2HDM and Flavor Physics

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In collaboration with

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hep-ph/1703.03426 and 1710.xxxxx

Brda, October 11, 2017.

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This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 674896.

Outline

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- The SM Higgs sector is the simplest possibility to accommodate observations.
- Hierarchy and flavor problems remain unsolved.
- Maybe there exist more scalar states?
- Much richer phenomenology with two Higgs doublets - **2HDM**.

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- Much richer phenomenology with two Higgs doublets - **2HDM**.
- What about a CP-odd Higgs lighter than $h(125)$? Can this scenario be accommodated in minimal 2HDM?

  $\Rightarrow$ Light CP-odd portal for DM – Coy Mediator, [Boehm et al. 2014].

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(ii) How can we search for the additional scalars in current/future flavor experiments?

$\Rightarrow$ Possible due to the *maturity of LQCD* and *unprecedented precision in flavor experiments*.

Outline

2HDM: Scalar Spectrum

Scalar potential:

$$V(\Phi_1,\Phi_2) = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 + m_{12}^2(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2$$
$$+ \lambda_3\Phi_1^\dagger\Phi_1\Phi_2^\dagger\Phi_2 + \lambda_4\Phi_1^\dagger\Phi_2\Phi_2^\dagger\Phi_1 + \frac{\lambda_5}{2}\left[(\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2\right],$$

with

$$\Phi_a = \begin{pmatrix} \phi_a^+ \\ \frac{1}{\sqrt{2}}(v_a + \rho_a + i\eta_a) \end{pmatrix}, \quad a = 1,2,$$

and $\mathbb{Z}_2$ symmetry $[\Phi_2 \to -\Phi_2]$.

- Soft-breaking term $\propto m_{12}^2 \Rightarrow$ more realistic spectrum.
- Physical particles: 3 neutral scalars (h, H, A) and one charged ($H^\pm$).

$$H^+ = \phi_1^+\sin\beta - \phi_2^+\cos\beta \qquad A^0 = \eta_1\sin\beta - \eta_2\cos\beta$$
$$H = -\rho_1\cos\alpha - \rho_2\sin\alpha \qquad h = \rho_1\sin\alpha - \rho_2\cos\alpha,$$

with $\tan\beta = v_2/v_1$.

General Constraints

- Scalar potential bounded from below if:

$$\lambda_{1,2} > 0, \qquad \lambda_3 > -(\lambda_1\lambda_2)^{1/2} \quad \text{and} \quad \lambda_3 + \lambda_4 - |\lambda_5| > -\sqrt{\lambda_1\lambda_2}.$$

- Stationary conditions ($\partial V/\partial v_{1,2} = 0$) determine m_{11}^2, m_{22}^2.

- Scalar scattering: unitarity bound on the S-wave partial wave amplitudes:

$$|a_\pm|, |b_\pm|, |c_\pm|, |f_\pm|, |e_{1,2}|, |f_1|, |p_1| < 8\pi$$

[more constraining than $|\lambda_i| \lesssim 4\pi$]

- Electroweak precision tests.
- SM-like couplings hZZ and hWW: $|\cos(\beta - \alpha)| \lesssim 0.3$.
- AND: $m_A < m_h/2$, watch out for $\Gamma(h \to AA)$ not to be large [$\lesssim 30\% \, \Gamma(h)^{SM}$]

- We randomly scan the parameters in the intervals:

$$\tan\beta \in (0.2, 50], \qquad \alpha \in \left(-\frac{\pi}{2}, \frac{\pi}{2}\right), \qquad \frac{|m_{12}^2|}{\sin\beta\cos\beta} = \left|M^2\right| \leq (1.2\ \text{TeV})^2,$$

$$m_{H^\pm} \in (m_W, 1.2\ \text{TeV}), \qquad m_H \in (m_h, 1.2\ \text{TeV}), \qquad m_A \in (20\ \text{GeV}, 1.2\ \text{TeV}),$$

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- These quantities fully determine the parameters in the scalar potential:

$$\lambda_1 = \frac{1}{v^2}\left(-\tan^2\beta M^2 + \frac{\sin^2\alpha}{\cos^2\beta} m_h^2 + \frac{\cos^2\alpha}{\cos^2\beta} m_H^2\right),$$

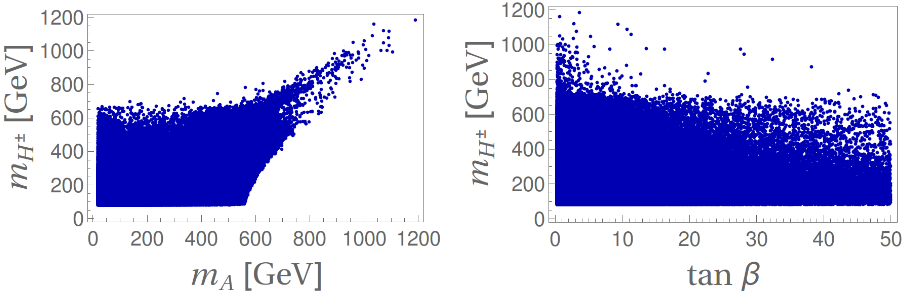
$$\lambda_2 = \frac{1}{v^2}\left(-\cot^2\beta M^2 + \frac{\cos^2\alpha}{\sin^2\beta} m_h^2 + \frac{\sin^2\alpha}{\sin^2\beta} m_H^2\right),$$

$$\lambda_3 = \frac{1}{v^2}\left(-M^2 + 2m_{H^\pm}^2 + \frac{\sin(2\alpha)}{\sin(2\beta)}(m_H^2 - m_h^2)\right),$$

$$\lambda_4 = \frac{1}{v^2}\left(M^2 + m_A^2 - 2m_{H^\pm}^2\right)$$

$$\lambda_5 = \frac{1}{v^2}\left(M^2 - m_A^2\right).$$

Results I. Generic Constraints



⇒ Light CP-odd Higgs ($m_A < m_h$) perfectly plausible.

⇒ Impossible to dissociate A and $H^\pm$ (gauge invariance).

⇒ Values of $\tan\beta \gtrsim 15$ require a tuning of parameters ($M^2 \approx m_H^2$).

Outline

2HDM: Yukawa sector

$$\mathcal{L}_Y = -\overline{Q'}_L(\Gamma_1^d \Phi_1 + \Gamma_2^d \Phi_2) d'_R - \overline{Q'}_L(\Gamma_1^u \Phi_1^c + \Gamma_2^u \Phi_2^c) u'_R \\ - \overline{L'}_L(\Gamma_1^\ell \Phi_1 + \Gamma_2^\ell \Phi_2) \ell'_R + \text{h.c.}$$

- $\Gamma_i^\alpha (\alpha = u, d, \ell$ and $i = 1, 2)$ Yukawa couplings.
- Q' (L'_L) quark (lepton) doublet.
- In general $\Rightarrow$ FCNC problematic.

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Simplest ways out

- Introduce $\mathbb{Z}_2$ symmetry $\Rightarrow$ d_R, u_R, ℓ_R coupling to one doublet each

  $\Rightarrow$ Models type I,II,X and Z

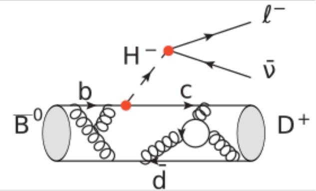
Model	u_R	d_R	L_R
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Type X	Φ_2	Φ_2	Φ_1
Type Z	Φ_2	Φ_1	Φ_2

- Alignment: Yukawa matrices proportional at Λ_{NP}. [Pich, Tuzon. 2009]

Outline

Flavor physics observables

- The charged Higgs can affect:
  - Tree-level decays ($b \to c\tau\nu$, $b \to u\tau\nu$):



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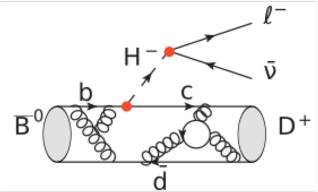
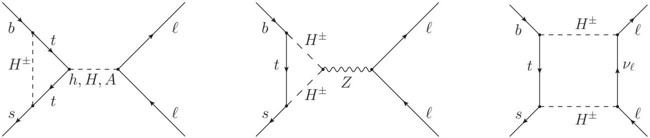


  - Loop-level decays ($b \to s\ell\ell$):



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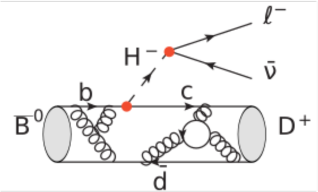

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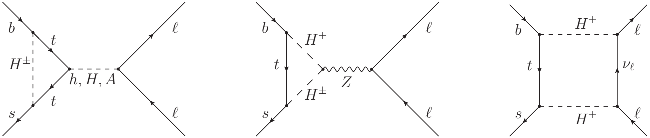


- A light CP-odd opens the possibility to explore new observables: pseudoscalar quarkonia decays ($\eta_{c,b} \to \ell^+\ell^-$) and Higgs decays ($h \to \eta_{c,b}\ell^+\ell^-$).

Outline

Standard (dim-6) eff. Hamiltonian for $b \to s\ell\ell$:

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left[\sum_{i=1}^{6} C_i(\mu)\mathcal{O}_i(\mu) + \sum_{i=7,8,9,10,P,S,\ldots} \Big(C_i(\mu)\mathcal{O}_i + C_i'(\mu)\mathcal{O}_i' \Big) \right]$$

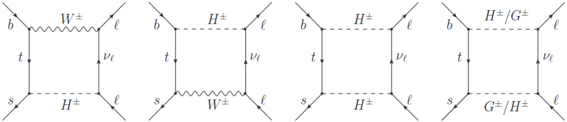
$$\mathcal{O}_9^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell), \qquad \mathcal{O}_{10}^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \gamma^5 \ell),$$

$$\mathcal{O}_S^{(\prime)} = (\bar{s} P_{R(L)} b)(\bar{\ell}\ell), \qquad \mathcal{O}_P^{(\prime)} = (\bar{s} P_{R(L)} b)(\bar{\ell}\gamma_5 \ell),$$

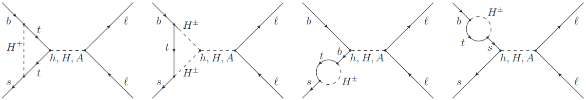
$$\mathcal{O}_7^{(\prime)} = m_b(\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}\,.$$

Relevant 2HDM contributions: C_S, C_P, C_7, C_9 and C_{10}.

- Boxes: C_S and C_P.

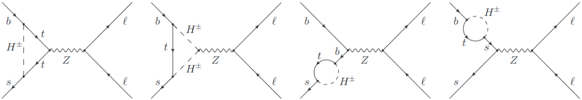


- (Pseudo-)scalar penguins: $C_{S(P)}$



$+ \ldots$

- Z penguins: C_P, C_9 and C_{10}.



- γ penguins: C_7 and C_9.

Important points:

- Couplings to down-type quarks and leptons can be enhanced, e.g. type II 2HDM with large $\tan\beta$.

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- $C_{S(P)}$ lift the helicity suppression in $\mathcal{B}(B_s \to \mu^+\mu^-)$:

$$\mathcal{B}(B_s \to \mu^-\mu^+) \propto |C_S|^2 + \left| C_P + \frac{2m_\mu m_b}{m_{B_s}^2} C_{10} \right|^2,$$

where

$$\mathcal{O}_P \propto \underbrace{(\bar{s}P_R b)(\bar{\ell}\gamma_5\ell)}_{\text{New contribution}}, \qquad \mathcal{O}_{10} \propto \underbrace{(\bar{s}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu\gamma_5\ell)}_{\text{Dominant in the SM}}, \qquad \ldots$$

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⇒ The $\mathcal{O}(m_\ell m_b/m_W^2)$ corrections to $\mathcal{C}_{S(P)}$ **must be computed** to reliably assess the 2HDM contributions.

⇒ Significant contributions by [Li et al. 1404.5865]. Issue of matching to order $\mathcal{O}(m_\ell m_b/m_W^2)$ recently clarified by [Arnan, Becirevic, Mescia and OS. 1703.03426].

2HDM and $b \to s\ell\ell$

Subtleties in the matching prescription [Arnan, Becirevic, Mescia and OS. 1703.03426]

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$$\frac{m_b}{m_W^2}\left(\bar{s}P_R b\right)\left(\bar{\ell}(\not{p}_b - \not{p}_s)P_R\ell\right) \simeq 2\frac{m_\ell m_b}{m_W^2} O_P \,,$$

where $p_b - p_s = p_+ + p_-$, i.e. $b(p_b) \to s(p_s)\ell^+(p_+)\ell^-(p_-)$.

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- While others **(of the same order)** cannot be matched onto $\mathcal{H}_{\text{eff}}^{(6)}$:

$$\frac{m_b}{m_W^2}\big(\bar{s}P_R b\big)\big(\bar{\ell}(\not{p}_b + \not{p}_s)P_R\ell\big) \to \text{non-trivial contribution!}$$

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⇒ The Hamiltonian needs to be extended by **derivative operators**.

These amplitudes can be matched onto derivative operators:

$$\mathcal{O}_{ij}^{\mathcal{T}\ell} = \frac{1}{m_W}(\bar{s}\gamma^\mu P_i b)\partial^\nu(\bar{\ell}\sigma_{\mu\nu}P_j\ell)$$

$$\mathcal{O}_{ij}^{\mathcal{T}q} = -\frac{1}{m_W}\partial^\nu(\bar{s}\sigma_{\mu\nu}P_i b)(\bar{\ell}\gamma^\mu P_j\ell) \qquad i,j = L,R.$$

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$$\frac{1}{m_W}\big(\bar{s}\gamma^\mu P_L b\big)\big(\bar{\ell}(\not{p}_b + \not{p}_s)\gamma_\mu P_R\ell\big) \to -\mathcal{O}_{LR}^{\mathcal{T}\ell} + \left(\mathcal{O}_S + \mathcal{O}_P + \frac{\mathcal{O}_T + \mathcal{O}_{T5}}{2}\right)\frac{m_b}{2m_W}.$$

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NB. This choice is not unique and can affect the Wilson coefficients

Example of Fierz trick:

$$\frac{1}{m_W}\left(\bar{s}\gamma_\mu P_L b\right)\left(\bar{\ell}\not{p}_b\,\gamma_\mu P_R \ell\right) = \frac{2}{m_W}\left(\bar{s}P_R\ell\right)\left(\bar{\ell}\not{p}_b P_L b\right)$$

$$= \frac{2m_b}{m_W}\left(\bar{s}P_R\ell\right)\left(\bar{\ell}P_R b\right)$$

$$= \frac{m_b}{m_W}\left[\left(\bar{s}P_R b\right)\left(\bar{\ell}P_R\ell\right) + \frac{1}{4}\left(\bar{s}\sigma_{\mu\nu}P_R b\right)\left(\bar{\ell}\sigma_{\mu\nu}P_L\ell\right)\right].$$

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$$= \frac{m_b}{m_W}\left[(\bar{s}P_R b)(\bar{\ell}P_R\ell) + \frac{1}{4}(\bar{s}\sigma_{\mu\nu}P_R b)(\bar{\ell}\sigma_{\mu\nu}P_L\ell)\right].$$

The piece of the amplitude with p_s gives rise to $\mathcal{O}_{LR}^{\mathcal{T}\ell}$ + other terms :

$$\frac{1}{m_W}(\bar{s}\gamma^\mu P_L b)(\bar{\ell}(\not{p}_b + \not{p}_s)\gamma_\mu P_R\ell) \to -\mathcal{O}_{LR}^{\mathcal{T}\ell} + \frac{m_b}{2m_W}\left(\mathcal{O}_S + \mathcal{O}_P + \frac{\mathcal{O}_T + \mathcal{O}_{T5}}{2}\right).$$

Back to phenomenology...

(Clean) exclusive $b \to s\ell\ell$ observables

◦ Use $f_{B_s}^{Latt.} = 224(5)\ \mathrm{MeV}$ and $\mathcal{B}(B_s \to \mu\mu)^{\mathrm{exp}} = 3.0(6)(^{3}_{2}) \times 10^{-9}$.
[LHCb, 2017]

$$\mathcal{B}(B_s \to \mu^+\mu^-) = \mathcal{F}_{B_s}\Big(f_{B_s}, C_{10} - C_{10}', C_P - C_P', C_S - C_S'\Big)$$

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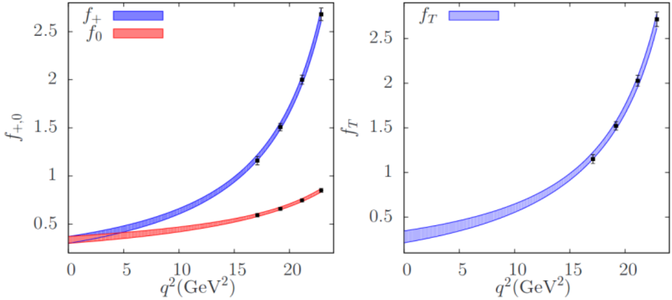
- Use $f_{+,0,T}^{B\to K}(q^2)^{Latt.}$ and $\mathcal{B}(B \to K\mu\mu)^{\text{exp}}_{q^2\in[15,22]\ \text{GeV}^2} = 8.5(3)(4) \times 10^{-8}$.

[LHCb, 2014]

$$\frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2}(B \to K\mu^+\mu^-) = \mathcal{F}_{BK}\left(f_{+,0,T}(q^2), C_9 + C_9', C_{10} + C_{10}', C_{7,S,P} + C_{7,S,P}'\right)$$

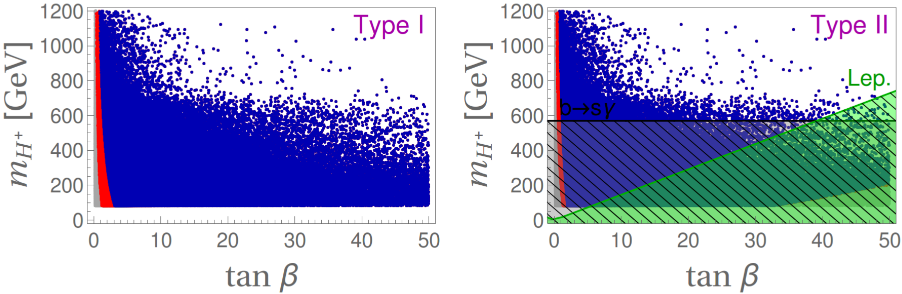
MILC [1509.06235]



Results consistent with HPQCD 1306.2384.

Results II. Flavor Constraints

Allowed points (at 3σ): $B_s \to \mu^+\mu^-$ (gray) and $\mathcal{B}(B \to K\mu\mu)_{\text{high } q^2}$ (red).



We also show the constraints from $\mathcal{B}(B \to \tau\nu)$ (green), and $\mathcal{B}(B \to X_s\gamma)$ (black hatched) [Misiak et al. 2016].

$\Rightarrow$ The $b \to s\ell\ell$ exclusive decays exclude values of $\tan\beta \lesssim 1$.

$\Rightarrow$ $\mathcal{B}(B \to \tau\nu)$ and $\mathcal{B}(D_s \to \tau\nu)$ (in green) are useful constraints for the Type-II model with large $\tan\beta$.

Lepton flavor universality violation (LFUV)?

[LHCb, 2014–2017]

$$R_K^{\text{central}} = \left.\frac{\mathcal{B}(B^+ \to K^+\mu\mu)}{\mathcal{B}(B^+ \to K^+ee)}\right|_{q^2\in(1,6)\ \text{GeV}^2} = 0.745 \pm^{0.090}_{0.074} \pm 0.036\,,$$

$$R_{K^*}^{\text{central}} = \left.\frac{\mathcal{B}(B \to K^*\mu\mu)}{\mathcal{B}(B \to K^*ee)}\right|_{q^2\in(1.1,6)\ \text{GeV}^2} = 0.685 \pm^{0.113}_{0.069} \pm 0.047\,,$$

In the whole discussion above, LFU was assumed. Can these scenarios explain $R_{K^{(*)}}^{\text{exp}} < R_{K^{(*)}}^{\text{SM}}$?

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In the whole discussion above, LFU was assumed. Can these scenarios explain $R_{K^{(*)}}^{\rm exp} < R_{K^{(*)}}^{\rm SM}$?

$\Rightarrow$ LFUV effects in $b \to s\ell\ell$ $(\ell = e, \mu)$ cannot be explained by general 2HDM (only $C_{S(P)}$ are LFUV).

See D. Becirevic talk for viable models!

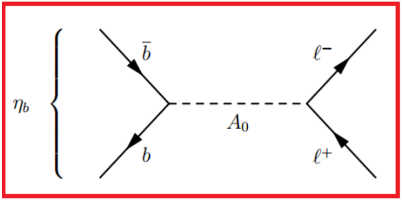
Outline

1. Motivation
2. Scalar spectrum and constraints
3. Flavor physics observables
    - Flavor probes of 2HDM scalars
    - 2HDM and exclusive $b \to s\ell\ell$ decays
    - Exploring the light CP-odd Higgs window
4. Summary and perspectives

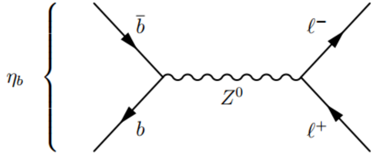
Future Experimental Possibilities: $m_A < 125$ GeV

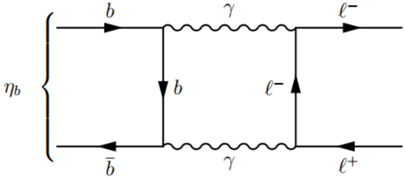
Large enhancements can be checked in the decays $\eta_{b,c} \to \ell^+\ell^- (J^P = 0^-)$:

- Process suppressed in the SM $\Rightarrow$ We are sensitive to New Physics.
- New Physics appears at tree-level.
- Non-perturbative QCD effects are under control (Lattice QCD).



VS





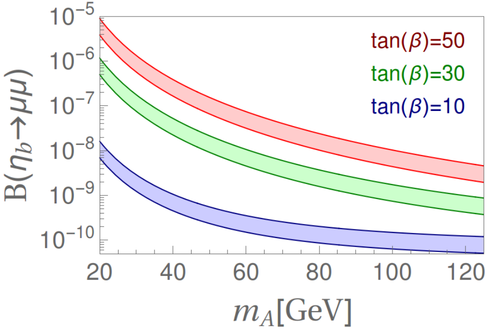
Future experimental possibilities: $m_A < 125$ GeV

Preliminary results

Large enhancements due to pseudo-scalar bosons can be checked in the decays $\eta_{b,c} \to \ell^+\ell^- (J^P = 0^-)$ and similar modes:

$$\mathcal{L}_Y \supset i \sum_{f=u,d,\ell} C_{Af} \frac{m_f}{v} \bar{f}\gamma_5 f A,$$

e.g., for 2HDM-II: $C_{Ad} = C_{A\ell} = \tan\beta$,



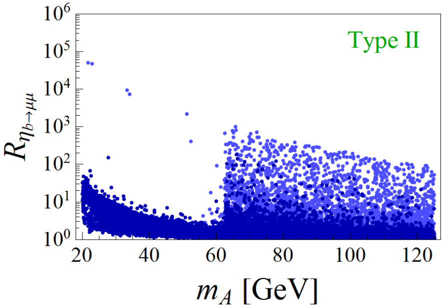
Future experimental possibilities: $m_A < 125$ GeV

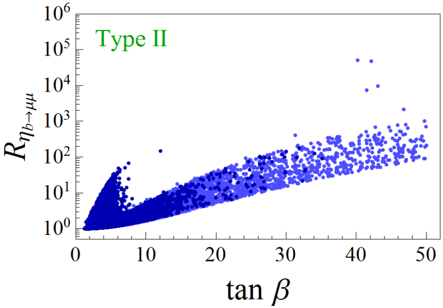
Preliminary results

Large enhancements due to pseudo-scalar bosons can be checked in the decays $\eta_{b,c} \to \ell^+\ell^-(J^P = 0^-)$ and similar modes:

$$R_{\eta_b \to \ell\ell} = \frac{\mathcal{B}(\eta_b \to \ell\ell)}{\mathcal{B}(\eta_b \to \ell\ell)^{\text{SM}}} .$$

e.g., for 2HDM-II: $C_{Ad} = C_{A\ell} = \tan\beta$,





Current limit: $\mathcal{B}(\eta_b \to \mu\mu) < 9 \times 10^{-3}$ [BaBar]. Can LHCb do better?

Outline

Summary and perspectives

- We derived the complete set of $b \to s\ell\ell$ effective coefficients in full generality.
- We elucidated the issue of $b \to s\ell\ell$ matching when the external momenta are kept nonzero.
- We showed that $\mathcal{B}(B \to K\mu\mu)_{\text{high } q^2}$ can also be helpful to constraint the 2HDM spectrum.

Most importantly,

$\Rightarrow$ Our expressions for the effective coefficients remain **general**.

$\Rightarrow$ More experimental precision can allow us in the future to reconstruct the Yukawa structure BSM by a bottom-up approach.

Furthermore...

There is still room for a light CP-odd A in minimal models (such as 2HDM)!

We proposed strategies to look for these particles:

$\Rightarrow$ Search for $\eta_{b,c} \to \ell\ell$ in LHCb, Belle-II and elsewhere.

[Becirevic, OS. To appear]

$\Rightarrow$ Higgs decays $h \to \eta_{b,c}\ell\ell$ can also be helpful.

[Becirevic, Melic, Patra, OS. 1705.01112]

Thank you!