Implications of BSM CP violation: EDM tests and the collider phenomenology

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arXiv:1607.02703, 1608.07975, 1706.09425
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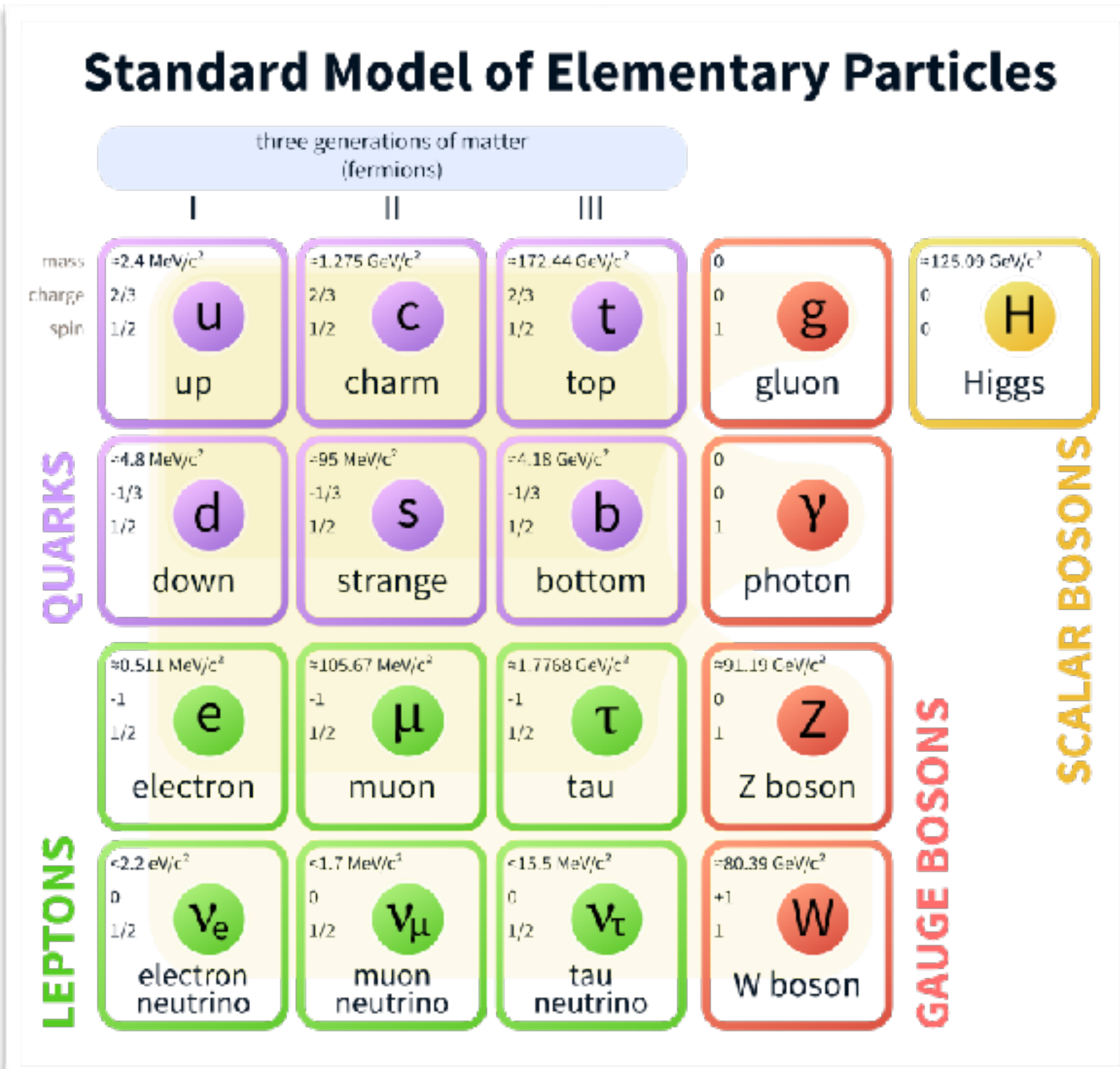
Outline

- CPV in the SM: CKM mixing, Jarlskog invariant, and relations to the baryon asymmetry
- 2HDM (T. D. Lee, `73): additional CPV source from the scalar sector
- EDM constraints: electrons, and atoms
- The LHC searches: diphoton, and Higgs pairs (very specific)

SM: three generational fermions



CKM matrix for SM quarks

- Three generational quark mixing:

$$\mathcal{L}_{\rm Yuk} = \sum_{i,j=1,2,3} \Big(-\frac{v}{\sqrt{2}} Y^d_{ij} \bar{d}^i_L d^j_R - \frac{v}{\sqrt{2}} Y^u_{ij} \bar{u}^i_L u^j_R + h.c. \Big)$$

can be diagonalized by

$$\begin{aligned} &u_L \to U_u u_L\,, \quad u_R \to K_u u_R\,, \quad d_L \to U_d d_L\,, \quad d_R \to K_d d_R \\ &U_u^\dagger Y_u K_u = M_u = \mathrm{diag}(m_u\,, m_c\,, m_t) \\ &U_d^\dagger Y_d K_d = M_d = \mathrm{diag}(m_d\,, m_s\,, m_b) \end{aligned}$$

- The Cabibbo-Kobayashi-Maskawa (CKM) matrix

$$\frac{e}{\sqrt{2} s_W} \Big[W^+_\mu \bar{u}^i_L \gamma^\mu V^{ij}_{\rm CKM} d^j_L + h.c. \Big]\,, \qquad V_{\rm CKM} = U_u^\dagger U_d$$

CKM matrix for SM quarks

- The 3×3 unitary CKM matrix: 9 d.o.f.s
- Six rephasing symmetries:

$$u^j_{L,R} \to \exp(i\alpha_j) u^j_{L,R}\,, \qquad d^j_{L,R} \to \exp(i\beta_j) d^j_{L,R}$$

for $\alpha_j = \beta_j = \theta$, V_{CKM} is unchanged. So 5 d.o.f.s can be eliminated.

- Standard parametrization:

$$V_{\text{CKM}} \quad = \quad \mathcal{R}_{23}(\theta_{23}) \begin{pmatrix} c_{13} & 0 & s_{13} e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta} & 0 & c_{13} \end{pmatrix} \mathcal{R}_{12}(\theta_{12})$$

$$\theta_{12} \approx 13.02^\circ\,, \qquad \theta_{23} \approx 2.36^\circ\,, \qquad \theta_{13} \approx 0.20^\circ\,, \qquad \delta \approx 69^\circ$$

EW CPV & Jarlskog invariant

- Under the $\mathcal{CP}$ transformation:

$$\Rightarrow \quad \frac{e}{\sqrt{2}s_W}\left[W_\mu^+ \bar{u}_L (V_{\rm CKM}^\dagger)^T \gamma^\mu d_L + W_\mu^- \bar{d}_L (V_{\rm CKM})^T \gamma^\mu u_L\right]$$

EW interaction is $\mathcal{CP}$ invariant if $V_{\rm CKM}$ is real. Alternatively, a non-zero Dirac phase δ in the CKM matrix implies CPV.

- The CPV is basis-independent.

$$\begin{aligned}
& u/d_R \to K_{u/d} U_{u/d}^\dagger u/d_R \Rightarrow Y_{u/d} = U_{u/d} M_{u/d} U_{u/d}^\dagger : \text{hermitian} \\
& \text{no CPV if } Y_{u/d} \text{ can be diagonalized simulataneously} \\
\det C \quad & = \quad \det(i[Y_u\,;\,Y_d]) = \ldots \\
& \propto \quad \frac{1}{v^6}(m_t - m_c)(m_t - m_u)(m_c - m_u) \\
& \quad\quad \times (m_b - m_s)(m_b - m_d)(m_s - m_d)\mathcal{J} \\
\text{Jarlskog invariant} \quad & : \quad \mathcal{J} = \Im(V_{11} V_{22} V_{12}^* V_{21}^*) = s_{12} s_{23} s_{13} c_{12} c_{23} c_{13}^2 s_\delta
\end{aligned}$$

Exp. tests: Kaon mixings

- The neutral kaons are $K^0 = (\bar{s}d)$ and $\bar{K}^0 = (s\bar{d})$, under the $\mathcal{CP}$ transformation:

$$\mathcal{CP}|K^0\rangle = |\bar{K}^0\rangle\,, \qquad \mathcal{CP}|\bar{K}^0\rangle = |K^0\rangle$$

$$\mathcal{CP}\text{ eigenstates} \quad : \quad |K_{1,2}\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle \pm |\bar{K}^0\rangle)$$

- Their decays (if no CPV): $K_1 \to \pi\pi$ (short-living), and $K_2 \to \pi\pi\pi$ (long-living). It turns out some long-lived kaons go to $\pi\pi$ ('64, Christenson, Cronin, Fitch, Turlay).

$$\text{mass eigenstates} \quad : K_S = K_1 + \epsilon K_2\,, \qquad K_L = K_2 - \epsilon K_1\,, \;\; \epsilon \sim 2 \times 10^{-3}$$

BAU

- The puzzle of baryon asymmetry in the Universe (BAU)
- Sakharov conditions (\`67): (1) Baryon-number violation; (2) <u>CP violation</u>; (3) out-of-equilibrium (strong first-order phase transition)

SM: insufficient for BAU

- The SM contains (1), which is $B+L$ violation through the instanton effect, but too small tunneling rate: $\sim \exp(-4\pi/\alpha_W) \sim 10^{-150}$.
- The SM also contains (2), but not sufficient:

$$
\begin{aligned}
B &\equiv \frac{n_B}{s} = \frac{n_b - n_{\bar{b}}}{s} \sim 10^{-11}\,, \quad \text{by CMB data} \\
B &\sim \frac{\alpha_W^4 T^3}{s}\delta_{\mathrm{CP}} \simeq 10^{-8}\delta_{\mathrm{CP}} \\
& \quad \delta_{\mathrm{CP}} = \frac{1}{v^6}(m_t - m_c)(m_t - m_u)(m_c - m_u) \\
& \quad \times (m_b - m_s)(m_b - m_d)(m_s - m_d)\mathcal{J} \sim 10^{-20}
\end{aligned}
$$

- The SM is impossible to achieve (3). By analyzing the one-loop Coleman-Weinberg potential,

$$\frac{\phi_c}{T_c} \sim \frac{2m_W^3 + m_Z^3}{\pi v M_h^2} \gtrsim 1 \Rightarrow M_h \lesssim 42 \ \mathrm{GeV}$$

CPV from scalar sector

PHYSICAL REVIEW D VOLUME 8, NUMBER 4 15 AUGUST 1973

A Theory of Spontaneous T Violation*

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(Received 11 April 1973)

A theory of spontaneous T violation is presented. The total Lagrangian is assumed to be invariant under the time reversal T and a gauge transformation (e.g., the hypercharge gauge), but the physical solutions are not. In addition to the spin-1 gauge field and the known matter fields, in its simplest form the theory consists of two complex spin-0 fields. Through the spontaneous symmetry-breaking mechanism of Goldstone and Higgs, the vacuum expectation values of these two spin-0 fields can be characterized by the shape of a triangle and their quantum fluctuations by its vibrational modes, just like a triangular molecule. T violations can be produced among the known particles through virtual excitations of the vibrational modes of the triangle which has a built-in T-violating phase angle. Examples of both Abelian and non-Abelian gauge groups are discussed. For renormalizable theories, all spontaneously T-violating effects are finite. It is found that at low energy, below the threshold of producing these vibrational quanta, T violation is always quite small.

CPV 2HDM

$$\mathcal{L} = \sum_{i=1,2} |D\Phi_i|^2 - V(\Phi_1, \Phi_2)$$

$$V(\Phi_1, \Phi_2) = m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - (m_{12}^2\Phi_1^\dagger\Phi_2 + H.c.) + \frac{1}{2}\lambda_1|\Phi_1|^4 + \frac{1}{2}\lambda_2|\Phi_2|^4$$
$$+ \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{1}{2}\left[\lambda_5(\Phi_1^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2) + H.c.\right]$$

with m_{12}^2 and λ_5 being complex.

$$\Phi_1 = \begin{pmatrix} -s_\beta H^+ \\ \frac{1}{\sqrt{2}}(v_1 + H_1^0 - is_\beta A) \end{pmatrix}, \qquad \Phi_2 = \begin{pmatrix} c_\beta H^+ \\ \frac{1}{\sqrt{2}}(v_2 e^{i\xi} + H_2^0 + ic_\beta A), \end{pmatrix}$$

Neutral Higgs masses

- Masses and mixings in the neutral sector:

$$\mathcal{M}_0^2 = \begin{pmatrix} \lambda_1 c_\beta^2 + \nu s_\beta^2 & (\lambda_{345} - \nu) s_\beta c_\beta & -\frac{1}{2}\mathrm{Im}(\lambda_5)\, s_\beta \\ (\lambda_{345} - \nu) s_\beta c_\beta & \lambda_2 s_\beta^2 + \nu c_\beta^2 & -\frac{1}{2}\mathrm{Im}(\lambda_5)\, c_\beta \\ -\frac{1}{2}\mathrm{Im}(\lambda_5)\, s_\beta & -\frac{1}{2}\mathrm{Im}(\lambda_5)\, c_\beta & -\mathrm{Re}(\lambda_5) + \nu \end{pmatrix} v^2$$

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = \mathcal{R}_{23}(\alpha_c)\,\mathcal{R}_{13}(\alpha_b)\,\mathcal{R}_{12}(\alpha + \frac{\pi}{2}) \begin{pmatrix} H_1^0 \\ H_2^0 \\ A^0 \end{pmatrix}$$

- Note that: $(\mathcal{M}_0^2)_{13} = (\mathcal{M}_0^2)_{23}\, t_\beta$,

$$\Rightarrow \quad (M_1^2 - M_2^2 s_{\alpha_c}^2 - M_3^2 c_{\alpha_c}^2) s_{\alpha_b} (1 + t_\alpha) = (M_2^2 - M_3^2)(t_\alpha t_\beta - 1) s_{\alpha_c} c_{\alpha_c}$$

Neutral Higgs couplings

$$\mathcal{L} = \begin{cases} -\left(\frac{c_\alpha}{s_\beta}\frac{m_t}{v}\right)\overline{Q}_L\tilde{\Phi}_2 t_R - \left(\frac{c_\alpha}{s_\beta}\frac{m_b}{v}\right)\overline{Q}_L\Phi_2 b_R + \text{h.c.} & \text{2HDM} - \text{I} \\ -\left(\frac{c_\alpha}{s_\beta}\frac{m_t}{v}\right)\overline{Q}_L\tilde{\Phi}_2 t_R + \left(\frac{s_\alpha}{c_\beta}\frac{m_b}{v}\right)\overline{Q}_L\Phi_1 b_R + \text{h.c.} & \text{2HDM} - \text{II}\,, \end{cases}$$

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

	$c_{t,i}$	$c_{b,i} = c_{\tau,i}$	$\tilde{c}_{t,i}$	$\tilde{c}_{b,i} = \tilde{c}_{\tau,i}$	a_i
I	$\mathcal{R}_{i2}/s_\beta$	$\mathcal{R}_{i2}/s_\beta$	$-\mathcal{R}_{i3}/t_\beta$	$\mathcal{R}_{i3}/t_\beta$	$\mathcal{R}_{i2}s_\beta + \mathcal{R}_{i1}c_\beta$
II	$\mathcal{R}_{i2}/s_\beta$	$\mathcal{R}_{i1}/c_\beta$	$-\mathcal{R}_{i3}/t_\beta$	$-\mathcal{R}_{i3}t_\beta$	$\mathcal{R}_{i2}s_\beta + \mathcal{R}_{i1}c_\beta$

EDM as indirect searches for the CPV

EDM experiments

- ACME collaboration (arXiv: 1310.7534)

$$\left|d_e/e\right| < 8.7 \times 10^{-29}\ \mathrm{cm}$$

- neutron (arXiv: hep-ex/0602020)

$$\left|d_n/e\right| < 2.9 \times 10^{-26}\ \mathrm{cm}$$

- Mercury-199 (arXiv: 1601.04339)

$$|d_{\mathrm{Hg}}/e| < 7.4 \times 10^{-30}\ \mathrm{cm}$$

- Radium-225 (arXiv: 1504.07477, 1606.04931)

$$\begin{aligned} \text{current} &: \quad |d_{\mathrm{Ra}}/e| < 5.0 \times 10^{-22}\ \mathrm{cm} \\ \text{projected} &: \quad |d_{\mathrm{Ra}}/e| < 1.0 \times 10^{-28}\ \mathrm{cm} \end{aligned}$$

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Improved limit on the ^{225}Ra electric dipole moment

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Background: Octupole-deformed nuclei, such as that of ^{225}Ra, are expected to amplify observable atomic electric dipole moments (EDMs) that arise from time-reversal and parity-violating interactions in the nuclear medium. In 2015 we reported the first "proof-of-principle" measurement of the ^{225}Ra atomic EDM.

Purpose: This work reports on the first of several experimental upgrades to improve the statistical sensitivity of our ^{225}Ra EDM measurements by orders of magnitude and evaluates systematic effects that contribute to current and future levels of experimental sensitivity.

Method: Laser-cooled and trapped ^{225}Ra atoms are held between two high-voltage electrodes in an ultrahigh-vacuum chamber at the center of a magnetically-shielded environment. We observe Larmor precession in a uniform magnetic field using nuclear-spin-dependent laser light scattering and look for a phase shift proportional to the applied electric field, which indicates the existence of an EDM. The main improvement to our measurement technique is an order-of-magnitude increase in spin-precession time, which is enabled by an improved vacuum system and a reduction in trap-induced heating.

Results: We have measured the ^{225}Ra atomic EDM to be less than 1.4×10^{-23} e cm (95% confidence upper limit), which is a factor of 36 improvement over our previous result.

Conclusions: Our evaluation of systematic effects shows that this measurement is completely limited by statistical uncertainty. Combining this measurement technique with planned experimental upgrades, we project a statistical sensitivity at the 1×10^{-28} e cm level and a total systematic uncertainty at the 4×10^{-29} e cm level.

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eEDM: effective descriptions

The effective Lagrangian term

$$\mathcal{L}_{\rm eff} \;=\; -\frac{i}{2} d_e \bar{e} \sigma_{\mu\nu}\gamma_5 e F^{\mu\nu} = i\frac{\delta_e}{\Lambda^2} e m_e \bar{e}\sigma_{\mu\nu}\gamma_5 e F^{\mu\nu}\,.$$

The ACME results:

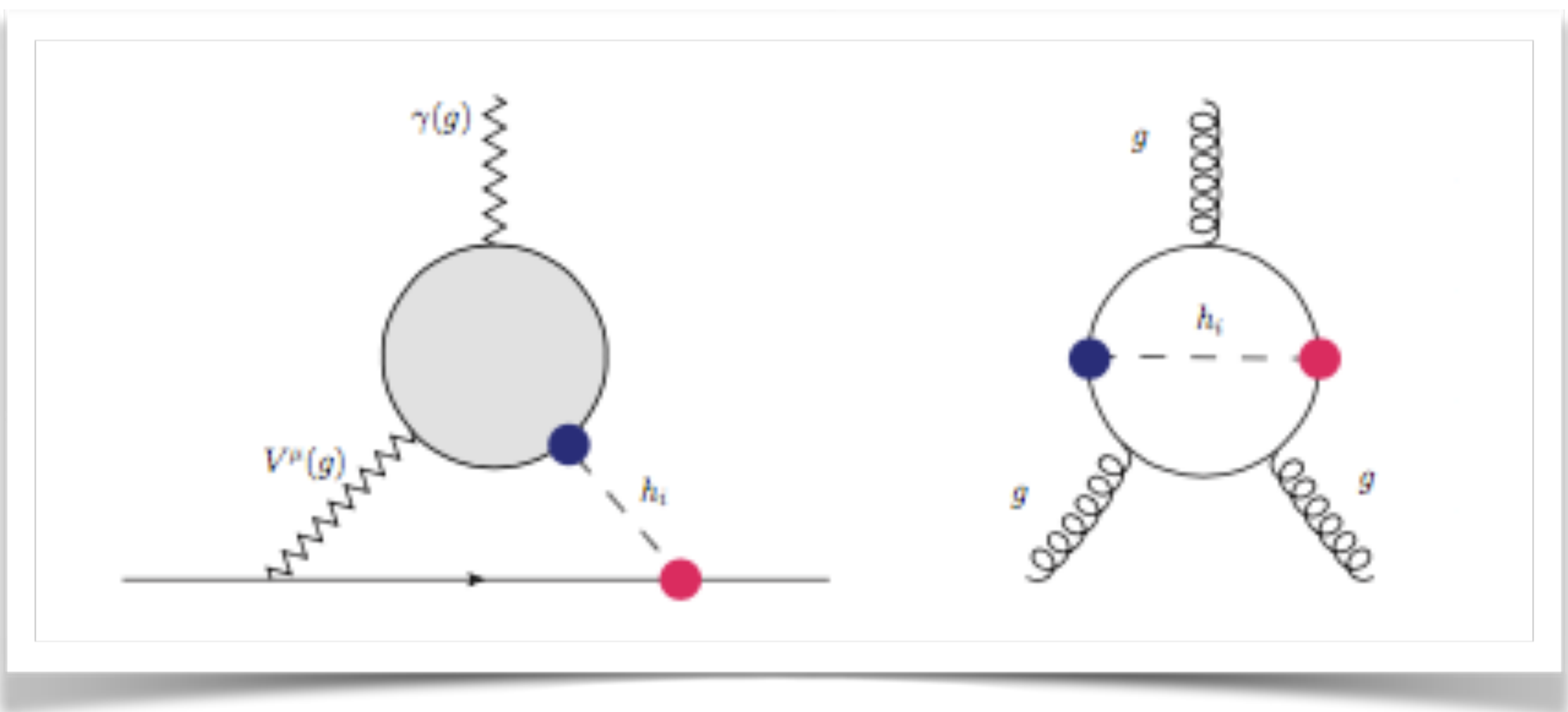
$$\left|\frac{d_e}{e}\right| < 8.7\times 10^{-29}\,\mathrm{cm} \Rightarrow \frac{2m_e}{v^2}|\delta_e| < 8.7\times 10^{-29}\,\mathrm{cm}$$

The total contributions

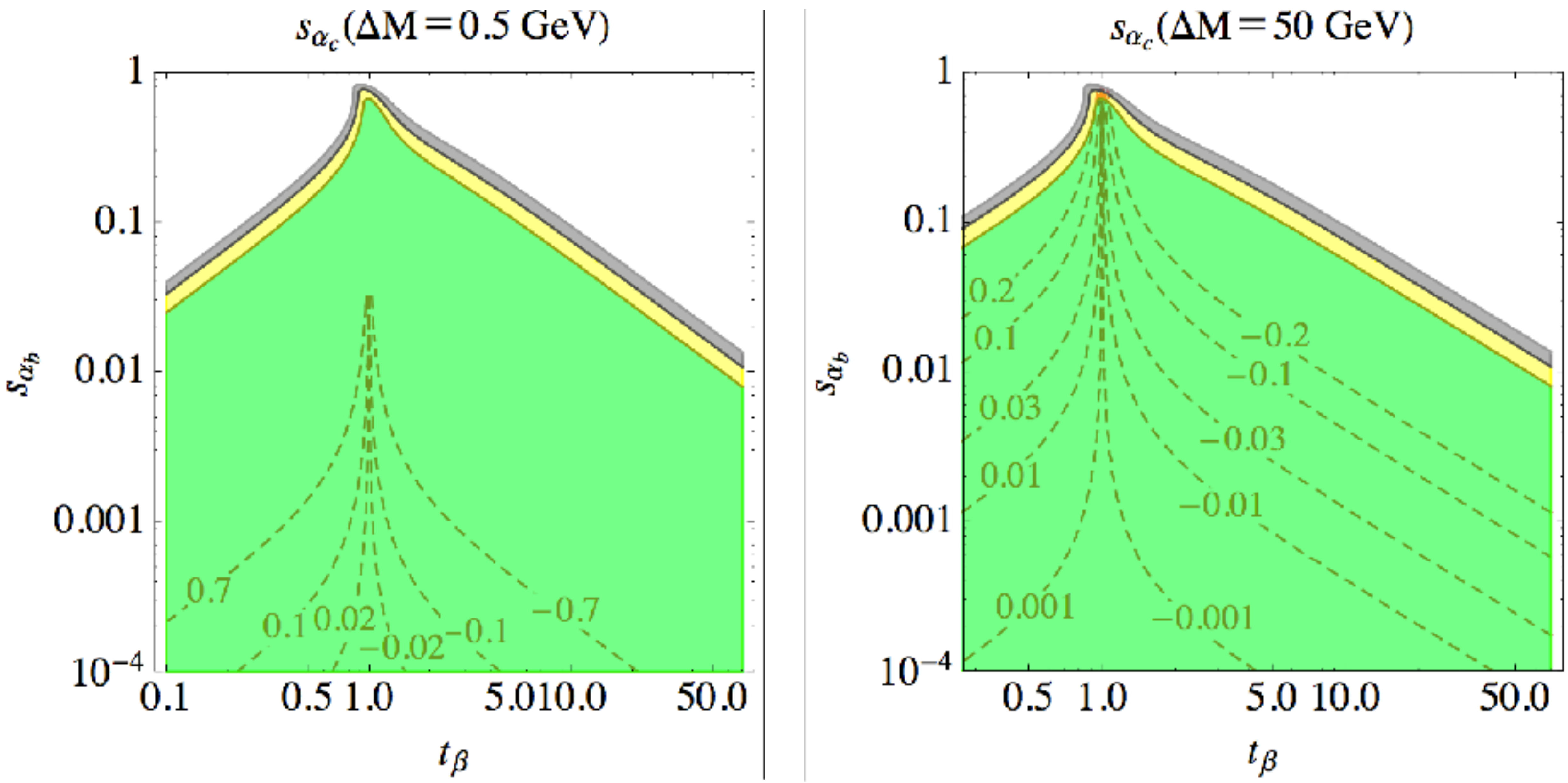
$$\begin{aligned}\delta_e \;=&\; (\delta_e)_t^{h_i\gamma\gamma} + (\delta_e)_t^{h_iZ\gamma} + (\delta_e)_W^{h_i\gamma\gamma} + (\delta_e)_W^{h_iZ\gamma} \\ +&\; (\delta_e)_{H^\pm}^{h_i\gamma\gamma} + (\delta_e)_{H^\pm}^{h_iZ\gamma} + (\delta_e)_H^{H^\pm W^\mp\gamma}\,.\end{aligned}$$

Atom EDM

- Three contributions: fEDM, qEDM, and three-gluon Weinberg operators
- Atoms: RGE to the hadron scale

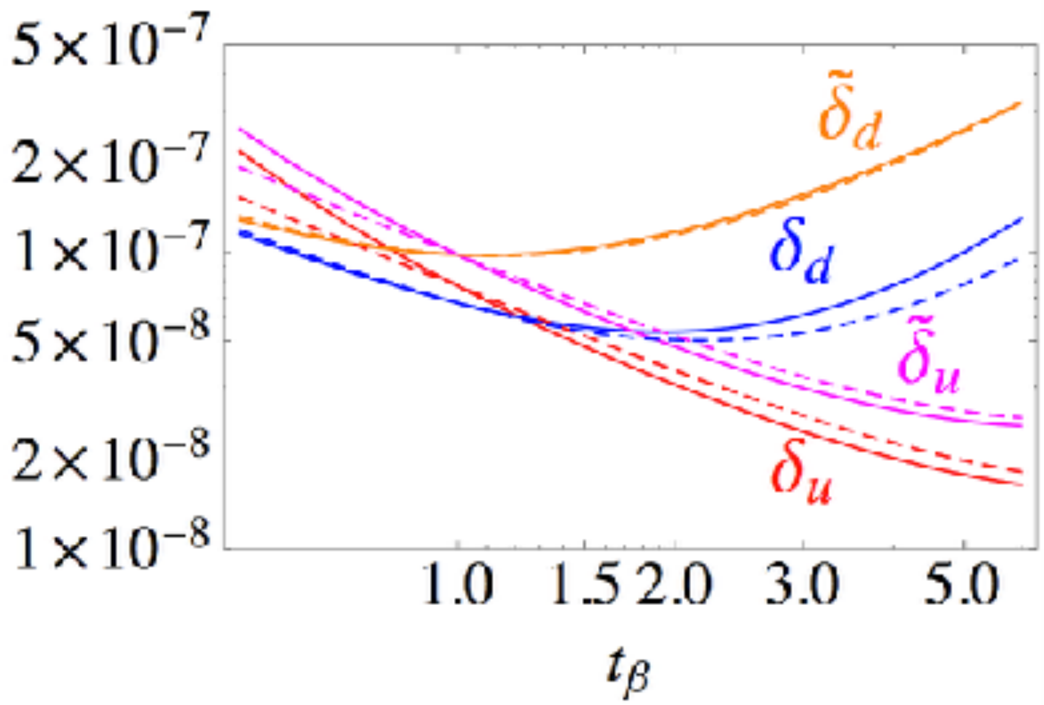


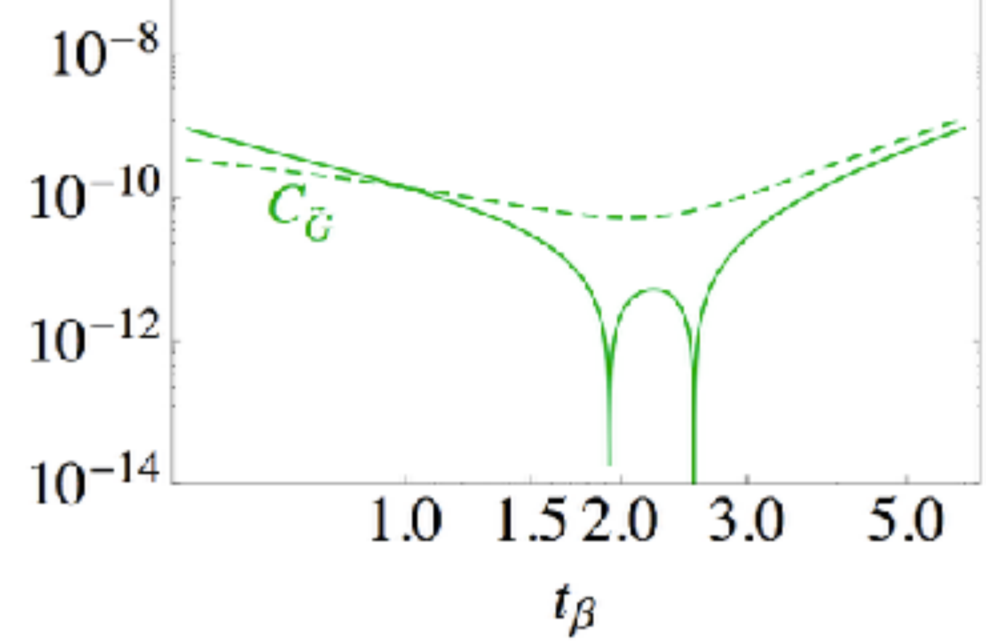
mass splitting Vs. CPV mixings



LG Bian, NC, 1608.07975

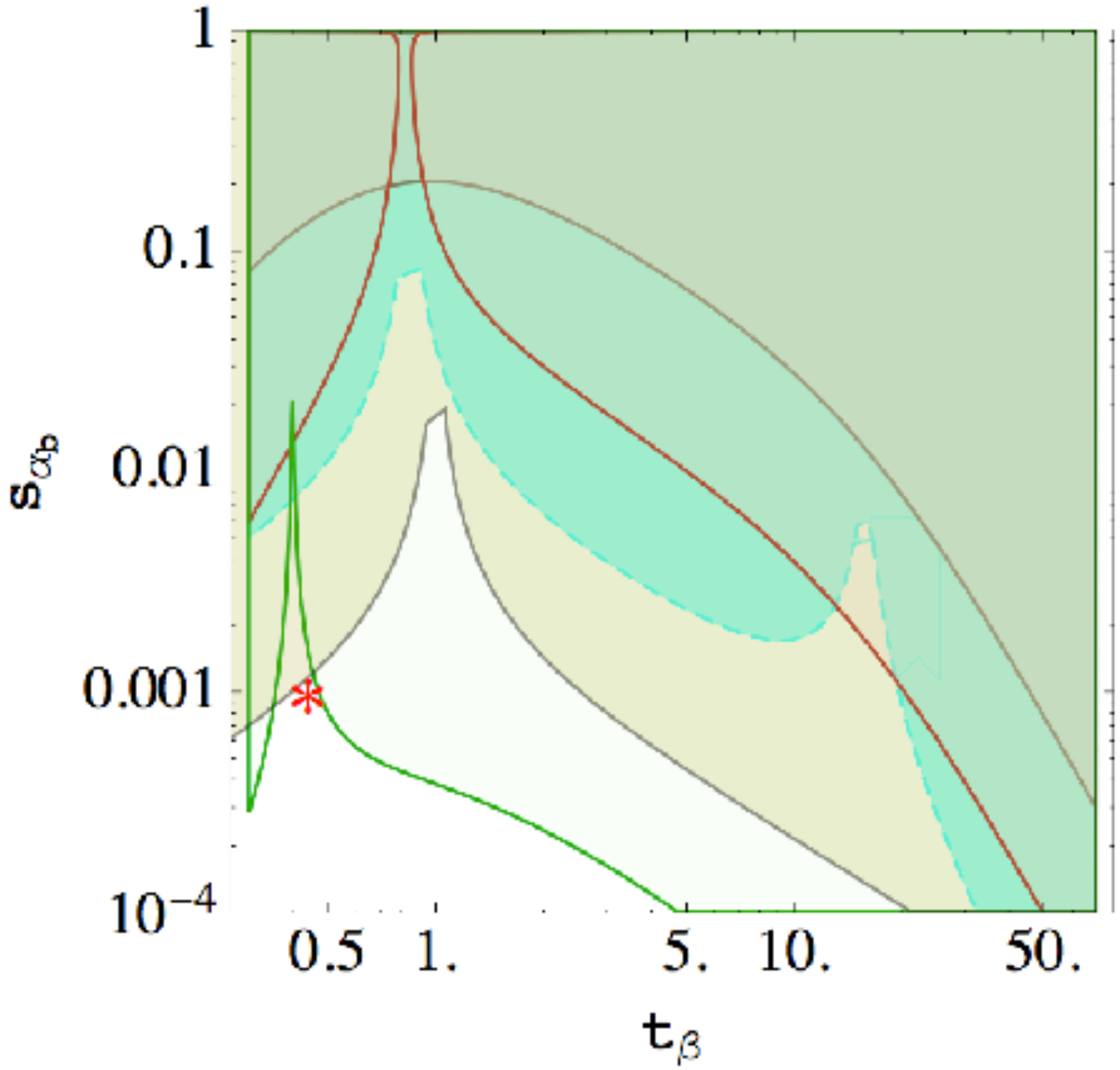
Heavy Higgs mass splittings && cancellations

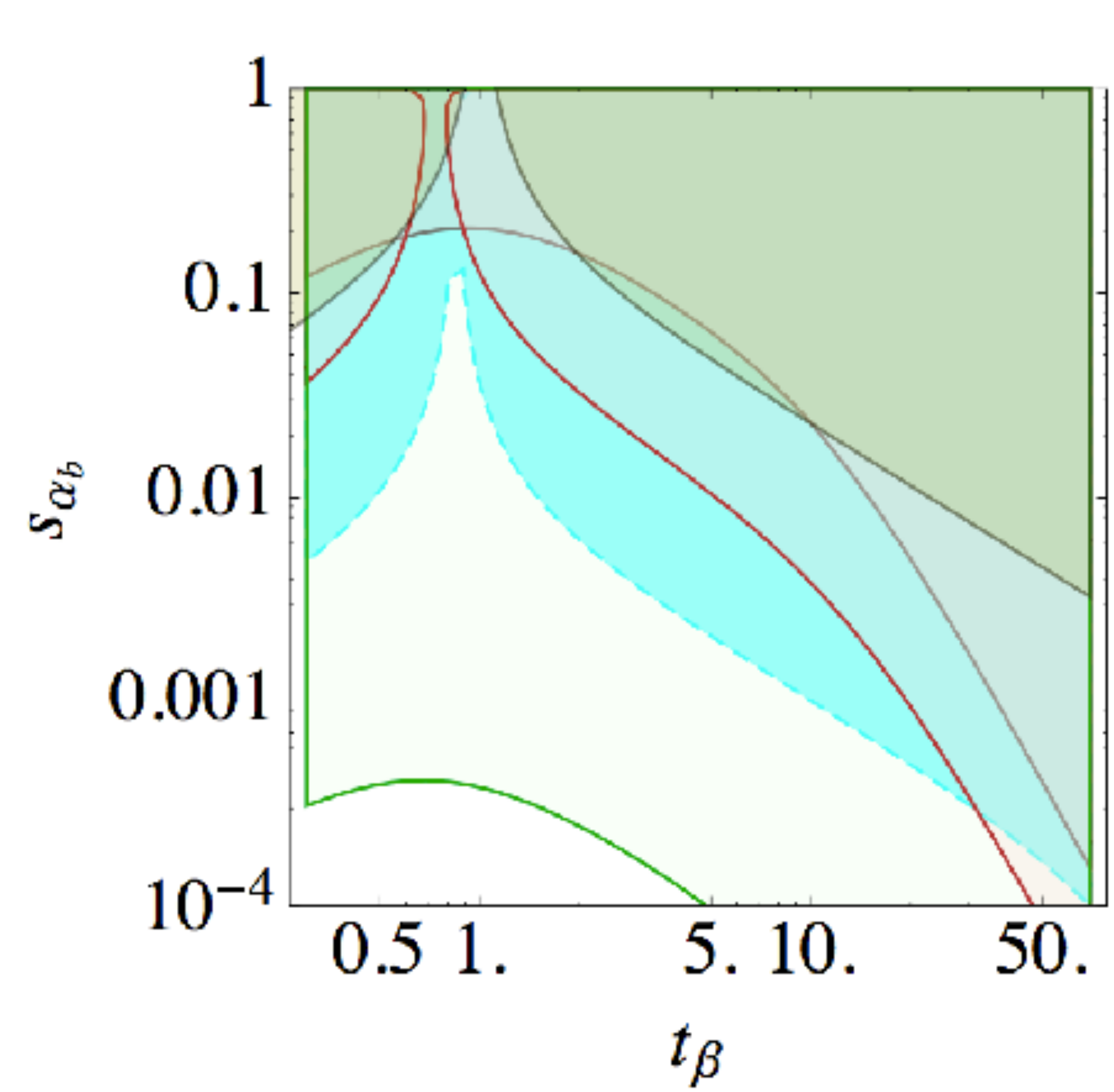




t_β	s_{α_b}	s_{α_c}	ΔM(GeV)
0.45	0.001	0.47	0.5
$\lvert d_e^{\rm tot}\rvert$	$d_e^{h_1}$	$d_e^{h_2}$	$d_e^{h_3}$
1.71×10^{-30}	9.37×10^{-30}	-3.10×10^{-28}	3.03×10^{-28}
$\lvert d_n^{\rm tot}\rvert$	$d_n^{h_1}$	$d_n^{h_2}$	$d_n^{h_3}$
2.12×10^{-28}	-2.75×10^{-28}	-3.43×10^{-26}	3.44×10^{-26}
$\lvert d_{\rm Hg}^{\rm tot}\rvert$	$d_{\rm Hg}^{h_1}$	$d_{\rm Hg}^{h_2}$	$d_{\rm Hg}^{h_3}$
3.76×10^{-31}	-1.63×10^{-31}	-3.00×10^{-28}	3.00×10^{-28}
$\lvert d_{\rm Ra}^{\rm tot}\rvert$	$d_{\rm Ra}^{h_1}$	$d_{\rm Ra}^{h_2}$	$d_{\rm Ra}^{h_3}$
7.95×10^{-29}	3.97×10^{-28}	-1.97×10^{-25}	1.97×10^{-25}

EDM constraints





LG Bian, NC, 1608.07975

Searches for diphoton in the CPV 2HDM

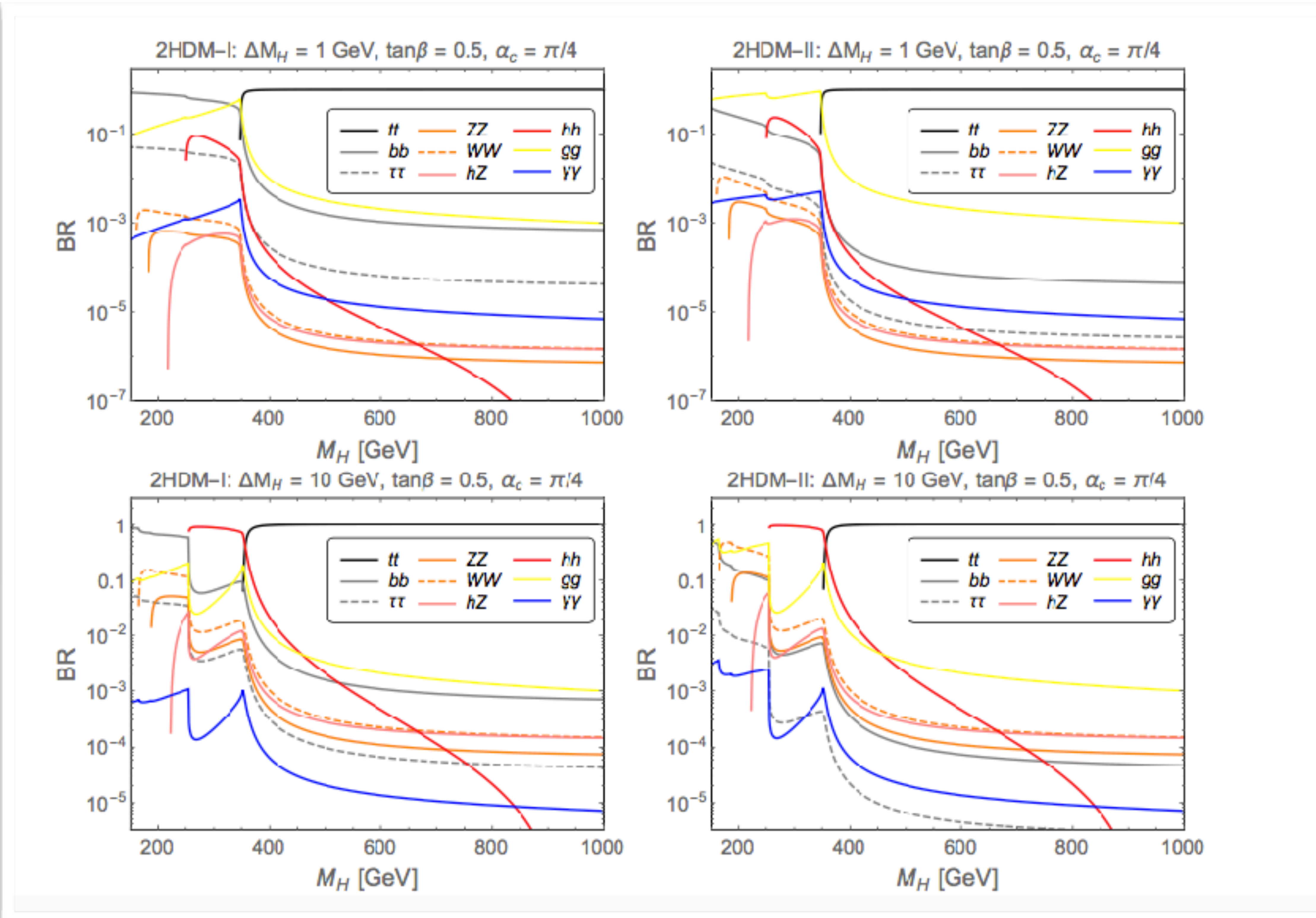
Why diphotons (for heavy resonances)?

- Pro’s: very good energy resolutions and triggering efficiency, compared to jets && leptons; no messy QCD background

- Con’s: decay Br’s can be very small (~10^-5) for heavy scalars (above the tt~ threshold) in a class of models such as 2HDM

- One more thing: **interference terms (resonance-background, and quasi-degenerate resonance)**

Examples of diphoton BR



Calculation of nearly-degenerate resonances

- The 2×2 propagator matrix for $H_{2,3}$:

$$P_{ij}(\hat{s}) = \begin{pmatrix} \hat{s} - M_2^2 + i\widehat{\Pi}_{22}(\hat{s}) & i\widehat{\Pi}_{23}(\hat{s}) \\ i\widehat{\Pi}_{23}(\hat{s}) & \hat{s} - M_3^2 + i\widehat{\Pi}_{33}(\hat{s}) \end{pmatrix}^{-1}$$

$$= \frac{1}{\det P_{ij}^{-1}(\hat{s})} \begin{pmatrix} \hat{s} - M_3^2 + i\widehat{\Pi}_{33}(\hat{s}) & -i\widehat{\Pi}_{23}(\hat{s}) \\ -i\widehat{\Pi}_{23}(\hat{s}) & \hat{s} - M_2^2 + i\widehat{\Pi}_{22}(\hat{s}) \end{pmatrix} .$$

- The self-energy terms for the propagator matrix:

$$\hat{\Pi}_{ij}(\hat{s}) = \hat{\Pi}_{ij}^{ff}(\hat{s}) + \hat{\Pi}_{ij}^{VV}(\hat{s}) + \hat{\Pi}_{ij}^{hZ}(\hat{s}) + \hat{\Pi}_{ij}^{hh}(\hat{s}) ,$$

$$\hat{\Pi}_{ii}^{XX}(M_i^2) \simeq M_i \Gamma_i^{XX}$$

Pilaftsis, hep-ph/9702393

Ellis, Lee, Pilaftsis, hep-ph/0404167

diphoton resonances

- Resonance, background, and interference via ggF process

$$\frac{d\hat{\sigma}^{\text{tot}}}{dz} = \frac{\alpha_e^2\,\alpha_s^2}{64\pi\,\hat{s}} \sum_{\{\lambda\}} \left|\mathcal{M}_{\{\lambda\}}^{\text{bkg}} + \mathcal{M}_{\{\lambda\}}^{\text{res}}\right|^2,$$

$$\frac{d\hat{\sigma}^{\text{res}}}{dz} = \frac{\alpha_e^2\,\alpha_s^2}{64\pi\,\hat{s}} \sum_{\{\lambda'\}} \left|\mathcal{M}_{\{\lambda'\}}^{\text{res}}\right|^2,$$

$$\frac{d\hat{\sigma}^{\text{intf}}}{dz} = \frac{\alpha_e^2\,\alpha_s^2}{64\pi\,\hat{s}} \sum_{\{\lambda'\}} \mathcal{M}_{\{\lambda'\}}^{\text{res}} \mathcal{M}_{\{\lambda'\}}^{\text{bkg}\,*} + H.c.\,,$$

$$\{\lambda'\} = \{\pm\pm\pm\pm\}, \qquad \{\pm\pm\mp\mp\}$$

Dicus, Willenbrock, Phys.Rev.D 37,1801 (1988)

diphoton backgrounds

- The helicity amplitudes for the background of $gg \to \gamma\gamma$:

$$
\begin{aligned}
\mathrm{Re}\mathcal{M}_{\pm\pm\pm\pm} &= \Big(\sum_q Q_q^2\Big)\Big\{1 + \frac{\hat{t}-\hat{u}}{\hat{s}} \log\Big|\frac{\hat{t}}{\hat{u}}\Big| \\
&+ \frac{\hat{t}^2+\hat{u}^2}{2\hat{s}^2}\Big[\log^2\Big|\frac{\hat{t}}{\hat{u}}\Big| + \pi^2\theta(\frac{\hat{t}}{\hat{u}})\Big]\Big\}, \\
\mathrm{Im}\mathcal{M}_{\pm\pm\pm\pm} &= -\Big(\sum_q Q_q^2\Big)\pi\Big[\theta(\hat{t}) - \theta(\hat{u})\Big] \cdot \Big(\frac{\hat{t}-\hat{u}}{\hat{s}} + \frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\log\Big|\frac{\hat{t}}{\hat{u}}\Big|\Big), \\
\mathcal{M}_{\pm\pm\mp\mp} &= -\Big(\sum_q Q_q^2\Big).
\end{aligned}
$$

- And the background of $q\bar{q} \to \gamma\gamma$:

$$
\frac{d\hat{\sigma}}{dz}(q\bar{q} \to \gamma\gamma) = \Big(\sum_q Q_q^4\Big)\frac{\pi\alpha_e^2}{3\hat{s}}\Big(\frac{\hat{t}}{\hat{u}} + \frac{\hat{u}}{\hat{t}}\Big)
$$

diphoton resonances

- The non-vanishing amplitudes from resonances:

$$\mathcal{M}^{\rm res}_{\pm\pm\pm\pm} = \frac{G_F \hat{s}^2}{128\,\pi^2} \sum_{jk=2,3} (c_{g,j} \pm i\tilde{c}_{g,j}) P_{jk} (c_{\gamma,k} \pm i\tilde{c}_{\gamma,k}) \,,$$

$$\mathcal{M}^{\rm res}_{\pm\pm\mp\mp} = \frac{G_F \hat{s}^2}{128\,\pi^2} \sum_{jk=2,3} (c_{g,j} \pm i\tilde{c}_{g,j}) P_{jk} (c_{\gamma,k} \mp i\tilde{c}_{\gamma,k})$$

- The effective $H_i gg$ and $H_i\gamma\gamma$ couplings are:

$$c_{g,i}/\tilde{c}_{g,i} = c_{q,i}/\tilde{c}_{q,i} A^{H/A}_{1/2}(\tau_q) \,,$$

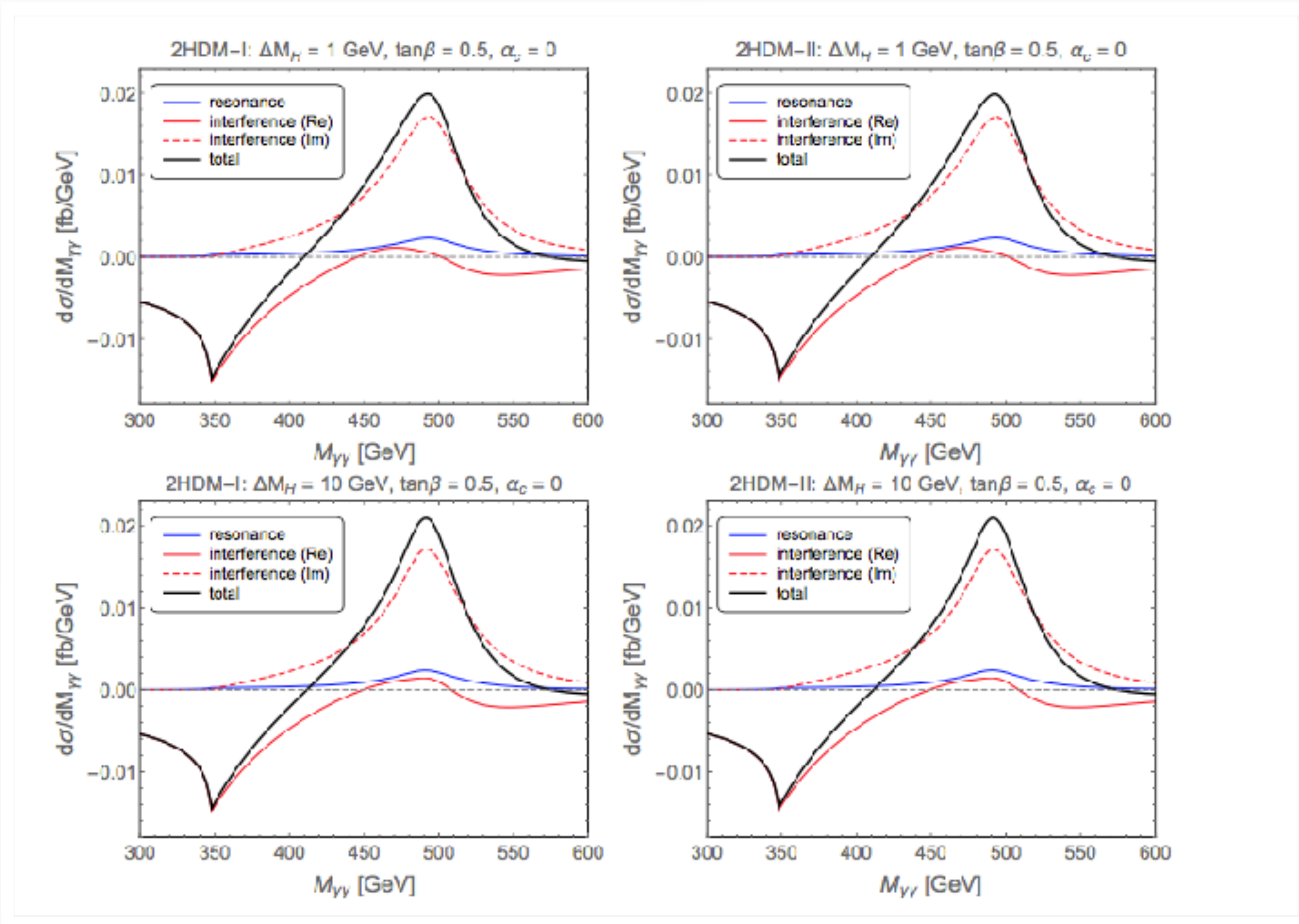
$$c_{\gamma,i}/\tilde{c}_{\gamma,i} = c_{f,i}/\tilde{c}_{f,i} N_{c,f} Q_f^2 A^{H/A}_{1/2}(\tau_f) + \ldots$$

diphoton interference

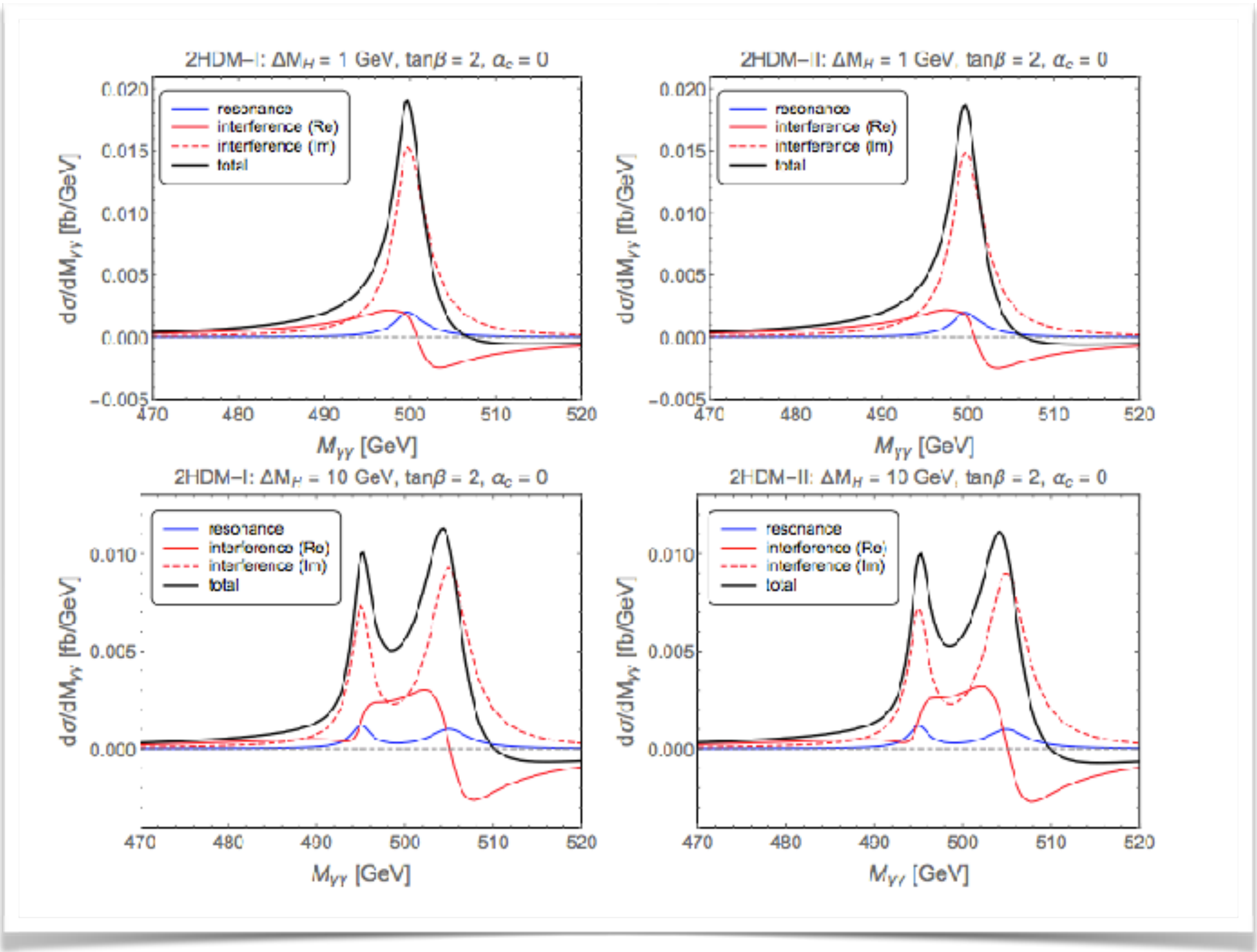
- The imaginary terms of $\mathcal{M}_{\pm\pm\pm\pm}$ and $\mathcal{M}_{\pm\pm\mp\mp}$ are vanishing, up to $\int dz$.
- Further split the interference terms:

$$
\begin{aligned}
\frac{d\hat{\sigma}^{\text{intf},\text{Re}}}{dz} &\propto 4\sum_{ij}\Big[(c_{g,i}c_{\gamma,j})^{\text{Re}}P_{ij}^{\text{Re}}(\mathcal{M}_{\pm\pm\pm\pm}+\mathcal{M}_{\pm\pm\mp\mp})^{\text{Re}} \\
&+ (\tilde{c}_{g,i}\tilde{c}_{\gamma,j})^{\text{Re}}P_{ij}^{\text{Re}}(-\mathcal{M}_{\pm\pm\pm\pm}+\mathcal{M}_{\pm\pm\mp\mp})^{\text{Re}}\Big] \\
\frac{d\hat{\sigma}^{\text{intf},\text{Im}}}{dz} &\propto 4\sum_{ij}\Big[-(c_{g,i}c_{\gamma,j})^{\text{Im}}P_{ij}^{\text{Im}}(\mathcal{M}_{\pm\pm\pm\pm}+\mathcal{M}_{\pm\pm\mp\mp})^{\text{Re}} \\
&+ (\tilde{c}_{g,i}\tilde{c}_{\gamma,j})^{\text{Im}}P_{ij}^{\text{Im}}(-\mathcal{M}_{\pm\pm\pm\pm}+\mathcal{M}_{\pm\pm\mp\mp})^{\text{Re}}\Big]
\end{aligned}
$$

diphoton line shapes: no CPV case



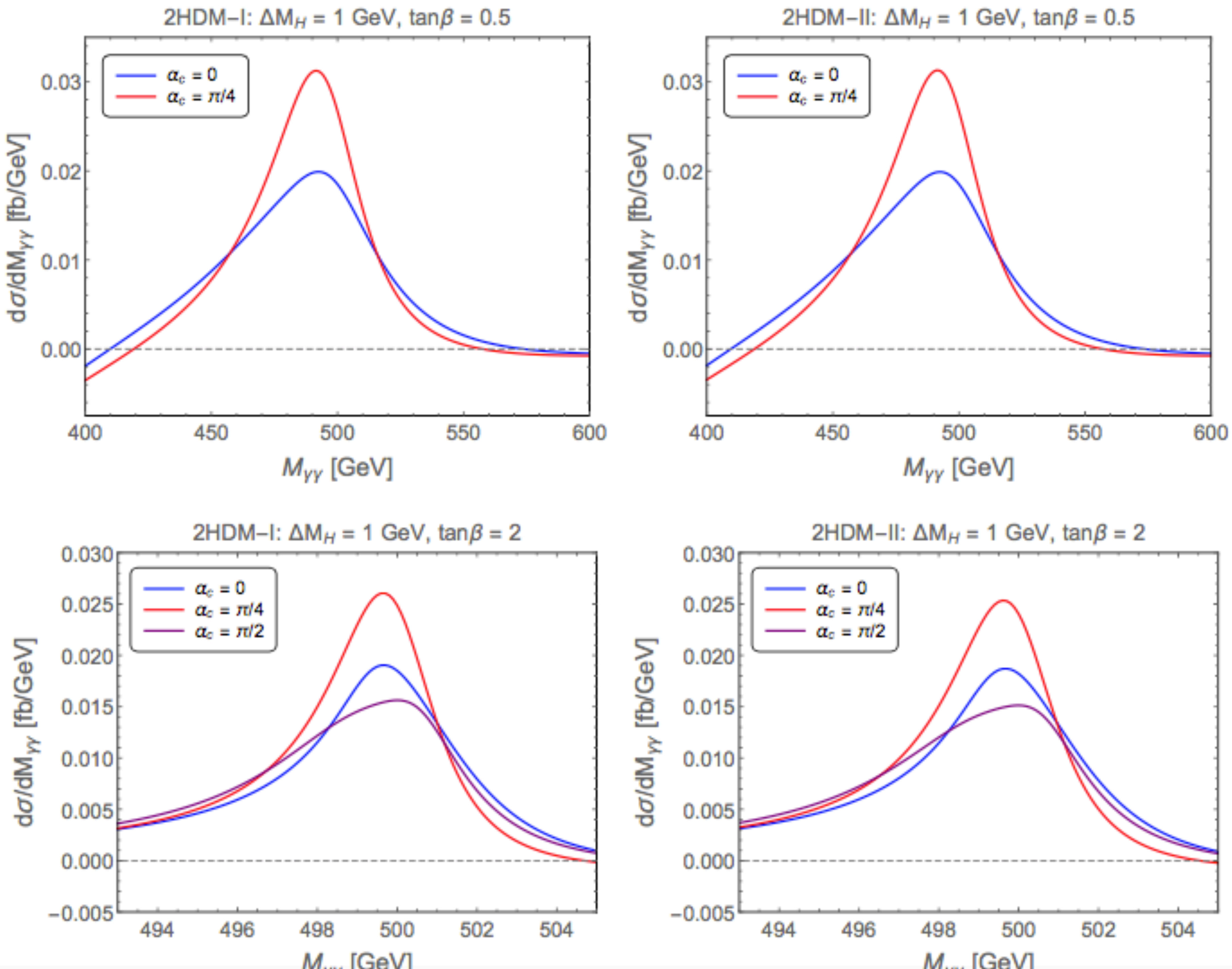
diphoton line shapes: no CPV case



Some remarks for the no-CPV case

- Around the scalar resonance of $M_{\gamma\gamma} \simeq M_H$, the real (imaginary) interference effects are destructive (constructive), respectively.
- The imaginary part of the interference term dominates around $M_{\gamma\gamma} \simeq M_H$, as $(M_{\gamma\gamma} - M_H)^2 \ll M_H \Gamma_H$, and $\Gamma_H \sim \Gamma_H^{t\bar{t}}$.
- The total width $\Gamma_H \propto 1/\tan^2\beta$. Significant separation with $\Delta M_H = 10\ \mathrm{GeV}$ and $\tan\beta = 2$, since $\Gamma_H < \Delta M_H$.
- A dip around $2m_t \simeq 350\ \mathrm{GeV}$ from the real interference, with the depth $P_{ij}^{-1}(2m_t) \sim \Gamma_H \propto \tan^{-2}\beta$.

CPV effects to diphoton



Some remarks for the CPV effects

- The overall CPV effects in the diphoton spectrum are controlled by the size of α_c .
- Enhancements occur at $M_{\gamma\gamma} \simeq M_H$, with a maximal CPV mixing of $\alpha_c = \pi/4$.
- The CPV effects depend also on $\tan\beta$.

The HL-LHC prospects

- To evaluate the signal and background events in a universal bin of 10 GeV:

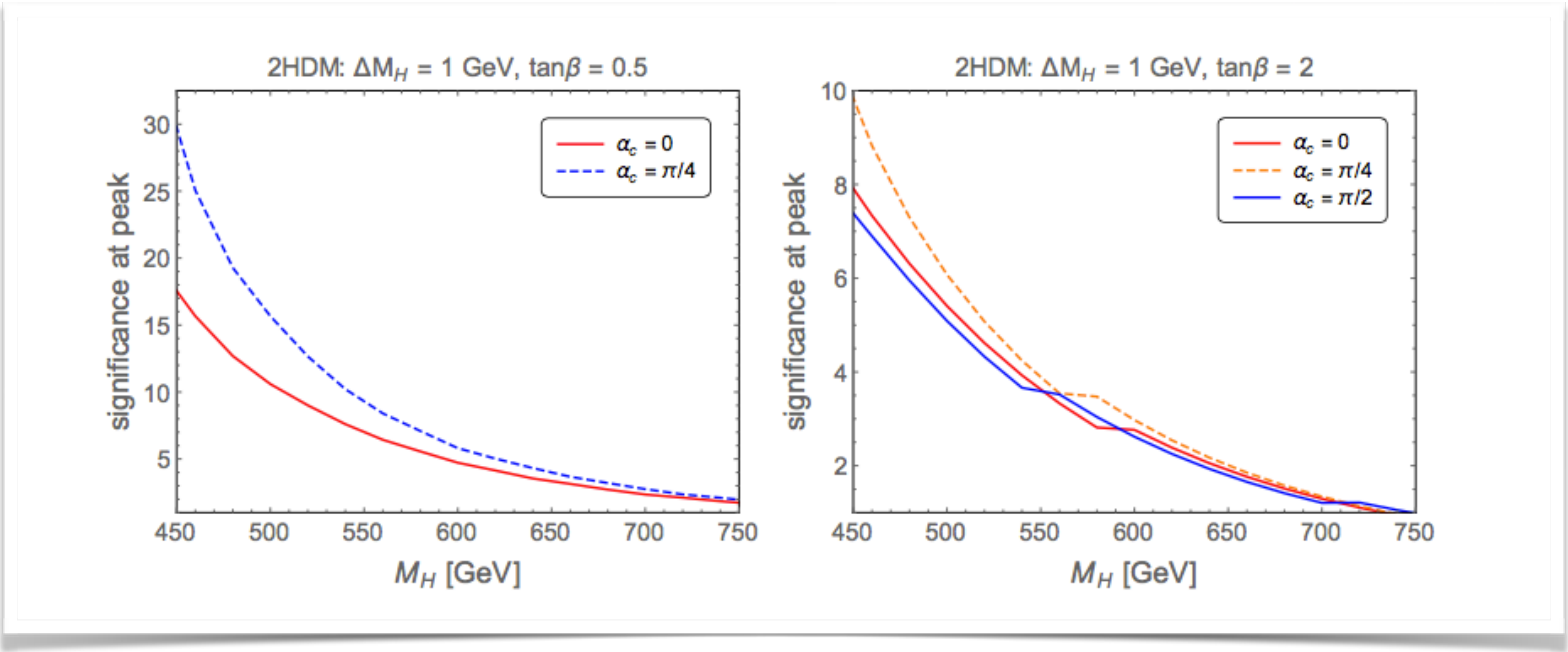
$$\Delta\sigma_{\gamma\gamma}(M_0) \quad = \quad \int_{M_0-5\,\mathrm{GeV}}^{M_0+5\,\mathrm{GeV}} dM_{\gamma\gamma}\, \frac{d\sigma}{dM_{\gamma\gamma}}$$

- Count the number of events per bin and estimate χ^2:

$$\chi^2 \quad = \quad \sum_{\mathrm{bins}} \left(\frac{N_{\gamma\gamma}^{\mathrm{signal}}(M_0)}{\sqrt{N_{\gamma\gamma}^{\mathrm{bkg}}(M_0)}} \right)^2$$

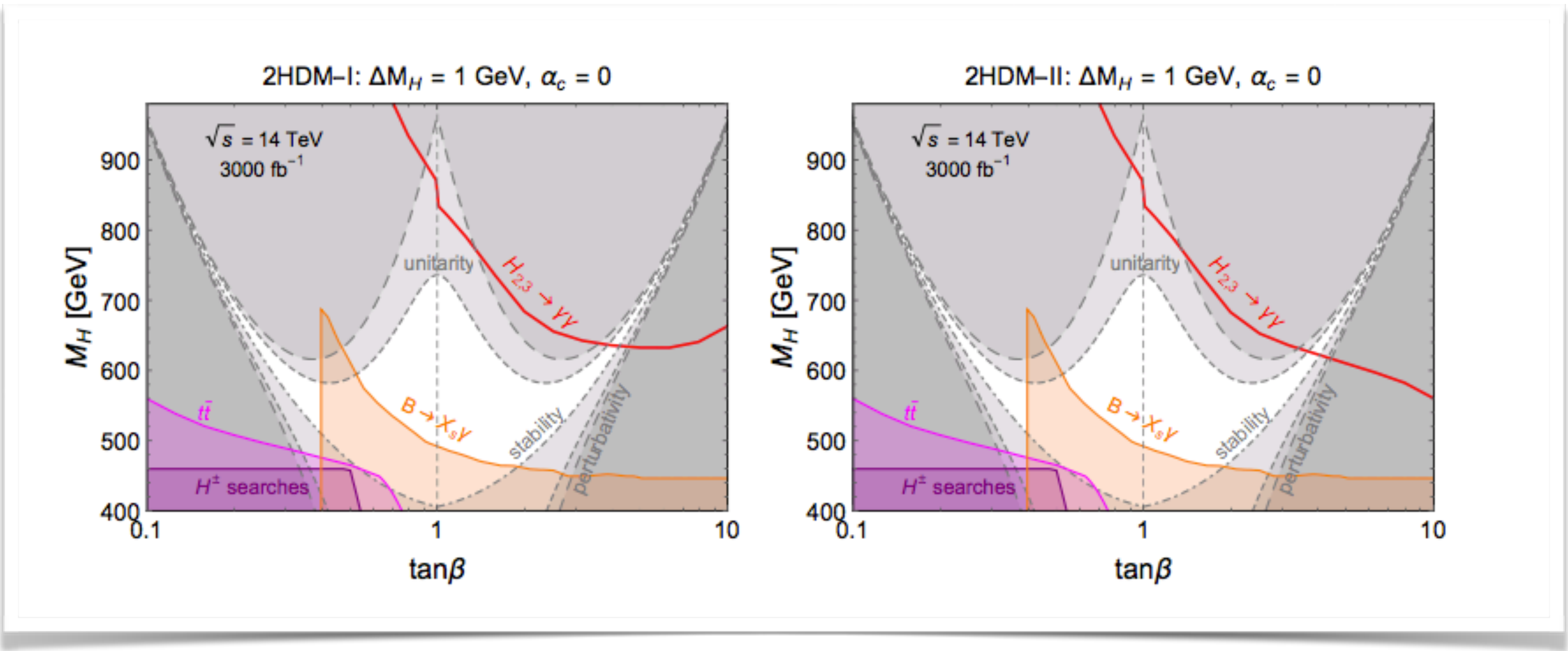
with $(A\epsilon) = 95\,\%$ and photon energy uncertainties $\lesssim 2\,\%$.

The HL-LHC significance



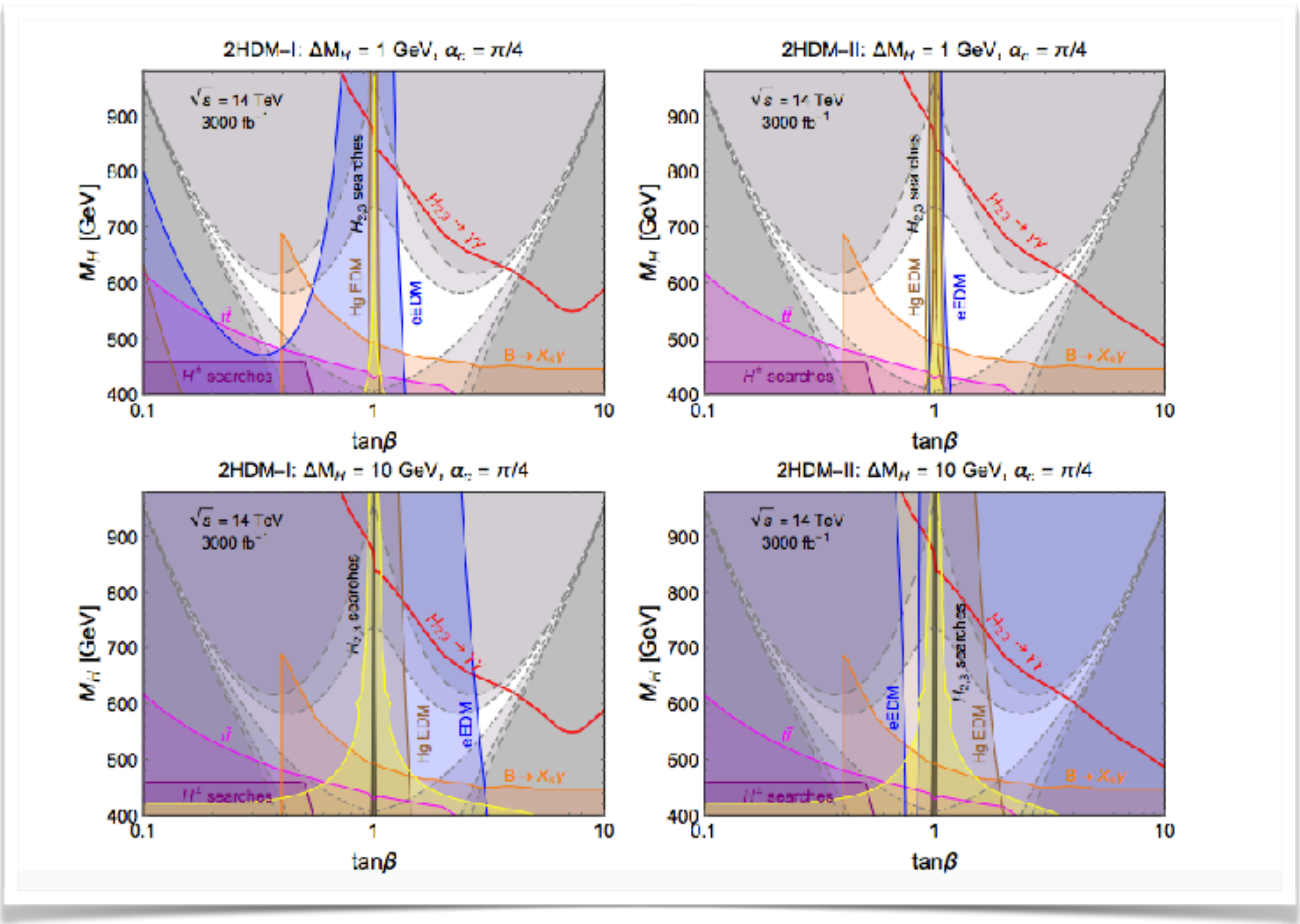
type-I and type-II are almost the same

The HL-LHC prospects: no CPV case

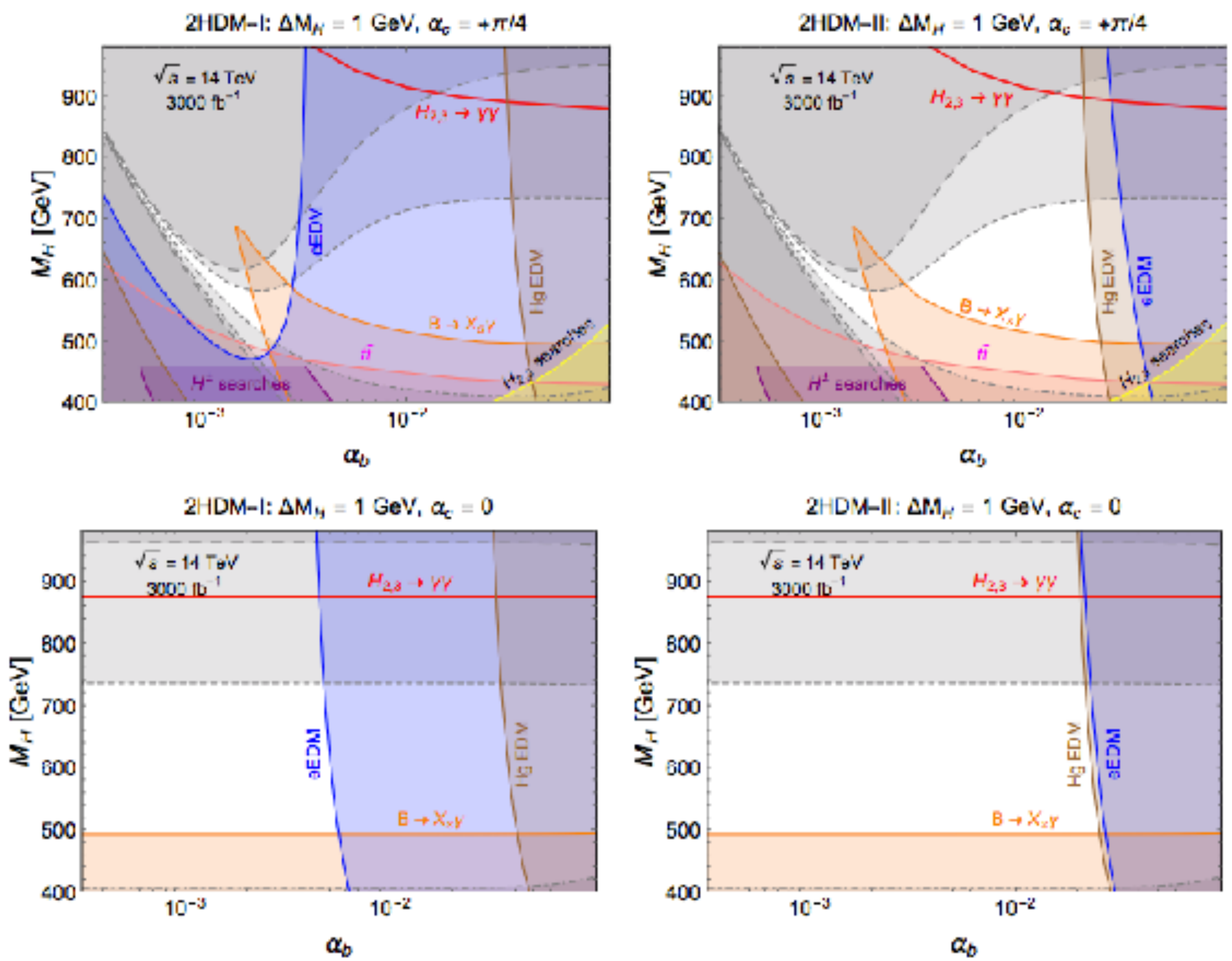


the mass splitting of 10 GeV are almost the same

The HL-LHC prospects: maximal CPV case



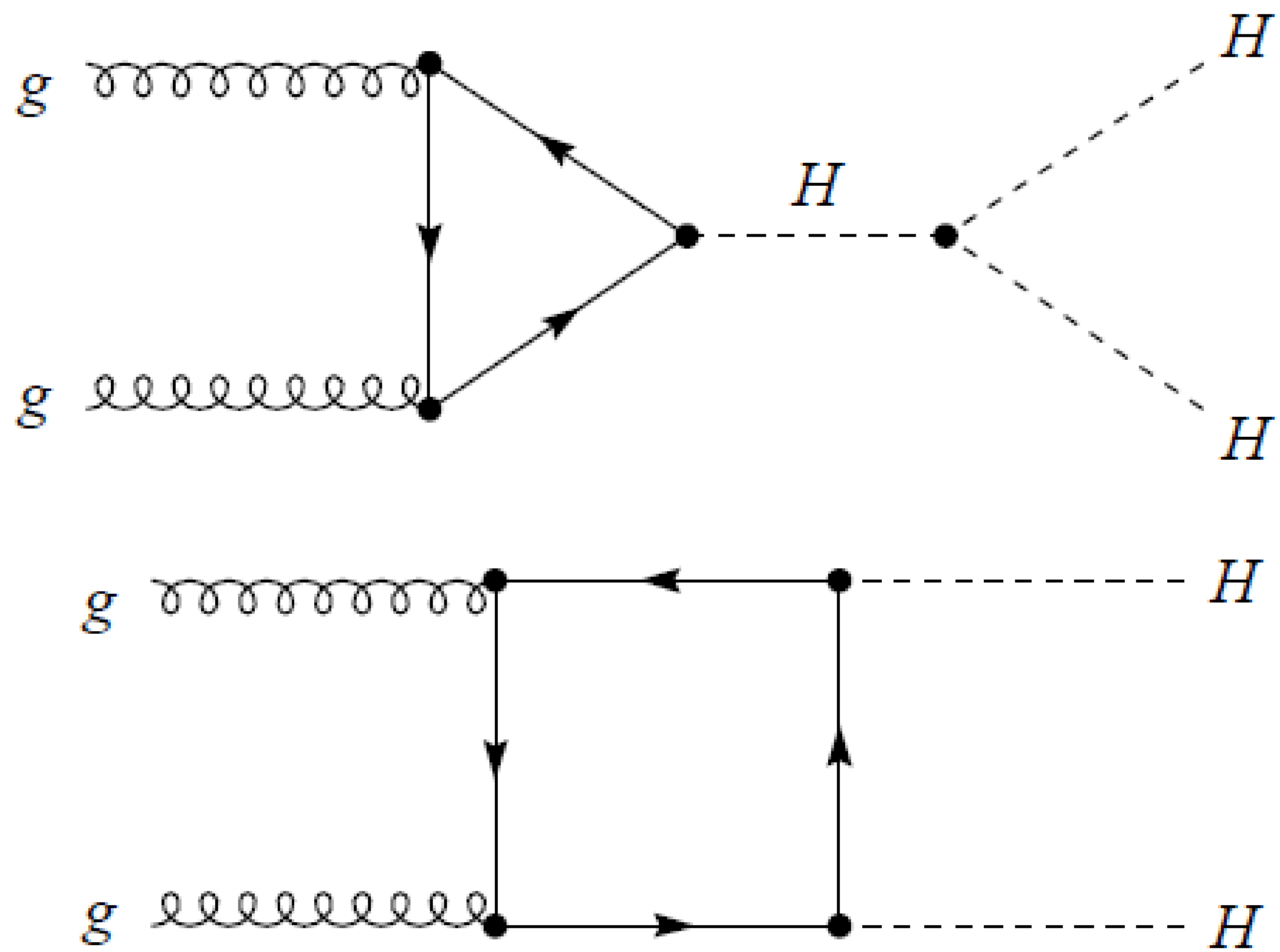
The HL-LHC prospects: maximal CPV case



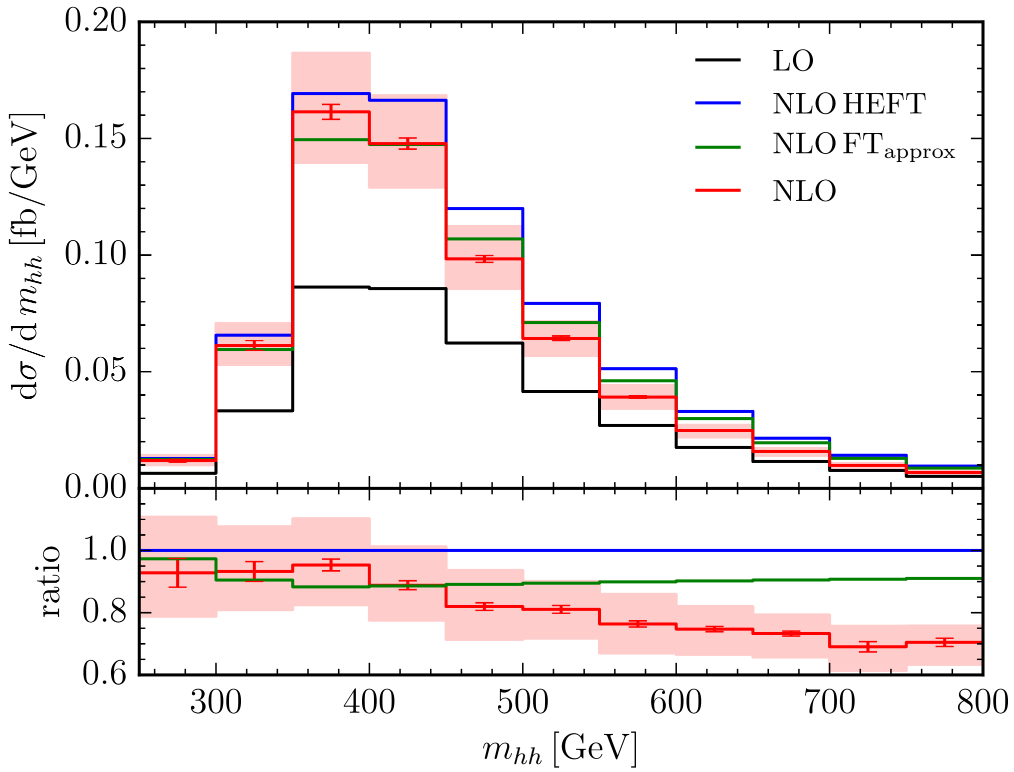
$$\tan\beta = 1\,, \qquad \alpha = -\pi/4$$

The Higgs pair productions in the CPV 2HDM (a special case)

The SM case: @pp



Plenh, Spira, Zerwas,
hep-ph/9603205



$$\sigma^{NLO} = 32.80^{+13\%}_{-12\%}\,\text{fb} \pm 0.4\%\,(\text{stat.}) \pm 0.1\%\,(\text{int.}).$$

Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Schubert, Zirke, 1604.06447

Special case for CPV 2HDM

Mass matrix

$$\mathcal{M}_0^2 \;=\; \begin{pmatrix} \lambda_1 c_\beta^2 + \nu s_\beta^2 & (\lambda_{345} - \nu) s_\beta c_\beta & -\frac{1}{2}\mathrm{Im}(\lambda_5 e^{2i\xi})\, s_\beta \\ (\lambda_{345} - \nu) s_\beta c_\beta & \lambda_2 s_\beta^2 + \nu c_\beta^2 & -\frac{1}{2}\mathrm{Im}(\lambda_5 e^{2i\xi})\, c_\beta \\ -\frac{1}{2}\mathrm{Im}(\lambda_5 e^{2i\xi})\, s_\beta & -\frac{1}{2}\mathrm{Im}(\lambda_5 e^{2i\xi})\, c_\beta & -\mathrm{Re}(\lambda_5 e^{2i\xi}) + \nu \end{pmatrix} v^2\,,$$

with

$$\lambda_{345} = \lambda_3 + \lambda_4 + \mathrm{Re}(\lambda_5 e^{2i\xi})\,, \qquad \nu \equiv \frac{\mathrm{Re}(m_{12}^2 e^{i\xi})}{v^2 s_\beta c_\beta}$$

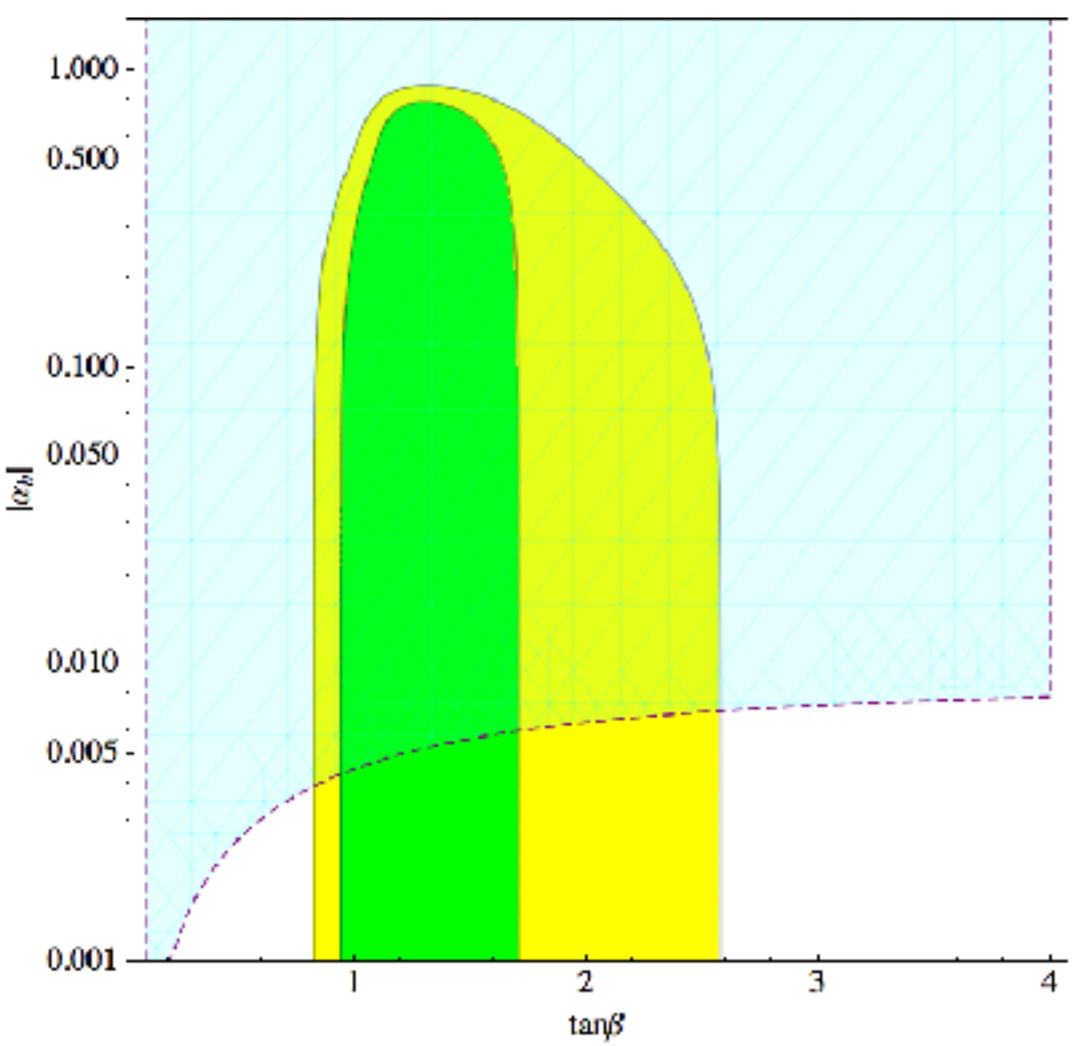
Constraint:

$$(M_1^2 - M_2^2 s_{\alpha_c}^2 - M_3^2 c_{\alpha_c}^2) s_{\alpha_b}(1 + t_\alpha) = (M_2^2 - M_3^2)(t_\alpha t_\beta - 1) s_{\alpha_c} c_{\alpha_c}$$

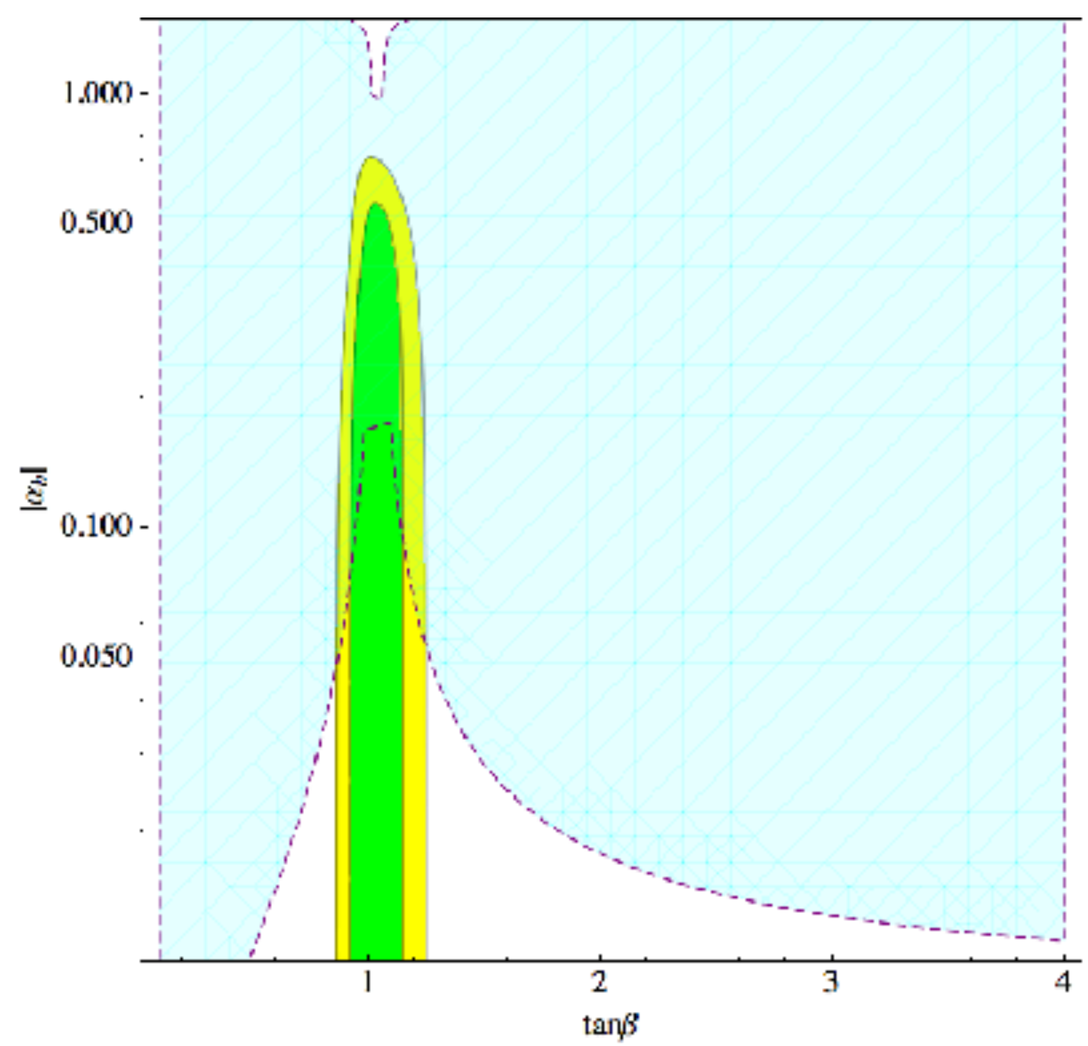
$$\xrightarrow{M_2 = M_3} \quad \alpha_b = 0\,, \quad \text{or} \quad \alpha = -\frac{\pi}{4}$$

SM-like Higgs fitting and eEDM

type-I



type-II



Including constraints

Combining the current LHC searches of WW, ZZ, $H \to hh \to b\bar{b} + \gamma\gamma$, $A \to hZ \to (b\bar{b} + \ell^+\ell^-/\tau^+\tau^- + \ell^+\ell^-)$.

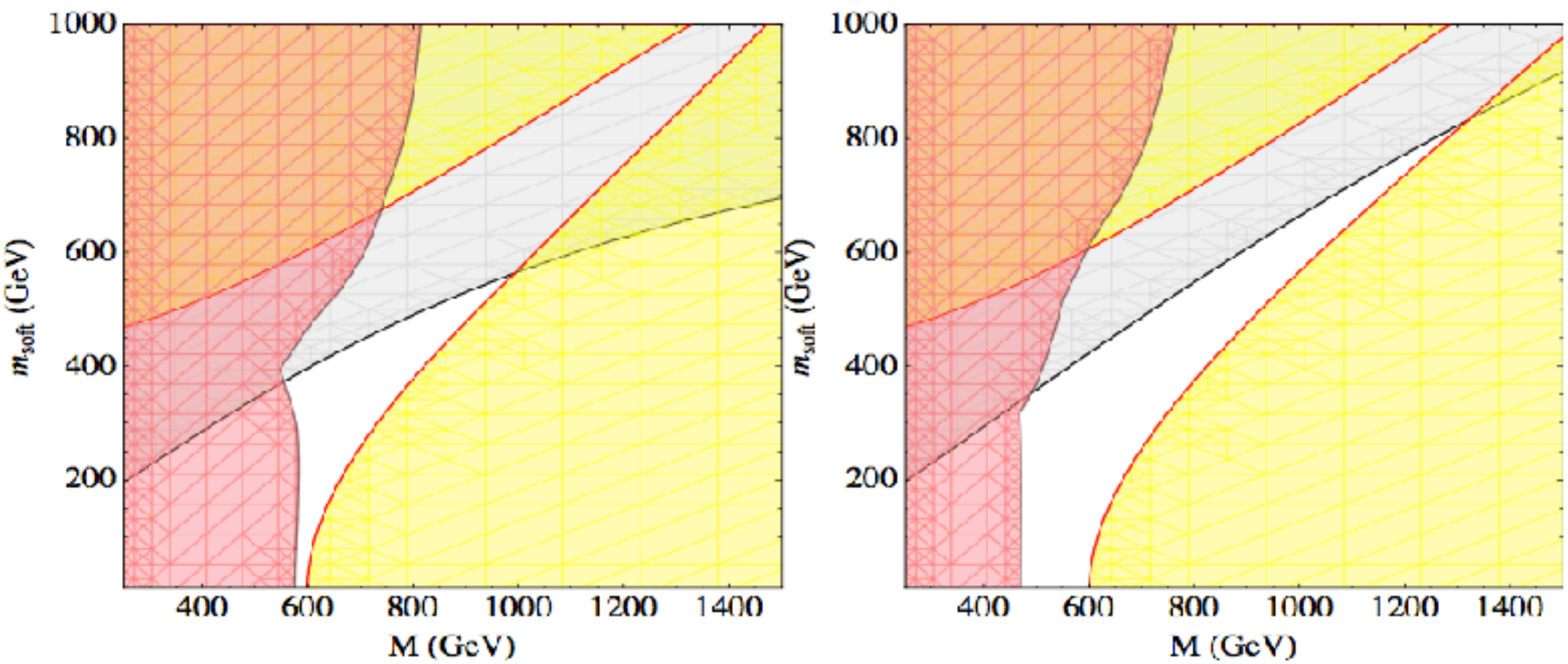
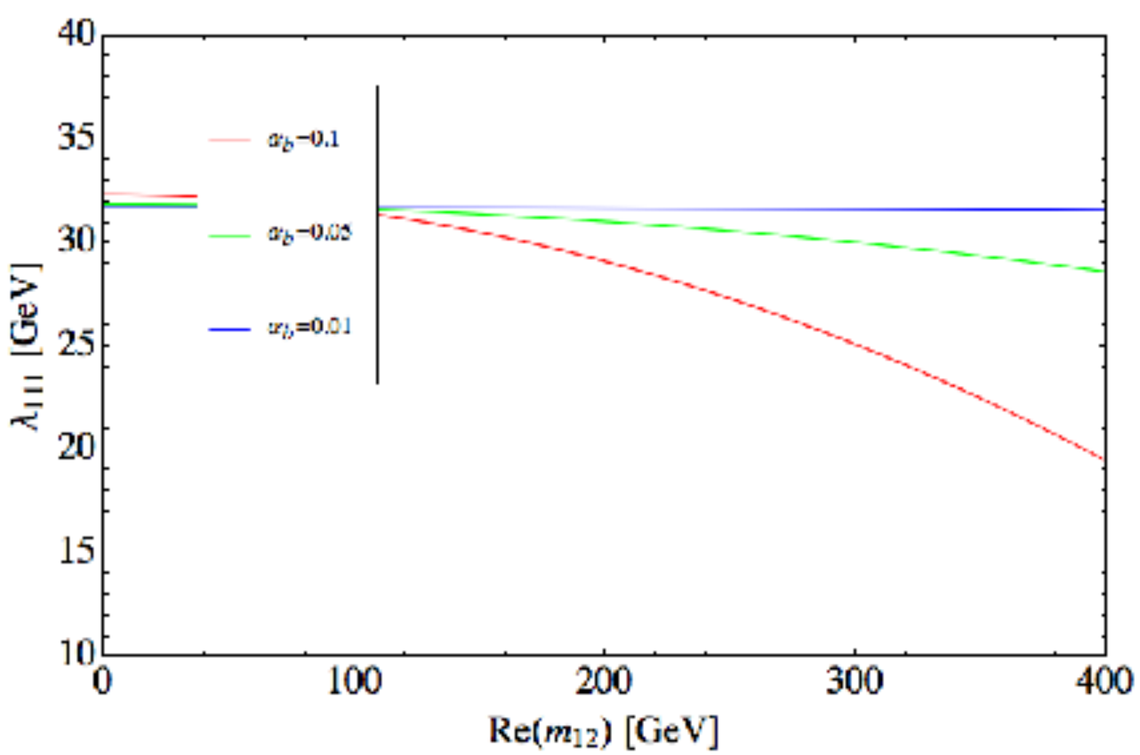


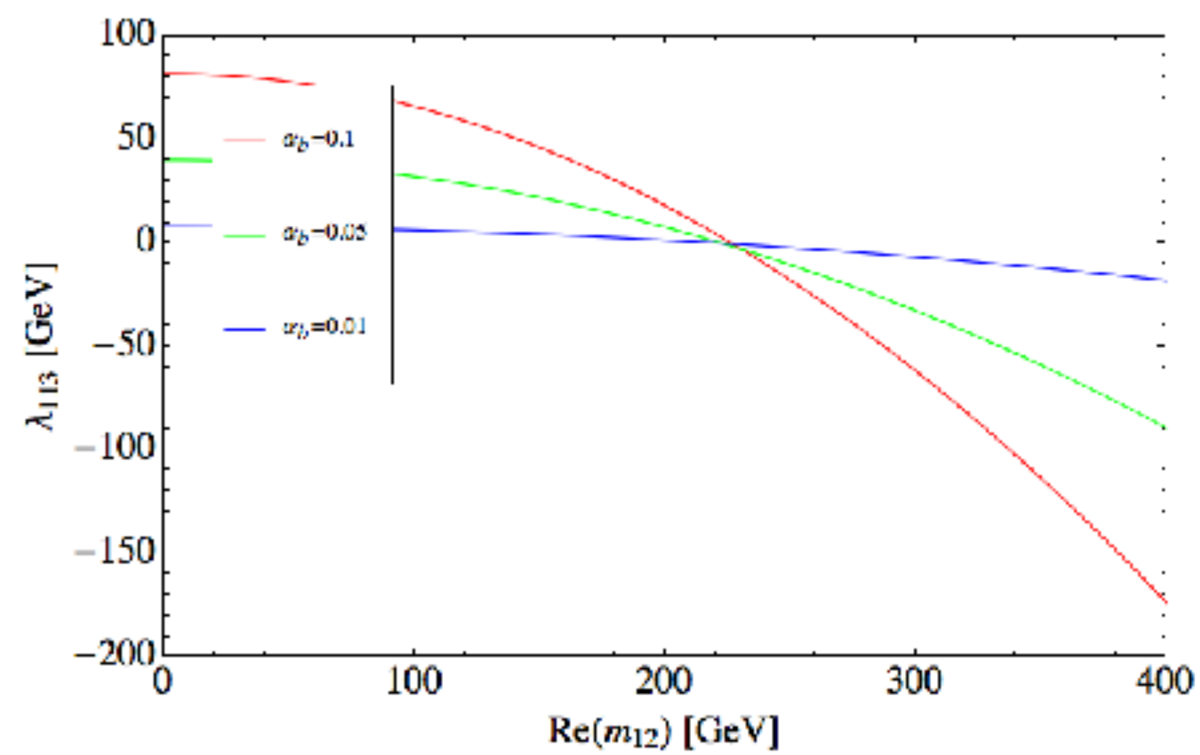
Figure : Left: $|\alpha_b| = 0.1$, right: $|\alpha_b| = 0.05$.

Higgs self-couplings

- With $\alpha = -\pi/4$, $t_\beta = 1.0$, and $\alpha_c = 0$:

$$\lambda_{111} \simeq \frac{M_1^2}{2v} + \frac{3M_1^2 - 8m_{\rm soft}^2}{4v} \cdot \alpha_b^2 + \mathcal{O}(\alpha_b^4)\,,$$
$$\lambda_{113} \simeq \frac{2M_1^2 + M_3^2 - 8m_{\rm soft}^2}{2v} \cdot \alpha_b + \mathcal{O}(\alpha_b^3)\,.$$

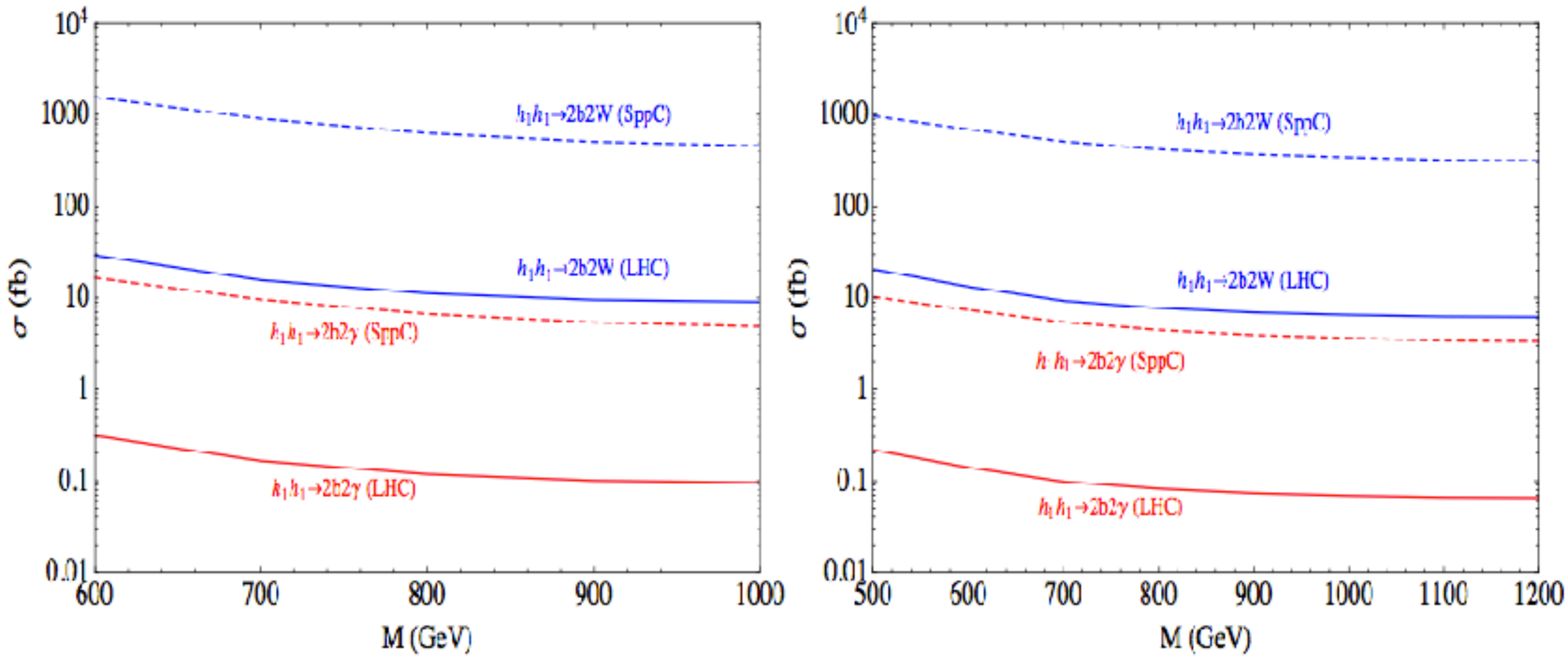




Benchmark models

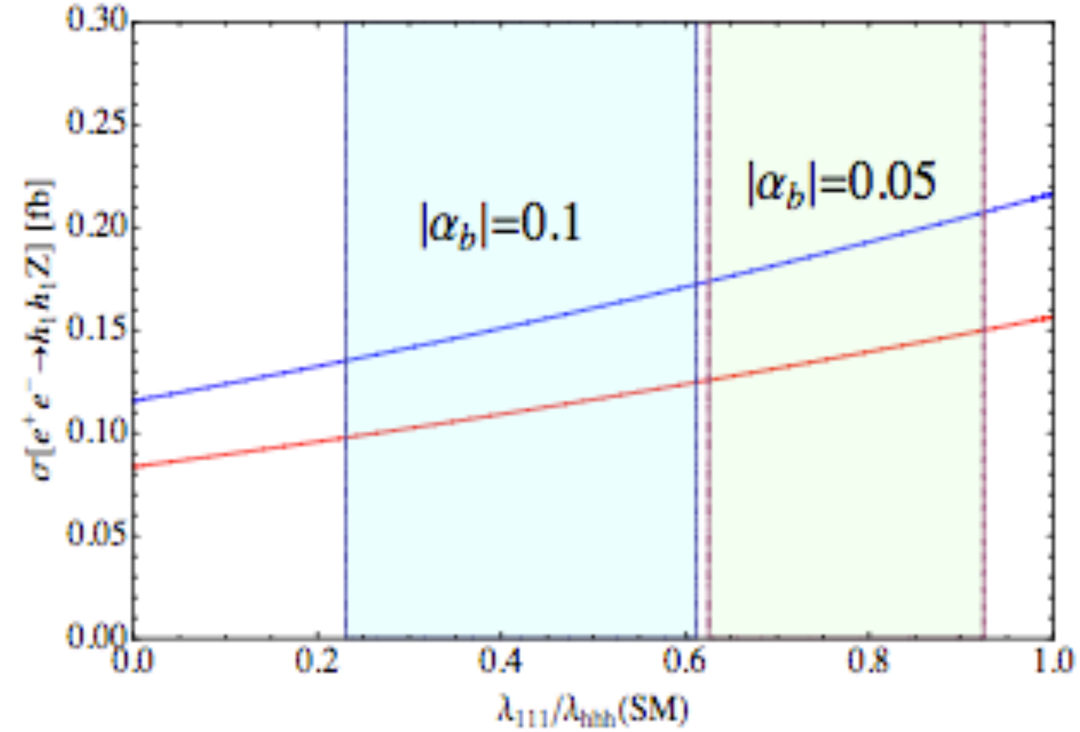
	$\lvert\alpha_b\rvert = 0.1$			$\lvert\alpha_b\rvert = 0.05$		
$M_2 = M_3$(GeV)	$m_{\rm soft}$(GeV)	λ_{111}(GeV)	λ_{113}(GeV)	$m_{\rm soft}$(GeV)	λ_{111}(GeV)	λ_{113}(GeV)
500	...	...	...	350	29.37	-70.33
600	400	19.45	-173.75	420	28.28	-102.66
700	440	16.80	-200.04	480	27.19	-133.01
800	480	13.89	-227.22	540	25.96	-167.14
900	520	10.74	-255.31	600	24.57	-205.05
1000	560	7.33	-284.30	660	23.05	-246.72
1100	...	...	...	710	21.66	-280.60
1200	...	...	...	770	19.87	-328.86

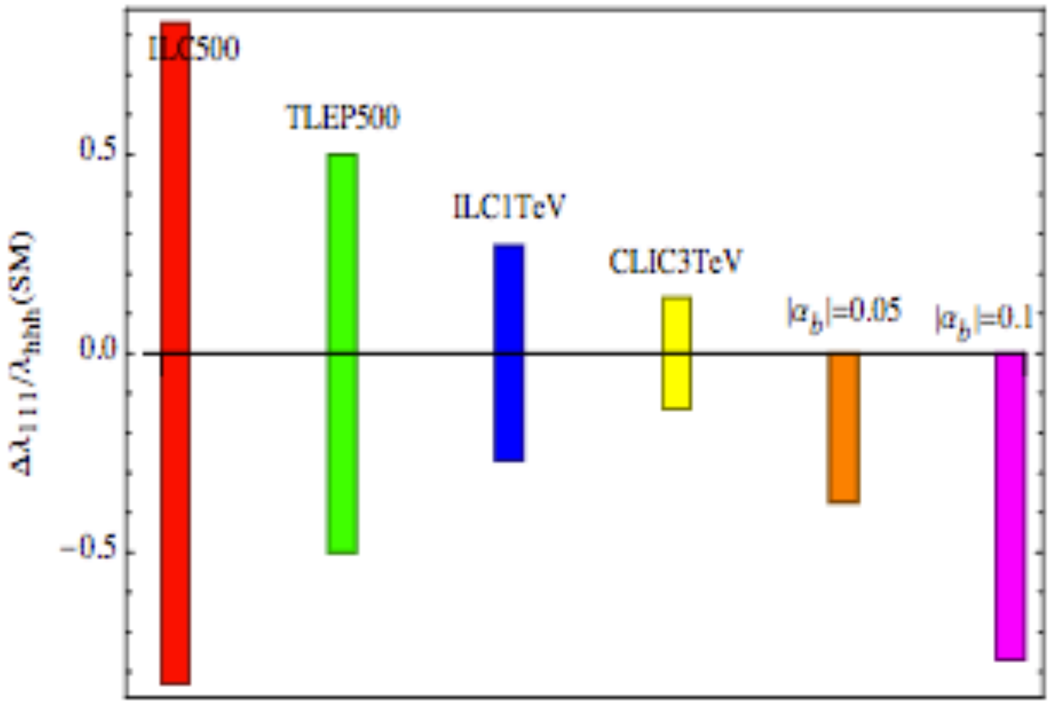
Cross sections at LHC/SppC



Cross sections of $\sigma[pp \to h_1 h_1 \to b\bar{b}\gamma\gamma]$ and $\sigma[pp \to h_1 h_1 \to b\bar{b}W^+W^-]$ for the benchmark models.

Higgs pairs at e+e-





Summary/Outlook

- The upgrade of the precise EDM experiments can further test the BSM CPV.

- Keep looking for BSM heavy Higgs boson @LHC: e.g., diphoton, can be complementary to the EDM bounds for small mass splitting regions.

- To look for tt~ resonance searches @LHC/SppC (**Carena && Liu**, 1608.07282), and tau+tau-, compare their sensitivities.

- Generalization to the other modes for the direct CPV measurements.

Thank you!

Searches for CPV in the SM-like Higgs

- h > tau tau: 1308.1094, 1501.03156, 1510.03850 (LHC), and 1703.04855 (CEPC)
- h > ZZ: 1502.03045
- tth: 1507.07926, 1605.03806 (LHC), and 1506.06453 (indirect at CEPC)
- Many more …

- This talk: focus on the CPV version of 2HDM (T. D. Lee, `73)

- EDM constraints: electrons, and atoms; CPV in SM-like or BSM Higgs boson(s); mass splitting and cancellations between heavy Higgs bosons

- The heavy resonance searches via diphotons @ HL-LHC: resonance-background, quasi-degenerate heavy Higgs bosons

Atom EDM

- Anatomy of contributions

$$
\begin{aligned}
d_f^E &\sim \sum_i (-c_f^i \tilde{c}_\gamma^i + \tilde{c}_f^i c_\gamma^i) \log \frac{\Lambda^2}{M_i^2} \\
d_q^C &\sim \sum_i (-c_q^i \tilde{c}_g^i + \tilde{c}_q^i c_g^i) \log \frac{\Lambda^2}{M_i^2} \\
C_{\tilde{G}} &\sim \sum_i c_q^i \tilde{c}_q^i \log \frac{\Lambda^2}{M_i^2}
\end{aligned}
$$

The 2HDM input parameters

- The total free input parameters in the *physical basis*:

$$M_1 = 125\ \mathrm{GeV}\,, M_{2\,,3}\,, m_{\mathrm{soft}}\,, \qquad (\alpha\,, \alpha_b\,, \alpha_c\,, \beta)$$

- Alignment limit of $\alpha = \beta - \pi/2$, favored by the current Higgs data.
- Small mass splitting of $\Delta M_H \equiv M_3 - M_2 = (1\,, 10)\ \mathrm{GeV}$, and fixed $m_{\mathrm{soft}} = 300\ \mathrm{GeV}$.
- The CPV mixing relation of

$$\sin\alpha_b = \frac{1}{2}\,\frac{(M_2^2 - M_3^2)\sin 2\alpha_c \tan 2\beta}{M_1^2 - M_2^2\sin^2\alpha_c - M_3^2\cos^2\alpha_c}$$

Non-real solutions of α_b are unphysical.

Constraints: unitarity, stability

$$
\begin{aligned}
a_0^0 &= \frac{1}{16\pi}\mathrm{diag}(X_{4\times4}\,, Y_{4\times4}\,, Z_{3\times3}\,, Z_{3\times3})\,,\\
a_0^+ &= \frac{1}{16\pi}\mathrm{diag}(Y_{4\times4}\,, Z_{3\times3}\,, \lambda_3-\lambda_4)\,,\\
a_0^{++} &= \frac{1}{16\pi}Z_{3\times3}\,,
\end{aligned}
$$

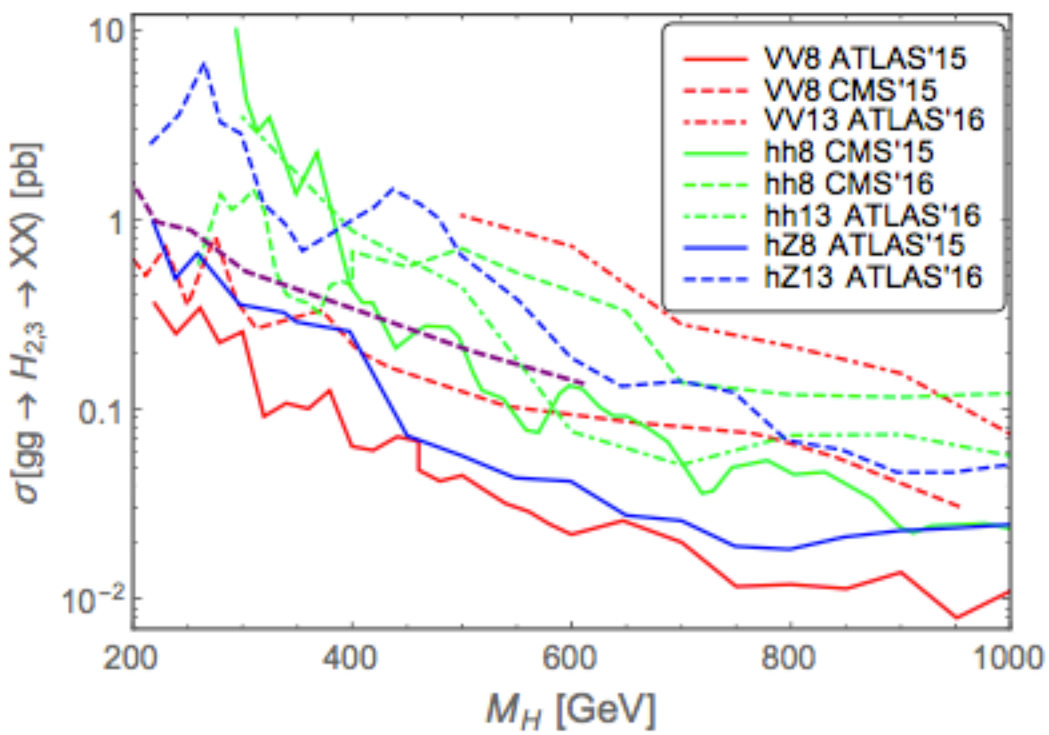
$$
X_{4\times4} = \begin{pmatrix} 3\lambda_1 & 2\lambda_3+\lambda_4 & 0 & 0 \\ 2\lambda_3+\lambda_4 & 3\lambda_2 & 0 & 0 \\ 0 & 0 & \lambda_3+2\lambda_4-3\mathrm{Re}\lambda_5 & 3\mathrm{Im}\lambda_5 \\ 0 & 0 & 3\mathrm{Im}\lambda_5 & \lambda_3+2\lambda_4-3\mathrm{Re}\lambda_5 \end{pmatrix},
$$

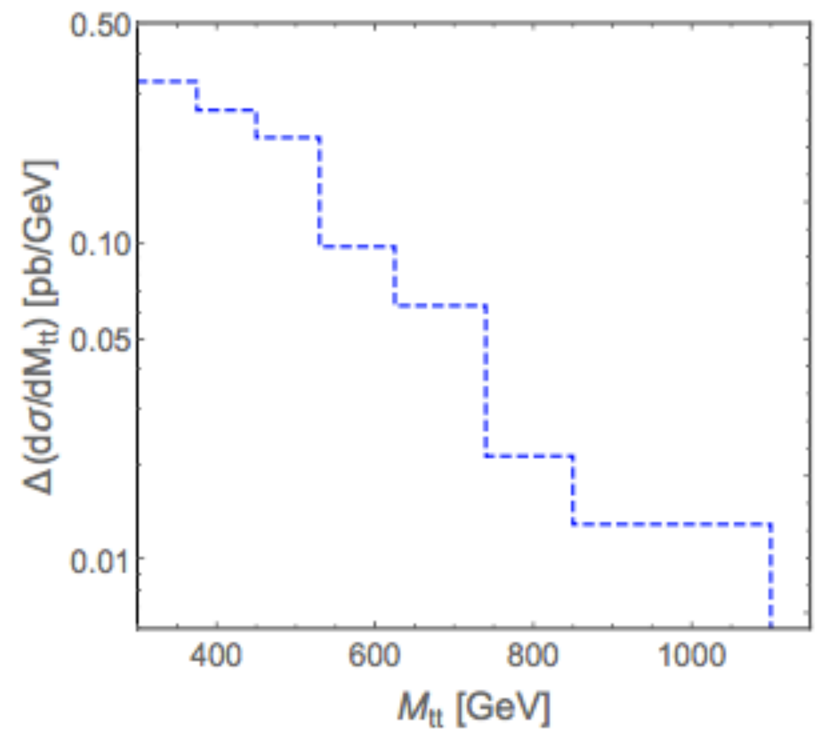
$$
Y_{4\times4} = \begin{pmatrix} \lambda_1 & \lambda_4 & 0 & 0 \\ \lambda_4 & \lambda_2 & 0 & 0 \\ 0 & 0 & \lambda_3+\mathrm{Re}\lambda_5 & \mathrm{Im}\lambda_5 \\ 0 & 0 & \mathrm{Im}\lambda_5 & \lambda_3-\mathrm{Re}\lambda_5 \end{pmatrix},
$$

$$
Z_{3\times3} = \begin{pmatrix} \lambda_1 & \mathrm{Re}\lambda_5+i\mathrm{Im}\lambda_5 & 0 \\ \mathrm{Re}\lambda_5-i\mathrm{Im}\lambda_5 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3+\lambda_4 \end{pmatrix}.
$$

$$
\lambda_{1,2} > 0\,, \qquad \lambda_3 > -\sqrt{\lambda_1\lambda_2}\,, \qquad \lambda_3+\lambda_4-|\lambda_5| > -\sqrt{\lambda_1\lambda_2}\,.
$$

LHC direct searches





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Combined constraints