BSM Higgs decays with quarkonia

Blaženka Melić

Institut Ruđer Bošković, Zagreb

work done in collaboration with D.Becirevic,O.Sumensari (LPT Orsay) and M. Patra (IRB)
arXiv: 1705.01112

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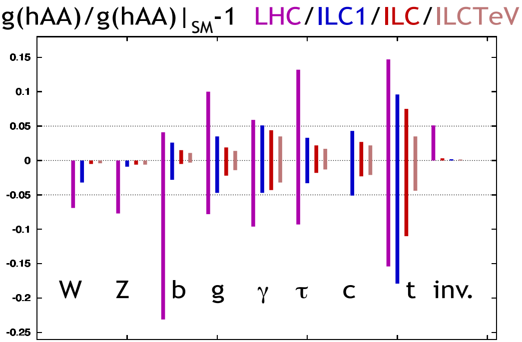
Outline

- Rare exclusive Higgs decays to a quarkonium and γ/Z and $\ell^+\ell^-$ final states

1. Introduction
2. $h \to V\gamma/Z$ $(V = J/\Psi, \Upsilon(nS))$ [Konig et.al. (1505.03870, 1609.06310), Bodwin et.al. 1306.5770]
3. $h \to PZ$ $(P = \eta_c, \eta_b)$
4. $h \to V\ell^+\ell^-$ $(V = J/\Psi, \Upsilon(nS))$ [Colangelo et.al. (1602.01372)]
5. $h \to P\ell^+\ell^-$ [Becirevic, BM, Patra, Sumensari (1705.01112)]

- Higgs is established as a SM particle of a mass 125 GeV
- activities in the precision measurements of its couplings to SM particles:



Comparison of the capabilities of LHC and ILC for model-independent measurements of Higgs Boson couplings. 14 TeV, 300 fb^{-1}/250 GeV, 250 fb^{-1}/500 GeV, 500 fb^{-1}/1 TeV, 1000 fb^{-1} [Peskin, arXiv:1207.2516]

- How to access light quark couplings ? - HIGGS DECAYS TO QUARKONIA

Exclusive Higgs Decays

- Difficult to obtain a direct measurement of the Higgs couplings to light fermions
  - Yukawa coupling $\propto m_q$, SM branching ratios very small

  - Huge QCD background and requires tagging to identify the flavour of the final state quark

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- The access to the light Yukawa couplings can be gained through **EXCLUSIVE HIGGS DECAYS:**

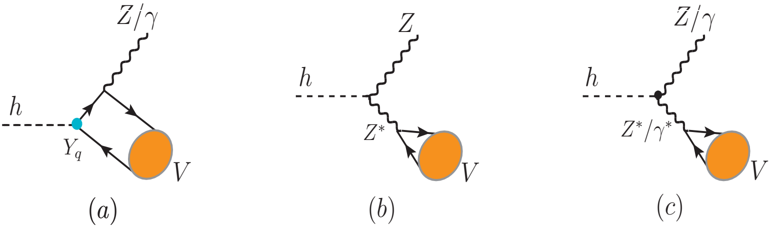
  - $h \to \mathcal{Q}Z/\gamma$ ($\mathcal{Q}$: vector meson, or pseudoscalar meson; $\mathcal{Q}$ = quarkonia)

  - possible for $u,\ d,\ c,\ s,\ b$ quarks

  - destructive interference between different diagram topologies makes some of these decays sensitive to the quark Yukawa couplings

- $h \to \mathcal{Q}\ell^+\ell^-$ ($\mathcal{Q} =$ *quarkonia*) decays can serve as a complementary channel to “direct” searches of new physics at the LHC

$h \to V\gamma$ ($V = J/\Psi, \Upsilon(nS)$)



Leading-order diagrams contributing to the decays $h \to VZ/\gamma$. Last graph contributes to one loop SM diagrams, $h \to Z\gamma, \gamma\gamma$

- "DIRECT" contribution : Higgs boson couples directly to the quark and the anti-quark pair from which the meson is formed, $\propto \kappa_q \frac{m_q}{v}, \; \kappa_q = 1$ in SM

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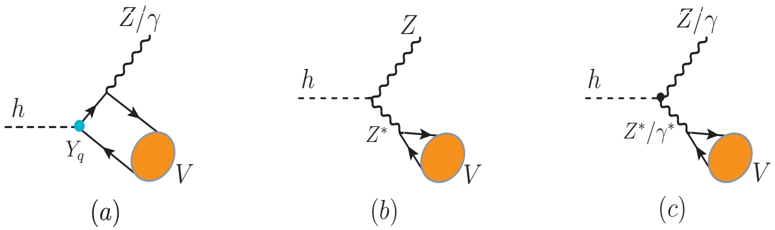

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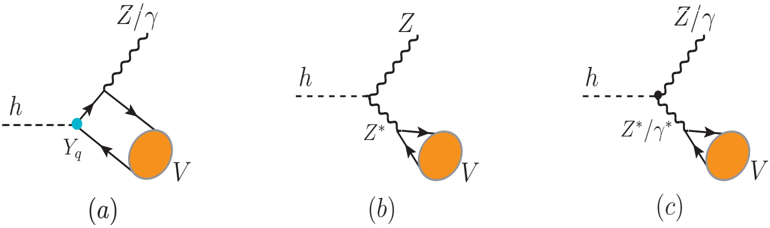
- "DIRECT" contribution : Higgs boson couples directly to the quark and the anti-quark pair from which the meson is formed, $\propto \kappa_q \frac{m_q}{v}, \ \kappa_q = 1$ in SM
- Calculated using the QCD factorization approach: separation between hard interactions and non-perturbative physics
- Large scale separation: convolution of the calculated hard scattering amplitude with the Light Cone Distribution Amplitudes of V

$h \to V\gamma$ ($V = J/\Psi, \Upsilon(nS)$)



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- "INDIRECT" contribution: meson is formed from an off-shell γ/Z through a local matrix element $\propto \langle V|\bar{q}\Gamma q|0\rangle \sim f_M$ (decay constant)

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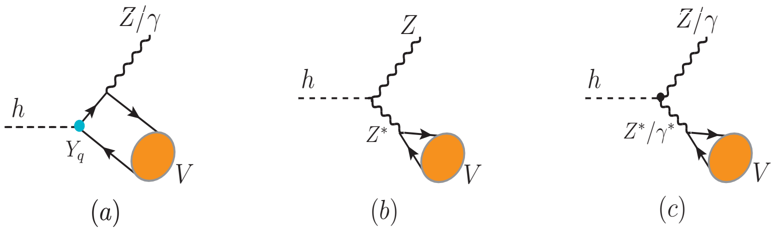

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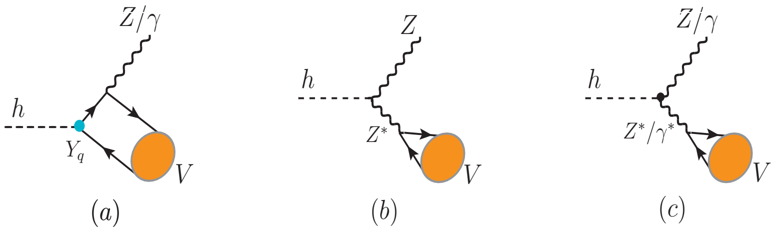
- "INDIRECT" contribution: meson is formed from an off-shell γ/Z through a local matrix element $\propto \langle V|\bar{q}\Gamma q|0\rangle \sim f_M$ (decay constant)
- Interplay between direct and indirect contributions, leads to a strong sensitivity on the quark Yukawa couplings

$h \to V\gamma$ $(V = J/\Psi, \Upsilon(nS))$



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- The decay amplitude of the Higgs into V and γ is

$$\mathcal{M}(h \to V\gamma) = e\frac{m_V}{v}\left(\epsilon_V^{\perp *} \cdot \epsilon_\gamma^{\perp *}\right) F_\perp^{V\gamma}$$
$$= \frac{e}{v}\left(\epsilon_V \cdot \epsilon_\gamma - \frac{1}{p_V \cdot p_\gamma}(p_V \cdot \epsilon_\gamma)(p_\gamma \cdot \epsilon_V)\right) F_\perp^{V\gamma}$$

$$F_\perp^{V\gamma} = F_{\perp(D)}^{V\gamma} + F_{\perp(ID)}^{V\gamma}$$

$h \to V\gamma \; (V = J/\Psi, \Upsilon(nS))$

$$\Gamma(h \to V\gamma) = \frac{\alpha}{2}\frac{m_h}{v^2} r_v(1 - r_V)|F_\perp^{V\gamma}|^2, \qquad F_\perp^{V\gamma} = F_{\perp(D)}^{V\gamma} + F_{\perp(ID)}^{V\gamma}$$

$$F_{\perp(D)}^{V\gamma} = \boxed{3Q_q\,\kappa_q \left[\frac{m_q}{m_V} f_V^\perp\,(1 + \frac{2}{3} r_V)\right]}$$

$0.366\kappa_c|_{J/\psi} \quad -1.598\kappa_b|_{\Upsilon(1S)}$

$$F_{\perp(ID)}^{V\gamma} = \boxed{\frac{\alpha}{\pi}\,\frac{1 - r_V}{2r_V}\, f_V^\perp \left[Q_q C_{\gamma\gamma}(p_{\gamma^*}^2) - \frac{g_V^q}{2s_W c_W}\frac{r_V}{r_Z - r_V} C_{\gamma Z}(p_{Z^*}^2)\right]}$$

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- The indirect contributions are usually the dominant ones, but for Υ, the direct contribution is comparable, leading to a cancellation between the two
- The direct and the indirect contributions to $h \to V\gamma$ decay amplitude interfere destructively in the SM [Konig, Neubert, arXiv:1505.03870]

$$\mathcal{B}(h \to J/\Psi, \gamma)|_{\rm SM} = (2.8 \pm 0.2) \times 10^{-6}$$
$$\mathcal{B}(h \to \Upsilon(nS), \gamma)|_{\rm SM} = (6.1^{+17.4}_{-6.1},\; 2.0^{+1.9}_{-1.3},\; 2.4^{+1.8}_{-1.3}) \times 10^{-10} \quad (n = 1, 2, 3)$$

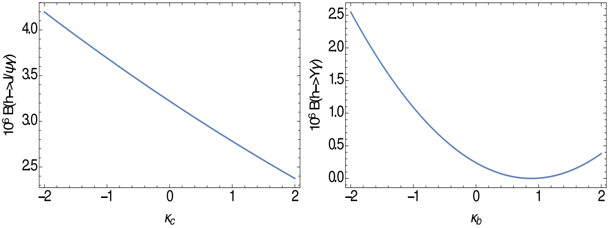

Figure: Branching ratios of $h \to (J/\psi, \Upsilon)\gamma$ as a function of κ_q (κ_q = 1 in SM case).

- $h \to J/\psi\gamma$ can probe Yukawa couplings of Higgs with a c-quark !
- ATLAS results at $\sqrt{s}$ = 8 TeV and 20.3 fb^{-1} / upper limits: [arXiv:1501.03276 [hep-ex]]
  $\mathcal{B}(h \to J/\Psi, \gamma) < 1.5 \times 10^{-3}$,
  $\mathcal{B}(h \to \Upsilon(nS), \gamma) < (1.3,\ 1.9,\ 1.3) \times 10^{-3}$

$\kappa_c < 429, \quad \kappa_b < 78$

- $h \to (J/\psi, \Upsilon)Z$ is interesting too, as the massive final state gauge boson can be also in a longitudinal polarization state / but is not sensitive to the Yukawa couplings

Two Higgs Doublet Model and Light CP-odd A-boson

Most general $SU(2) \times U(1)$ potential

$$V(\Phi_1, \Phi_2) = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 + m_{12}^2 (\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1) + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \frac{\lambda_5}{2} \left[(\Phi_1^\dagger \Phi_2)^2 + (\Phi_2^\dagger \Phi_1)^2 \right] + \left[\lambda_6 (\Phi_1^\dagger \Phi_1) + \lambda_7 (\Phi_2^\dagger \Phi_2) \right] \left[(\Phi_1^\dagger \Phi_2) + (\Phi_2^\dagger \Phi_1) \right],$$

$m_{12}^2, \ \lambda_5, \ \lambda_6, \lambda_7$, in general complex $\Longrightarrow$ 14 real parameters

• Most frequently studied model : softly broken with a discrete $\mathbb{Z}_2$ symmetry and without CP violation $(\Phi_1 \leftrightarrow \Phi_1, \ \Phi_2 \leftrightarrow -\Phi_2) \Longrightarrow \lambda_5, \ \lambda_6, \lambda_7 = 0$

• Φ_a is parametrized as

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

with $v = \sqrt{v_1^2 + v_2^2} = 246.22$ GeV.

• The mass matrices of the Higgs bosons are diagonalized by introducing the mixing angles α and β

$$\begin{pmatrix}\phi_1^+\\ \phi_2^+\end{pmatrix} = \begin{pmatrix}\cos\beta & -\sin\beta\\ \sin\beta & \cos\beta\end{pmatrix}\begin{pmatrix}G^+\\ H^+\end{pmatrix}, \qquad \begin{pmatrix}\eta_1\\ \eta_2\end{pmatrix} = \begin{pmatrix}\cos\beta & -\sin\beta\\ \sin\beta & \cos\beta\end{pmatrix}\begin{pmatrix}G^0\\ A\end{pmatrix},$$

$$\begin{pmatrix}\rho_1\\ \rho_2\end{pmatrix} = \begin{pmatrix}\cos\alpha & -\sin\alpha\\ \sin\alpha & \cos\alpha\end{pmatrix}\begin{pmatrix}H\\ h\end{pmatrix}, \qquad \tan\beta = \frac{v_2}{v_1}$$

scalar sector of the 2HDM is rich:

- 2 CP-even Higgs particles: h, H
- 1 CP-odd Higgs particle: A
- a pair of charged Higgs particles: $H^\pm$

The Yukawa Sector

$$\mathcal{L}_Y = -\frac{\sqrt{2}}{v} H^+ \left\{ \bar{u} \left[\zeta^d \, V_{\mathrm{CKM}} m_d P_R - \zeta^u \, m_u V_{\mathrm{CKM}} P_L \right] d + \zeta^\ell \, \bar{\nu} m_\ell P_R \ell \right\}$$
$$- \frac{1}{v} \sum_{f, \varphi_i^0 \in \{h,H,A\}} \xi^f_{\varphi_i^0} \, \varphi_i^0 \left[\bar{f} m_f P_R f \right] + \mathrm{h.c.}, \qquad \xi_A^u = -i\zeta^u, \; \xi_A^{d,\ell} = i\zeta^{d,\ell}$$

- Type I : All the fermions couple to only Φ_2
- Type II : u, c, t couple to Φ_2, whereas d, s, b and ℓ couple to Φ_1
- Type X : q couple to Φ_2, whereas ℓ couple to Φ_1 ('lepton specific')
- Type Z : u, c, t and ℓ couple to Φ_2, whereas d, s, b couple to Φ_1 ('flipped')

Model	ζ^d	ζ^u	ζ^ℓ
Type I	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type II	$-\tan\beta$	$\cot\beta$	$-\tan\beta$
Type X (lepton specific)	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type Z (flipped)	$-\tan\beta$	$\cot\beta$	$\cot\beta$

Scanning the 2HDM parameter space

$$\tan\beta \in (0.2, 50), \qquad \alpha \in \left(-\frac{\pi}{2}, \frac{\pi}{2}\right), \qquad \left|M^2\right| \leq (1.2\ \mathrm{TeV})^2,$$

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

- Theoretical Constraints :
  - Stability of the scalar potential and the electroweak vacuum
  - Perturbative unitarity of the elastic scattering of the longitudinally polarized gauge bosons and the scalar bosons,
    $W_L^+W_L^-$, Z_LZ_L, hh, Z_Lh, Ah, hH, Z_LH, AH, Z_LA, AA, HH, $W_L^+H^-$, $H^+W_L^-$, H^+H^-
  - Electroweak Precision Tests

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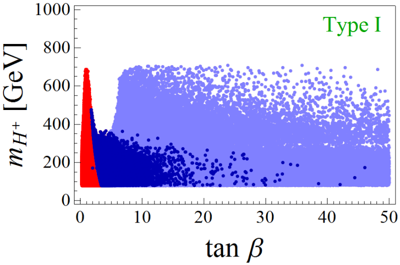
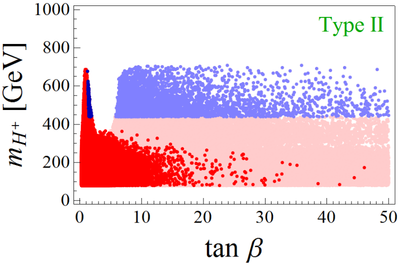
  - Electroweak Precision Tests
- Experimental Constraints : identifying the lightest CP-even state h as SM-like
  - Concentrating on the alignment limit, $|\cos(\beta-\alpha)| \leq 0.3$
  - Constraint from $\Gamma_h/\Gamma_h^{\mathrm{SM}} \leq 1.42$ due to the additional decay channel provided $m_A \leq m_h/2$

$$\Gamma(h\to AA) = \frac{|\lambda_{hAA}|^2}{32\pi}\frac{v^2}{m_h}\sqrt{1-\frac{4m_A^2}{m_h^2}}$$

$$\Gamma(h\to ZA) = \frac{1}{16\pi}\frac{\cos^2(\beta-\alpha)}{m_h^3 v^2}\lambda^{3/2}(m_h, m_Z, m_A)\,.$$

Results of the scan of parameters after imposing theoretical and experimental constraints. Darker/lighter points correspond to the *free*/*fine-tuned* scan. Red points are forbidden by the flavor bounds





- fine tuned scans (light blue) with $m_H \approx |M|$ designed to focus on “hard to reach” regions
- strong constrains by measurements of the inclusive radiative B-meson decay branching ratio ($B \to X_s\gamma,\ b \to s\mu^+\mu^-$) [Arnan et.al. arXiv:1703.03426]
- In Type I models prefer $\tan\beta \geq 4$
- In Type II models bounds are $\tan\beta$ independent and constrains $m_H^{\pm} \geq 439$ GeV

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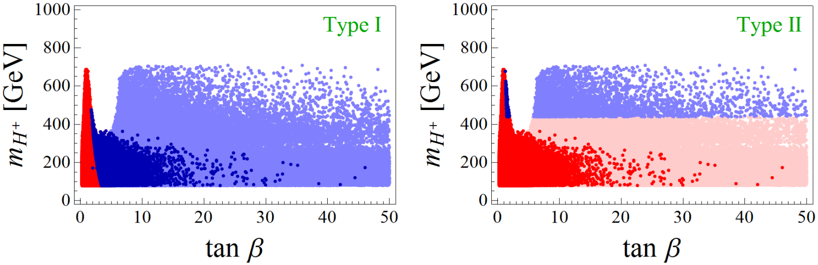

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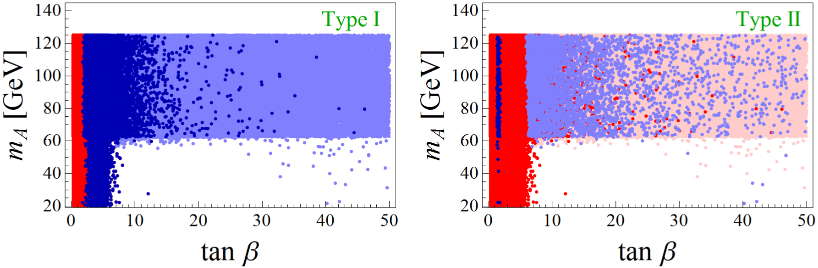
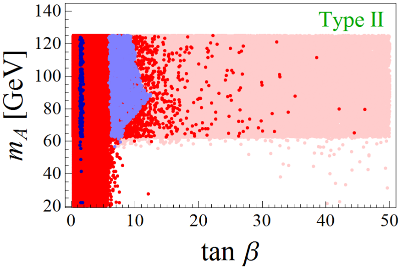
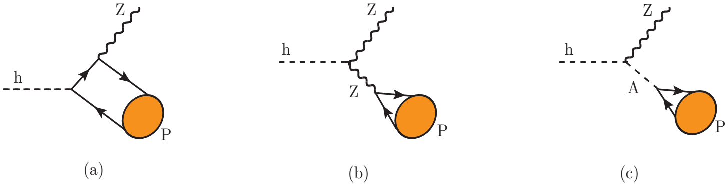


Impact from the direct searches of extra Higgs states - LHC and LEP $\rightarrow$ strong constraints on TYPE II model:



Exclusive $h \to PZ$ $(P = \eta_c, \eta_b)$ decay with the light CP-odd A-boson



$$(a)|_{\rm SM} \quad F_D^{PZ} = -f_P\, g_A^q\, \kappa_q \boxed{\left[m_P^2 - 3m_q^2\right]} \frac{m_h^4 - m_Z^4 + 4m_Z^2 m_h^2 \ln \frac{m_Z}{m_h}}{(m_h^2 - m_Z^2)^3} \quad \text{negligible}$$

strong suppression of the direct contributions sensitive to Y_c, Y_b, makes **$\mathbf{h \to \eta_{b,c} Z}$** unsuitable for searches for new-physics effects on light quark Yukawa couplings

$$(b)|_{\rm SM} + (c)|_{\rm 2HDM} \qquad F_{ID}^{PZ} = \frac{\boxed{m_Z^2}}{m_Z^2 - m_P^2} f_P g_A^q - \frac{f_P}{m_A^2 - m_P^2 + i m_A \Gamma_A} \frac{m_P^2}{2}\, \xi_A^q \cos(\beta - \alpha)$$

$$\mathcal{B}(h \to \eta_c Z)|_{\rm SM} \approx (1.08 \pm 0.01) \times 10^{-5}, \quad \mathcal{B}(h \to \eta_b Z)|_{\rm SM} \approx (2.97 \pm 0.05) \times 10^{-5}$$

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$$F^{PZ} = \frac{m_Z^2}{m_Z^2 - m_P^2} f_P g_A^q - \frac{f_P}{m_A^2 - m_P^2 + i m_A \Gamma_A} \frac{m_P^2}{2} \xi_A^q \cos(\beta - \alpha)$$

$$R^Z_{\eta_{cb}} = \frac{\mathcal{B}(h \to \eta_{cb} Z)^{\mathrm{2HDM}}}{\mathcal{B}(h \to \eta_{cb} Z)^{\mathrm{SM}}} = \frac{\Gamma(h \to \eta_{cb} Z)^{\mathrm{2HDM}}}{\Gamma(h \to \eta_{cb} Z)^{\mathrm{SM}}} \boxed{\frac{\Gamma^{\mathrm{SM}}_{\mathrm{tot}}}{\Gamma^{\mathrm{2HDM}}_{\mathrm{tot}}}}$$

0.7

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0.7

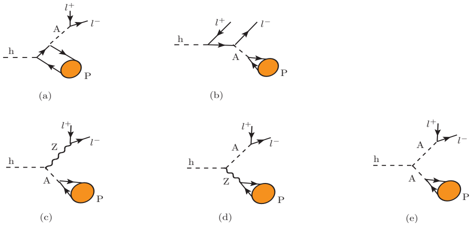
Ratio	$R^Z_{\eta_c}$	$R^Z_{\eta_b}$
Type I	$(0.7, 1.0)$	$(0.6, 1.0)$
Type II	$(0.7, 1.0)$	$(0.7, 1.7)$
Type X	$(0.7, 1.0)$	$(0.7, 1.0)$
Type Z	$(0.7, 1.0)$	$(0.6, 1.7)$

Table: Resulting intervals for the ratios obtained from the scans in various types of 2HDM.

$h \to (\eta_c, \eta_b) Z$ is insensitive to 2HDM scenarios

Exclusive $h \to P\ell^+\ell^-$ decay with the light CP-odd A-boson

$$\Gamma(h \to P\ell^+\ell^-) \simeq \Gamma(h \to PZ^* \to P\ell^+\ell^-) + \Gamma(h \to PA^* \to P\ell^+\ell^-).$$



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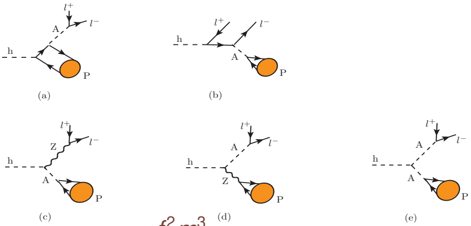


$$\Gamma(h \to PZ^* \to P\ell^+\ell^-) = \frac{f_P^2 m_Z^3}{384\pi^2 \Gamma_Z m_h^3 v^6} \left[\cos^2(2\theta_W) + 4\sin^4\theta_W\right]$$

$$\left(\boxed{g_A^q}_{\text{SM}} - \frac{\xi_A^q m_P^2 \boxed{\cos(\beta-\alpha)}}{2(m_A^2 - m_P^2)} \right)^2 \lambda^{3/2}(m_h^2, m_P^2, m_Z^2)$$

$$\Gamma(h \to PA^* \to P\ell^+\ell^-) = \frac{f_P^2 m_A}{512\pi^2 \Gamma_A m_h^3 v^2} \left(\frac{m_\ell \xi_A^\ell}{v}\right)^2 \left[\boxed{\lambda_{hAA}} \frac{m_P^2}{m_A^2 - m_P^2} \frac{\xi_A^q}{v} v^2 \right.$$

$$\left. + 2\,\boxed{\cos(\beta-\alpha)} \frac{g_A^q}{v}(m_h^2 - m_A^2) \right]^2 \lambda^{1/2}(m_h^2, m_P^2, m_A^2)$$

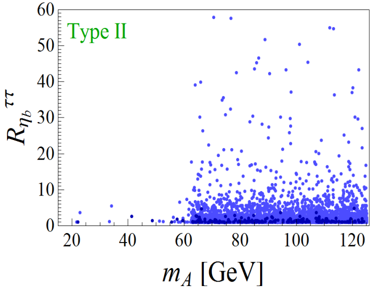
$$R^{\tau\tau}_{\eta_{cb}} = \frac{\mathcal{B}(h \to \eta_{cb}\tau^+\tau^-)^{\rm 2HDM}}{\mathcal{B}(h \to \eta_{cb}\tau^+\tau^-)^{\rm SM}} ,$$

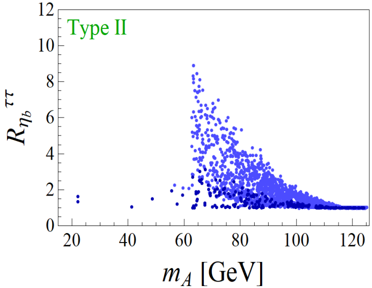
$$R^{\mu\mu}_{\eta_{cb}} = \frac{\mathcal{B}(h \to \eta_{cb}\mu^+\mu^-)^{\rm 2HDM}}{\mathcal{B}(h \to \eta_{cb}\mu^+\mu^-)^{\rm SM}} ,$$

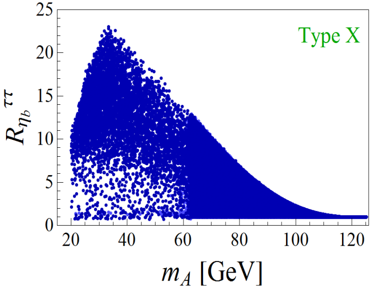
Ratio	$R^{\mu\mu}_{\eta_c}$	$R^{\mu\mu}_{\eta_b}$	$R^{\tau\tau}_{\eta_c}$	$R^{\tau\tau}_{\eta_b}$
Type I	$(0.7, 1.0)$	$(0.7, 1.0)$	$(0.7, 3.3)$	$(0.7, 3.6)$
Type II	$(0.7, 1.0)$	$(0.7, 1.3)$	$(0.8, 3.2)$	$(0.9, 58)$
Type X	$(0.7, 1.1)$	$(0.7, 1.1)$	$(0.7, 21)$	$(0.7, 23)$
Type Z	$(0.7, 1.0)$	$(0.7, 1.1)$	$(0.7, 1.1)$	$(0.8, 1.2)$

Resulting intervals for the ratios obtained from the scans in various types of 2HDM

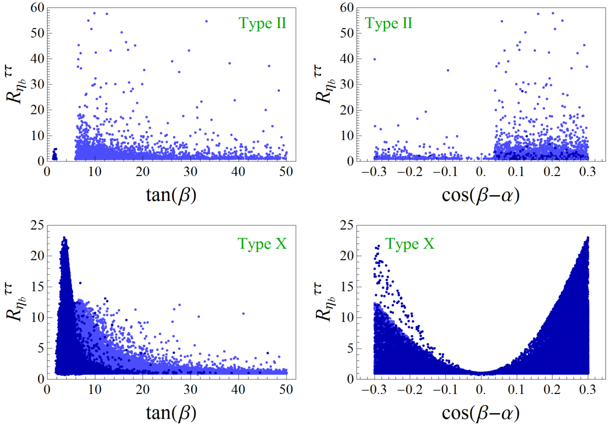
$h \to (\eta_c, \eta_b)\ell^+\ell^-$ is sensitive to 2HDM scenarios
Type I, Type II, Type X



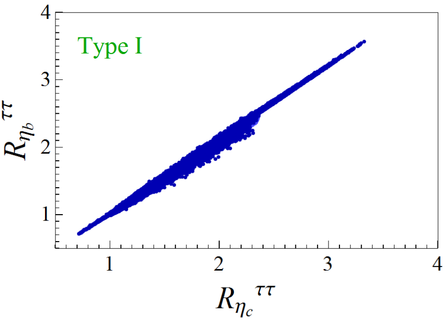


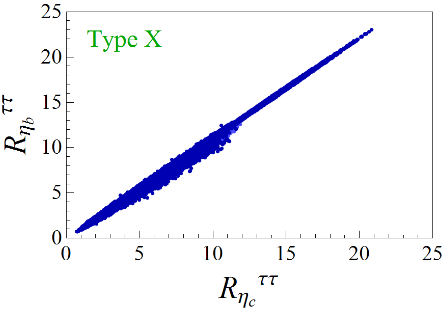


- Type II model is far more constrained than Type X because of (a) $B \to X_s \gamma$ constraint and from (b) direct searches
- Enhancement of $R^{\tau\tau}_{\eta_b}$ in 2HDM due to $\Gamma(h \to PA^* \to P\ell^+\ell^-) \propto m_\ell^2$
- These decay modes can serve as possible probes of the light CP-odd Higgs ($m_A \lesssim m_h$)



Large enhancements possible in full allowed region of the parameter space, making $h \to P\ell^+\ell^-$ the ideal channel to look for CP-odd Higgs A





- Correlation of the ratios $R_{\eta_c}^{\tau\tau}$ and $R_{\eta_b}^{\tau\tau}$ in Type I and Type X models (Yukawa couplings to A are equal for up and down quarks in these models)
- $\Gamma(h \to PA^* \to P\ell^+\ell^-) \propto (m_\ell \xi_A^l)^2 \xi_A^q$, $\xi_A^c = \xi_A^b$

Model	ξ_A^d	ξ_A^u	ξ_A^ℓ
Type I	$-\cot\beta$	$\cot\beta$	$-\cot\beta$
Type X (lepton specific)	$-\cot\beta$	$\cot\beta$	$\tan\beta$

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- Correlations of the ratios $R^{\tau\tau}_{\eta_c}$ and $R^{\tau\tau}_{\eta_b}$ will be an efficient channel to disentagle among various 2HDM scenarios