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CP-violation in the three Higgs doublet model and charged Higgs phenomenology [JHEP 07 (2021) 158]

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Overview

Motivation of charged Higgs and 3HDM (3-Higgs-Doublets-Model)

- Existence of charged Higgs boson?

	SPIN 0	SPIN 1/2	SPIN 1
Charge 0	H	ν_e, ν_μ, ν_τ	γ, Z, g
Charge ±1	$H^\pm$?	$e^\pm, \mu^\pm, \tau^\pm, u, d, c, s, t, b$	$W^\pm$

Reason for 3HDM:

- Not much literature attention as 2HDM.
- Rich scalar structure.
- Extra sources of CP-violation in charged scalar sector (vs. generic 2HDM).

Charged Higgs in 3HDM (Weinberg)

- Three active isospin fields $\Phi_i (i = 1, 2, 3)$ are introduced, and each contain a vacuum expectation value with sum rule :

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ (v_i + \phi_i^{0,real} + i\phi_i^{0,imag})/\sqrt{2} \end{pmatrix}, \sum_i v_i^2 = v_{sm}^2 = (246 GeV)^2$$

- A unitary 3×3 matrix U is introduced in order to specify charged Higgs mass eigenstates (Left) from charged fields (Right) rotation: [Y. Grossman, 1994]

$$\begin{pmatrix} G_1^+ \\ H_2^+ \\ H_3^+ \end{pmatrix} = U \begin{pmatrix} \phi_1^+ \\ \phi_2^+ \\ \phi_3^+ \end{pmatrix}.$$

3HDM Scalar potential under $Z_2 \times Z_2$ symmetry

$$
\begin{aligned}
V &= m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 + m_{33}^2 \Phi_3^\dagger \Phi_3 \\
&- [m_{12}^2 \Phi_1^\dagger \Phi_2 + m_{13}^2 \Phi_1^\dagger \Phi_3 + m_{23}^2 \Phi_2^\dagger \Phi_3 + \text{h.c.}] \\
&+ \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \frac{1}{2}\lambda_3 (\Phi_3^\dagger \Phi_3)^2 \\
&+ \lambda_{12} (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_{13} (\Phi_1^\dagger \Phi_1)(\Phi_3^\dagger \Phi_3) + \lambda_{23} (\Phi_2^\dagger \Phi_2)(\Phi_3^\dagger \Phi_3) \\
&+ \lambda'_{12} (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \lambda'_{13} (\Phi_1^\dagger \Phi_3)(\Phi_3^\dagger \Phi_1) + \lambda'_{23} (\Phi_2^\dagger \Phi_3)(\Phi_3^\dagger \Phi_2) \\
&+ \frac{1}{2}[\lambda''_{12} (\Phi_1^\dagger \Phi_2)^2 + \lambda''_{13} (\Phi_1^\dagger \Phi_3)^2 + \lambda''_{23} (\Phi_2^\dagger \Phi_3)^2 + \text{h.c.}],
\end{aligned}
$$

[G. Cree and H.E. Logan, 2011]

- 6 complex parameters: 3 soft-breaking masses $m_{12}^2, m_{13}^2, m_{23}^2$, 3 quartic couplings $\lambda''_{12}, \lambda''_{13}, \lambda''_{23}$.
- Five parameters could be eliminated and leaves only one left for charged scalar CP-violation resource ($\text{Im}(\lambda''_{12})$).

Charged Higgs mixing matrix U in 3HDM

- The matrix U can be written explicitly as a function of four parameters $\tan\beta$, $\tan\gamma$, θ, and δ, where :

$$\tan\beta = v_2/v_1, \qquad \tan\gamma = \sqrt{v_1^2 + v_2^2}/v_3 \,.$$

- v_1, v_2, and v_3 are the vacuum expectation values of the three Higgs doublets.
- θ is the mixing angle between H_2^+ and H_3^+.
- δ is the CP-violating phase source. $(\mathrm{Im}(\lambda''_{12}))$
- The explicit form of U given as :

$$= \begin{pmatrix} s_\gamma c_\beta & s_\gamma s_\beta & c_\gamma \\ -c_\theta s_\beta e^{-i\delta} - s_\theta c_\gamma c_\beta & c_\theta c_\beta e^{-i\delta} - s_\theta c_\gamma s_\beta & s_\theta s_\gamma \\ s_\theta s_\beta e^{-i\delta} - c_\theta c_\gamma c_\beta & -s_\theta c_\beta e^{-i\delta} - c_\theta c_\gamma s_\beta & c_\theta s_\gamma \end{pmatrix}$$

Here s, c denote the sine or cosine of the respective parameter.

Yukawa Couplings of charged Higgs in 3HDM

- Charged Higgs Yukawa interactions are written by :

$$\mathcal{L}_{H_i^\pm} = -\sum_{i=2}^{3} H_i^+ \{ \frac{\sqrt{2}V_{ud}}{v_{sm}} \bar{u}(m_d X_i P_R + m_u Y_i P_L)d + \frac{\sqrt{2}m_l}{v_{sm}} Z_i \bar{\nu}_L l_R \} + H.c.$$

- Yukawa couplings for H_i^+ (with $i = 2, 3$) can be written as :

$$X_i = \frac{U^\dagger_{di}}{U^\dagger_{d1}}, \qquad Y_i = -\frac{U^\dagger_{ui}}{U^\dagger_{u1}}, \qquad Z_i = \frac{U^\dagger_{\ell i}}{U^\dagger_{\ell 1}}.$$

- Five independent versions of Yukawa interactions of 3HDM with NFC based on charged assignment of two softly-broken discrete Z_2 symmetries.

	u	d	ℓ
3HDM(Type I)	2	2	2
3HDM(Type II)	2	1	1
3HDM(Lepton-specific)	2	2	1
3HDM(Flipped)	2	1	2
3HDM(Democratic)	2	1	3

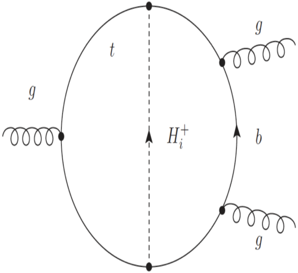
Electric-diopole moment(EDM) constraints for CP-violation

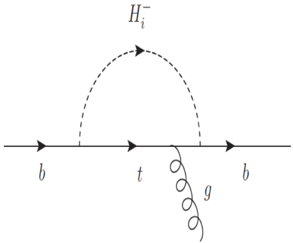
	SM Prediction	Experimental bound
Neutron-EDM(nEDM)	$\sim 10^{-31} - 10^{-32}$ e cm.	$\lvert d_n \rvert < 1.8 \times 10^{-26}$ e cm. [*Phys.Rev.Lett. 124 (2020) 8, 081803*]
Electron-EDM(eEDM)	$\sim 10^{-38}$ e cm.	$\lvert d_e \rvert < 1.1 \times 10^{-29}$ e cm. [*Nature. 562 (2018) 7727, 355–360*]

- nEDM and eEDM in SM with CKM phases [Maxim and Adam 2005, hep-ph/0504231].

$$\mathcal{L}_{H_i^\pm} = -\sum_{i=2}^{3} H_i^+ \{ \frac{\sqrt{2}V_{ud}}{v_{sm}} \bar{u}(m_d X_i P_R + m_u Y_i P_L) d + \frac{\sqrt{2}m_l}{v_{sm}} Z_i \bar{\nu}_L l_R \} + H.c.$$

3-gluon contribution and Chromo-EDM for nEDM

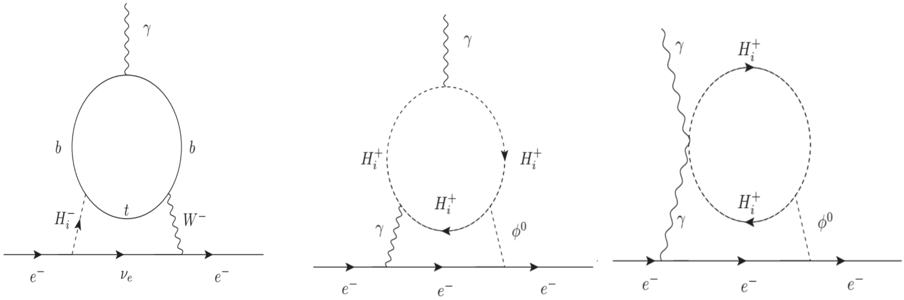




[Jung and Pich, 2014]

- Light quark masses suppress four quark fermion operators and up- and down-type quark Chromo-EDMs.
- Left. Weinberg operator (3-gluon).
- Right. b-quark Chromo-EDM ($d_b^C(\mu_{tH})$).

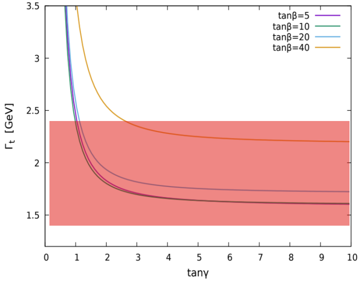
Barr-Zee diagram for eEDM



- Left. $H_i^+ f_u \bar{f}_d$ is the dominant contribution.
- Middle and Right. No $\Phi^0 e^+ e^-$ and $\Phi^0 H_i^+ H_i^-$ (no CP-violation phase in neutral sector).
- $\Phi^0 H_i^+ H_j^-$ may have CP-violation however the coupling does not appear in such diagram as photon couples to charged Higgs is diagonal.

Perturbativity, top width and other constraints

- Perturbativity: $\Gamma_{H^\pm}$ into $tb < \frac{M_{H^\pm}}{2}$. [V.D. Barger, J. Hewett and R. Phillips, 1990]
- Top decay width: $M_{H_i^\pm} < m_t$. $\Gamma(t \to H_i^\pm b)$ into SM top decay width. $\Gamma_t = 1.9 \pm 0.5$ GeV. [PDG,2020]



$M_{H^\pm_{2,3}} = 85, 500$ GeV, $\theta = -\pi/4, \delta = 0.85\pi$.

EDMs, $\bar{B} \to X_s\gamma$ and other constraints

$$\mathcal{L}_{H_i^\pm} = -\sum_{i=2}^{3} H_i^+ \{ \frac{\sqrt{2}V_{ud}}{v_{sm}} \bar{u}(m_d X_i P_R + m_u Y_i P_L)d + \frac{\sqrt{2}m_l}{v_{sm}} Z_i \bar{\nu}_L l_R \} + H.c.$$

- After the effective field framework and dimensional analysis work as A2HDM[Jung and Pich, 2014], results are extrapolated and calculated to constrain the $\text{Im}(X_i Y_i^*)$ (nEDM) and $\text{Im}(Y_i^* Z_i)$ (eEDM).
- Perturbativity,top width and collider constraints included.

$$CMS, JHEP11(2018)115.\ \ 8\,TeV$$

$$ATLAS, Eur.Phys.J.C73(2013)2465.\ \ 7\,TeV$$

$$CMS, JHEP07(2019)142.\ \ 13\,TeV$$

- BR($\bar{B} \to X_s\gamma$). [A. Akeroyd, S. Moretti, T. Shindou and M. Song, 2021]

$$M_{H_2^\pm}, M_{H_3^\pm}, \tan\beta, \tan\gamma, \theta, \delta.$$

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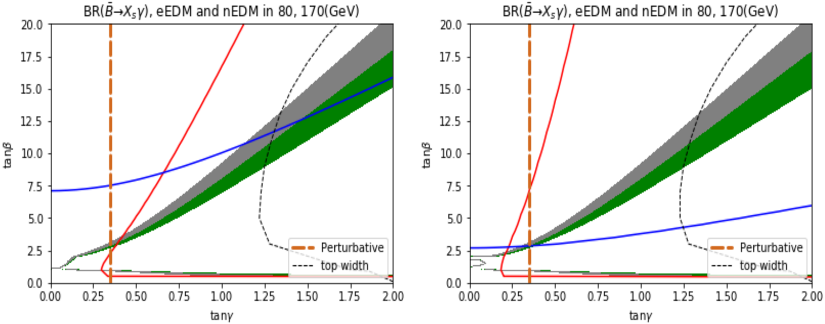
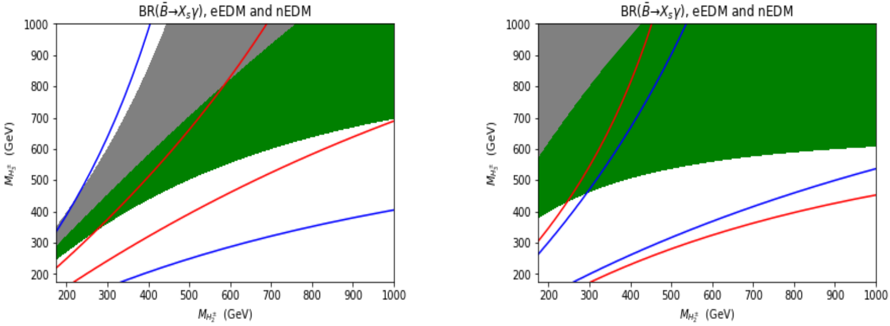
EDMs, $\bar{B} \to X_s\gamma$ and other constraints (Lower masses)



2 σ BR($\bar{B} \to X_s\gamma$)(Grey (higher) and Green (lower) area), eEDM(above blue curve), nEDM(right part of red curve) with $M_{H^\pm_{2,3}} = 80, 170$ GeV, $\theta = -0.3$. Left. $\delta = 0.96\pi$. Right. $\delta = 0.985\pi$.

BR($\bar{B} \to X_s\gamma$) and two EDMs(nEDM and eEDM) under $[M_{H_2^\pm}, M_{H_3^\pm}]$ (Heavy masses)



2 σ BR($\bar{B} \to X_s\gamma$)(Grey (higher) and Green (lower) area), eEDM(between blue lines), nEDM(between red lines) with $\theta = -\pi/2.1$, $\tan\beta = 20$, $\delta = \pi/2$.
Left Panel: $\tan\gamma = 1$. Right Panel: $\tan\gamma = 2$.

Summary

- We studied charged Higgs sector in 3HDM (contains 3 active doublets).
- In the case of isolation of neutral sector, the contribution of EDMs (nEDM and eEDM) for charged scalar sector are calculated based on the mixing parameters ($tan\beta, \tan\gamma, \theta, \delta$) and masses of charged Higgs states.
- Together with perturbativity, top width, collider and $\bar{B} \to X_s\gamma$ constraints, we study the surviving parameter space of charged Higgs states in 3HDM.
- In particular, the suppression of EDM constraint from degeneracy of two charged Higgs masses ($M_{H_2^\pm}, M_{H_3^\pm}$) are realised. (GIM-like mechanism)
- Tunnel effect generated from charged Higgs mass degeneracy due to unitarity of charged Higgs mixing matrix U.

Thanks for Listening

Backup slides

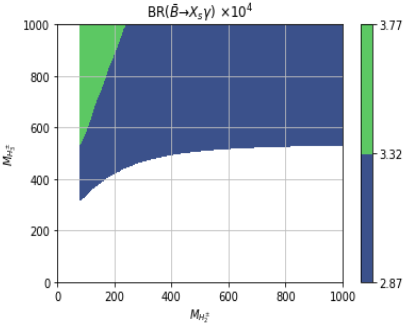
Branching ratio of $\bar{B} \to X_s\gamma$

- short distance pertubative $b \to s\gamma$ ($|\bar{D}|$)
- short distance perturbative $b \to s\gamma g$ (A) (gluon Bremsstrahlung process)
- Long distance non perturbative corrections to scale $\frac{1}{m_b^2}$ and $\frac{1}{m_c^2}$.

$$\begin{aligned}
\Gamma(\bar{B} \to X_s\gamma) &= \frac{G_F^2}{32\pi^4}|V_{ts}^* V_{tb}|^2 \alpha_{em} m_b^5 \\
&\times \left\{ |\bar{D}|^2 + A + \frac{\delta_\gamma^{NP}}{m_b^2}|C_7^{0,\text{eff}}(\mu_b)|^2 \right. \\
&+ \left. \frac{\delta_c^{NP}}{m_c^2}\mathrm{Re}\left[[C_7^{0,\text{eff}}(\mu_b)]^* \times \left(C_2^{0,\text{eff}}(\mu_b) - \frac{1}{6}C_1^{0,\text{eff}}(\mu_b) \right) \right] \right\}. \\
\mathrm{BR}(\bar{B} \to X_s\gamma) &= \frac{\Gamma(\bar{B} \to X_s\gamma)}{\Gamma_{SL}}\mathrm{BR}_{SL}
\end{aligned}$$

- Γ_{SL} is the semileptonic decay width and BR_{SL} is the measured semileptonic decay branching ratio.

BR($\bar{B} \to X_s\gamma$) under $[M_{H_2^\pm}, M_{H_3^\pm}]$



3 σ BR($\bar{B} \to X_s\gamma$) in the plane $[m_{H_2^\pm}, m_{H_3^\pm}]$, with $\theta = -\pi/2.1$, $\tan\beta = 10$, $\tan\gamma = 1$. Left Panel: $\delta = 0$. Right Panel: $\delta = \pi/2$. δ has large effect on BR

Cancellation in charged Higgs contribute to EDMs continued

- Such sort of GIM-like mechanism is due to the unitarity of the charged Higgs mixing matrix U.
- nEDM constrains $\mathrm{Im}(X_i Y_i^*)$ and eEDM constrains $\mathrm{Im}(Y_i^* Z_i)$.
- eEDM contribution is zero for Type I and Flipped 3HDM as $Y_i = Z_i$.
- nEDM contribution is zero for Type I and Lepton-specific 3HDM as $X_i = Y_i$.

$$X_i = \frac{U^\dagger_{di}}{U^\dagger_{d1}}, \qquad Y_i = -\frac{U^\dagger_{ui}}{U^\dagger_{u1}}, \qquad Z_i = \frac{U^\dagger_{\ell i}}{U^\dagger_{\ell 1}}.$$

	u	d	ℓ
3HDM(Type I)	2	2	2
3HDM(Type II)	2	1	1
3HDM(Lepton-specific)	2	2	1
3HDM(Flipped)	2	1	2
3HDM(Democratic)	2	1	3

Cancellation in charged Higgs contribute to EDMs continued

By taking the Democratic-type model for nEDM as an example,

$$\begin{aligned} X_i Y_i^* &= -\frac{U_{1i}^\dagger U_{i2}}{U_{11}^\dagger U_{12}}, \\ \sum_{i=2}^{3} \mathrm{Im}(X_i Y_i^*) f(M_{H_i^+}) &= -\frac{1}{U_{11}^\dagger U_{12}} [\mathrm{Im}(U_{12}^\dagger U_{22}) f(M_{H_2^+}) \\ &+ \mathrm{Im}(U_{13}^\dagger U_{32}) f(M_{H_3^+})]. \end{aligned}$$

- where $f(M_{H_i^+})$ represents the dependence of the diagram on the charged Higgs boson mass.
- In the case of $M_{H_2^\pm} = M_{H_3^\pm} \equiv m$, such result will be $= -\frac{1}{U_{11}^\dagger U_{12}} \mathrm{Im}(\delta_{12}) f(m) = 0$ as $\mathrm{Im}(X_2 Y_2^*)$ = - Im $(X_3 Y_3^*)$

Formulas for charged Higgs in nEDM

[Jung and Pich, 2014]

$$
\begin{aligned}
|d_n(C_W)/e| &= \left[1.0\,{}^{+1.0}_{-0.5}\right] \times 20\,\mathrm{MeV}\, C_W(\mu_h), \mu_h \approx 1\mathrm{GeV} \\
C_W(\mu_h) &= \eta_{c-h}^{\kappa_W}\eta_{b-c}^{\kappa_W}\left(\eta_{t-b}^{\kappa_W} C_W(\mu_{tH}) + \eta_{t-b}^{\kappa_C}\frac{g_s^3(\mu_b)}{8\pi^2 m_b}\frac{d_b^C(\mu_{tH})}{2}\right) \\
\frac{d_b^C(\mu_{tH})}{2} &= -\frac{G_F}{\sqrt{2}}\frac{1}{16\pi^2}|V_{tb}|^2 m_b(\mu_{tH})[\mathrm{Im}(-X_2Y_2^*)x_{tH_2}\left(\frac{\log(x_{tH_2})}{(x_{tH_2}-1)^3}\right. \\
&+ \left.\frac{(x_{tH_2}-3)}{2(x_{tH_2}-1)^2}\right) + \mathrm{Im}(-X_3Y_3^*)x_{tH_3}\left(\frac{\log(x_{tH_3})}{(x_{tH_3}-1)^3} + \frac{(x_{tH_3}-3)}{2(x_{tH_3}-1)^2}\right)]
\end{aligned}
$$

- where $x_{tH_i} = m_t^2/M_{H_i^\pm}^2$, $\eta_{a-b} = \frac{\alpha_s(a)}{\alpha_s(b)}$ and $C_W(\mu_{tH}) = 0$.
- $\kappa_i = \gamma_i/(2\beta_0)$, where $\gamma_W = N_C + 2n_f$ and $\gamma_C = 10C_F - 4N_C$.

Formulas for charged Higgs in eEDM

$$
\begin{aligned}
d_e(M_{H_2^\pm}, M_{H_3^\pm})_{BZ} &= -m_e \frac{24 G_F^2 M_W^2}{(4\pi)^4} |V_{tb}|^2 \\
&\times \Big[\mathrm{Im}(-Y_2^* Z_2) \left(q_t F_t(z_{H_2^\pm}, z_W) + q_b F_b(z_{H_2^\pm}, z_W) \right) \\
&+ \mathrm{Im}(-Y_3^* Z_3) \left(q_t F_t(z_{H_3^\pm}, z_W) + q_b F_b(z_{H_3^\pm}, z_W) \right) \Big]
\end{aligned}
$$

where $q_t = 2/3$ and $q_b = -1/3$ are quark electric charges, $z_a = M_a^2/m_t^2$.

$$
\begin{aligned}
F_q(z_{H_i^\pm}, z_W) &= \frac{T_q(z_{H_i^\pm}) - T_q(z_W)}{z_{H_i^\pm} - z_W}, \\
T_t(x) &= \frac{1-3x}{x^2}\frac{\pi^2}{6} + \left(\frac{1}{x} - \frac{5}{2}\right)\log x - \frac{1}{x} - \left(2 - \frac{1}{x}\right)\left(1 - \frac{1}{x}\right)\mathrm{Li}_2(1-x), \\
T_b(x) &= \frac{2x-1}{x^2}\frac{\pi^2}{6} + \left(\frac{3}{2} - \frac{1}{x}\right)\log x + \frac{1}{x} - \frac{1}{x}\left(2 - \frac{1}{x}\right)\mathrm{Li}_2(1-x).
\end{aligned}
$$

Perturbativity, top width and collider constraints continued

- Perturbativity: $\Gamma_{H^\pm}$ into $tb < \frac{M_{H^\pm}}{2}$. [V.D. Barger, J. Hewett and R. Phillips, 1990]

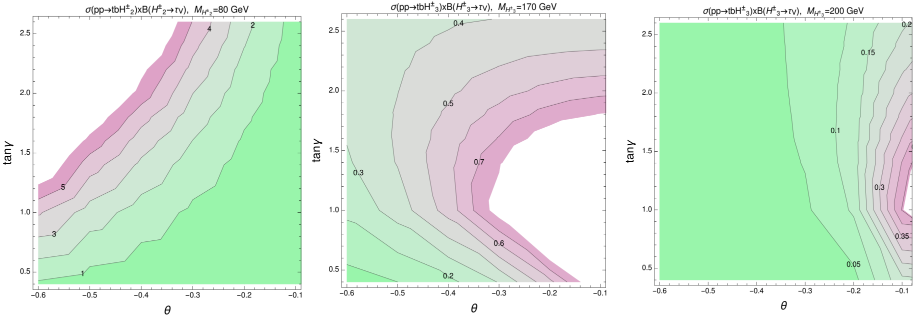
$$\Gamma(H^+ \to t\bar{b}) \simeq \frac{3G_F m_t^2}{4\sqrt{2}\pi \tan^2\beta} M_{H^+} < \frac{1}{2} M_{H^+}, \text{or} \ \tan\beta \gtrsim 0.34. (\text{Type}-\text{I})$$

$$\Gamma(H^+ \to t\bar{b}) \simeq \frac{3G_F m_b^2 \tan^2\beta}{4\sqrt{2}\pi} M_{H^+} < \frac{1}{2} M_{H^+}, \text{or} \ \tan\beta \lesssim 125, (\text{Type}-\text{II})$$

- Top decay width: $M_{H_i^\pm} < m_t$.

$$\Gamma(t \to H_i^\pm b) = \frac{G_f m_t}{8\sqrt{2}\pi}[m_t^2|Y_i|^2 + m_b^2|X_i|^2](1 - M_{H_i^\pm}^2/m_t^2)^2$$

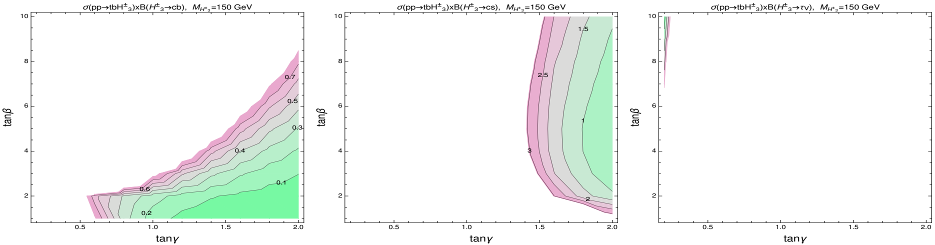
Perturbativity, top width and collider constraints continued



$\sigma(pp \to H_i^{\pm} tb) \times BR(H_i^{\pm} \to \tau\nu_\tau)$. $\tan\beta = 20, \delta = 0.9\pi$. $[\theta, \tan\gamma]$.
Left. $H_2^{\pm} = 80$ GeV. Center. $H_3^{\pm} = 170$ GeV. Right. $H_3^{\pm} = 200$ GeV.

CMS, *JHEP*07(2019)142. 13 *TeV*

Perturbativity, top width and collider constraints continued



$$\sigma(pp \to H_i^\pm tb) \times BR(H_i^\pm \to cb/cs/\tau\nu_\tau).\ \theta = -0.5, \delta = 0.95\pi.$$

$$[\tan\gamma, \tan\beta], H_2^\pm = 80\ \text{GeV},\ H_3^\pm = 150\ \text{GeV}.$$

Left. BR($H_3^\pm \to cb$). Center. BR($H_3^\pm \to cs$). Right. BR($H_3^\pm \to \tau\nu_\tau$).

$CMS, JHEP11(2018)115.\ 8\,TeV$

$ATLAS, Eur.Phys.J.C73(2013)2465.\ 7\,TeV$

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