Light charged Higgs boson scenario in 3HMDs

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Based on A. Akeroyd, S. Moretti, KY, E. Yildirim, arXiv: 1605.05881

KY, arXiv: 1609.04590

Charged 2016

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1 doublet is confirmed, then?

- Higgs discovery in h → τ τ : Existence an $SU(2)_L$ doublet scalar.

$$y\overline{L_L}\Phi\tau_R$$

$SU(2)_L\times U(1)_Y \sim$ (**2**, 1/2) (**1**, -1)

The unique solution is Φ ~ (**2**, 1/2)

- Question: How many doublets are there?

$$\Phi_1,\ \Phi_2,\ \ldots,\Phi_N??$$

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- Question: How many doublets are there?

$$\Phi_1,\ \Phi_2,\ \ldots,\Phi_N??$$

- MHDMs automatically satisfy $\rho_{tree} = 1$.

- MHDMs can reproduce predictions in the minimal Higgs sector.

- MHDMs appear in many new physics beyond the SM.

New Physics & Multi-Doublet Models

New Physics		Higgs Sector
SUSY	→	At least 2 doublets
Composite Higgs models	→	Depends on a coset space ex, $SO(6)/SO(4)\times SO(2)$ → 2HDM
Extended EWGS	→	Multi-doublet structure appears in a low energy effective theory.
BSM phenomena (Neutrino masses, DM, Baryon asymmetry, Muon g-2, ⋯)	→	Additional doublets are often introduced.

New Physics & Multi-Doublet Models

New Physics

- SUSY
- Composite Higgs models
- Extended EWGS

Higgs Sector

At least 2 doublets

Depends on a coset space

ex, SO(6)/SO(4)×SO(2) → 2HDM

Multi-doublet structure appears in

In this talk, we discus the phenomenology of **charged Higgs bosons** and its difference between in 2HDMs and 3HDMs.

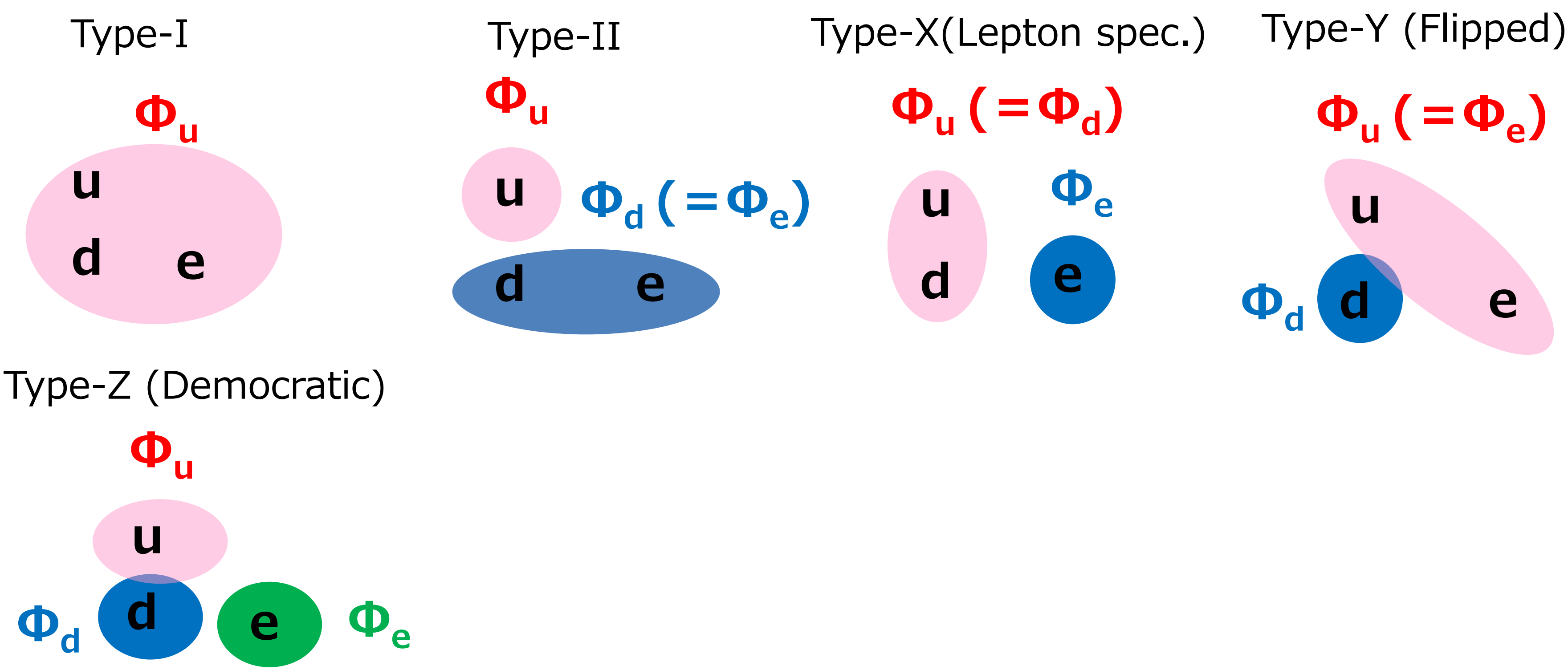
Baryon asymmetry, Muon g-2, ⋯)

Type of Yukawa interaction in NFC

Glashow, Weinberg (1977); Grossman (1994)

- Simple way to **naturally** avoid the tree level FCNCs is to consider the Lagrangian.

$$-\mathcal{L}_Y = Y_u \bar{Q}_L (i\sigma_2)\Phi_u^* u_R + Y_d \bar{Q}_L \Phi_d d_R + Y_e \bar{L}_L \Phi_e e_R + \text{h.c.}$$



Content

- Introduction
- Charged Higgs bosons in 2HDMs and 3HDMs
- Phenomenology
  - Flavour physics
  - Collider physics
- Summary

2HDM/3HDM

2HDM

- 4 types of Yukawa int.
- Higgs basis (one angle)

$$\begin{pmatrix}\Phi_1\\ \Phi_2\end{pmatrix} = \begin{pmatrix}\cos\beta & -\sin\beta\\ \sin\beta & \cos\beta\end{pmatrix}\begin{pmatrix}\Phi\\ \Psi\end{pmatrix}$$

Φ ← v, NGBs

Ψ ← $H^\pm$

$\tan\beta = v_2/v_1$

- 1 pair of $H^\pm$
- 2 parameters: $\tan\beta$, $mH^\pm$

3HDM (See also *Cree & Logan PRD84, 2011*)

- 5 types of Yukawa int.
- Higgs basis (two angles)

$$\begin{pmatrix}\Phi_1\\ \Phi_2\\ \Phi_3\end{pmatrix} = R_{13}(\gamma)R_{12}(\beta)\begin{pmatrix}\Phi\\ \Psi_1\\ \Psi_2\end{pmatrix}$$

Φ ← v, NGBs

Ψ_1 ← $\tilde{H}_1^\pm$

Ψ_2 ← $\tilde{H}_2^\pm$

R_{ij}: (i-j) rot.

$$\tan\beta = v_2/\sqrt{v_1^2+v_3^2}$$

$$\tan\gamma = v_3/v_1$$

$$\begin{pmatrix}\tilde{H}_1^\pm\\ \tilde{H}_2^\pm\end{pmatrix} = \begin{pmatrix}\cos\theta_C & -\sin\theta_C\\ \sin\theta_C & \cos\theta_C\end{pmatrix}\begin{pmatrix}H_1^\pm\\ H_2^\pm\end{pmatrix}$$

- 2 pairs of $H^\pm$
- 5(+1) para: β, γ, θ_C $mH_1^\pm$, $mH_2^\pm$ (δ_{cp})

Yukawa interactions

- Yukawa Lagrangian is given in the Higgs basis as

$$\mathcal{L}_Y = \bar{Q}_L Y_d \Phi_d d_R + \cdots$$

$$= \frac{\sqrt{2}}{v} \bar{Q}_L M_d [\Phi + \underline{\textstyle\sum_a \xi_d^a \Psi_a}] d_R + \cdots$$

Charged Higgs couplings

Interaction of charged Higgs bosons

$$-\mathcal{L}_Y = \frac{\sqrt{2}}{v}\sum_a \left[X_a \bar{u}(V_{\rm CKM} m_d P_R)d + Y_a \bar{u}(m_u V_{\rm CKM} P_L)d + Z_a \bar{\nu}(m_e P_R)e\right]H_a^+$$

2HDM

$X = \xi_d$, $Y = -\xi_u$, $Z = \xi_e$

	ξ_u	ξ_d	ξ_e
Type-I	cotβ	cotβ	cotβ
Type-II	cotβ	-tanβ	-tanβ
Type-X	cotβ	cotβ	-tanβ
Type-Y	cotβ	-tanβ	cotβ

3HDM

$$\begin{pmatrix} X_1 \\ X_2 \end{pmatrix} = \begin{pmatrix} c_C & s_C \\ -s_C & c_C \end{pmatrix}\begin{pmatrix} \xi_d^1 \\ \xi_d^2 \end{pmatrix} \quad \begin{pmatrix} Y_1 \\ Y_2 \end{pmatrix} = -\begin{pmatrix} c_C & s_C \\ -s_C & c_C \end{pmatrix}\begin{pmatrix} \xi_u^1 \\ \xi_u^2 \end{pmatrix} \quad \begin{pmatrix} Z_1 \\ Z_2 \end{pmatrix} = \begin{pmatrix} c_C & s_C \\ -s_C & c_C \end{pmatrix}\begin{pmatrix} \xi_e^1 \\ \xi_e^2 \end{pmatrix}$$

	ξ_u^1	ξ_d^1	ξ_e^1	ξ_u^2	ξ_d^2	ξ_e^2
Type-I	cotβ	cotβ	cotβ	0	0	0
Type-II	cotβ	-tanβ	-tanβ	0	-tanγ/cosβ	-tanγ/cosβ
Type-X	cotβ	cotβ	-tanβ	0	0	-tanγ/cosβ
Type-Y	cotβ	-tanβ	cotβ	0	-tanγ/cosβ	0
Type-Z	cotβ	-tanβ	-tanβ	0	-tanγ/cosβ	cotγ/cosβ

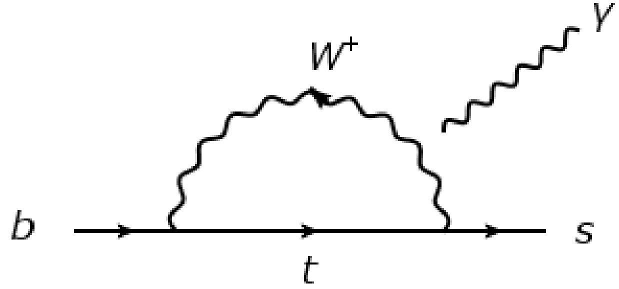
$b \to s\gamma$ (leading order)

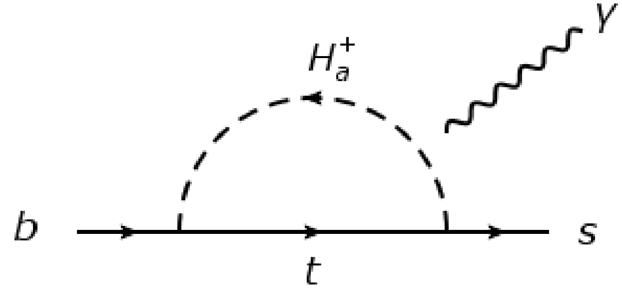
- Effective Lagrangian w/ m_s = 0 (integ. out the heavy d.o.f. e.g., W, t, $H^\pm$)

$$\mathcal{L}_{\rm eff} \supset \frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} C_7(\mu)\mathcal{O}_7(\mu)$$

Dim. 6 dipole operator:

$$\mathcal{O}_7(\mu) = \frac{e}{16\pi^2}\bar{m}_b(\mu)(\bar{s}_L\sigma^{\mu\nu}b_R)F_{\mu\nu}$$





$$C_7(\mu, m_{H_a^\pm}) = C_{7,{\rm SM}}(\mu) + \sum_a \left[(X_a Y_a^*)C_{7,XY}(\mu, m_{H_a^\pm}) + |Y_a|^2 C_{7,YY}(\mu, m_{H_a^\pm})\right]$$

b → s γ (leading order)

- Effective Lagrangian w/ $m_s = 0$ (integ. out the heavy d.o.f. e.g., W, t, $H^\pm$)

$$\mathcal{L}_{\rm eff} \supset \frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} C_7(\mu)\mathcal{O}_7(\mu)$$

Dim. 6 dipole operator:

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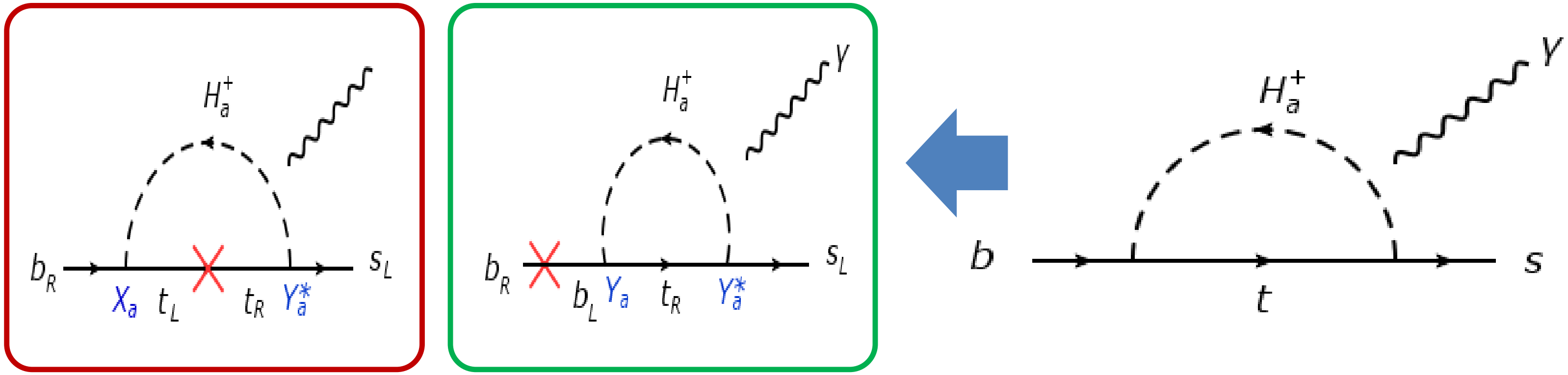
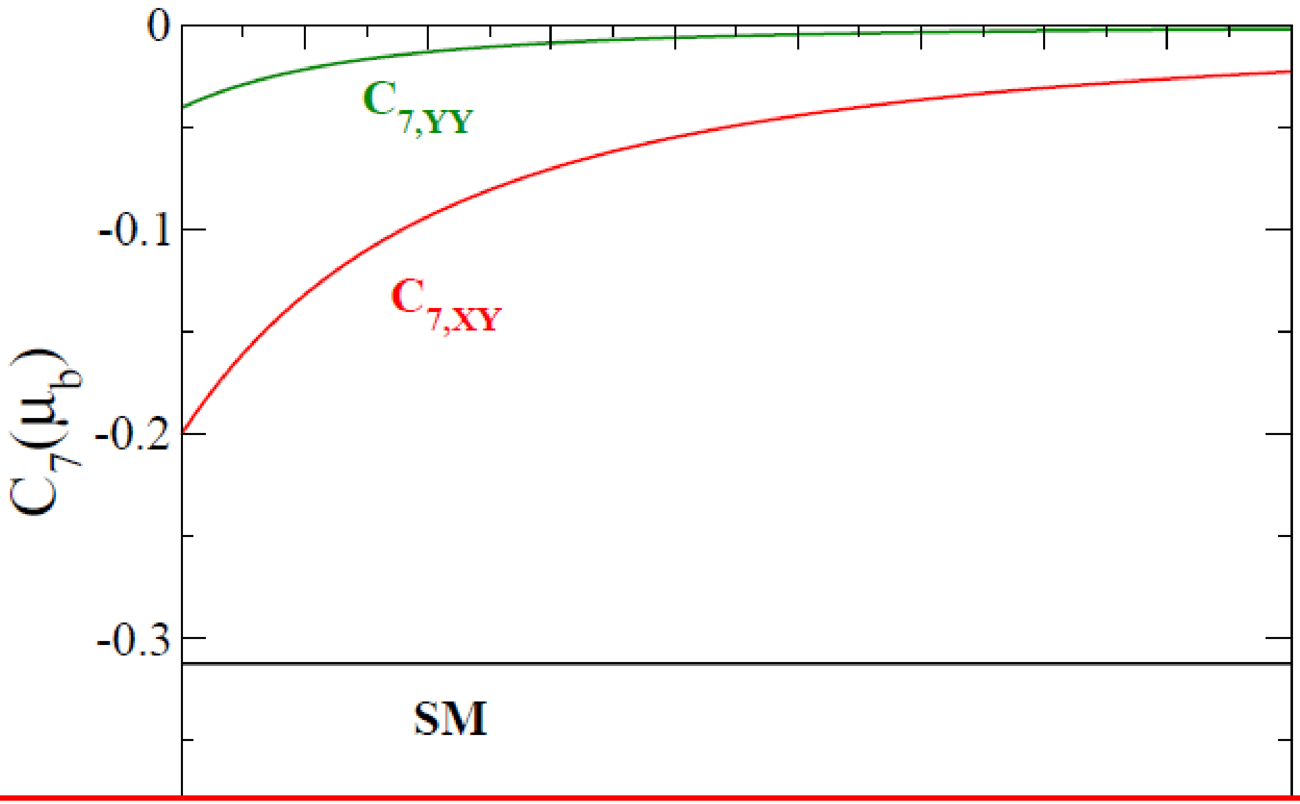


$$C_7(\mu, m_{H_a^\pm}) = C_{7,\rm SM}(\mu) + \sum_a \left[(X_a Y_a^*)C_{7,XY}(\mu, m_{H_a^\pm}) + |Y_a|^2 C_{7,YY}(\mu, m_{H_a^\pm})\right]$$

$$\Gamma(b \to s\gamma) = \frac{G_F^2}{32\pi^4}|V_{ts}^* V_{tb}|^2 \alpha_{\rm em} m_b^5 |C_7(\mu = \mu_b)|^2$$

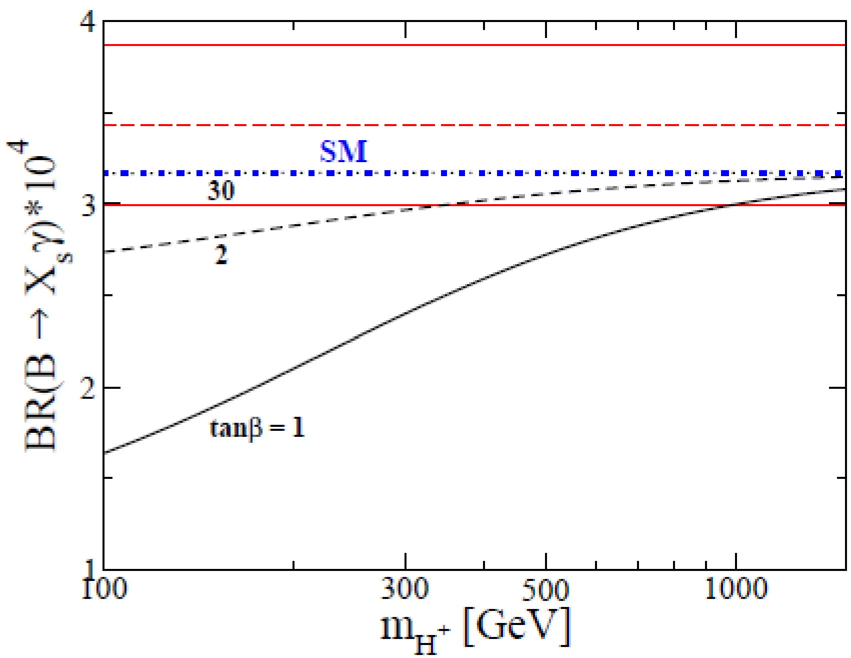
Wilson Coefficient at LO



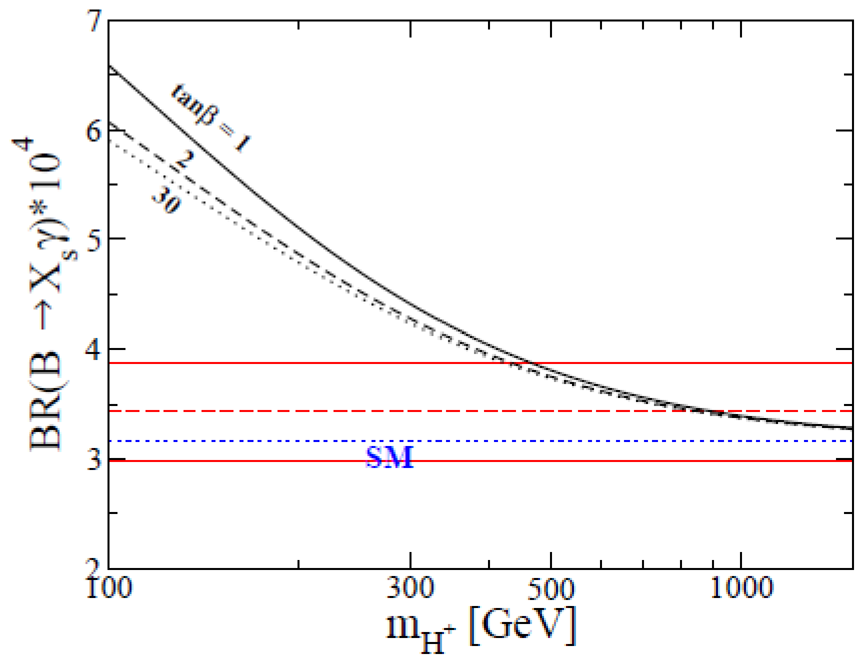
X Y* > 0 : Constructive, X Y* < 0 : Destructive

$B \to X_s \gamma$ @NLO (2HDM)

Type-I, X ($XY^* = -\cot^2\beta$)



Type-II, Y ($XY^* = +1$)

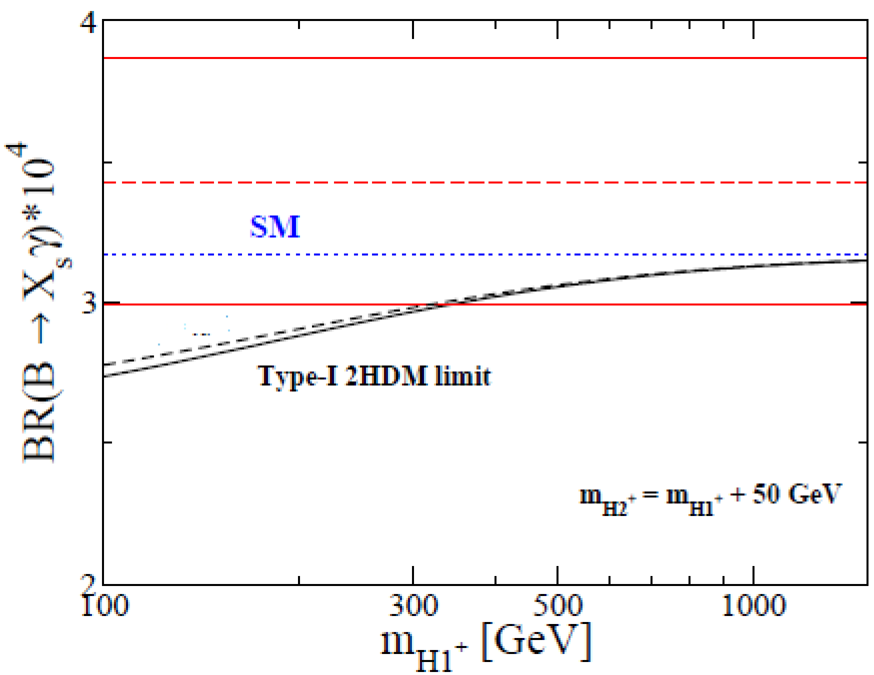


Type-I, -X: Light charged Higgs is strongly constrained only low tanβ

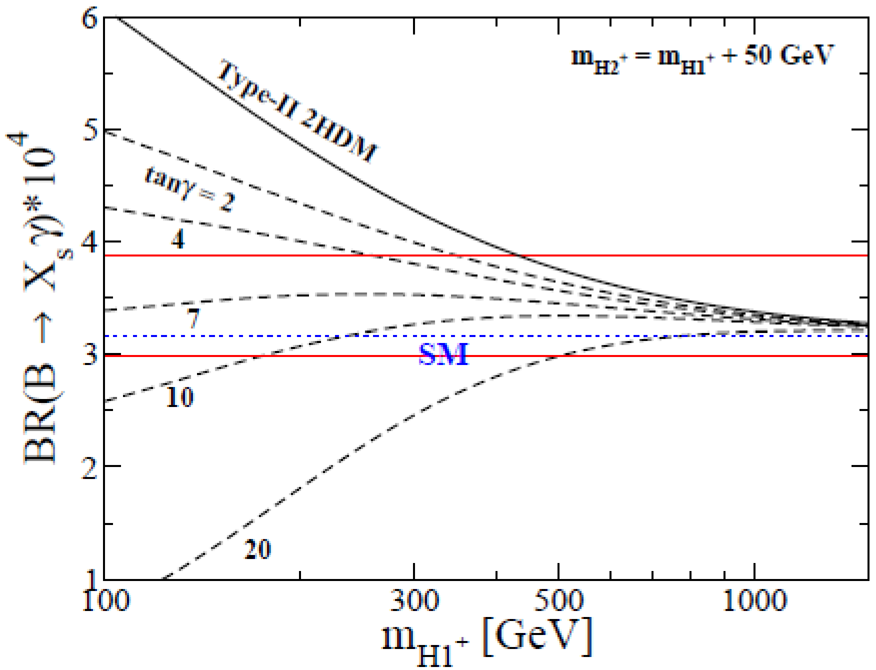
Type-II, -Y: mH+ > ~450 GeV (480 GeV@ NNLO, *Misiak, et.al*)

$B \to X_s \gamma$ @NLO (3HDM, $\tan\beta = 2$, $\theta_C = -\pi/4$)

Type-I, X (no γ dependence)



Type-II, Y, Z



Type-I, X: Almost the same as in the 2HDM

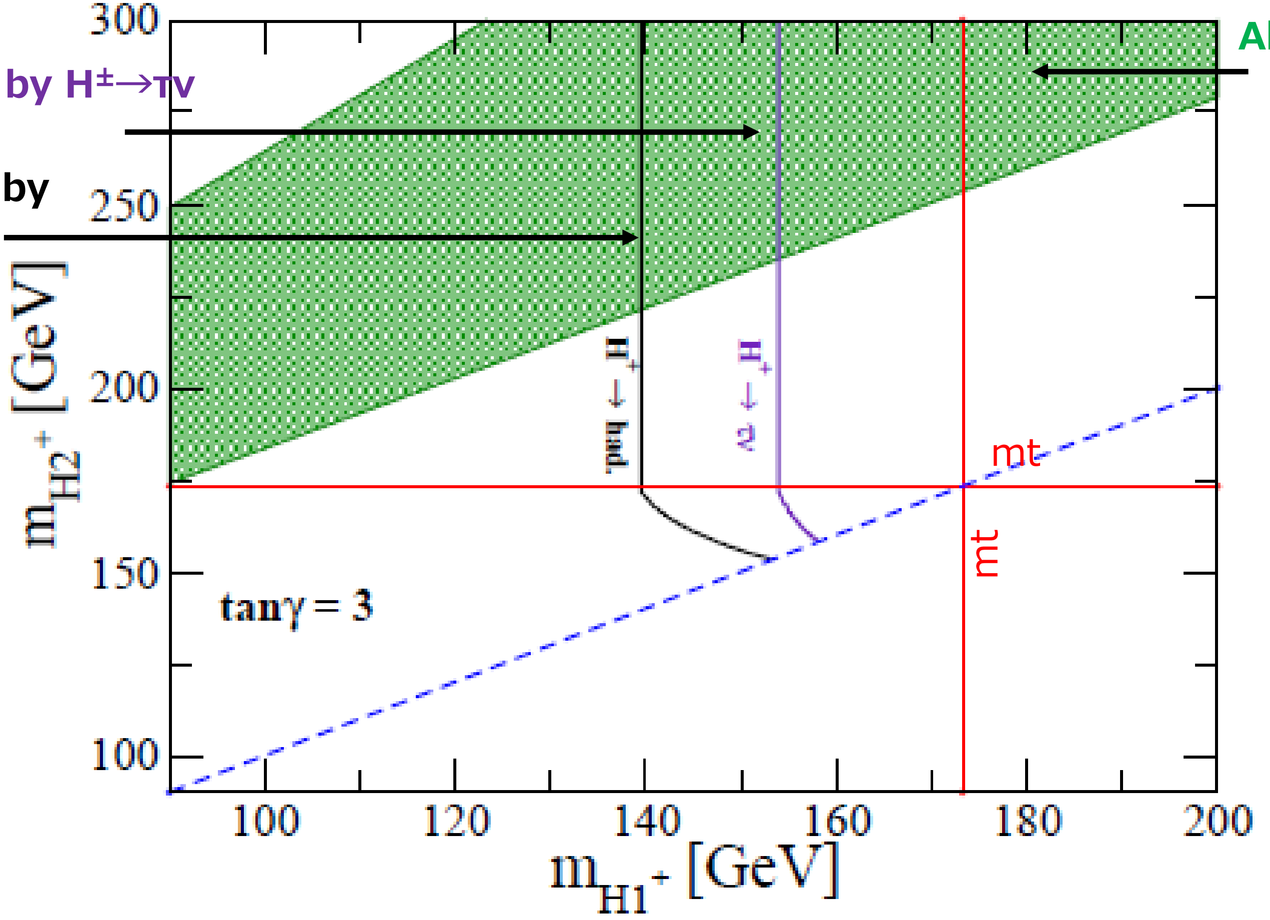
Type-II, Y, Z: Cancellation happens when $\tan\gamma \neq 0$. Light $H^\pm$ is possible.

Allowed regions (3HDM-Y, $\tan\beta = 2$, $\theta_C = -\pi/4$)

Excluded by $H^{\pm} \to \tau\nu$

Excluded by $H^{\pm} \to jj$

Allowed by $B \to X_s \gamma$



Allowed regions (3HDM-Y, tanβ =2, θ_C = -π/4)

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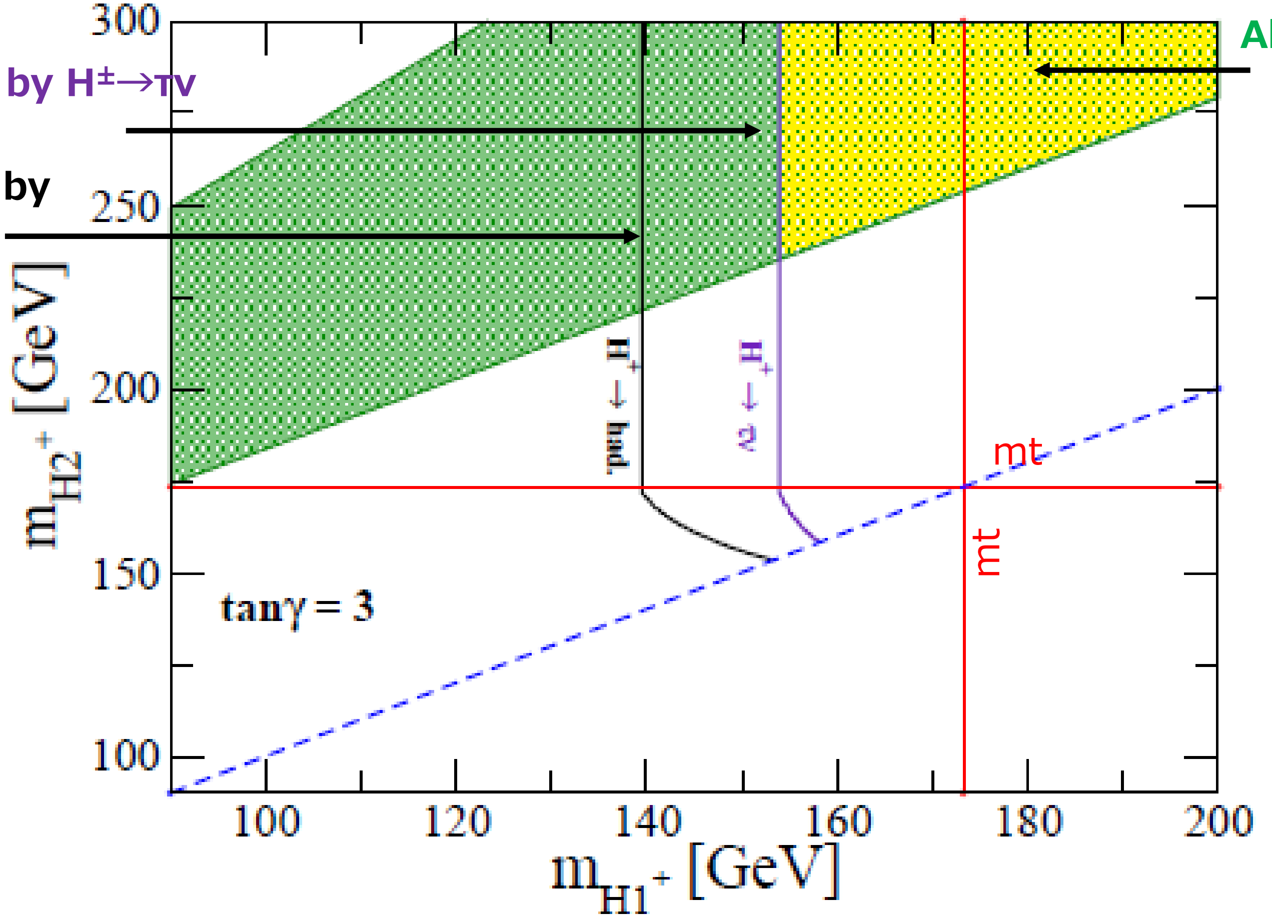
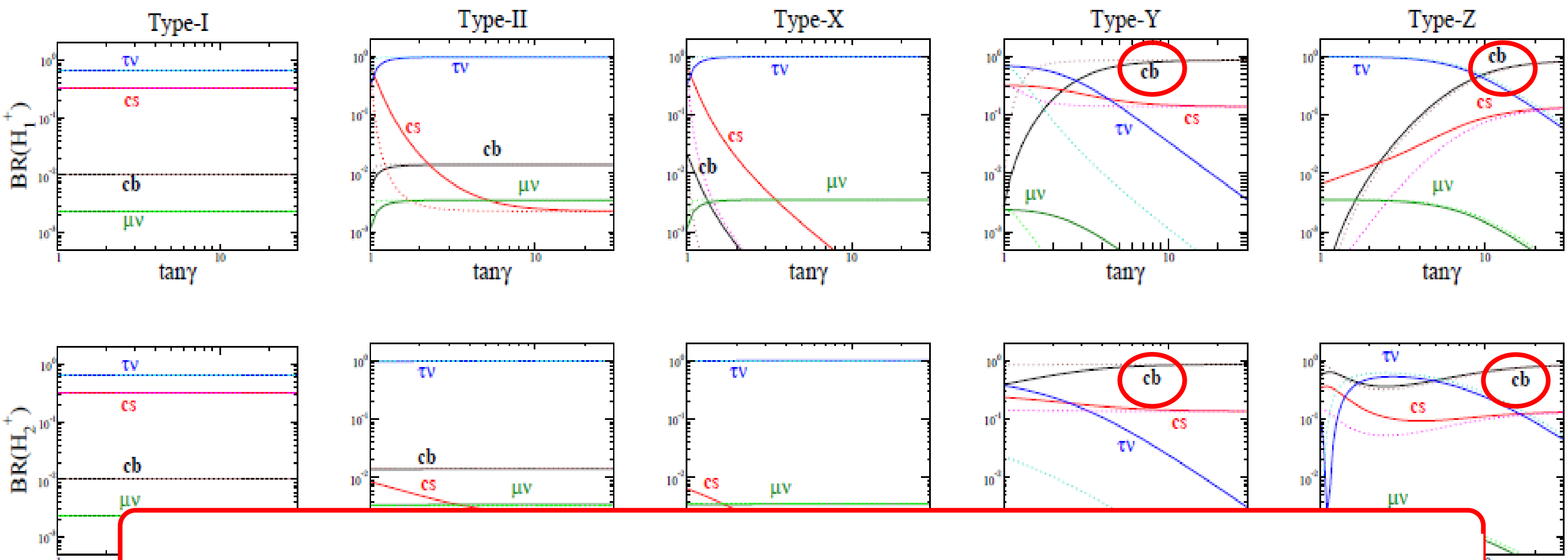


Decay of charged Higgs bosons

See also for 2HDMs; Aoki, Kanemura, Tsumura, KY *PRD80, 2009*

3HDM, m_{H1} = 100 GeV, m_{H2} = 150 GeV, $\tan\beta$ = 2 (5), θ_c = $-\pi/4$

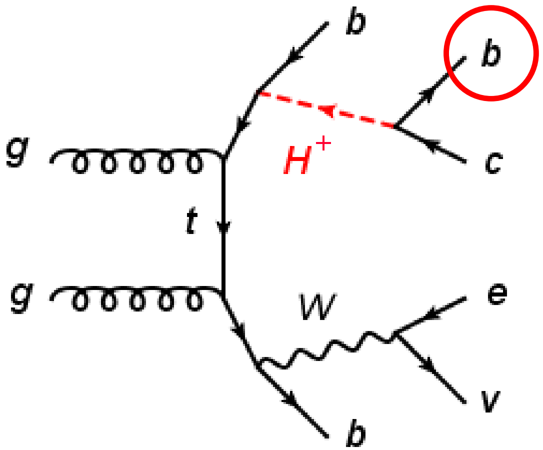


★**In 2HDM-Y, $H^+ \to cb$ can be dominant, but $b\to s\gamma$.**

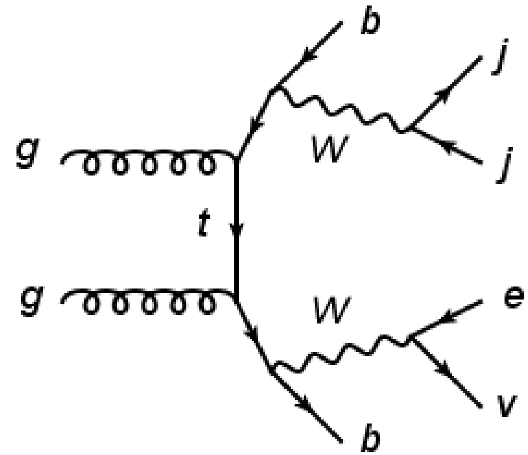
★ **$H^+ \to cb$ can be the smoking gun sig. of the 3HDM!**

Collider signatures

Signal



Background



Akeroyd, Moretti, Hernandez-Sanchez, PRD85 (2012)

$$\frac{[S/\sqrt{B}]_{\rm btag}}{[S/\sqrt{B}]_{\not{b}{\rm tag}}} \sim \frac{\epsilon_b\sqrt{2}}{\sqrt{(\epsilon_j+\epsilon_c)}} \sim 2.13.$$

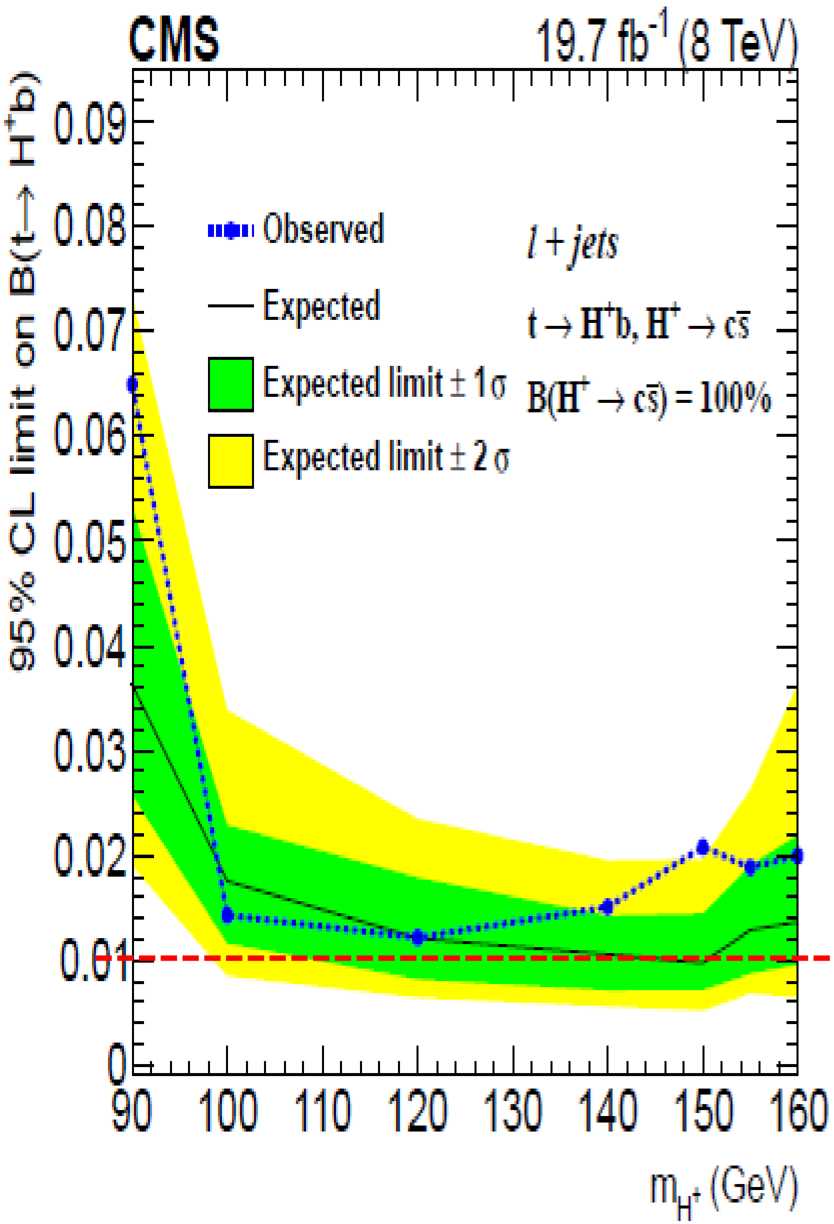
ε_b (b tagging eff.)= 0.5

ε_c (c miss tagging rate)= 0.1

ε_j (j miss tagging rate)= 0.01

★3rd b-quark tagging is important to reduce the BG!

1510.04252 hep-ex [CMS]



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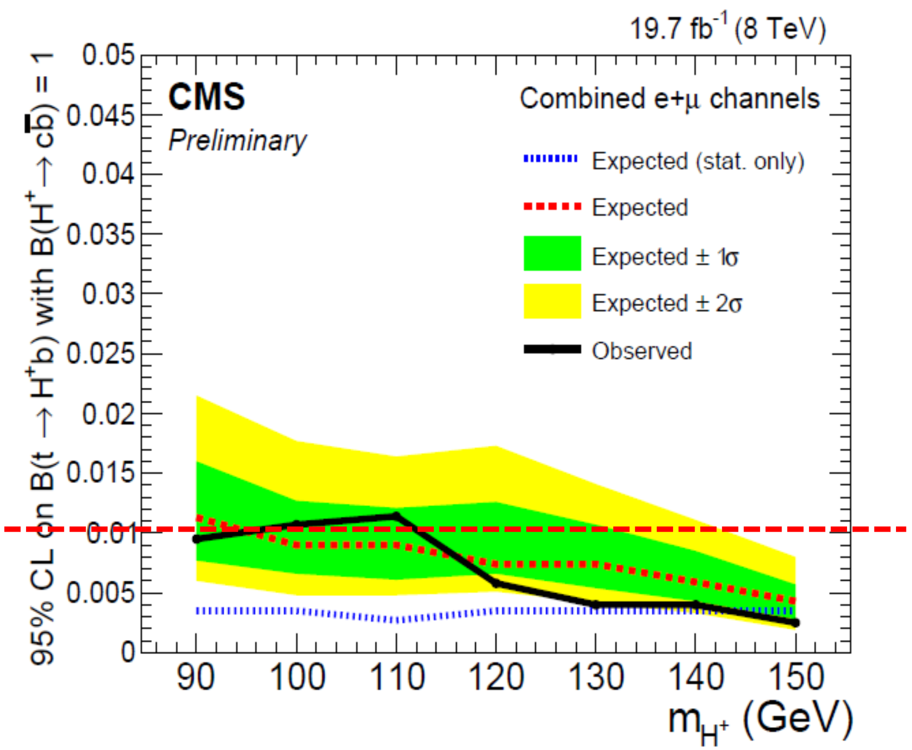
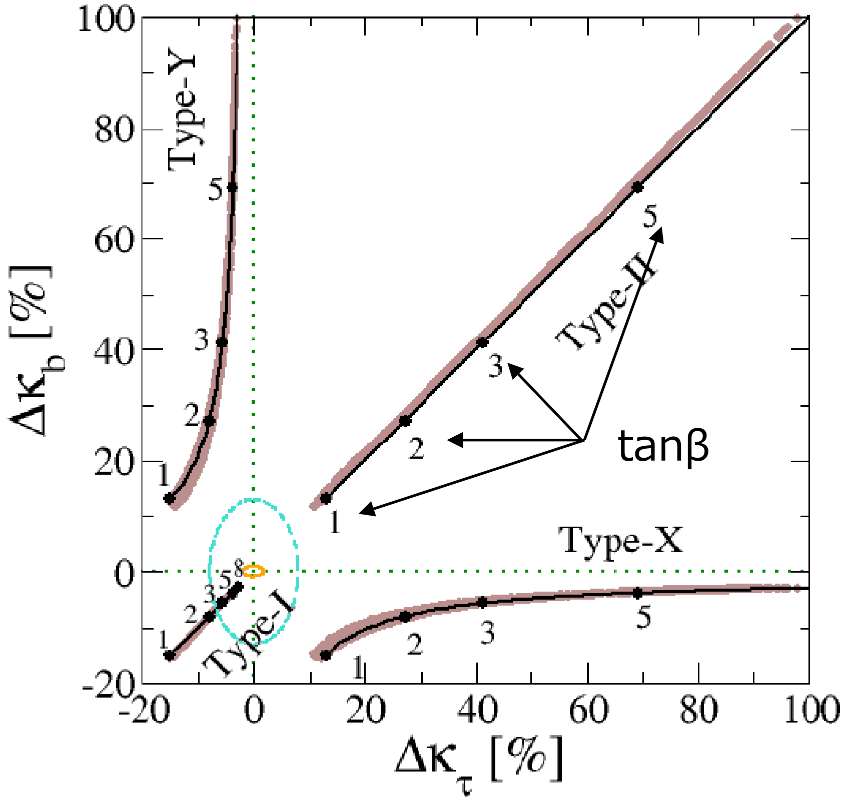


h(125) couplings ($\Delta\kappa_X = g_{hXX}^{3HDM}/g_{hXX}^{SM} - 1$)

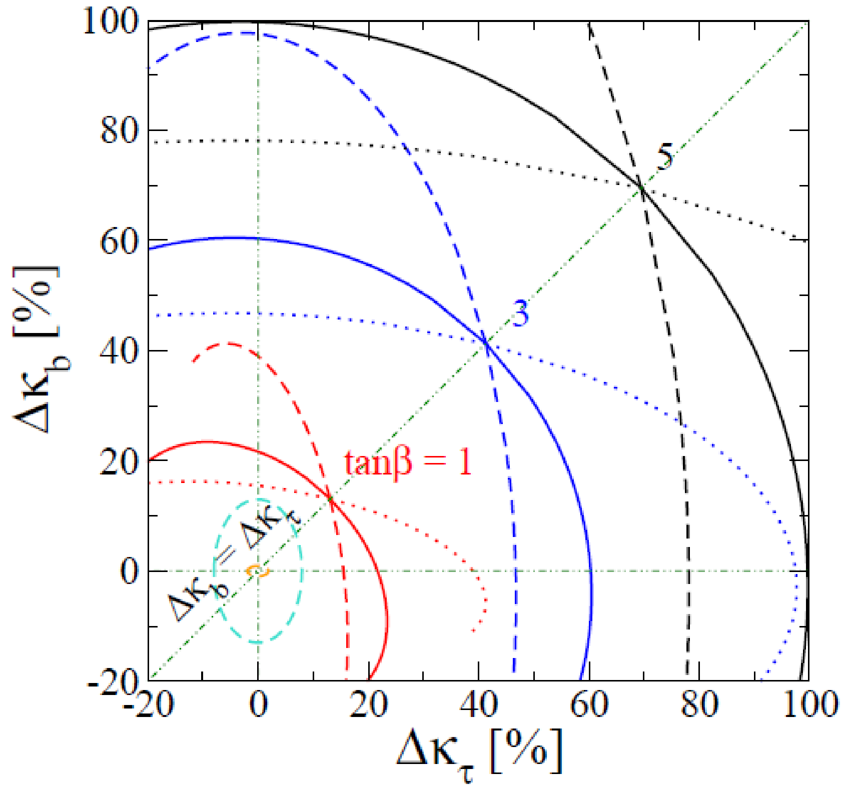
Under $\Delta\kappa_V = -1\%$, $\Delta\kappa_t < 0$

tanγ = 1 (solid)
tanγ = 2 (dash)
tanγ = ½ (dot)
Others are scanned

2HDM



3HDM (Type-Z)



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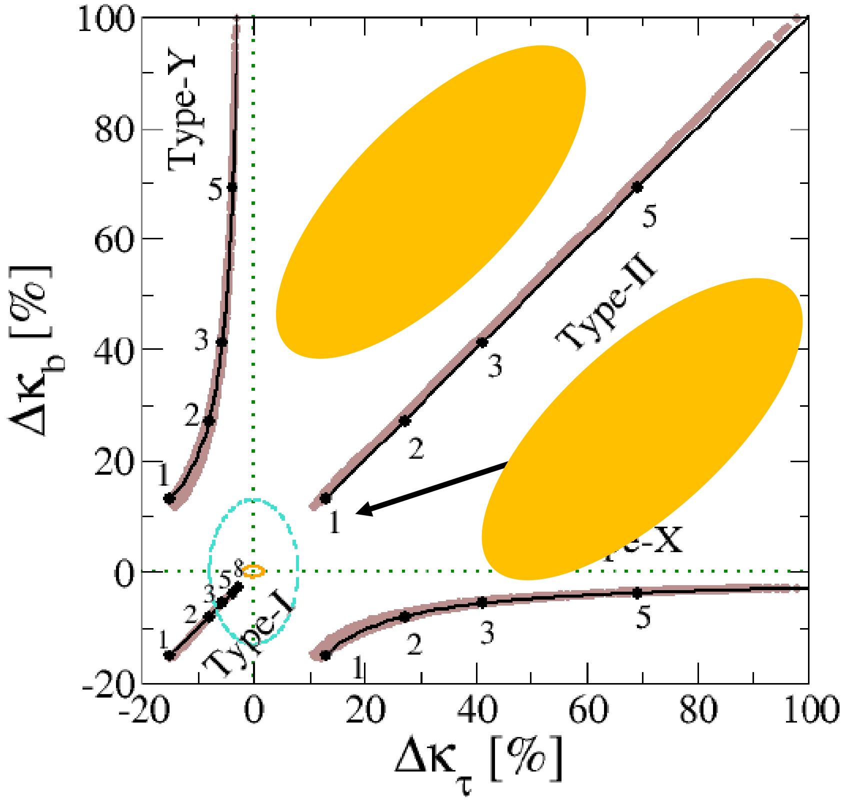
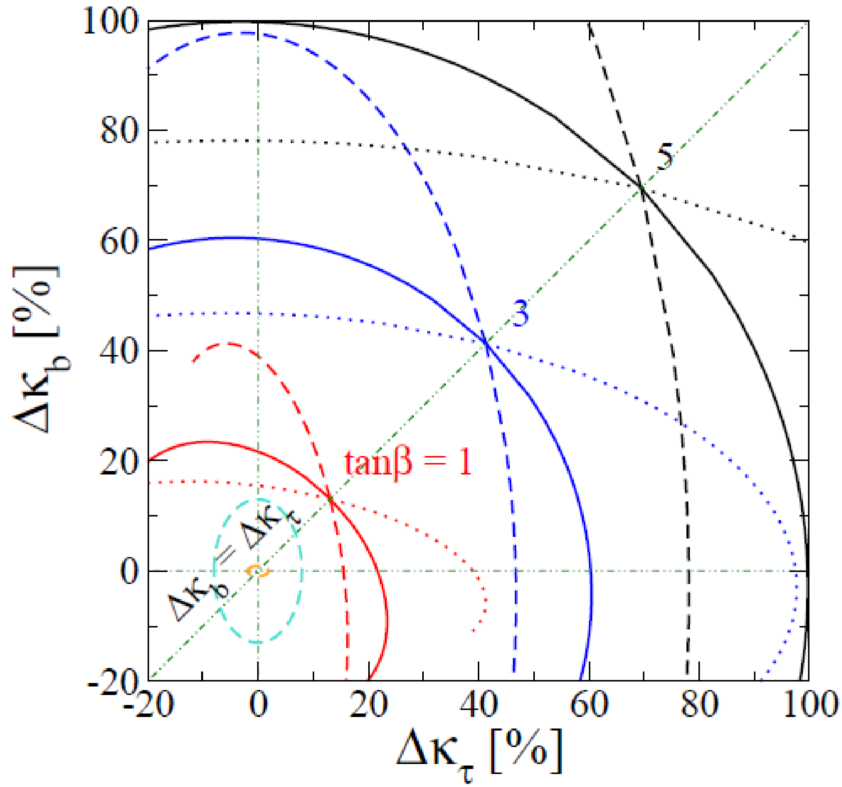
2HDM



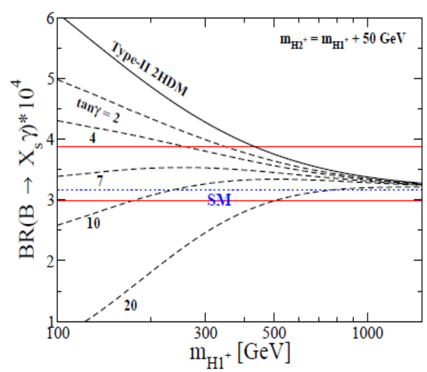
3HDM (Type-Z)

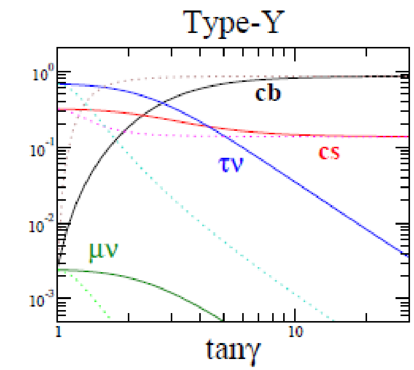


Summary

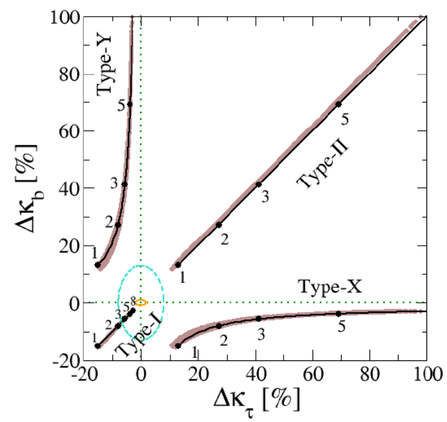
- The Higgs sector could have the multi-doublet structure like "flavour" .
- There are critical differences between the 2HDMs and the 3HDMs (N≥ 3).

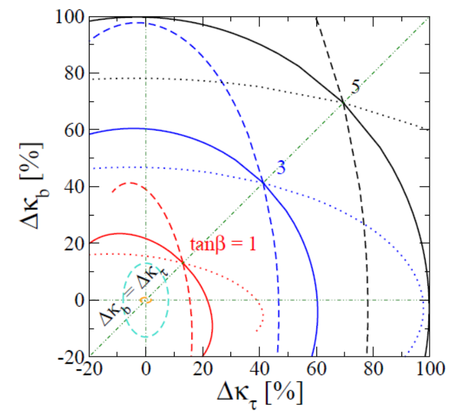
★ Cancellation in $B \to X_s \gamma$





★ $H^{\pm} \to cb$ can be smoking gun.





★ Deviation in h(125) couplings

Higgs basis in 3HDMs

$$\begin{pmatrix} \Phi_1 \\ \Phi_2 \\ \Phi_3 \end{pmatrix} = R \begin{pmatrix} \Phi \\ \Psi_2 \\ \Psi_3 \end{pmatrix}$$

$$R == \begin{pmatrix} \cos\gamma & 0 & -\sin\gamma \\ 0 & 1 & 0 \\ \sin\gamma & 0 & \cos\gamma \end{pmatrix} \begin{pmatrix} \cos\beta & -\sin\beta & 0 \\ \sin\beta & \cos\beta & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

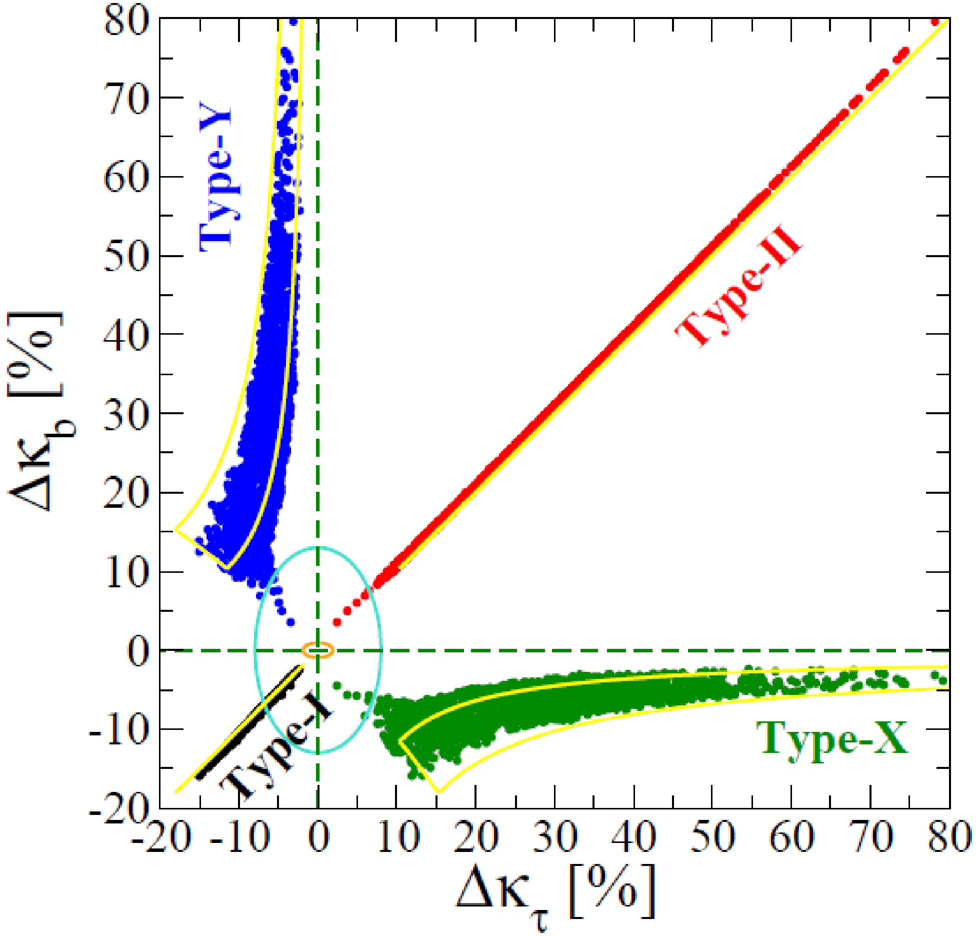
$$= \begin{pmatrix} \cos\beta\cos\gamma & -\sin\beta\cos\gamma & -\sin\gamma \\ \sin\beta & \cos\beta & 0 \\ \cos\beta\sin\gamma & -\sin\beta\sin\gamma & \cos\gamma \end{pmatrix},$$

$$\xi_f^a = R_{fa}/R_{f1}$$

	Φ_u	Φ_d	Φ_e	ξ_u^1	ξ_d^1	ξ_e^1	ξ_u^2	ξ_d^2	ξ_e^2
Type-I	Φ_2	Φ_2	Φ_2	cotβ	cotβ	cotβ	0	0	0
Type-II	Φ_2	Φ_1	Φ_1	cotβ	-tanβ	-tanβ	0	-tanγ/cosβ	-tanγ/cosβ
Type-X	Φ_2	Φ_2	Φ_1	cotβ	cotβ	-tanβ	0	0	-tanγ/cosβ
Type-Y	Φ_2	Φ_1	Φ_2	cotβ	-tanβ	cotβ	0	-tanγ/cosβ	0
Type-Z	Φ_2	Φ_1	Φ_3	cotβ	-tanβ	-tanβ	0	-tanγ/cosβ	cotγ/cosβ

$\Delta\kappa_\tau$ VS $\Delta\kappa_b$ in 2HDMs (1-loop)

$\Delta\kappa_V = (-1 \pm 0.4)\%$, $\Delta\kappa_t < 0$



Parameter scan:

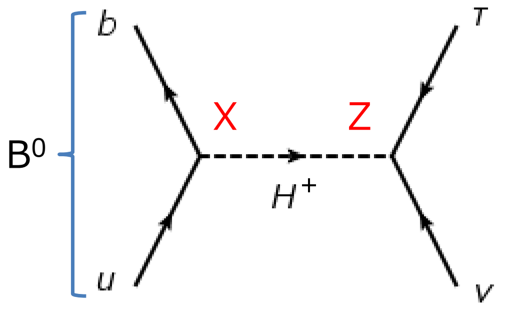
- $\tan\beta > 1$
- $m_\Phi > 300$ GeV
- $\sin(\beta-\alpha) < 1$
- $|\lambda_{h\Phi\Phi}| > 0$
- $\Lambda_{cutoff} > 3$ TeV

Other flavour constraints

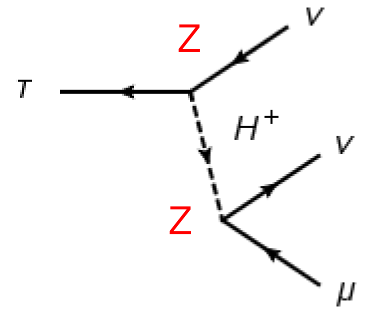
- $B \to \tau\nu$
- $\tau \to \mu\nu\nu$
- $Z \to bb$

Cree, Logan, PRD84 (2011)

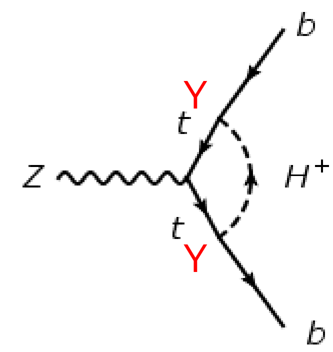
- $t \to H^{\pm}b$(LHC)



$|X^*Z| < 1080\ (m_{H+}/100\ \text{GeV})^2$



$|Z| < 40\ (m_{H+}/100\ \text{GeV})$



$|Y| < 0.72 + 0.34\ (m_{H+}/100\ \text{GeV})$

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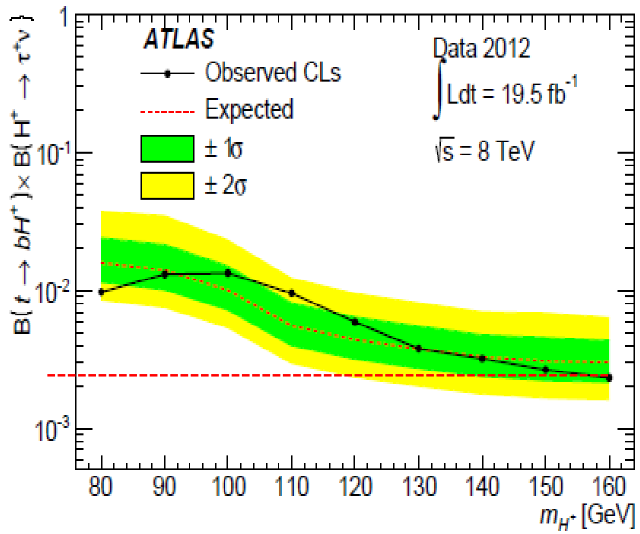

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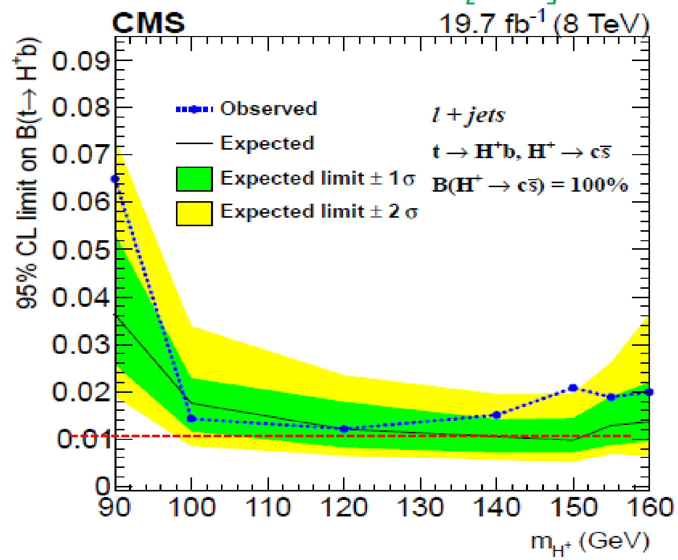
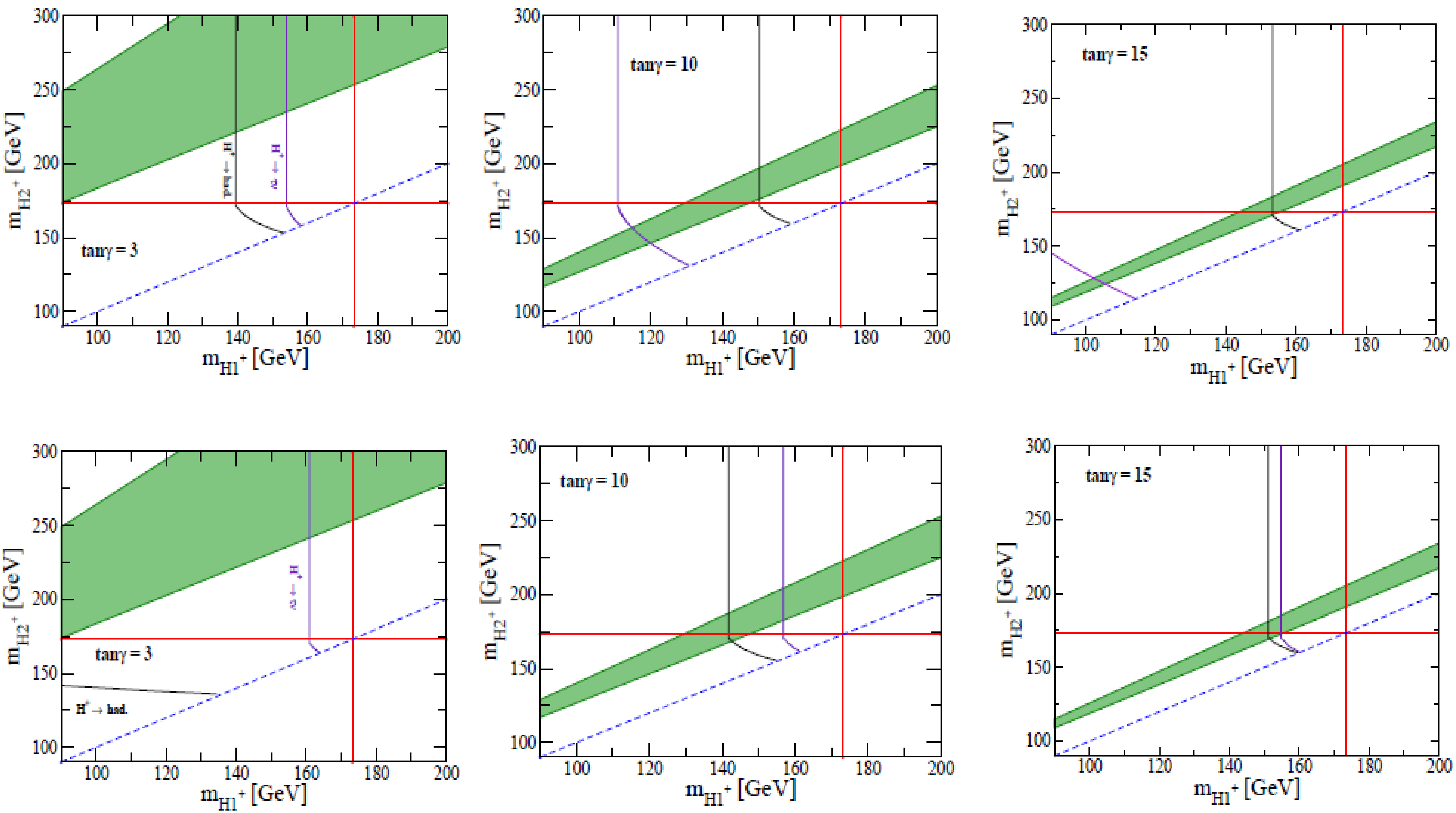
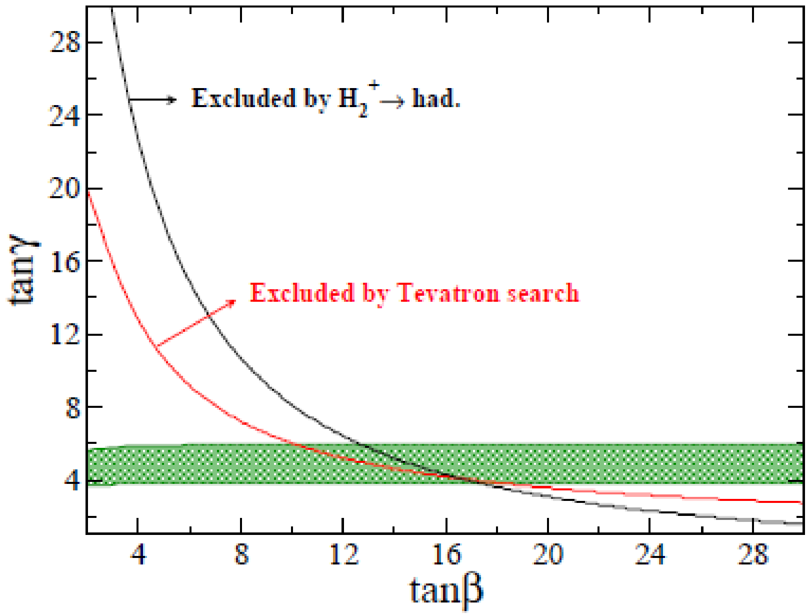


Combined Analysis

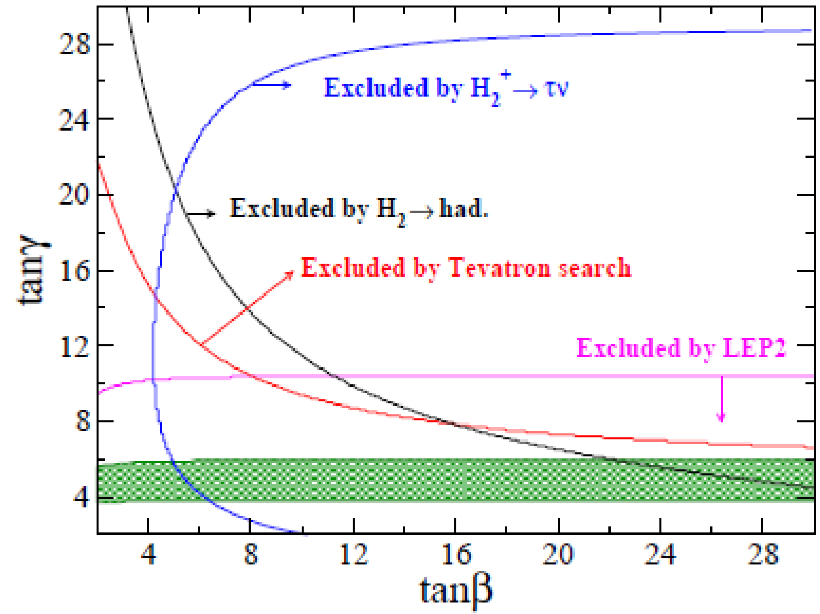


Scenario for $m_{H1+} \sim m_W$

Type-Y 3HDM

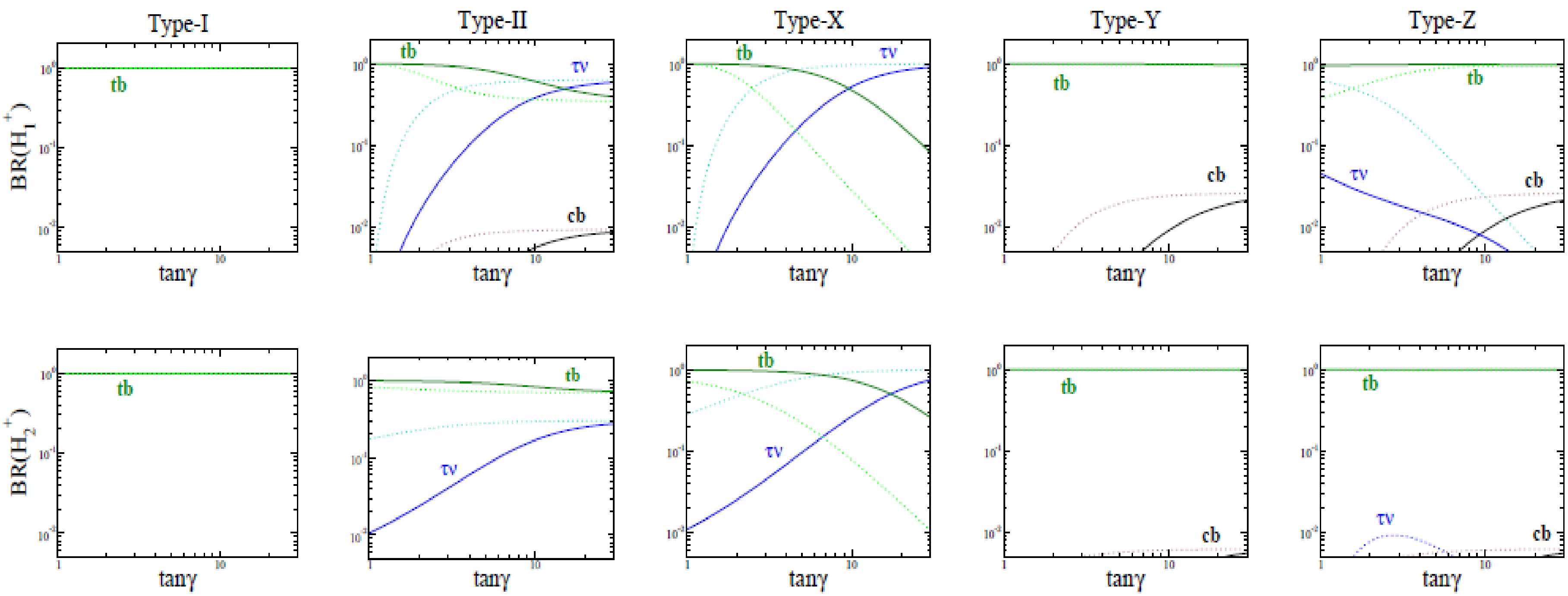


Type-Z 3HDM



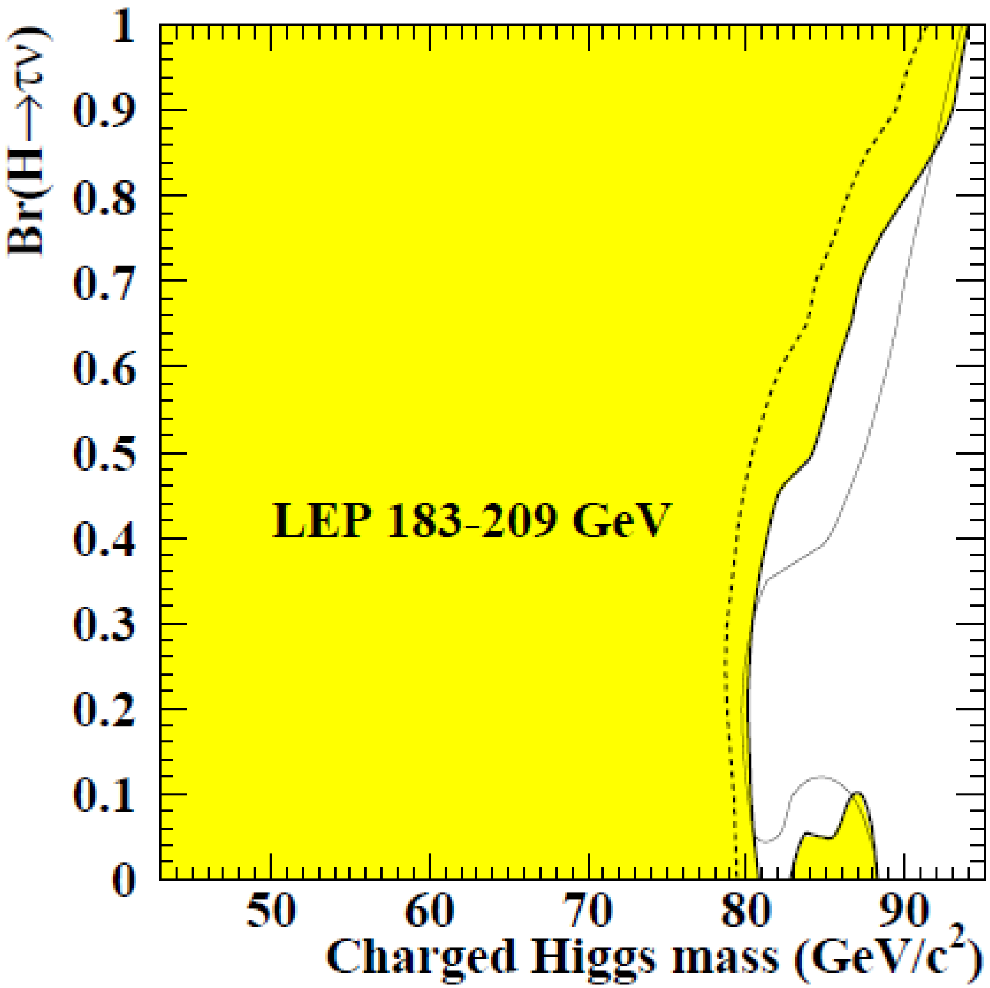
Charged Higgs decays

3HDM, m_{H1} = 200 GeV, m_{H2} = 250 GeV, tanβ = 2 (5), θc = -π/4



Type-I, Y, Z: tb, Type-II, X : τν @ large tanγ

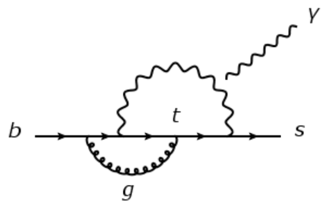
Scenario for $m_{H1+} \sim m_W$



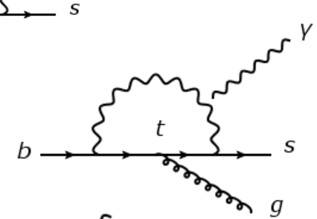
$B \to X_s\, \gamma$ @NLO

- To compare the exp. value of BR($B \to X_s \gamma$) , we need to take into account the three factors

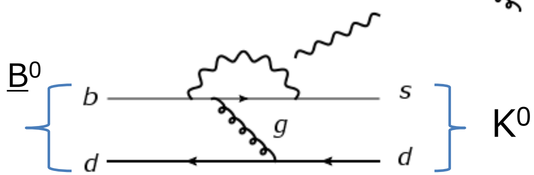
1. Gluon-loop



2. Gluon-emission



3. Non-purt. effects



$$\Gamma(B \to X_s\gamma)_{\rm NLO} = \Gamma^{\rm NLO}_{b\to s\gamma} + \Gamma_{b\to s\gamma g} + \Gamma_{\rm non\text{-}pert.}$$

$$\mathrm{BR}(B \to X_s\gamma) = \frac{\Gamma(B\to X_s\gamma)}{\Gamma(B\to X_c\ell\nu)}\mathrm{BR}(B \to X_c\ell\nu)$$

[NLO calculation]
Ciuchini, Franco, Martinelli, Reina, Silvestrini, PLB334, 137 (1994), [hep-ph/9406239].

Ciuchini, Degrassi, Gambino, Giudice, NPB527, 21 (1998), [hep-ph/9710335].

Borzumati, Greub, PRD58, 074004 (1998), [hep-ph/9802391].

Kagan, Neubert, EPJC7, 5 (1999), [hep-ph/9805303].

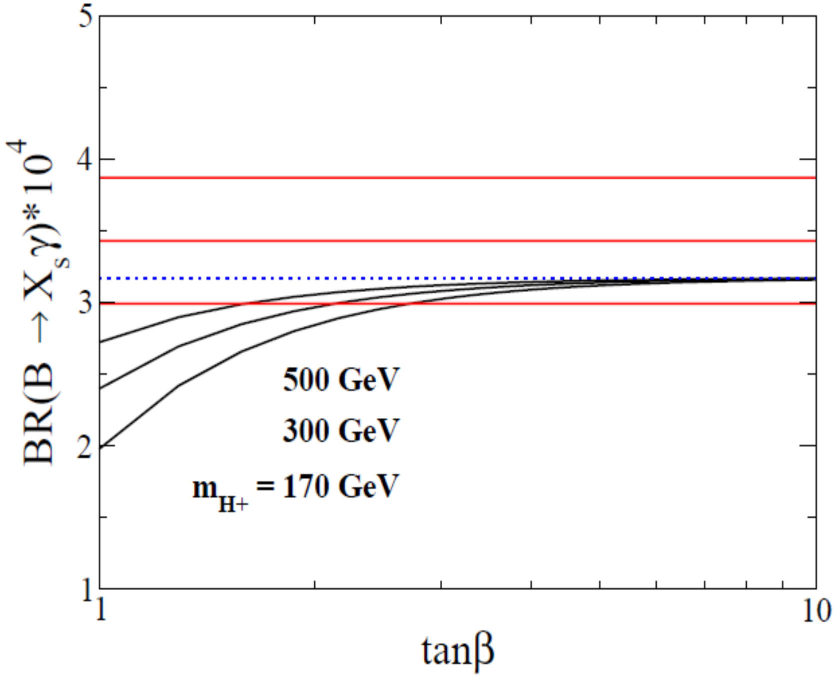
Gambino, Misiak, NPB611, 338 (2001), [hep-ph/0104034].

[NNLO calculation]
Hermann, Misiak, Steinhauser, JHEP1211, 036 (2012), [arXiv:1208.2788 [hep-ph]].

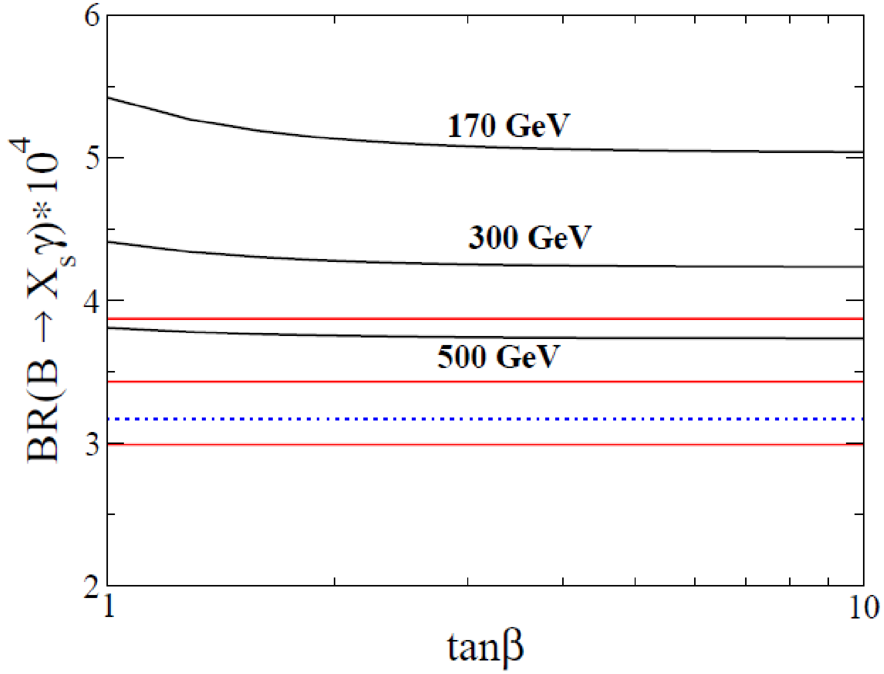
Misiak et.al, PRL114, 221801 (2015), [arXiv:1503.01789 [hep-ph]].

$B \to X_s \gamma$ (2HDM)

Type-I, X



Type-II, Y

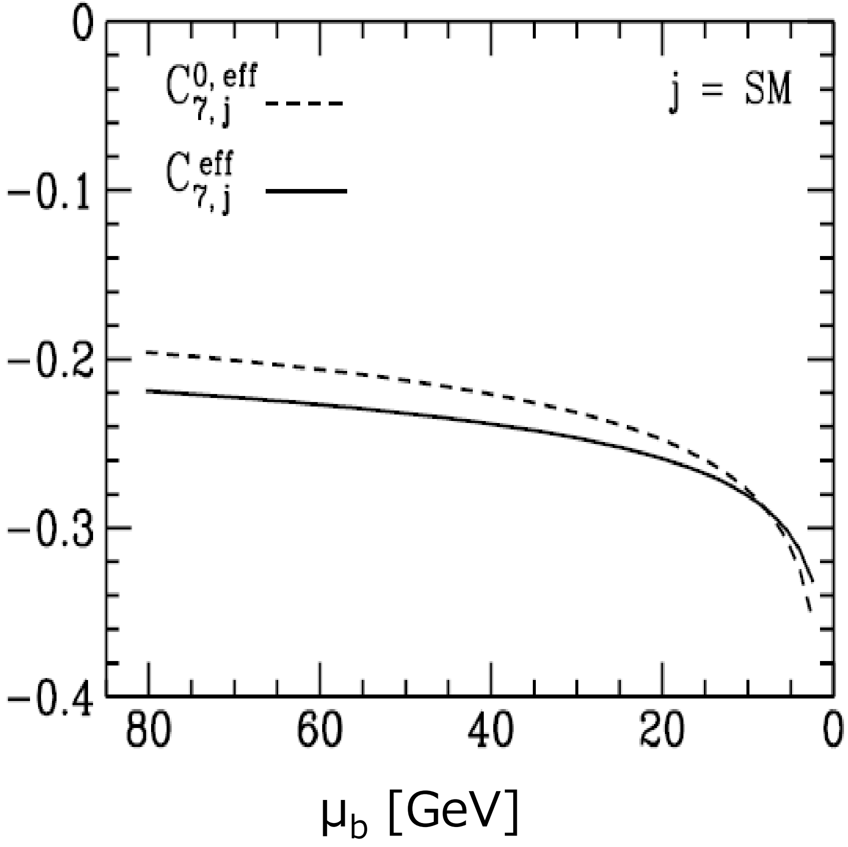


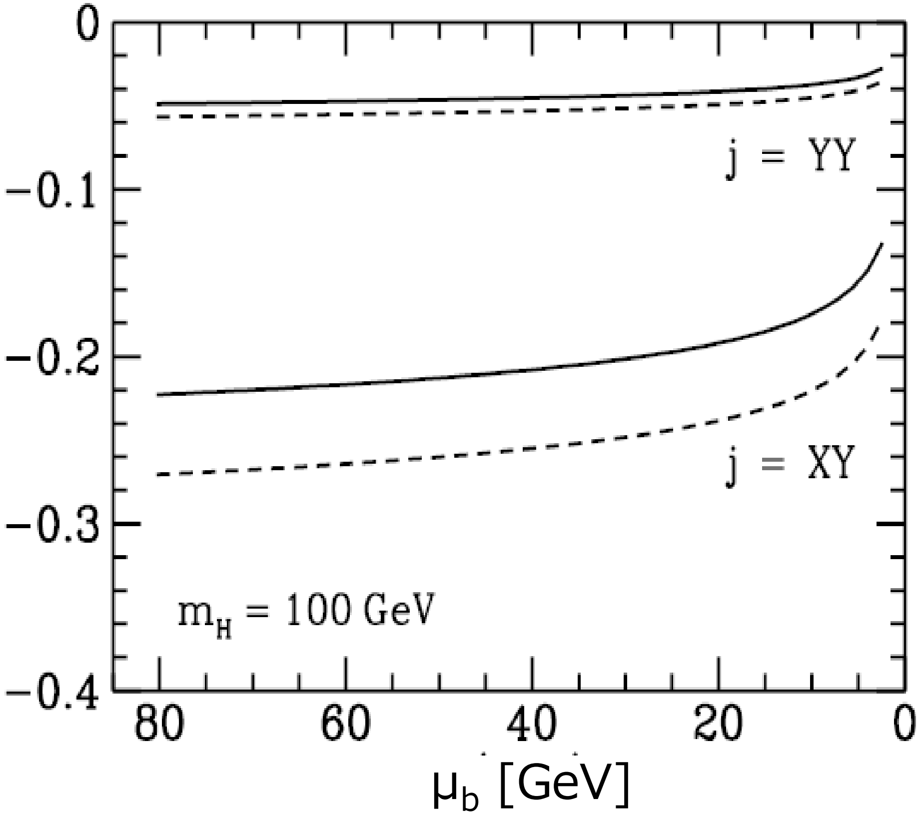
Type-I, -X　: tanβ > ~3 でmH+ < mt が許される。

Type-II, -Y, : less sensitivity to tanβ

LO → NLO

Borzumati, Greub, PRD58, 074004 (1998)





Higgs potential of 2HDM

- Higgs potential with softly-broken Z_2 symmetry and CP-conservation

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

- 8 parameters

v (=246 GeV), m_h (=125 GeV),
m_H, m_A, m_{H+}, **sin(β-α), tanβ**, and **M^2**

$$M^2 = m_3^2/(\sin\beta\cos\beta)$$

- Mass parameters [sin(β-α) ~1]

$m_h^2 \sim \lambda v^2$, $m_\Phi^2 \sim M^2 + \lambda' v^2$

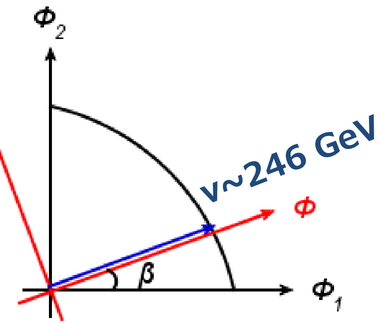
$\Phi = H^\pm, A, H$

Two Higgs Doublet Model (2HDM)

- The Higgs basis

$$\begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \Phi \\ \Psi \end{pmatrix}$$

$\tan\beta = v_2/v_1$



NG boson

Charged Higgs

$$\Phi = \begin{bmatrix} G^+ \\ \frac{1}{\sqrt{2}}(h_1' + v + iG^0) \end{bmatrix}$$

$$\Psi = \begin{bmatrix} H^+ \\ \frac{1}{\sqrt{2}}(h_2' + iA) \end{bmatrix}$$

CP-even Higgs

CP-odd Higgs

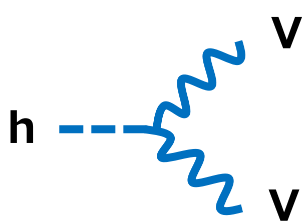
$$\begin{pmatrix} h_1' \\ h_2' \end{pmatrix} \begin{pmatrix} \cos(\beta-\alpha) & \sin(\beta-\alpha) \\ -\sin(\beta-\alpha) & \cos(\beta-\alpha) \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}$$

SM-like Higgs with 125 GeV

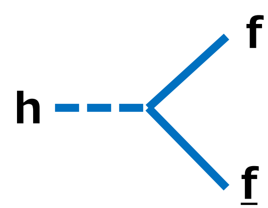
★ **Alignment limit: $(R_H)_{11} \to 1$**

hVV and hff couplings → SM

$$\mathcal{L}_Y = \bar{Q}_L Y_d \Phi_d d_R + \cdots = \frac{\sqrt{2}}{v} \bar{Q}_L M_d [\Phi + \textstyle\sum_a \xi_d^a \Psi_a] d_R + \cdots$$



= (SM) × $(R_H)_{11}$



= (SM) × $[(R_H)_{11} + \Sigma_a \xi_f^a (R_H)_{a1}]$

Gauge/Yukawa interactions

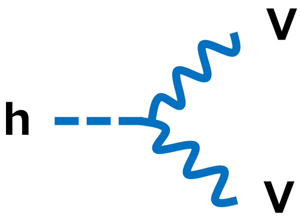
- Gauge interaction

$$\mathcal{L}_{\rm kin} = |D_\mu \Phi|^2 + \sum_a |D_\mu \Psi_a|^2$$

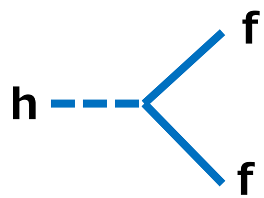
- Yukawa interaction

$$\xi_f^a = R_{fa}/R_{f1}$$

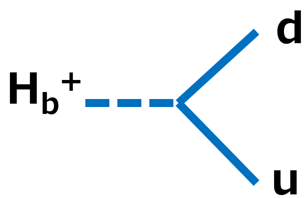
$$\mathcal{L}_Y = \bar{Q}_L Y_d \Phi_d d_R + \cdots \; = \frac{\sqrt{2}}{v}\bar{Q}_L M_d [\Phi + \sum_a \xi_d^a \Psi_a] d_R + \cdots$$



$= (SM) \times (R_H)_{11}$



$= (SM) \times [(R_H)_{11} + \Sigma_a\, \xi_f^a\, (R_H)_{a1}]$



$= \Sigma_a\, \xi_d^a\, (R_C)_{ab}$

Higgs basis

Weak basis Higgs basis

$$\begin{pmatrix} \Phi_1 \\ \Phi_2 \\ \vdots \\ \Phi_N \end{pmatrix} = R \begin{pmatrix} \Phi \\ \Psi_2 \\ \vdots \\ \Psi_N \end{pmatrix}$$

$$\Phi = \begin{pmatrix} G^+ \\ \frac{v+\tilde{H}_1+iG^0}{\sqrt{2}} \end{pmatrix}$$

G^+, G^0:NG boson

$$\Psi_a = \begin{pmatrix} \tilde{H}_a^+ \\ \frac{\tilde{H}_a+i\tilde{A}_a}{\sqrt{2}} \end{pmatrix}$$

a = 2,⋯, N

$$R = R_{12}(\beta_1)R_{13}(\beta_2)\cdots R_{1N}(\beta_{N-1})$$

R_{ij} : rotation for the (i,j) plane.

$$\begin{pmatrix} \tilde{A}_2 \\ \tilde{A}_3 \\ \vdots \\ \tilde{A}_N \end{pmatrix} = R_A \begin{pmatrix} A_2 \\ A_3 \\ \vdots \\ A_N \end{pmatrix} \quad \begin{pmatrix} \tilde{H}_2^\pm \\ \tilde{H}_3^\pm \\ \vdots \\ \tilde{H}_N^\pm \end{pmatrix} = R_C \begin{pmatrix} H_2^\pm \\ H_3^\pm \\ \vdots \\ H_N^\pm \end{pmatrix} \quad \begin{pmatrix} \tilde{H}_1 \\ \tilde{H}_2 \\ \vdots \\ \tilde{H}_N \end{pmatrix} = R_H \begin{pmatrix} h \\ H_2 \\ \vdots \\ H_N \end{pmatrix}$$

125 GeV