CP asymmetries of $\overline{B} \to X_s/X_d\gamma$ in models with three Higgs doublets [arXiv:2009.05779]

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Overview

1. Motivation of 3HDM
2. Higgs fields in 3HDM (Three-Higgs-Doublet-Model)
3. Mixing matrix and Yukawa couplings for Charged Higgs
4. BR($\bar{B} \to X_s\gamma$) constraints for charged Higgs
5. CP-asymmetry observables ($\mathcal{A}^{\rm tot}_{X_s\gamma}$, $\Delta\mathcal{A}_{X_s\gamma}$, and $\mathcal{A}_{\rm CP}(\bar{B} \to X_{s+d}\gamma)$)
6. CP-asymmetry against mixing parameters and charged Higgs masses
7. Summary

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
- Supersymmetry, Dark Matter...
- Extra sources of CP-violation (Matter-antimatter asymmetry)

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: [C. Albright,J. Smith and S.-H.H.Tye 1980] [Y. Grossman 1994]

$$\begin{pmatrix} G^+ \\ H_1^+ \\ H_2^+ \end{pmatrix} = U \begin{pmatrix} \phi_1^+ \\ \phi_2^+ \\ \phi_3^+ \end{pmatrix}.$$

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_1^+ and H_2^+
- δ is the CP-violating phase.
- The explicit form of U given as :
[C. Albright,J. Smith and S.-H.H.Tye 1980]

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

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:

$$\mathcal{L}_{H_i^\pm} = -\sum_{i=1}^{2} H_i^+ \{ \frac{\sqrt{2} V_{ud}}{v_{sm}} \bar{u}(m_d X_i P_R + m_u Y_i P_L) d + \frac{\sqrt{2} m_l}{v_{sm}} Z_i \bar{\nu}_L l_R \} + H.c.$$

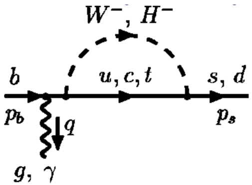
- Yukawa couplings for H_i^+ (with $i = 1, 2$) can be written as:

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

- 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

BR($\bar{B} \to X_s\gamma$) constraint for $H^\pm$



- Leading order diagram involves loop with charged Higgs and top.
- BR($\bar{B} \to X_s\gamma$) constrain $|Y_i^2|$, $X_i Y_i^*$ and $M_{H_i^\pm}$.
- Parameter space difference between 2HDM ($\tan\beta = \frac{v_2}{v_1}$) and 3HDM ($\tan\beta$, $\tan\gamma$, θ, δ)
- Evaluate NLO BR($\bar{B} \to X_s\gamma$) through 2HDM [F. Borzumati and C. Greub, arXiv:hep-ph/9802391]and extrapolate to 3HDM account from two charged Higgs boson states and corresponding Yukawa couplings.

Low effective Hamiltonian for $\bar{B} \to X_s\gamma$

$$H_{\text{eff}} = -\frac{4G_f}{\sqrt{2}} V_{ts}^* V_{tb} \sum_i^8 C_i(\mu_b) O_i(\mu_b)$$

$$\begin{aligned} O_2 &= \bar{s}_L \gamma_\mu c_L \bar{c}_L \gamma^\mu b_L \\ O_7 &= \frac{em_b}{16\pi^2} \bar{s}_L \sigma_{\mu\nu} F^{\mu\nu} b_R, \\ O_8 &= \frac{g_s m_b}{16\pi^2} \bar{s}_L \sigma_{\mu\nu} G_a^{\mu\nu} t_a b_R \end{aligned}$$

Where the charged Higgs contribution are dominant at Wilson coefficient(current-current operator) C_2, (magnetic penguin operator) $C_7(b \to s\gamma)$and$C_8(b \to sg)$.

NLO Wilson coefficients contribution

NLO Wilson coefficients at the matching scale $\mu_W = M_W$ are as follows:

$$C_1^{1,\text{eff}}(\mu_W) = 15 + 6\ \ln\frac{\mu_W^2}{M_W^2},$$

$$C_4^{1,\text{eff}}(\mu_W) = E_0 + \frac{2}{3}\ \ln\frac{\mu_W^2}{M_W^2} + |Y_1|^2 E_{H_1^+} + |Y_2|^2 E_{H_2^+}$$

$$C_i^{1,\text{eff}}(\mu_W) = 0 \quad (i = 2, 3, 5, 6)$$

$$C_7^{1,\text{eff}}(\mu_W) = C_{7,SM}^{1,\text{eff}}(\mu_W) + |Y_1|^2 C_{7,Y_1Y_1}^{1,\text{eff}}(\mu_W) +$$

$$|Y_2|^2 C_{7,Y_2Y_2}^{1,\text{eff}}(\mu_W) + (X_1 Y_1^*) C_{7,X_1Y_1}^{1,\text{eff}}(\mu_W) + (X_2 Y_2^*) C_{7,X_2Y_2}^{1,\text{eff}}(\mu_W)$$

$$C_8^{1,\text{eff}}(\mu_W) = C_{8,SM}^{1,\text{eff}}(\mu_W) + |Y_1|^2 C_{8,Y_1Y_1}^{1,\text{eff}}(\mu_W) +$$

$$|Y_1|^2 C_{8,Y_2Y_2}^{1,\text{eff}}(\mu_W) + (X_1 Y_1^*) C_{8,X_1Y_1}^{1,\text{eff}}(\mu_W) + (X_2 Y_2^*) C_{8,X_2Y_2}^{1,\text{eff}}(\mu_W).$$

Evolution to $\mu_b = M_b$ scale

Then running to the μ_b scale by renormalization group yields Wilson coefficents by :

$$C_i^{\text{eff}}(\mu_b) = \exp\left(\int_{\alpha_s(\mu_b)}^{\alpha_s(\mu_W)} \frac{\gamma_{ij}(\alpha)}{\beta(\alpha)} \mathrm{d}\alpha \right) C_i^{\text{eff}}(\mu_W)$$

Which is the solution of this:

$$\mu \frac{d}{d\mu} C_i^{eff}(\mu) = C_j^{eff}(\mu)\gamma_{ij}^T(\mu)$$

Where $\gamma_{ij}(\mu)$ is the 8×8 anomalous dimension matrix

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

CP-asymmetry observables ($\mathcal{A}^{\rm tot}_{X_s\gamma}$, $\Delta\mathcal{A}_{X_s\gamma}$, and $\mathcal{A}_{\rm CP}(\bar{B} \to X_{s+d}\gamma)$)

- $\bar{B} \to X_s\gamma$ alone does not give any evidence on new Physics since SM and experiment are quite good agreement even in NNLO prediction.
- Direct CP-asymmetry $\mathcal{A}^{\rm tot}_{X_{s(d)}\gamma}$: $\frac{\Gamma(\overline{B}\to X_{s(d)}\gamma)-\Gamma(B\to X_{s(d)}\gamma)}{\Gamma(\overline{B}\to X_{s(d)}\gamma)+\Gamma(B\to X_{s(d)}\gamma)}$
- Difference of CP-asymmetry $\Delta\mathcal{A}_{X_s\gamma}$: $\mathcal{A}^{\pm}_{X_s\gamma} - \mathcal{A}^{0}_{X_s\gamma}$
- Untagged CP-asymmetry $\mathcal{A}_{\rm CP}(\bar{B} \to X_{s+d}\gamma)$: $\frac{\mathcal{A}_{X_s\gamma}+R_{ds}\mathcal{A}_{X_d\gamma}}{1+R_{ds}}$.$R_{ds} \approx |V_{td}/V_{ts}|^2$
- B^0 for neutral B mesons ($\mathcal{A}^{0}_{X_{s(d)}\gamma}$) and $B, \bar{B}$ for charged B mesons(B^+, B^-) ($\mathcal{A}^{\pm}_{X_{s(d)}\gamma}$).

CP-asymmetry measurements recent and future

	BELLE	BABAR	World Average
$\mathcal{A}^{\rm tot}_{X_s\gamma}$	$(1.44 \pm 1.28 \pm 0.11)\%$	$(1.73 \pm 1.93 \pm 1.02)\%$	$1.5\% \pm 1.1\%$
$\mathcal{A}_{\rm CP}(\bar{B} \to X_{s+d}\gamma)$	$(2.2 \pm 3.9 \pm 0.9)\%$	$(5.7 \pm 6.0 \pm 1.8)\%$	$1.0\% \pm 3.1\%$
$\Delta\mathcal{A}_{X_s\gamma}$	$(3.69 \pm 2.65 \pm 0.76)\%$	$(5.0 \pm 3.9 \pm 1.5)\%$	$4.1\% \pm 2.3\%$

BELLE II	SM Prediction	Leptonic tag	Hadronic tag	Sum of exclusives
$\mathcal{A}_{X_s\gamma}$	$-1.9\% < \mathcal{A}_{X_s\gamma} < 3.3\%$	x	x	0.19%
$\mathcal{A}_{\rm CP}(\bar{B} \to X_{s+d}\gamma)$	0	0.48%	0.70%	x
$\Delta\mathcal{A}_{X_s\gamma}$	0	x	1.3%	0.3%

- Both SM $\Delta\mathcal{A}_{X_s\gamma}$ and $\mathcal{A}_{\rm CP}(\bar{B} \to X_{s+d}\gamma)$ are 0 due to real Wilson coefficients and CKM unitarity respectively.
- Due to SM $\mathcal{A}_{\rm CP}(\bar{B} \to X_{s+d}\gamma)$ is essentially zero, 2.5% with an error 0.5% could constitute a 5σ signal of physics beyond SM.

$\bar{B} \to X_s\gamma$ and three CP-asymmetry observables

- 6 parameters taken (two charged Higgs masses($M_{H_1^\pm}, M_{H_2^\pm}$), four mixing parameters($\tan\beta, \tan\gamma, \theta, \delta$))
- We take the 3σ measured allowed range : $2.87 \leq \bar{B} \to X_s\gamma \leq 3.77$ $(\times 10^{-4})$ with central value $3.32(\times 10^{-4})$ to set the limit. And take 3σ world average CP-asymmetry observables for allowed parameter space.
- Flipped, Type II, and Democratic 3HDM parameter space are taken since the Yukawa coupling structure are similar.

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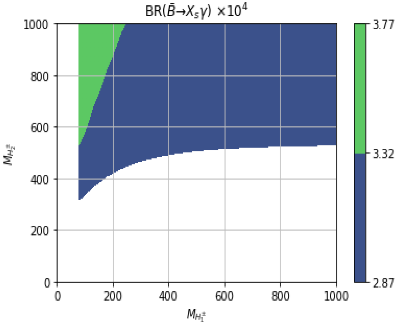
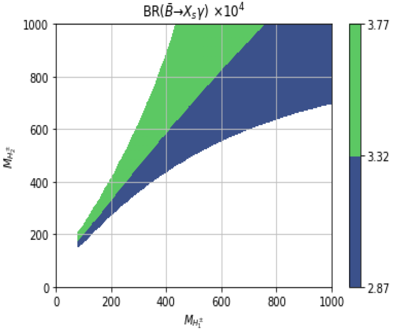
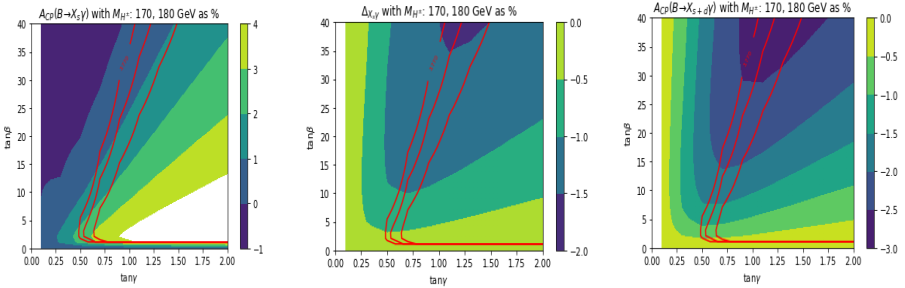
BR($\bar{B} \to X_s\gamma$) under [$M_{H_1^\pm}, M_{H_2^\pm}$]





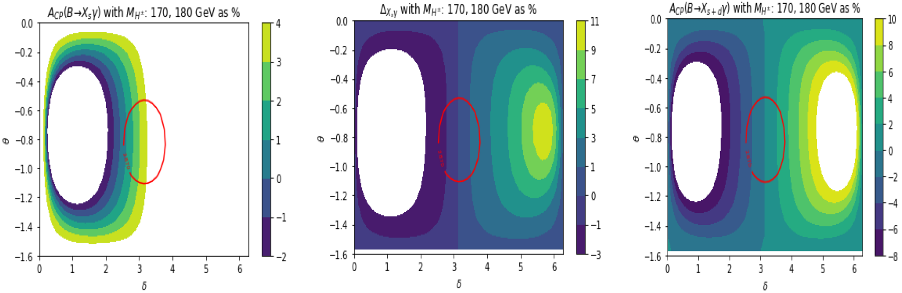
3 σ BR($\bar{B} \to X_s\gamma$) in the plane [$m_{H_1^\pm}, m_{H_2^\pm}$], with $\theta = -\pi/2.1$, $\tan\beta = 10$, $\tan\gamma = 1$. Left Panel: $\delta = 0$. Right Panel: $\delta = \pi/2$. δ has large effect on BR

$\mathcal{A}^{\rm tot}_{X_s\gamma}$, $\Delta\mathcal{A}_{X_s\gamma}$, and $\mathcal{A}_{\rm CP}(B \to X_{s+d}\gamma)$ under $[\tan\gamma, \tan\beta]$



CP-asymmetry observables in the plane $[\tan\gamma, \tan\beta]$, with $\theta = -\frac{\pi}{4}$, $\delta = 2.64$.
Left Panel: $\mathcal{A}^{\rm tot}_{X_s\gamma}$. Middle Panel: $\Delta\mathcal{A}_{X_s\gamma}$. Right Panel: $\mathcal{A}_{\rm CP}(B \to X_{s+d}\gamma)$.
Between the red color lines are allowed by $\bar{B} \to X_s\gamma$. 2.5% can be achieved.

$\mathcal{A}^{\rm tot}_{X_s\gamma}$, $\Delta\mathcal{A}_{X_s\gamma}$, and $\mathcal{A}_{\rm CP}(\bar{B}\to X_{s+d}\gamma)$ under $[\delta,\theta]$



CP-asymmetry observables in the plane $[\delta,\theta]$, with $\tan\beta = 35$, $\tan\gamma = 1.32$. Left Panel: $\mathcal{A}^{\rm tot}_{X_s\gamma}$. Middle Panel: $\Delta\mathcal{A}_{X_s\gamma}$. Right Panel: $\mathcal{A}_{\rm CP}(\bar{B}\to X_{s+d}\gamma)$. Inside the red color ellipse is allowed by $\bar{B}\to X_s\gamma$. 2.5% can be achieved.

Summary

- We studied charged Higgs sector in 3HDM (contains 3 active doublets)
- We studied NLO BR($\bar{B} \to X_s\gamma$) in 3HDM.
- CP-asymmetry observables ($\mathcal{A}^{\mathrm{tot}}_{X_s\gamma}$, $\Delta\mathcal{A}_{X_s\gamma}$, and $\mathcal{A}_{\mathrm{CP}}(\bar{B} \to X_{s+d}\gamma)$) can give a signal at BELLE II in 3HDM.
- $\mathcal{A}_{\mathrm{CP}}(\bar{B} \to X_{s+d}\gamma)$ is of particular interest as SM prediction is essentially zero.

Thanks for Listening

Backup slides

CP-asymmetry observables $\mathcal{A}_{X_{s(d)}\gamma}$ and $\Delta\mathcal{A}_{X_s\gamma}$

$$
\begin{aligned}
\mathcal{A}_{X_{s(d)}\gamma} &\approx \pi\left\{\left[\left(\frac{40}{81}-\frac{40}{9}\frac{\Lambda_c}{m_b}\right)\frac{\alpha_s}{\pi}+\frac{\tilde{\Lambda}_{17}^c}{m_b}\right]\mathrm{Im}\frac{C_2}{C_{7\gamma}}\right. \\
&- \left(\frac{4\alpha_s}{9\pi}-4\pi\alpha_s e_{\rm spec}\frac{\tilde{\Lambda}_{78}}{m_b}\right)\mathrm{Im}\frac{C_{8g}}{C_{7\gamma}} \\
&- \left.\left(\frac{\tilde{\Lambda}_{17}^u-\tilde{\Lambda}_{17}^c}{m_b}+\frac{40}{9}\frac{\Lambda_c}{m_b}\frac{\alpha_s}{\pi}\right)\mathrm{Im}\left(\epsilon_{s(d)}\frac{C_2}{C_{7\gamma}}\right)\right\} \\
\Delta\mathcal{A}_{X_s\gamma} &\approx 4\pi^2\alpha_s\frac{\tilde{\Lambda}_{78}}{m_b}\mathrm{Im}\frac{C_{8g}}{C_{7\gamma}}\,.
\end{aligned}
$$

$\tilde{\Lambda}_{17}^u, \tilde{\Lambda}_{17}^c, \tilde{\Lambda}_{78}$ are long distance hadronic parameters. $\Lambda_c = 0.38$ GeV.
$e_{spec} = -\frac{1}{3}(\mathcal{A}^0_{X_{s(d)}\gamma})$ or $\frac{2}{3}(\mathcal{A}^{\pm}_{X_{s(d)}\gamma})$.
$\epsilon_s = (V_{ub}V_{us}^*)/(V_{tb}V_{ts}^*), \epsilon_d = (V_{ub}V_{ud}^*)/(V_{tb}V_{td}^*)$.

$$
\begin{aligned}
-660\text{ MeV} < \tilde{\Lambda}_{17}^u < +660\text{ MeV}\,, \\
-7\text{ MeV} < \tilde{\Lambda}_{17}^c < +10\text{ MeV}\,, \\
17\text{ MeV} < \tilde{\Lambda}_{78} < 190\text{ MeV}
\end{aligned}
$$