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)

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

Y_k : hypercharge

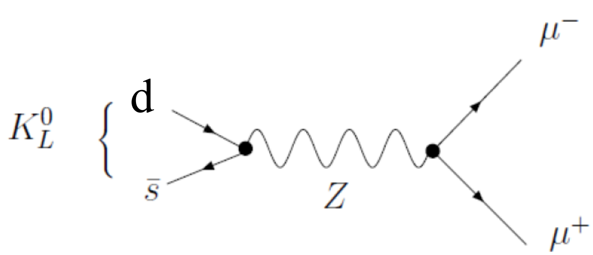
T_k : isospin

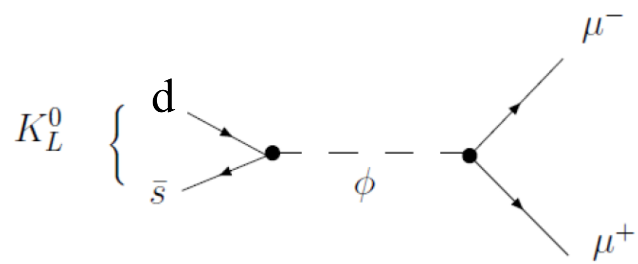
v_k : vev

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

Multi Higgs doublets (+ singlets)

② To avoid tree-level FCNC





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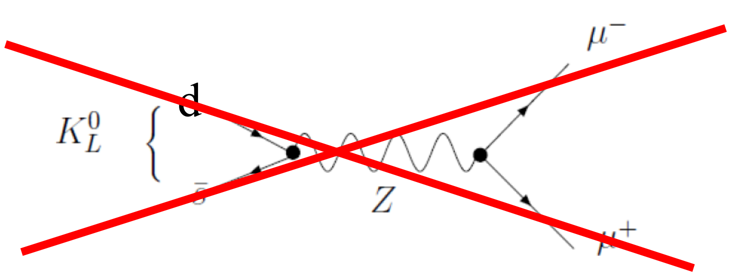
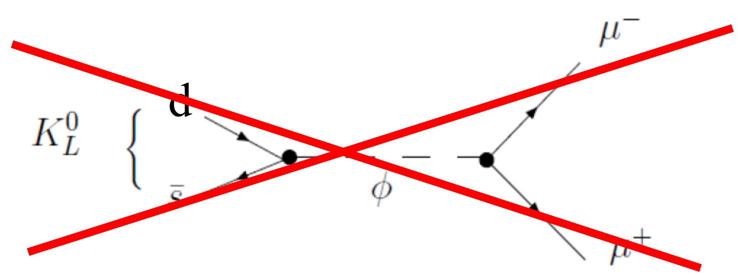


GIM mechanism



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 *Holdom arXiv/0606146*
- Radiative neutrino mass model
  - **m_ν** *Zee, Phys Lett.B 93 (1980)*
  - **m_ν+ DM** *Ma, PRD 73 (2006)*
  - **m_ν + DM + $\not{B}$** *Aoki, Kanemura, Seto PRL 102 (2009)*

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

Higgs potential under the discrete symmetry

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

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

$$\Phi_1 \to +\Phi_1 \qquad \Phi_2 \to -\Phi_2$$

Physical degrees of freedom : 8-3=5 **$H^\pm$, A, H, h**

↑ **Higgs mechanism** (under 3) — **Charged** ($H^\pm$), **CP-odd** (A), **CP-even** (H, h)

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

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

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)

	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-II THDM: MSSM
  - Φ_1 couples to down-type quarks and leptons.
  - Φ_2 couples to up-type quarks.
  - $b \to s\gamma$ bound is very strong
  - ➡ **Light H^+ is forbidden**

- Type-X THDM : AKS model
  - Φ_1 couples to leptons
  - Φ_2 couples to quarks
  - $b \to s\gamma$ bound is mild ➡ **Light H^+ is possible !**

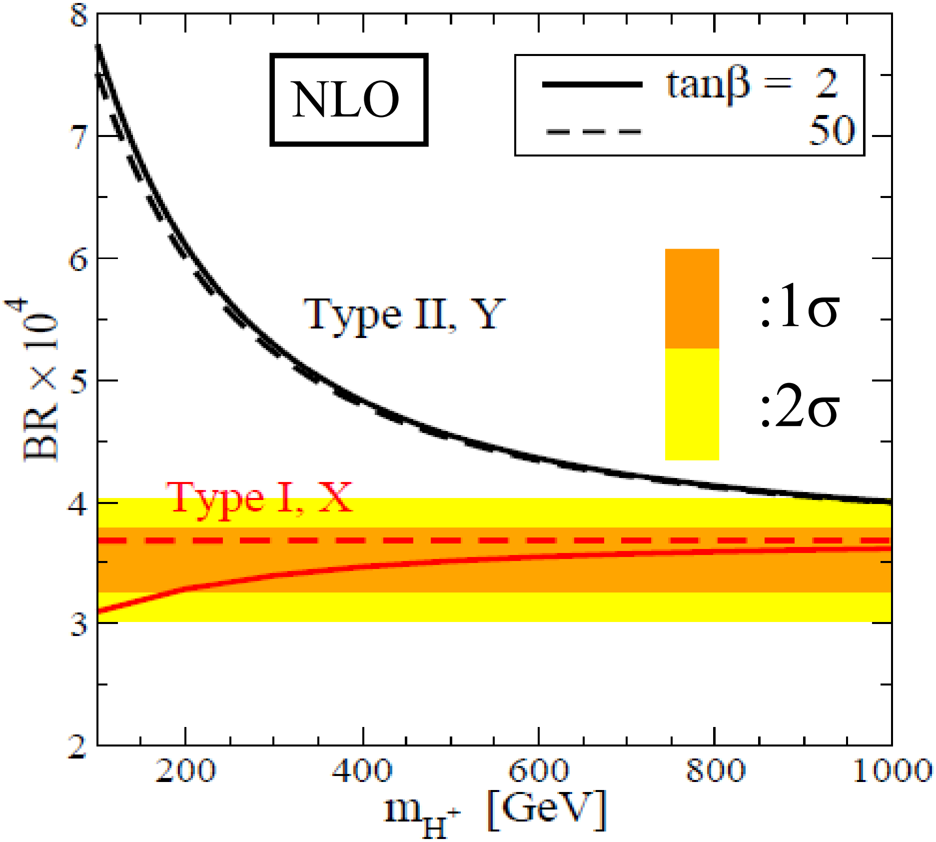
Barger, Hewett, Phillips PRD 41 (1990)

Grossman NPB 426 (1994)

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

$b \to s\gamma$

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).

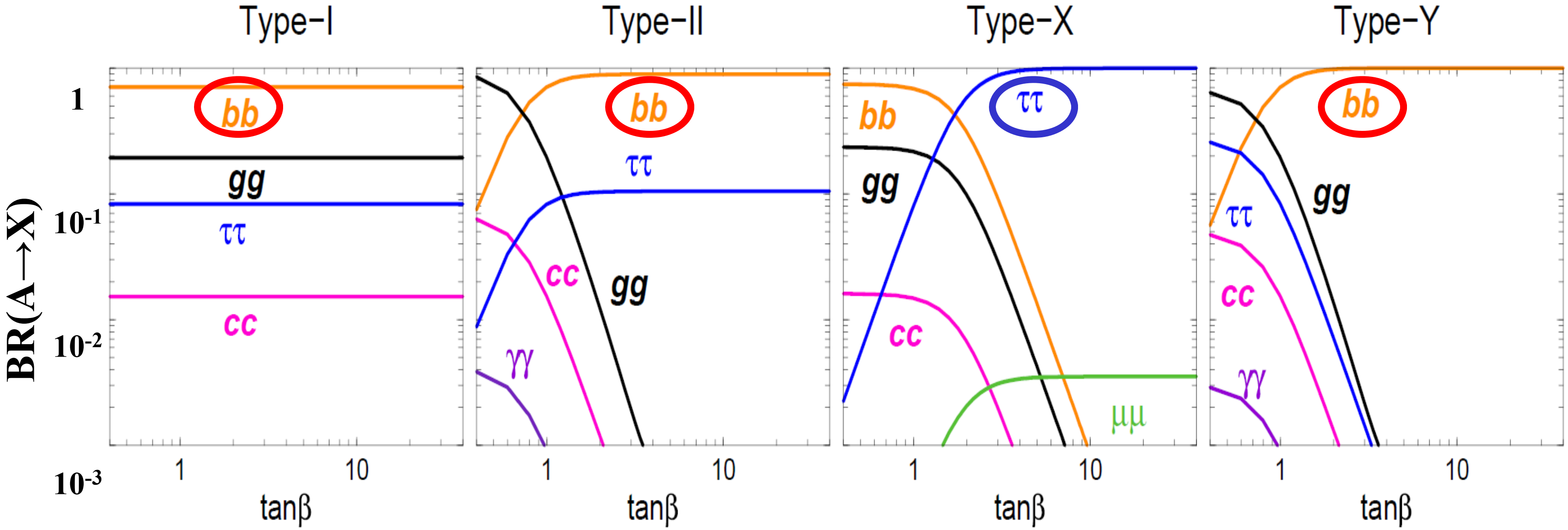
m_{H+} > 295GeV [95% C.L.] (Type-II,Y)

No bound (Type-I, -X)

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

A decays

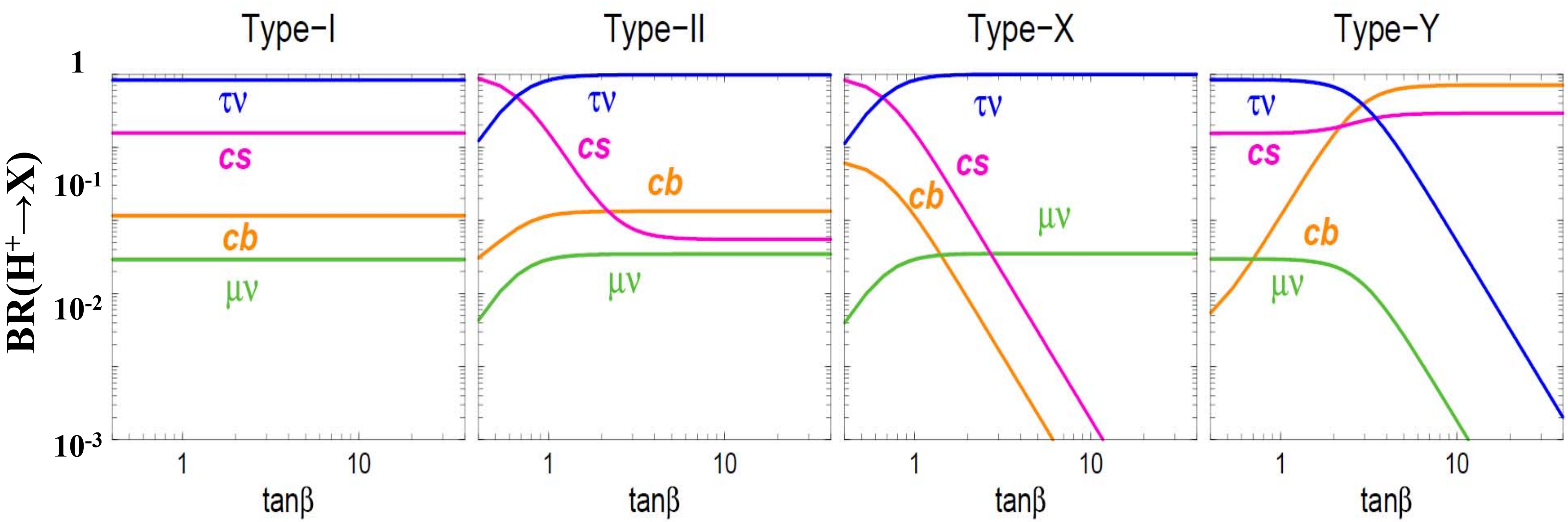
$m_A = m_{H+} = 150 GeV$



Type-I, -II, -Y → bb , Type-X → $\tau^+\tau^-$
(Also H decays when sin(β-α)=1)

H^+ decays

$m_A = m_{H+} = 150GeV$



Type-I, -II, -X → τν , **Type-Y** → cb (hadron jets)

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

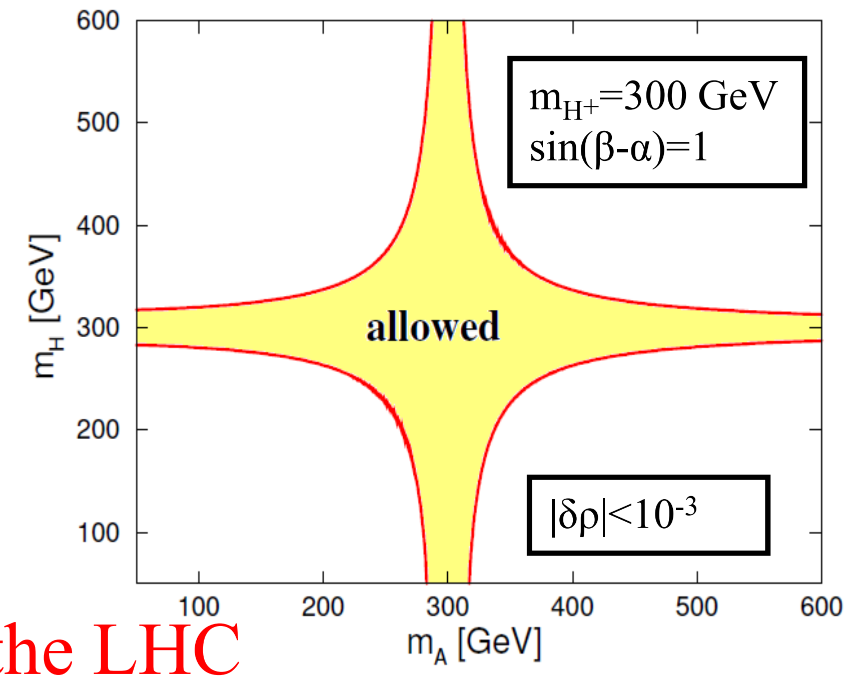
- Scenario

$m_A = m_H = m_{H+}$:130~150GeV

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

$M \sim m_A = m_H = m_{H+}$

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



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

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

(ATLAS TDR)

$\tan\beta=10$, $m_A=150$GeV, MSSM

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

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 $p_T>15$GeV and $\eta<2.5$.
- τ τ's invariant mass cut.

  $m_{\tau\tau}-1.5\sigma<m_{\tau\tau}< m_{\tau\tau}+1.5\sigma$

  $\sigma\sim27$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 $p_T>15$GeV and $\eta<3.2$.
- τ τ's invariant mass cut.

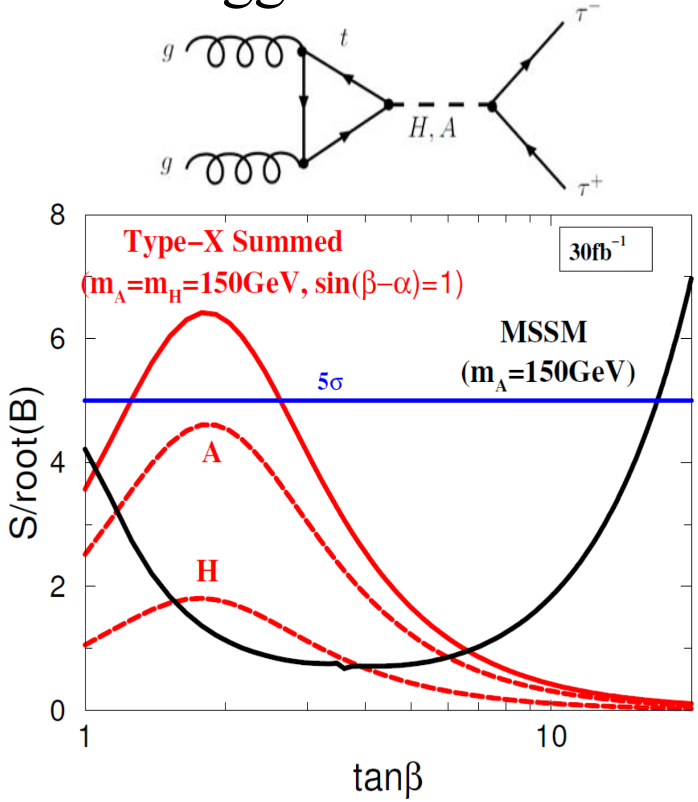
  $m_{\tau\tau}-1.5\sigma<m_{\tau\tau}< m_{\tau\tau}+1.5\sigma$

  $\sigma\sim39$GeV

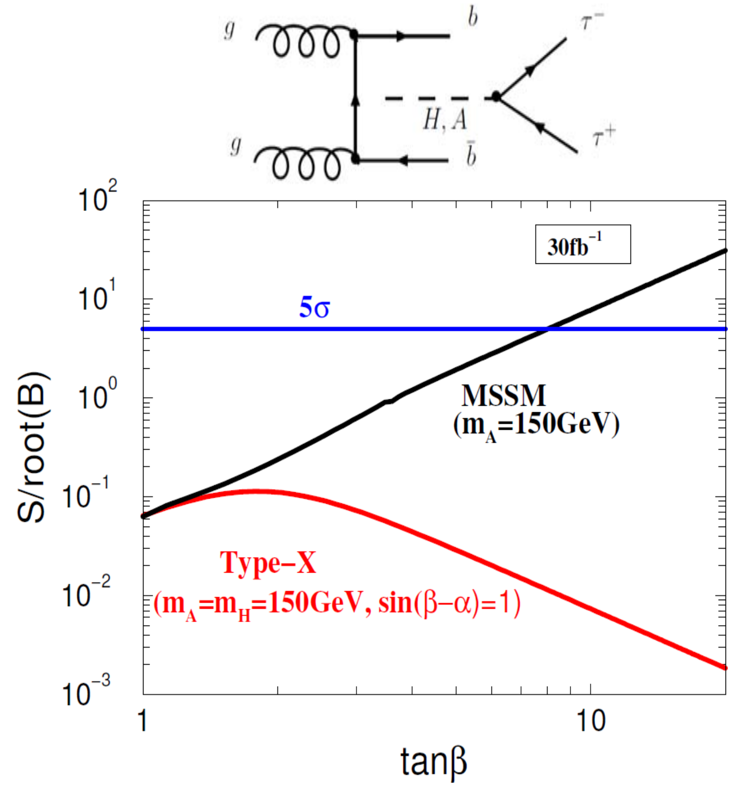
Significance (S/root(B))

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

$gg \to \tau^+\tau^-$

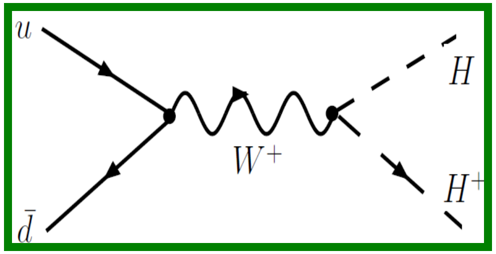


$pp \to bb\tau^+\tau^-$



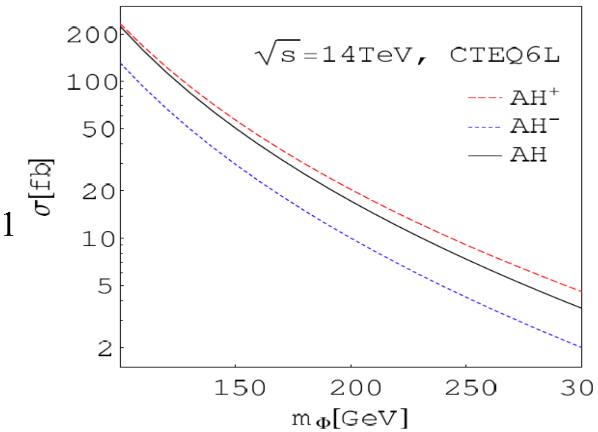
	Low tanβ	Mid tanβ	High tanβ
Type-X	**Direct**		
MSSM			**Direct** **Associate**

AH$^+$ (HH$^+$) production at the LHC (300fb^{-1})



σ(ud→HH$^+$)～100fb

30000 AH$^+$ (HH$^+$) events at 300fb^{-1}



bbτν final states

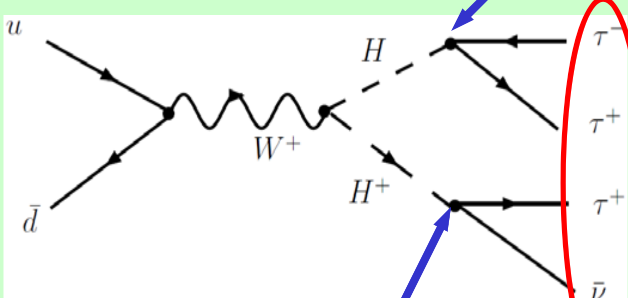
detailed analysis: ***Cao, Kanemura, Yuan hep-ph/0402226***

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

ττν final states

BR(H→τ$^+$ τ$^-$)～100%

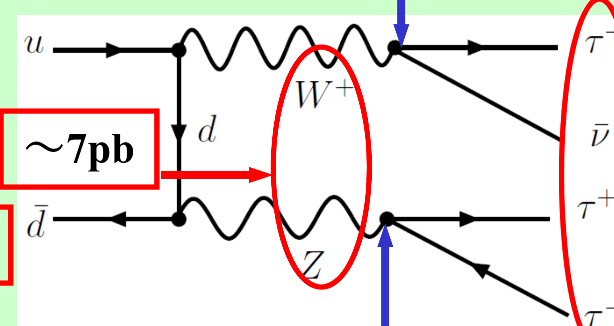
BR(W$^+$→τ$^+$ν)～10%



~30000 events

BR(H$^+$→τ$^+$ν)～100%

～7pb



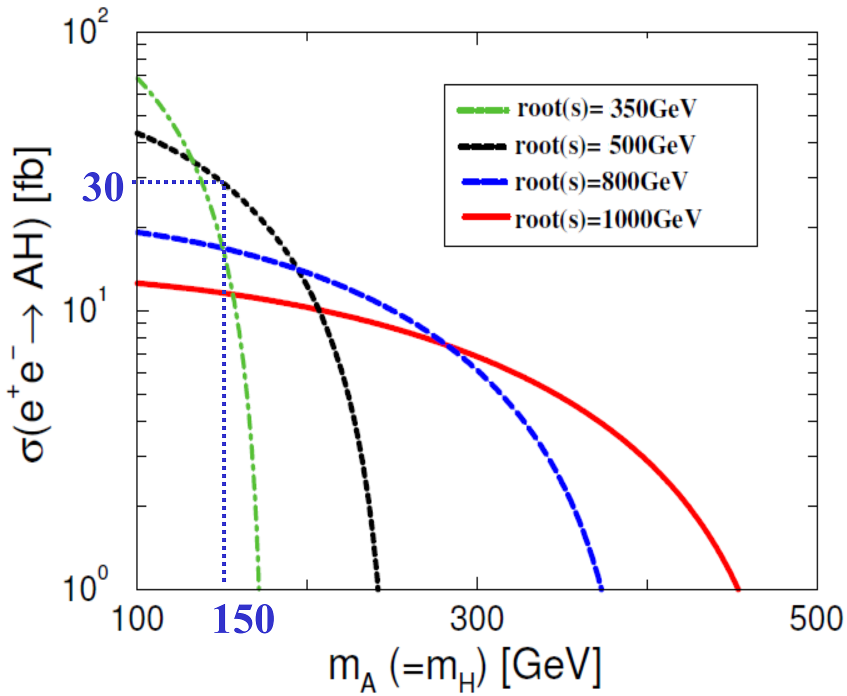
BR(Z→τ$^+$ τ$^-$)～3%

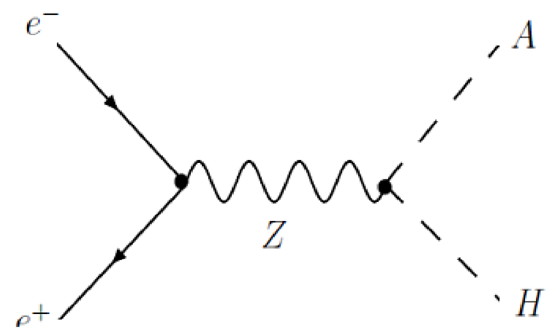
~6300 events

bbτν→MSSM (Type-II) ττν→Type-X

Physics of the Type-X THDM at the ILC

Discrimination of the models at the ILC





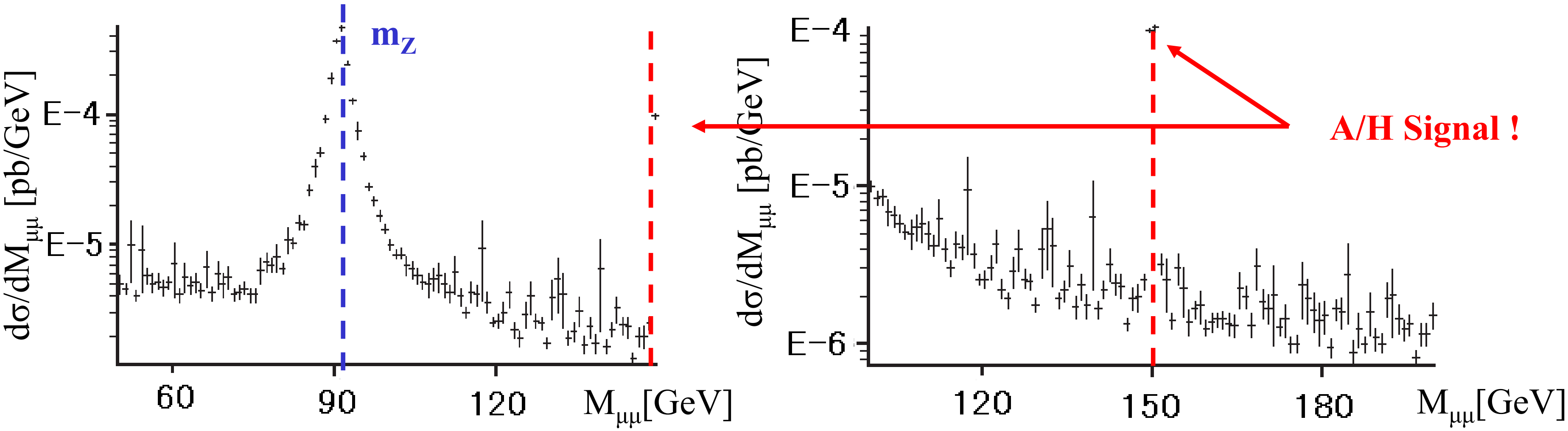
m_A=m_H=150GeV, sin(β-α)=1, tanβ=10
and root(s)=500GeV

	Type-II	Type-X
BR (A/H→ττ)	0.105	0.995
BR (A/H→μμ)	***O*** (10^{-4})	0.003

Type-X branching ratio of leptonic decay is much larger than Type-II one.
The **ττμμ** and **ττττ** mode are valuable to study
the Type-X Yukawa interaction.

Signal background analysis for ττμμ events

The **μμ** 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
$\lvert\cos\theta\rvert < 0.99$	0.190	0.912	1.67	0.974
$\lvert\cos\theta\rvert < 0.9$	0.179	0.647	0.103	0.585
$M_{\mu\mu} \lessgtr m_\Phi \pm 5$ GeV	0.191	0.002	0.009	0.007

For L=500fb^{-1}

After invariant mass cuts

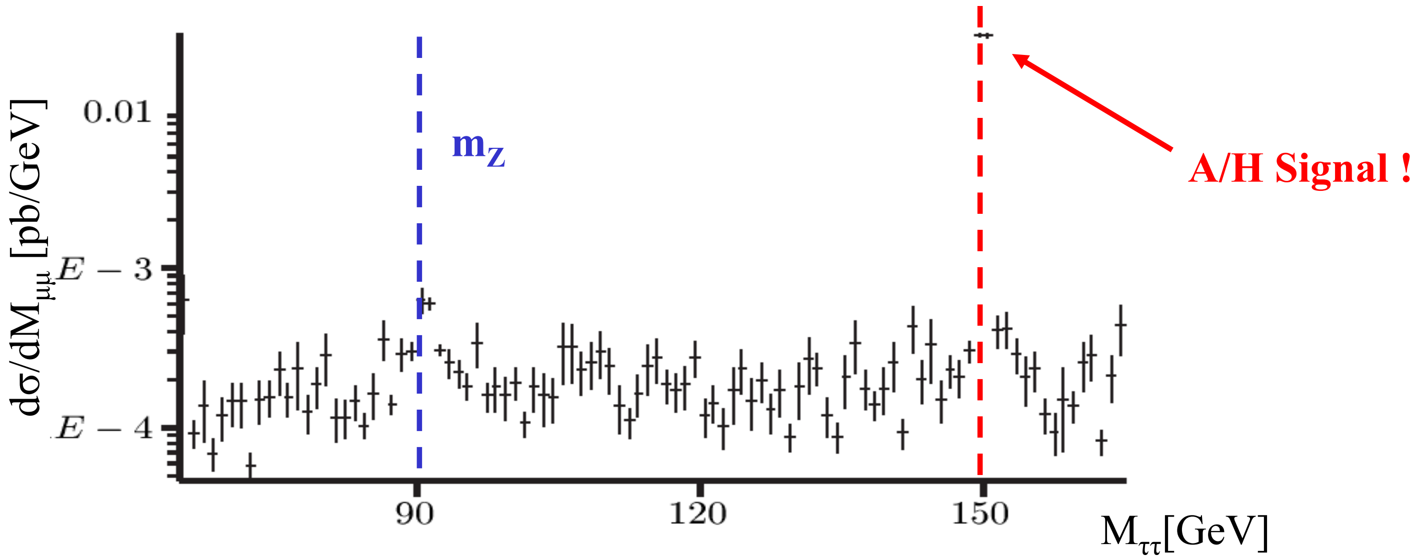
S~96

B~9

Taking kinematical cuts we can obtain S/Sqrt(S+B) ~ 9

Signal background analysis for ττ ττ events

The **ττ** invariant mass distribution

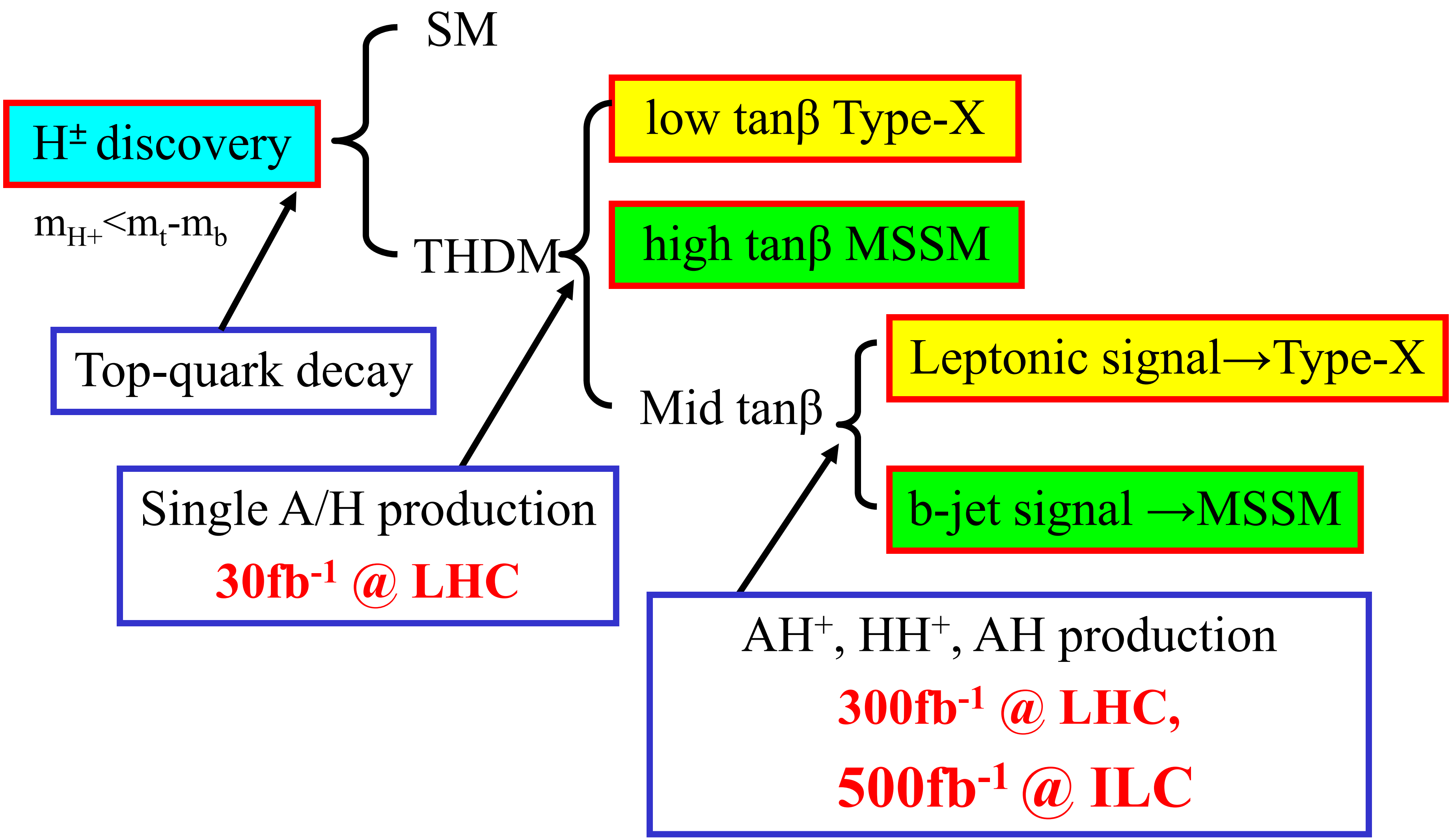


$\sigma_{\tau\tau\tau\tau}$ [fb]	AH	ZZ	$Z\gamma$	$\gamma\gamma$
No cut	27.0	0.482	0.804	0.371
$\lvert\cos\theta\rvert < 0.99$	26.5	0.449	0.645	0.269
$\lvert\cos\theta\rvert < 0.9$	25.0	0.324	0.423	0.171
$M_{\tau\tau} \lessgtr m_\Phi \pm 15$ GeV	14.7	0.021	0.039	0.021

For $L=500fb^{-1}$
After cuts
S~7350
B~41

Taking kinematical cuts we can obtain S/Sqrt(S+B) ~ 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.

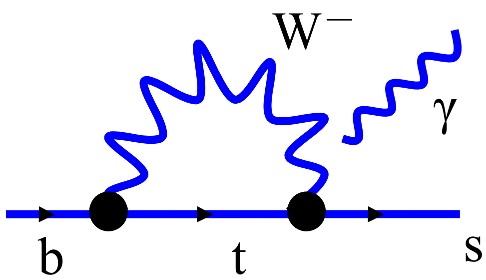
- The Type-II THDM corresponds to the MSSM Yukawa interaction, while the Type-X is motivated such as in the TeV scale model of neutrino, dark matter, and baryogenesis.

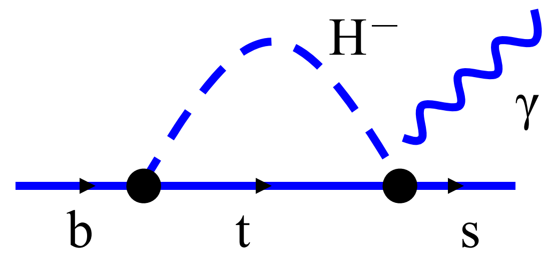
- In the Type-X, $b \to s\gamma$ bound is very mild.
  $\to$ Light charged Higgs scenario is possible.

- 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→sγ





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

Barger, Hewett, Phillips PRD 41 (1990)

Type-II, Y

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

Type-I, X

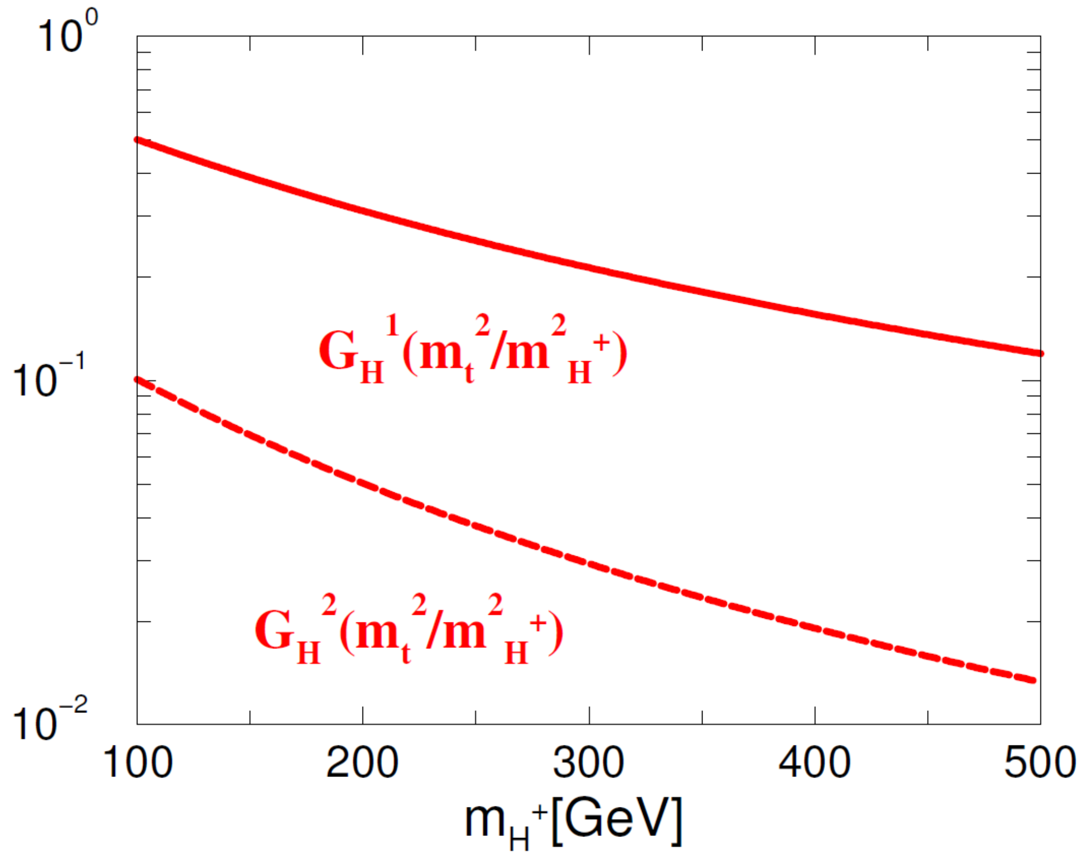
$$\Gamma(b\to s\gamma)=\frac{\alpha_{EM}G_F^2 m_b^5}{128\pi^4}\left|V_{ts}^*V_{tb}\left[G_W\left(\frac{m_t^2}{m_W^2}\right)-\cot^2\beta G_H^1\left(\frac{m_t^2}{m_{H^\pm}^2}\right)+\cot^2\beta G_H^2\left(\frac{m_t^2}{m_{H^\pm}^2}\right)\right]\right|^2$$

In the Type-X THDM, destructive interferences occur between the W and the $H^\pm$ contributions.

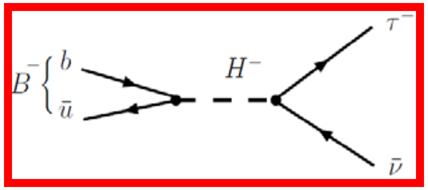
$$G_W(x) = \frac{2-7x+11x^2}{4(1-x)^3} - \frac{1}{2} + \frac{3x^3}{2(1-x)^4}\ln x + \frac{2}{3}\left[\frac{1-5x-2x^2}{4(1-x)^3} - \frac{1}{4} - \frac{3x^2}{2(1-x)^4}\ln x\right]$$

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

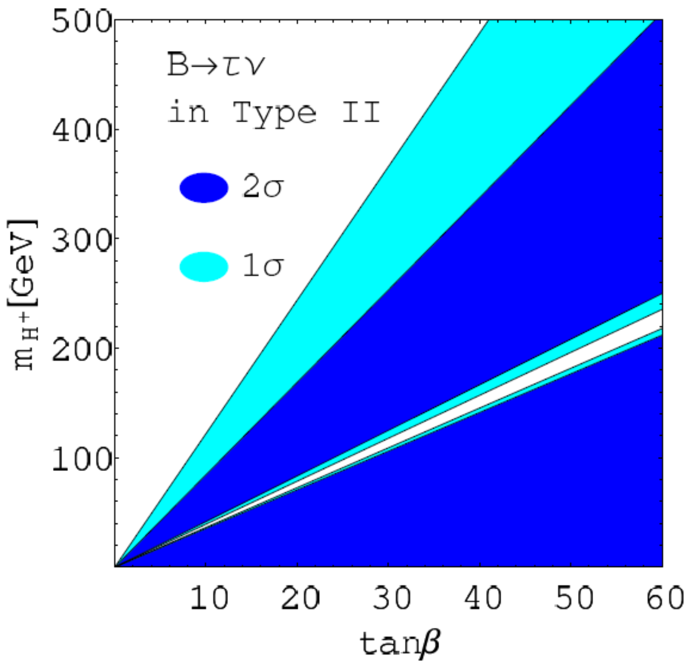
$$G_H^2(x) = \frac{x}{2(1-x)^4}\left[\left(\frac{1}{6} - x + \frac{1}{2}x^2 + \frac{1}{3}x^3 - x^2\ln x\right) + \frac{2}{3}\left(\frac{1}{3} + \frac{1}{2}x - x^2 + \frac{1}{6}x^3 + x\ln x\right)\right]$$



B→τν

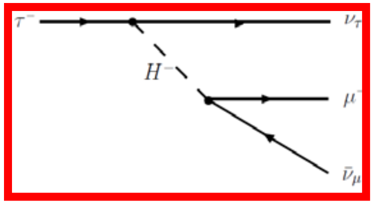


$$\frac{\Gamma^{\rm THDM}_{B^-\to\tau^-\nu}}{\Gamma^{\rm SM}_{B^-\to\tau^-\nu}} \sim \begin{cases} \left[1-\frac{m_B^2}{m_{H^\pm}^2}\tan^2\beta\right]^2 & \text{:Type-II} \\ \left[1-\frac{m_B^2}{m_{H^\pm}^2}1\right]^2 & \text{:Type-X} \end{cases}$$

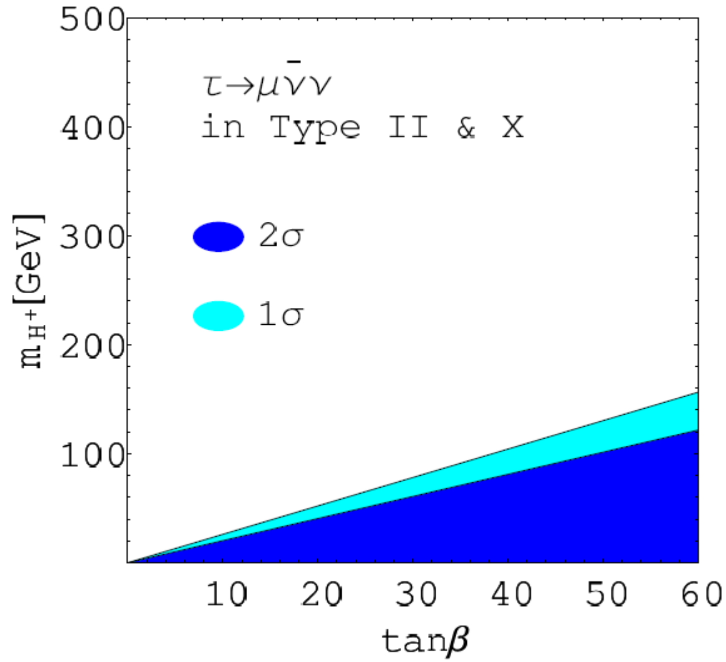


Type-X no bound

τ→μνν



$$\frac{\Gamma^{\rm THDM}_{\tau^-\to\mu^-\nu\bar\nu}}{\Gamma^{\rm SM}_{\tau^-\to\mu^-\nu\bar\nu}} \sim 1-\frac{2m_\mu^2}{m_{H^\pm}^2}\tan^2\beta$$



If m_{H+}>100GeV, then tanβ=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-