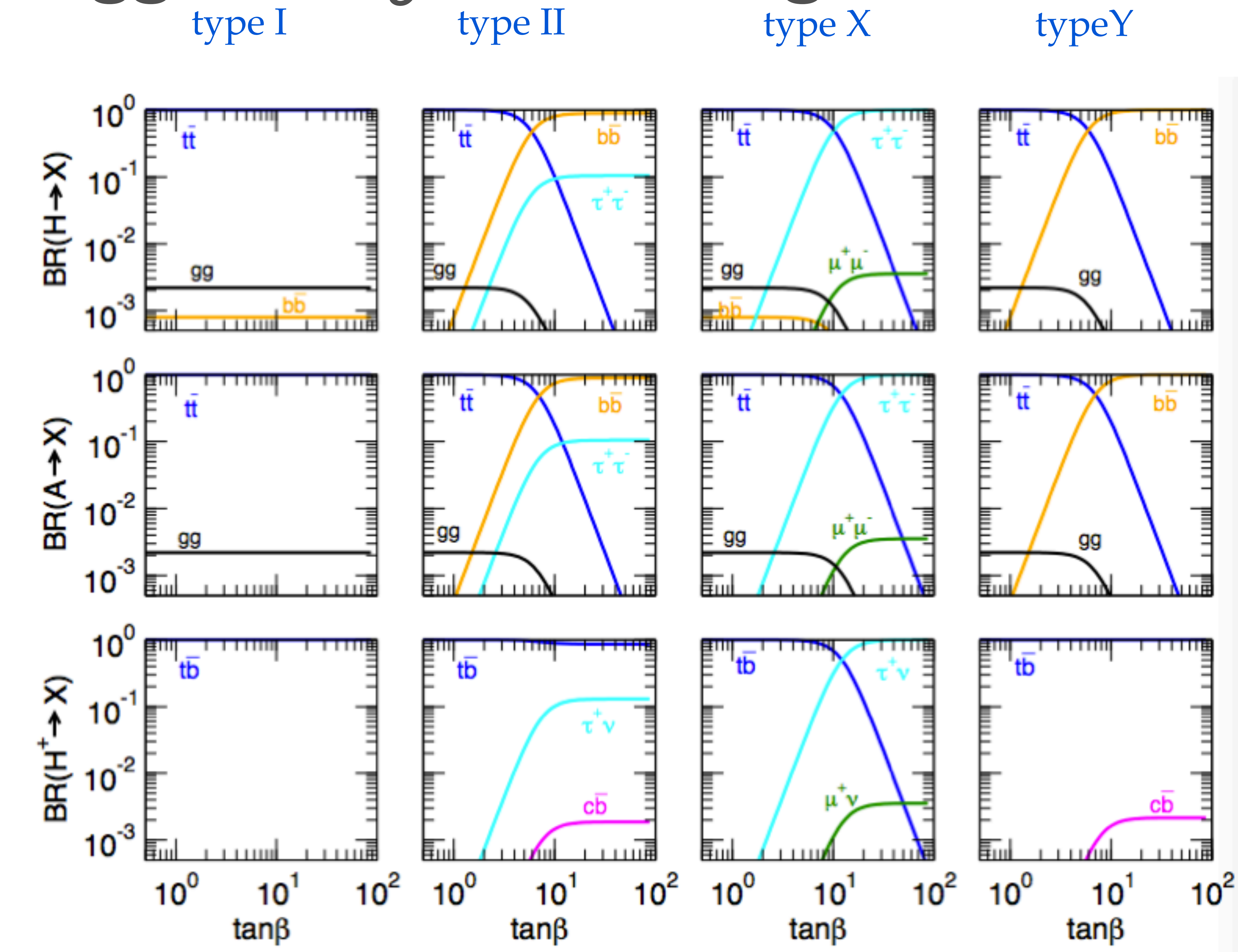


Higgs decay branching ratio

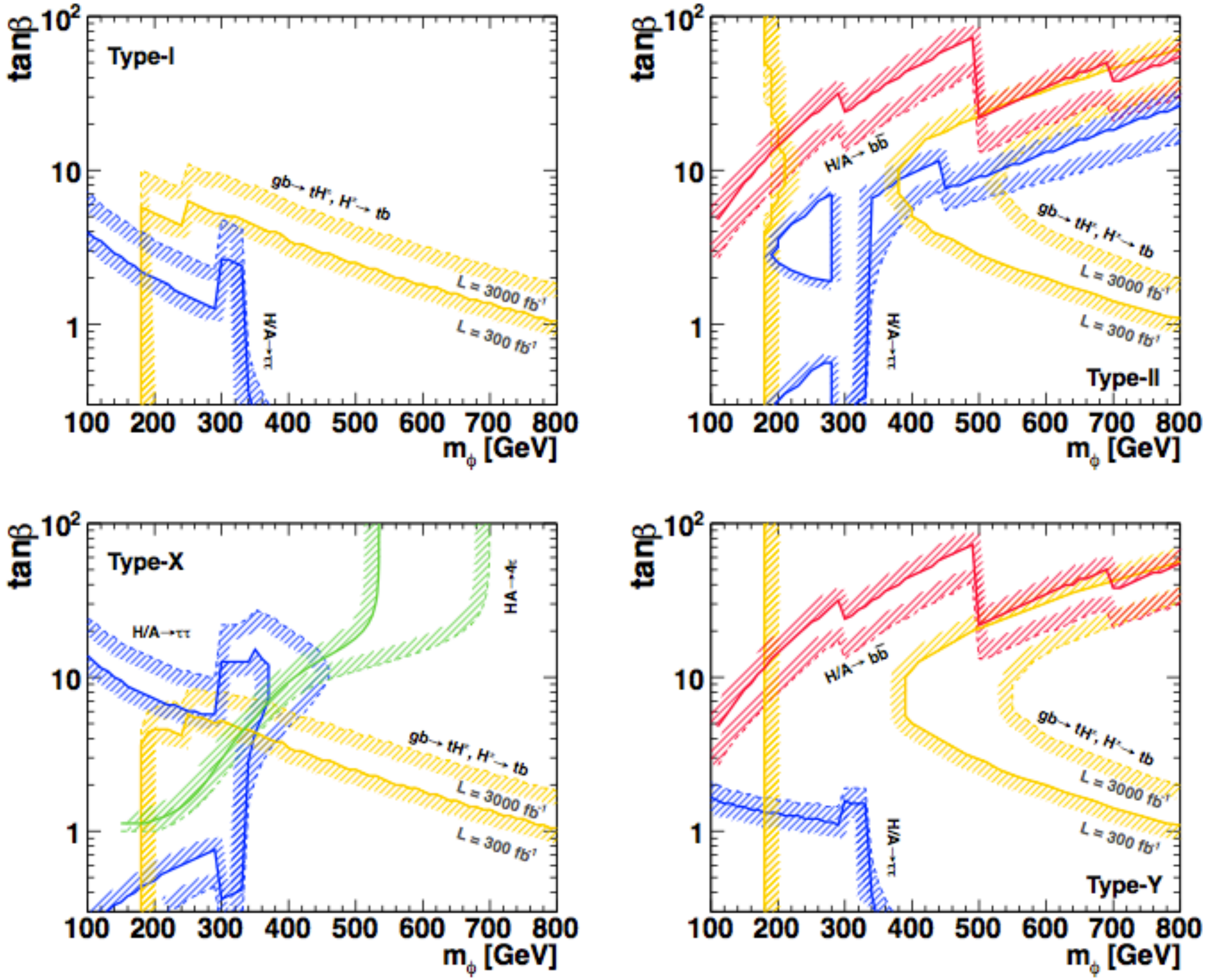
500 GeV Higgs
SM-like limit
$m_H = m_A = m_{H^\pm}$
$\sin(\beta-\alpha) = 1$

H to top decay open

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



2 sigma exclusion regions (theoretical prediction)



Higgs Production process at ILC

sqrt (s) < 2M

below the pair production mass threshold

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

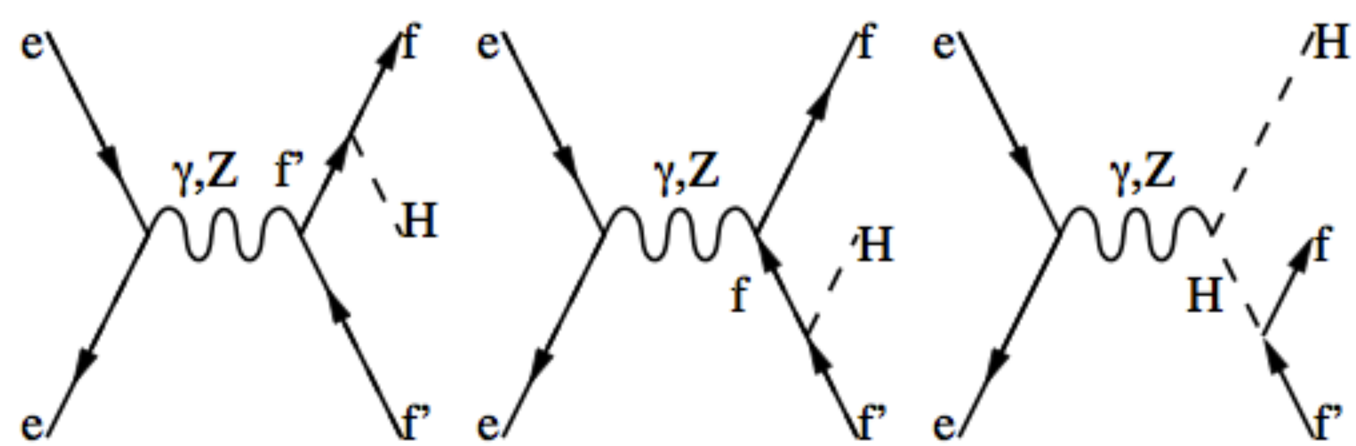
$$e^+e^- \to b\bar{b}H/A$$
$$e^+e^- \to \tau^+\tau^- H/A$$

sqrt (s) > 2M

above the pair production mass threshold

e+e-> H+H- / HA

$$e^-e^+ \to \bar{t}bH^+, t\bar{b}H^-$$
$$e^-e^+ \to W^\mp H^\pm \text{(one loop)}$$
$$e^-e^+ \to e^-\bar{\nu}H^+, e^+\nu H^- \text{(one loop)}$$
$$e^-e^+ \to Z^0 W^\mp H^\pm$$
$$e^-e^+ \to h^0 W^\mp H^\pm$$
$$e^-e^+ \to H^0 W^\mp H^\pm$$
$$e^-e^+ \to A^0 W^\mp H^\pm$$
$$e^-e^+ \to e^-e^+ W^\mp H^\pm$$
$$e^-e^+ \to \nu_e\bar{\nu}_e W^\mp H^\pm$$
$$e^-e^+ \to e^-\bar{\nu}_e Z^0 H^+, e^+\nu_e Z^0 H^-$$
$$e^-e^+ \to e^-\bar{\nu}_e h^0 H^+, e^+\nu_e h^0 H^-$$
$$e^-e^+ \to e^-\bar{\nu}_e H^0 H^+, e^+\nu_e H^0 H^-$$
$$e^-e^+ \to e^-\bar{\nu}_e A^0 H^+, e^+\nu_e A^0 H^-.$$



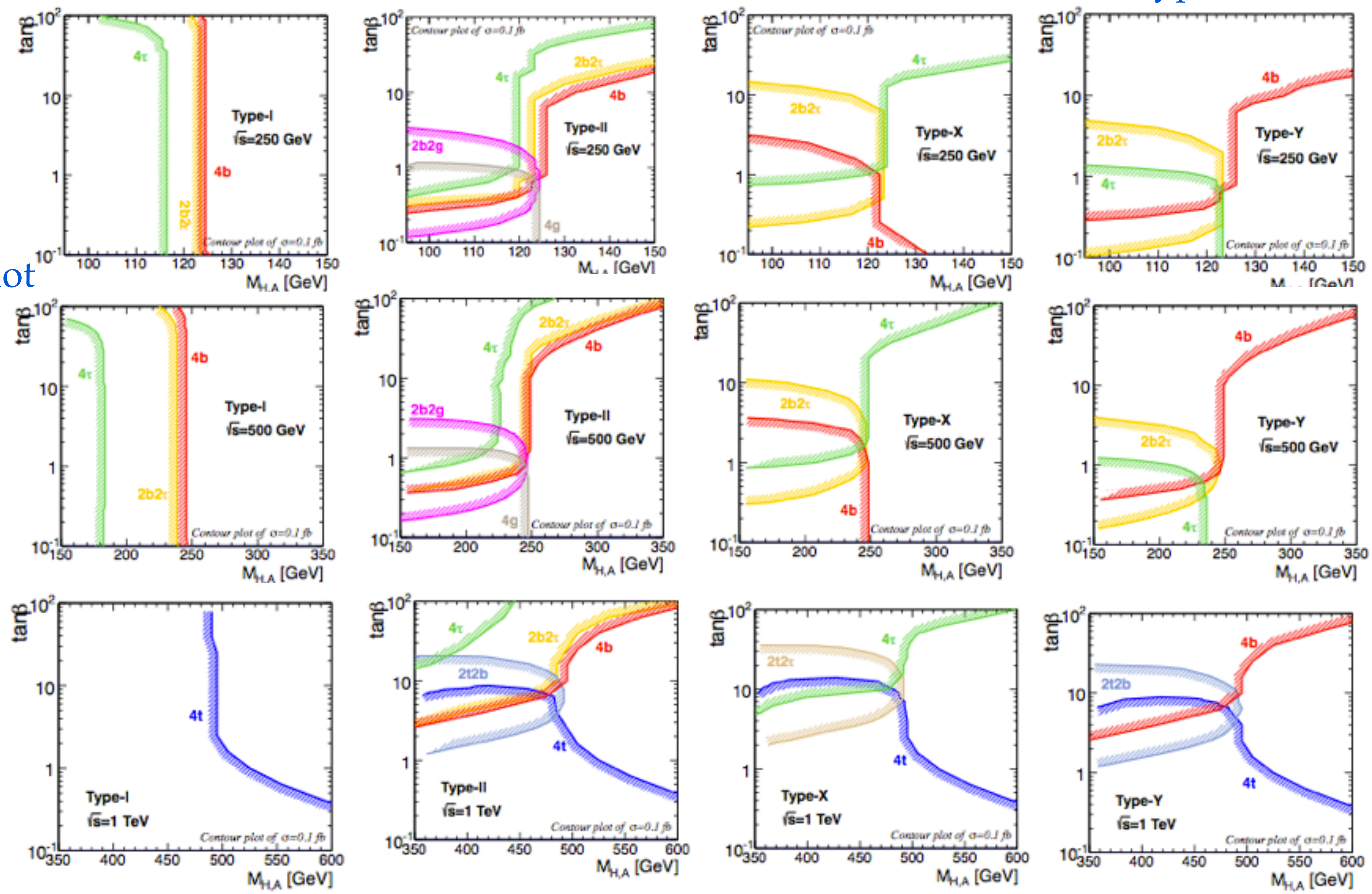
type II 2HDM study : Kanemura et.al, (2001), Moretti(2002)

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

Search for extra Higgs bosons at ILC after LHC

neutral Higgs | type I | type II | type X | typeY

0.1fb
contour plot



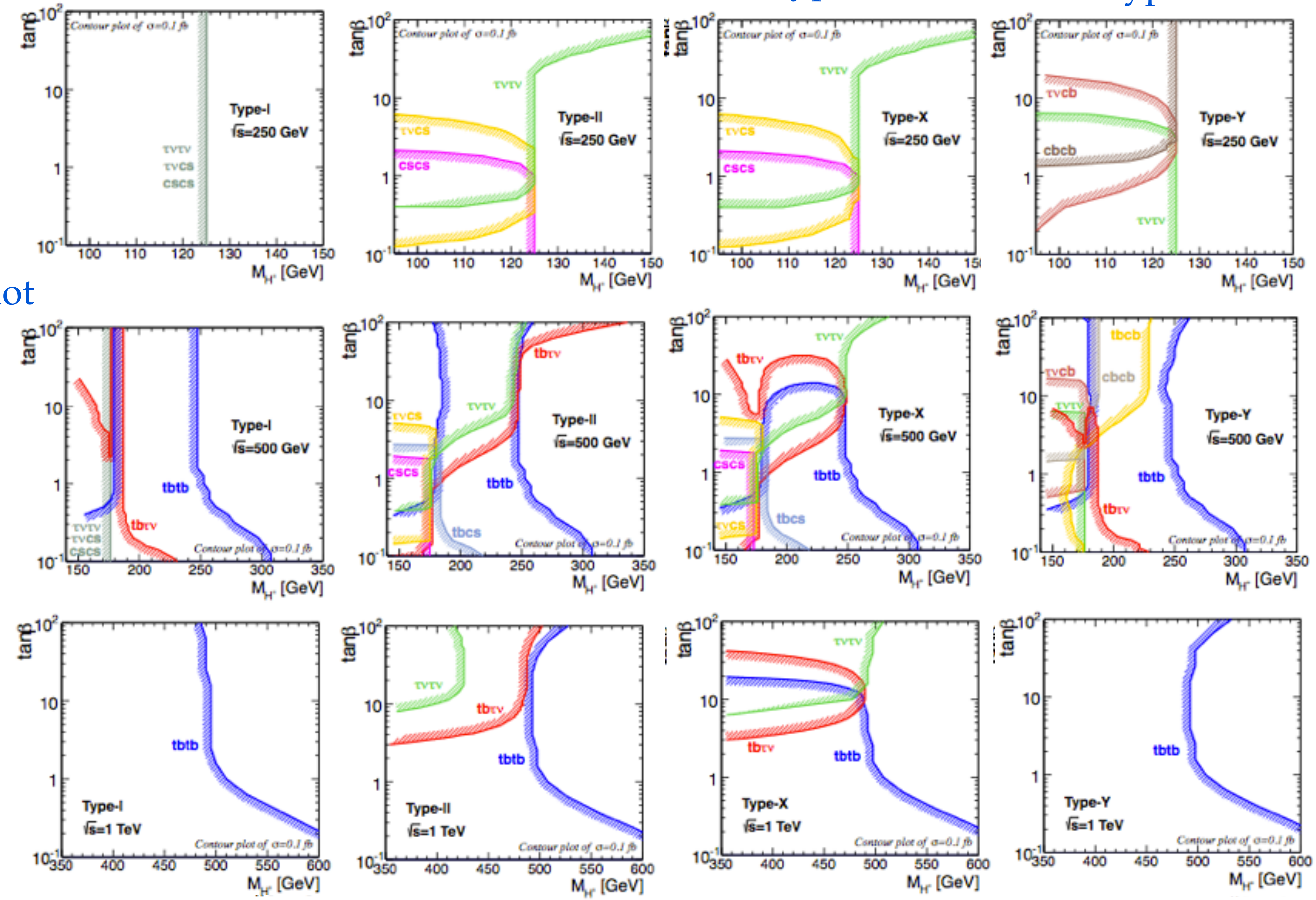
sensitive to different types

Wednesday, 28 May, 14

Search for extra Higgs bosons at ILC after LHC

Charged Higgs | type I | type II | type X | typeY

0.1fb contour plot



SM background

Signature	$\sqrt{s} = 250$ GeV	$\sqrt{s} = 500$ GeV	$\sqrt{s} = 1$ TeV
$4b$	18	7.2	2.9
4τ	4.4	1.6	0.63
$2\tau 2b$	28	10	3.5
$2\tau 2\nu$	210	94.4	35.8
$tb\tau\nu$	5.7×10^{-4}	122.7	40
$2t2b$	–	1.7	5.1
$2t2\tau$	–	0.14	0.34
$4t$	–	–	1.4×10^{-3}

TABLE III: Background cross sections in unit of fb for the four-particle processes at the ILC. Total cross sections without kinematical cuts are calculated by **Madgraph** [123].

without kinematic cuts

Benchmark scenarios

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

Benchmark scenarios

$(m_\phi, \tan\beta)$		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	$4t$	$tbtb$	$4t, 2t2b$	$tbtb$	$4t$	$tbtb$	$4t, 2t2b$	$tbtb$

TABLE V: The similar table as Table IV, but for $m_\phi = 400$ GeV. ILC1TeV represents the ILC run of 1 TeV.

Summary

- We made a complementary study on Higgs bosons in Type I, II, X and Y 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!