Complementarity of LHC and EDMs for Exploring Higgs CP Violation

Chien-Yi Chen

Brookhaven National Lab

C.-Y.C., S. Dawson, Y. Zhang [arXiv:hep-ph:1503.01114]

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Outline

- Theory overview on two Higgs doublet models (2HDMs) with CP violation (CPV)

- Constraints:

  - EDMs

  - Light and heavy Higgs searches

- Conclusion

Motivations

* CP violation, important ingredient to explain baryon asymmetry (one of Sakharov's necessary conditions)

* Higgs sector of supersymmetry (type-II 2HDM)

* Interesting to study CPV in extended Higgs models

* Combine low energy EDMs and high energy collider experiment to bound the parameter space

Theory: 2HDM

- ❖ Scalar potential:

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

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

$$\tan\beta = v_2/v_1$$
$$v = \sqrt{v_1^2 + v_2^2} = 246 \text{ GeV}$$

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 $m_{12}^2, \lambda_5, \lambda_6,$ and λ_7 can be complex

- ❖ Imposing a Z$_2$ symmetry to avoid tree-level FCNCs:

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

  - ❖ Type-II 2HDM: $d_R \to -d_R, u_R \to u_R,$ and $\ell_R \to -\ell_R$

- ❖ Implies $m_{12}^2, \lambda_6,$ and λ_7 are equal to zero.

Theory: 2HDM

- There exist a rephrasing invariant CP phase

$$\text{Im}\left[\lambda_5^*(m_{12}^2)^2\right]$$

⮕ | break Z2 softly |

- Introduce a rotation matrix to get the mass eigenstates

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

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

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

- CPV phases $\quad -\dfrac{\pi}{2} < \alpha_b \le \dfrac{\pi}{2} \qquad -\dfrac{\pi}{2} \le \alpha_c \le \dfrac{\pi}{2}$

Theory overview

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

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

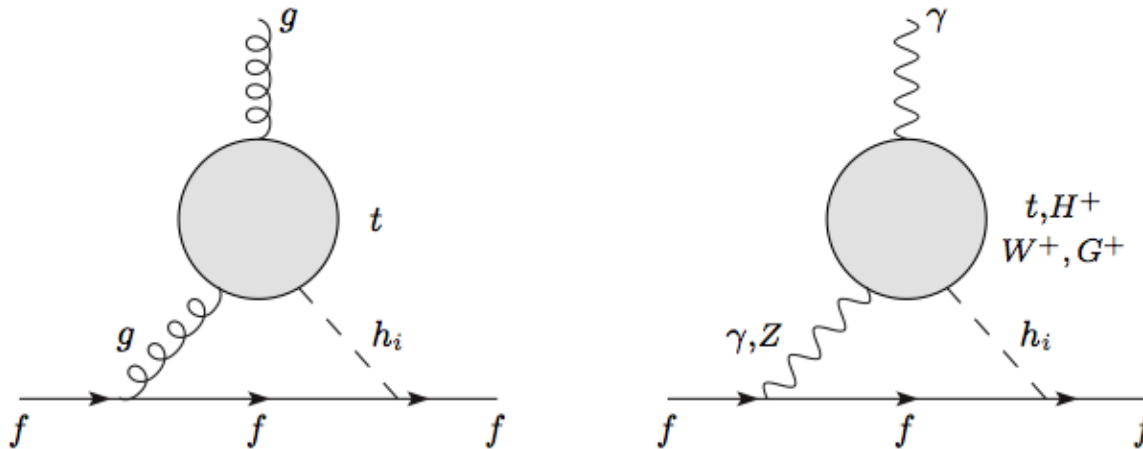|	$c_{t,i}$	$c_{b,i} = c_{\tau,i}$	$\tilde{c}_{t,i}$	$\tilde{c}_{b,i} = \tilde{c}_{\tau,i}$	a_i
Type I	$R_{i2}/\sin\beta$	$R_{i2}/\sin\beta$	$-R_{i3}\cot\beta$	$R_{i3}\cot\beta$	$R_{i2}\sin\beta + R_{i1}\cos\beta$
Type II	$R_{i2}/\sin\beta$	$R_{i1}/\cos\beta$	$-R_{i3}\cot\beta$	$-R_{i3}\tan\beta$	$R_{i2}\sin\beta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

- 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 $\cos\alpha = \sin\beta$.
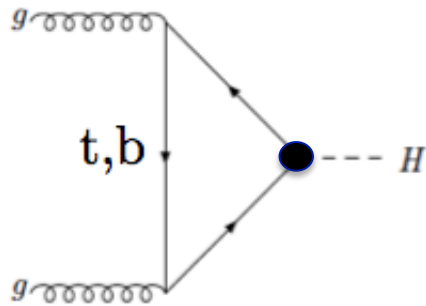
- h_1 is the 125 GeV Higgs

Electric dipole moment

- Electron EDM: $|d_e| < 8.7 \times 10^{-28} e \text{ cm}$, by ACME experiment

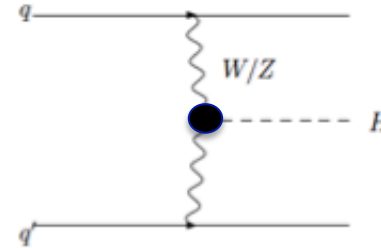- Mainly from Barr-Zee diagrams (one loop contribution is suppressed by two powers of y_e)

Production at LHC

- Gluon fusion (ggF)

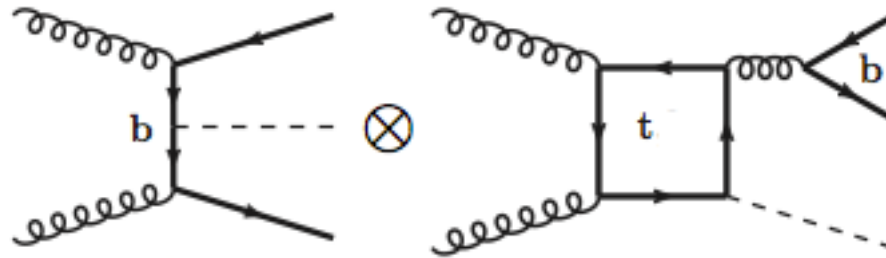$$-i\frac{m_f}{v}\left(c_{f,i} + i\gamma_5 \tilde{c}_{f,i}\right)$$

- Vector boson fusion (VBF)

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

Production at LHC

❖ 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

$$\Gamma_{tot}(h_i) = \Gamma(h_i \to W^+ W^-) + \Gamma(h_i \to ZZ) + \Gamma(h_i \to t\bar{t}) + \Gamma(h_i \to b\bar{b})$$
$$+ \Gamma(h_i \to \tau^+ \tau^-) + \Gamma(h_i \to gg) + \Gamma(h_i \to Zh_1) + \Gamma(h_i \to h_1 h_1)$$

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

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

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

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. [arXiv: 1304.0213] [CMS PAS HIG-14-011]

- Because in the the alignment limit, and CP conserving

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

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

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

- In the CP violating case,

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

$$h_{2,3} \to Zh_1 \ \checkmark$$
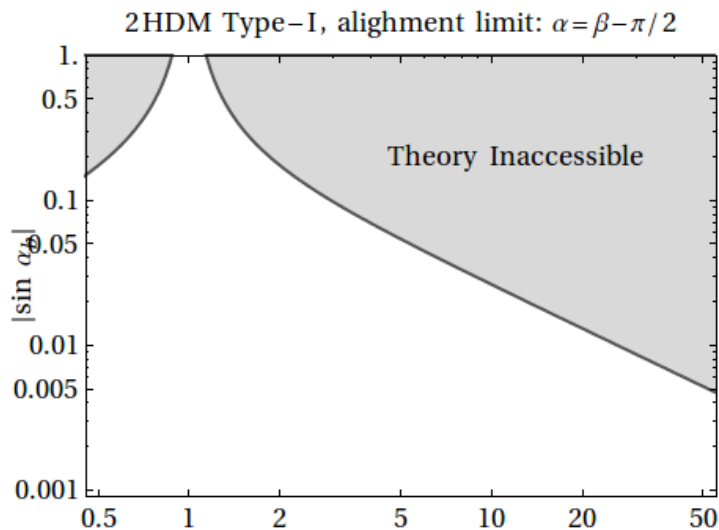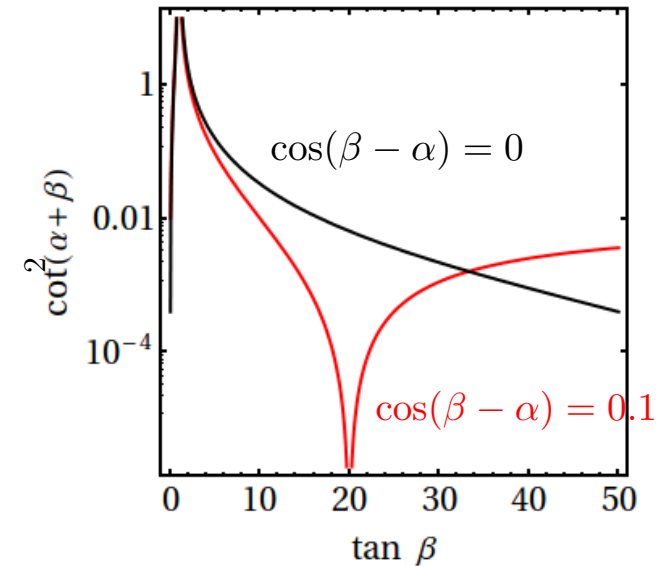
With approximate Z₂

$$m_{12}^2, \lambda_5 \neq 0$$
$$\lambda_6, \lambda_7 = 0$$

Theoretical constraints

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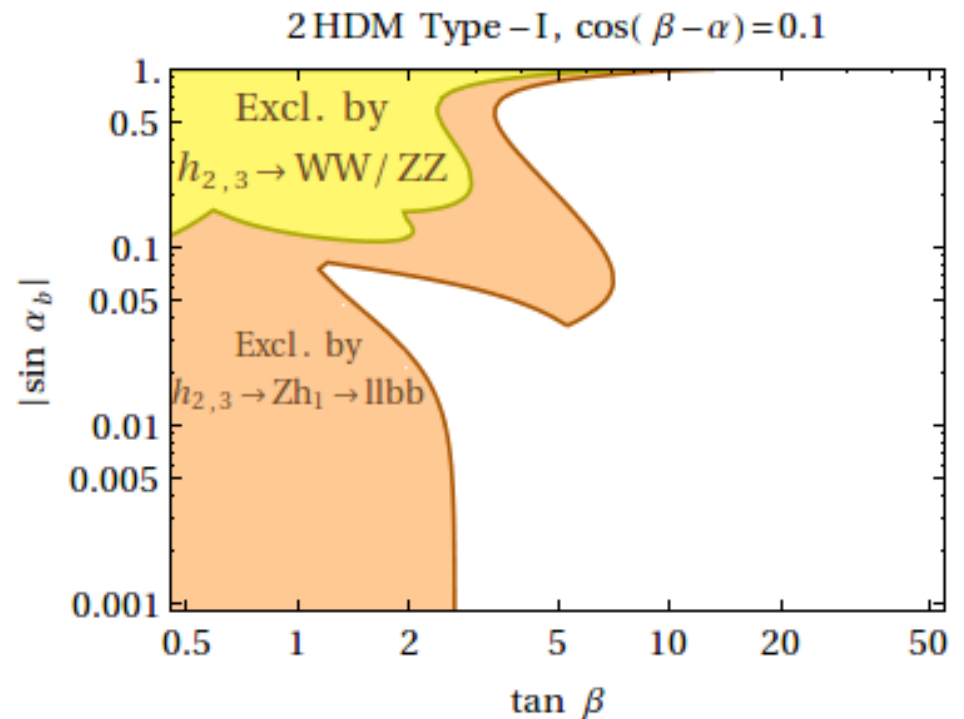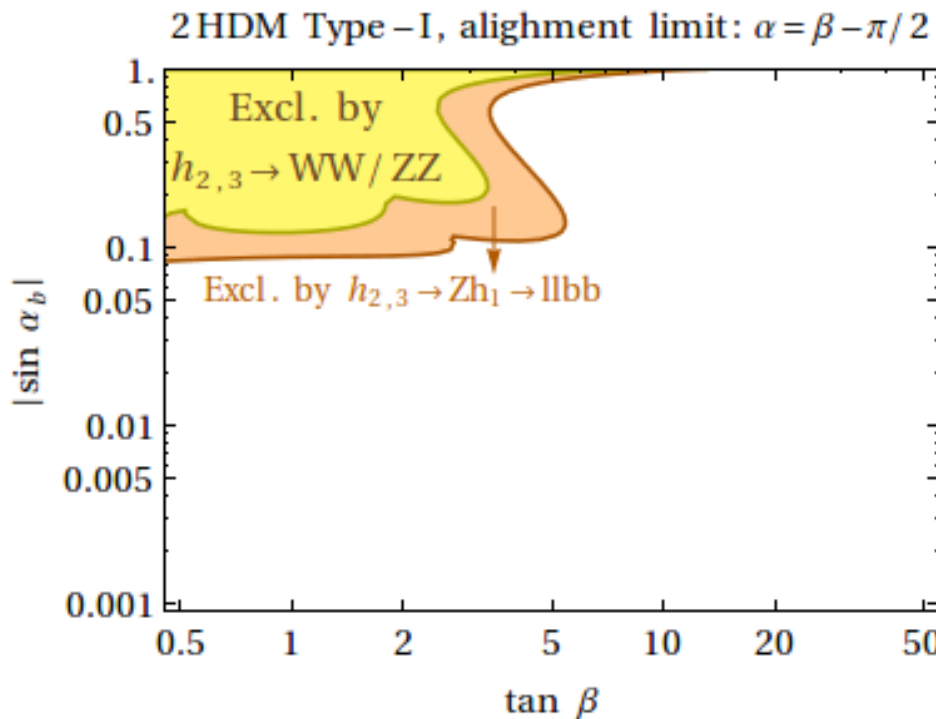
❖ Condition for α_c to have a real solution:

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

❖ Same distributions for type I and II

$\cos(\beta-\alpha) = 0$

$\cos(\beta-\alpha) = 0.1$

2HDM Type−I, alighment limit: $\alpha = \beta - \pi/2$

Theory Inaccessible

2HDM Type−I, $\cos(\beta-\alpha) = 0.1$

Theory Inaccessible
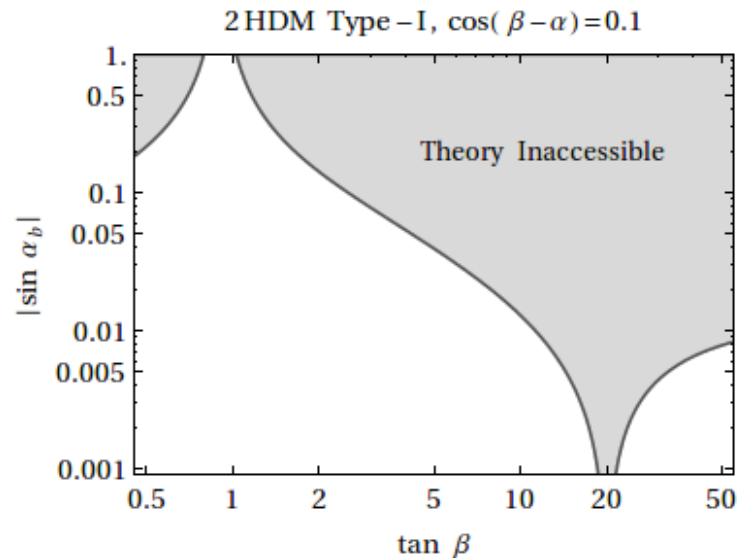
LHC data

- 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

2 HDM Type $-$ I, alighment limit: $\alpha = \beta - \pi/2$

Excl. by $h_{2,3} \to WW/ZZ$

Excl. by $h_{2,3} \to Zh_1 \to llbb$

2 HDM Type $-$ I, $\cos(\beta - \alpha) = 0.1$

Excl. by $h_{2,3} \to WW/ZZ$

Excl. by $h_{2,3} \to Zh_1 \to llbb$

Result: Type-I

* Combine with theory inaccessible region and EDMs

Type−I w. approximate Z_2: m_{h_2} =400GeV, m_{h_3} =450GeV, $m_{H^\pm}$ =420GeV, v=1
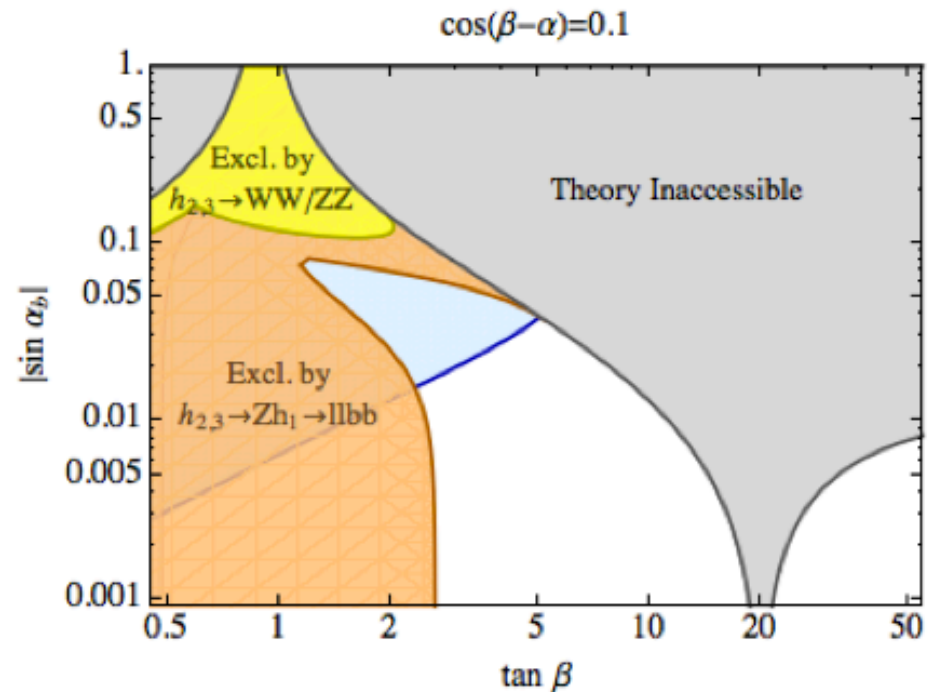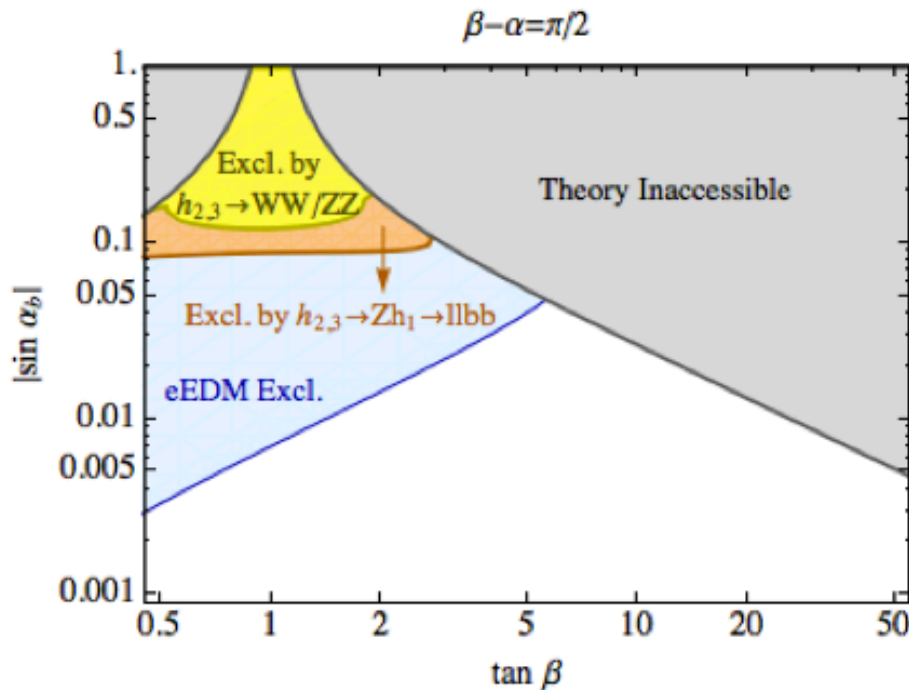
Result: Type-II

- ❖ Combine with theory inaccessible region and EDMs

Type−II w. approximate Z_2: $m_{h_2} = 400$GeV, $m_{h_3} = 450$GeV, $m_{H^\pm} = 420$GeV, $v=1$
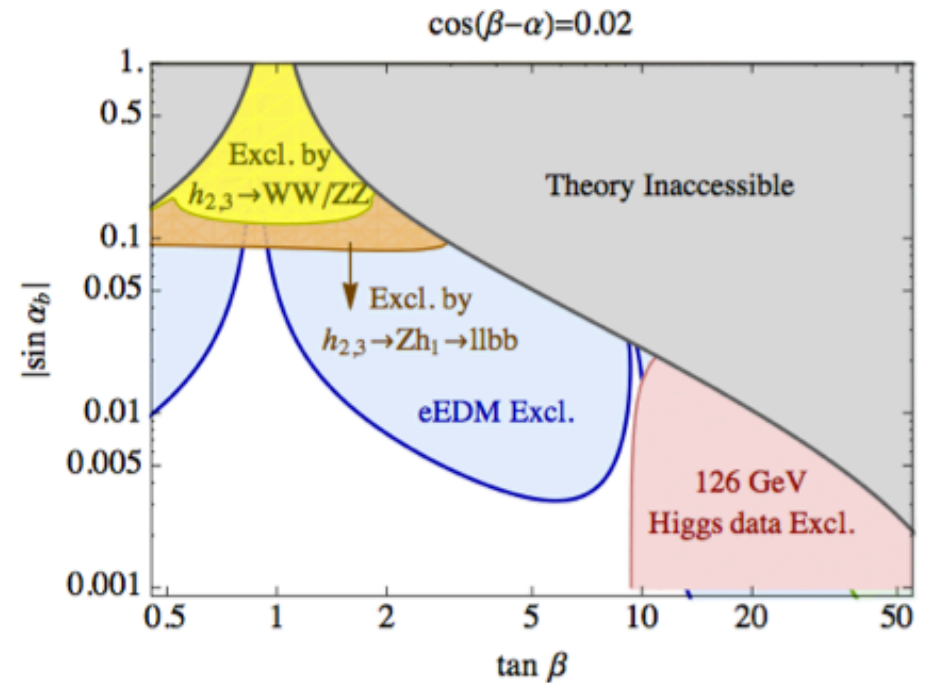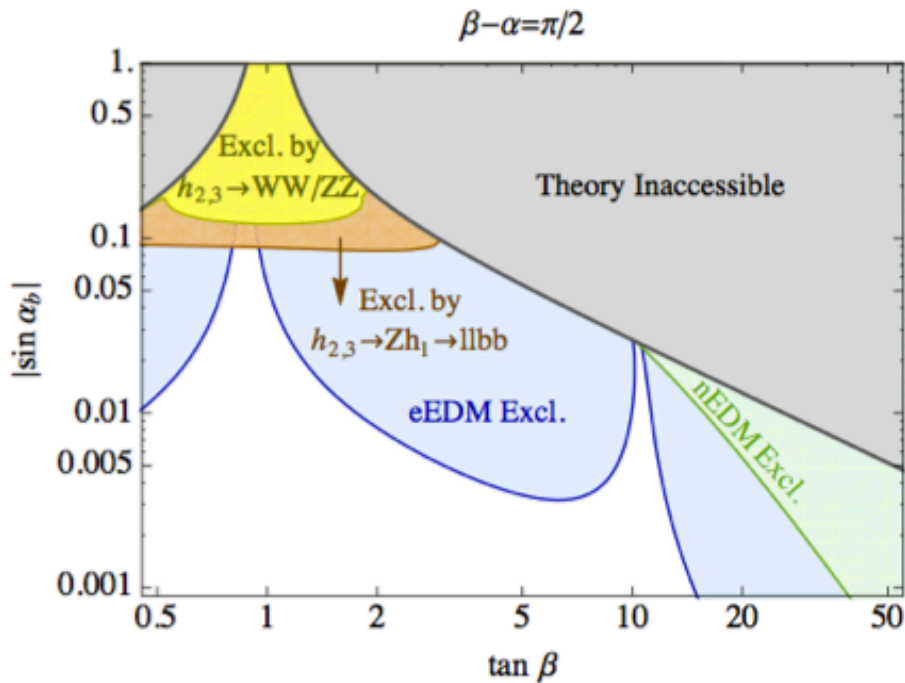
Take home message
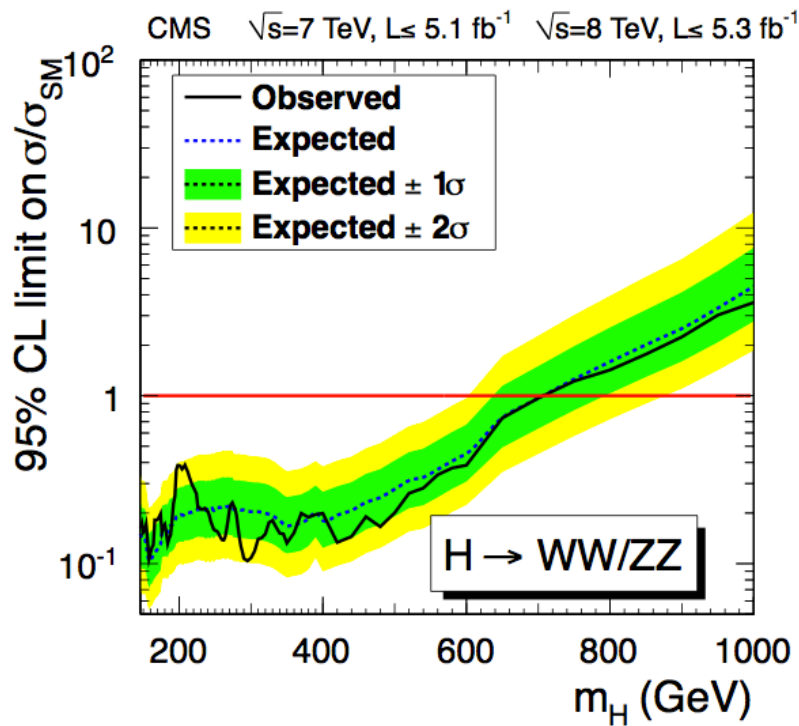
- Bounds from light Higgs coupling measurement are not constraining

- Nice complementarity between bounds from EDMs and Heavy Higgs searches

- For the mass of heavy Higgs larger than 600 GeV the collider bounds become weaker

- Heavy Higgses can not decouple in order to have nonzero CP violation

THANK YOU!

BACKUP SLIDES

LHC data

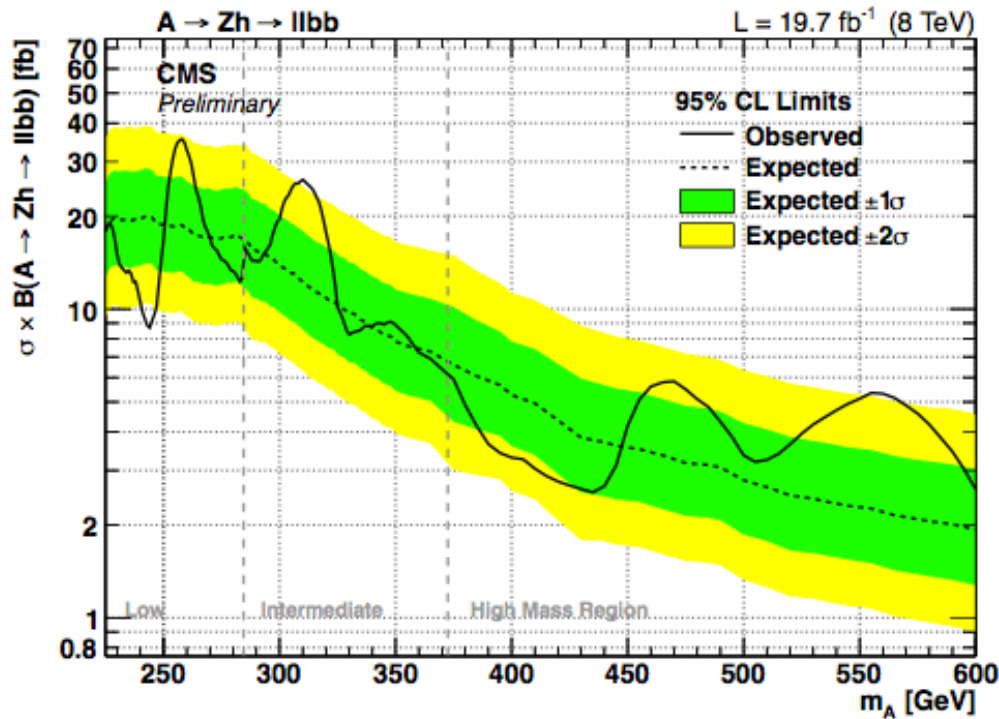❖ Heavy Higgs constraints: $h_{2,3} \rightarrow WW/ZZ$

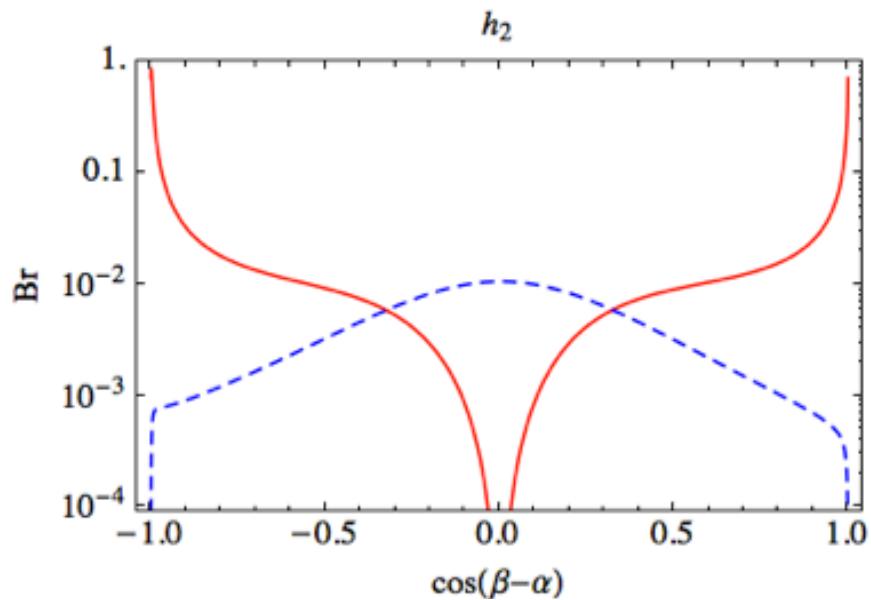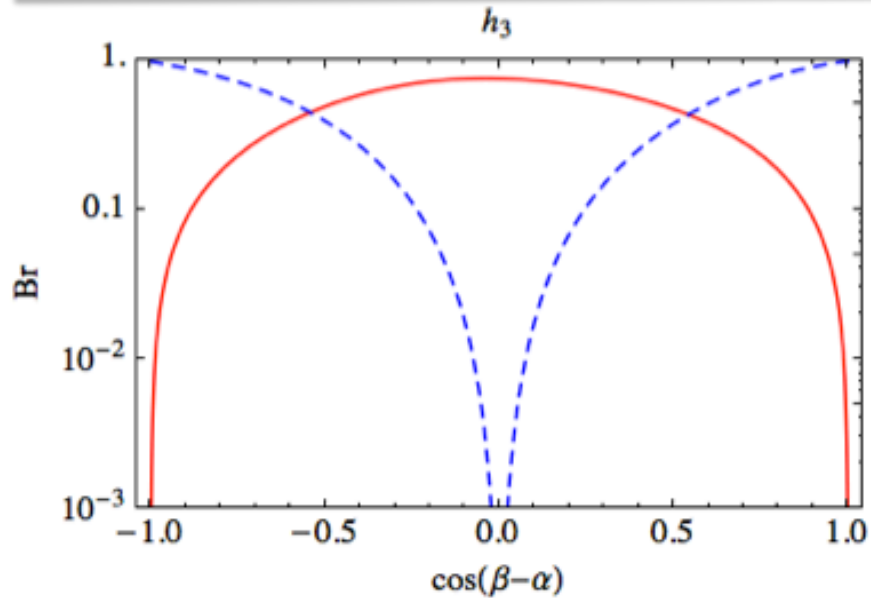Rule out region $m_H < 700$ GeV

[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]

Decays into VV and Vh₁

Red: $h_i \rightarrow VV$

Blue: $h_i \rightarrow Zh_1$
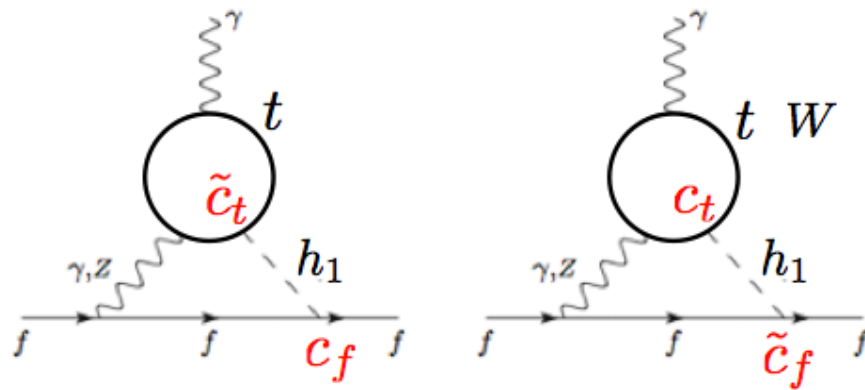
❖ Relate α_b and α_c

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

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

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

$$+ (m_{h_1}^2 - m_{h_2}^2 \sin^2 \alpha_c - m_{h_3}^2 \cos^2 \alpha_c) \sin \alpha \sin \alpha_b \Big]$$
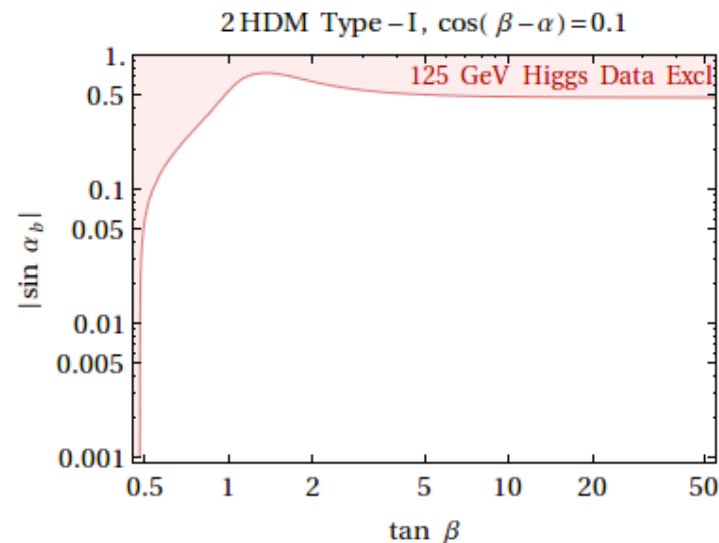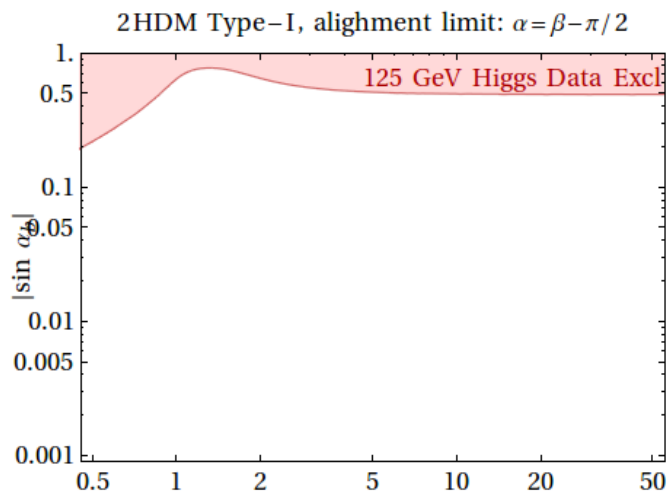
Electric dipole moment

* For type II, cancelation occurs when $c_t \tilde{c}_e \approx c_e \tilde{c}_t \approx a \tilde{c}_e$

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

2 HDM Type−I, alighment limit: $\alpha = \beta - \pi/2$

125 GeV Higgs Data Excl

2 HDM Type−I, $\cos(\beta - \alpha) = 0.1$

125 GeV Higgs Data Excl

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
$\mu_{\tau\tau}$	0.91 ± 0.27	1.4 ± 0.4
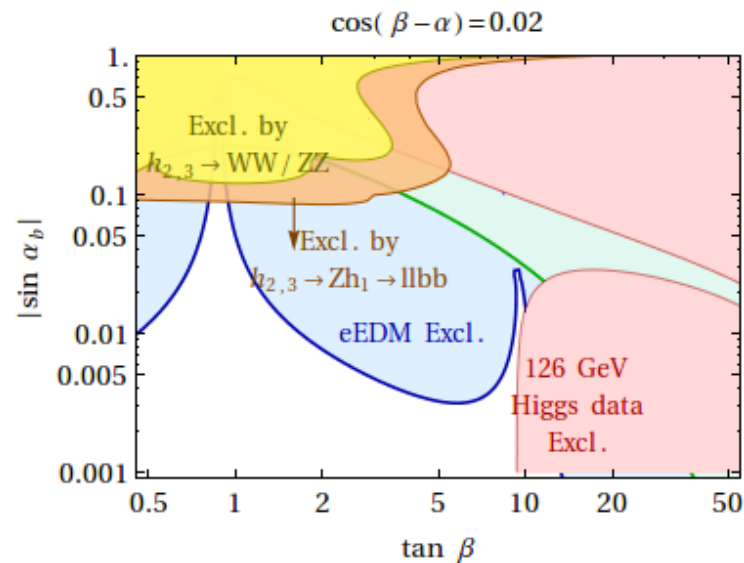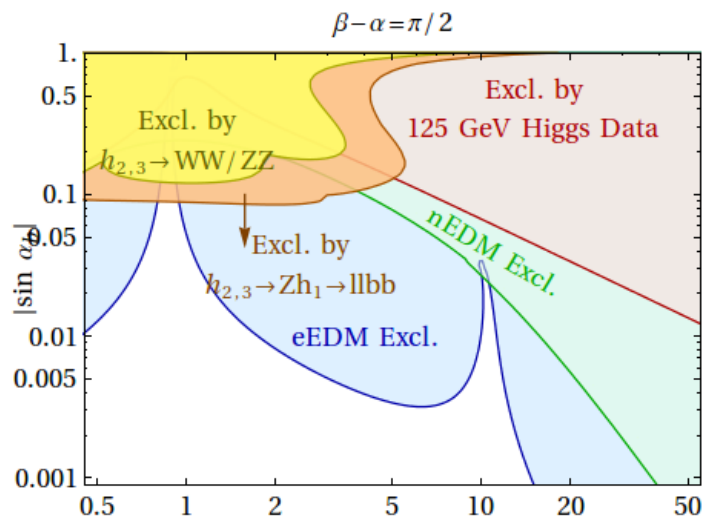
Without approximate Z_2

Results: without approximate Z₂

- ❖ 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.

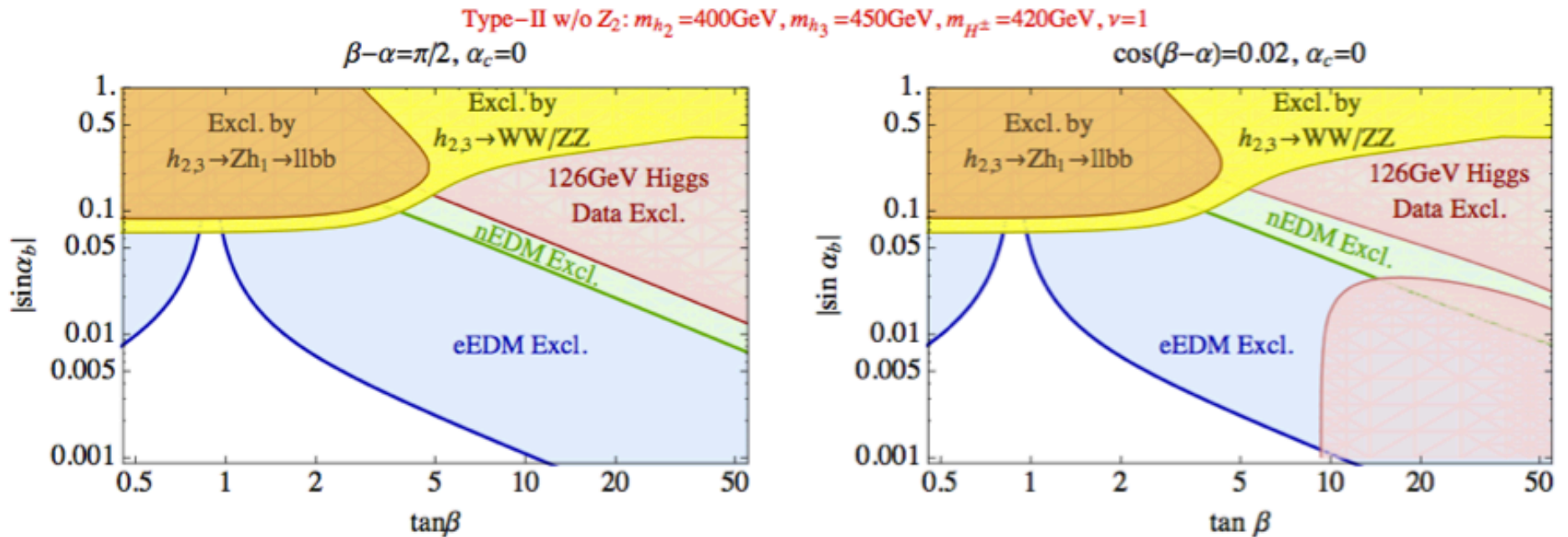# Results: Type-I

- Bounds from $h_{2,3} \to Z h_1 \to l^+ l^- b\bar{b}$ excludes region for $\tan\beta < 5$

- Nice complementarity between bounds from EDMs and Heavy Higgs searches

Type$-$I w/o Z_2: $m_{h_2} = 400\,\text{GeV}$, $m_{h_3} = 450\,\text{GeV}$, $m_{H^\pm} = 420\,\text{GeV}$, $v = 1$
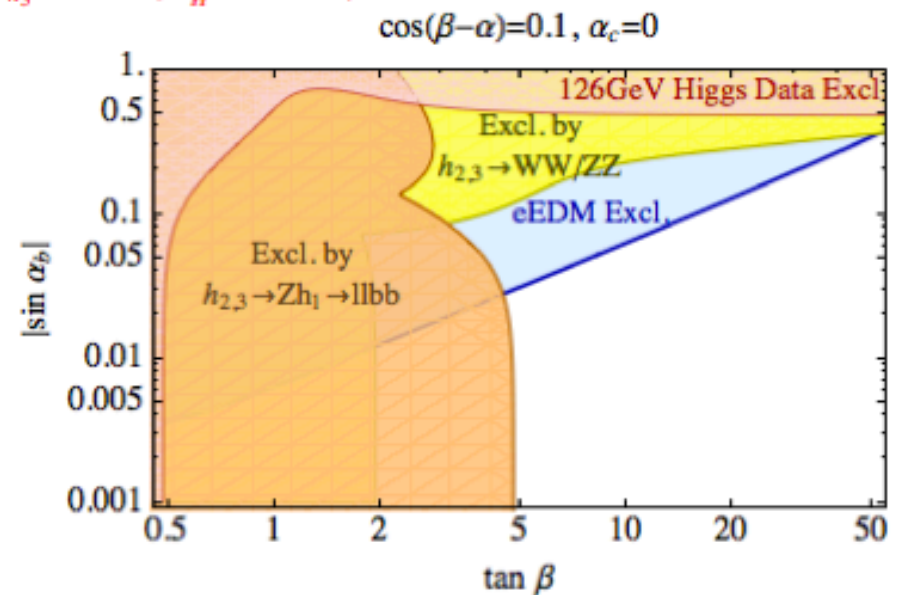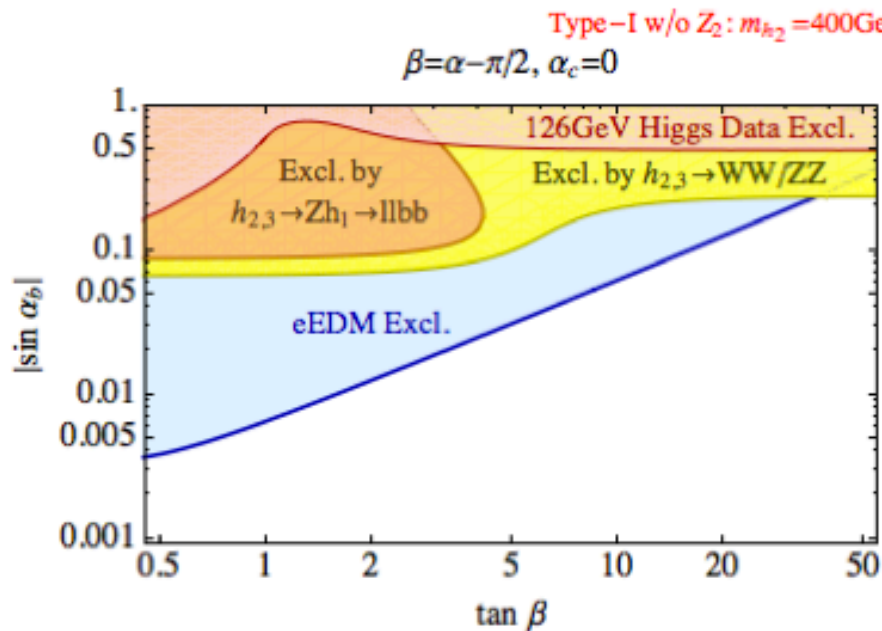
Results: Type-II

- 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

Type−II w/o Z_2: $m_{h_2}=400\text{GeV}$, $m_{h_3}=450\text{GeV}$, $m_{H^\pm}=420\text{GeV}$, $v=1$

Limits from oblique parameters

$m_{h_2}=400$ GeV, $m_{h_3}=450$ GeV, $\alpha_c=0$

$m_{h_2}=400$ GeV, $m_{h_3}=450$ GeV, $\alpha_c=\alpha_b$

$m_{h_2}=550$ GeV, $m_{h_3}=600$ GeV, $\alpha_c=0$

$m_{h_2}=550$ GeV, $m_{h_3}=600$ GeV, $\alpha_c=\alpha_b$

$|\sin\alpha_b|$

$m_{H^\pm}-m_{h_2}$ (GeV)