Complementarity of LHC and EDMs for Exploring Higgs CP Violation

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The CP Nature of the Higgs Boson
Amherst, May 2, 2015

Outline

- Theory overview on 2HDM
  - Approximate Z_2 (soft Z_2)
  - Without approximate Z_2
- Constraints:
  - EDMs
  - Light and heavy Higgs searches

Motivations

- Explanation of baryon asymmetry
- Higgs sector of supersymmetry
- K or B meson mixing
- Combine low energy EDMs and high energy collider experiment to bound the parameter space

Theory: 2HDM

- Scalar potential:

$$V(\phi_1,\phi_2) = -\frac{1}{2}\left[m_{11}^2(\phi_1^\dagger\phi_1) + \left(m_{12}^2(\phi_1^\dagger\phi_2) + \text{h.c.}\right) + m_{22}^2(\phi_2^\dagger\phi_2)\right]$$
$$+\frac{\lambda_1}{2}(\phi_1^\dagger\phi_1)^2 + \frac{\lambda_2}{2}(\phi_2^\dagger\phi_2)^2 + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1)$$
$$+\frac{1}{2}\left[\lambda_5(\phi_1^\dagger\phi_2)^2 + \lambda_6(\phi_1^\dagger\phi_2)(\phi_1^\dagger\phi_1) + \lambda_7(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_2) + \text{h.c.}\right] .$$

$$\phi_1 = \begin{pmatrix} -\sin\beta H^+ \\ \frac{1}{\sqrt{2}}(v\cos\beta + H_1^0 - i\sin\beta A^0) \end{pmatrix}, \quad \phi_2 = e^{i\xi}\begin{pmatrix} \cos\beta H^+ \\ \frac{1}{\sqrt{2}}(v\sin\beta + H_2^0 + i\cos\beta A^0) \end{pmatrix}$$

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

Theory: 2HDM

- Scalar potential:

$$V(\phi_1,\phi_2) = -\frac{1}{2}\left[m_{11}^2(\phi_1^\dagger\phi_1) + \left(m_{12}^2(\phi_1^\dagger\phi_2) + \text{h.c.}\right) + m_{22}^2(\phi_2^\dagger\phi_2)\right]$$
$$+\frac{\lambda_1}{2}(\phi_1^\dagger\phi_1)^2 + \frac{\lambda_2}{2}(\phi_2^\dagger\phi_2)^2 + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1)$$
$$+\frac{1}{2}\left[\lambda_5(\phi_1^\dagger\phi_2)^2 + \lambda_6(\phi_1^\dagger\phi_2)(\phi_1^\dagger\phi_1) + \lambda_7(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_2) + \text{h.c.}\right] .$$

- In general $m_{12}^2, \lambda_5, \lambda_6, \text{ and } \lambda_7$ can be complex
- Imposing a Z2 symmetry to avoid tree-level FCNCs:

$$\phi_1 \to -\phi_1 \qquad \phi_2 \to \phi_2 .$$

  - Type-I 2HDM: $d_R \to d_R, u_R \to u_R, \text{ and } \ell_R \to \ell_R$
  - Type-II 2HDM: $d_R \to -d_R, u_R \to u_R, \text{ and } \ell_R \to -\ell_R$
- Implies $m_{12}^2, \lambda_6, \text{ and } \lambda_7$ are equal to zero.

Theory: 2HDM

- Mass matrix in (H_1^0, H_2^0, A^0) basis:

$$\mathcal{M}^2 = v^2 \begin{pmatrix} \lambda_1 c_\beta^2 + \nu s_\beta^2 & (\lambda_{345} - \nu) c_\beta s_\beta & -\frac{1}{2}\mathrm{Im}\lambda_5\, s_\beta \\ (\lambda_{345} - \nu) c_\beta s_\beta & \lambda_2 s_\beta^2 + \nu c_\beta^2 & -\frac{1}{2}\mathrm{Im}\lambda_5\, c_\beta \\ -\frac{1}{2}\mathrm{Im}\lambda_5\, s_\beta & -\frac{1}{2}\mathrm{Im}\lambda_5\, c_\beta & -\mathrm{Re}\lambda_5 + \nu \end{pmatrix}$$

$$\nu \equiv \mathrm{Re}(m_{12})^2/(v^2 \sin 2\beta)$$

- Introduce a rotation matrix to get the mass eigenstates

$$(h_1, h_2, h_3)^T = R(H_1^0, H_2^0, A^0)^T$$

$$R = \begin{pmatrix} -s_\alpha c_{\alpha_b} & c_\alpha c_{\alpha_b} & s_{\alpha_b} \\ s_\alpha s_{\alpha_b} s_{\alpha_c} - c_\alpha c_{\alpha_c} & -s_\alpha c_{\alpha_c} - c_\alpha s_{\alpha_b} s_{\alpha_c} & c_{\alpha_b} s_{\alpha_c} \\ s_\alpha s_{\alpha_b} c_{\alpha_c} + c_\alpha s_{\alpha_c} & s_\alpha s_{\alpha_c} - c_\alpha s_{\alpha_b} c_{\alpha_c} & c_{\alpha_b} c_{\alpha_c} \end{pmatrix}$$

$$s_\alpha = \sin\alpha \qquad c_\alpha = \cos\alpha$$

- CPV phases $\quad -\frac{\pi}{2} < \alpha_b \leq \frac{\pi}{2} \qquad -\frac{\pi}{2} \leq \alpha_c \leq \frac{\pi}{2}$

Theory overview

$$R = \begin{pmatrix} -s_\alpha c_{\alpha_b} & c_\alpha c_{\alpha_b} & s_{\alpha_b} \\ s_\alpha s_{\alpha_b} s_{\alpha_c} - c_\alpha c_{\alpha_c} & -s_\alpha c_{\alpha_c} - c_\alpha s_{\alpha_b} s_{\alpha_c} & c_{\alpha_b} s_{\alpha_c} \\ s_\alpha s_{\alpha_b} c_{\alpha_c} + c_\alpha s_{\alpha_c} & s_\alpha s_{\alpha_c} - c_\alpha s_{\alpha_b} c_{\alpha_c} & c_{\alpha_b} c_{\alpha_c} \end{pmatrix}$$

$$\mathcal{L} = \sum_{i=1}^{3} \left[-m_f \left(c_{f,i} \bar{f} f + \tilde{c}_{f,i} \bar{f} i \gamma_5 f \right) \frac{h_i}{v} + \left(2 a_i M_W^2 W_\mu W^\mu + a_i M_Z^2 Z_\mu Z^\mu \right) \frac{h_i}{v} \right]$$

	$c_{t,i}$	$c_{b,i} = c_{\tau,i}$	$\tilde{c}_{t,i}$	$\tilde{c}_{b,i} = \tilde{c}_{\tau,i}$	a_i
Type I	$R_{i2}/\sin\beta$	$R_{i2}/\sin\beta$	$-R_{i3}\cot\beta$	$R_{i3}\cot\beta$	$R_{i2}\sin\beta + R_{i1}\cos\beta$
Type II	$R_{i2}/\sin\beta$	$R_{i1}/\cos\beta$	$-R_{i3}\cot\beta$	$-R_{i3}\tan\beta$	$R_{i2}\sin\beta + R_{i1}\cos\beta$

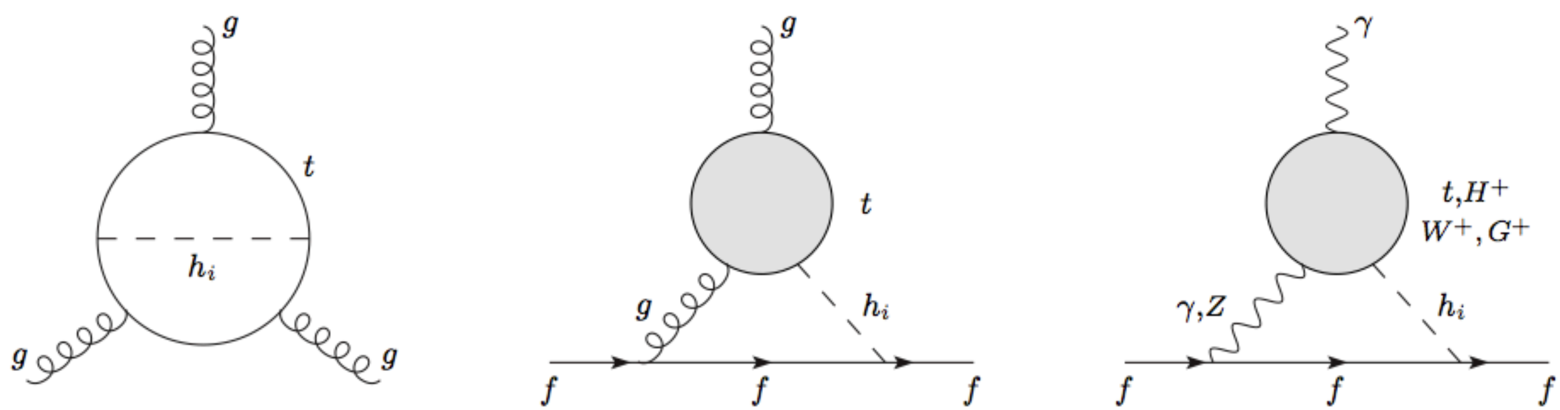
- Keeping in mind $$\frac{1}{\sin^2\beta} = 1 + \cot^2\beta$$ $$\frac{1}{\cos^2\beta} = 1 + \tan^2\beta$$

- Alignment limit: $\sin(\beta - \alpha) = 1, \sin\alpha = -\cos\beta$ and $\cos\alpha = \sin\beta$.

- h_1 is the 125 Higgs

Electric dipole moment

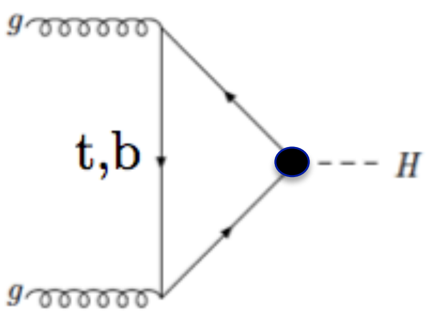
- Mainly from Barr-Zee diagrams
- For more details, see S. Inoue’s talk!



[arXiv: 1403.4257]

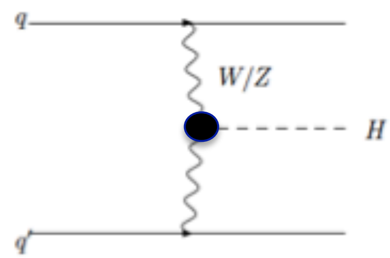
Production

- Gluon fusion (ggF)



$$-i\frac{m_f}{v}(c_{f,i} + i\gamma_5\tilde{c}_{f,i})$$

- Vector boson fusion (VBF)



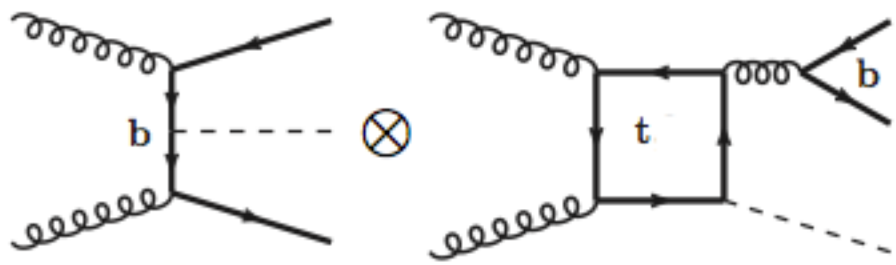
$$-i\frac{2m_V^2}{v}a_i$$

$$R^i_{gg} = \frac{\sigma(gg \to h_i)}{\sigma(gg \to H_{\rm SM})} = \frac{\left|c_{t,i}A^H_{1/2}(\tau^i_t) + c_{b,i}A^H_{1/2}(\tau^i_b)\right|^2 + \left|\tilde{c}_{t,i}A^A_{1/2}(\tau^i_t) + \tilde{c}_{b,i}A^A_{1/2}(\tau^i_b)\right|^2}{\left|A^H_{1/2}(\tau^i_t) + A^H_{1/2}(\tau^i_b)\right|^2}$$

where $\tau^i_f = m^2_{h_i}/(4m^2_f)$

Production

- bbh: 4 flavor scheme



$$\sigma(b\bar{b} \to h_i) = (c_{b,i})^2 \sigma_b^H(m_{h_i}) + c_{t,i} c_{b,i} \sigma_t^H(m_{h_i}) + (\tilde{c}_{b,i})^2 \sigma_b^A(m_{h_i}) + \tilde{c}_{t,i} \tilde{c}_{b,i} \sigma_t^A(m_{h_i})$$

[LHC Higgs Cross section Working Group]

Decay

$$\Gamma_{tot}(h_i) = \Gamma(h_i \to W^+W^-) + \Gamma(h_i \to ZZ) + \Gamma(h_i \to t\bar{t}) + \Gamma(h_i \to b\bar{b}) + \Gamma(h_i \to \tau^+\tau^-) + \Gamma(h_i \to gg) + \Gamma(h_i \to Zh_1) + \Gamma(h_i \to h_1h_1)$$

$$\Gamma(h_i \to VV) = (a_i)^2 \frac{G_F m_{h_i}^3}{16\sqrt{2}\pi}\delta_V \left(1 - \frac{4M_V^2}{m_{h_i}^2}\right)^{1/2} \left[1 - \frac{4M_V^2}{m_{h_i}^2} + \frac{3}{4}\left(\frac{4M_V^2}{m_{h_i}^2}\right)^2\right]$$

$$\Gamma(h_i \to Zh_1) = \frac{|g_{iz1}|^2}{16\pi m_{h_i}^3}\sqrt{\left(m_{h_i}^2 - (m_{h_1} + M_Z)^2\right)\left(m_{h_i}^2 - (m_{h_1} - M_Z)^2\right)} \times \left[-(2m_{h_i}^2 + 2m_{h_1}^2 - M_Z^2) + \frac{1}{M_Z^2}(m_{h_i}^2 - m_{h_1}^2)^2\right],$$

$$g_{iz1} = (e/\sin 2\theta_W)\left[(-\sin\beta R_{11} + \cos\beta R_{12})R_{i3} - (-\sin\beta R_{i1} + \cos\beta R_{i2})R_{13}\right]$$

Important point

- In order for the 125 GeV Higgs to have CP violating couplings, the heavy Higgs states must not decouple.
- e.g. in the alignment limit,

$$m_{h_2} \simeq m_{h_3} \equiv m_{H^+} \gg m_{h_1}$$

$$|\sin 2\alpha_b| \simeq \frac{|\mathrm{Im}\lambda_5|\, v^2}{m_{H^+}^2} \tan\beta$$

Important point

- Focus on $h_{2,3} \to WW/ZZ$ and $h_{2,3} \to Zh_1 \to l^+l^-b\bar{b}$ channels.
- Because in the the alignment limit, and CP conserving

$$h \to WW/ZZ \quad \checkmark$$

$$H, A \not\to WW/ZZ$$

$$H, A \not\to Zh$$

- In the CP violating case,

$$h_{1,2,3} \to WW/ZZ \quad \checkmark$$

$$h_{2,3} \to Zh_1 \quad \checkmark$$

With approximate Z_2

$$m_{12}^2, \lambda_5 \neq 0$$

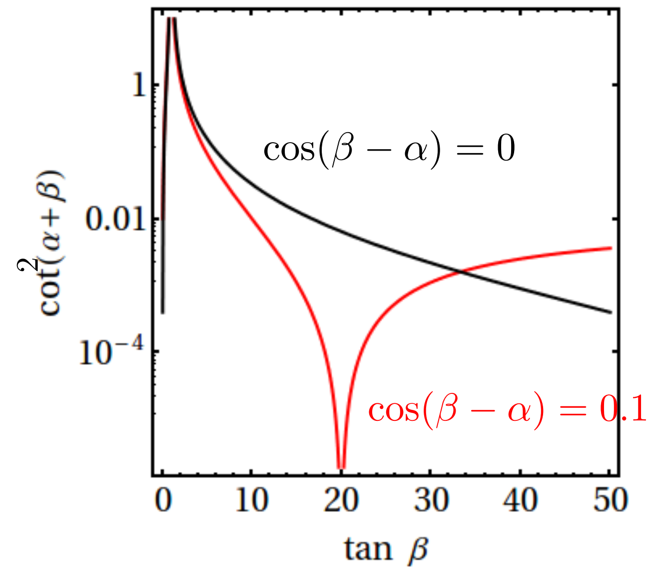
$$\lambda_6, \lambda_7 = 0$$

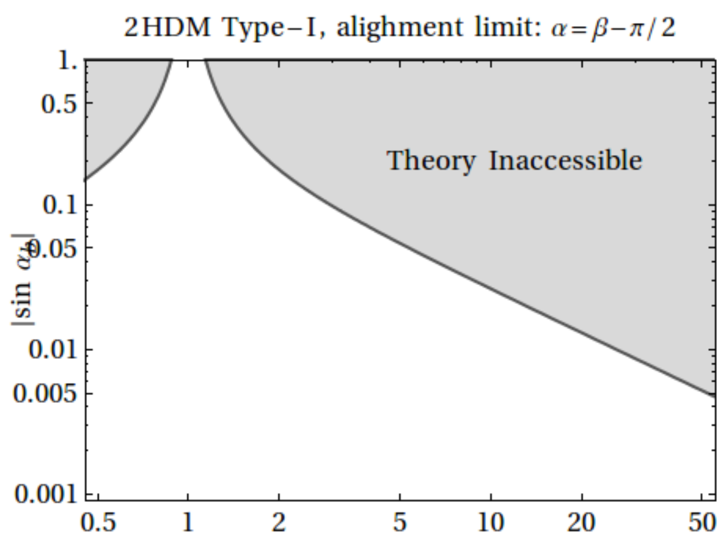
Theoretical constraints

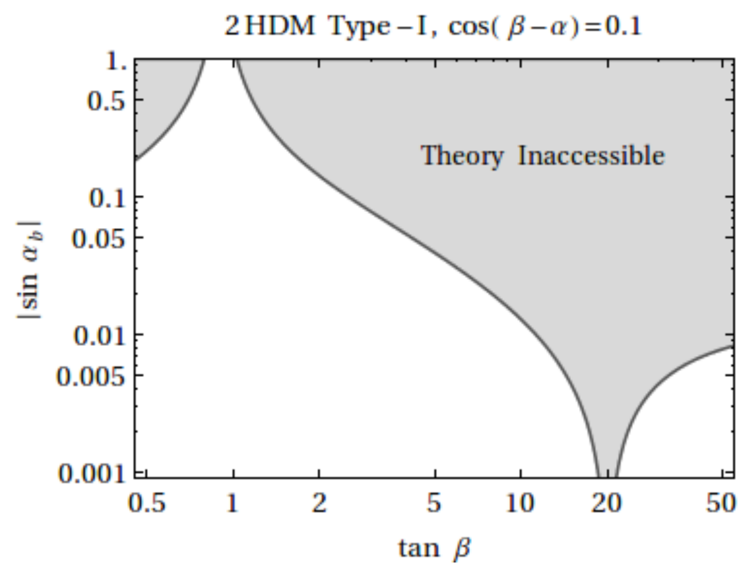
- α_b and α_c are related
- Condition for α_c to have a real solution:

$$\sin^2\alpha_b \le \frac{(m_{h_3}^2 - m_{h_2}^2)^2 \cot^2(\alpha+\beta)}{4(m_{h_2}^2 - m_{h_1}^2)(m_{h_3}^2 - m_{h_1}^2)} \equiv \sin^2\alpha_b^{\max}$$

- Same distributions for type I and II

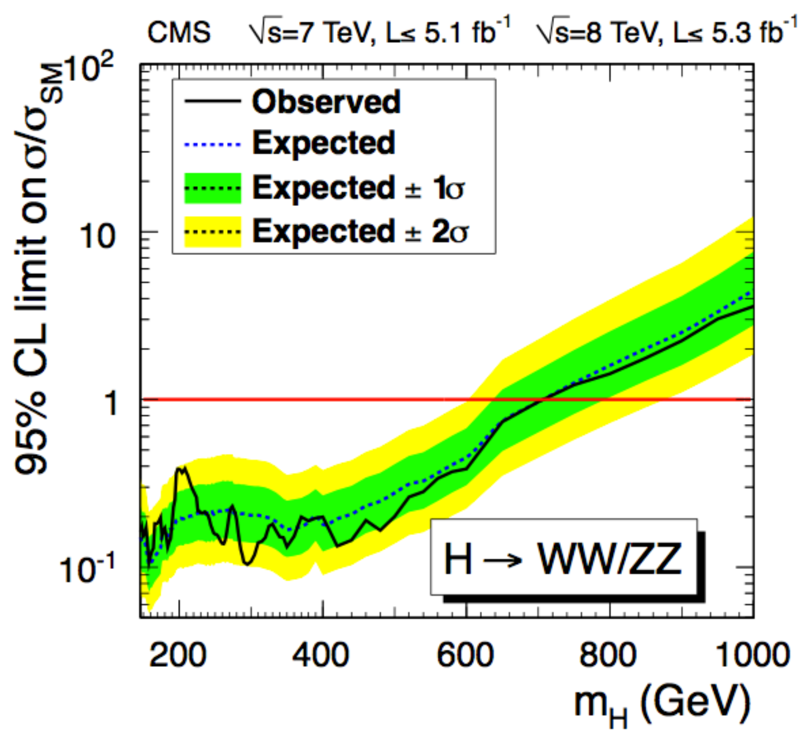






LHC data

- Heavy Higgs constraints: $h_{2,3} \to WW/ZZ$

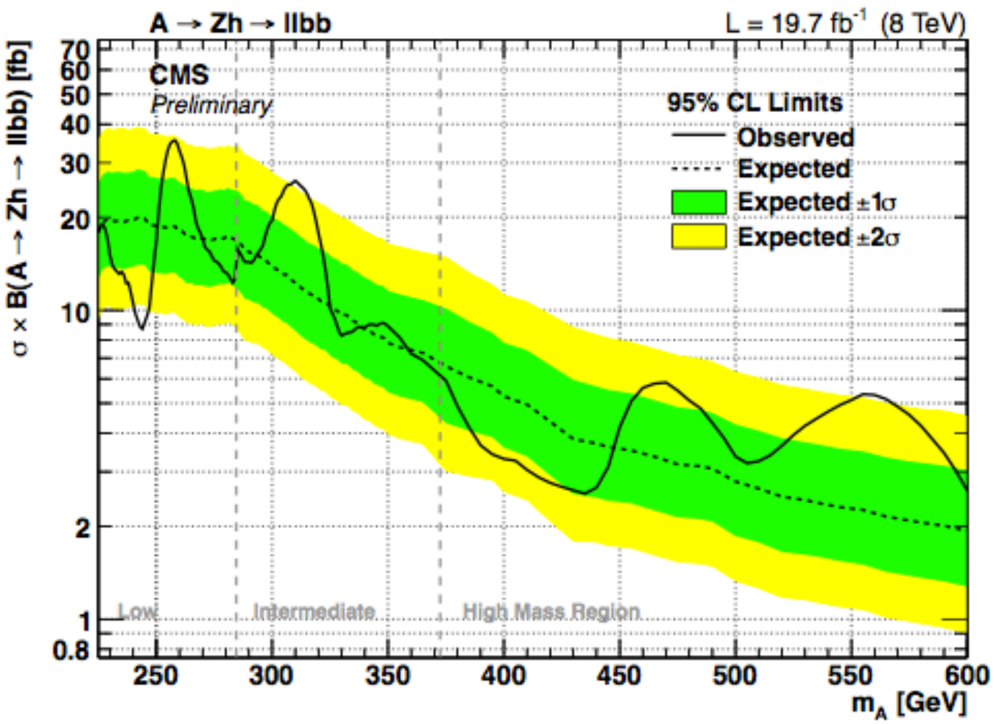


Rule out region $m_H < 700$ GeV

[arXiv: 1304.0213]

LHC data

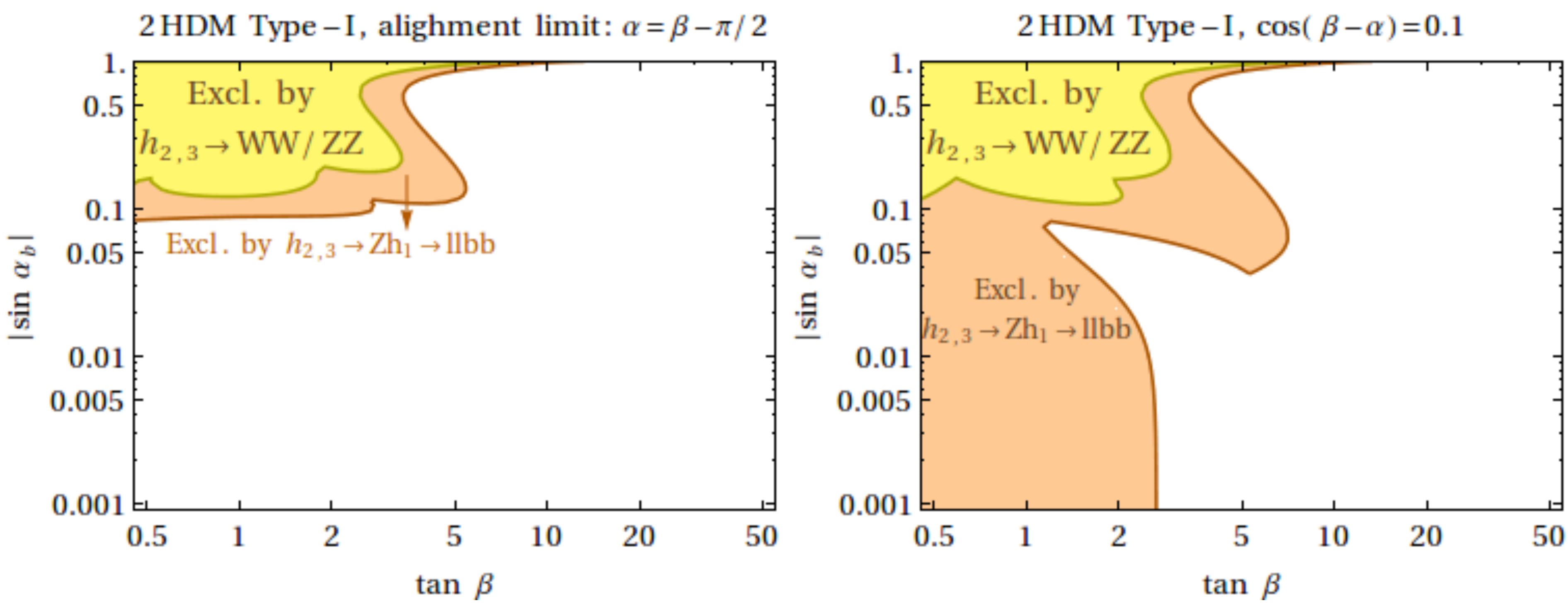
- Heavy Higgs constraints: $h_{2,3} \to Zh_1 \to l^+l^-b\bar{b}$



[CMS PAS HIG-14-011]

LHC data

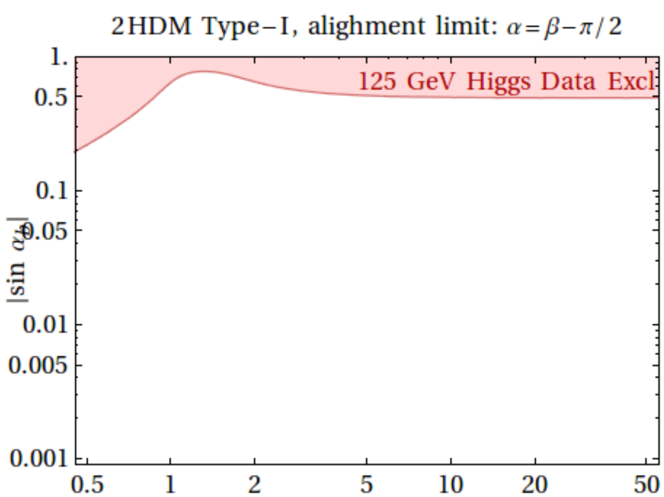
- Heavy Higgs constraints: $h_{2,3} \to WW/ZZ$ and $h_{2,3} \to Zh_1 \to l^+l^-b\bar{b}$
- In the alignment limit, heavy Higgses don't decay in to WW/ZZ
- Bounds are not very different between type-I and type-II
- Bounds are sensitive to the deviations from the alignment limit
- Large tan beta region is not ruled out due to tth coupling in production

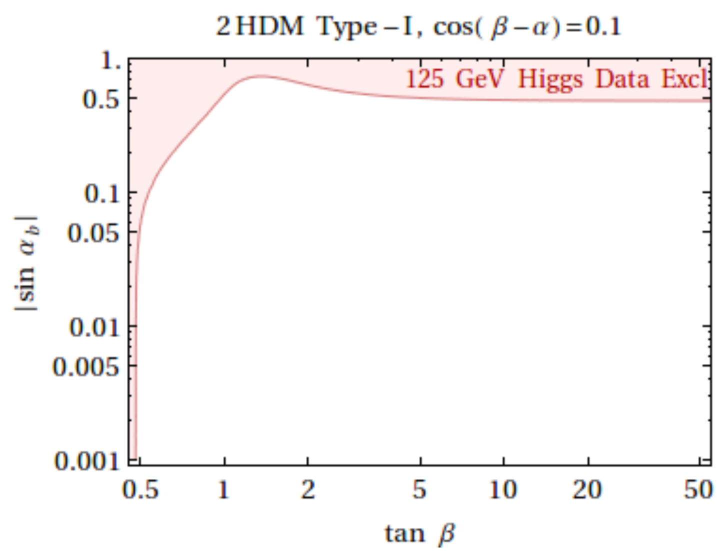


Light Higgs data: Type-I

- Not constraining compared with other bounds
- Not sensitive to α_c

Channel	μ_{CMS}	μ_{ATLAS}
μ_{WW}	0.83 ± 0.21	$1.09^{+0.23}_{-0.21}$
μ_{ZZ}	1.0 ± 0.29	$1.44^{+0.40}_{-0.33}$
$\mu_{\gamma\gamma}$	1.13 ± 0.24	1.17 ± 0.27
μ_{bb}	0.93 ± 0.49	0.5 ± 0.4
$\mu_{\tau\tau}$	0.91 ± 0.27	1.4 ± 0.4





Light Higgs data: Type-II

- Not constraining compared with other bounds

Channel	μ_{CMS}	μ_{ATLAS}
μ_{WW}	0.83 ± 0.21	$1.09^{+0.23}_{-0.21}$
μ_{ZZ}	1.0 ± 0.29	$1.44^{+0.40}_{-0.33}$
$\mu_{\gamma\gamma}$	1.13 ± 0.24	1.17 ± 0.27
μ_{bb}	0.93 ± 0.49	0.5 ± 0.4
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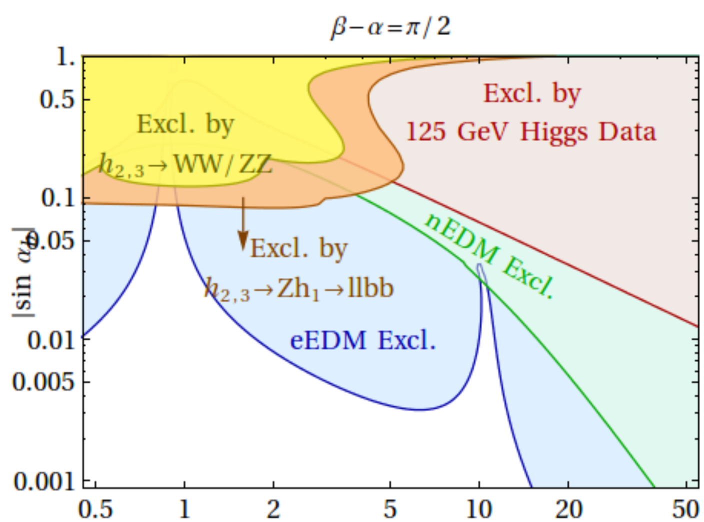
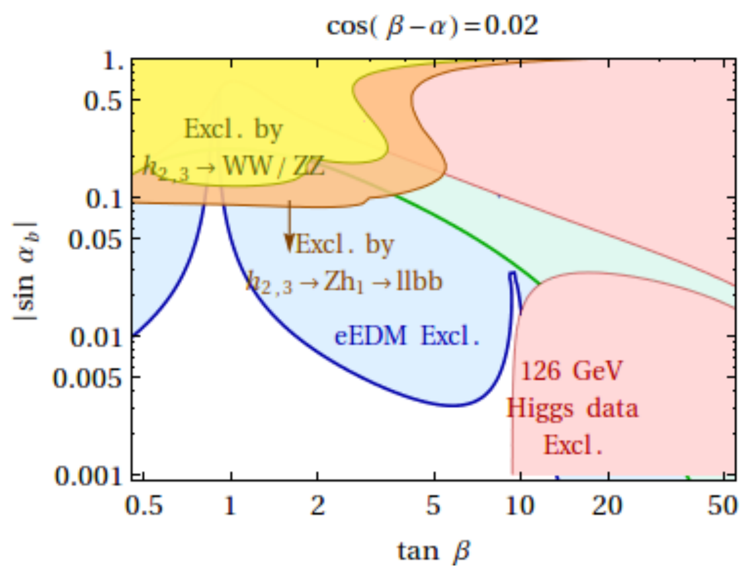
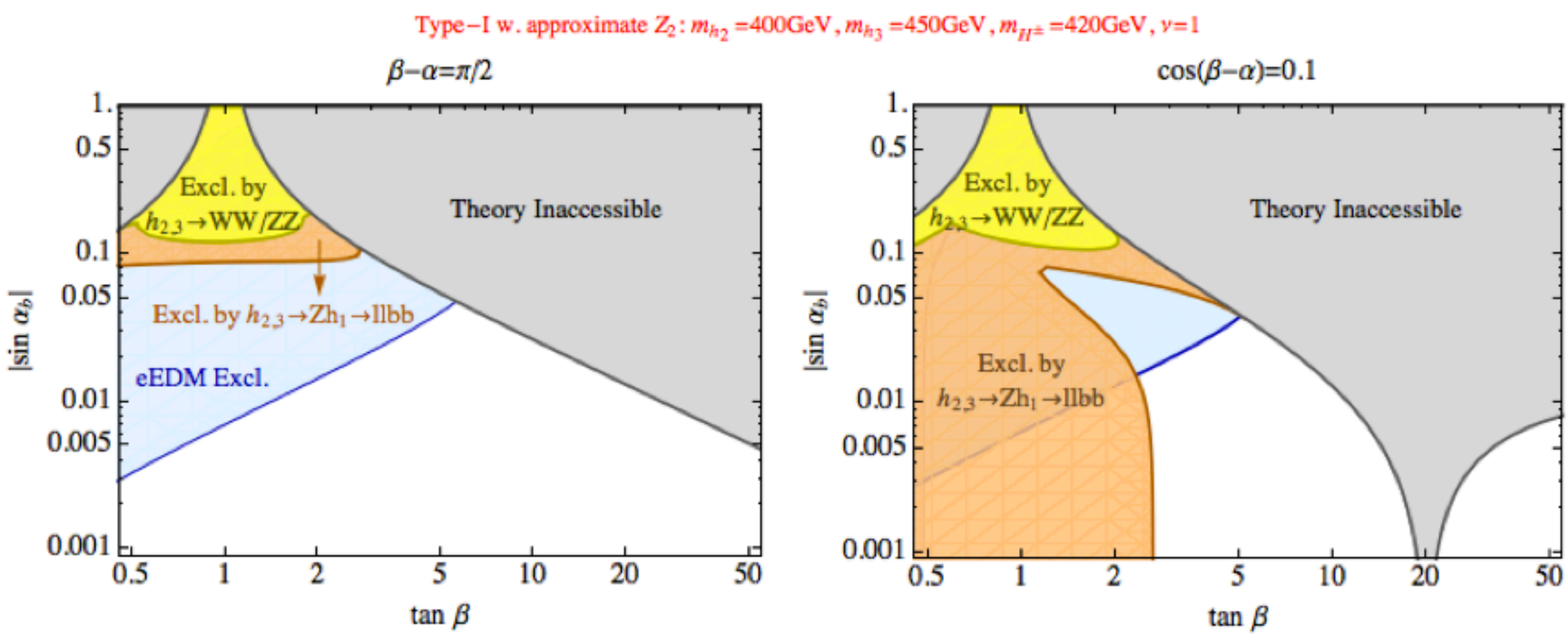




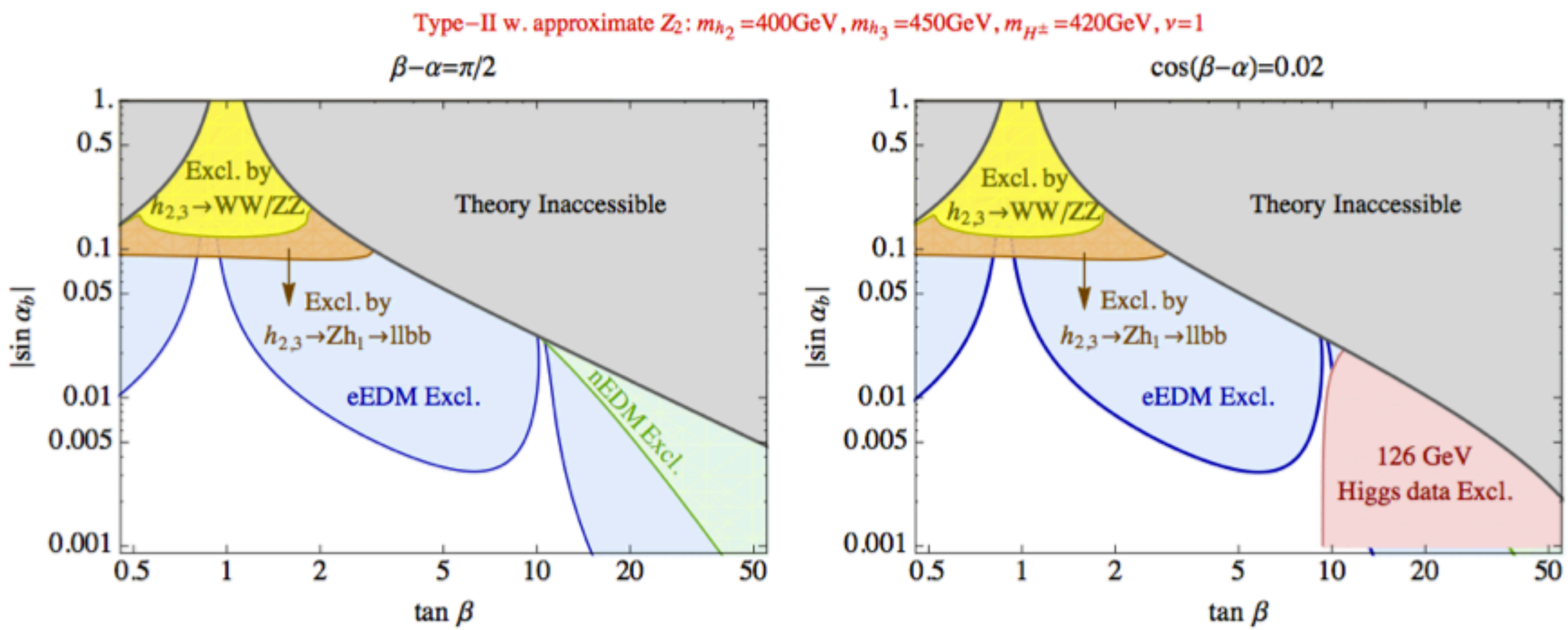
Result: Type-I

- Combine with theory inaccessible region



Result: Type-II

- Combine with theory inaccessible region



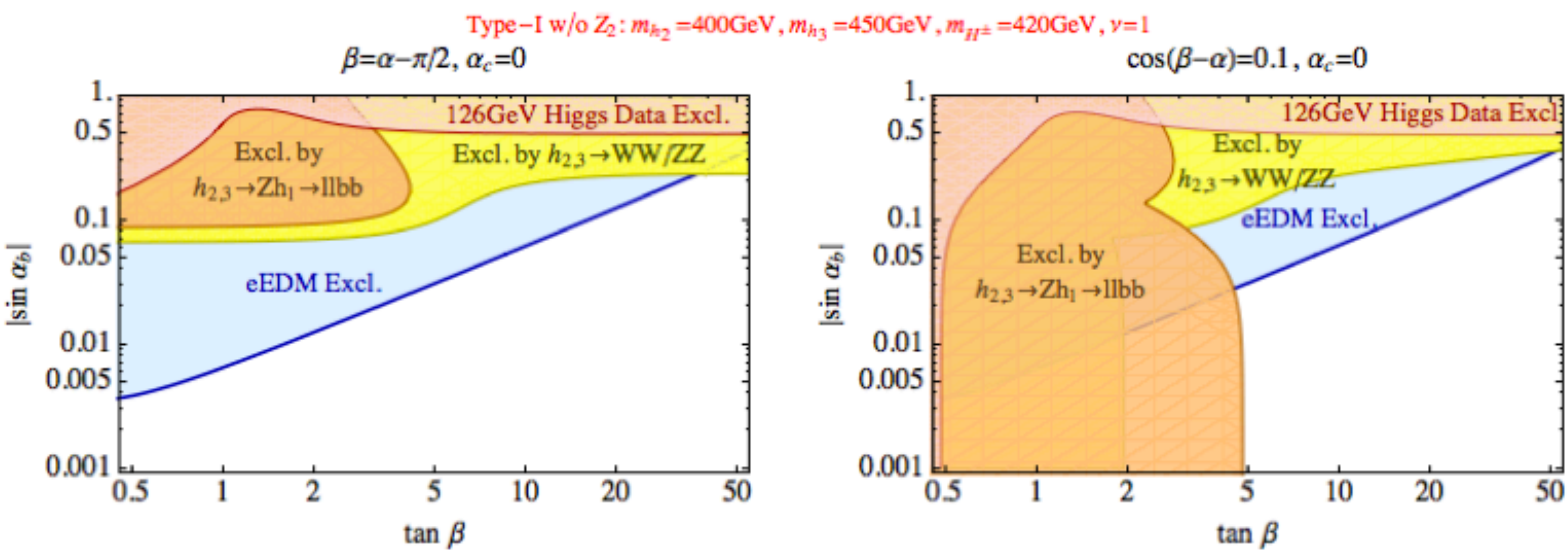
Without approximate Z_2

Results: without approximate Z_2

- Nonzero λ_6 and λ_7
- Assuming that tree-level FCNCs is suppressed by other mechanism, such as MFV
- For the mass of heavy Higgs larger than 600 GeV the collider bounds become weaker
- CP violating phases α_b and α_c are independent parameters so there is no theory inaccessible region.

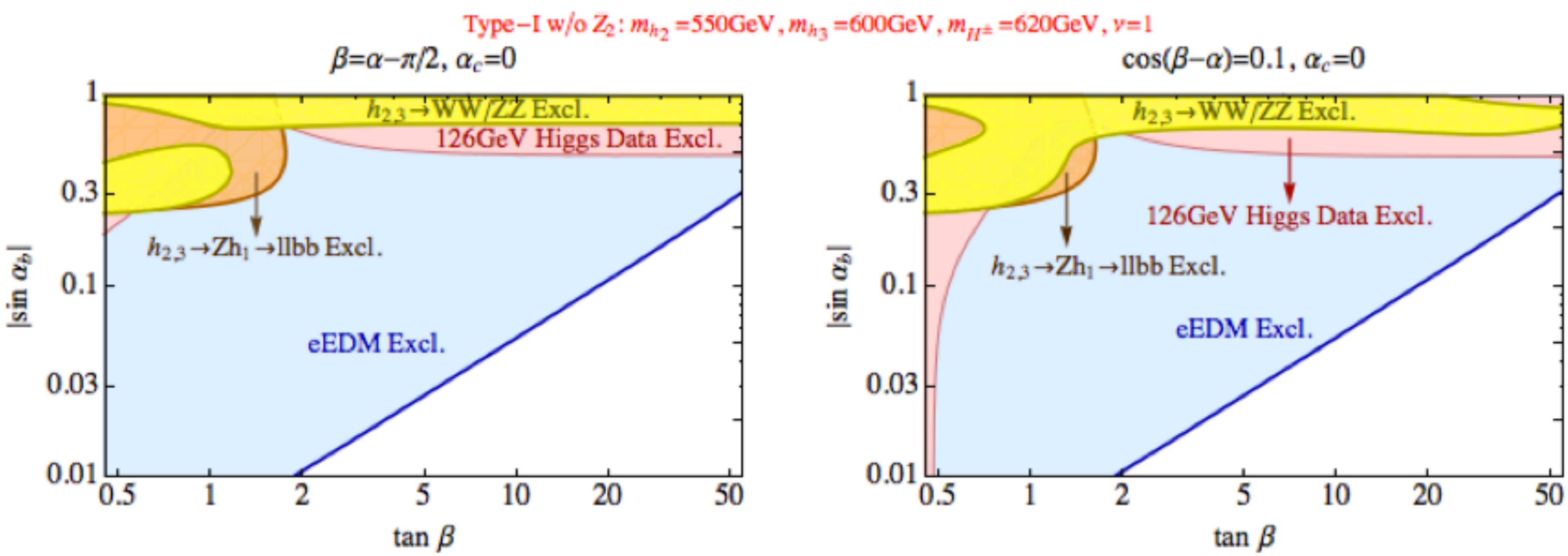
Results: Type-I

- Bounds from $h_{2,3} \to Zh_1 \to l^+l^-b\bar{b}$ excludes region for $\tan\beta < 5$
- Nice complementarity between bounds from EDMs and Heavy Higgs searches



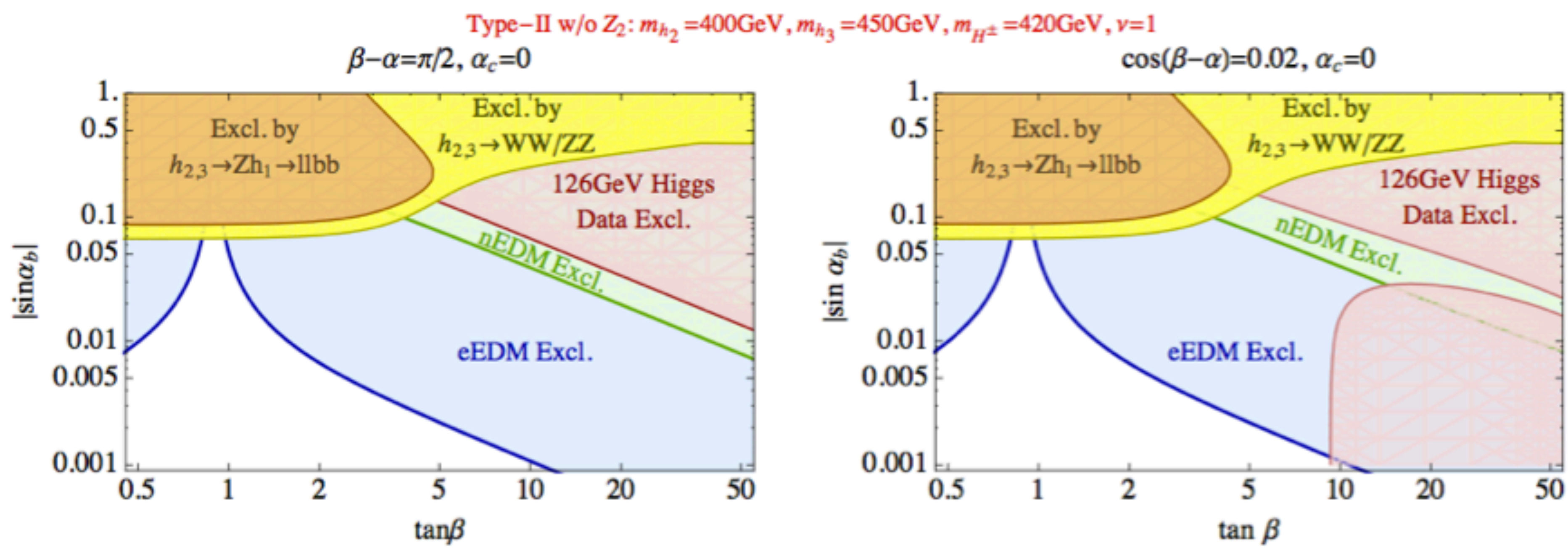
Results: Type-I

- Now consider masses of heavy Higgses larger than 500 GeV
- Limits from heavy Higgs searches are weak than those of EDMs for $m_{h_{2,3}} > 600$ GeV



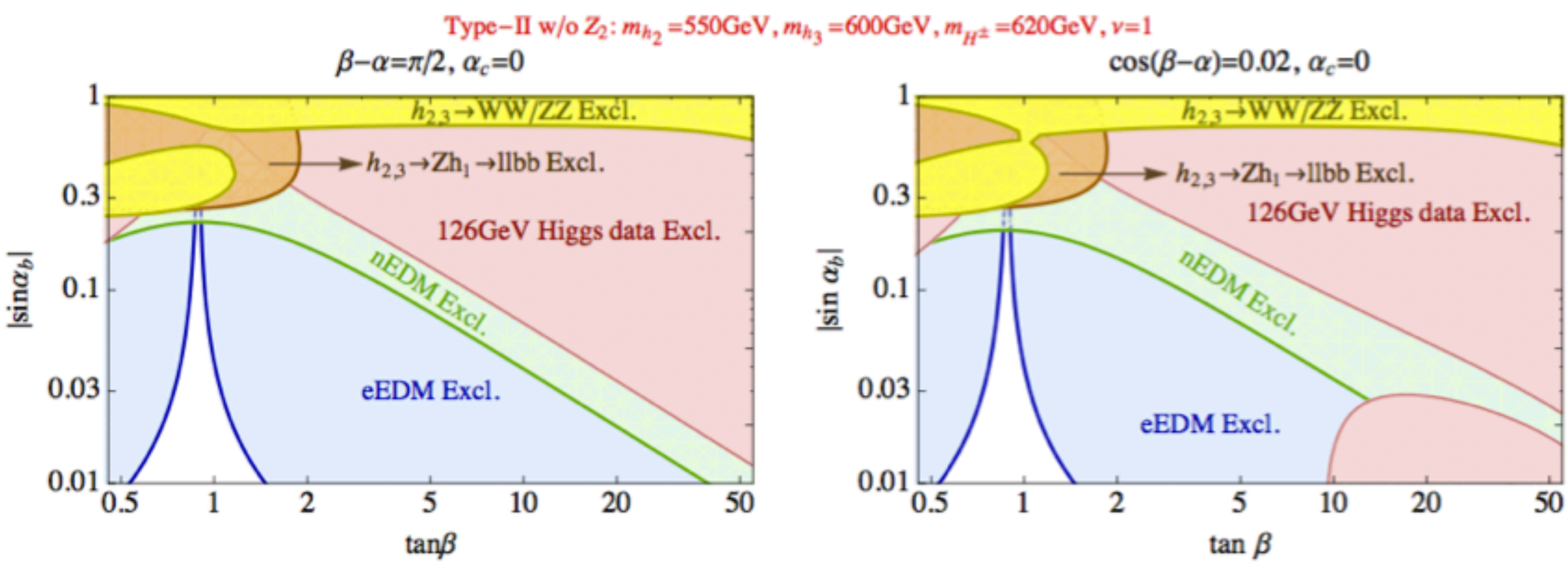
Results: Type-II

- Bounds from $h_{2,3} \to Zh_1 \to l^+l^-b\bar{b}$ close the window at $\tan\beta \sim 1$
- Nice complementarity between bounds from EDMs and Heavy Higgs searches

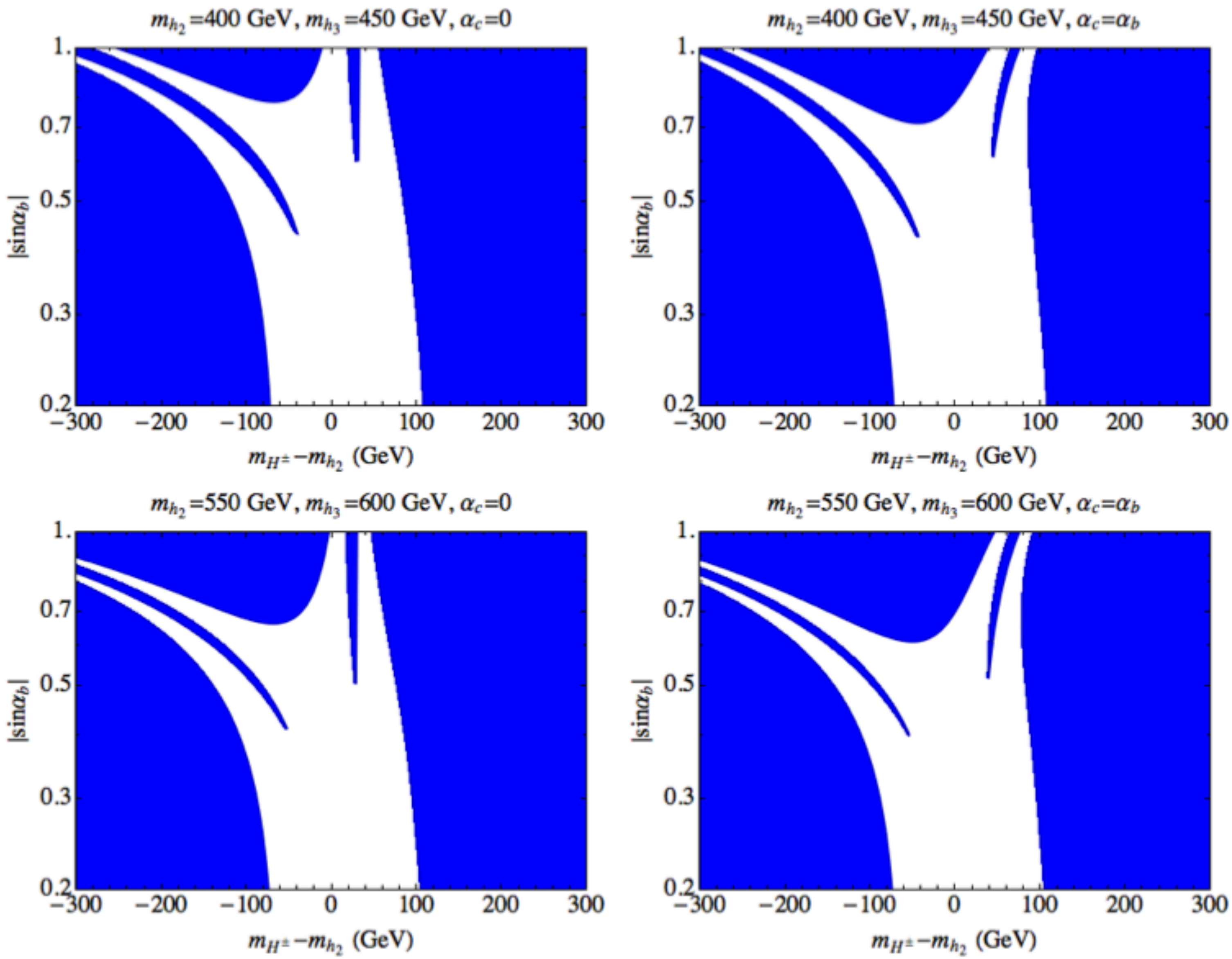


Results: Type-II

- Now consider masses of heavy Higgses larger than 500 GeV
- Limits from heavy Higgs searches are weak than those of EDMs for $m_{h_{2,3}} > 600$ GeV



Limits from oblique parameters



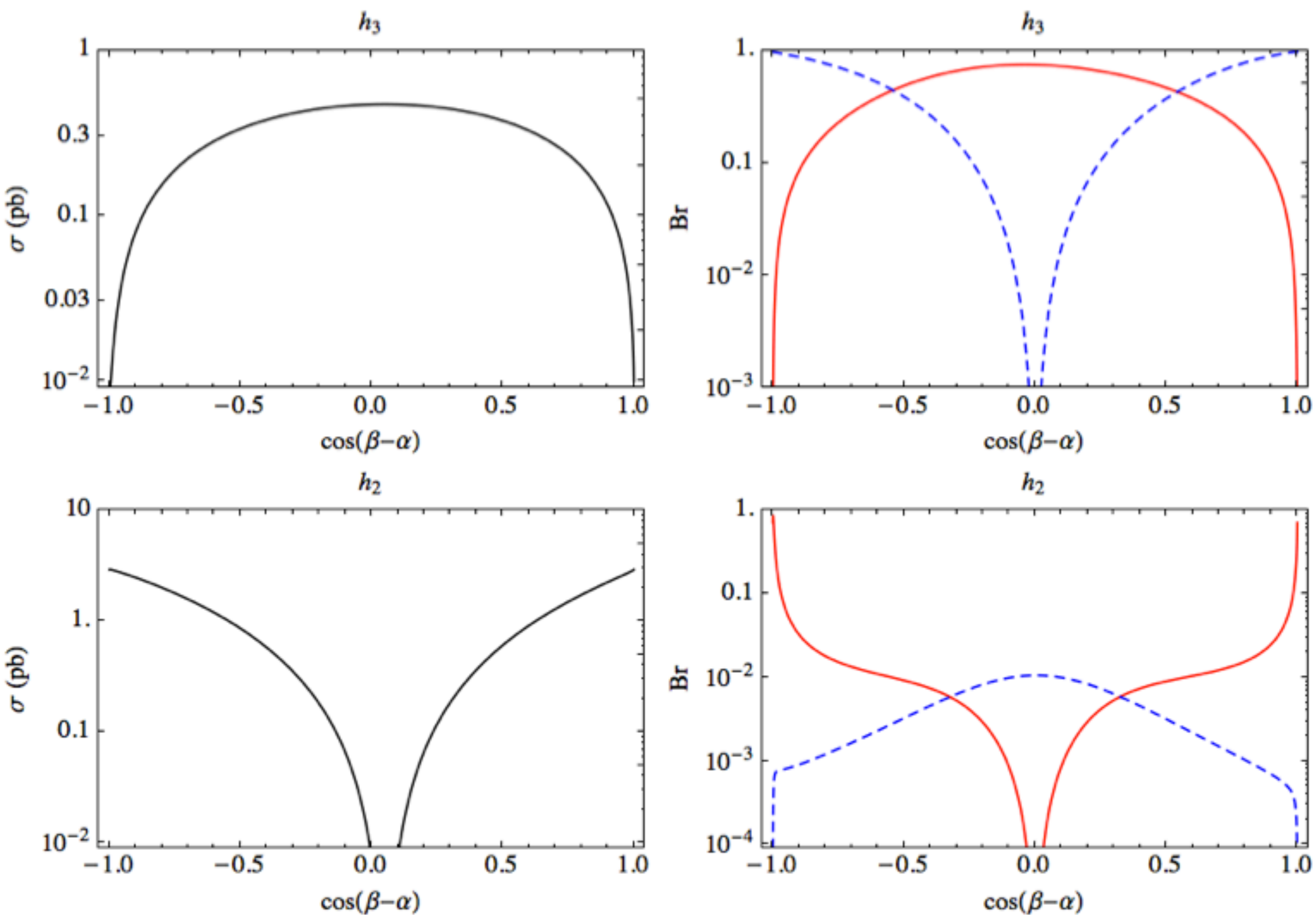
Take home message

- Bounds from light Higgs coupling measurement are not constraining
- Nice complementarity between bounds from EDMs and Heavy Higgs searches
- Uncertainties of neutron EDM is still big
- Heavy Higgses can not decouple in order to have nonzero CP violation

THANK YOU!

BACKUP SLIDES

Decays into VV and Vh$_1$



Red: $h_i \to VV$

Blue: $h_i \to Zh_1$

- Relate α_b and α_c

$$\tan\beta = \frac{(m_{h_2}^2 - m_{h_3}^2)\cos\alpha_c\sin\alpha_c + (m_{h_1}^2 - m_{h_2}^2\sin^2\alpha_c - m_{h_3}^2\cos^2\alpha_c)\tan\alpha\sin\alpha_b}{(m_{h_2}^2 - m_{h_3}^2)\tan\alpha\cos\alpha_c\sin\alpha_c - (m_{h_1}^2 - m_{h_2}^2\sin^2\alpha_c - m_{h_3}^2\cos^2\alpha_c)\sin\alpha_b}$$

$$\alpha_c = \begin{cases} \alpha_c^-, & \alpha+\beta \leq 0 \\ \alpha_c^+, & \alpha+\beta > 0 \end{cases}, \qquad \tan\alpha_c^{\pm} = \frac{\mp|\sin\alpha_b^{\max}| \pm \sqrt{\sin^2\alpha_b^{\max} - \sin^2\alpha_b}}{\sin\alpha_b}\sqrt{\frac{m_{h_3}^2 - m_{h_1}^2}{m_{h_2}^2 - m_{h_1}^2}}$$

$$\mathrm{Im}\lambda_5 = \frac{2\cos\alpha_b}{v^2\sin\beta}\Big[(m_{h_2}^2 - m_{h_3}^2)\cos\alpha\sin\alpha_c\cos\alpha_c + (m_{h_1}^2 - m_{h_2}^2\sin^2\alpha_c - m_{h_3}^2\cos^2\alpha_c)\sin\alpha\sin\alpha_b\Big]$$