$B^0_{s,d} \to \ell^+\ell^-$ Decays in the Aligned Two-Higgs-Doublet Model

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Motivation

Three important features of purely leptonic B-meson decays: $B^0_{s,d} \to \ell^+\ell^-$

- Very small branching ratio;
  - loop induced only process in SM
  - helicity-suppressed by the factor: m_ℓ / m_b
  - GIM suppression
- Theoretical clean: the only hadronic uncertainty factors are: f_{B_s} or f_{B_d};
- Sensitive to new physics: non-SM scalar and pseudoscalar interactions.

Golden Channel!

$B^0_{s,d} \to \ell^+\ell^-$: The Experimental status V.S. SM prediction

- Current measurements by CMS and LHCb: weighted world average

$$\overline{\mathcal{B}}(B^0_s \to \mu^+\mu^-)_{\rm exp.} = (2.9 \pm 0.7) \times 10^{-9}$$
$$\overline{\mathcal{B}}(B^0_d \to \mu^+\mu^-)_{\rm exp.} = \left(3.6\,^{+1.6}_{-1.4}\right) \times 10^{-10}$$

[CMS-PAS-BPH-13-007]

- SM predictions:
  - The latest predictions: NLO EW + NNLO QCD:

$$\overline{\mathcal{B}}_{B_s\to e^+e^-} = (8.54 \pm 0.55) \times 10^{-14}\,, \qquad \overline{\mathcal{B}}_{B_d\to \mu^+\mu^-} = (1.06 \pm 0.09) \times 10^{-10}\,,$$
$$\overline{\mathcal{B}}_{B_s\to \mu^+\mu^-} = (3.65 \pm 0.23) \times 10^{-9}\,, \qquad \overline{\mathcal{B}}_{B_d\to e^+e^-} = (2.48 \pm 0.21) \times 10^{-15}\,,$$
$$\overline{\mathcal{B}}_{B_s\to \tau^+\tau^-} = (7.73 \pm 0.49) \times 10^{-7}\,, \qquad \overline{\mathcal{B}}_{B_d\to \tau^+\tau^-} = (2.22 \pm 0.19) \times 10^{-8}\,,$$

[Bobeth, Gorbahn, Hermann, Misiak, Stamou, Steinhauser, arXiv:1311.0903]

  - The error budgets for $B^0_s \to \mu^+\mu^-$ and $B^0_d \to \mu^+\mu^-$

	f_{B_q}	CKM	τ^q_H	M_t	α_s	other param.	non-param.	$\sum$
$\overline{\mathcal{B}}_{B^0_s\to\mu^+\mu^-}$	4.0%	4.3%	1.3%	1.6%	0.1%	$< 0.1\%$	1.5%	6.4%
$\overline{\mathcal{B}}_{B^0_d\to\mu^+\mu^-}$	4.5%	6.9%	0.5%	1.6%	0.1%	$< 0.1\%$	1.5%	8.5%

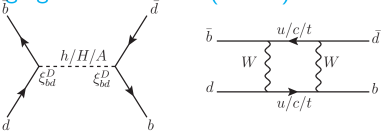
General 2HDM and FCNC

- Two Higgs doublet model: the simplest non-trivial extension on the SM

$$\Phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\left(G^+ \cos\beta - H^+ \sin\beta\right) \\ v\cos\beta - h\sin\alpha + H\cos\alpha + i\left(G^0\cos\beta - A\sin\beta\right) \end{pmatrix},$$

$$\Phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\left(G^+ \sin\beta + H^+ \cos\beta\right) \\ v\sin\beta + h\cos\alpha + H\sin\alpha + i\left(G^0\sin\beta + A\cos\beta\right) \end{pmatrix}.$$

- Two Yukawa coupling matrices ⇒ non-diagonal Yukawa matrices elements ⇒ tree level flavour changing neutral current(FCNC)



(a) (b)

- Possible solutions
  - make the non-diagonal Yukawa coupling vanish: impose a Z_2 symmetry on the Lagrangian [Glashow and Weinberg (1977)];
  - make the scalar couplings small enough: Type-III 2HDM model [Cheng and Sher (1987)]

Aligned 2HDM: Yukawa coupling

- It's convenient to study Yukawa coupling in Higgs basis

$$\Phi_1 = \begin{bmatrix} G^+ \\ \frac{1}{\sqrt{2}}\left(v + S_1 + iG^0\right) \end{bmatrix}, \qquad \Phi_2 = \begin{bmatrix} H^+ \\ \frac{1}{\sqrt{2}}\left(S_2 + iS_3\right) \end{bmatrix},$$

- Yukawa coupling in Higgs basis

$$\mathcal{L}_Y = -\frac{\sqrt{2}}{v}\left[\bar{Q}'_L(M'_d\Phi_1 + Y'_d\Phi_2)d'_R + \bar{Q}'_L(M'_u\tilde{\Phi}_1 + Y'_u\tilde{\Phi}_2)u'_R + \bar{L}'_L(M'_\ell\Phi_1 + Y'_\ell\Phi_2)\ell'_R\right] + \text{h.c.},$$

- Assuming the two different Yukawa coupling proportional to each other, in mass-eigenstate basis

$$Y_{d,\ell} = \varsigma_{d,\ell}\, M_{d,\ell}\,, \qquad Y_u = \varsigma_u^*\, M_u\,,$$

  The alignment parameters ς_f are arbitrary complex numbers.

- The Yukawa coupling after alignment

$$\mathcal{L}_Y = -\frac{\sqrt{2}}{v}\, H^+ \left\{\bar{u}\left[\varsigma_d\, VM_dP_R - \varsigma_u\, M_u^\dagger VP_L\right] d + \varsigma_\ell\, \bar{\nu}M_\ell P_R\ell\right\}$$

$$-\frac{1}{v}\sum_{\varphi_i^0, f} y_f^{\varphi_i^0}\, \varphi_i^0\, \left[\bar{f}M_fP_Rf\right] + \text{h.c.}\,,$$

Aligned 2HDM and Z_2 symmetry

- three new universal parameters introduced ς_f: an arbitrary complex number;

  $\Rightarrow$ new sources of CP violation;

- all the neutral-current interactions are diagonal in flavour;
- all leptonic couplings are diagonal in flavour due to the absence of ν_R;
- The usual $\mathcal{Z}_2$ symmetric models recovered by the following assignment of ς_f

Model	ς_d	ς_u	ς_l
Type I	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type II	$-\tan\beta$	$\cot\beta$	$-\tan\beta$
Type X	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type Y	$-\tan\beta$	$\cot\beta$	$\cot\beta$
Inert	0	0	0

The effective weak Hamiltonian

- The effective weak Hamiltonian of $B^0_{s,d} \to \ell^+\ell^-$

$$\mathcal{H}_{\rm eff} = -\frac{G_F\,\alpha}{\sqrt{2}\pi s_W^2}\left[V_{tb}V_{tq}^*\sum_i^{10,S,P}\left(C_i\,\mathcal{O}_i + C_i'\,\mathcal{O}_i'\right) + \text{h.c.}\right],$$

$$\mathcal{O}_{10} = (\bar{q}\gamma_\mu P_L b)\,(\bar{\ell}\gamma^\mu\gamma_5\ell)\,, \qquad \mathcal{O}_{10}' = (\bar{q}\gamma_\mu P_R b)\,(\bar{\ell}\gamma^\mu\gamma_5\ell)\,,$$

$$\mathcal{O}_S = \frac{m_\ell m_b}{M_W^2}\,(\bar{q}P_R b)\,(\bar{\ell}\ell)\,, \qquad \mathcal{O}_S' = \frac{m_\ell m_b}{M_W^2}\,(\bar{q}P_L b)\,(\bar{\ell}\ell)\,,$$

$$\mathcal{O}_P = \frac{m_\ell m_b}{M_W^2}\,(\bar{q}P_R b)\,(\bar{\ell}\gamma_5\ell)\,, \qquad \mathcal{O}_P' = \frac{m_\ell m_b}{M_W^2}\,(\bar{q}P_L b)\,(\bar{\ell}\gamma_5\ell)\,,$$

- Operators with $\bar{\ell}\gamma^\mu\ell$: vanish when contracted with the B-meson momentum p_μ;
- $\mathcal{O}_i'$: proportional to the light-quark mass $m_q \ll m_b$ and can be neglected;
- Tensor operators: have no contributions due to $\langle 0|\bar{q}\sigma_{\mu\nu}b|\bar{B}^0_q(p)\rangle = 0$
- Anomalous dimension of $\mathcal{O}_i^{(\prime)}$ is zero: no contribution from renormalization due to QCD correction.

Automatic calculation of Feynman Diagrams in Mathematica

- Write model files for FeynRules, include the Lagrangian and constraints;
- generate all the Feynman rules and a model file for FeynArts automatically;
- generate the Feynman diagrams and original amplitudes for the physical process by FeynArts;
- evaluate the Feynman amplitudes:
  - compute the analytic results in FeynArts directly;
  - pass the Feynman amplitudes to FeynCalc for further evaluation;
  - pass the Feynman amplitudes to FormCalc for further evaluation (only in Feynman gauge);

The Wilson Coefficient

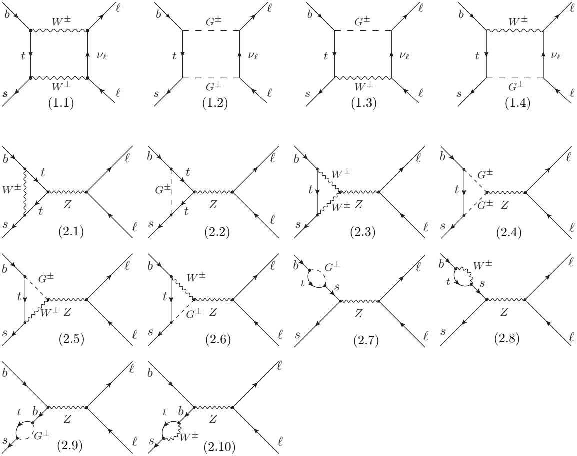
- The Wilson Coefficients $\mathcal{C}_i$: require equality of 1PI Green functions calculated in the full and in the effective theory.
- In the full theory: need to evaluate various box, penguin and self-energy diagrams .
- The sum of Wilson coefficients in Feynman gauge

$$
\begin{aligned}
C_{10} &= C_{10}^{\rm SM} + C_{10}^{\rm Z\,penguin,\,A2HDM}\,, \\
C_S &= C_S^{\rm box,\,SM} + C_S^{\rm box,\,A2HDM} + C_S^{\varphi_i^0,\,\rm A2HDM}\,, \\
C_P &= C_P^{\rm box,\,SM} + C_P^{\rm Z\,penguin,\,SM} + C_P^{\rm GB\,penguin,\,SM} + C_P^{\rm box,\,A2HDM} \\
&\quad + C_P^{\rm Z\,penguin,\,A2HDM} + C_P^{\rm GB\,penguin,\,A2HDM} + C_P^{\varphi_i^0,\,\rm A2HDM}\,.
\end{aligned}
$$

- All calculations are performed in both the Feynman $(\xi = 1)$ and the unitary $(\xi = \infty)$ gauges, to check the gauge independence.

The Wilson Coefficient in SM: C_{10}

C_{10} in the SM: generated from the W-box and Z-penguin diagrams;
[Inami and Lim, '81; Buchalla and Buras, '99; Bobeth, Gorbahn, Hermann, Misiak, Stamou and Steinhauser, 1311.0903]

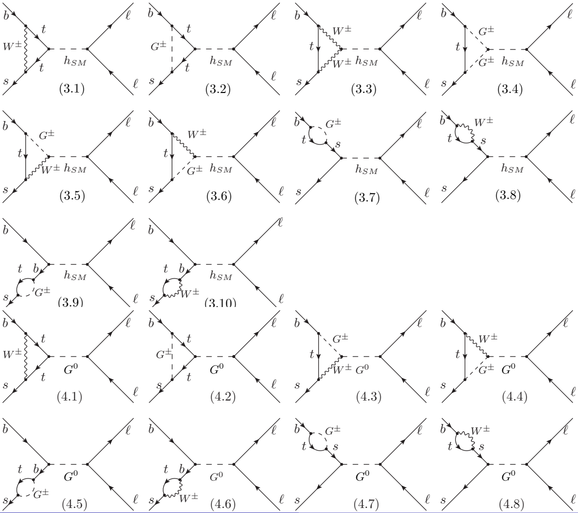


$$C_{10}^{\rm SM} = -\eta_Y^{\rm EW}\,\eta_Y^{\rm QCD}\; Y_0(x_t)$$

- $\eta_Y^{\rm EW} = 0.977$: the NLO EW matching corrections and QED RG running; [Bobeth, Gorbahn and Stamou, 1311.1348]
- $\eta_Y^{\rm QCD} = 1.010$: the NLO and NNLO QCD corrections; [Hermann, Misiak and Steinhauser,1311.1347]

The Wilson Coefficient in SM: C_S and C_P

C_S and C_P in SM: generated from the W-box, Z-penguin, Higgs-penguin and Goldstone-penguin diagrams.

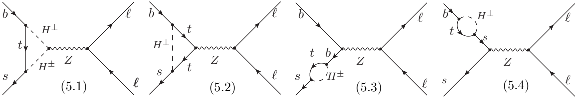


$$C_S^{\rm SM} = C_{S,\,\rm Unitary}^{\rm box,\,SM} + C_{S,\,\rm Unitary}^{\rm h\ penguin,\,SM} = C_{S,\,\rm Feynman}^{\rm box,\,SM} + C_{S,\rm Feynman}^{\rm h\ penguin,\,SM}$$

$$C_P^{\rm SM} = C_{P,\rm Unitary}^{\rm box,\,SM} + C_{P,\,\rm Unitary}^{\rm Z\ penguin,\,SM} = C_{P,\,\rm Feynman}^{\rm box,\,SM} + C_{P,\rm Feynman}^{\rm Z\ penguin,\,SM} + C_{P,\,\rm Feynman}^{\rm GB\ penguin,\,SM}$$

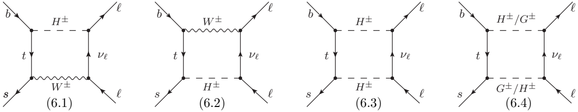
The Wilson Coefficient in A2HDM: I

- Z penguin diagrams in A2HDM: contribute to C_{10}^{A2HDM} and C_P

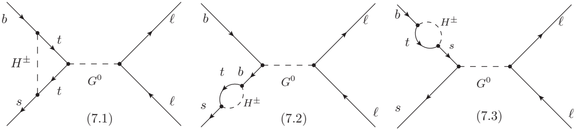


$$C_{10}^{\mathrm{A2HDM}} = |\varsigma_u|^2 F_1(x_t, x_{H^\pm})$$

- Box diagrams in A2HDM: contribute to C_S and C_P

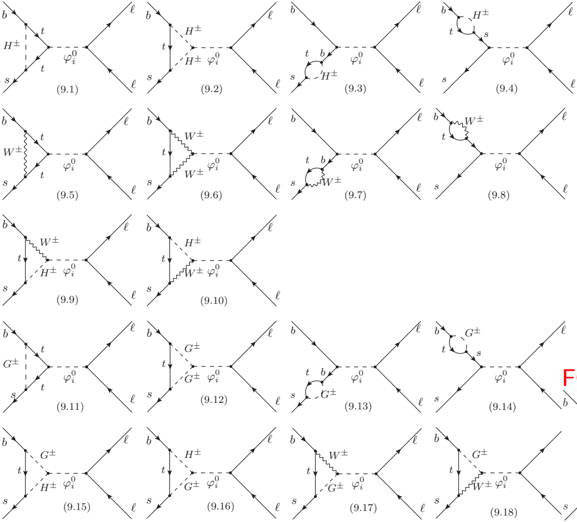


- Goldstone-Boson penguin diagrams in A2HDM: contribute to C_P



The Wilson Coefficient in A2HDM: II

one-loop penguin + tree-level FCNC contribution from $\mathcal{L}_{FCNC}$

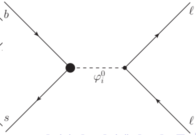


In CP conserving case :

$C_S^{\varphi_i^0,\,\mathrm{A2HDM}}$ from $\varphi_i^0 = (h, H)$

$C_P^{\varphi_i^0,\,\mathrm{A2HDM}}$ from $\varphi_i^0 = A$

FCNC



The Branching Ratio of $B^0_{s,d} \to \ell^+\ell^-$

- The CP conserved averaged time-integrated branching ratio (include the effect of $B_q - \bar{B}_q$ mixing)
  [De Bruyn, Fleischer, Knegjens etal, 1204.1735; 1204.1737; Buras, Fleischer, Girrbach, Knegjens, 1303.3820]

$$\overline{\mathcal{B}}(B^0_q \to \ell^+\ell^-) = \frac{G_F^4 M_W^4}{8\pi^5 \Gamma_H^q} \left| V_{tb} V^*_{tq} C_{10}^{\rm SM} \right|^2 f^2_{B_q} M_{B_q} m_\ell^2 \sqrt{1 - \frac{4 m_\ell^2}{M^2_{B_q}}} \times \left[|P|^2 + \left(1 - \frac{\Delta\Gamma_q}{\Gamma_L^q}\right) |S|^2 \right].$$

$$P \equiv \frac{C_{10}}{C_{10}^{\rm SM}} + \frac{M^2_{B_q}}{2M_W^2} \left(\frac{m_b}{m_b + m_q} \right) \frac{C_P}{C_{10}^{\rm SM}}, \qquad S \equiv \sqrt{1 - \frac{4m_\ell^2}{M^2_{B_q}}} \frac{M^2_{B_q}}{2M_W^2} \left(\frac{m_b}{m_b + m_q} \right) \frac{C_S}{C_{10}^{\rm SM}}$$

- the ratio of branching ratio

$$\overline{R}_{q\ell} \equiv \frac{\overline{\mathcal{B}}(B^0_q \to \ell^+\ell^-)}{\overline{\mathcal{B}}(B^0_q \to \ell^+\ell^-)_{\rm SM}} = \left[|P|^2 + \left(1 - \frac{\Delta\Gamma_q}{\Gamma_L^q}\right) |S|^2 \right],$$

- $\overline{R}_{s\mu} = 0.79 \pm 0.20$ and $\overline{R}_{d\mu} = 3.38^{+1.53}_{-1.35}$ are used as constraints on the model parameters.

Choice of the model parameters

10 free parameters in our results:

$$\varsigma_{u,d,\ell}, \quad (M_H, M_A, M_{H^\pm}) \quad \tilde{\alpha}, \quad (\lambda_3, \lambda_7), \quad C_R(M_W)$$

- Four parameters can be fixed for simplicity:
  - the mixing angle $\tilde{\alpha}$: $|\cos\tilde{\alpha}| > 0.90$ (68% CL) [Celis, Ilisie and Pich, 1302.4022; 1310.7941]
  - $|\lambda_{3,7}| \lesssim 8\pi$; [Gunion, Haber,Kane and Dawson (2000); Branco, Ferreira, Lavoura, Rebelo, Sher and Silva(2011)]
  - $C_R(M_W)$: no strong constraint yet.

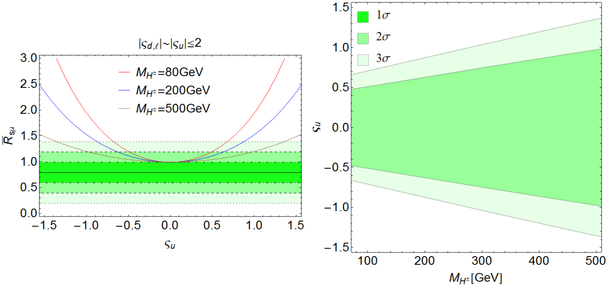
  They are less sensitive to $\overline{R}_{s\mu}$, so

  $$\lambda_3 = \lambda_7 = 1, \quad \cos\tilde{\alpha} = 0.95, \quad C_R(M_W) = 0$$

- Six parameters to be analysed later:
  - neutral scalar masses: $M_H \geq M_h \simeq 126$ GeV, $M_H \in [130, 500]$ GeV, $M_A \in [80, 500]$ GeV
  - charged Higgs mass and ς_u: $M_{H^\pm} \in [80, 500]$ GeV with requiring $|\varsigma_u| \leq 2$. [Celis, Ilisie and Pich, 1302.4022; 1310.7941; Jung, Pich and Tuz on, 1006.0470; Jung, Li and Pich, 1208.1251]
  - ς_d and ς_ℓ: $|\varsigma_{d,\ell}| \leq 50$

Numerical Analysis I: small ς_d, ς_ℓ

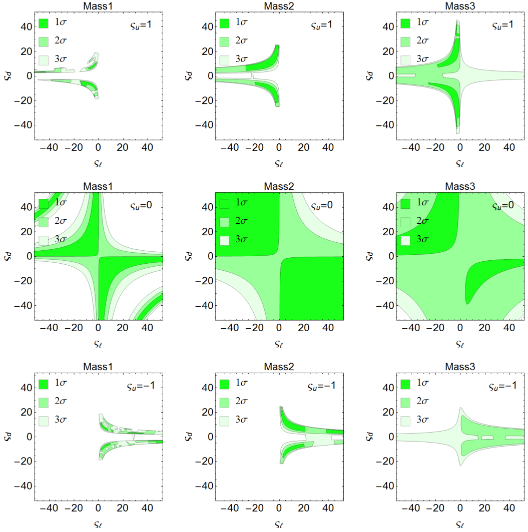
- $|\varsigma_{d,\ell}| \sim |\varsigma_u| \leq 2$: $C_{S,P}$ are negligible, C_{10}^{A2HDM} only involve ς_u and $M_{H^\pm}$



- The ratio $\overline{R}_{s\mu}$ puts strong upper bound on the parameter: $|\varsigma_u| \leq 0.49\ (0.97)$ with $M_{H^\pm} = 80\ (500)$ GeV, at 95% CL.
- For lager $M_{H^\pm}$, the bound become weaker: $\lim\limits_{x_{H^+}\to\infty} C_{10}^{\text{A2HDM}} = 0$.

Numerical Analysis II: large ς_d, ς_ℓ

$\varsigma_{d,\ell} \in [-50, 50]$: C_S and C_P can induce a significant enhancement.



Mass1 :

$$M_{H^\pm} = M_A = 80 \text{ GeV}$$
$$M_H = 130 \text{ GeV}$$

Mass2 :

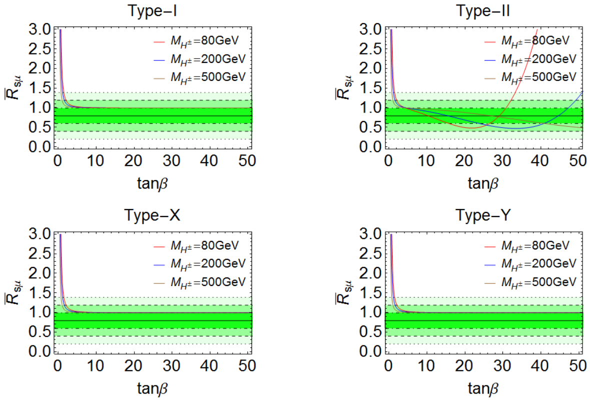
$$M_{H^\pm} = M_A = M_H = 200 \text{ GeV}$$

Mass3 :

$$M_{H^\pm} = M_A = M_H = 500 \text{ GeV}$$

Numerical Analysis III: $\mathcal{Z}_2$ symmetric models

The discrete $\mathcal{Z}_2$ symmetric models: particular cases of the CP-conserving A2HDM



- type-I, type-X and type-Y are almost indistinguishable; $\tan\beta \geq 1.5$ at 95% CL under constraint from $\overline{R}_{s\mu}$;
- For type-II model, an enhancement of $\overline{R}_{s\mu}$ is still possible in the large $\tan\beta$ region.

Summery

- $B^0_{s,d} \to \ell^+\ell^-$ decays are studied within the general framework of the A2HDM.

- A complete one-loop calculation of C_{10}, C_S and C_P are performed in box and penguin diagrams, both in Feynman gauge and unitary gauge. The relations of gauge dependence are examined.

- We investigated the impact and constraints of various model parameters on the branching ratios with the current data on $\overline{\mathcal{B}}(B^0_s \to \mu^+\mu^-)$

- The resulting information about the model parameters will be useful for the model building and is complementary to the collider physics;