Introduction to the extended Higgs sector: 2HDM

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Purpose

- To introduce some theoretical backgrounds and phenomenological implications on the extended Higgs sector beyond the SM, such as the 2HDM.

- To focus on the 2HDM, which is (i) mostly studied due to many well-motivated theoretical framework and pheno implications, (ii) more accessible at the ongoing/upcoming collider searches.

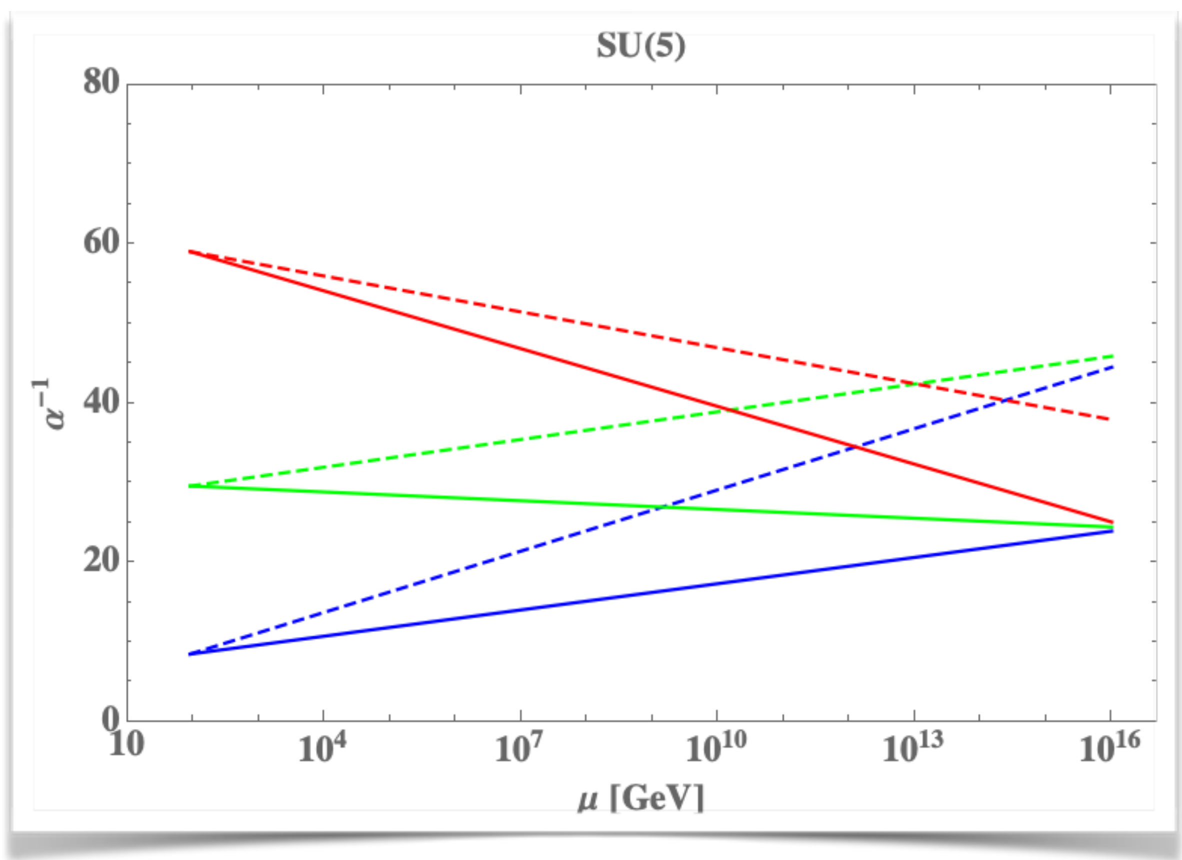
- Mainly focus on the LHC direct searches: the current constraints from the 125 GeV Higgs measurement, and the direct searches for heavy Higgs bosons at the leading order.

- Other extensions such as singlets/triplets are possible, since they can form gauge-invariant operators with the SM Higgs doublet, e.g. $|\Phi|^2|\mathbb{S}|^2$, $|\Phi|^2\mathrm{Tr}(\Sigma^2)$.

Background

- The minimal SM Higgs sector: one complex Higgs doublet Φ, LHC measurement of $M_h = 125$ GeV [2012].

- Let us consider some BIG picture beyond the SM, the unification of three fundamental interactions? In the framework of GUT(+SUSY), three gauge couplings unify at $\sim 10^{16}$ GeV.



Background

- In the GUTs, the EW sector usually contains two Higgs doublets.

- For the Georgi-Glashow $\mathrm{SU}(5)$, one usually considers the SUSY extension. The GUT-scale Higgs sector must contain super-fields of $\mathbf{5_H}$ and $\bar{\mathbf{5}}_\mathbf{H}$ to be anomaly-free. The scalar components give the $(H_u)_{Y=+1}$ and $(H_d)_{Y=-1}$ fields at the EW scale.

- $(H_u)_{Y=+1}$ couples to the up-quarks, and $(H_d)_{Y=-1}$ couples to the down-quarks/charged leptons, this is known as the Type-II 2HDM.

- Beyond the $\mathrm{SU}(5)$: $\mathrm{SU}(6)$, two Higgs doublets come from $\bar{\mathbf{6}}_\mathbf{H}$ and $\mathbf{15_H}$, also a Type-II 2HDM (2106.00223)

Background

- The first 2HDM proposal was by T. D. Lee (non-SUSY), to seek for the CP-violating sources beyond the CKM matrix in the quark sector.

- One can always allow a relative phase between two Higgs doublets, i.e., $\langle \Phi_1 \rangle \sim \frac{v_1}{\sqrt{2}}, \langle \Phi_2 \rangle \sim e^{i\xi} \frac{v_2}{\sqrt{2}}$

- The whole lecture will not cover the CPV 2HDM. Its mixing pattern is more complicated, and also involves EDM experiment.

- All current studies of the 2HDM from the pheno motives are viewed as the effective approach at the EW scale, $\sim \mathcal{O}(100)\,\mathrm{GeV}$.

References

- The book: *The Higgs Hunter's Guide*, [Gunion, Haber, Kane, Dawson]
- MSSM Higgs and collider pheno: hep-ph/0503172 (SM Higgs), 0503173 [Djouadi]
- A quite ``recent" review: 1106.0034
- Collider pheno of the general 2HDM: 1305.2424, 1504.04630
- CPV aspects of the 2HDM, and the EDM probes: 1403.4257 [Inoue, Ramsey-Musolf, Zhang]

The 2HDM
(CP-conserving)

The general 2HDM

- I use the SM fermion irreps of (with $Q_e = T^3 + Y/2$)
  $Q_L = (\mathbf{3}\,, \mathbf{2}\,, +\frac{1}{3})$ $u_R = (\mathbf{3}\,, \mathbf{1}\,, +\frac{4}{3})$ $d_R = (\mathbf{3}\,, \mathbf{1}\,, -\frac{2}{3})$
  $L_L = (\mathbf{1}\,, \mathbf{2}\,, -1)$ $\ell_R = (\mathbf{1}\,, \mathbf{1}\,, -2)$

- The most general 2HDM contains two complex Higgs doublets of Φ_1 and Φ_2, both under the irrep of $\mathbf{2}_{+1}$ of the $\mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y$.

- Φ_1 and Φ_2 have 8 real scalar d.o.fs. By Nambu-Goldstone theorem: # Physical Higgs bosons = # real scalar d.o.fs - # NGB = 4*2 - 3 = 5, we expect 5 Higgs bosons rather than one.

- The renormalizable Lagrangian: $\mathscr{L} = \mathscr{L}_{\mathrm{kin}} + \mathscr{L}_{Yukawa} - V(\Phi_1\,, \Phi_2)$

- The kinematic term is simple: $\mathscr{L}_{\mathrm{kin}} = |D_\mu \Phi_1|^2 + |D_\mu \Phi_2|^2$
  where $D_\mu \Phi_j = (\partial_\mu - igW_\mu^i \sigma^i/2 - ig' B_\mu/2)\Phi_j$

The 2HDM potential

- The most general 2HDM potential determined by gauge-invariance and renormalizability :
  $V(\Phi_1, \Phi_2) = m_{11}^2 |\Phi_1|^2 + m_{22}^2 |\Phi_2|^2 - (m_{12}^2 \Phi_1^\dagger \Phi_2 + H.c.)$
  $\frac{\lambda_1}{2} |\Phi_1|^4 + \frac{\lambda_2}{2} |\Phi_2|^4 + \lambda_3 |\Phi_1|^2 |\Phi_2|^2 + \lambda_4 |\Phi_1^\dagger \Phi_2|^2$
  $\left[\frac{\lambda_5}{2}(\Phi_1^\dagger \Phi_2)^2 + \lambda_6 (\Phi_1^\dagger \Phi_1)(\Phi_1^\dagger \Phi_2) + \lambda_7 (\Phi_2^\dagger \Phi_2)(\Phi_1^\dagger \Phi_2) + H.c.\right]$
  This is called the *generic basis,* a more useful one is called the *physical basis*.

- In the CPV case, $m_{12}^2, \lambda_{5,6,7}$ are complex. In the CPC case, all parameters are real. We consider the soft-breaking $\mathbb{Z}_2$ symmetry, which sets $\lambda_{6,7} = 0$.

The 2HDM potential

- Expressed in components: $\Phi_j = \left(\pi_j^+ , \frac{1}{\sqrt{2}}(v_j + h_j + i\pi_j^0) \right)^T j = 1\,,2$

- To count the d.o.f.: four charged complex scalars of $(\pi_1^\pm , \pi_2^\pm)$, two neutral real scalars of $(h_1\,, h_2)$, and two neutral pseudo-real scalars of $(\pi_1^0\,, \pi_2^0)$. These states are called the *gauge eigenstates*. We shall obtain the *mass eigenstates* from the 2HDM potential.

- The NGBs correspond to longitudinal components of $(W^\pm\,, Z^0)$, coming from two states from the $(\pi_1^\pm\,, \pi_2^\pm)$ and one state from the $(\pi_1^0\,, \pi_2^0)$. One is left with two charged Higgs bosons of $H^\pm$, one pseudo-real (CP-odd) Higgs boson of A, and two real (CP-even) Higgs bosons of $(h\,, H)$.

The 2HDM potential

- To obtain the Higgs spectrum, one first minimizes the 2HDM potential in the unitary gauge, i.e., $\langle \Phi_j \rangle = \frac{1}{\sqrt{2}} \left(0\,,\, v_j\right)^T$,

  $$\frac{\partial V}{\partial v_j} = 0 \Rightarrow$$

  $$m_{11}^2 = m_{12}^2 \tan\beta - \frac{1}{2}\left(\lambda_1 v_1^2 + \lambda_{3+4+5} v_2^2\right)$$

  $$m_{22}^2 = m_{12}^2/\tan\beta - \frac{1}{2}\left(\lambda_2 v_2^2 + \lambda_{3+4+5} v_1^2\right)$$

  to replace them into the Higgs potential.

- Two Higgs VEVs: $v_1^2 + v_2^2 = v^2 = (\sqrt{2}G_F)^{-1}$, $\tan\beta = v_2/v_1$

The 2HDM potential

- The charged Higgs bosons

$$-\mathcal{L}_{\pi_i^\pm} = \left[m_{12}^2 - \frac{1}{2}\lambda_{4+5}v^2 \sin\beta\cos\beta\right](\pi_1^-, \pi_2^-)\begin{pmatrix} \tan\beta & -1 \\ -1 & 1/\tan\beta \end{pmatrix}\begin{pmatrix} \pi_1^+ \\ \pi_2^+ \end{pmatrix}.$$

$$\Rightarrow M_\pm^2 = \frac{m_{12}^2}{\sin\beta\cos\beta} - \frac{1}{2}\lambda_{4+5}v^2$$

- The CP-odd Higgs bosons

$$-\mathcal{L}_{\pi_i^0} = \frac{1}{2}\left(m_{12}^2 - \lambda_5 v^2 \sin\beta\cos\beta\right)\cdot(\pi_1^0, \pi_2^0)\begin{pmatrix} \tan\beta & -1 \\ -1 & 1/\tan\beta \end{pmatrix}\begin{pmatrix} \pi_1^0 \\ \pi_2^0 \end{pmatrix},$$

$$\Rightarrow M_A^2 = \frac{m_{12}^2}{\sin\beta\cos\beta} - \lambda_5 v^2$$

- The zero-mass states correspond to the NGBs.

The 2HDM potential

- The CP-even Higgs bosons

$$-\mathcal{L}_{h_i} = (h_1\,, h_2) \begin{pmatrix} \mathcal{M}^2_{11} & \mathcal{M}^2_{12} \\ \mathcal{M}^2_{21} & \mathcal{M}^2_{22} \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix} \,,$$

$$\mathcal{M}^2 = M_A^2 \begin{pmatrix} s_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & c_\beta^2 \end{pmatrix} + v^2 \begin{pmatrix} \lambda_1 c_\beta^2 + \lambda_5 s_\beta^2 & \lambda_{3+4} s_\beta c_\beta \\ \lambda_{3+4} s_\beta c_\beta & \lambda_2 s_\beta^2 + \lambda_5 c_\beta^2 \end{pmatrix} \,,$$

- The mass matrix does not have zero eigenvalue in general and will be diagonalized by a orthogonal transformation:

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} \cdot \begin{pmatrix} h_1 \\ h_2 \end{pmatrix} \qquad \begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} c_\alpha & -s_\alpha \\ s_\alpha & c_\alpha \end{pmatrix} \cdot \begin{pmatrix} H \\ h \end{pmatrix} \,.$$

α is called the mixing angle between two CP-even Higgs bosons of $(h\,, H)$

The 2HDM potential

- The parameters of λ_i in the 2HDM potential cannot be directly determined, one can measure Higgs boson masses and mixings through experiments.

- The transformation between the *generic basis* and the *physical basis* is useful [to check it yourself]:

$$
\begin{aligned}
\lambda_1 &= \frac{M_h^2 s_\alpha^2 + M_H^2 c_\alpha^2 - m_{12}^2 t_\beta}{v^2 c_\beta^2}\,, \\
\lambda_2 &= \frac{M_h^2 c_\alpha^2 + M_H^2 s_\alpha^2 - m_{12}^2/t_\beta}{v^2 s_\beta^2}\,, \\
\lambda_3 &= \frac{1}{v^2}\Big[\frac{(M_H^2 - M_h^2) s_\alpha c_\alpha}{s_\beta c_\beta} + 2M_\pm^2 - \frac{m_{12}^2}{s_\beta c_\beta}\Big]\,, \\
\lambda_4 &= \frac{1}{v^2}(M_A^2 - 2M_\pm^2 + \frac{m_{12}^2}{s_\beta c_\beta})\,, \\
\lambda_5 &= \frac{1}{v^2}(\frac{m_{12}^2}{s_\beta c_\beta} - M_A^2)\,.
\end{aligned}
$$

The 2HDM potential

- A little summary: the 2HDM parameters in the physical basis include masses of $(M_h\,, M_H\,, M_A\,, M_\pm\,, m_{12}^2)$, and two angles of $(\alpha\,, \tan\beta)$.

- To probe the Higgs self-couplings in the 2HDM: to transform λ_i into the quantities in the *physical basis*, such as λ_{hhh}, λ_{hhH}, and etc. In the CP-conserving 2HDM, there cannot be CP-violating terms like λ_{hhA}.

  Example:

$$\lambda_{hhh} = \frac{M_h^2}{2v}\left[s_{\beta-\alpha} + 2c_{\beta-\alpha}^2(s_{\beta-\alpha} + \frac{c_{\beta-\alpha}}{t_{2\beta}})\right] - \frac{m_{12}^2}{s_\beta c_\beta v}c_{\beta-\alpha}^2(s_{\beta-\alpha} + \frac{c_{\beta-\alpha}}{t_{2\beta}})$$

$\Rightarrow \lambda_{hhh}^{\rm SM} = \dfrac{M_h^2}{2v}$ under the alignment limit of $c_{\beta-\alpha} \to 0$

$$\lambda_{hhH} = \frac{c_{\beta-\alpha}}{v}\left[(M_H^2 + 2M_h^2)(-1 + 2c_{\beta-\alpha}^2 - \frac{s_{2(\beta-\alpha)}}{t_{2\beta}}) + \frac{2m_{12}^2}{s_\beta c_\beta}(2 + \frac{3s_{2(\beta-\alpha)}}{2t_{2\beta}} - 3c_{\beta-\alpha}^2)\right]$$

$$\Rightarrow \lambda_{hhH} \to 0$$

The MSSM 2HDM

- The MSSM 2HDM potential contains three different contributions:
  (1) The D-term from the SUSY kinematic terms
  (2) The F-term of $\mu H_u H_d$ from the super potential, this leads to a SUSY μ-problem
  (3) soft SUSY-breaking terms

- The full MSSM Higgs potential reads
  $V = (|\mu|^2 + m_1^2)|H_u|^2 + (|\mu|^2 + m_2^2)|H_d|^2 - B\mu\epsilon_{\alpha\beta}(H_u^\alpha H_d^\beta + H.c.)$
  $+\frac{g^2 + g^{\prime 2}}{8}(|H_u|^2 - |H_d|^2)^2 + \frac{g^{\prime 2}}{2}|H_u^\dagger H_d|^2$

  To make it simple: $\lambda_1 = \lambda_2 = -\lambda_3 = \frac{1}{4}(g^2 + g^{\prime 2}) \quad \lambda_4 = \frac{1}{2}g^{\prime 2}$

  The MSSM Higgs masses (tree-level): $M_A^2 = B\mu$, $M_\pm^2 = M_A^2 + m_W^2$,

  $M_{h,H}^2 = \frac{1}{2}\left[M_A^2 + m_Z^2 \mp ((M_A^2 + m_Z^2)^2 - 4M_A^2 m_Z^2 \cos^2 2\beta)^{1/2}\right]$

  A general pattern is: $M_A \sim M_\pm \sim M_H$

The Higgs-gauge

- Let us get back to the Higgs-gauge interactions in the *physical basis,* which can be decomposed as:
  $\mathscr{L}_{kin} = \mathscr{L}_{\text{free}} + \mathscr{L}_{\phi VV} + \mathscr{L}_{\phi\phi VV} + \mathscr{L}_{\phi\phi V}$

- The most important terms:
  $$\mathscr{L}_{\phi VV} = \Big(\frac{2m_W^2}{v}W^{+\mu}W_\mu^- + \frac{m_Z^2}{v}Z^\mu Z_\mu\Big)(s_{\beta-\alpha}h + c_{\beta-\alpha}H)$$
  We can parametrize $\xi_h^V = s_{\beta-\alpha}$ and $\xi_H^V = c_{\beta-\alpha}$.
  $c_{\beta-\alpha} = \cos(\beta - \alpha)$ is a very useful parametrization, $c_{\beta-\alpha} \to 0$ with the global fit, and this is called the *alignment limit*.

- In the most pheno studies, one assumes $M_h = 125\,\mathrm{GeV}$, and other states of $(H\,, A\,, H^\pm)$ to be heavy.

  Under this limit, only the h is responsible for the EWSB, and the H does not quite couple to gauge bosons. Phenomenologically, the H mostly couples to the fermions but not bosons.

The Higgs-gauge

- Some other Higgs-gauge couplings:

$$G(AhZ^{\mu}) = \frac{g}{2c_W} c_{\beta-\alpha}(p_A + p_h)^{\mu}$$

$$G(AHZ^{\mu}) = -\frac{g}{2c_W} s_{\beta-\alpha}(p_A + p_H)^{\mu}$$: $A \to hZ/HZ$ decays

$$G(hhW_{\mu}^{+}W_{\nu}^{-}) = G(HHW_{\mu}^{+}W_{\nu}^{-}) = \frac{i}{2} g^2 \eta_{\mu\nu}$$

$$G(hhZ_{\mu}Z_{\nu}) = G(HHZ_{\mu}Z_{\nu}) = \frac{i}{2}(g^2 + g'^2)\eta_{\mu\nu}$$: neutral Higgs pair productions at lepton colliders

$$G(Z_{\mu}H^{+}H^{-}) = -\frac{g}{2c_W} c_{2W}(p^{+} + p^{-})_{\mu}$$

$$G(A_{\mu}H^{+}H^{-}) = -ie(p^{+} + p^{-})_{\mu}$$: charged Higgs pair productions

The 2HDM Yukawa

- The most general 2HDM Yukawa can be:
$$-\mathscr{L}_Y = Y_{ij}^{d1}\bar{Q}_{iL}d_{jR}\Phi_1 + Y_{ij}^{d2}\bar{Q}_{iL}d_{jR}\Phi_2$$
$$+Y_{ij}^{\ell 1}\bar{L}_{iL}\ell_{jR}\Phi_1 + Y_{ij}^{\ell 2}\bar{L}_{iL}\ell_{jR}\Phi_2 + Y_{ij}^{u1}\bar{Q}_{iL}u_{jR}\tilde{\Phi}_1 + Y_{ij}^{u2}\bar{Q}_{iL}u_{jR}\tilde{\Phi}_2 + H.c.$$
Here, $\tilde{\Phi}_i \equiv i\Phi_i^*\sigma_2$, with $Y = -1$.

- This is problematic, since there can be tree-level flavor-changing neutral currents (FCNC).

- This is to be avoided by assigning all right-handed fermions of a given charge to one particular Higgs doublet, by Paschos-Glashow-Weinberg.

The 2HDM Yukawa

- There are usually four types of Yukawa assignments in the general 2HDM:

	u_R	d_R	ℓ_R
Type-I	Φ_2	Φ_2	Φ_2
Type-II	Φ_2	Φ_1	Φ_1
Lepton-specific	Φ_2	Φ_2	Φ_1
Flipped	Φ_2	Φ_1	Φ_2

- Most of the general 2HDM discussions focus on the Type-I and Type-II.

- For the MSSM, two Higgs doublets of $(H_u)_{Y=+1}$ and $(H_d)_{Y=-1}$ with opposite hyper charges to cancel the $[\mathrm{SU}(2)_L]^2\mathrm{U}(1)_Y$ anomaly. It is thus a Type-II 2HDM.

The 2HDM Yukawa

- Express the Yukawa couplings in terms of the mass eigenstates:

$$-\mathscr{L}_Y = \sum_f \frac{m_f}{v}\left(\xi_h^f \bar{f} f h + \xi_H^f \bar{f} f H - i\xi_A^f \bar{f}\gamma_5 f A\right)$$

$$+\sqrt{2}\left[V_{ud}(\frac{m_u}{v}\xi_A^u \bar{u} P_L d + \frac{m_d}{v}\xi_A^d \bar{u} P_R d) + \frac{m_\ell}{v}\xi_A^\ell \bar{\nu}_\ell P_R \ell\right] H^+ + H.c.$$

- $\xi_h^f, \xi_H^f, \xi_A^f$ are Yukawa couplings normalized to the SM Higgs Yukawa couplings.

The 2HDM Yukawa

	Type-I	Type-II	LS	Flipped
ξ_h^u	$s_{\beta-\alpha} + \frac{c_{\beta-\alpha}}{t_\beta}$	$s_{\beta-\alpha} + \frac{c_{\beta-\alpha}}{t_\beta}$	$s_{\beta-\alpha} + \frac{c_{\beta-\alpha}}{t_\beta}$	$s_{\beta-\alpha} + \frac{c_{\beta-\alpha}}{t_\beta}$
ξ_h^d	$s_{\beta-\alpha} + \frac{c_{\beta-\alpha}}{t_\beta}$	$s_{\beta-\alpha} - t_\beta c_{\beta-\alpha}$	$s_{\beta-\alpha} + \frac{c_{\beta-\alpha}}{t_\beta}$	$s_{\beta-\alpha} - t_\beta c_{\beta-\alpha}$
ξ_h^ℓ	$s_{\beta-\alpha} + \frac{c_{\beta-\alpha}}{t_\beta}$	$s_{\beta-\alpha} - t_\beta c_{\beta-\alpha}$	$s_{\beta-\alpha} - t_\beta c_{\beta-\alpha}$	$s_{\beta-\alpha} + \frac{c_{\beta-\alpha}}{t_\beta}$
ξ_H^u	$c_{\beta-\alpha} - \frac{s_{\beta-\alpha}}{t_\beta}$	$c_{\beta-\alpha} - \frac{s_{\beta-\alpha}}{t_\beta}$	$c_{\beta-\alpha} - \frac{s_{\beta-\alpha}}{t_\beta}$	$c_{\beta-\alpha} - \frac{s_{\beta-\alpha}}{t_\beta}$
ξ_H^d	$c_{\beta-\alpha} - \frac{s_{\beta-\alpha}}{t_\beta}$	$c_{\beta-\alpha} + t_\beta s_{\beta-\alpha}$	$c_{\beta-\alpha} - \frac{s_{\beta-\alpha}}{t_\beta}$	$c_{\beta-\alpha} + t_\beta s_{\beta-\alpha}$
ξ_H^ℓ	$c_{\beta-\alpha} - \frac{s_{\beta-\alpha}}{t_\beta}$	$c_{\beta-\alpha} + t_\beta s_{\beta-\alpha}$	$c_{\beta-\alpha} + t_\beta s_{\beta-\alpha}$	$c_{\beta-\alpha} - \frac{s_{\beta-\alpha}}{t_\beta}$
ξ_A^u	$\frac{1}{t_\beta}$	$\frac{1}{t_\beta}$	$\frac{1}{t_\beta}$	$\frac{1}{t_\beta}$
ξ_A^d	$-\frac{1}{t_\beta}$	t_β	$-\frac{1}{t_\beta}$	t_β
ξ_A^ℓ	$-\frac{1}{t_\beta}$	t_β	t_β	$-\frac{1}{t_\beta}$

Exercise: write down these couplings under the alignment limit of $c_{\beta-\alpha} = 0$

Some theoretical constraints

Constraints

- Before we consider any pheno implications, there are several theoretical constraints to the 2HDM.

- Generally, the self-couplings in the 2HDM potential cannot be arbitrarily too large and/or too negative.

- These are nothing new, but something already existing for the SM Higgs $V(\Phi) = \mu^2 |\Phi|^2 + \lambda |\Phi|^4$.

- Higgs potential bounded from below (BFB), the Higgs potential cannot become negative: $\lambda > 0$

Constraints

- Lee-Quigg-Thacker unitarity bound (1977): use the Goldstone equivalence theorem to constrain the NGB scattering processes.

- The joint neutral scalar scattering processes forming a 4×4 matrix for the amplitudes. $(W_L^+ W_L^-, \frac{1}{\sqrt{2}} Z_L Z_L, \frac{1}{\sqrt{2}} hh, Z_L h)$

- $\left| \mathrm{Re}(a_l) \right| \leq \frac{1}{2} \Rightarrow \; |\lambda| \leq 2\pi \Rightarrow m_h^{\mathrm{SM}} \leq 870\,\mathrm{GeV}$

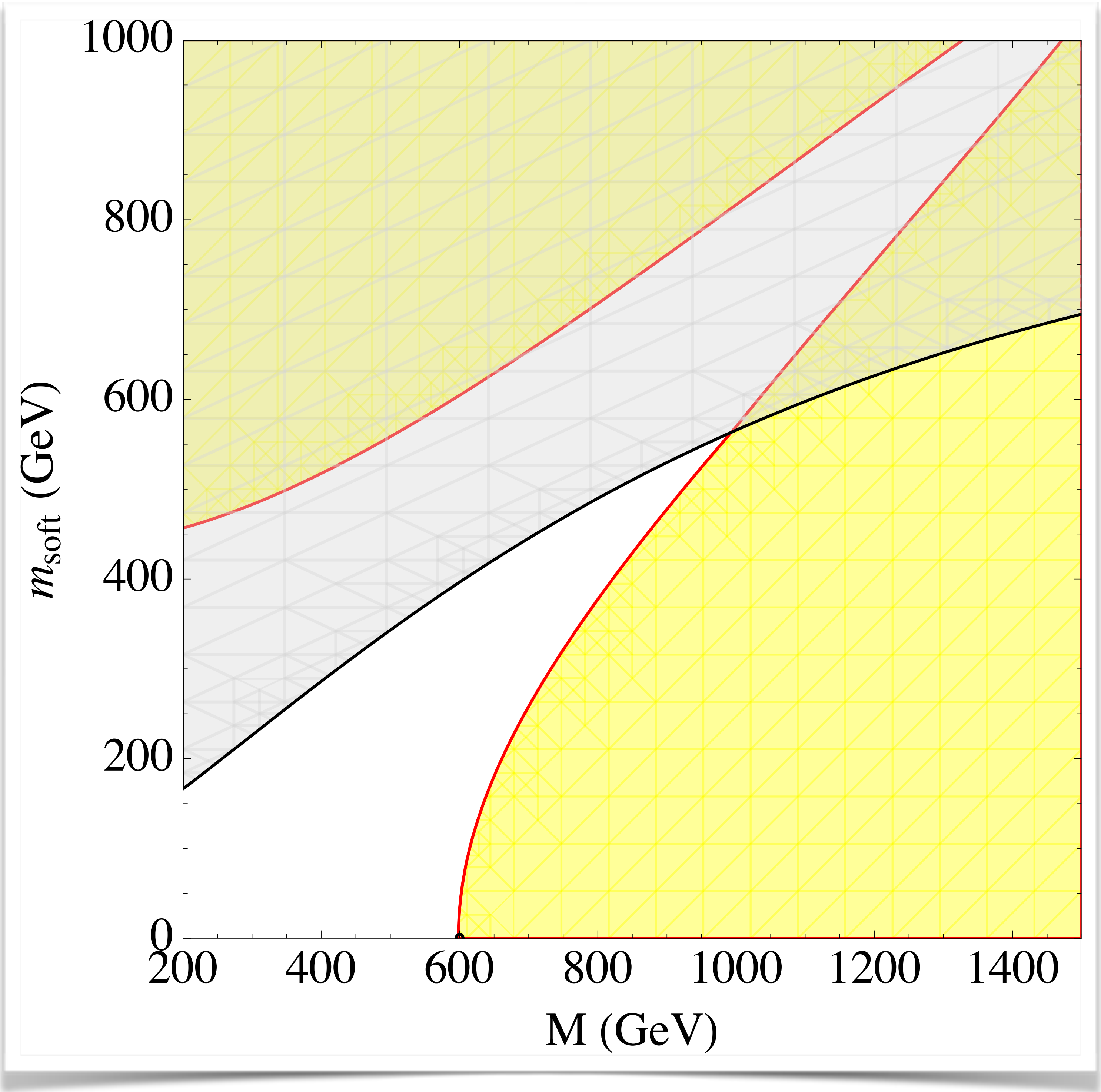
Constraints

- In the 2HDM: the BFB requires no direction can lead to $V < 0$. [hep-ph/0207010]
  $\lambda_{1,2} > 0\,, \lambda_3 > -\sqrt{\lambda_1\lambda_2}\,, \lambda_3 + \lambda_4 - |\lambda_5| > -\sqrt{\lambda_1\lambda_2}$

- Unitarity bound [hep-ph/0508020, 1509.06060] :
  $(W_j^+W_j^-\,, \frac{1}{\sqrt{2}}Z_jZ_j\,, \frac{1}{\sqrt{2}}h_jh_j\,, Z_jh_j\,, W_1^{\pm}W_2^{\mp}\,, Z_1Z_2\,, h_1h_2\,, h_{1,2}Z_{2,1})$

$$a_0^0 = \frac{1}{16\pi}\begin{pmatrix} X_{4\times4} & 0 & 0 & 0 \\ 0 & Y_{4\times4} & 0 & 0 \\ 0 & 0 & Z_{3\times3} & 0 \\ 0 & 0 & 0 & Z_{3\times3} \end{pmatrix}, \qquad X_{4\times4} = \begin{pmatrix} 3\lambda_1 & 2\lambda_3+\lambda_4 & 3\sqrt{2}\lambda_6^R & 3\sqrt{2}\lambda_6^I \\ 2\lambda_3+\lambda_4 & 3\lambda_2 & 3\sqrt{2}\lambda_7^R & 3\sqrt{2}\lambda_7^I \\ 3\sqrt{2}\lambda_6^R & 3\sqrt{2}\lambda_7^R & \lambda_3+2\lambda_4+3\lambda_5^R & 3\lambda_5^I \\ 3\sqrt{2}\lambda_6^I & 3\sqrt{2}\lambda_7^I & 3\lambda_5^I & \lambda_3+2\lambda_4-3\lambda_5^R \end{pmatrix},$$

Constraints



Constraints

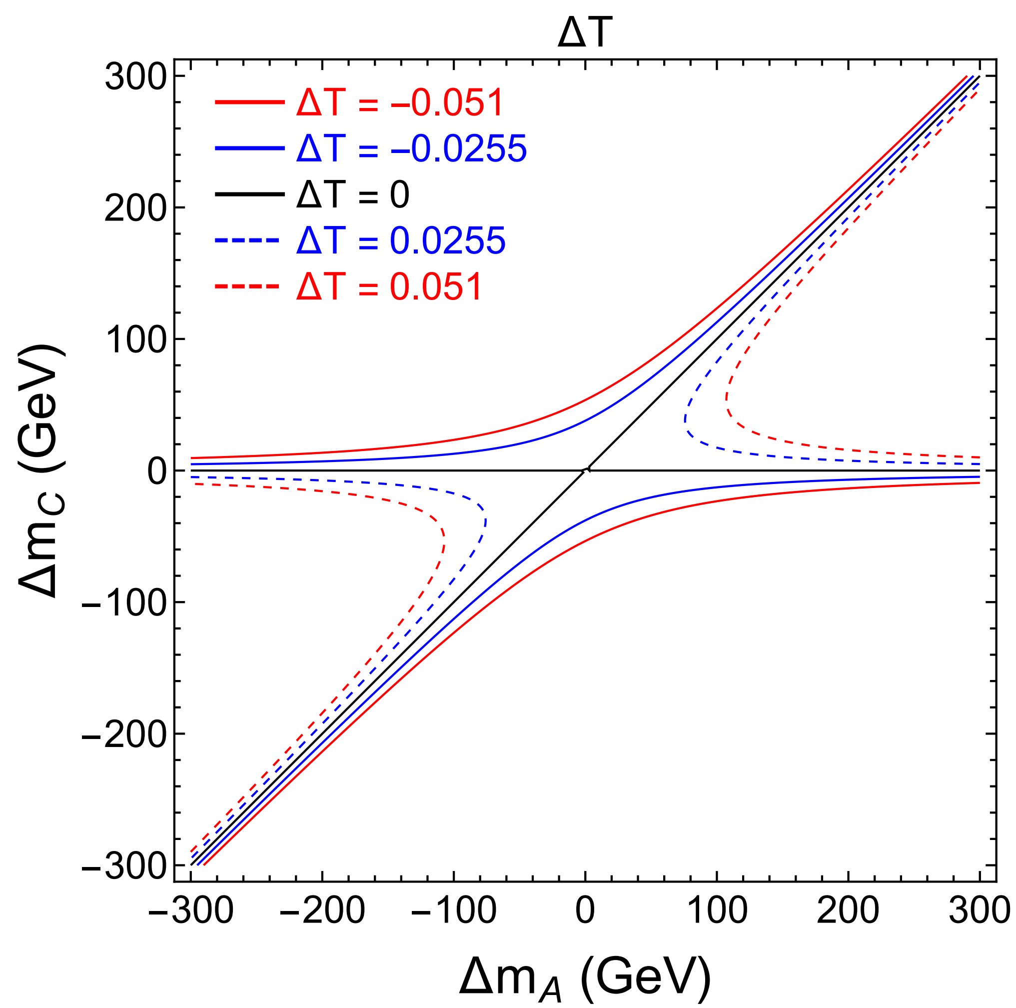
- The EW precision measurements (Peskin-Takeuchi S, T, U oblique parameters), which are one-loop corrections to the W^+W^-, ZZ propagators.

	Current (1.7×10^7 Z's)				CEPC ($10^{10} Z$'s)				FCC-ee ($7\times10^{11} Z$'s)				ILC ($10^9 Z$'s)			
	σ	correlation			σ (10^{-2})	correlation			σ (10^{-2})	correlation			σ (10^{-2})	correlation		
		S	T	U		S	T	U		S	T	U		S	T	U
S	0.04 ± 0.11	1	0.92	-0.68	2.46	1	0.862	-0.373	0.67	1	0.812	0.001	3.53	1	0.988	-0.879
T	0.09 ± 0.14	–	1	-0.87	2.55	–	1	-0.735	0.53	–	1	-0.097	4.89	–	1	-0.909
U	-0.02 ± 0.11	–	–	1	2.08	–	–	1	2.40	–	–	1	3.76	–	–	1

measure of the custodial symmetry: $\rho \simeq 1 + \alpha\Delta T$

Constraints

- The full analysis of the S, T, U parameter in the 2HDM: H.J.He, Polonsky, S. Su (hep-ph/0102144)



$$\Delta m_A \equiv M_A - M_H \,, \Delta m_C \equiv M_\pm - M_H$$

EW precision points to the degenerate heavy Higgs bosons

The pheno of 2HDM

The LHC fit

- So far, the LHC only finds one SM-like Higgs boson of $M_h = 125\,\mathrm{GeV}$, no other (heavier) Higgs bosons in the spectrum were found yet.

- Meanwhile, we can learn something from the LHC measurements of the $125\,\mathrm{GeV}$ Higgs boson already. This is usually performed through a global fit of
$$\chi^2 \equiv \sum_i \frac{(\mu_i^{\mathrm{2HDM}} - \mu_i^{\mathrm{obs}})^2}{\sigma_i^2}$$
$\mu_i^{\mathrm{2HDM}} = (\sigma \times \mathrm{Br})^{\mathrm{2HDM}} / (\sigma \times \mathrm{Br})^{\mathrm{SM}}$ for specific signal channels

The LHC fit

- μ_i^{obs} and σ_i come from the experiments, a summary from the Run-I data is here (Gu, Li, Liu, Su, Su, 1709.06103):

Channel	Production	Run-I	Channel	Production	Run-I
$\gamma\gamma$	ggh	$1.10^{+0.23}_{-0.22}$	$\tau^+\tau^-$	ggh	$1.0^{+0.6}_{-0.6}$
	VBF	$1.3^{+0.5}_{-0.5}$		VBF	$1.3^{+0.4}_{-0.4}$
	Wh	$0.5^{+1.3}_{-1.2}$		Wh	$-1.4^{+1.4}_{-1.4}$
	Zh	$0.5^{+3.0}_{-2.5}$		Zh	$2.2^{+2.2}_{-1.8}$
	$t\bar{t}h$	$2.2^{+1.6}_{-1.3}$		$t\bar{t}h$	$-1.9^{+3.7}_{-3.3}$
WW^*	ggh	$0.84^{+0.17}_{-0.17}$	$b\bar{b}$	Wh	$1.0^{+0.5}_{-0.5}$
	VBF	$1.2^{+0.4}_{-0.4}$		Zh	$0.4^{+0.4}_{-0.4}$
	Wh	$1.6^{+1.2}_{-1.0}$	ZZ^*	$t\bar{t}h$	$1.15^{+0.99}_{-0.94}$
	Zh	$5.9^{+2.6}_{-2.2}$		ggh	$1.13^{+0.34}_{-0.31}$
	$t\bar{t}h$	$5.0^{+1.8}_{-1.7}$		VBF	$0.1^{+1.1}_{-0.6}$

The LHC fit

- How to make the fit in practice? In principle, they involve productions and decay branching ratios with the 2HDM couplings.

- Productions: four channels of ggh, VBF, Vh, and $t\bar{t}h$.

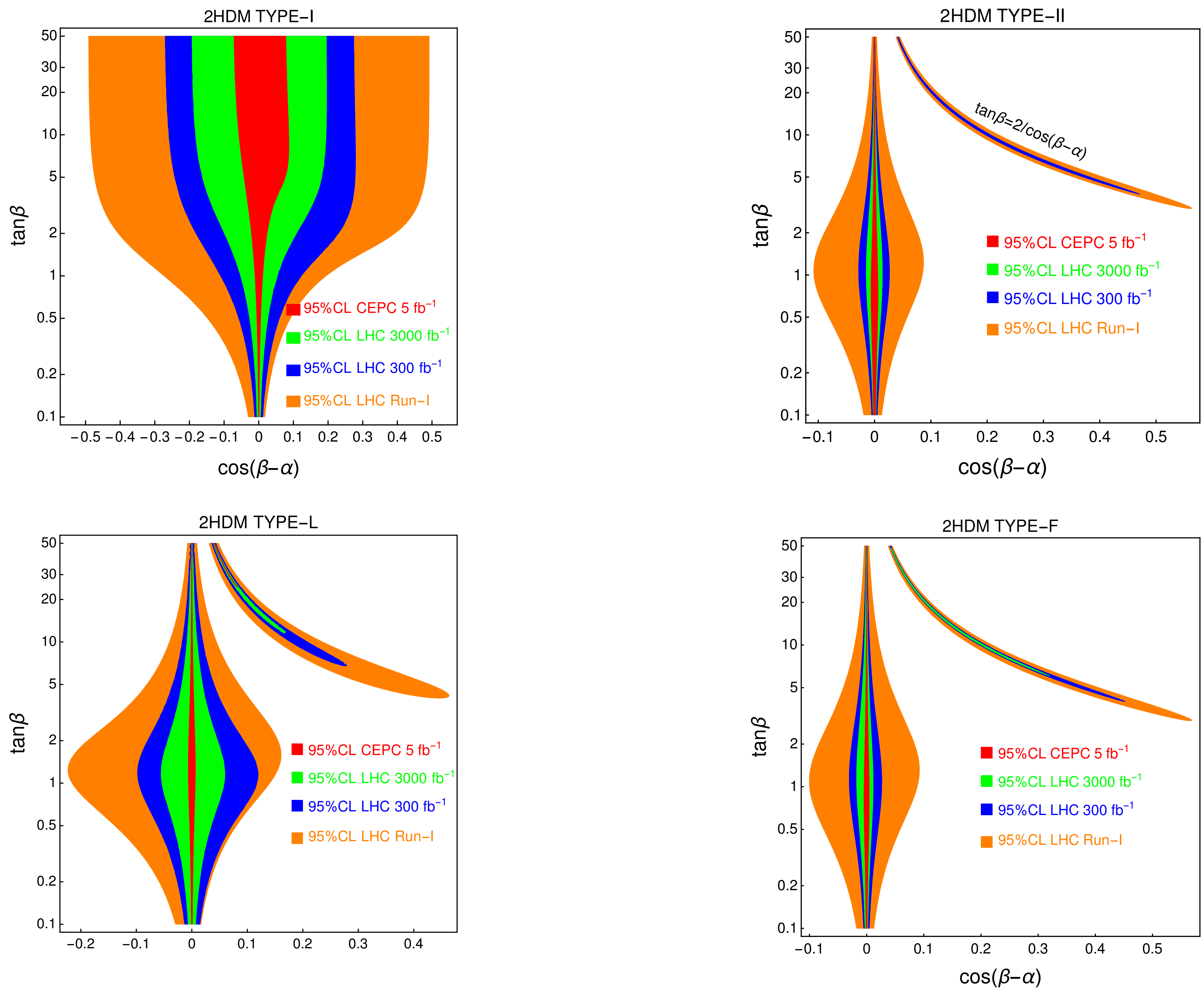
$$\frac{\sigma_{2\mathrm{HDM}}(gg \to h)}{\sigma_{\mathrm{SM}}(gg \to h)} = \frac{\sigma_{2\mathrm{HDM}}(t\bar{t}h)}{\sigma_{\mathrm{SM}}(t\bar{t}h)} = (\xi_h^u)^2$$

$$\frac{\sigma_{2\mathrm{HDM}}(\mathrm{VBF})}{\sigma_{\mathrm{SM}}(\mathrm{VBF})} = \frac{\sigma_{2\mathrm{HDM}}(Vh)}{\sigma_{\mathrm{SM}}(Vh)} = (\xi_h^V)^2$$

- Decays: the best tool is the 2HDMC (https://2hdmc.hepforge.org/). [to give a demo here]

The LHC fit

- 1709.06103



The LHC fit

- The alignment limits of $c_{\beta-\alpha} \to 0$ are shown for all four types of 2HDM. More constrained regions are expected from the Run-II and the future e^+e^- colliders.

- The large-$\tan\beta$ regions are highly constrained in the Type-II, LS, Flipped.

- There are also the ``wrong-sign" bends in the Type-II, LS, Flipped, where ξ_h^d and/or $\xi_h^\ell \to -1$.

The LHC searches

- Next: What do these constraints mean to the future searches to the heavy states in the 2HDM?

- The neutral Higgs bosons $(H\,,A)$ are mostly produced via the ggF, plus the $t\bar{t}$-associated productions.

- The neutral Higgs bosons $(H\,,A)$ can mostly decay into fermions, rather than the vector bosons. The loop-induced final states of $(gg\,,\gamma\gamma\,,\gamma Z)$ are suppressed.

- Several exotic decays: $A \to hZ\,, HZ\,, H^{\pm}W^{\mp}$, either suppressed by alignment limit or phase space.

The LHC searches

- Possible search channels for neutral Higgs bosons under the alignment limit:

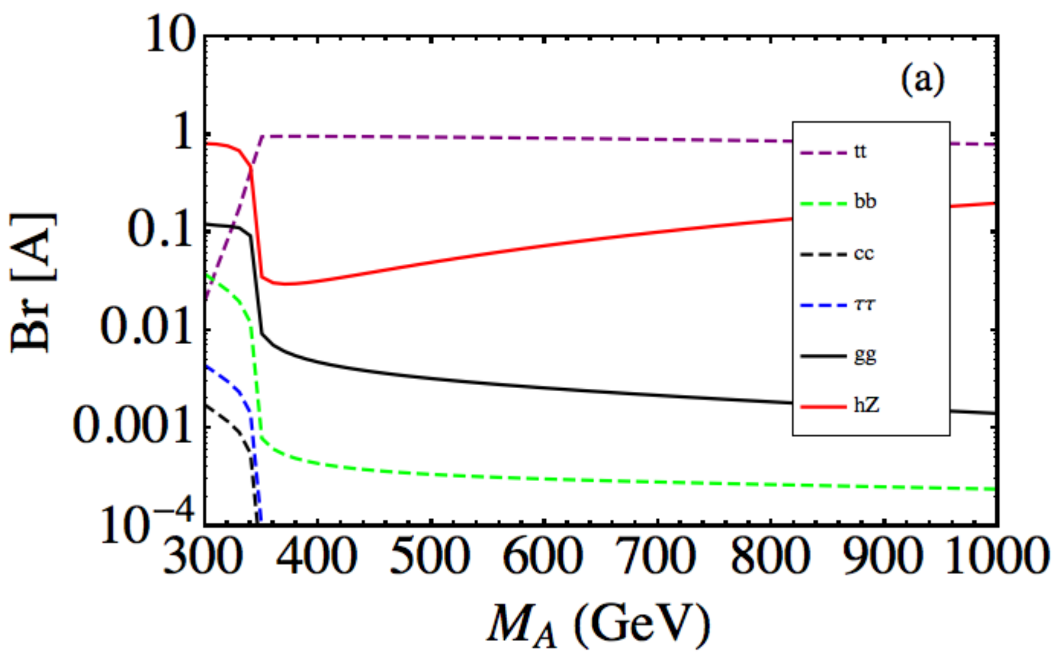
A decays	Final states	Alignment limit
SM fermions	$A \to (\tau^+\tau^-, \mu^+\mu^-)$	✓
	$A \to (t\bar{t}, b\bar{b})$	✓
Exotics	$A \to hZ$	–
	$A \to HZ$	✓
	$A \to H^\pm W^\mp$	✓
Loops	$A \to (gg, \gamma\gamma, \gamma Z)$	✓

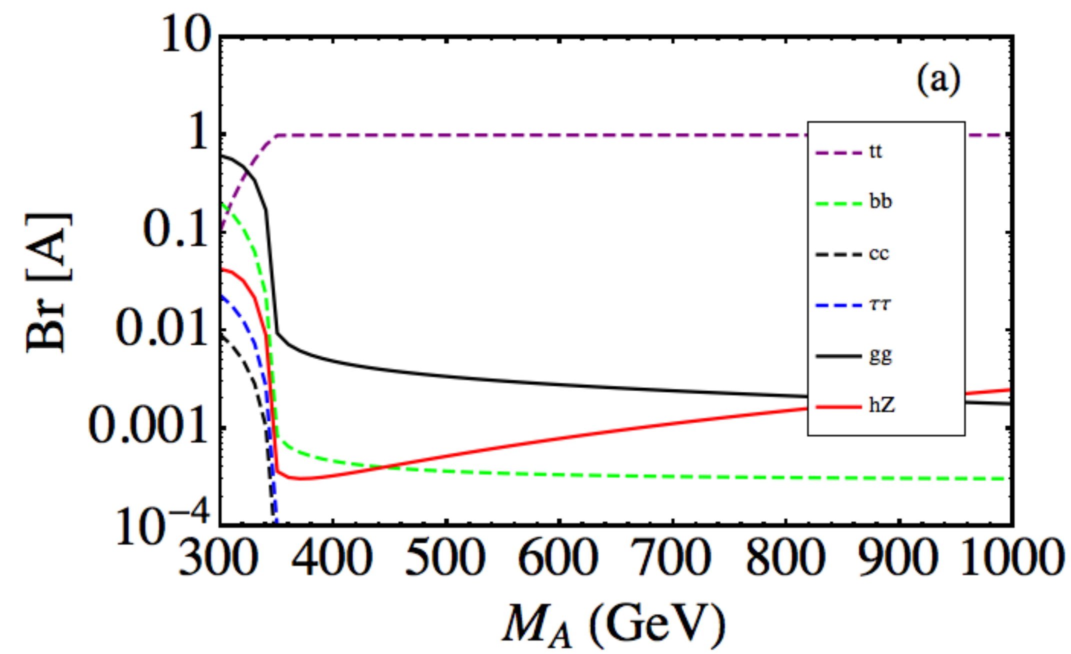
H decays	Final states	Alignment limit
SM fermions	$H \to (\tau^+\tau^-, \mu^+\mu^-)$	✓
	$H \to (t\bar{t}, b\bar{b})$	✓
gauge bosons	$H \to (WW, ZZ)$	–
Exotics	$H \to AZ$	✓
	$H \to H^\pm W^\mp$	✓
	$H \to hh$	–
	$H \to AA$	–
	$H \to H^+H^-$	✓
Loops	$H \to (gg, \gamma\gamma, \gamma Z)$	✓

NC, Jinmian Li, Yandong Liu, 1509.03848

The A/H decays

- This is usually the leading decay modes with $\tan\beta = 1$

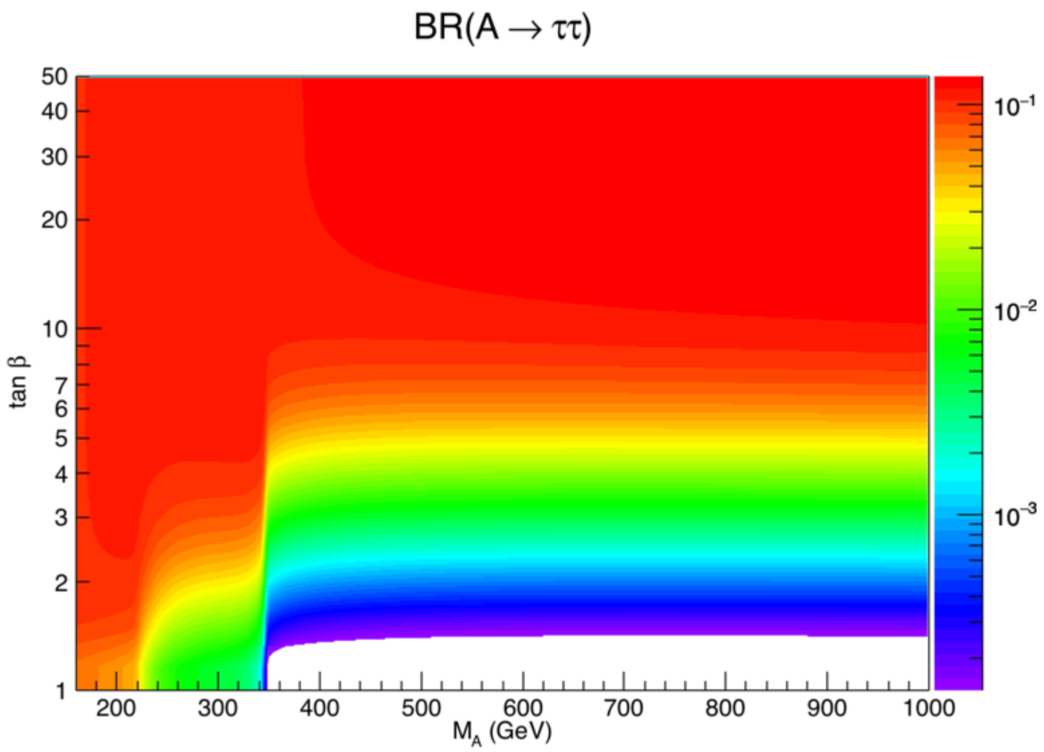


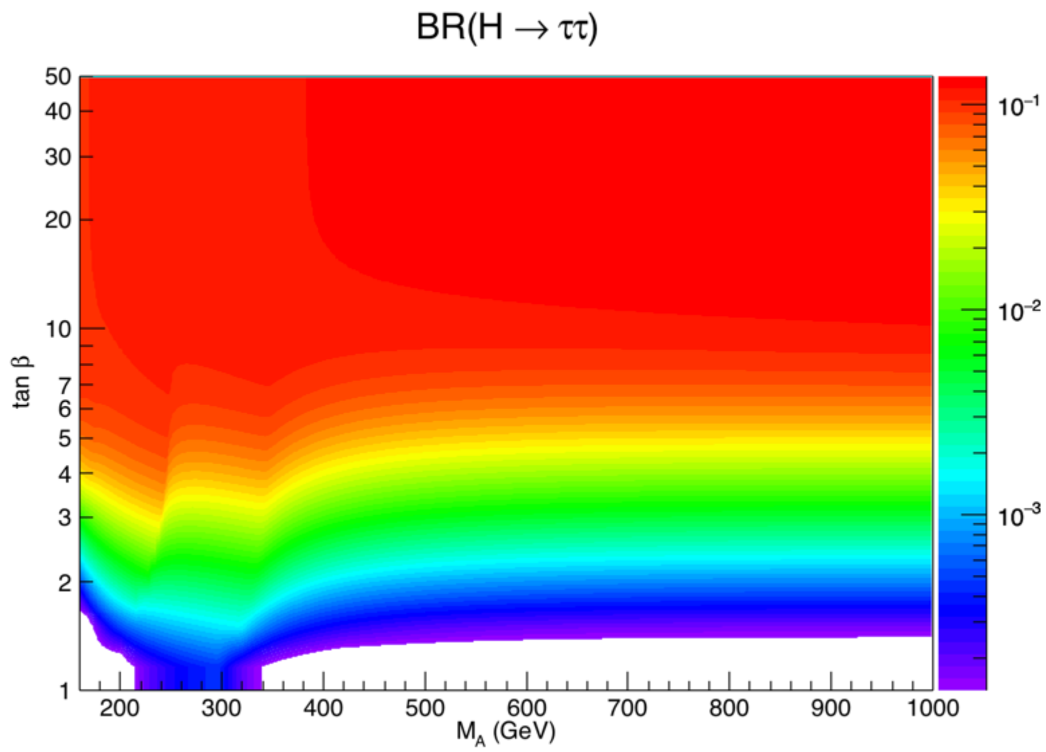


Left: Type-I, Right: Type-II

The A/H decays

- $A/H \to \tau\tau$ dependences on $\tan\beta$ (Type-II)



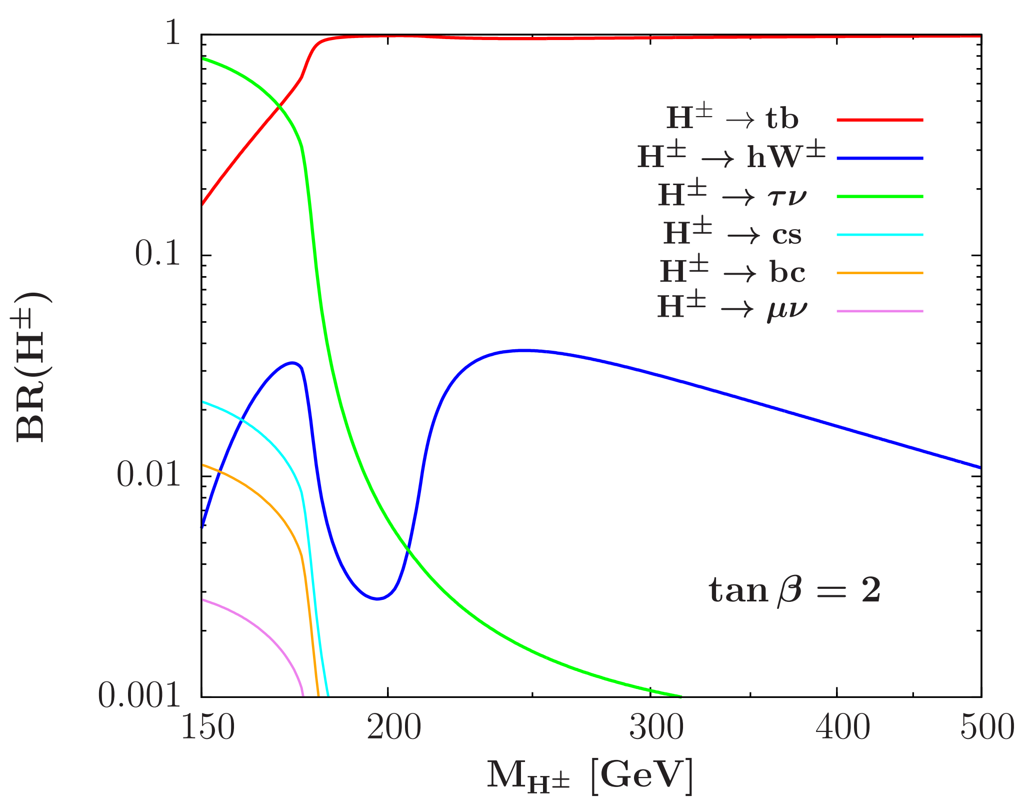


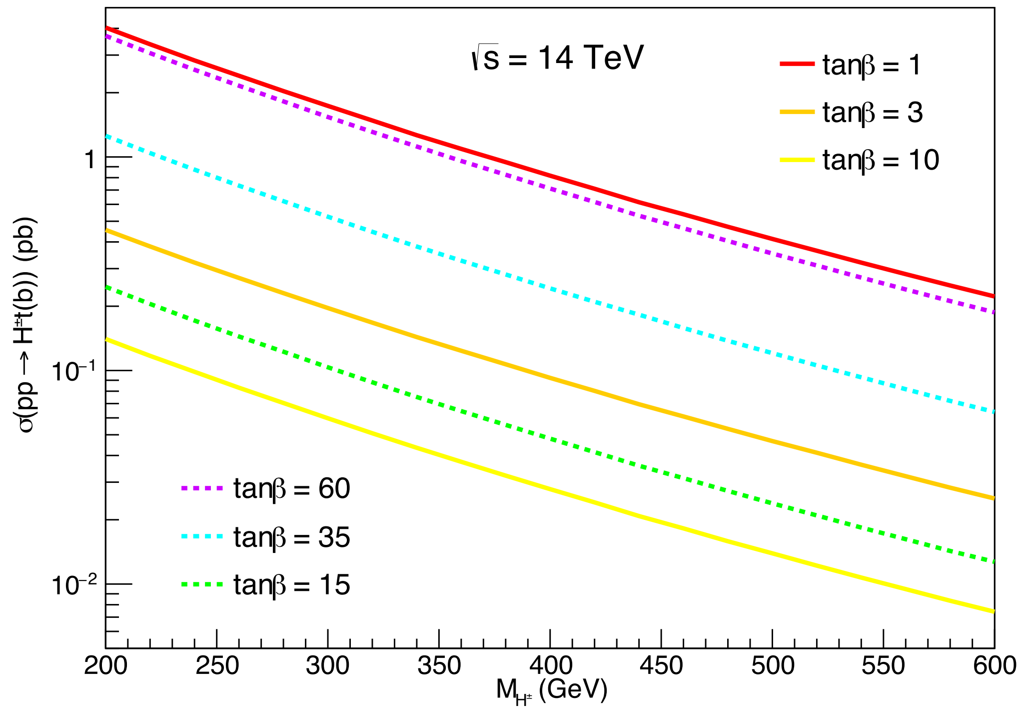
1502.05653

The LHC searches

- In the Type-II: $g_{H^\pm \bar{t} b} \sim m_b t_\beta (1+\gamma_5) + m_t (1-\gamma_5)/t_\beta$

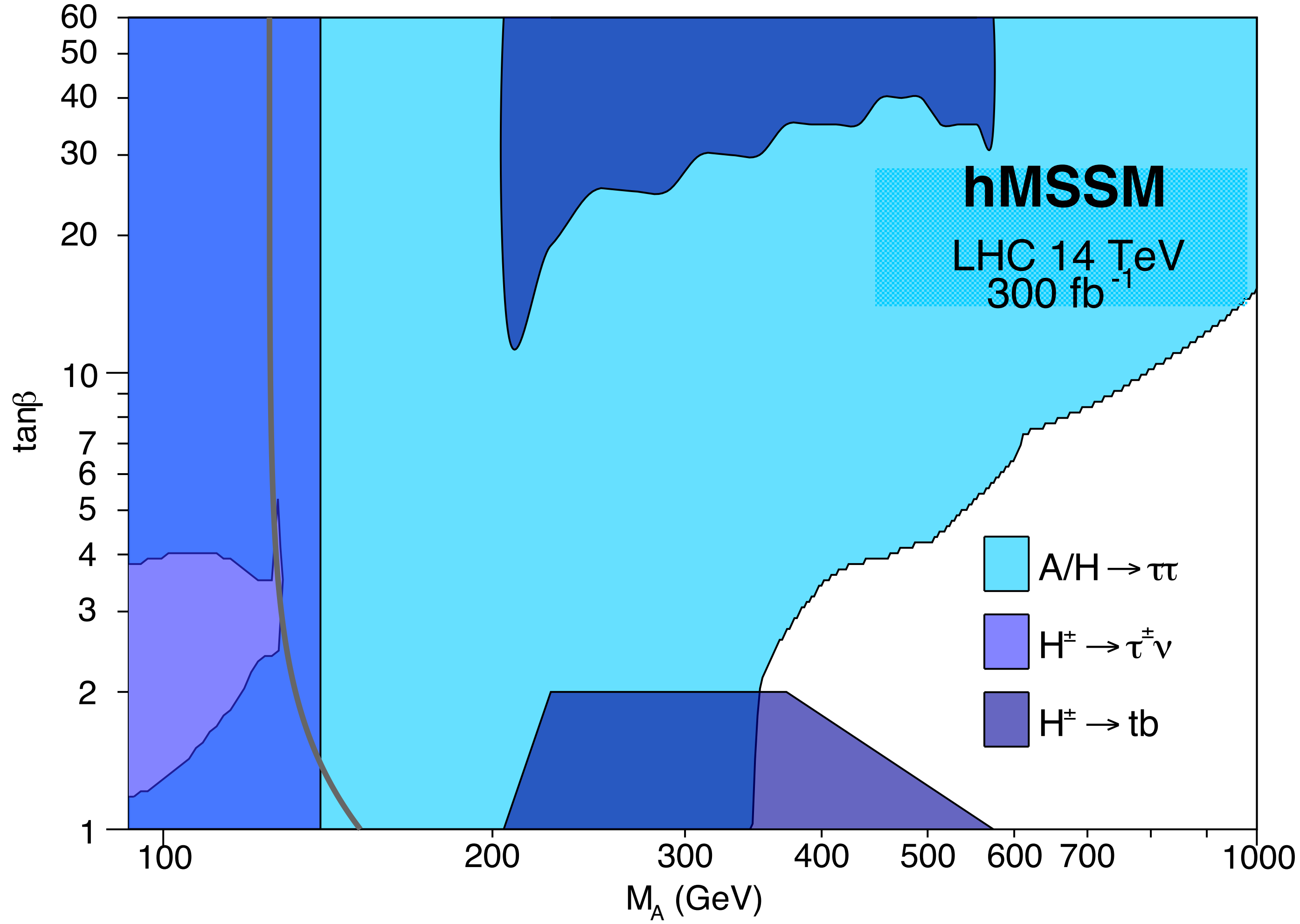
- The charged Higgs bosons $H^\pm$ are mostly produced via three-body productions of $pp \to tbH^\pm$, and decays into tb. Both the low-t_β and high-t_β regions are sensitive.





The $A/H/H^{\pm}$ searches

- The $\tau\tau$ searches covers the large-$\tan\beta$ regions (Type-II)



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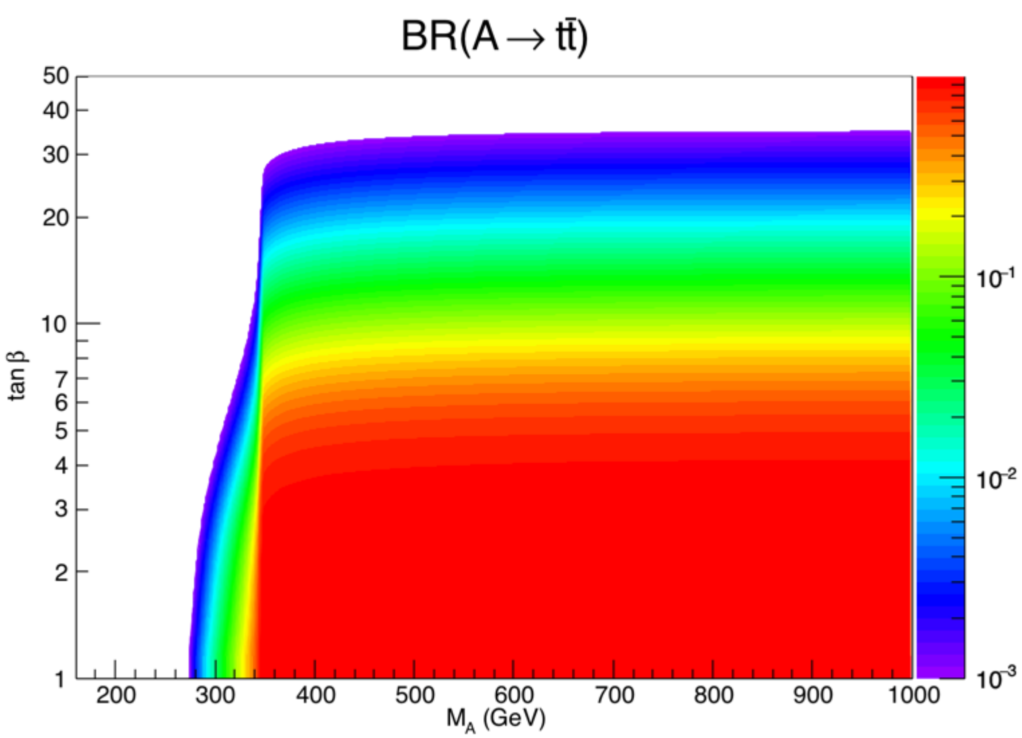
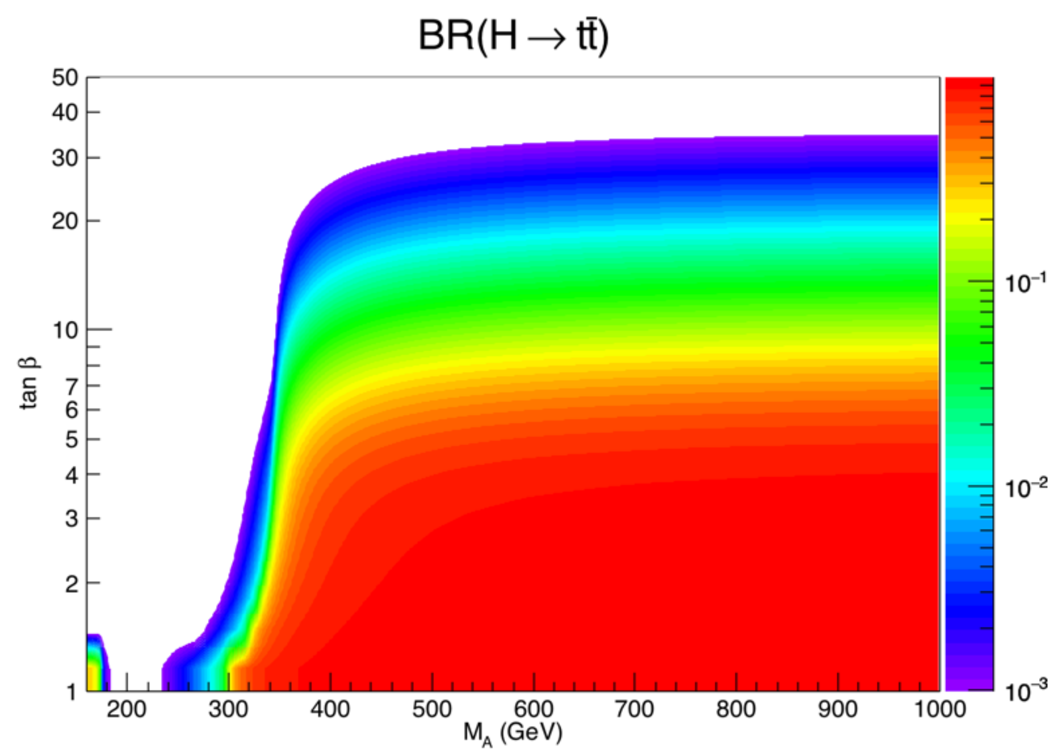
The A/H decays

- $A/H \to t\bar{t}$ dependences on $\tan\beta$ (Type-II)





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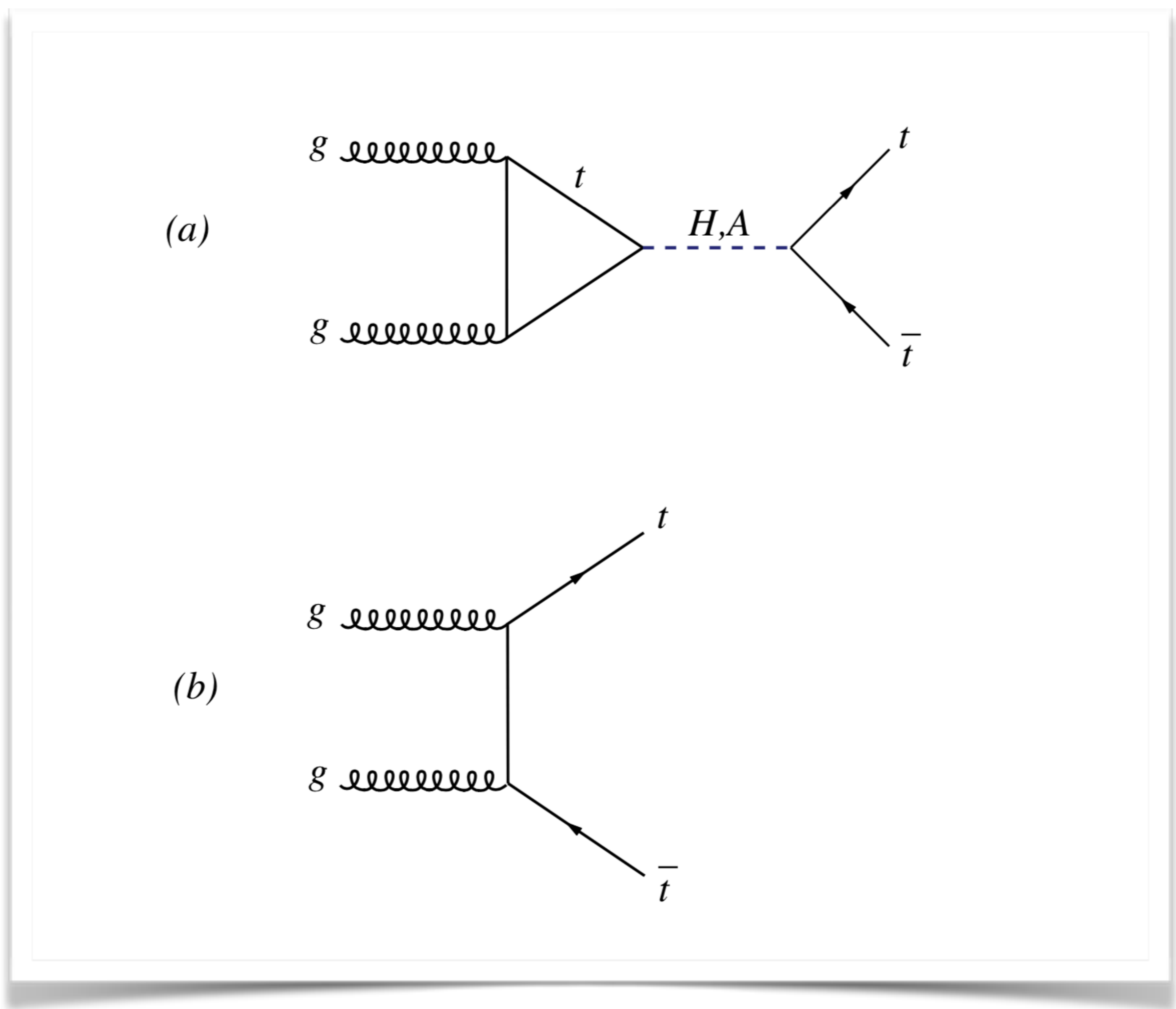
$A/H \to t\bar{t}$

- $A/H \to t\bar{t}$ is particularly challenging, due to the strong interference effects:



hep-ph/9404359

$A/H \to t\bar{t}$

- Master equation for signals:

$$\hat{\sigma}_{\text{sig}}(\hat{s}) = \int d\text{PS}\Big(|\mathscr{A}_{res} + \mathscr{A}_{\text{bkg}}|^2 - |\mathscr{A}_{\text{bkg}}|^2 \Big)$$

$$= \hat{\sigma}_{\text{res.}}(\hat{s}) + \hat{\sigma}_{\text{int.}}(\hat{s})$$

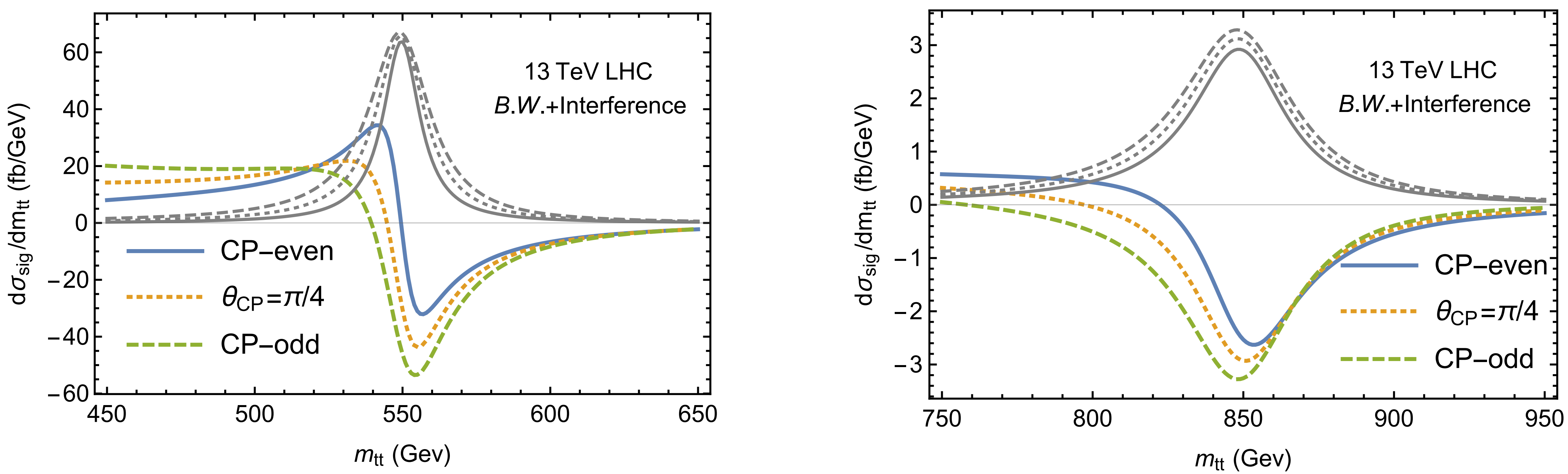
- CP-even and CP-odd cases (Dicus, Willenbrock 1994)

$$\hat{\sigma}^{\text{even}}_{\text{res.}}(\hat{s}) \propto \frac{\alpha_s^2 \hat{s}^2}{v^2}\beta^3 \left| \frac{(\xi_H^t)^2 I_{1/2}(\hat{s}/4m_t^2)}{\hat{s} - M_H^2 + iM_H\Gamma_H} \right|^2$$

$$\hat{\sigma}^{\text{even}}_{\text{int.}}(\hat{s}) \propto -\frac{\alpha_s^2}{64\pi}\beta^2 \text{Re}\Big[\frac{(\xi_H^t)^2 I_{1/2}(\hat{s}/4m_t^2)}{\hat{s} - M_H^2 + iM_H\Gamma_H} \Big]$$

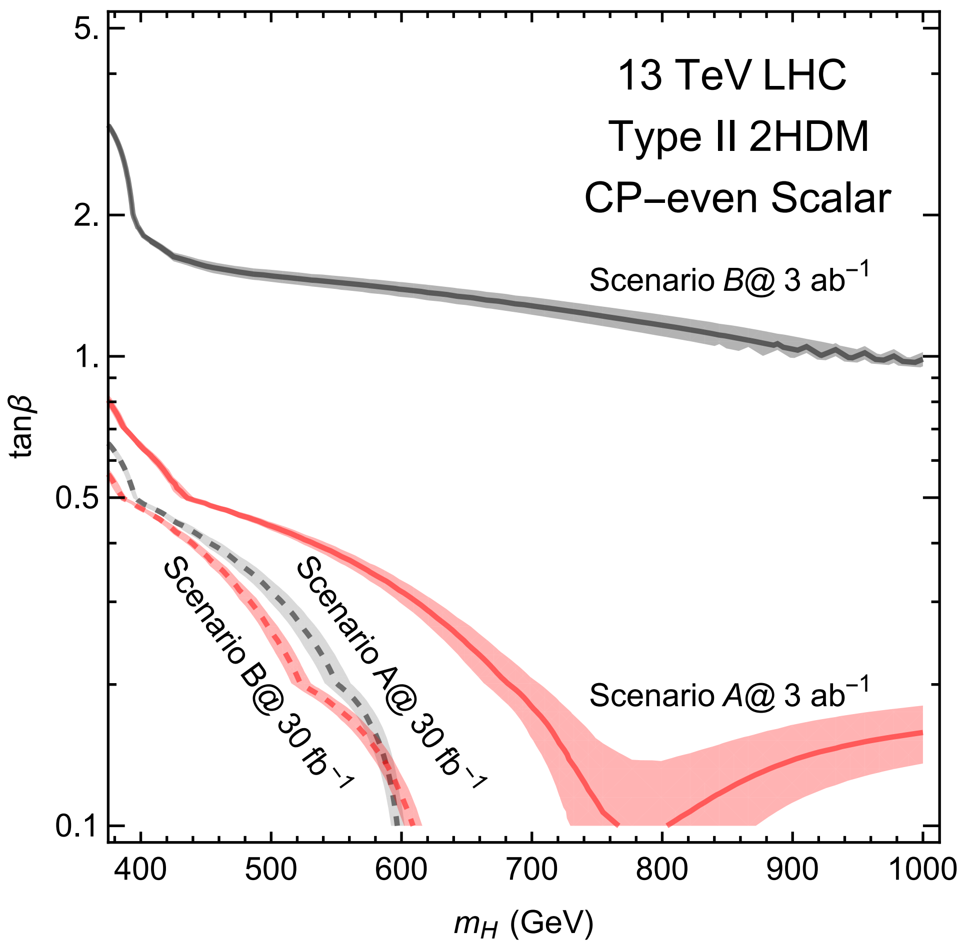
$A/H \to t\bar{t}$

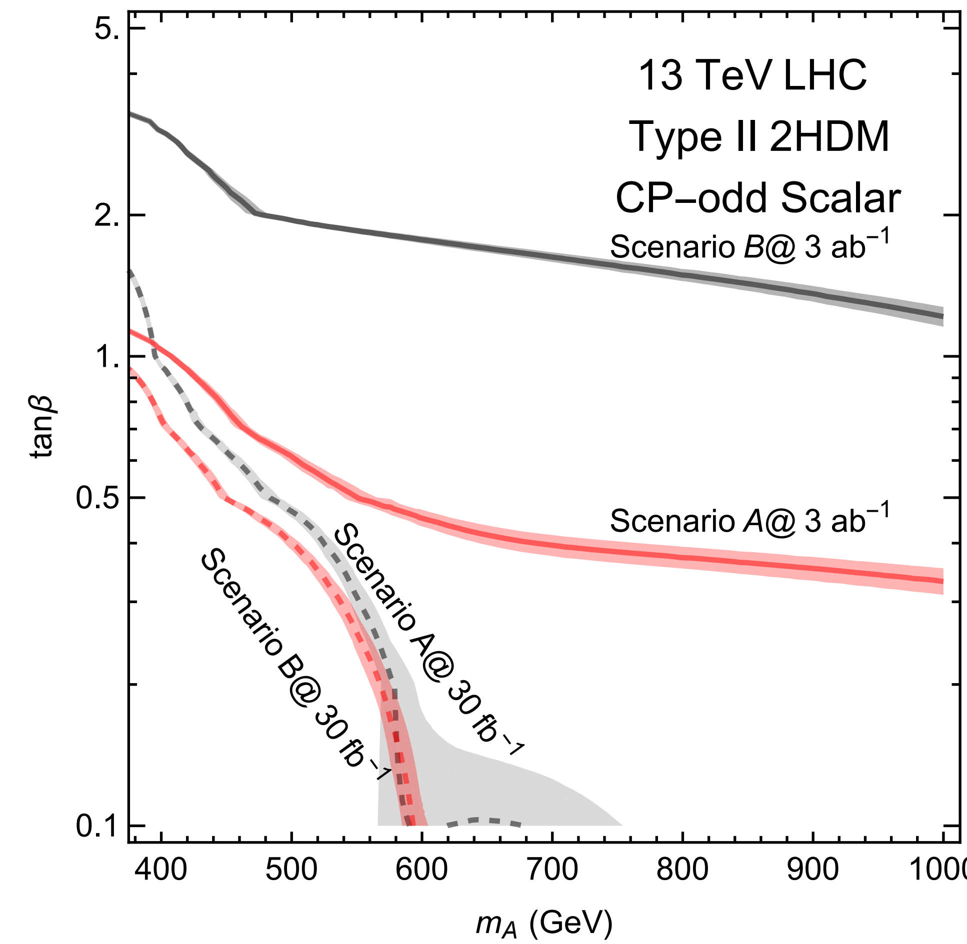
- The line shapes with/w.o. the interferences



Carena, Z.Liu, 1608.07282

$A/H \to t\bar{t}$





	$\Delta m_{t\bar{t}}$	Efficiency	Systematic Uncertainty
Scenario A	15%	8%	4% at 30 fb^{-1}, halved at $3\,\text{ab}^{-1}$
Scenario B	8%	5%	4% at 30 fb^{-1}, scaled with $\sqrt{L}$

Carena, Z.Liu, 1608.07282

Summary

- I also hope this gives the audiences some brief ideas on what can be expected from the 2HDM. I restrict myself from too many technical details.
- Some of the ongoing research topics: the UV origins of the 2HDM (from GUT), the CPV 2HDM (both EDM probes and the collider signatures), and the related topics of the EW phase transitions.