

Models of Yukawa interaction in the two Higgs doublet model, and their collider phenomenology



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Collaborators

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arXiv:0902.4665 [hep-ph]

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Possibility of extended Higgs models

- Higgs boson has not been discovered.
 - Various possibilities for extended Higgs sector
- Problems which cannot be explained in the SM
 - Need to go the beyond SM
 - Extended Higgs models appear in low energy effective theories

- **Hierarchy problem**
- **Tiny neutrino mass**
- **Dark matter**
- **Baryon asymmetry of Universe**

Extended Higgs models ↔ New physics

Two basic constraints from the experimental data

① Electroweak precision measurements (LEP)

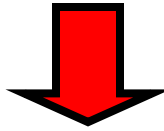
$$\rho_{\text{tree}} = \frac{\sum_k v_k^2 [T_k(T_k + 1) - Y_k^2] c_k}{\sum_k 2Y_k^2 v_k^2} = 1$$

Y_k : hypercharge

T_k : isospin

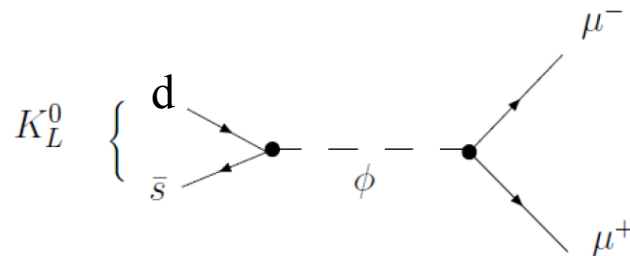
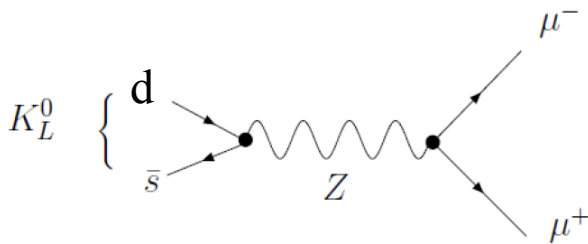
v_k : vev

$c_k = \begin{cases} 1 & \text{for complex field} \\ 1/2 & \text{for real field} \end{cases}$



Multi Higgs doublets (+ singlets)

② To avoid tree-level FCNC



Two basic constraints from the experimental data

① Electroweak precision measurements (LEP)

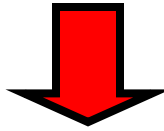
$$\rho_{\text{tree}} = \frac{\sum_k v_k^2 [T_k(T_k + 1) - Y_k^2] c_k}{\sum_k 2Y_k^2 v_k^2} = 1$$

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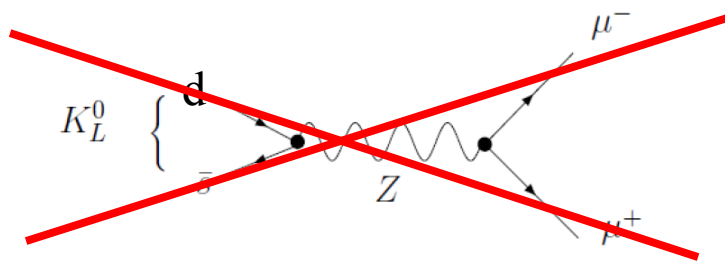
v_k : vev

$c_k = \begin{cases} 1 & \text{for complex field} \\ 1/2 & \text{for real field} \end{cases}$

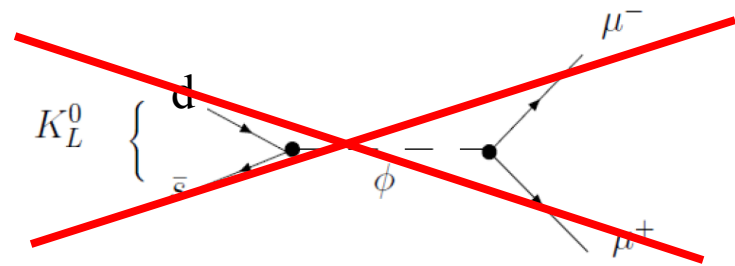


Multi Higgs doublets (+ singlets)

② To avoid tree-level FCNC



GIM mechanism



Discrete Z_2 symmetry

Two-Higgs-Doublet Model (THDM)

- Simplest extended Higgs model
- SM : Φ_1 THDM : Φ_1, Φ_2
- Physical states : H_{SM} h, H, A, H^\pm

THDM	{	MSSM, NMSSM, etc...	
		Possible models of DSB	<i>Holdom arXiv/0606146</i>
		Radiative neutrino mass model	
		<ul style="list-style-type: none">• m_ν <i>Zee, Phys Lett.B 93 (1980)</i>• $m_\nu + \text{DM}$ <i>Ma, PRD 73 (2006)</i>• $m_\nu + \text{DM} + \cancel{\text{B}}$ <i>Aoki, Kanemura, Seto PRL 102 (2009)</i>	

So, it would be valuable to study collider phenomenology of THDM.

Higgs potential under the discrete symmetry

$$\begin{aligned}
 V(\Phi_1, \Phi_2) = & m_1^2 |\Phi_1|^2 + m_2^2 |\Phi_2|^2 - m_3^2 [\Phi_1^\dagger \Phi_2 + h.c.] \\
 & + \frac{1}{2} \lambda_1 |\Phi_1|^4 + \frac{1}{2} \lambda_2 |\Phi_2|^4 + \lambda_3 |\Phi_1|^2 |\Phi_2|^2 + \lambda_4 |\Phi_1^\dagger \Phi_2|^2 \\
 & + \left[\frac{\lambda_5}{2} (\Phi_1^\dagger \Phi_2)^2 + h.c. \right]
 \end{aligned}$$

$$\Phi_i = \begin{pmatrix} \omega_i^+ \\ \frac{1}{\sqrt{2}}(v_i + h_i - i z_i) \end{pmatrix}$$

$$\begin{aligned}
 \Phi_1 & \rightarrow +\Phi_1 \\
 \Phi_2 & \rightarrow -\Phi_2
 \end{aligned}$$

Physical degrees of freedom : 8-3=5

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

↑
Higgs mechanism

Charged CP-odd CP-even

The physical states are defined by the mixing angles α and β .

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \mathbf{R}(\alpha) \begin{pmatrix} H \\ h \end{pmatrix}, \quad \begin{pmatrix} z_1 \\ z_2 \end{pmatrix} = \mathbf{R}(\beta) \begin{pmatrix} z \\ A \end{pmatrix}, \quad \begin{pmatrix} \omega_1^+ \\ \omega_2^+ \end{pmatrix} = \mathbf{R}(\beta) \begin{pmatrix} \omega^+ \\ H^+ \end{pmatrix}, \quad \mathbf{R}(\theta) = \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix}$$

The ratio of vevs is defined by $\tan \beta = v_2/v_1$.

And the soft breaking mass parameter is $M = m_3/\sqrt{\sin \beta \cos \beta}$.

Type of Yukawa interaction in THDM

Four types of Yukawa interactions
under the discrete symmetry (to avoid FCNC)

- Type-II THDM: MSSM

Φ_1 couples to down-type quarks
and leptons.

Φ_2 couples to up-type quarks.

$b \rightarrow s\gamma$ bound is very strong

 **Light H^+ is forbidden**

	Φ_1	Φ_2	Q^i	L^i	u_R^i	d_R^i	e_R^i
Type-I	+	-	+	+	-	-	-
Type-II	+	-	+	+	-	+	+
Type-X	+	-	+	+	-	-	+
Type-Y	+	-	+	+	-	+	-

- Type-X THDM : AKS model

Φ_1 couples to leptons

Φ_2 couples to quarks

$b \rightarrow s\gamma$ bound is mild



Light H^+ is possible !

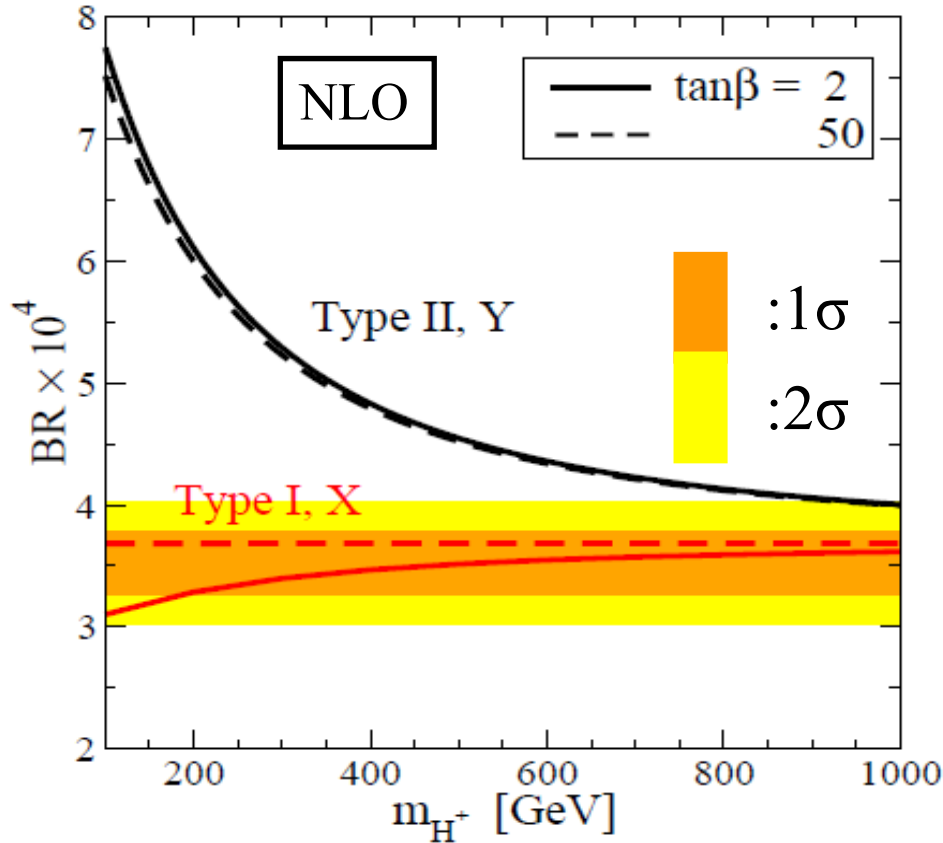
Barger, Hewett, Phillips PRD 41 (1990)

Grossman NPB 426 (1994)

In this talk, we mainly discuss the Type-X THDM and the MSSM

$b \rightarrow s\gamma$

Aoki, Kanemura, Tsumura, K.Y
arXiv:0902.4665 [hep-ph]



NLO calculation

Ciuchini et al. Nucl. Phys. B 527, 21 (1998).

NNLO calculation

Misiak, Steinhauser, Nucl. Phys. B 764, 62 (2007).

Misiak et al., PRL. 98, 022002 (2007).

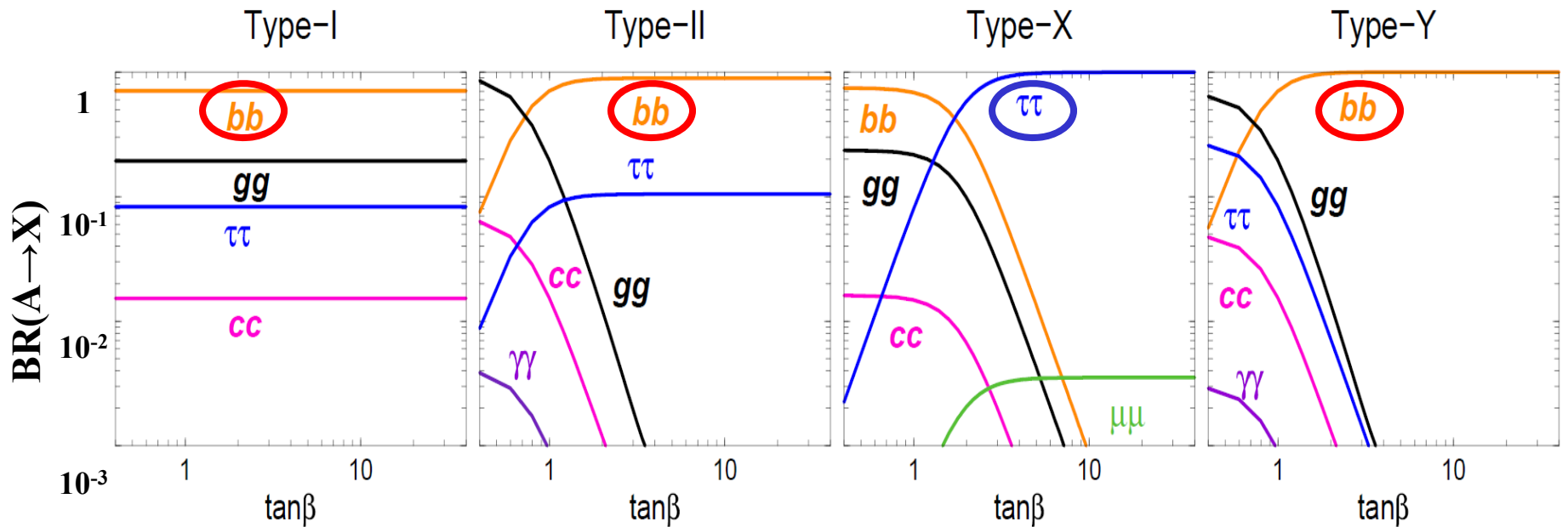
$m_{H^+} > 295 \text{ GeV}$ [95% C.L.] (Type-II, Y)

No bound (Type-I, -X)

Light charged Higgs are possible in the **Type-X** and **MSSM**

A decays

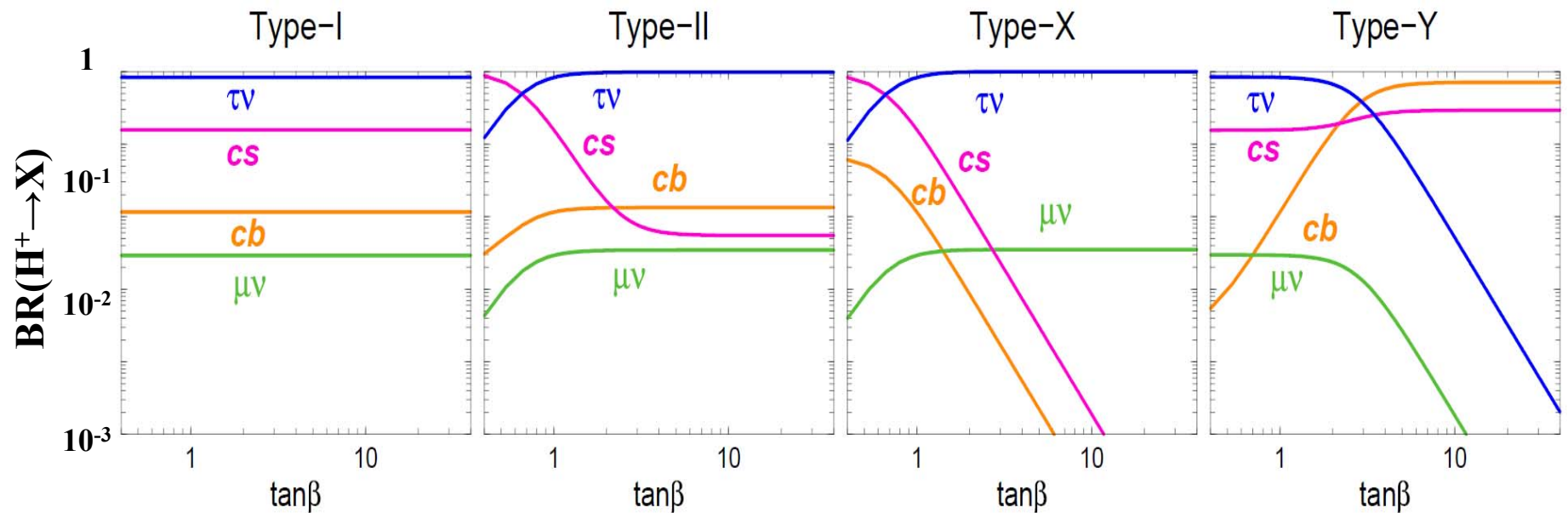
$$m_A = m_{H^\pm} = 150 \text{ GeV}$$



Type-I, -II, -Y $\rightarrow bb$, **Type-X** $\rightarrow \tau^+\tau^-$
(Also H decays when $\sin(\beta-\alpha)=1$)

H^+ decays

$$m_A = m_{H^+} = 150 \text{ GeV}$$



Type-I, -II, -X $\rightarrow \tau\nu$, **Type-Y** $\rightarrow cb$ (hadron jets)

Discrimination between models in the light charged Higgs scenario at the LHC

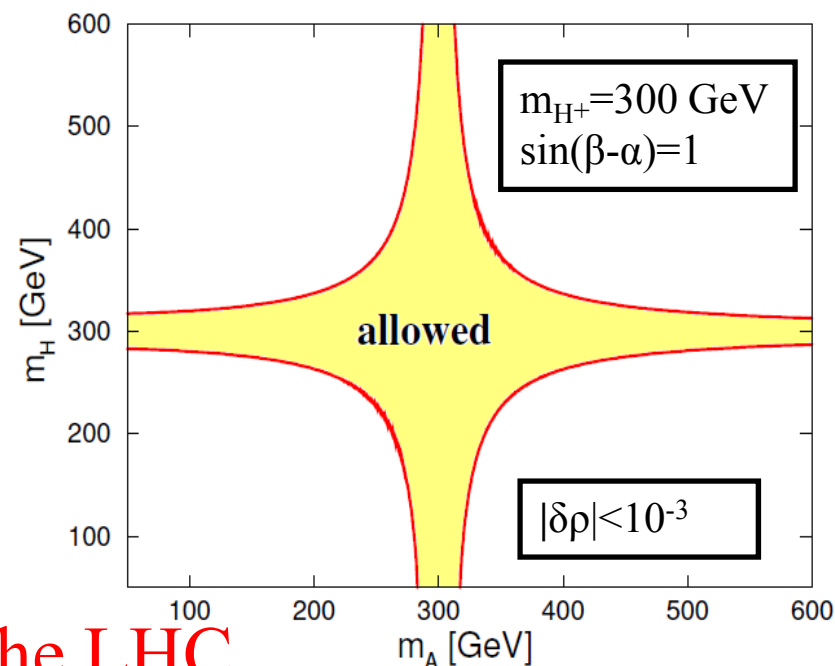
- **Scenario**

$$m_A = m_H = m_{H^\pm} : 130 \sim 150 \text{ GeV}$$

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

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

Custodial symmetry exists, and perturbative unitarity is satisfied with this condition.



- Single A/H production at the LHC
- Higgs pair production (AH^\pm , HH^\pm) at the LHC

Single A/H production at the LHC (30fb^{-1})

$\tan\beta=10$, $m_A=150\text{GeV}$, MSSM

(ATLAS TDR)

$gg \rightarrow A/H \rightarrow \tau^+ \tau^-$

Signal (after the cut) : 49

Background (after the cut)

W+jet	:	530
tt	:	7
bb	:	14
Z/ γ^*	:	163
Sum	:	714

Kinematical cuts

- A veto against b-jets for $p_T > 15\text{GeV}$ and $\eta < 2.5$.
- $\tau \tau$'s invariant mass cut.
 $m_{\tau\tau} - 1.5\sigma < m_{\tau\tau} < m_{\tau\tau} + 1.5\sigma$
 $\sigma \sim 27\text{GeV}$

$pp \rightarrow bbA/H \rightarrow bb\tau^+ \tau^-$

Signal (after the cut) : 72

Background (after the cut)

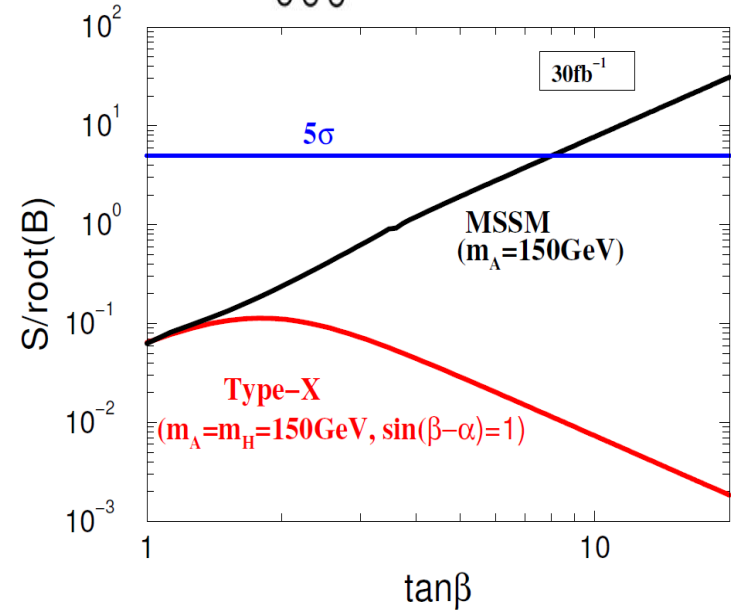
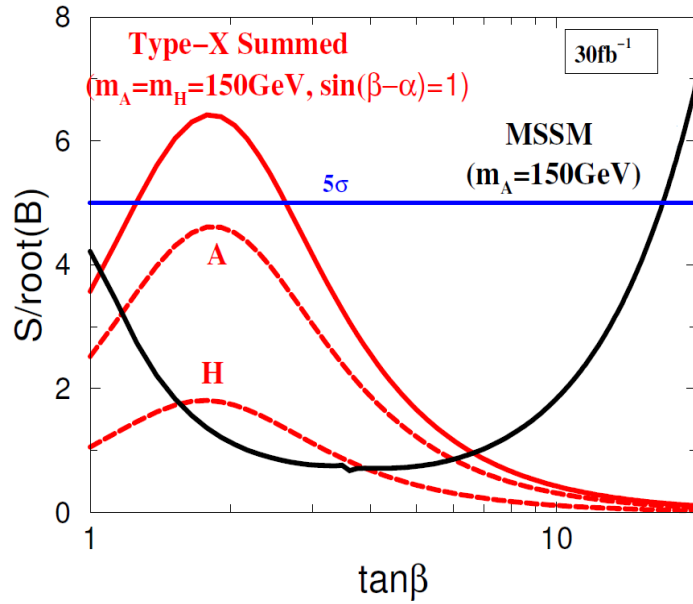
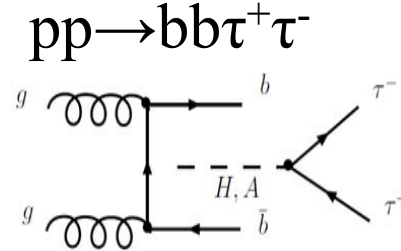
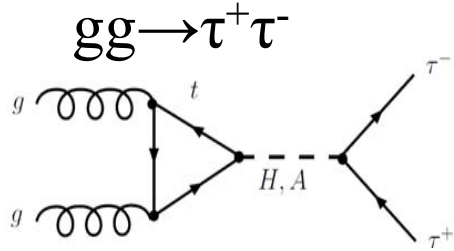
W+jet	:	46
tt	:	6
bb	:	29
Z/ γ^*	:	5
Sum	:	86

Kinematical cuts

- At least one tagged b-jet.
- At most two non-b jets with $p_T > 15\text{GeV}$ and $\eta < 3.2$.
- $\tau \tau$'s invariant mass cut.
 $m_{\tau\tau} - 1.5\sigma < m_{\tau\tau} < m_{\tau\tau} + 1.5\sigma$
 $\sigma \sim 39\text{GeV}$

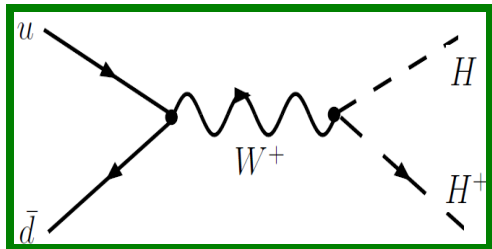
Significance (S/root(B))

Aoki, Kanemura, Tsumura, K.Y arXiv:0902.4665 [hep-ph]

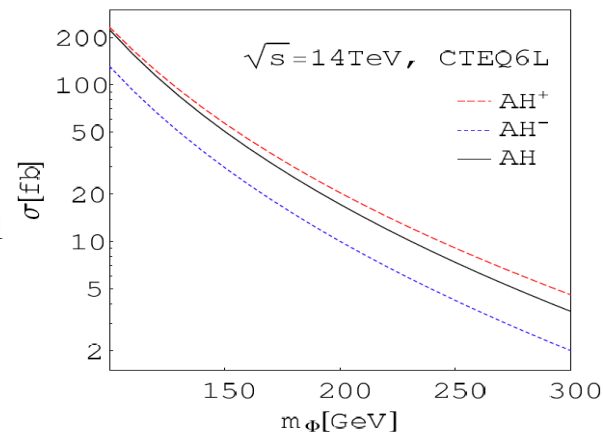


	Low $\tan\beta$	Mid $\tan\beta$	High $\tan\beta$
Type-X	Direct		
MSSM			

AH⁺ (HH⁺) production at the LHC (300fb⁻¹)



$\sigma(u\bar{d} \rightarrow HH^+) \sim 100\text{fb}$
 30000 AH⁺ (HH⁺) events at 300fb⁻¹



bb $\tau\nu$ final states

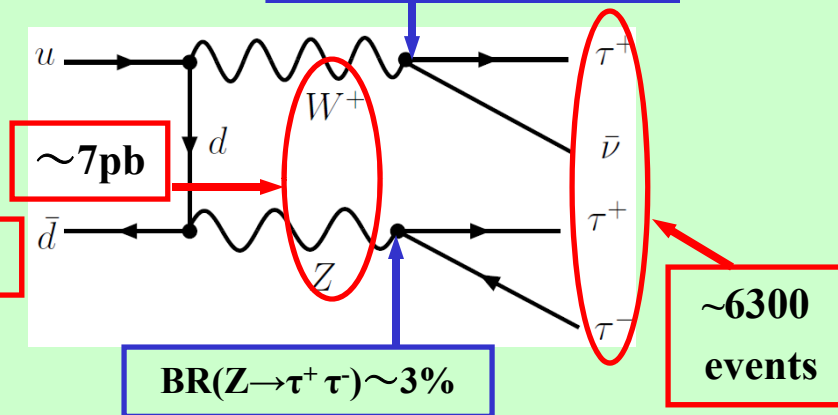
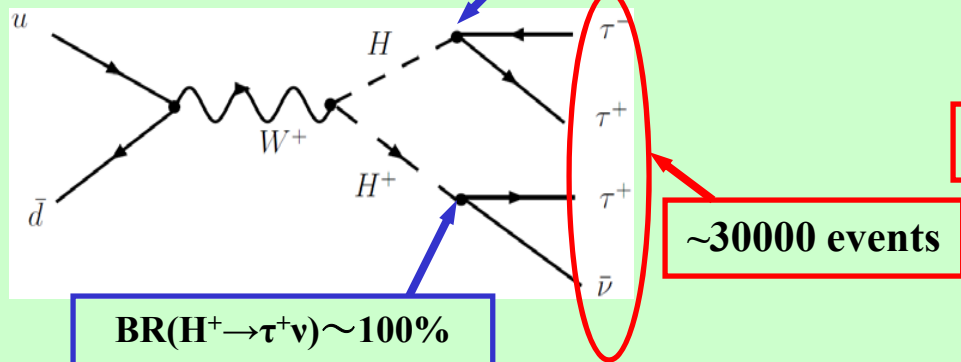
detailed analysis: [Cao, Kanemura, Yuan hep-ph/0402226](#)

In the MSSM taking kinematical cuts there is possibility to detect this final states.

$\tau\tau\nu$ final states

BR(H $\rightarrow\tau^+\tau^-$) \sim 100%

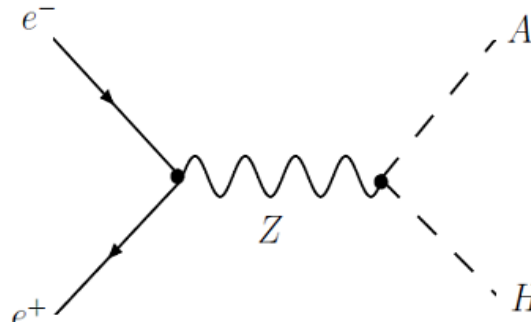
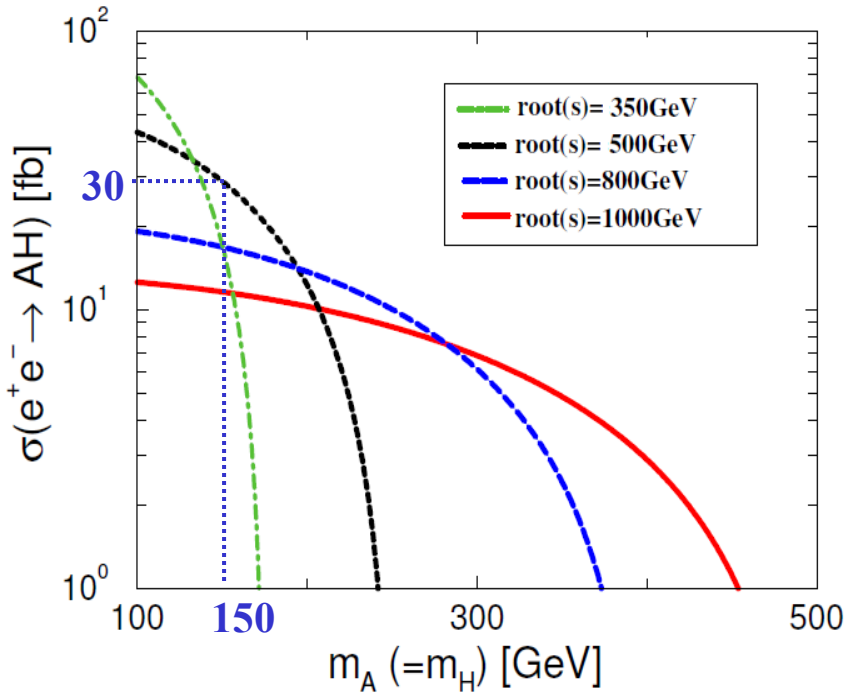
BR(W⁺ $\rightarrow\tau^+\nu$) \sim 10%



bb $\tau\nu$ \rightarrow MSSM (Type-II) $\tau\tau\nu$ \rightarrow Type-X

Physics of the Type-X THDM at the ILC

Discrimination of the models at the ILC



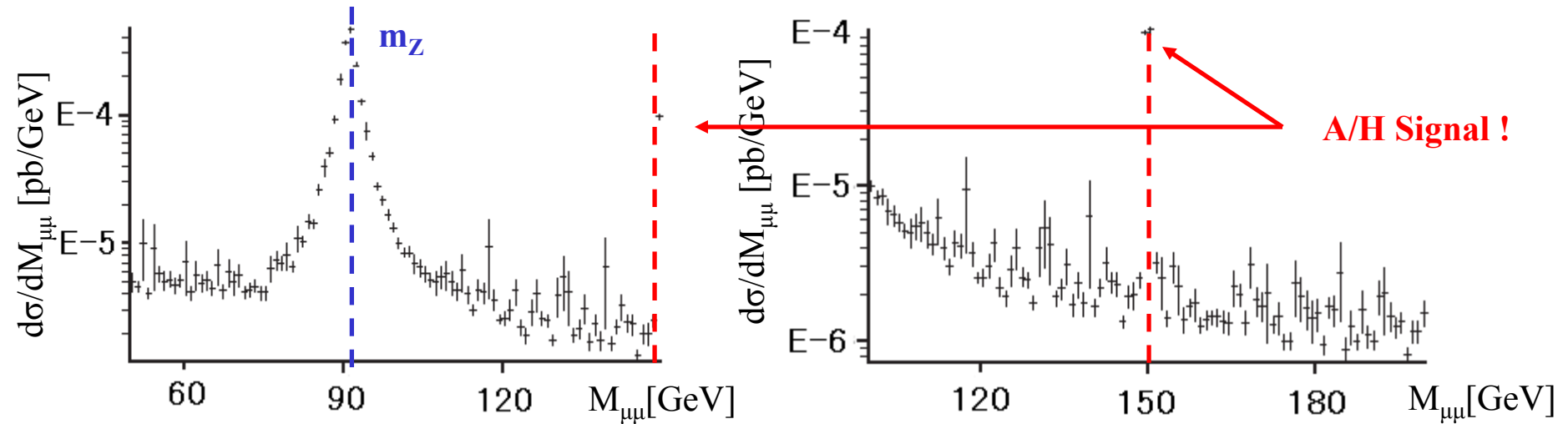
$m_A = m_H = 150 \text{ GeV}$, $\sin(\beta - \alpha) = 1$, $\tan\beta = 10$
and $\text{root}(s) = 500 \text{ GeV}$

	Type-II	Type-X
BR ($A/H \rightarrow \tau\tau$)	0.105	0.995
BR ($A/H \rightarrow \mu\mu$)	$\mathcal{O}(10^{-4})$	0.003

Type-X branching ratio of leptonic decay is much larger than Type-II one.
The $\tau\tau\mu\mu$ and $\tau\tau\tau\tau$ mode are valuable to study
the Type-X Yukawa interaction.

Signal background analysis for $\tau\tau\mu\mu$ events

The $\mu\mu$ invariant mass distribution



$\sigma_{\mu\mu\tau\tau}$ [fb]	AH	ZZ	$Z\gamma$	$\gamma\gamma$
No cut	0.192	0.954	2.60	1.72
$ \cos\theta < 0.99$	0.190	0.912	1.67	0.974
$ \cos\theta < 0.9$	0.179	0.647	0.103	0.585
$M_{\mu\mu} \leq m_{\Phi} \pm 5$ GeV	0.191	0.002	0.009	0.007

For $L=500\text{fb}^{-1}$

After invariant mass cuts

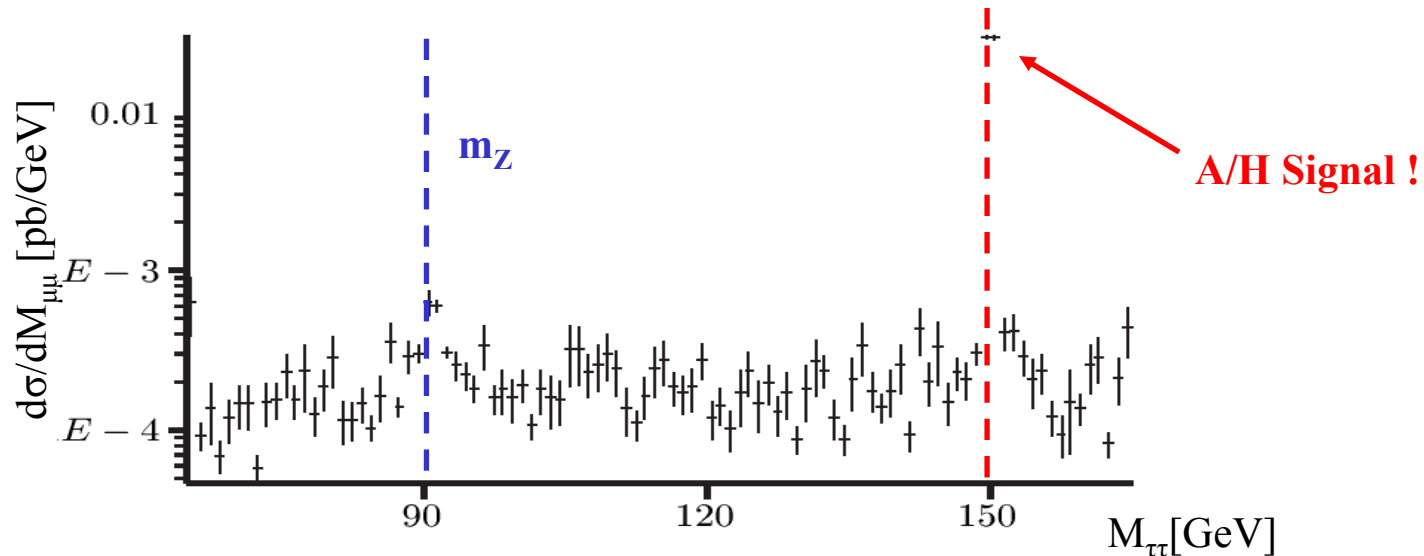
$S \sim 96$

$B \sim 9$

Taking kinematical cuts we can obtain $S/\sqrt{S+B} \sim 9$

Signal background analysis for $\tau\tau$ events

The $\tau\tau$ invariant mass distribution



$\sigma_{\tau\tau\tau\tau}$ [fb]	AH	ZZ	$Z\gamma$	$\gamma\gamma$
No cut	27.0	0.482	0.804	0.371
$ \cos\theta < 0.99$	26.5	0.449	0.645	0.269
$ \cos\theta < 0.9$	25.0	0.324	0.423	0.171
$M_{\tau\tau} \leq m_{\Phi} \pm 15$ GeV	14.7	0.021	0.039	0.021

For $L=500\text{fb}^{-1}$

After cuts

$S \sim 7350$

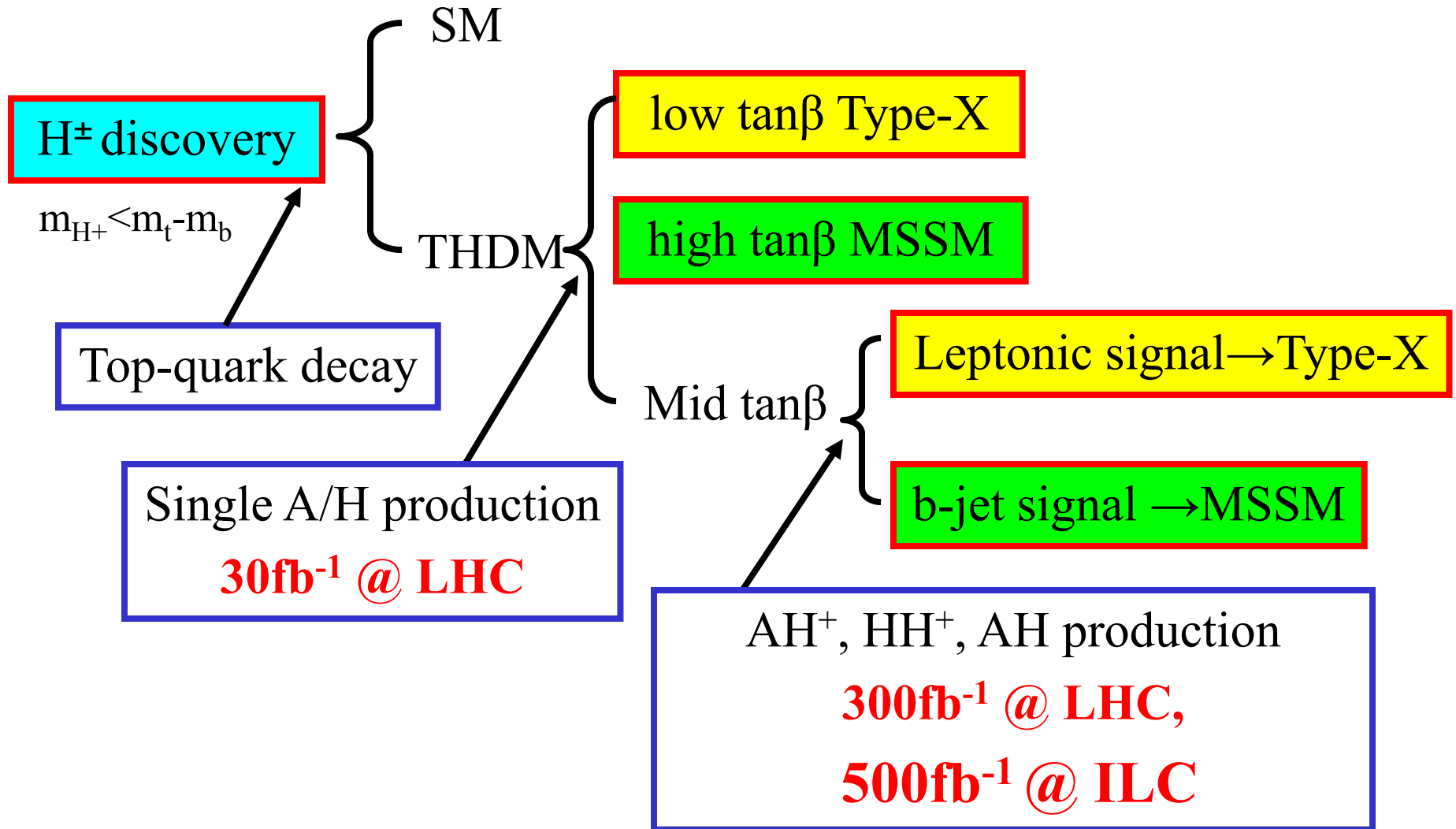
$B \sim 41$

Taking kinematical cuts we can obtain $S/\sqrt{S+B} \sim 85$!!

But we assumed that tau tagging efficiency is 100%

→ Realistic simulation study is necessary.

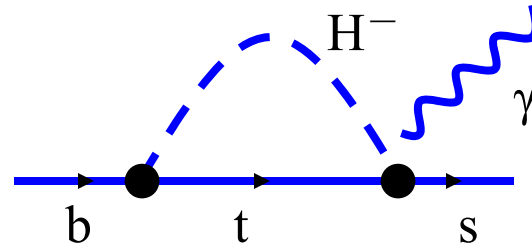
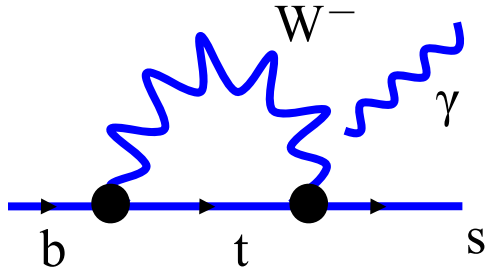
Summary of the model discrimination in the light H^\pm scenario



Summary

- In the THDM, there are four types of Yukawa interaction under the discrete symmetry to avoid tree-level FCNC.
- The Type-II THDM corresponds to the MSSM Yukawa interaction, while the Type-X is motivated such as in the TeV scale model of neutrino, dark matter, and baryogenesis.
- In the Type-X, $b \rightarrow s\gamma$ bound is very mild.
→ Light charged Higgs scenario is possible.
- By measuring single A/H production (LHC) and AH^+ , HH^+ , AH production (LHC and ILC), one could test the **Type-X THDM**.
- Extended Higgs models \Leftrightarrow New physics

$b \rightarrow s \gamma$



	Type-II, Y	Type-I, X
$\bar{s}tH^-$	$\frac{\sqrt{2}}{v} V_{ts}^* [m_s \tan \beta P_L + m_t \cot \beta P_R]$	$\frac{\sqrt{2}}{v} V_{ts}^* [-m_s \cot \beta P_L + m_t \cot \beta P_R]$
$\bar{t}bH^+$	$\frac{\sqrt{2}}{v} V_{tb} [m_b \tan \beta P_R + m_t \cot \beta P_L]$	$\frac{\sqrt{2}}{v} V_{tb} [-m_b \cot \beta P_R + m_t \cot \beta P_L]$

Type-II, Y

Barger, Hewett, Phillips PRD 41 (1990)

$$\Gamma(b \rightarrow s \gamma) = \frac{\alpha_{EM} G_F^2 m_b^5}{128 \pi^4} \left| V_{ts}^* V_{tb} \left[G_W \left(\frac{m_t^2}{m_W^2} \right) + 1 \cdot G_H^1 \left(\frac{m_t^2}{m_{H^\pm}^2} \right) + \cot^2 \beta G_H^2 \left(\frac{m_t^2}{m_{H^\pm}^2} \right) \right] \right|^2$$

Type-I, X

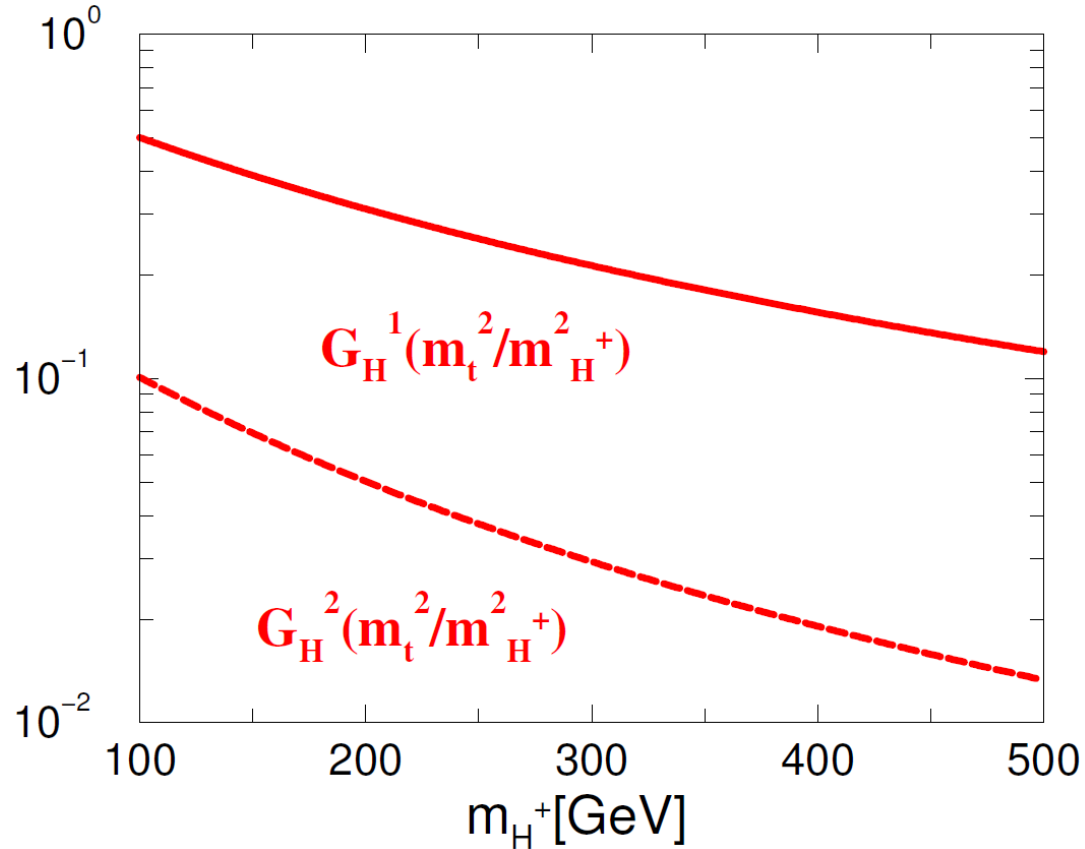
$$\Gamma(b \rightarrow s \gamma) = \frac{\alpha_{EM} G_F^2 m_b^5}{128 \pi^4} \left| V_{ts}^* V_{tb} \left[G_W \left(\frac{m_t^2}{m_W^2} \right) - \cot^2 \beta G_H^1 \left(\frac{m_t^2}{m_{H^\pm}^2} \right) + \cot^2 \beta G_H^2 \left(\frac{m_t^2}{m_{H^\pm}^2} \right) \right] \right|^2$$

In the Type-X THDM, destructive interferences occur between the W and the H[±] contributions.

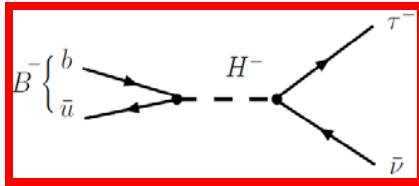
$$G_W(x) = \frac{2 - 7x + 11x^2}{4(1-x)^3} - \frac{1}{2} + \frac{3x^3}{2(1-x)^4} \ln x + \frac{2}{3} \left[\frac{1 - 5x - 2x^2}{4(1-x)^3} - \frac{1}{4} - \frac{3x^2}{2(1-x)^4} \ln x \right]$$

$$G_H^1(x) = \frac{x}{(1-x)^3} \left[\frac{1}{2}(1-x^2) + x \ln x - \frac{2}{3} \left(\frac{3}{2} - 2x + \frac{1}{2}x^2 + \ln x \right) \right]$$

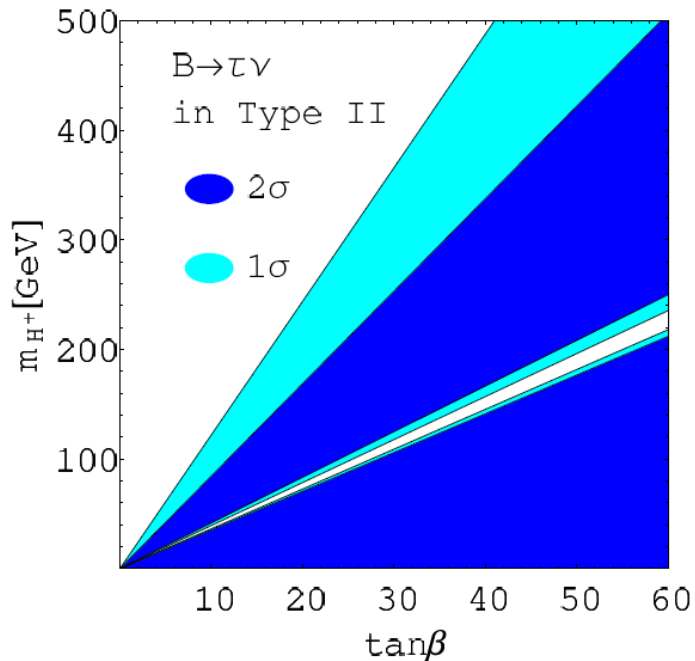
$$G_H^2(x) = \frac{x}{2(1-x)^4} \left[\left(\frac{1}{6} - x + \frac{1}{2}x^2 + \frac{1}{3}x^3 - x^2 \ln x \right) + \frac{2}{3} \left(\frac{1}{3} + \frac{1}{2}x - x^2 + \frac{1}{6}x^3 + x \ln x \right) \right]$$



$B \rightarrow \tau \nu$

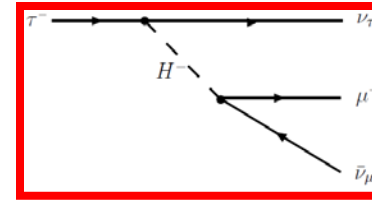


$$\frac{\Gamma_{B^- \rightarrow \tau^- \nu}^{\text{THDM}}}{\Gamma_{B^- \rightarrow \tau^- \nu}^{\text{SM}}} \sim \begin{cases} \left[1 - \frac{m_B^2}{m_{H^\pm}^2} \tan^2 \beta \right]^2 & \text{: Type-II} \\ \left[1 - \frac{m_B^2}{m_{H^\pm}^2} 1 \right]^2 & \text{: Type-X} \end{cases}$$

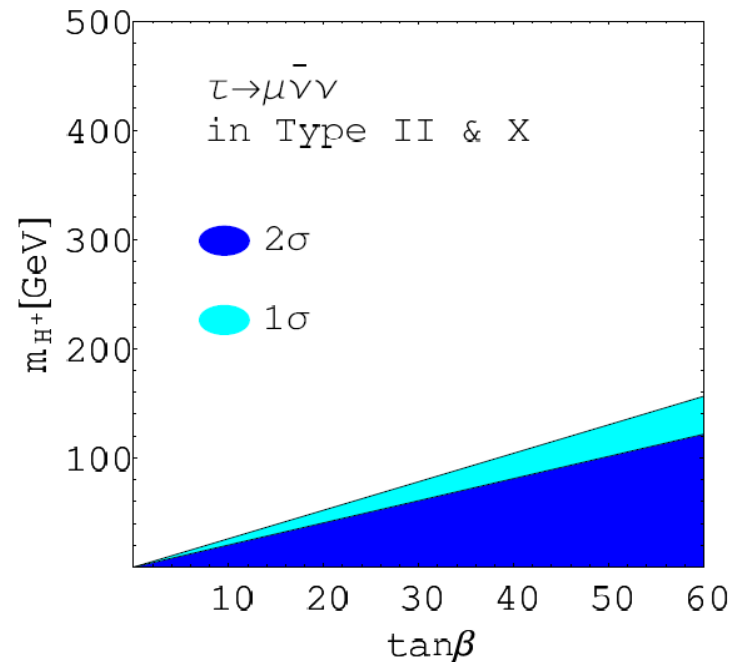


Type-X no bound

$\tau \rightarrow \mu \nu \bar{\nu}$



$$\frac{\Gamma_{\tau^- \rightarrow \mu^- \nu \bar{\nu}}^{\text{THDM}}}{\Gamma_{\tau^- \rightarrow \mu^- \nu \bar{\nu}}^{\text{SM}}} \sim 1 - \frac{2m_\mu^2}{m_{H^\pm}^2} \tan^2 \beta$$



If $m_{H^+} > 100 \text{ GeV}$, then $\tan \beta = 60$ is allowed

D.s.Du arXiv:0709.1315 [hep-ph]

Krawczyk, Sokolowska arXiv:0711.4900 [hep-ph]

Aoki, Kanemura, Tsumura, K.Y arXiv:0902.4665 [hep-ph]