Higgs Sector Beyond the Standard Model and a Role of Quarkonia

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LPT - Orsay

New Possibilities in Physics of Quarkonia, IHP, September 24, 2015

Motivations

- So far no clear signal of NP has been found at the LHC.
- No other scalar gb below $m_h = 125.7(4)$ GeV - LEP and Tevatron [above?]
- λ indeed small [$m_h^2 = 2\lambda v^2$], perturbativity OK, but metastability of the SM vacuum at very high energies (academic problem?)
- Hierarchy and Flavor problems remain unsolved.
- SUSY solution to hierarchy contrived. [Else?]

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- Hierarchy and Flavor problems remain unsolved.
- Attack the problem pragmatically – from the scalar sector [2HDM].
- What about a gb CP-odd below $m_h = 125.7(4)$ GeV? Rarely asked a question!
- DM portal: mediating interactions between SM and DM fermions.

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Can a light CP-odd Higgs be accommodated in 2HDM?

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

2HDM

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

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

and Z_2 symmetry $[\Phi_{1,2}\to -\Phi_{1,2}] \oplus$ SB term $\propto m_{12}^2$

- Two of the six fields can be gauged away
- Remaining spectrum

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

with

$$\boxed{\tan\beta = \frac{v_2}{v_1}, \qquad \tan(2\alpha) = \frac{2(-m_{12}^2+\lambda_{345}v_1v_2)}{m_{12}^2(v_2/v_1 - v_1/v_2) + \lambda_1 v_1^2 - \lambda_2 v_2^2}}$$

2HDM

Scalar potential:

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In other words,

$$\lambda_1 = \frac{1}{v^2}\left(-\tan^2\beta M^2 + \frac{\sin^2\alpha}{\cos^2\beta}m_h^2 + \frac{\cos^2\alpha}{\cos^2\beta}m_H^2\right)$$
$$\lambda_2 = \frac{1}{v^2}\left(-\cot^2\beta M^2 + \frac{\cos^2\alpha}{\sin^2\beta}m_h^2 + \frac{\sin^2\alpha}{\sin^2\beta}m_H^2\right)$$
$$\lambda_3 = \frac{1}{v^2}\left(-M^2 + 2m_{H^\pm}^2 + \frac{\sin 2\alpha}{\sin 2\beta}(m_H^2 - m_h^2)\right)$$
$$\lambda_4 = \frac{1}{v^2}\left(M^2 + m_A^2 - 2m_{H^\pm}^2\right)$$
$$\lambda_5 = \frac{1}{v^2}\left(M^2 - m_A^2\right)$$

where $M^2 \equiv \dfrac{m_{12}^2}{\sin\beta\cos\beta}$

2HDM

Scalar potential:

$$V(\Phi_1,\Phi_2) = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2$$

$$+ \lambda_3\Phi_1^\dagger\Phi_1\Phi_2^\dagger\Phi_2 + \lambda_4\Phi_1^\dagger\Phi_2\Phi_2^\dagger\Phi_1 + \frac{\lambda_5}{2}\left[(\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2\right]$$

or conversely,

$$m_H^2 = M^2\sin^2(\alpha-\beta) + \left(\lambda_1\cos^2\alpha\cos^2\beta + \lambda_2\sin^2\alpha\sin^2\beta + \frac{\lambda_{345}}{2}\sin 2\alpha\sin 2\beta\right)v^2$$

$$m_h^2 = M^2\cos^2(\alpha-\beta) + \left(\lambda_1\sin^2\alpha\cos^2\beta + \lambda_2\cos^2\alpha\sin^2\beta - \frac{\lambda_{345}}{2}\sin 2\alpha\sin 2\beta\right)v^2$$

$$m_A^2 = M^2 - \lambda_5 v^2$$

$$m_{H^\pm}^2 = M^2 - \frac{\lambda_{45}}{2}v^2$$

where $M^2 \equiv \dfrac{m_{12}^2}{\sin\beta\cos\beta}$

Generic Constraints

- Scalar potential bounded from below if:

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

- Vacuum Stability ($\partial V/\partial v_{1,2} = 0$) amounts to solving

$$m_{11}^2 + \frac{\lambda_1 v_1^2}{2} + \frac{\lambda_3 v_2^2}{2} = \frac{v_2}{v_1}\left[m_{12}^2 - (\lambda_4+\lambda_5)\frac{v_1 v_2}{2}\right]$$
$$m_{22}^2 + \frac{\lambda_2 v_2^2}{2} + \frac{\lambda_3 v_1^2}{2} = \frac{v_1}{v_2}\left[m_{12}^2 - (\lambda_4+\lambda_5)\frac{v_1 v_2}{2}\right]$$

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

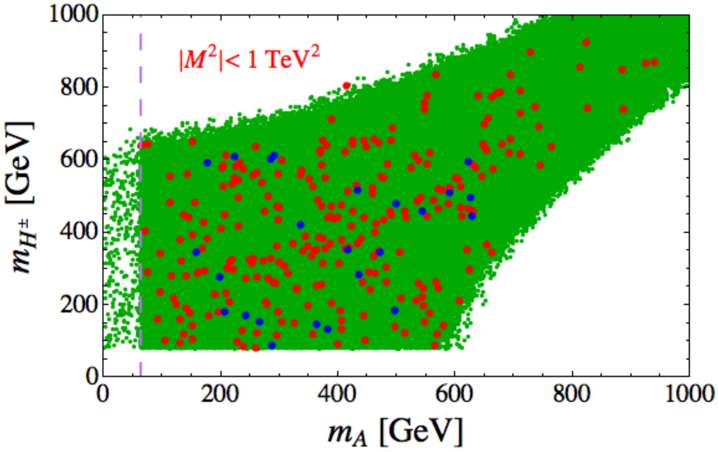
$$|a_\pm|, |b_\pm|, |c_\pm|, |f_\pm|, |e_{1,2}|, |f_1|, |p_1| < 8\pi$$

- AND: $m_A < m_h/2$ watch out for $\Gamma(h \to AA)$ not to be large [$\lesssim 30\% \Gamma^{SM}(h)$]

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

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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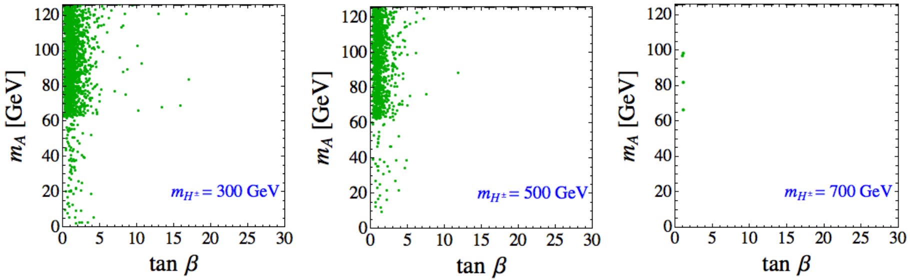

2HDM: Yukawa sector

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

- Γ_i^α ($\alpha = u, d, \ell$ et $i = 1, 2$) Yukawa couplings
- Q'_L (L'_L) quark (lepton) doublet
- FCNC problematic!

$$\mathcal{L}_{\mathrm{Y}}^{nc} = - \sum_{f=u,d,\ell} \frac{m_f}{v} \left(C_{hf}\ \bar{f} f h + C_{Hf}\ \bar{f} f H - i C_{Af}\ \bar{f} \gamma_5 f A \right)$$

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$$- \overline{L'}_L(\Gamma_1^\ell \Phi_1 + \Gamma_2^\ell \Phi_2) \ell'_R + \text{h.c.}$$

Ways out

- Introduce $\mathcal{Z}_2 \Rightarrow d'_R, u'_R, \ell'_R$ coupling to one doublet each $\Rightarrow$ models type I, II, X et 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

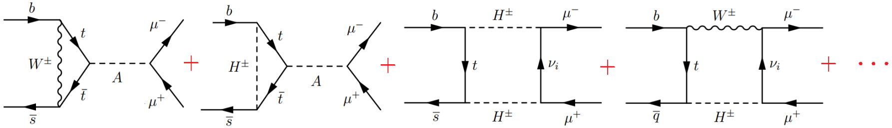
- Alignment – Yukawa matrices (nearly) proportional

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

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:

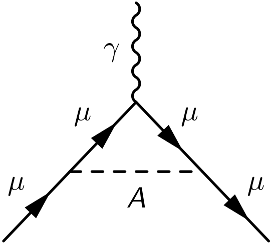
$$\mathcal{B}(B_s \to \mu^- \mu^+) \propto |C_S|^2 + \left| C_P + \frac{2 m_\mu m_b}{m_{B_s}^2} C_{10} \right|^2$$

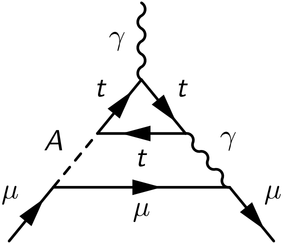
where C_i are Wilson coefficients of

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

$(g-2)_\mu$

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.





Results II. Flavor Constraints

- We separated two situations: $m_A < m_h/2$ or $m_A > m_h/2$.
- 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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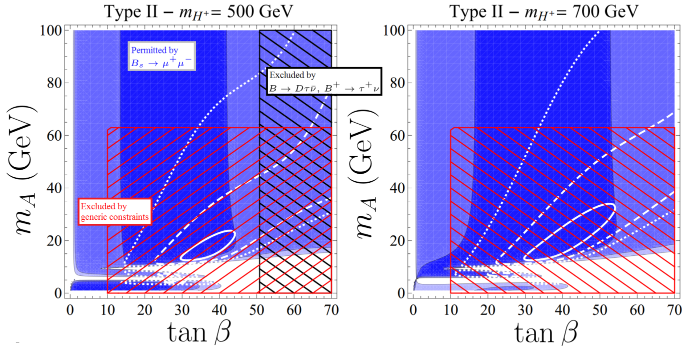

- $(g-2)_\mu$ is not a reliable constraint (white lines) . . .

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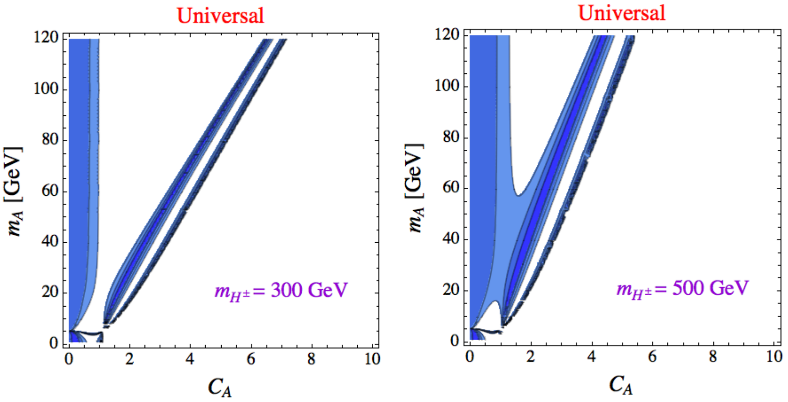
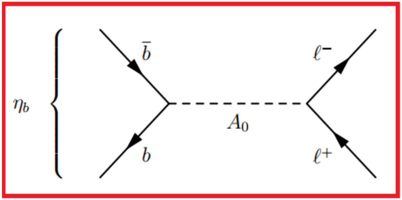
- What if C_{Af} were universal?



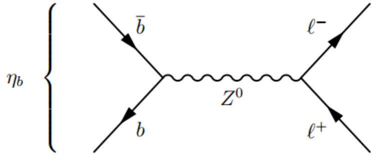
Future Experimental possibilities

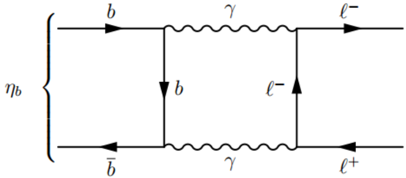
Large enhancements can be checked in the decays $\eta_{b,c} \to \ell^+\ell^-(J^P = 0^-)$:

- 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

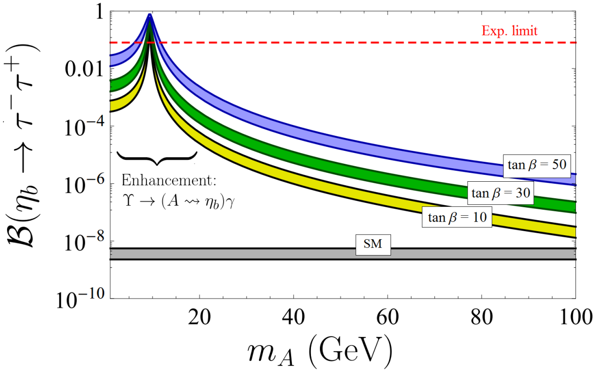




Future Experimental possibilities

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,



Perspectives

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

The situation can change with

- More accurate measurements of $B_s \to \mu^- \mu^+$ at LHCb.
- Search for $\eta_{b,c} \to \ell^- \ell^+$ in Belle-2, LHCb and elsewhere.
- B_c decays can be very useful too! If

$$R_{D^{(*)}} = \frac{B(B \to D^{(*)}\tau\nu_\tau)}{B(B \to D^{(*)}\mu\nu_\mu)}$$

  is indeed at odds with SM then the same effect of charged Higgs should be testable in $B_c \to \tau\nu_\tau$, $B_c \to J/\psi\ell\nu_\ell$ and $B_c \to \eta_c\ell\nu_\ell$, and even in $\Upsilon \to B_c\ell\nu_\ell$.

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N.B. In the whole discussion above, lepton flavour universality was assumed!

LFUV effects can be tested too!