

# On the CP-odd Higgs

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In collaboration with

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[hep-ph/1512.05623](#)  $\oplus$  [1602.xxxx](#)

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*Rencontre de Physique des Particules, LAPTh, January 26, 2016.*

# Motivations

- So far no **clear** signal of NP has been found at the LHC.
- Hierarchy and Flavor problems remain unsolved.
- The discovery of  $h(125)$  opens the possibility to **pragmatically** explore the scalar spectrum BSM – **2HDM**.

# Motivations

- So far no **clear** signal of NP has been found at the LHC.
- Hierarchy and Flavor problems remain unsolved.
- The discovery of  $h(125)$  opens the possibility to **pragmatically** explore the scalar spectrum BSM – **2HDM**.
- Two attractive scenarios in the context of 2HDM:
  - I. CP-odd with  $m_A \approx 750$  GeV as suggested by CMS + ATLAS.
  - II. Light CP-odd portal for Dark Matter:  $m_A < m_h = 125$  GeV.

Coy Mediator: [Boehm et al. 1401.6458]

Can these scenarios be accommodated in **minimal 2HDM**?

What can we learn from *low-energy processes*?

# 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  $[\Phi_2 \rightarrow -\Phi_2]$ .

- SB 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  $\tan \beta = v_2/v_1$ .

# Generic Constraints

# General Constraints

- Scalar potential bounded from below if:

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

- 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:

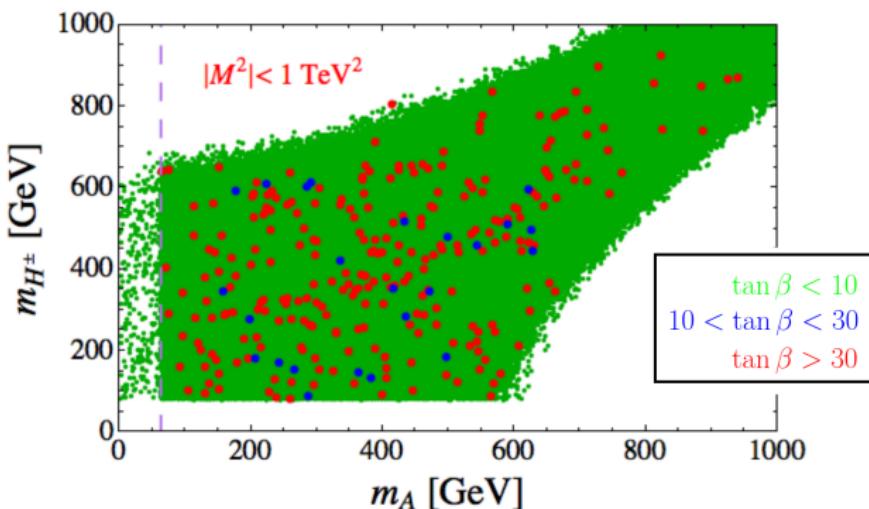
$$|a_{\pm}|, |b_{\pm}|, |c_{\pm}|, |f_{\pm}|, |e_{1,2}|, |f_1|, |p_1| < 8\pi$$

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

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

# Results I - Generic Constraints

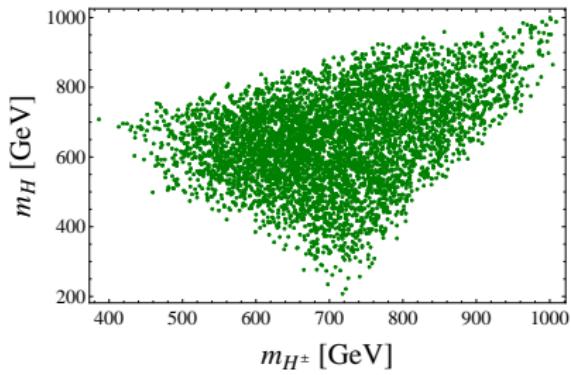
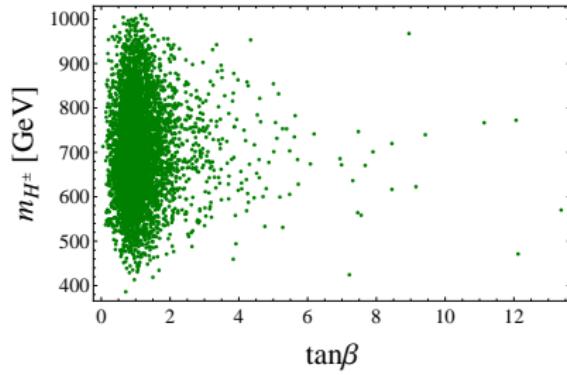
- We studied the 2HDM scenarios with  $m_h = 125$  GeV.
- Using the general theory constraints  $\Rightarrow$  light CP-odd ( $m_A < 125$  GeV) is perfectly **plausible** for  $\tan \beta < 10$ .



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

# Results I - Generic Constraints

- For fixed  $m_A = 750 \pm 30 \text{ GeV}$ , the other masses become bounded from below AND above:



$$200 \text{ GeV} \lesssim m_H \lesssim 1 \text{ TeV} \quad \text{and} \quad 400 \text{ GeV} \lesssim m_{H^\pm} \lesssim 1 \text{ TeV}$$

- Conclusions independent of additional fermionic degrees of freedom.

# Flavor Constraints

## 2HDM: Yukawa sector

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

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

## 2HDM: Yukawa sector

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

Simplest ways out

- Introduce  $\mathbb{Z}_2$  symmetry  $\Rightarrow d_R, u_R, \ell_R$  coupling to one doublet each  
 $\Rightarrow$  Models type I,II,X and Z

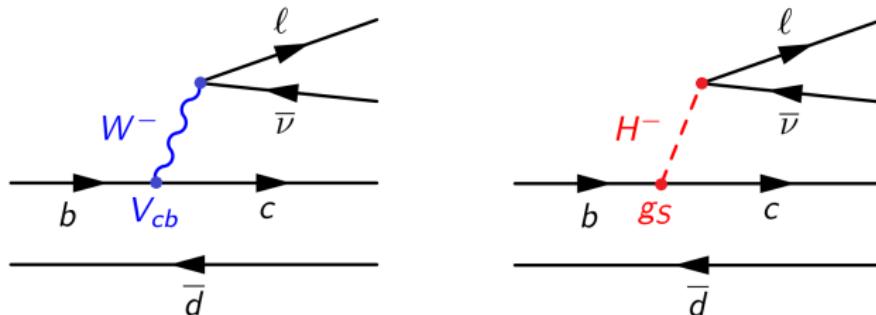
Model	$u_R$	$d_R$	$L_R$
Type I	$\Phi_2$	$\Phi_2$	$\Phi_2$
Type II	$\Phi_2$	$\Phi_1$	$\Phi_1$
Type X	$\Phi_2$	$\Phi_2$	$\Phi_1$
Type Z	$\Phi_2$	$\Phi_1$	$\Phi_2$

- Alignment: Yukawa matrices proportional at  $\Lambda_{\text{NP}}$ .

# Flavor Observables: $m_A \approx 750$ GeV

In the  $m_A \approx 750$  GeV benchmark,

- Flavor observables are practically insensitive to  $m_A \approx 750$  GeV.
- $H^\pm$  modifies  $B \rightarrow D\tau\bar{\nu}$  and  $B \rightarrow \tau\bar{\nu}$  at **tree-level**.

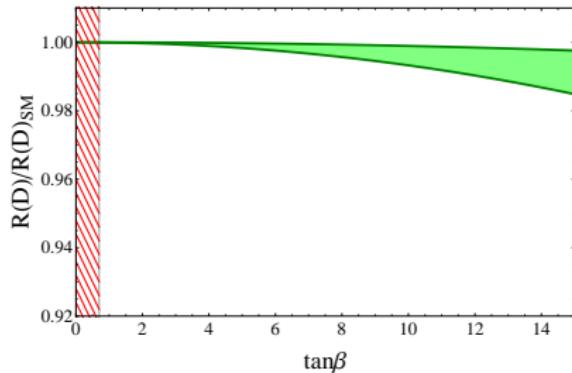
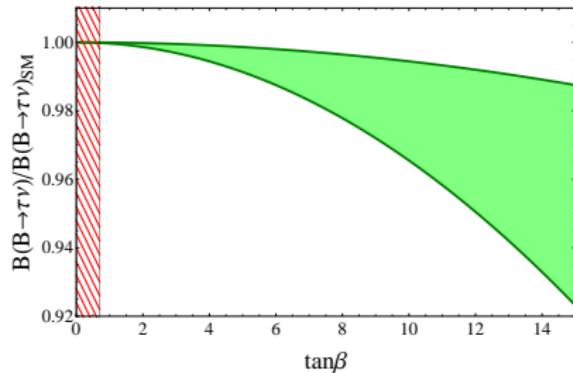


- $B_s \rightarrow \mu^-\mu^+$  is modified at loop-level (**box & penguin**).

# Flavor Observables: $m_A \approx 750$ GeV

Predictions –  $m_A \approx 750$  GeV framework (model type II):

- $\mathcal{B}(B \rightarrow \tau \bar{\nu})$  modified by mostly 10%.
- Unclear experimental situation for  $B \rightarrow D \tau \bar{\nu} \dots$



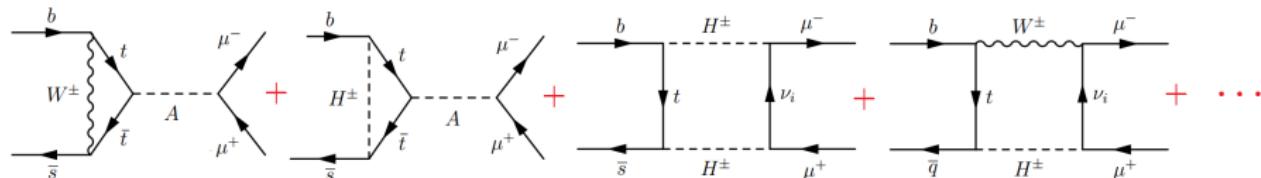
⇒ Fully consistent with (semi)-leptonic  $B$  decays AND other indirect tests (EWPT).

# Flavor Observables: $m_A < 125$ GeV

Light pseudo-scalars are strongly constrained by

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

New (scalar) contributions:



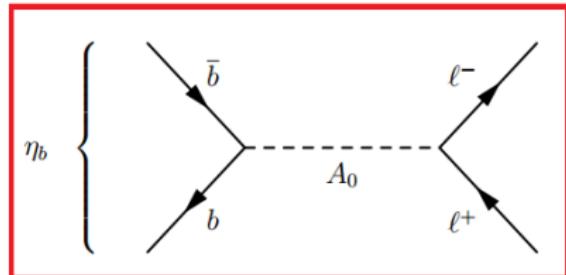
⇒ Impossible to dissociate  $A$  and  $H^\pm$  (gauge invariance).

Scenario **consistent** with low-energy data. Can we **check** it **somewhere else?**

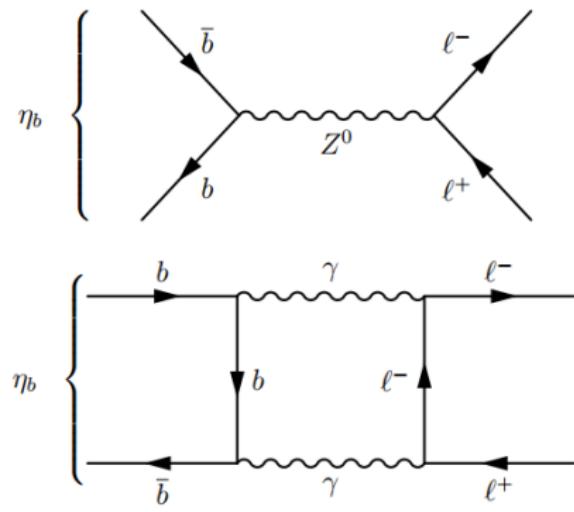
# Future Experimental Possibilities: $m_A < 125$ GeV

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

- 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).



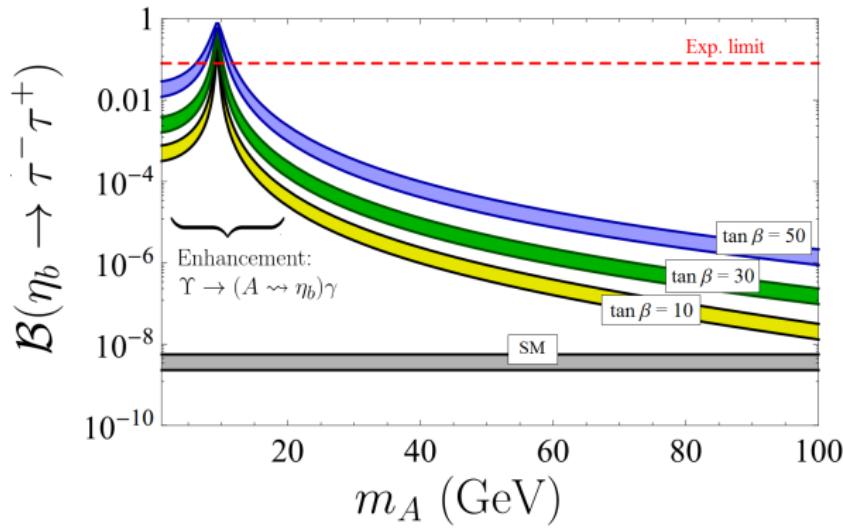
VS



# Future Experimental Possibilities: $m_A < 125$ GeV

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

For 2HDM-II,



# Perspectives

Both scenarios ( $m_A = 750$  GeV and  $m_A < 125$  GeV) are **consistent** with indirect constraints (**theory & flavor**).

The situation can change with

- More accurate measurements of  $B_s \rightarrow \mu^-\mu^+$  and (semi)-leptonic  $B$  decays at LHC and Belle-2.
- Search for  $B_c$  decays:  $B_c \rightarrow \tau\bar{\nu}_\tau$  and  $B_c \rightarrow \eta_c \ell\nu_\ell$ .

and for the light CP-odd scenario:

- Search for  $\eta_{b,c} \rightarrow \ell^-\ell^+$  in Belle-2, LHC and elsewhere.

Thank you!