

\* **based on:** *Two Higgs doublets, Effective Interactions and a Strong First-Order Electroweak Phase Transition*  
by Anisha, LB, Christoph Englert and Margarete Mühlleitner  
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# Linking Higgs pair production with a strong first-order electroweak phase transition in a 2HDM-EFT \*

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19th Workshop of the LHC Higgs Working Group

# Baryon Asymmetry of the Universe (BAU)

initial: *Big Bang* (symmetric universe)  $\Leftrightarrow$  today: **BAU** (asymmetric universe)

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departure from thermal equilibrium  $\Rightarrow$  electroweak phase transition (EWPT)

[D. Kirznits, 1972], [L. Dolan, R. Jackiw, 1974]

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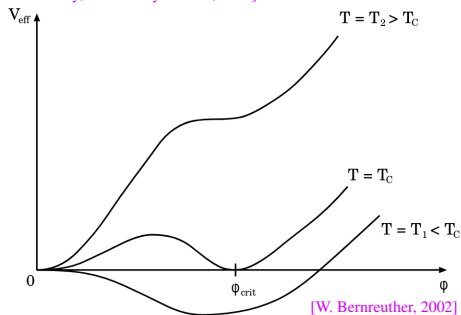
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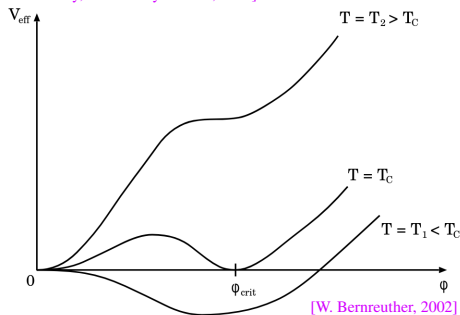
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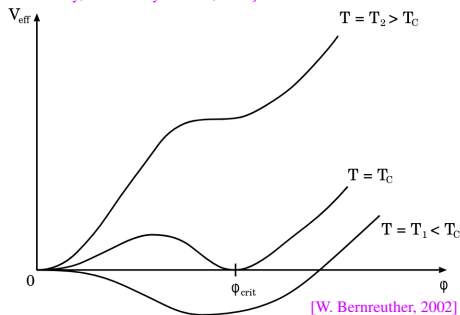
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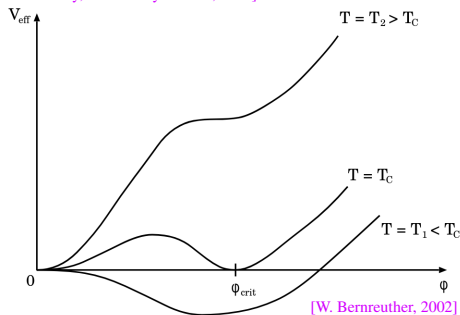
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⇒ need BSM models that enable an **SFOEWPT\*** + *non-standard CPV*



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**What are the phenomenological implications on Higgs-Pair production?**

# Model Framework

- CP-conserving 2HDM, **softly broken** discrete  $\mathbb{Z}_2$  symmetry:  $\Phi_1 \rightarrow -\Phi_1, \Phi_2 \rightarrow \Phi_2$   
[T. D. Lee, 1973], [G. C. Branco et al., 2012]

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- inclusion of (purely scalar) dim-6 EFT contributions to the Higgs potential [Anisha et al., 2019]

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{2HDM}} + \sum_i \frac{C_6^i}{\Lambda^2} O_6^i \quad \Rightarrow \quad V_{\text{dim-6}} = - \sum_i \frac{C_6^i}{\Lambda^2} O_6^i$$

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- absorb dim-6 contributions (to scalar masses) in shifts  $\lambda_i \rightarrow \lambda_i + \delta\lambda_i, m_{12}^2 \rightarrow m_{12}^2 + \delta m_{12}^2$
- $\Rightarrow$  scalar mass spectrum same as for dim-4 @ LO  
 $\Rightarrow$  shift EFT effects into **Higgs self-couplings** & **multi-Higgs final states**



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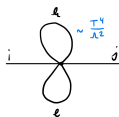
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- dim-6 thermal mass correction

$$\Pi_{ij}^{(1)}(\mathbf{p} \rightarrow 0, \omega_n \rightarrow 0) \equiv \Pi_{ij}^{(1)}(0)$$

$$= \sum_k \kappa_{ij}^k T \sum_n \int \frac{d^3 p}{(2\pi)^3} \mathcal{D}_{kk}(\omega_n, \omega_p)$$

$$+ \sum_{k,l} \kappa_{ij}^{kl} T^2 \sum_{n,m} \int \frac{d^3 p_1}{(2\pi)^3} \mathcal{D}_{kk}(\omega_n, \omega_{p_1}) \int \frac{d^3 p_2}{(2\pi)^3} \mathcal{D}_{ll}(\omega_m, \omega_{p_2})$$



# Electroweak Phase Transition at Finite Temperature

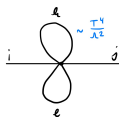
- vacuum state including finite temperature effects: *1-loop corrected effective potential @ finite temperature*
- general form:

$$V^{(1)}(\omega, T) = \underbrace{V^{(0)}(\omega)}_{\text{tree-level, dim-6}} + \underbrace{V^{\text{CW}}(\omega)}_{\substack{T\text{-indep.} \\ \text{Coleman-Weinberg} \\ \text{potential} \\ \text{renormalized in } \overline{\text{MS}}\text{-scheme}}} + \underbrace{V^T(\omega, T)}_{\substack{T\text{-dep.} \\ \text{UV finite} \\ \text{IR finite after resummation} \\ m^2 \rightarrow m^2 + \Pi^{(1)}(0)}} + \underbrace{V^{\text{CT}}(\omega)}_{\substack{\text{finite shift of} \\ \text{scalar masses} \\ \text{and mixing angles}}}$$

[S. Coleman, E. Weinberg, 1973]                      [M. Carrington, 1992],  
[R. Parwani, 1992],  
[P. Arnold, O. Espinosa, 1993]                      [P. Basler et al., 2017]

- dim-6 thermal mass correction

$$\Pi_{ij}^{(1)}(\mathbf{p} \rightarrow 0, \omega_n \rightarrow 0) \equiv \Pi_{ij}^{(1)}(0)$$



$$= \sum_k \kappa_{ij}^k T \sum_n \int \frac{d^3 p}{(2\pi)^3} \mathcal{D}_{kk}(\omega_n, \omega_p)$$

$$+ \sum_{k,l} \kappa_{ij}^{kl} T^2 \sum_{n,m} \int \frac{d^3 p_1}{(2\pi)^3} \mathcal{D}_{kk}(\omega_n, \omega_{p_1}) \int \frac{d^3 p_2}{(2\pi)^3} \mathcal{D}_{ll}(\omega_m, \omega_{p_2})$$

- $V^{\text{CT}}$  absorbs NLO scalar mass and angle shift [P. Basler et al., 2017]

$$0 = \partial_{\phi_i} (V^{\text{CW}} + V^{\text{CT}}|_{\vec{\omega}=\vec{\omega}_{\text{tree}}})$$

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→ *viable* parameter points pass constraints imposed by:

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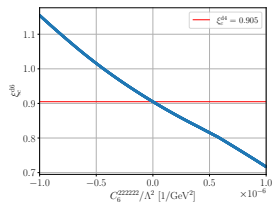
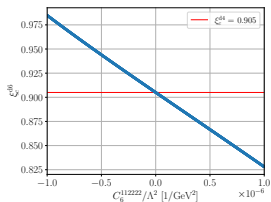
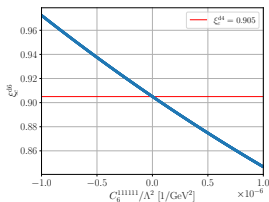
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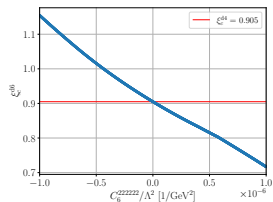
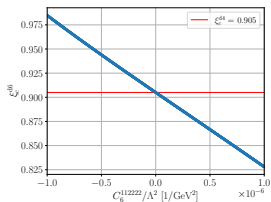
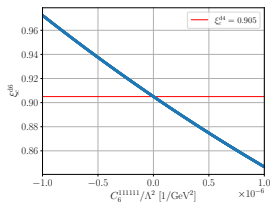
⇒ **SFOEWPT**:  $\xi_c \equiv \frac{v_c}{T_c} \gtrsim 1$

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→ impact of individual Wilson coefficients on  $\xi_c^{d6}$  for  $\xi_c^{d4} \simeq 0.9$ :

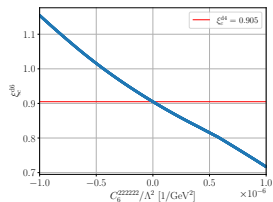
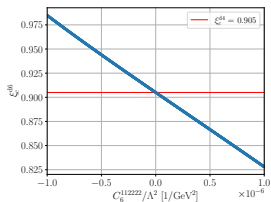
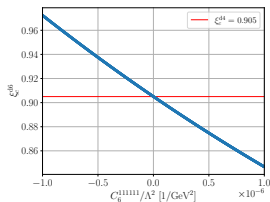
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⇒ Do these additional terms lead to collider-relevant implications?

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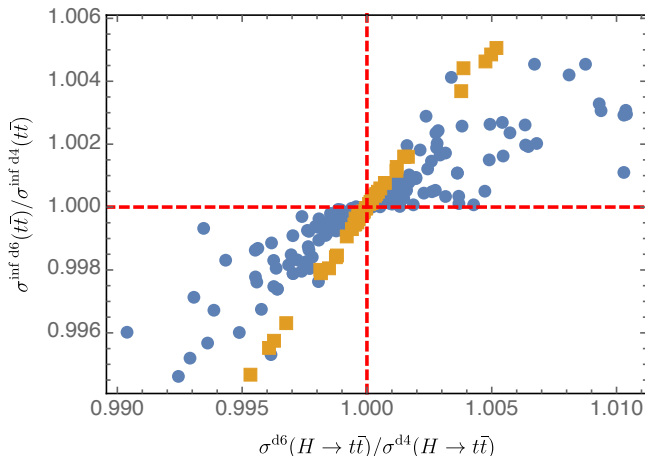
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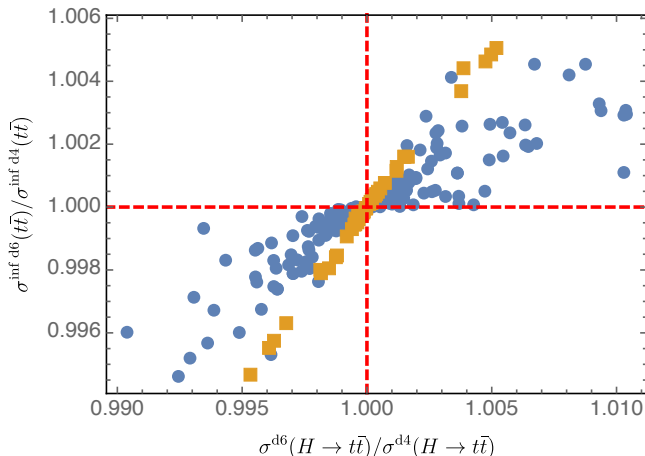
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- $|1 - \xi_c^{\text{d4}}| \propto$  resonant modifications
- **no** phenomenologically observable modifications



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⇒ fixing scalar masses → EFT effects shifted to Higgs self-couplings

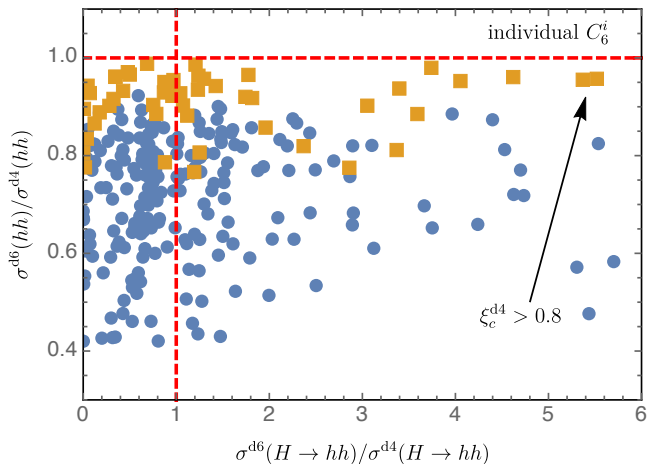
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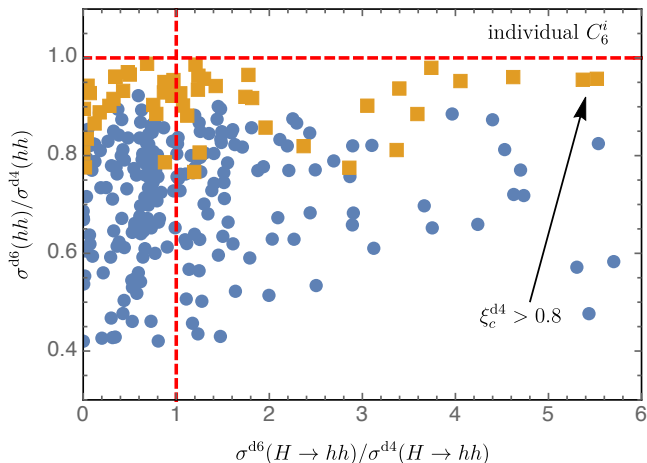


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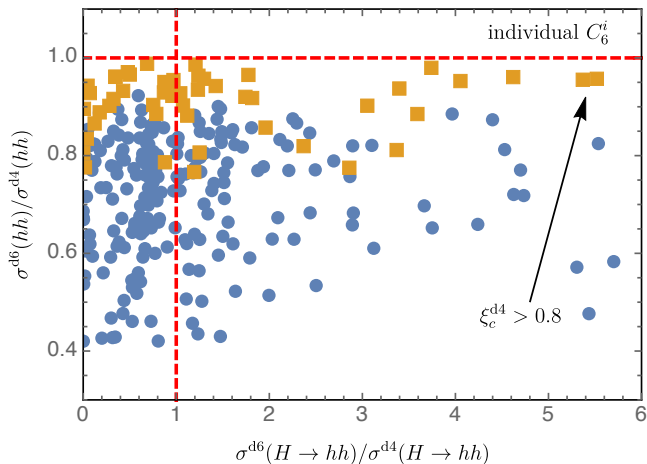
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⇒ **resonant** modifications up to factor 6!

→ *but* resonance  $H \rightarrow hh$  small as  $H \rightarrow \bar{t}t$  preferred

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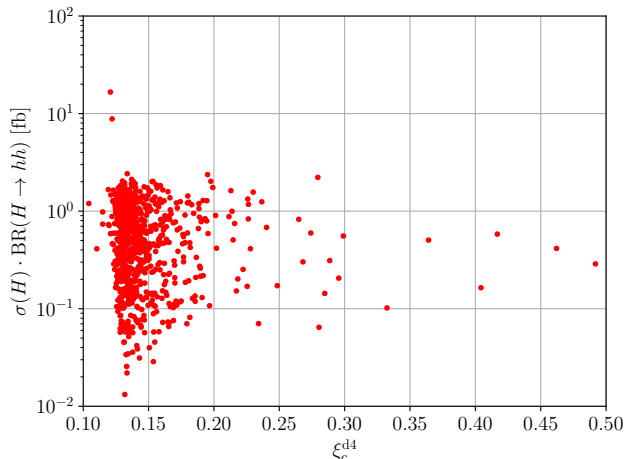
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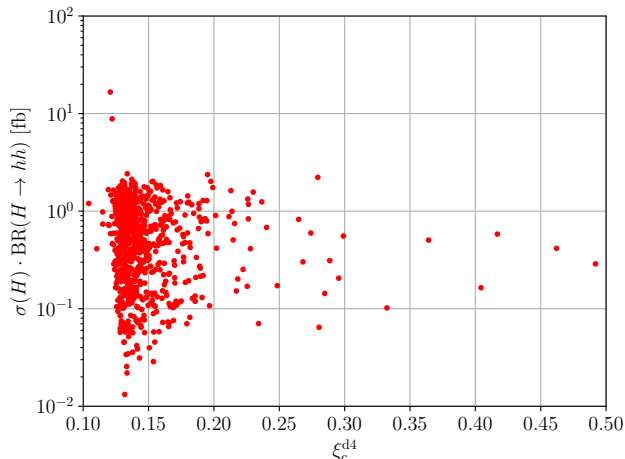


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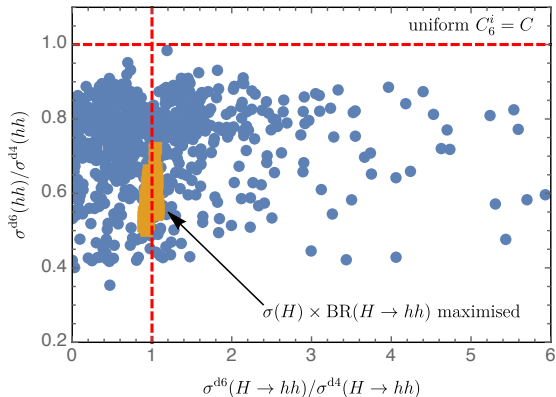
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⇒ change  $C_6^i \equiv C$  uniformly to achieve  $\xi_c^{d6} \simeq 1$  perturbatively



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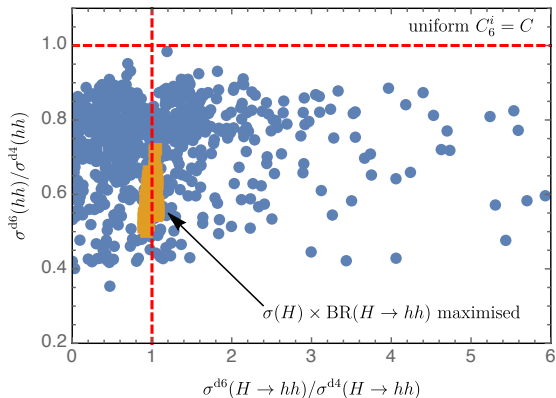
- *uniform* Wilson coefficient scan for  $\xi_c^{d4} > 0.3$  and enhanced  $BR(H \rightarrow hh)$  sample



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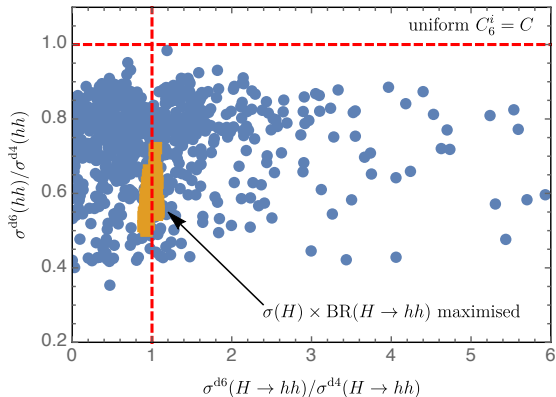


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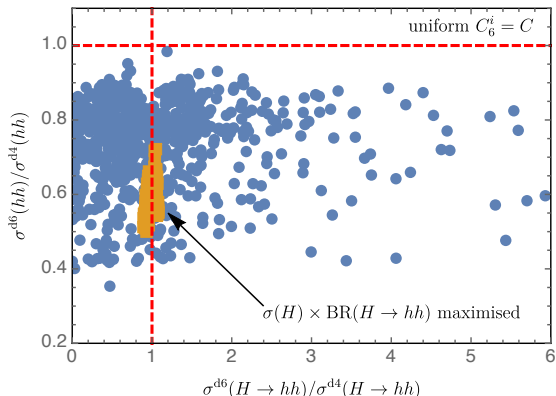


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- **Higgs-philic points:** 5-10% modification in resonance contribution, up to -50% in continuum

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**Thanks for Your attention!**