Accessing the Electroweak Phase Transition through Top Quark and Higgs Boson Production

Lisa Biermann

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21st Workshop of the LHC Higgs Working Group

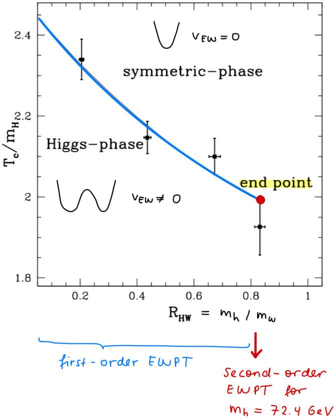
Going Beyond the SM, with Extended Scalar Sectors

- **Extensions** of the Standard Model scalar sector…
  - → Provide $m_h = 125\,\text{GeV}$ in agreement with collider data
    - → Ensured in parameter scans by using `ScannerS` [Coimbra et al. '13; Mühlleitner et al. '20] linked with `HiggsTools` [Bahl et al. '22]
  - → *Additionally* provide…
    - DM candidates
    - New sources of $\mathcal{CP}$ violation
    - **(Strong) first-order electroweak phase transition** (EWPT)

    [Sakharov '67]
    - ⇒ Successful electroweak baryogenesis! [Cohen, Kaplan, Nelson '93; Morrissey, Ramsey-Musolf '12, ..]

Phase diagram of the SM

[Csikor, Fodor, Heitger, '99]



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[Sakharov '67] (New sources of $\mathcal{CP}$ violation; (Strong) first-order electroweak phase transition)

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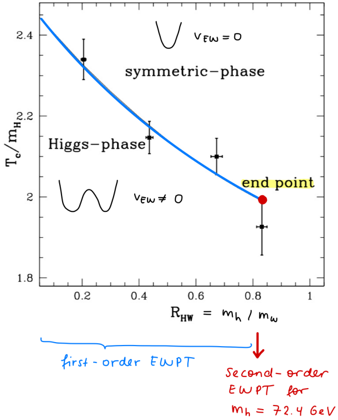

- Extensions considered in this talk:

$$V = \boldsymbol{m_{11}^2|\Phi_1|^2} + m_{22}^2|\Phi_2|^2 - \left[\boldsymbol{m_{12}^2}\Phi_1^\dagger\Phi_2 + \text{h.c.}\right]$$

$$+ \boldsymbol{\frac{\lambda_1}{2}|\Phi_1|^4} + \frac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}\left[\boldsymbol{\lambda_5}(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}\right]$$

$$+ \frac{1}{2}m_S^2\Phi_S^2 + \frac{\lambda_8}{8}\Phi_S^4 + \frac{\lambda_7}{2}|\Phi_1|^2\Phi_S^2 + \frac{\lambda_8}{2}|\Phi_2|^2\Phi_S^2$$

$$- \sum_i \frac{C_6^i}{\Lambda^2}\mathcal{O}_6^i$$

w/ softly broken $\mathbb{Z}_2$ symmetry ($\Phi_{1,2} \to \pm\Phi_{1,2}$)

2HDM = Two-Higgs Doublet Model [Lee '73; Ginzburg, Krawczyk, Osland '02; Gunion, Haber '03; Branco et al. '12; ..]

R2HDM: $\{m_{12}^2,\ \lambda_5\} \in \mathbb{R} \ \to \{h,\ H,\ A,\ H^\pm\}$

C2HDM: $\{m_{12}^2,\ \lambda_5\} \in \mathbb{C} \ \to \{h_1,\ h_2,\ h_3,\ H^\pm\}$

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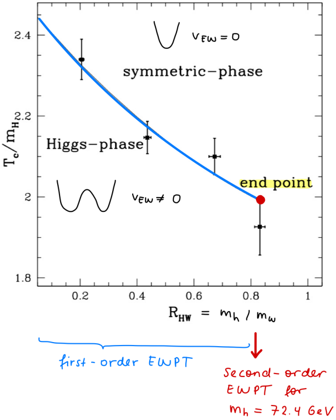

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$$- \sum_i \frac{C_6^i}{\Lambda^2}\mathcal{O}_6^i$$

N2HDM = Next-to-Minimal 2HDM
[He et al. '09; Grzadkowski, Osland '10; Logan '11; Boucenna, Profumo '11; Mühlleitner et al '19; ..]

w/ softly broken $\mathbb{Z}_2$ symmetry: $\Phi_{1,2} \to \pm\Phi_{1,2},\ \Phi_S \to \Phi_S$
$\mathbb{Z}_2'$ symmetry: $\Phi_{1,2} \to \Phi_{1,2},\ \Phi_S \to -\Phi_S$

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  [Sakharov '67] (for the last two items)

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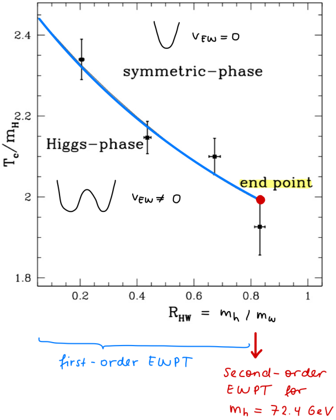

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$$-\sum_i \frac{C_6^i}{\Lambda^2}\mathcal{O}_6^i$$

w/ softly broken $\mathbb{Z}_2$ symmetry ($\Phi_{1,2} \to \pm\Phi_{1,2}$)

2HDM-EFT = 2HDM Effective Field Theory

[Crivellin et al. '16; Karmakar, Rakshit '17; Banerjee et al. '20; ..]

Studying Phase Transitions with BSMPT

v1: P. Basler, M. Mühlleitner [arXiv:1803.02846]
v2: P. Basler, M. Mühlleitner, J. Müller [arXiv:2007.01725]
v3: P. Basler, **LB**, M. Mühlleitner, J. Müller, R. Santos, J. Viana [arXiv:2404.19037] *new!*

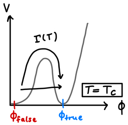
Get it: `https://github.com/phbasler/BSMPT` !

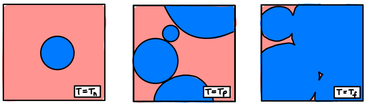
- Model-independent implementation of the one-loop daisy-resummed effective potential at finite temperature

$$V^{(1)}(\omega, T) = \underbrace{V^{(0)}(\omega)}_{\text{tree-level}} + \underbrace{V^{\text{CW}}(\omega)}_{T\text{-indep.}} + \underbrace{V^{T}(\omega, T)}_{T\text{-dep.}} + \underbrace{V^{\text{CT}}(\omega)}_{\text{finite shift}}$$

$V^{(0)}(\omega)$	$V^{\text{CW}}(\omega)$	$V^{T}(\omega, T)$	$V^{\text{CT}}(\omega)$
tree-level	T-indep. *Coleman-Weinberg* potential, renormalized in $\overline{MS}$-scheme	T-dep., UV finite, IR finite after resummation $m^2 \to m^2 + \Pi^{(1)}(0)$	finite shift of scalar masses and mixing angles, OS-scheme
	[S. Coleman, E. Weinberg, 1973]	[M. Carrington, 1992], [R. Parwani, 1992], [P. Arnold, O. Espinosa, 1993]	[P. Basler et al., 2017]

- v3:
  - Multi-step phase tracking
  - Calculation of the false vacuum decay and characteristic temperatures
  - Sourced gravitational wave spectra





- 'Strength' of the first-order EWPT:

$$\xi(T) \equiv \frac{\overline{\omega}_{\text{EW}}(T)}{T}, \quad \overline{\omega}_{\text{EW}}(T=0) = 246\,\text{GeV}$$

Strong first-order EWPT: $\boxed{\xi_c \equiv \xi(T=T_c) \gtrsim 1}$ (baryon wash-out condition) [Morrissey, Ramsey-Musolf '12]

but: PT takes place at $T \sim T_p < T_c$

(T_c only prerequisite for PT $\to$ vacuum trapping! [Baum et al. '21; Biekötter et al. '21/'23])

Electroweak Phase Transitions from a Collider Angle

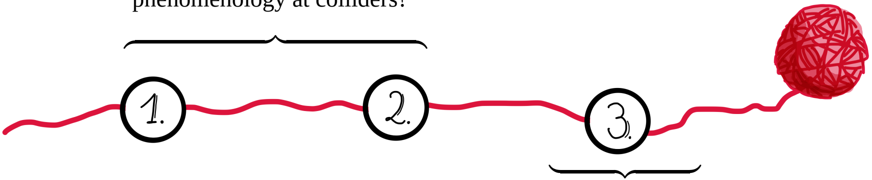
Anisha, D. Azevedo, **LB**, C. Englert, M. Mühlleitner [arXiv:2311.06353]

$\bar{f} f \phi^3$

Anisha, **LB**, C. Englert, M. Mühlleitner [arXiv:2204.06966]

ϕ^6

How do 2HDM-EFT modifications that lead to $\xi_c^{\mathrm{d6}} \gtrsim 1$ impact phenomenology at colliders?



How does an EWPT imprint on multi-Higgs production?

LB, C. Borschensky, C. Englert, M. Mühlleitner, W. Naskar [arXiv:2408.08043]

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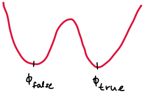
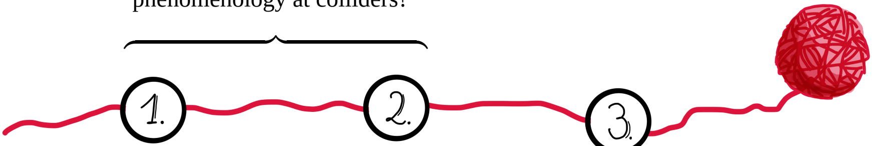


How do 2HDM-EFT modifications that lead to $\xi_c^{\mathrm{d6}} \gtrsim 1$ impact phenomenology at colliders?

$\rightarrow$ Using $\xi_c \gtrsim 1$ condition (prerequisite for an EWPT)



EWPT identified via $\xi_p \gtrsim 1 \leftarrow$ (EWPT takes place)

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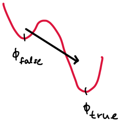

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Scalar-Fermion Dim-6 2HDM-EFT

Anisha, D. Azevedo, **LB**, C. Englert, M. Mühlleitner
[arXiv:2311.06353]

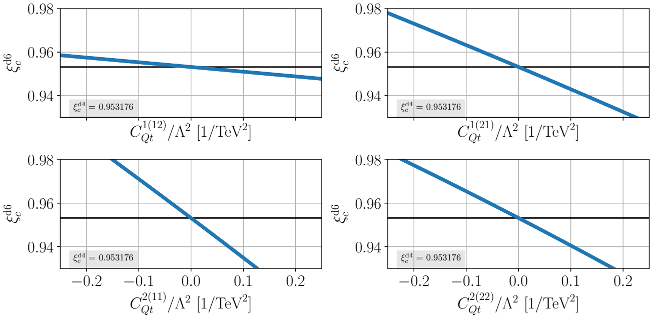
- Can we have **dim-6 enhanced** EWPTs in a Type-2 2HDM with

$$\xi_c^{\mathrm{d4}} < 1 \xrightarrow{\text{dim-6}} \xi_c^{\mathrm{d6}} \gtrsim 1\,?$$

- 2HDM extended by dim-6 top-Yukawa modifications:

$$V_{\mathrm{d6}}^{(0)} = V_{\mathrm{d4}}^{(0)}(\Phi_1,\,\Phi_2) - \sum_{ijk} \frac{C_{Qt}^{i(jk)}}{\Lambda^2} \mathcal{O}_{Qt}^{i(jk)}$$

$\mathcal{O}_{Qt}^{1(12)}$	$(\overline{Q}_L\, t_R\, \widetilde{\Phi}_1)(\Phi_1^\dagger \Phi_2)$
$\mathcal{O}_{Qt}^{1(21)}$	$(\overline{Q}_L\, t_R\, \widetilde{\Phi}_1)(\Phi_2^\dagger \Phi_1)$
$\mathcal{O}_{Qt}^{2(11)}$	$(\overline{Q}_L\, t_R\, \widetilde{\Phi}_2)(\Phi_1^\dagger \Phi_1)$
$\mathcal{O}_{Qt}^{2(22)}$	$(\overline{Q}_L\, t_R\, \widetilde{\Phi}_2)(\Phi_2^\dagger \Phi_2)$



→ **Perturbativity** ensured by requiring linear response in ξ_c^{d6} when varying $C_{Qt}^{i(jk)}/\Lambda^2$

⇒ SFOEWPT achievable in agreement with exp. constraints ✓

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- Redefinition of Yukawa coupling to obtain dim-4 Yukawa interaction shifts dim-6 effects into coupling modifiers

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

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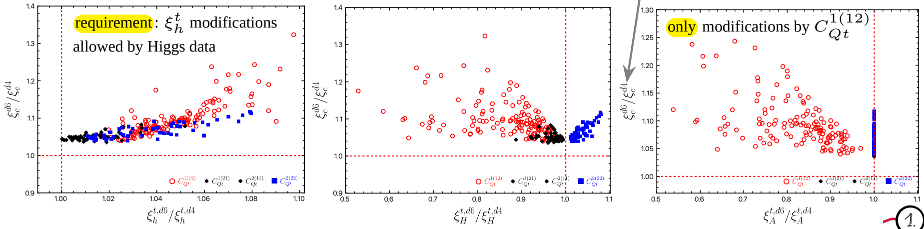
$A t \gamma_5 \bar{t}$: $$\xi_A^t = \cot\beta + \frac{v^3}{M_t}\frac{1}{\sqrt{2}\Lambda^2}\left[\cos\beta\; C_{Qt}^{1(12)}\right]$$

Coupling modifications for $\xi_c^{\rm d6} \gtrsim 1$ (individual C_{Qt}^i choices):

$1 - \xi_c^{\rm d4}$ limited mostly by h signal strength constraints

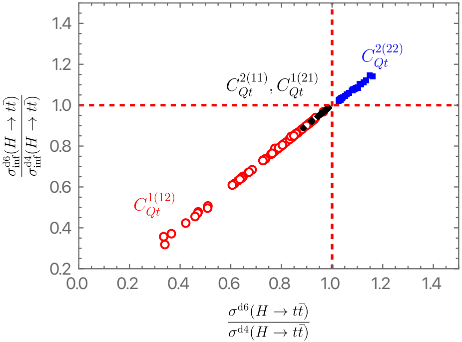


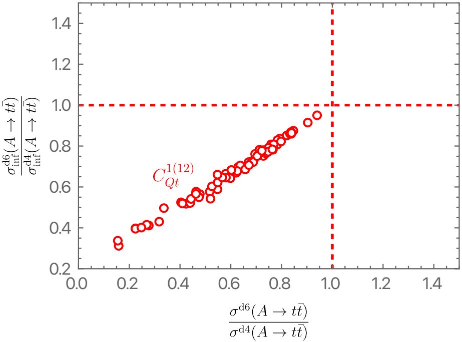
$t\bar{t}$ production

Anisha, D. Azevedo, **LB**, C. Englert, M. Mühlleitner [arXiv:2311.06353]

resonant production: $\sigma(H/A \to t\bar{t}) \propto |\mathcal{M}(gg \to H/A \to t\bar{t})|^2$

interference: $\sigma_{\text{inf}} \propto \text{Re}\{\mathcal{M}(gg \to H/A \to t\bar{t})\mathcal{M}^*(gg \to t\bar{t})\}$





- Underabundance of resonant H/A production if $\xi_c^{\text{d6}} \gtrsim 1$ achieved through variation of $C_{Qt}^{1(12)}$

$\Rightarrow$ If SFOEWPT realized via $C_{Qt}^{1(12)}$ the current LHC BSM sensitivity is *overestimated*!

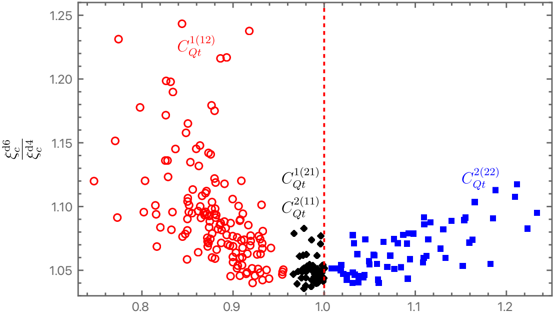
- $C_{Qt}^{2(22)}$ can lead to a 20 % enhancement for $H \to t\bar{t}$ while $A \to t\bar{t}$ is unchanged

$\to$ *But*: Sensitivity for resonant $t\bar{t}$ production is already limited at dim-4 due to destructive signal-background interference [Gaemers, Hoogeveen, ’84; Jung, Song, Yoon ’15; Basler et al. ’19]

$\Rightarrow$ Possible further reduction in signal rate does not change observed outcome qualitatively, experimental strategies remain valid

$t\bar{t}t\bar{t}$ production

Anisha, D. Azevedo, **LB**, C. Englert, M. Mühlleitner [arXiv:2311.06353]



includes all Higgs contributions in s and t channels

- Four-top final state does not suffer from destructive signal-background interference
  $\rightarrow$ Sensitivity to resonances not limited by interference!
  [Kanemura et al. '15; Alvarez et al. '17/'19; Blekman et al. '22; Anisha et al. '23]

$\rightarrow$ **Increase** of cross section via $C_{Qt}^{2(22)}$

$\rightarrow$ **Decrease** of cross section via $C_{Qt}^{1(12)}$ and $C_{Qt}^{1(21)}$, $C_{Qt}^{2(11)}$ $\Rightarrow$ **LHC sensitivity** *overestimated*!

Purely Scalar Dim-6 2HDM-EFT

Anisha, **LB**, C. Englert, M. Mühlleitner [arXiv:2204.06966]

- Can we have **dim-6 enhanced** strong first-order EWPTs in a Type-2 2HDM?

$$\xi_c^{\mathrm{d4}} < 1 \xrightarrow{\text{dim-6}} \xi_c^{\mathrm{d6}} \gtrsim 1$$

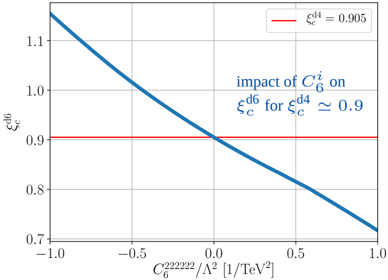
2HDM extended by scalar dim-6 operators:

$$V_{\mathrm{d6}}^{(0)} = V_{\mathrm{d4}}^{(0)}(\Phi_1, \Phi_2) - \sum_i \frac{C_6^i}{\Lambda^2} \mathcal{O}_6^i$$

$\mathcal{O}_6^{111111}$	$(\Phi_1^\dagger\Phi_1)^3$	$\mathcal{O}_6^{222222}$	$(\Phi_2^\dagger\Phi_2)^3$
$\mathcal{O}_6^{111122}$	$(\Phi_1^\dagger\Phi_1)^2(\Phi_2^\dagger\Phi_2)$	$\mathcal{O}_6^{112222}$	$(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)^2$
$\mathcal{O}_6^{122111}$	$(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)(\Phi_1^\dagger\Phi_1)$	$\mathcal{O}_6^{122122}$	$(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)$
$\mathcal{O}_6^{121211}$	$(\Phi_1^\dagger\Phi_2)^2(\Phi_1^\dagger\Phi_1)$ + h.c.	$\mathcal{O}_6^{121222}$	$1(\Phi_1^\dagger\Phi_2)^2(\Phi_2^\dagger\Phi_2)$ + h.c.

- Absorb dim-6 contributions (to scalar mass matrix) in shifts $\lambda_i \to \lambda_i + \delta\lambda_i$ and $m_{12}^2 \to m_{12}^2 + \delta m_{12}^2$

⇒ Shift of EFT effects into **Higgs self-couplings** and **multi-Higgs final states**

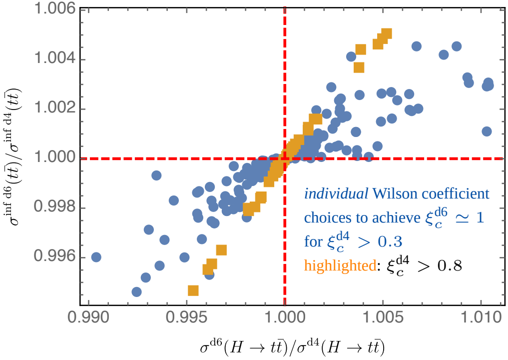


⇒ Linear response $\sim C_6^i \to$ perturbativity ✓

⇒ SFOEWPT achievable in agreement with experimental constraints ✓

$t\bar{t}$ production

Anisha, **LB**, C. Englert, M. Mühlleitner [arXiv:2204.06966]



- **Top-philic** exotic Higgs with $\text{BR}(H \to t\bar{t}) \gtrsim 0.8$

$\rightarrow$ Prime candidate for exotic Higgs discovery

$$d\sigma \propto |\underbrace{\mathcal{M}(gg \to H \to t\bar{t})}_{\text{resonant production}}|^2 + \underbrace{2\,\text{Re}\{\mathcal{M}(gg \to H \to t\bar{t})\overbrace{\mathcal{M}^*(gg \to t\bar{t})}^{\text{QCD continuum}}\}}_{\text{interference cross section} \equiv \sigma^{\text{inf}}}$$

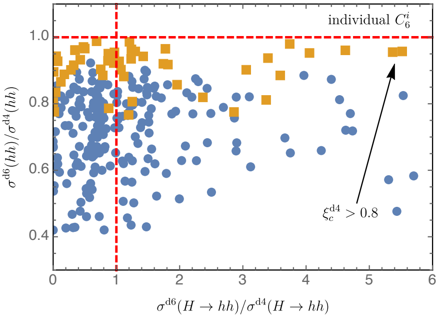
can be *destructive* [Gaemers, Hoogeveen, ’84; Jung, Song, Yoon ’15; Basler et al. ’19]

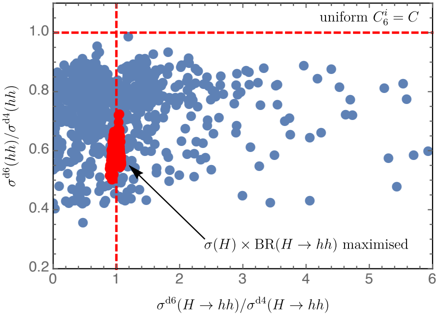
$\rightarrow$ $(1 - \xi_c^{\text{d4}}) \propto$ resonant modifications

$\Rightarrow$ **No** phenomenologically observable modifications neither for resonant production, nor for interference

hh production

Anisha, **LB**, C. Englert, M. Mühlleitner
[arXiv:2204.06966]





Individual C_6^i for $\xi_c^{d6} \simeq 1$

→ **Decreased** continuum $\propto (1 - \xi_c^{d4})$ due to enhancement of λ_{hhh} up to $\mathcal{O}(50\,\%)$
[Baglio et al. '20]

→ **Resonant** modifications up to factor 6 correlated with modification of λ_{Hhh}

⇒ Constraining ξ_c via *separate* measurement of continuum and on-shell H production (*but* low BR $(H \to hh)$)

Uniform C_6^i for $\xi_c^{d6} \simeq 1$

on-shell production and di-Higgs continuum less statistically limited

- **Top-philic** sample plus **Higgs-philic** sample
- Higgs-philic H suffer from low $\xi_c^{d4} \to$ large Higgs potential modifications are required to achieve $\xi_c^{d6} \gtrsim 1 \to$ decreased continuum ratio down to $-50\,\%$

→ Resonant enhancements up to 2.5 for cross section values of $\mathcal{O}(\mathrm{fb})$

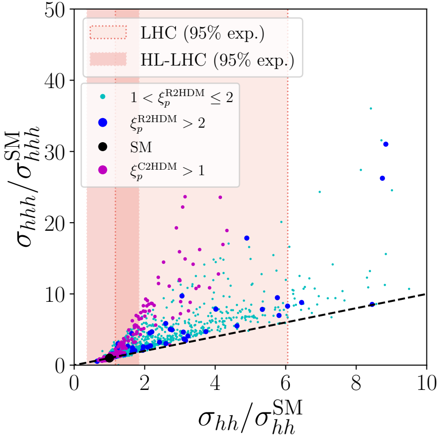
⇒ Anticipate LHC sensitivity in $b\bar{b}b\bar{b}$ and $b\bar{b}\tau\bar{\tau}$ channels!

Probing the EWPT via hh and hhh

LB, C. Borschensky, C. Englert, M. Mühlleitner, W. Naskar
[arXiv:2408.08043]

- Additional resonantly produced BSM scalars can lead to large enhancements of $hh(h)$ rates
  [Basler et al. '19; Abouabid et al. '22; Dawson et al. '23; Stylianou, Weiglein '24]

talk by **Osama Karkout** on Thursday
on multi-Higgs production and EWPTs
in the Two-Real-Singlet model
[Karkout et al., '24]



- hh and hhh cross sections can be enhanced for $\xi_p > 1$ (while showing clear correlation)

→ Relative enhancement larger for hhh

→ **R2HDM**: $H \to hh$ probed in wider kinematic range through nested Hh production and new resonant $H \to hhh$ decays

→ **C2HDM**: additional neutral ($\mathcal{CP}$-mixed) resonances lead to even larger enhancement of hhh over hh

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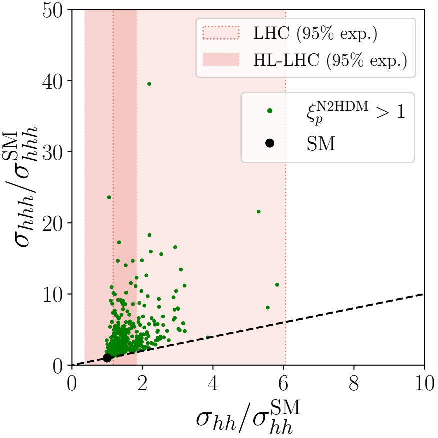


→ **N2HDM**: hhh enhanced by factor of 20 compared to hh enhancement while *not* showing overly anomalous behaviour in hh

⇒ Look for hhh even if hh seems SM-like!

Conclusions

- BSM physics that allows for a **strong first-order EWPT** (SFOEWPT) might be close to the TeV scale with LHC-relevant implications:

→ Modifications of the top-Higgs interactions in a 2HDM allow for an SFOEWPT and can (further) reduce sensitivity in $t\bar{t}$ and $t\bar{t}t\bar{t}$

→ Purely scalar dynamics that drive an SFOEWPT for a 2HDM modify $t\bar{t}$ (not measurable) and hh (continuum reduction and **resonant enhancement** within LHC reach)

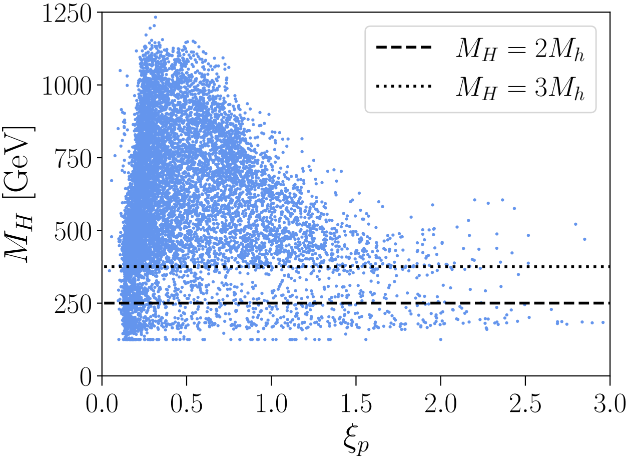
→ Significant **enhancement of triple Higgs production rate** possible together with almost SM-like di-Higgs production in N2HDM for SFOEWPT points!

⇒ We can derive indirect constraints on the EWPT from top-pair and multi-Higgs production measurements!

Thanks!

Mass Spectrum and ξ_p

LB, C. Borschensky, C. Englert, M. Mühlleitner, W. Naskar
[arXiv:2408.08043]



→ EWPT driven by light spectra of BSM scalars

→ Stronger PTs: Most points have correlated resonant $H \to hh$ and $Hh \to hhh \to$ wider phase space $\Rightarrow$ larger hhh enhancement

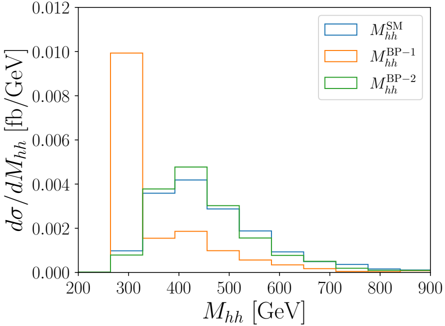
Invariant Mass Distributions

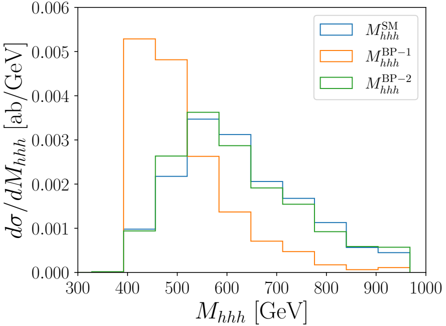
LB, C. Borschensky, C. Englert, M. Mühlleitner, W. Naskar [arXiv:2408.08043]

BP1: largely enhanced
(hhh enhancement $\times 4$ larger than hh enhancement)
$m_H \simeq 2m_h$

BP2: SM-like point

BPs	$\sigma_{hh}/\sigma_{hh}^{\text{SM}}$	$\sigma_{hhh}/\sigma_{hhh}^{\text{SM}}$	M_H [GeV]
BP1 (largely enhanced)	3.24	15.26	274.29
BP2 (SM-like)	1.02	1.02	469.30





- Large enhancement in resonance region
- Underproduction for $M_{hh} \gtrsim m_H$ (destructive interference between triangle and box topologies enhanced)

- Threshold region $M_{hhh} \simeq 3m_h$ probes wider range of $M_{h_i h_j} \simeq 2m_H$ enhancement ($pp \to Hh,\ H \to hh$)

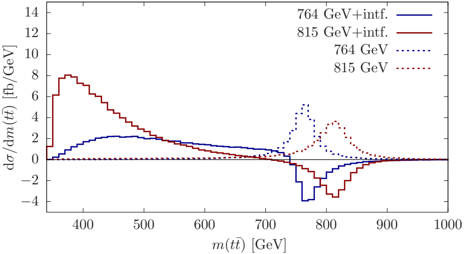
$\to$ Comparably larger enhancement of hhh compared to hh

Interference in $t\bar{t}$ vs in $t\bar{t}t\bar{t}$

Top-Pair Production $t\bar{t}$

[Gaemers, Hoogeveen, '84; Jung, Song, Yoon '15]

P. Basler, S. Dawson, C. Englert, M. Mühlleitner
[arXiv:1909.09987]

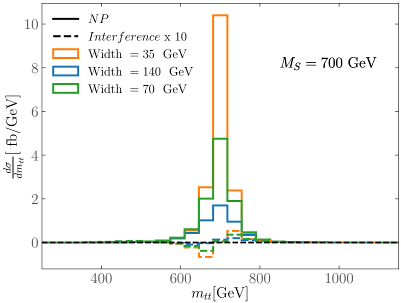


- Destructive interference between $gg \to H_i \to t\bar{t}$ and non-resonant amplitude contribution $gg \to t\bar{t}$

$\rightarrow$ Resonance is removed by interference!

Four-Top Final State $t\bar{t}t\bar{t}$

Anisha, O. Atkinson, A. Bhardwaj, C. Englert, W. Naskar
[arXiv:2302.08281]



$\Rightarrow$ Resonance is robust against interference!