Effective 2HDM Yukawa Interactions and a Strong First-Order Electroweak Phase Transition

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Based upon, arXiv: 2311.06353 , in collaboration with

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LHC Higgs WG3 - Extended Higgs Sector subgroup meeting

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Motivation

- Origin of the baryon asymmetry of the universe (BAU) is an open problem. Bennett et al 1212.5225

- This can be explained through the process of electroweak baryogenesis through Electroweak Phase Transitions (EWPT) with the requirement that these are strong first order (SFO)

  *all three Sakharov conditions are fulfilled. Sakharov '67

$$\xi_c \equiv v_c/T_c > 1$$

- SM fails to achieve SFOEWPT $\Longrightarrow$ a strong hint for the existence of BSM. Kajantie et al '96, Csikor et al '99
  - 2HDM is a well motivated BSM model to achieve SFOEWPT.
  - However, 2HDM Type II as compared to Type I struggles to get SFOEWPT in light of current experimental constraints. Basler et al 1612.04086, Atkinson et al 2107.05650
  - 2HDM Type II potential extended with dimension-6 scalar EFT operators solves the problem along with their implications on Higgs pair production. Anisha et al 2204.06966

- To look for new physics effects, top quark plays a critical role.
  - due to large mass and Higgs coupling ~ 1
    - contribute to SM precision measurements.
    - processes like $t\bar{t}$ pairs act as sensitive probe for BSM states via top couplings

- In this work, our aim is to address the possibility to get SFOEWPT in 2HDM type II with the special focus on top quark
  - by using EFT operators that vary top Yukawa couplings Baldes, Konstandin, Servant 1604.04526
  - further studying the implications of these variations on multi-top final states.

2HDM Type II: Model Information

T.D. Lee '73
Gunion Haber '03
Branco et al 1106.0034

Φ_1 (1,2,1/2), Φ_2 (1,2,1/2)

$$V_{\text{dim-4}}(\Phi_1,\Phi_2) = m_{11}^2(\Phi_1^\dagger\Phi_1) + m_{22}^2(\Phi_2^\dagger\Phi_2) - m_{12}^2(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1) + \lambda_1(\Phi_1^\dagger\Phi_1)^2 + \lambda_2(\Phi_2^\dagger\Phi_2)^2$$
$$+ \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}\lambda_5[(\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2]$$
$$+ \left(\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)\right)\left(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1\right)$$

For $\mathbb{Z}_2$ symmetry, $\lambda_6 = \lambda_7 = 0$

CP even

$$\mathcal{L}_{\text{Yuk}}^{\text{dim-4}} = -Y_1^e\bar{L}\Phi_1 e - Y_2^e\bar{L}\Phi_2 e - Y_1^d\bar{Q}\Phi_1 d - Y_2^d\bar{Q}\Phi_2 d - Y_1^u\bar{Q}\tilde{\Phi}_1 u - Y_2^u\bar{Q}\tilde{\Phi}_2 u + \text{h.c.}$$

where, $\tilde{\Phi} = i\tau_2\Phi^*$

For Type II $$\mathcal{L}_{\text{Yuk}}^{\text{dim-4}} = -Y_1^e\bar{L}\Phi_1 e - Y_1^d\bar{Q}\Phi_1 d - Y_2^u\bar{Q}\tilde{\Phi}_2 u + \text{h.c.}$$

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \zeta_1 + i\psi_1) \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \zeta_2 + i\psi_2) \end{pmatrix}$$

Five physical scalars are related to unphysical fields as

$$\begin{pmatrix} H \\ h \end{pmatrix} = R(\alpha)\begin{pmatrix} \zeta_1 \\ \zeta_2 \end{pmatrix}, \quad \begin{pmatrix} G^0 \\ A \end{pmatrix} = R(\beta)\begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix}, \quad \begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix} = R(\beta)\begin{pmatrix} \phi_1^\pm \\ \phi_2^\pm \end{pmatrix}$$

where, $R(x) = \begin{pmatrix} \cos x & \sin x \\ -\sin x & \cos x \end{pmatrix}$

with α, β are the mixing angles

In mass basis

$$\mathcal{L}_{\text{Yuk}}^{\text{dim-4}} = -\sum_{f=u,d,\ell} \frac{m_f}{v}\left(\xi_h^f\, \bar{f} f h + \xi_H^f\, \bar{f} f H - i\xi_A^f\, \bar{f}\gamma_5 f A\right)$$
$$+\left[\frac{\sqrt{2}V_{ud}}{v}\bar{u}\left(m_d\,\xi_A^d \mathrm{P_R} + m_u\,\xi_A^u \mathrm{P_L}\right) d\, H^+ + \frac{\sqrt{2}}{v} m_\ell\,\xi_A^l (\bar{\nu}\mathrm{P_R}\ell) H^+ + \text{h.c.}\right]$$

In our work, only interested in neutral states

Coupling modifiers

Model	ξ_h^t	$\xi_h^{b(\tau)}$	ξ_H^t	$\xi_H^{b(\tau)}$	ξ_A^t	$\xi_A^{b(\tau)}$
Type II	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cot\beta$	$\tan\beta$

shown only for the third generation fermions

- To modify the scalar-fermion couplings, EFT dimension-6 operators following 2HDM model gauge symmetry are added.

EFT with 2HDM as low scale theory

$$\mathcal{L}_{\text{Yuk}}^{\text{EFT}} = \mathcal{L}_{\text{Yuk}}^{\text{dim-4}} + \sum_i \frac{C_i}{\Lambda^2} O_i$$

Here, O_i are the operators and C_i are the corresponding WCs.

Λ is the EFT cutoff scale

- Operators of class $\Psi^2\Phi^3$ are added to the Yukawa Lagrangian.

Crivellin 1608.00975
Karmakar Rakshit 1707.00716
Anisha et al 1905.11047
Dermisek Hermanek 2405.20511

2HDMEFT dim 6 operators of class $\Psi^2\Phi^3$

$O_{L\tau}^{1(21)}$	$(\bar{L}\tau\Phi_1)(\Phi_2^\dagger\Phi_1)$	$O_{L\tau}^{2(22)}$	$(\bar{L}\tau\Phi_2)(\Phi_2^\dagger\Phi_2)$	$O_{L\tau}^{2(11)}$	$(\bar{L}\tau\Phi_2)(\Phi_1^\dagger\Phi_1)$
$O_{L\tau}^{1(12)}$	$(\bar{L}\tau\Phi_1)(\Phi_1^\dagger\Phi_2)$	$O_{Qb}^{1(21)}$	$(\bar{Q}\,b\,\Phi_1)(\Phi_2^\dagger\Phi_1)$	$O_{Qb}^{2(22)}$	$(\bar{Q}\,b\,\Phi_2)(\Phi_2^\dagger\Phi_2)$
$O_{Qb}^{2(11)}$	$(\bar{Q}\,b\,\Phi_2)(\Phi_1^\dagger\Phi_1)$	$O_{Qb}^{1(12)}$	$(\bar{Q}\,b\,\Phi_1)(\Phi_1^\dagger\Phi_2)$	$O_{Qt}^{2(22)}$	$(\bar{Q}t\tilde{\Phi}_2)(\Phi_2^\dagger\Phi_2)$
$O_{Qt}^{1(12)}$	$(\bar{Q}\,t\,\tilde{\Phi}_1)(\Phi_1^\dagger\Phi_2)$	$O_{Qt}^{2(11)}$	$(\bar{Q}\,t\,\tilde{\Phi}_2)(\Phi_1^\dagger\Phi_1)$	$O_{Qt}^{1(21)}$	$(\bar{Q}\,t\,\tilde{\Phi}_1)(\Phi_2^\dagger\Phi_1)$
$O_{L\tau}^{1(11)}$	$(\bar{L}\tau\Phi_1)(\Phi_1^\dagger\Phi_1)$	$O_{L\tau}^{2(12)}$	$(\bar{L}\tau\Phi_2)(\Phi_1^\dagger\Phi_2)$	$O_{L\tau}^{1(22)}$	$(\bar{L}\tau\Phi_1)(\Phi_2^\dagger\Phi_2)$
$O_{L\tau}^{2(21)}$	$(\bar{L}\tau\Phi_2)(\Phi_2^\dagger\Phi_1)$	$O_{Qb}^{1(11)}$	$(\bar{Q}\,b\,\Phi_1)(\Phi_1^\dagger\Phi_1)$	$O_{Qb}^{2(12)}$	$(\bar{Q}\,b\,\Phi_2)(\Phi_1^\dagger\Phi_2)$
$O_{Qb}^{1(22)}$	$(\bar{Q}\,b\,\Phi_1)(\Phi_2^\dagger\Phi_2)$	$O_{Qb}^{2(21)}$	$(\bar{Q}\,b\,\Phi_2)(\Phi_2^\dagger\Phi_1)$	$O_{Qt}^{1(11)}$	$(\bar{Q}\,t\,\tilde{\Phi}_1)(\Phi_1^\dagger\Phi_1)$
$O_{Qt}^{2(21)}$	$(\bar{Q}\,t\,\tilde{\Phi}_2)(\Phi_2^\dagger\Phi_1)$	$O_{Qt}^{1(22)}$	$(\bar{Q}\,t\,\tilde{\Phi}_1)(\Phi_2^\dagger\Phi_2)$	$O_{Qt}^{2(12)}$	$(\bar{Q}\,t\,\tilde{\Phi}_2)(\Phi_1^\dagger\Phi_2)$

Anisha et al 1905.11047

For Type II $\mathbb{Z}_2$ symmetry is invoked as

for τ, bottom $\Phi_1 \to \Phi_1,\ \Phi_2 \to -\Phi_2$

for top $\Phi_1 \to -\Phi_1,\ \Phi_2 \to \Phi_2$

We ignore all magenta coloured couplings in our analysis.

WCs C_i are taken to be real

Effects of EFT operators

Modifications in the fermion masses

$$\Delta M_\Psi = -\frac{1}{2\sqrt{2}\Lambda^2}\left[C^{1(11)}_{Q\Psi}v_1^3 + v_1^2 v_2(C^{1(12)}_{Q\Psi} + C^{1(21)}_{Q\Psi} + C^{2(11)}_{Q\Psi}) + v_1 v_2^2(C^{1(22)}_{Q\Psi} + C^{2(12)}_{Q\Psi} + C^{2(21)}_{Q\Psi}) + C^{2(22)}_{Q\Psi}v_2^3\right]$$

for $\Psi \equiv \{t, b, \tau\}$

For Type II

$$M_t = \frac{v_2}{\sqrt{2}}\left[Y_2^t - \frac{1}{2\Lambda^2}\left(v_1^2(C^{1(12)}_{Qt} + C^{1(21)}_{Qt} + C^{2(11)}_{Qt}) + C^{2(22)}_{Qt}v_2^2\right)\right]$$

$$M_b = \frac{v_1}{\sqrt{2}}\left[Y_1^b - \frac{1}{2\Lambda^2}\left(C^{1(11)}_{Qb}v_1^2 + v_2^2(C^{1(22)}_{Qb} + C^{2(12)}_{Qb} + C^{2(21)}_{Qb})\right)\right]$$

$$M_\tau = \frac{v_1}{\sqrt{2}}\left[Y_1^\tau - \frac{1}{2\Lambda^2}\left(C^{1(11)}_{L\tau}v_1^2 + v_2^2(C^{1(22)}_{L\tau} + C^{2(12)}_{L\tau} + C^{2(21)}_{L\tau})\right)\right]$$

Considering fermion masses as to be input parameters

$$M_t = \frac{v_2}{\sqrt{2}}\mathcal{Y}_2^t\,, \qquad M_b = \frac{v_1}{\sqrt{2}}\mathcal{Y}_1^b\,, \qquad M_\tau = \frac{v_1}{\sqrt{2}}\mathcal{Y}_1^\tau$$

$\Longrightarrow$

- Dimension-4 Yukawa couplings are redefined
- Shifts in Yukawa also affect the coupling modifiers.

Effects of operators on top quark couplings

Considering only top-quark related operators, redefined Yukawa is

$$Y_2^t \to \mathcal{Y}_2^t + \frac{1}{2\Lambda^2}\Big(v_1^2(C_{Qt}^{1(12)} + C_{Qt}^{1(21)} + C_{Qt}^{2(11)}) + C_{Qt}^{2(22)} v_2^2\Big)$$

With these redefinitions, coupling modifiers also get contributions

Considering only neutral scalar states.

$$\boxed{ht\bar{t}} \qquad \xi_h^t = \frac{\cos\alpha}{\sin\beta} + \frac{v^3}{M_t}\frac{1}{\sqrt{2}\Lambda^2}\Big[-C_{Qt}^{2(22)}\cos\alpha\sin^2\beta + \cos\beta\sin\beta\sin\alpha\left(C_{Qt}^{1(12)} + C_{Qt}^{1(21)} + C_{Qt}^{2(11)}\right)\Big]$$

$$\boxed{Ht\bar{t}} \qquad \xi_H^t = \frac{\sin\alpha}{\sin\beta} + \frac{v^3}{M_t}\frac{1}{\sqrt{2}\Lambda^2}\Big[-C_{Qt}^{2(22)}\sin\alpha\sin^2\beta - \cos\beta\sin\beta\cos\alpha\,(C_{Qt}^{1(12)} + C_{Qt}^{1(21)} + C_{Qt}^{2(11)})\Big]$$

$$\boxed{At\gamma^5\bar{t}} \qquad \xi_A^t = \cot\beta + \frac{v^3}{M_t}\frac{1}{\sqrt{2}\Lambda^2}\Big[\cos\beta\, C_{Qt}^{1(12)}\Big]$$

Reduce to usual 2HDM relations when $\Lambda \to \infty$

Pseudoscalar coupling gets modified with only $C_{Qt}^{1(21)}$

Effective potential at finite temperature

General contributions to effective potential at finite temperature

$$
\begin{aligned}
V_{\text{eff}}(\omega, T) &= V(\omega) + V_T(\omega, T) \\
&= \boxed{V_{\text{dim-4}}(\omega)} + \boxed{V_{\text{CW}}(\omega)} + \boxed{V_{\text{CT}}(\omega)} + \boxed{V_T(\omega, T)}
\end{aligned}
$$

for a classical field configuration ω

- $V_{\text{dim-4}}(\omega)$: Tree level potential
- $V_{\text{CW}}(\omega)$: Coleman-Weinberg potential → One-loop contributions at zero temperature. UV divergences fixed in $\overline{MS}$ scheme. Coleman Weinberg '73
- $V_{\text{CT}}(\omega)$: Counter term potential → To fix the one loop masses and mixing angles to tree level values. Basler et al 1612.04086
- $V_T(\omega, T)$: Temperature dependent thermal mass contributions $\propto T^2, T^4$ → Include self energy corrections to the scalar masses in the high temperature and soft momentum limit. Dolan Jackiw '74, Carrington '92, Quiros '99

To obtain loop corrected effective potential at finite temperature, dim-4 potential is combined with the Yukawa modifications and additional scalar-fermion interactions due to EFT operators.

Effective potential at finite temperature

General contributions to effective potential at finite temperature

$$V_{\text{eff}}(\omega, T) = V(\omega) + V_T(\omega, T)$$

for a classical field configuration ω

$$= V_{\text{dim-4}}(\omega) + V_{\text{CW}}(\omega) + V_{\text{CT}}(\omega) + V_T(\omega, T)$$

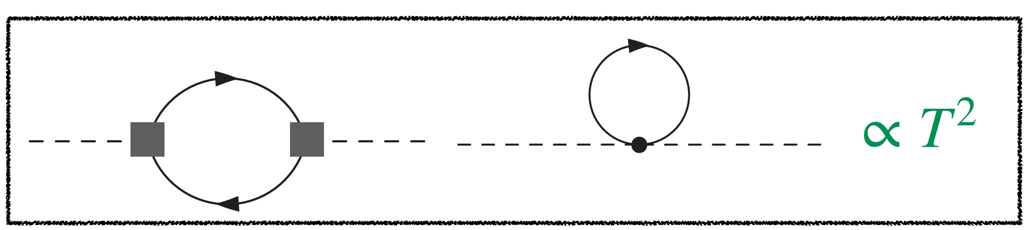
- $V_{\text{dim-4}}(\omega)$: Tree level potential
- $V_{\text{CW}}(\omega)$: Coleman-Weinberg potential
- $V_{\text{CT}}(\omega)$: Counter term potential
- $V_T(\omega, T)$: Temperature dependent thermal mass contributions $\propto T^2, T^4$

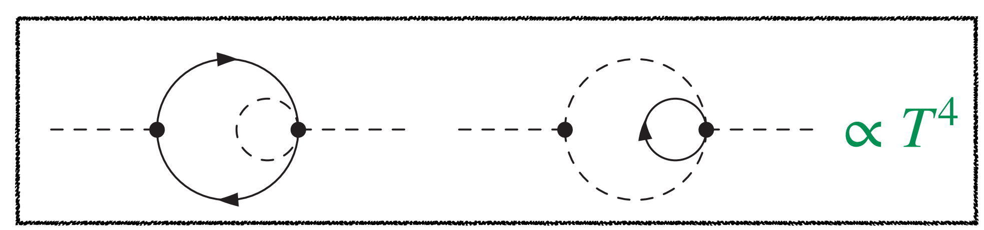
Effects of dim-6 $\Psi^2\Phi^3$ operators

$\Psi^2\Phi^3$ operators → Dim-4 Yukawa modifications → Shift the dim-4 potential

$\Psi^2\Phi^3$ operators → Additional contributions to scalar-fermion interactions (4 and 5 point vertices)

- to the thermal masses due to modified scalar- fermion interactions





The effective potential truncated at dim-6 i.e considered upto $1/\Lambda^2$ in the expansion.

otherwise CT will require dim-8 operators

To obtain the effective potential with the top-quark dim-6 operators, we used BSMPT

Basler Mühlleitner 1803.02846 Basler et al 2007.01725 Basler et al 2404.19037

Model Implementation & Scan Methodology

Scan ranges of the 2HDM dim-4 input parameters

m_h [GeV]	m_H [GeV]	m_A [GeV]	$m_{H^\pm}$ [GeV]	$\tan\beta$	c_{HVV}	m_{12}^2 [GeV^2]
125.09	130...3000	30...3000	800...3000	0.8...30	-0.3...1.0	10^{-5}...10^7

For the WCs ranges, the perturbative values are taken with $\Lambda = 1$ TeV

ScannerS

Coimbra et al 1301.2599

Mühlleitner et al 2007.02985

Parameter points generated are checked for the consistency with the theoretical and experimental constraints.

Unitarity

Vacuum stability

Boundedness from below

HDECAY — branching ratios of scalars

HiggsSignals — Higgs signal strengths

HiggsBounds — Higgs searches from LEP, LHC

Flavour constraints

BSMPT

Basler Mühlleitner 1803.02846

Basler et al 2007.01725

Basler et al 2404.19037

- loop-corrected effective potential is implemented.
- minimisation of loop-corrected potential is done i.e. vacuum structure is explored $\longrightarrow v(T)$ at a given temperature T

Calculates the strength of PT : $\xi_c \equiv v_c/T_c$

For SFOEWPT: $\xi_c \equiv v_c/T_c > 1$

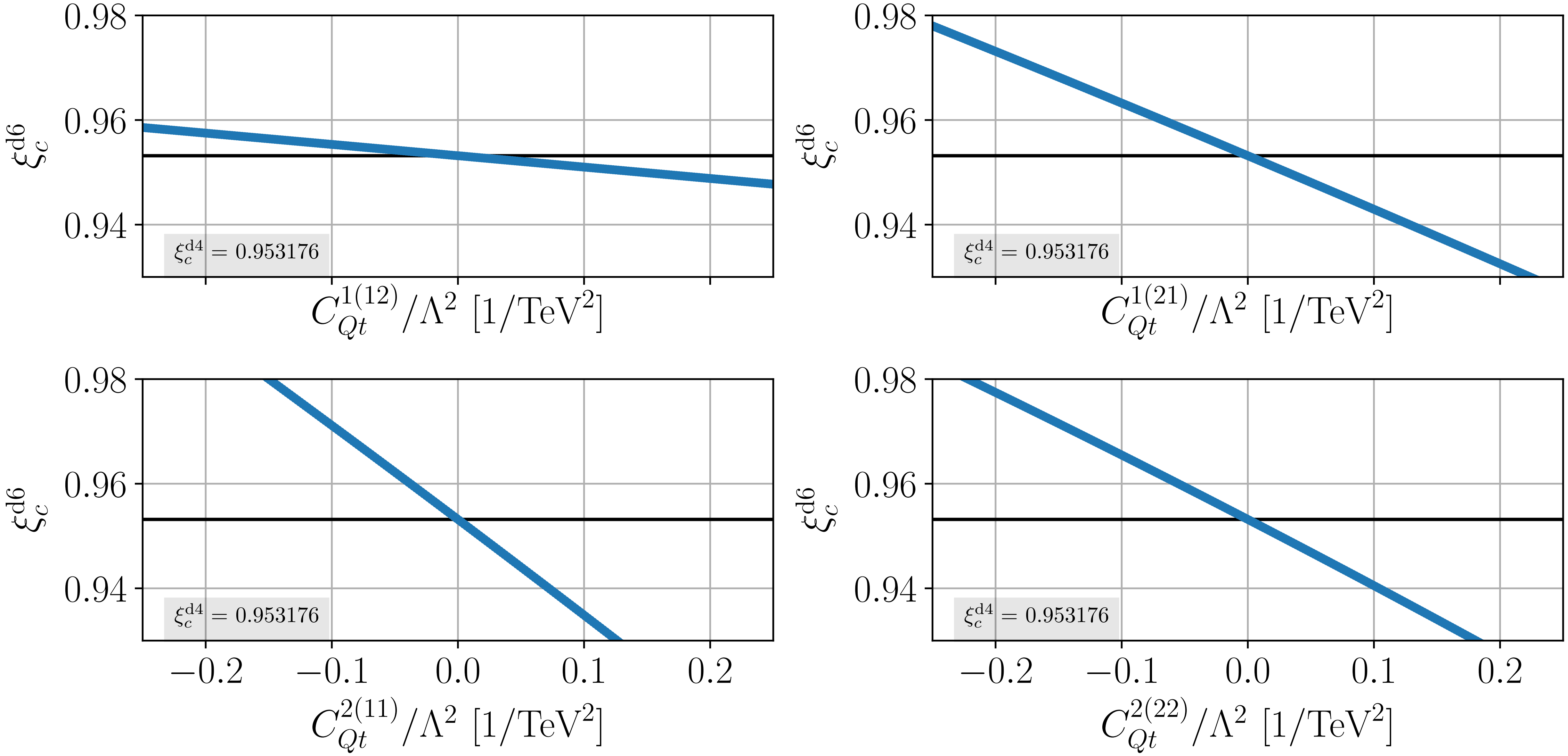
Sample points generated with

- 2HDM type II dim-4 input parameters for which $\xi_c^{\text{d4}} < 1$
- Varying individual WCs to get SFOEWPT i.e. $\xi_c^{\text{d6}} \simeq 1$

Response of the WCs

For a representative parameter point

m_h [GeV]	m_H [GeV]	m_A [GeV]	$m_{H^\pm}$ [GeV]	$\tan\beta$	c_{HVV}	m_{12}^2 [GeV^2]	$\xi_c^{\rm d4}$
125.09	683	872	868	1.658	0.00350	205007	0.95



Linear response of WCs on strength of phase transitions

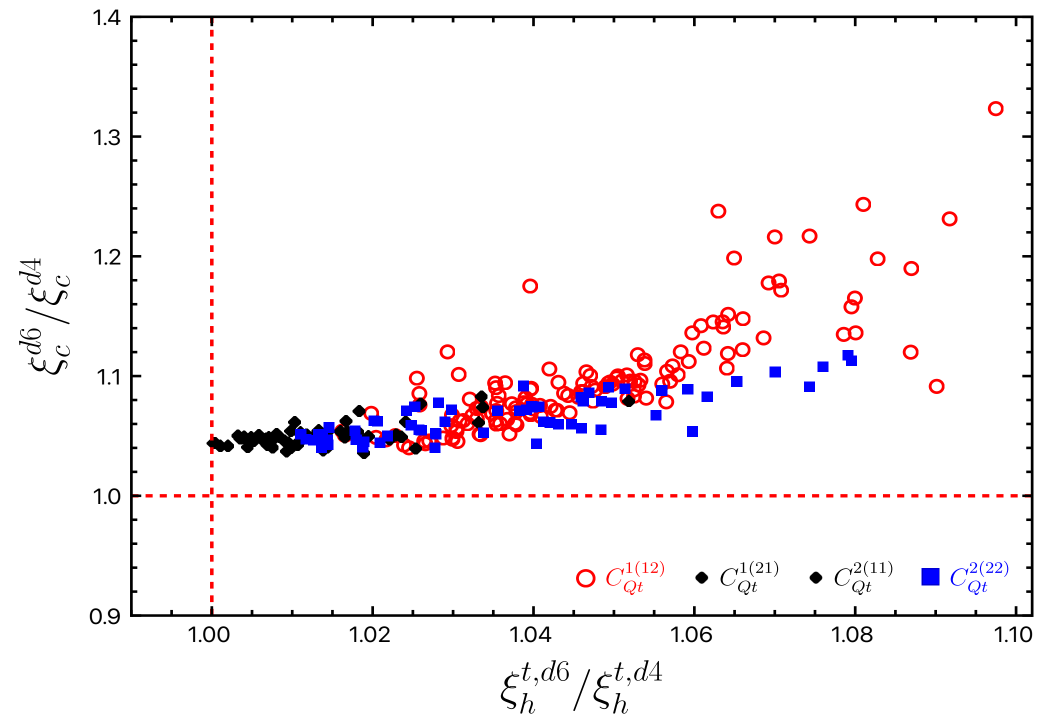
For negative values of WCs, $\xi_c^{\rm d6} \simeq 1$

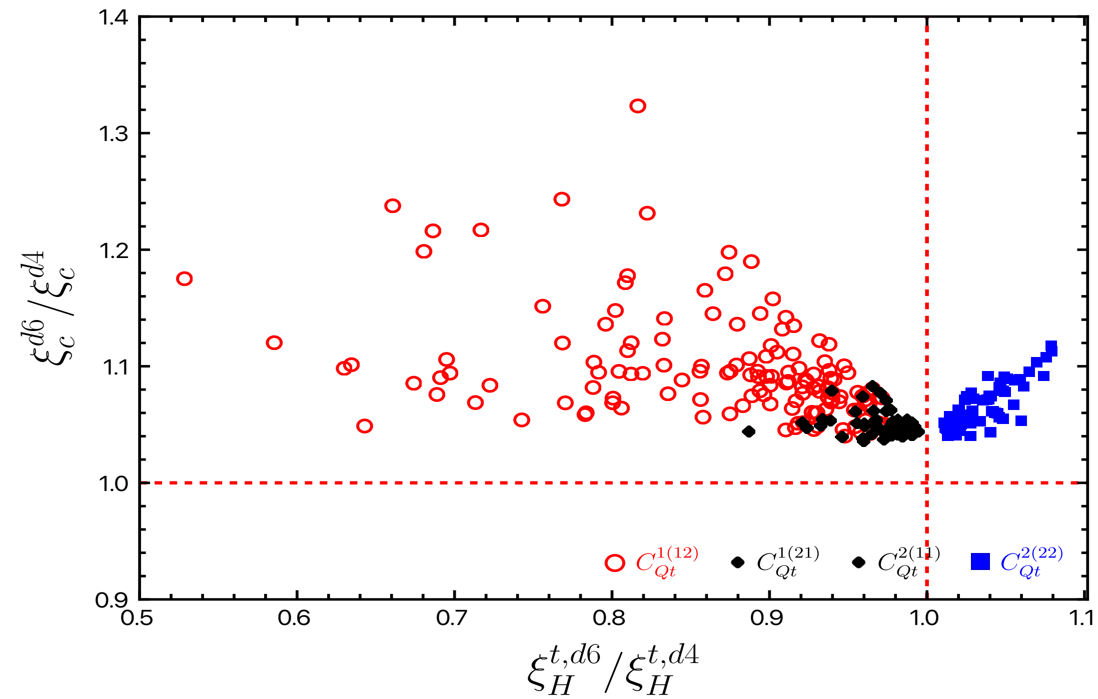
Phenomenological Implications of Top-Philic Phase Transitions

Interplay between coupling modifiers and strength of PT

- Yukawa-sector modifications using WCs enable a stronger phase transition.

$\xi_c^{\rm d4} < 0.96$





- Effect of $O_{Qt}^{1(12)}$ to get $\xi_c^{\rm d6} \to 1$

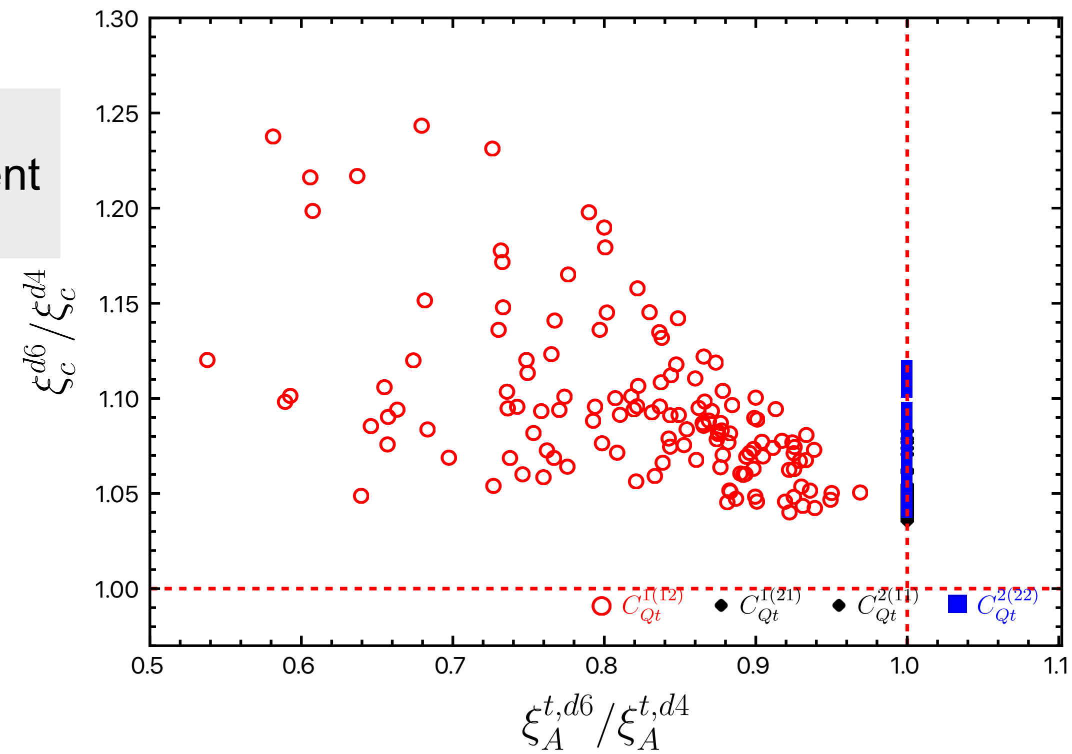
$$\xi_h^t(C_{Qt}^{1(12)}) > \xi_h^t(C_{Qt}^{1(12)} = 0)$$

for light Higgs, coupling modifications are in agreement with current Higgs data

$$\xi_H^t(C_{Qt}^{1(12)}) < \xi_H^t(C_{Qt}^{1(12)} = 0)$$

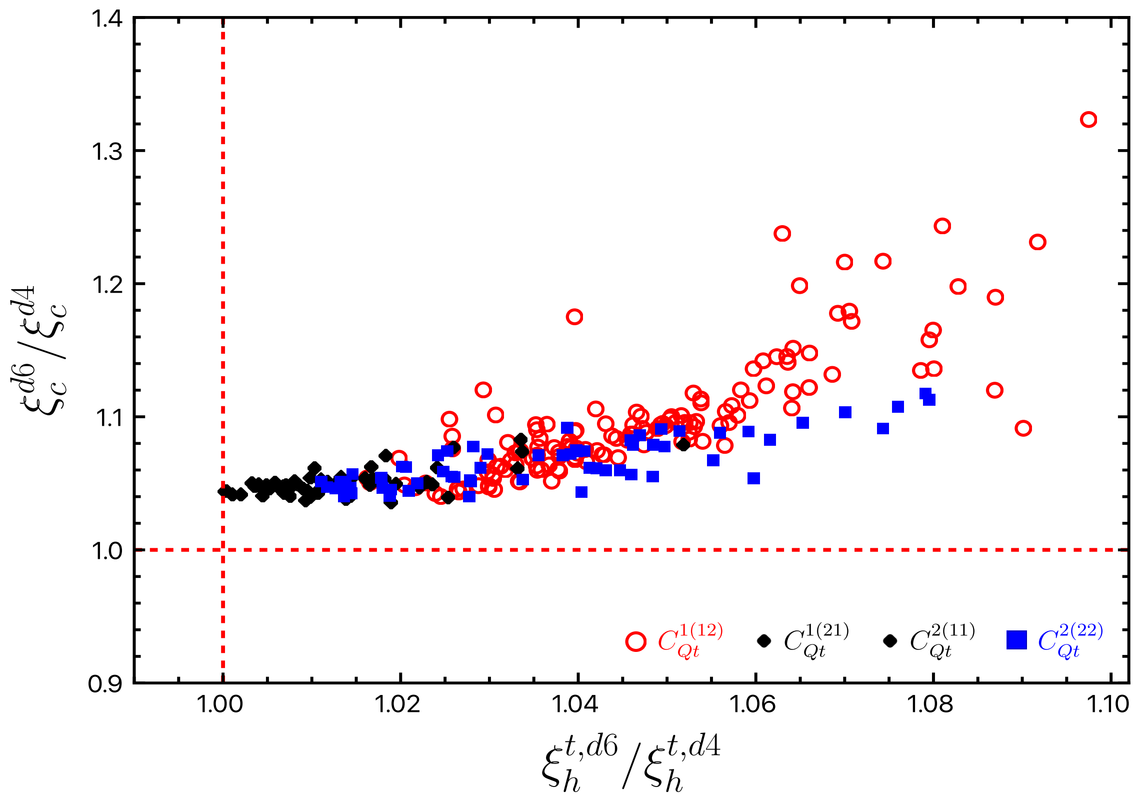
$$\xi_A^t(C_{Qt}^{1(12)}) < \xi_A^t(C_{Qt}^{1(12)} = 0)$$

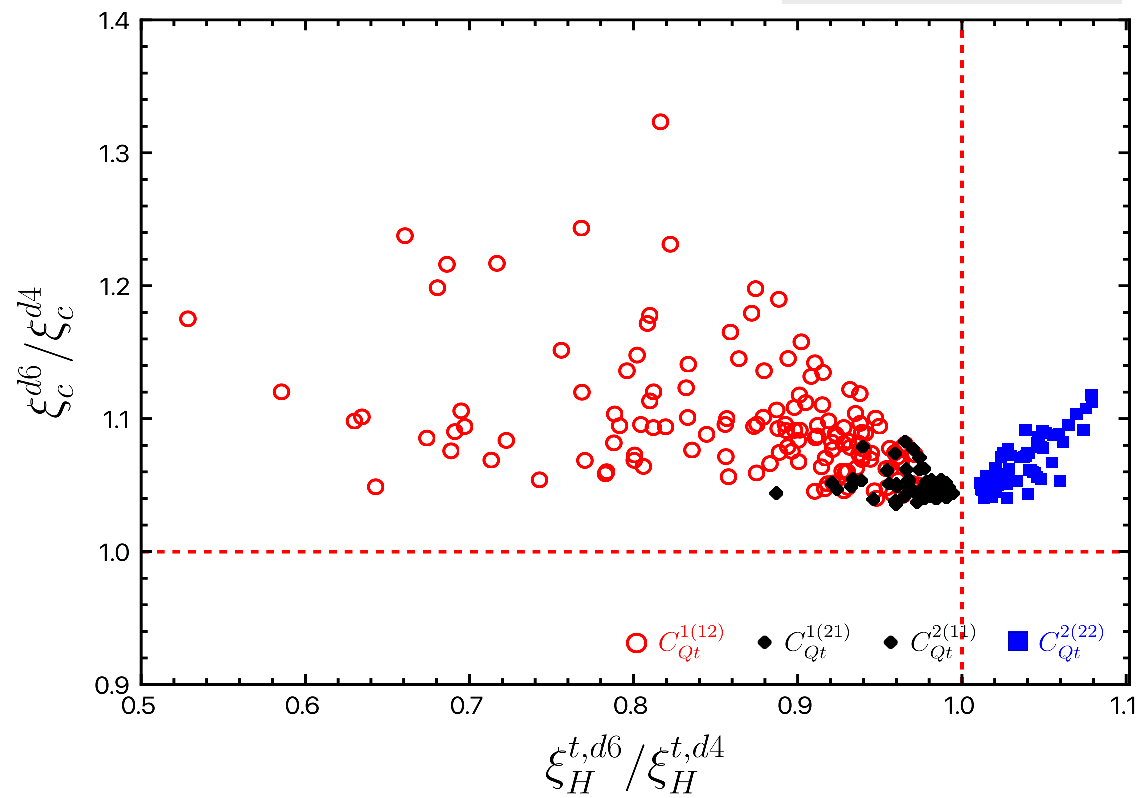
- Similar but reduced effect of $O_{Qt}^{1(21)}, O_{Qt}^{2(11)}$



Interplay between coupling modifiers and strength of PT

$\xi_c^{\rm d4} < 0.96$





- Effect of $O_{Qt}^{2(22)}$
- For both h and H, $\xi^t(C_{Qt}^{2(22)}) > \xi^t(C_{Qt}^{2(22)} = 0)$

  Coupling Modifications are correlated:

$$\left.\frac{\xi_h^{t,\rm d6}}{\xi_h^{t,\rm d4}}\right|_{O_{Qt}^{2(22)}} = \left.\frac{\xi_H^{t,\rm d6}}{\xi_H^{t,\rm d4}}\right|_{O_{Qt}^{2(22)}} = 1 - C_{Qt}^{2(22)}\frac{v^2}{\Lambda^2}\frac{v}{\sqrt{2}M_t}\sin^3\beta$$

- Due to this, the phenomenology modifications for h and H are also fully correlated.
- Coupling modifiers correlations can lead to interesting phenomenology of neutral scalars departing away from dim-4 expectation.

Effects on top pair production

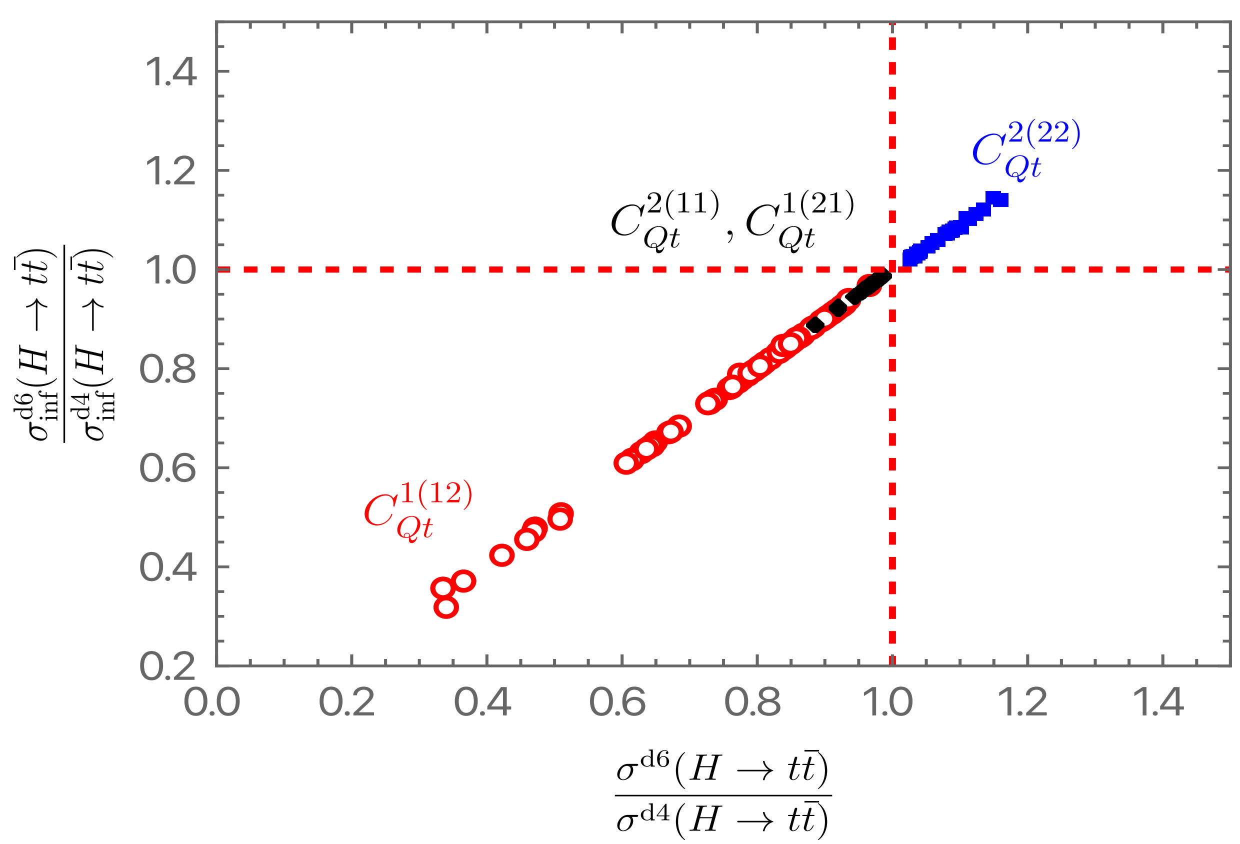
ATLAS 1707.06025
CMS 1908.01115

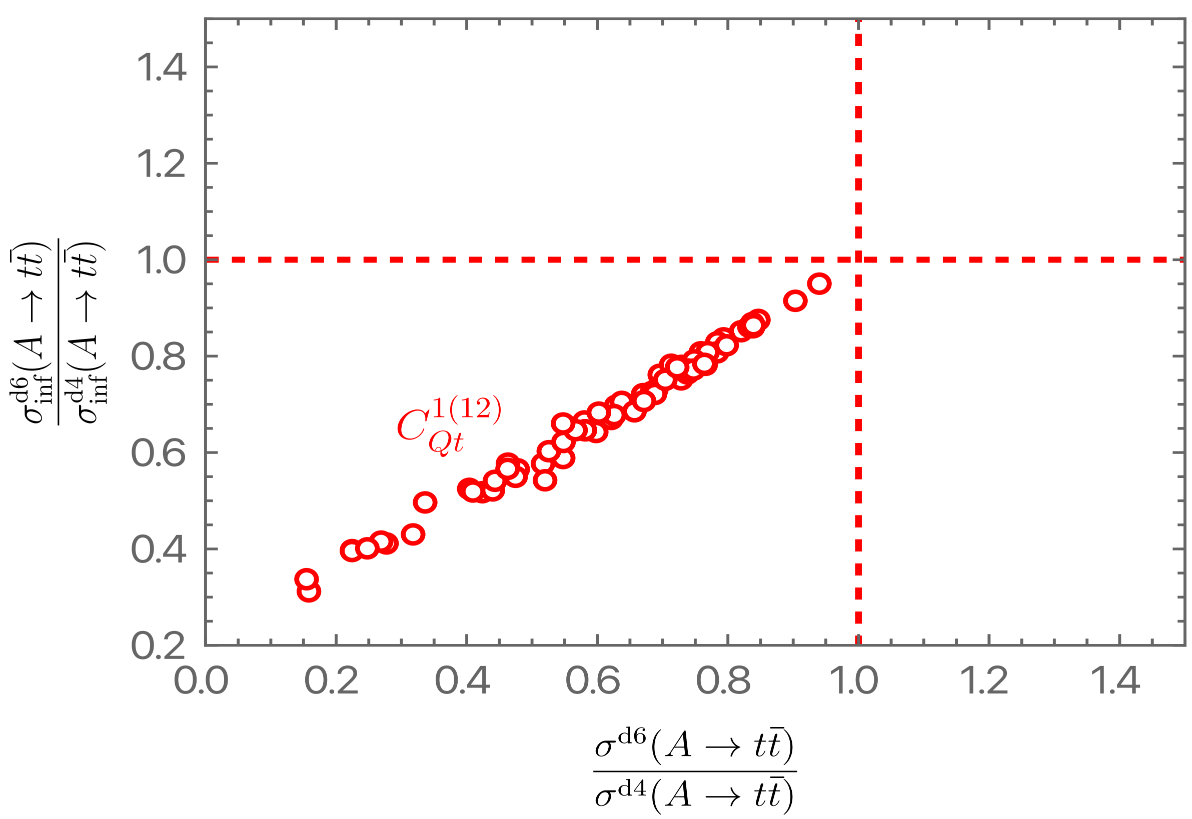
- Prime channel for the effect of top modifications is resonant production of $t\bar{t}$ via exotic scalar.
- In presence of interference, the cross-section is

Gaemers, Hoogeveen '84
Basler et al 1909.09987

$$\mathrm{d}\sigma \sim |\mathcal{M}(gg \to H/A \to t\bar{t})|^2 + 2\,\mathrm{Re}\left\{\mathcal{M}(gg \to H/A \to t\bar{t})\mathcal{M}^*_{\mathrm{bkgd}}\right\}$$

dominant background is QCD induced $gg \to t\bar{t}$





- $O_{Qt}^{1(12)}$ coupling modifications leading to SFOEWPT, decreases signal rate for both H/A states whereas $O_{Qt}^{2(22)}$ increases the signal rate for H.

Interpreted from interplay of coupling modifiers with ξ_c.

- Resonant $t\bar{t}$ pair production is very limited due to destructive signal-background interference.

constraints are weak.

- WCs modifications do not qualitatively change the observed LHC outcome.

Current LHC sensitivity is overestimated for $O_{Qt}^{1(12)}$

Effects on 4 top production

ATLAS 2303.15061
CMS 2305.13439

- Other channel to look for the effect of top Yukawa modifications is the exotic process of $pp \to t\bar{t}t\bar{t}$.

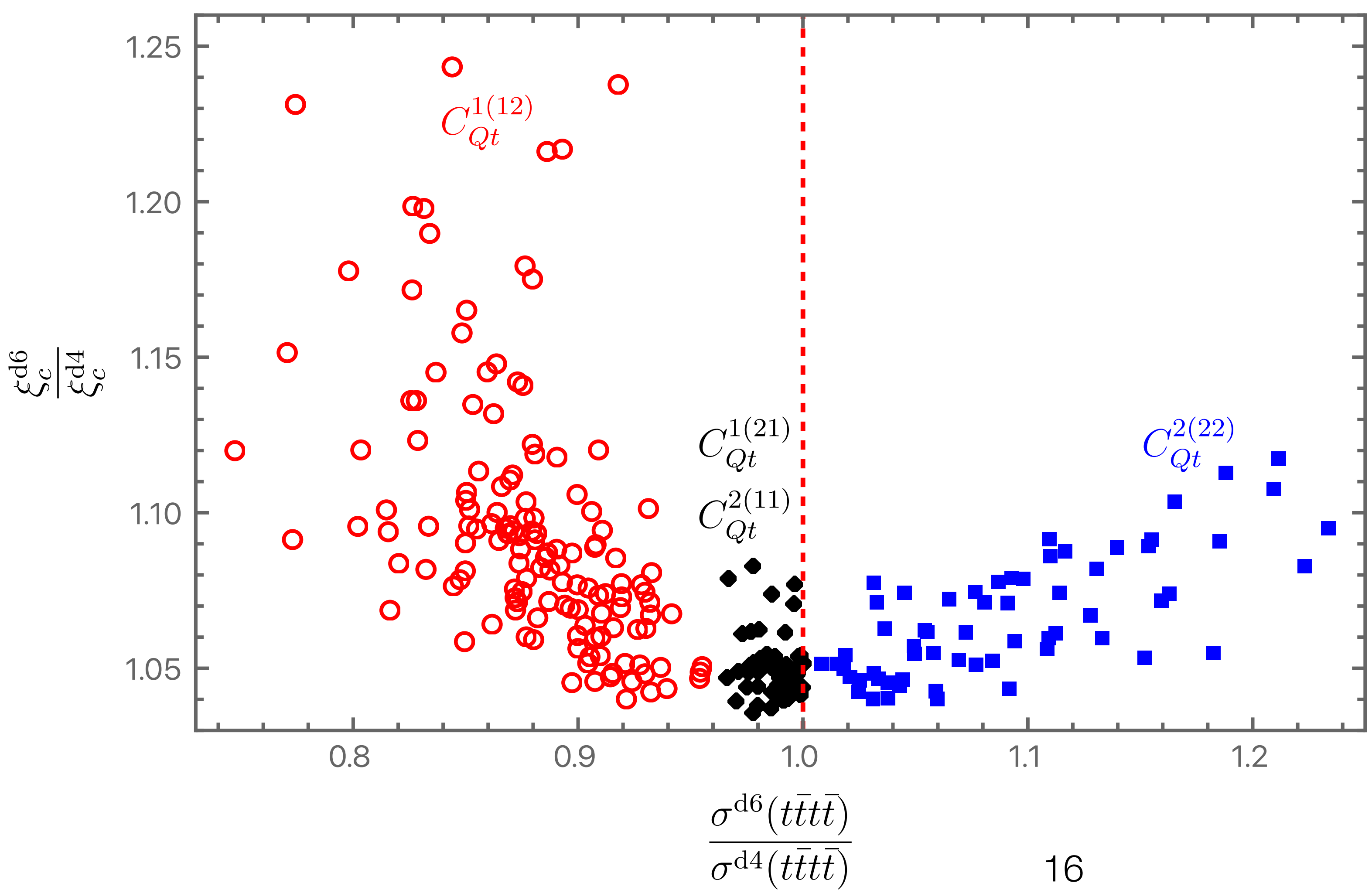
Dev Pilaftsis 1408.3405 Alvarez et al 1611.05032
Alvarez et al 1910.09581 Darmè et al 2104.09512
Blekman et al 2208.04085

- This process is a motivated channel for BSM discoveries with no interference effects.

Anisha et al 2302.08281

- Included all Higgs contributions in s and t channels for the $t\bar{t}t\bar{t}$ production.

- Correlations of modified production cross-section with the modification in the strength of phase transition with different WCs are



Similar effects to $gg \to H/A \to t\bar{t}$

Top-Yukawa modifications to get

$$\xi_c^{d6} \to 1$$

- with $O_{Qt}^{2(22)}$, leads to increase in production cross-section.
- with $O_{Qt}^{1(12)}, O_{Qt}^{1(21)}, O_{Qt}^{2(11)}$ cross-section decreases.

Conclusions

- We studied the effect of adding $\Psi^2\Phi^3$ 2HDMEFT dimension-6 operators to 2HDM type II.
- These operators are added from the prospective to overcome the shortcomings of 2HDM type II to achieve SFOEWPT.
- To drive $\xi_c \to 1$, these top-scalar couplings in agreement with the current experimental constraints, needs to be shifted away from its 2HDM expectations.
- These modifications to get $\xi_c \sim 1$, also lead to implications in the heavy scalars phenomenology predominantly for $O_{Qt}^{1(12)}$ (modifies both CP even and CP-odd)
    - decreased resonant production of $t\bar{t}$, $tt\bar{t}\bar{t}$ via exotic scalar.
    - but this suppression does not impact the current experimental LHC outcome.
- This is an interesting prospect for future LHC exotic Higgs searches, where the phenomenological consequences of the modifications addressing the cosmological shortcomings are explored in light of the sensitivity of future LHC runs.

Thank you for the attention !