On the (light) CP-odd Higgs

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hep-ph/1506.xxxxx

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June 22, 2015

Motivations

- So far no clear signal of NP has been found at the LHC.
- Understanding the spectrum of scalars beyond the SM is crucial.
- Possibility of light CP-odd Higgs A:

$$m_A < m_h \approx 125 \text{ GeV}.$$

- DM portal: mediating interactions between SM and DM fermions.

Coy Mediator: [Boehm et al. 1401.6458]
[Arina et al. 1409.0007]

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Can a light CP-odd Higgs be accommodated in 2HDM?   What can we learn from *low-energy processes*?

Results I. Generic Constraints

- We studied the 2HDM scenarios with light CP-odd Higgs ($m_A < m_h$) .
- Using the general theory constraints $\Rightarrow$ light CP-odd is perfectly **plausible**.

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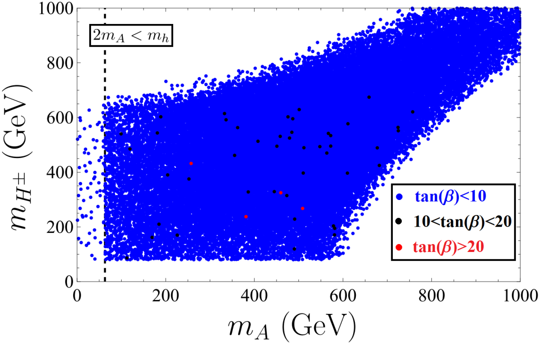

Results II. Flavor Constraints

- We separated the situation with $m_A < m_h/2$ from $m_A > m_h/2$.
- Former case: important possible signatures in $\Upsilon \to \eta_b \gamma$ (mixing $A - \eta_b$).
- Major constraint from $B_s \to \mu^+\mu^-$: $H^\pm$ cannot be dissociated from A .
- $B \to D\tau\nu$ and $B^+ \to \tau^+\nu$ - useful constraint for $m_{H^\pm} \lesssim 500$ GeV.

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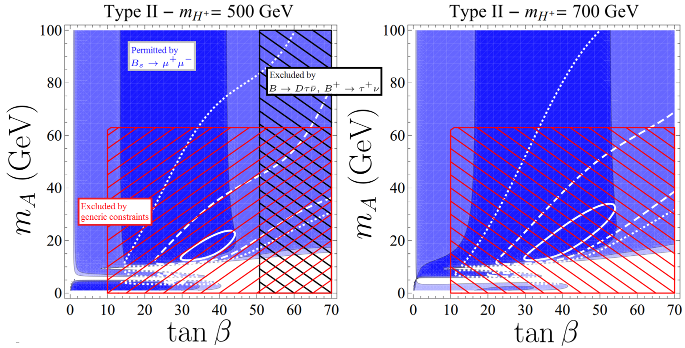
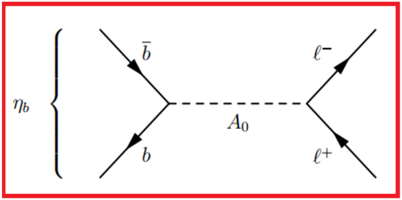


- $(g-2)_\mu$ is not a reliable constraint (white lines) . . .

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).



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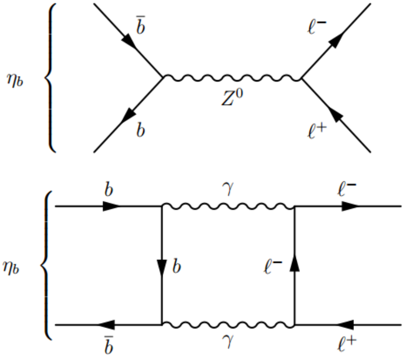


Perspectives

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

The situation can change with

- More precise measurements of $B_s \to \mu^- \mu^+$ at LHCb.
- Search for $\eta_{b,c} \to \ell^- \ell^+$ in Belle-II, LHCb.

Thank you! See poster for more!

Back-up Slides

Our Framework

We consider a 2HDM with a (softly broken) $\mathbb{Z}_2$ symmetry:

- Rich spectrum: 3 neutral scalars (h, H, A) and one charged ($H^{\pm}$).
- $\mathbb{Z}_2$ symmetry needed to forbid tree-level FCNC $\Rightarrow$ 4 different realizations (types I and II, Lepton-Specific and Flipped).

Our analysis imposes

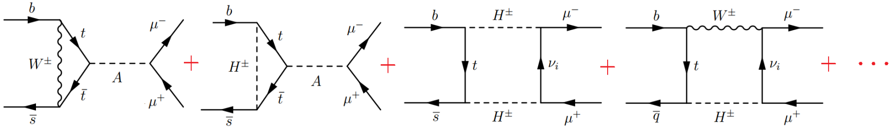
- General theoretical limits on the 2HDM spectrum (eg. unitarity).
- The requirement that h couplings are not far from SM ($\Rightarrow$ small value of $\Gamma(h \to AA)$).
- Flavor constraints.

Flavor Observables

Flavor observables can provide strong constraints:

- $\Upsilon \to \gamma\eta_b$, through mixing $A \rightsquigarrow \eta_b$.
- $B_s \to \mu^-\mu^+$. Pich et al. 1404.5865

New (scalar) contributions:



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

Flavor observables can provide strong constraints:

- $\Upsilon \to \eta_b \gamma$ and $\Upsilon \to \gamma \tau^- \tau^+$.
- $B_s \to \mu^- \mu^+$. Pich et al. 1404.5865

In our framework, the relevant contributions are:

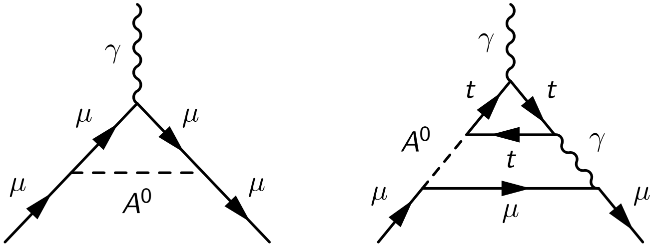
$$\mathcal{B}(B_s \to \mu^- \mu^+) \propto |C_S|^2 + \left| C_P + \frac{2 m_\mu m_b}{m_{B_s}^2} C_{10} \right|^2,$$

where C_i are Wilson coefficients of

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

$(g-2)_\mu$

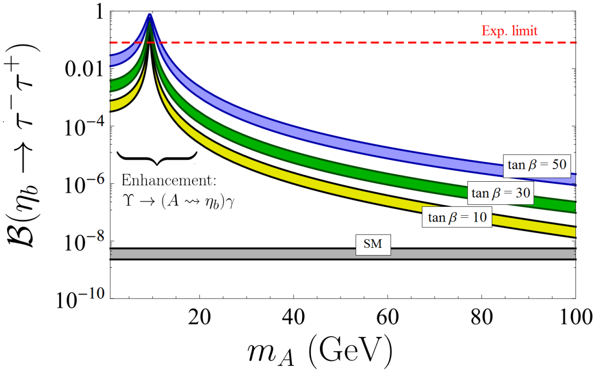
1. We don't know if the anomaly is due to NP.
2. Problematic cancellation between 1 and 2-loop diagrams (Barr-Zee) $\Rightarrow$ A more systematic study is needed.



Future Experimental possibilities

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.

For 2HDM-II,



Generic Constraints

Scalar potential:

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

- Limits on $\Gamma(h\to AA) \ll \Gamma_h^{\mathrm{SM}}$ for $m_A < m_h/2$:

$$|g_{hAA}| \ll v \Rightarrow M^2 \lesssim m_A^2 + \frac{1}{2}m_h^2$$
$$\Rightarrow M^2 < m_h^2.$$

- For large $\tan\beta$:

$$|\lambda_i| \leq 4\pi \Rightarrow m_h^2 \lesssim M^2 \lesssim m_H^2.$$

$\Rightarrow$ Impossible to have small $\Gamma(h\to AA)$ with $m_A < m_h/2$ and $\tan\beta \gtrsim 10$.