* talk based on: *Two Higgs doublets, Effective Interactions and a Strong First-Order Electroweak Phase Transition*

by Anisha, LB, Christoph Englert and Margarete Mühlleitner [2204.06966]

Interplay between an SFOEWPT and Higgs pair production in a 2HDM-EFT *

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Young Scientist Meeting CRC 2022

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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- EWBG takes place around $T \sim T_{\text{EW}}$
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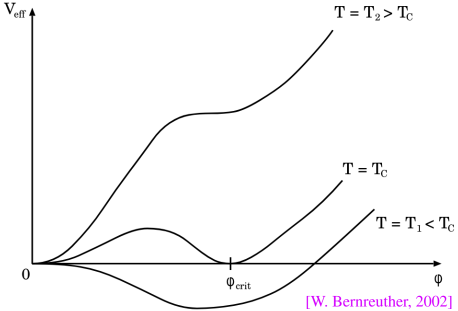

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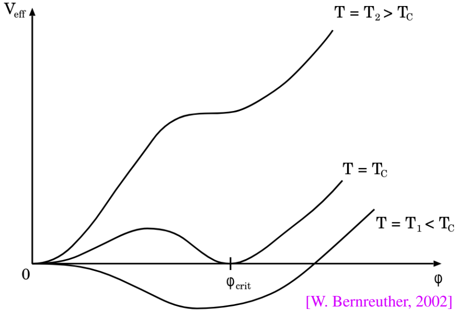

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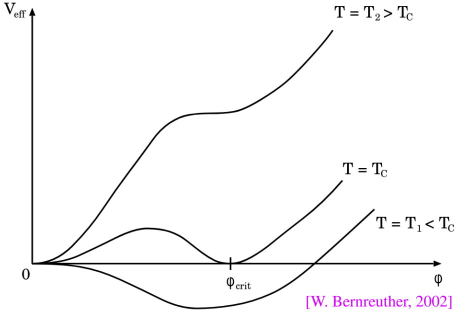

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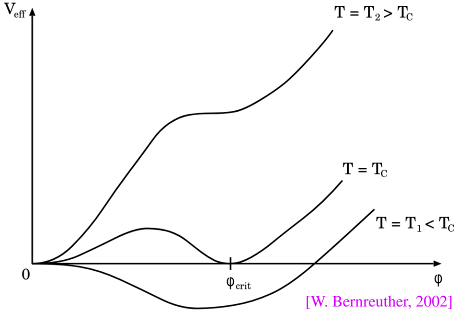

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⇒ need BSM models that enable an SFOEWPT* + *non-standard CPV*

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

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

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

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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 $\lambda_i \to \lambda_i + \delta\lambda_i$, $m_{12}^2 \to m_{12}^2 + \delta m_{12}^2$

$\Rightarrow$ 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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- general form:

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$V^{T}(\omega, T)$: T-dep., UV finite, IR finite after resummation $m^2 \to m^2 + \Pi^{(1)}(0)$ [M. Carrington, 1992], [R. Parwani, 1992], [P. Arnold, O. Espinosa, 1993]

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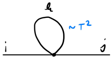
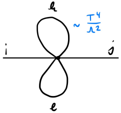
- dim-6 thermal mass correction

$$\Pi^{(1)}_{ij}(\boldsymbol{p} \rightarrow 0, \omega_n \rightarrow 0) \equiv \Pi^{(1)}_{ij}(0)$$

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

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





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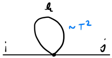
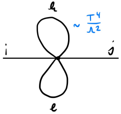
$V^{\text{CW}}(\omega)$: T-indep. *Coleman-Weinberg* potential, renormalized in $\overline{MS}$-scheme [S. Coleman, E. Weinberg, 1973]

$V^{T}(\omega, T)$: T-dep., UV finite, IR finite after resummation $m^2 \to m^2 + \Pi^{(1)}(0)$ [M. Carrington, 1992], [R. Parwani, 1992], [P. Arnold, O. Espinosa, 1993]

$V^{\text{CT}}(\omega)$: finite shift of scalar masses and mixing angles [P. Basler et al., 2017]

- dim-6 thermal mass correction





$$\Pi_{ij}^{(1)}(\boldsymbol{p} \to 0, \omega_n \to 0) \equiv \Pi_{ij}^{(1)}(0)$$

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

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

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

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

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

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$\rightarrow$ *viable* parameter points pass constraints imposed by:

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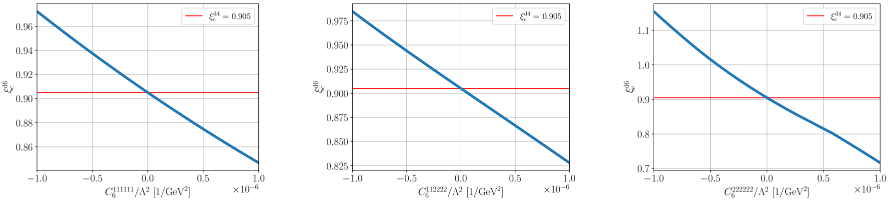
$\Rightarrow$ **SFOEWPT**: $\boxed{\xi_c \equiv \frac{v_c}{T_c} \gtrsim 1}$

Phenomenological Aspects of Effective 2HDM Phase Transitions



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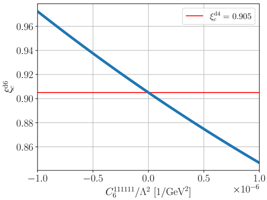

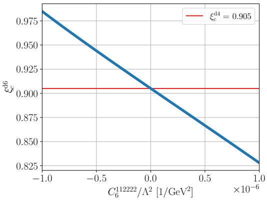

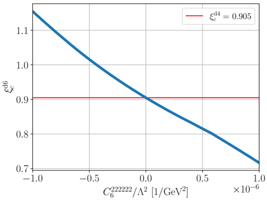

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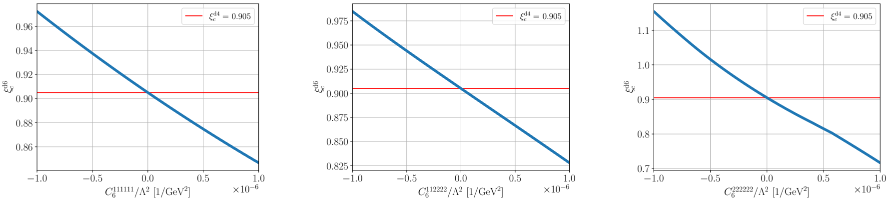

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$\Rightarrow$ Do these additional terms lead to collider-relevant implications?

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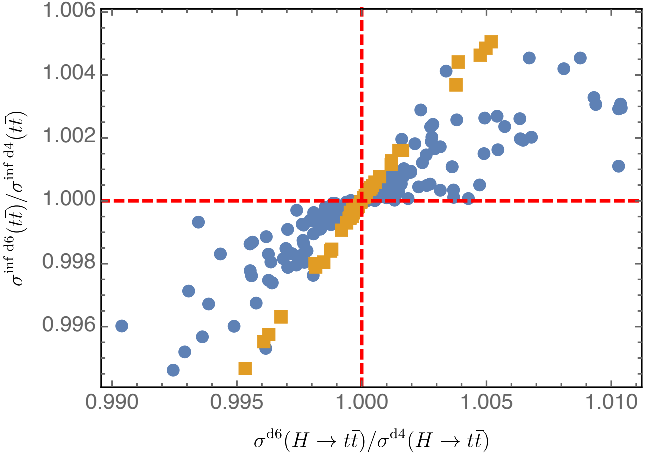

- *individual* Wilson coefficient choices to achieve $\xi_c^{\mathrm{d6}} \simeq 1$ for $\xi_c^{\mathrm{d4}} > 0.3$
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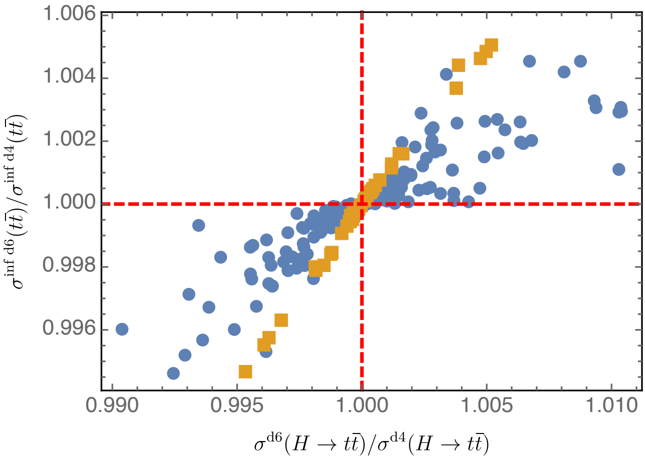

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→ $|1 - \xi_c^{\mathrm{d4}}| \propto$ resonant modifications

→ **no** phenomenologically observable modifications

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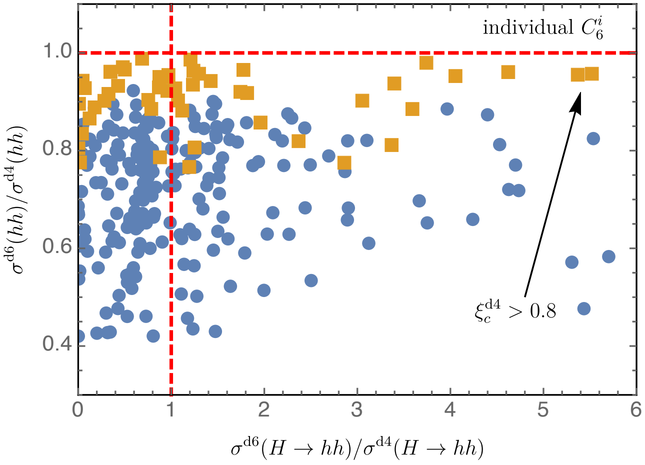

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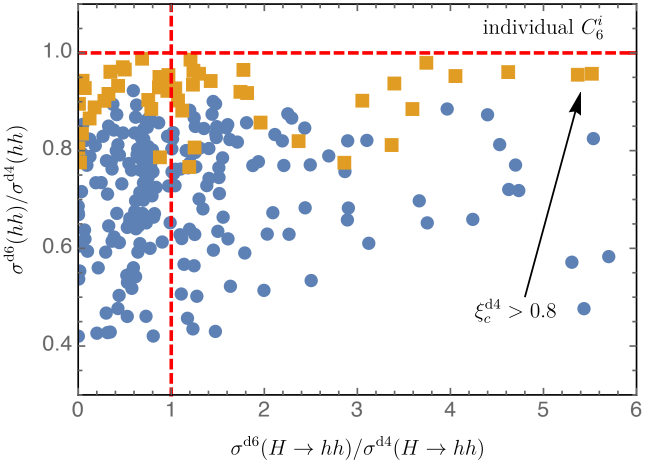

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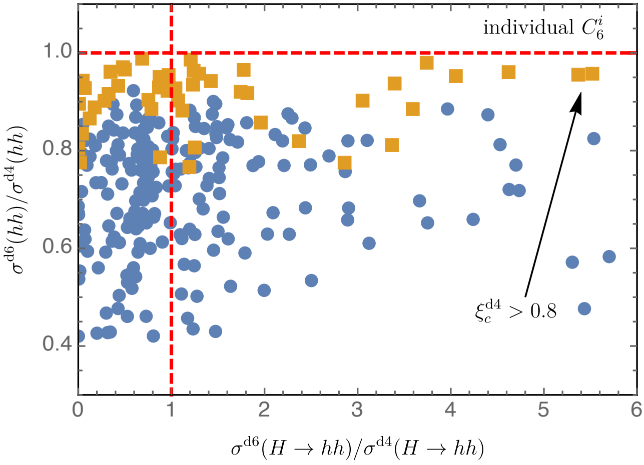

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$\Rightarrow$ **resonant** modifications up to factor 6!

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

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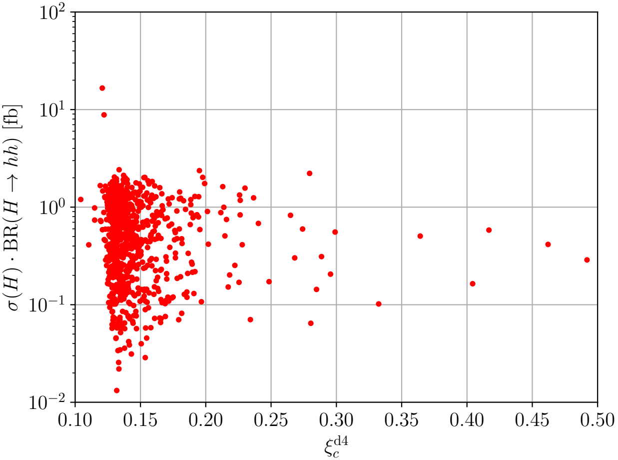

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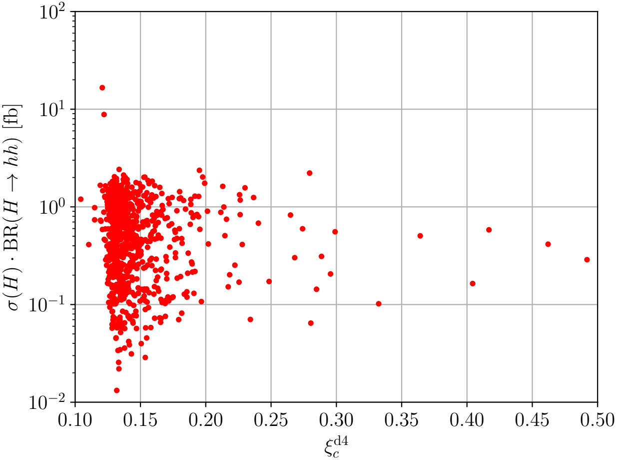

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$\Rightarrow$ change $C_6^i \equiv C$ *uniformly* to achieve $\xi_c^{\mathrm{d6}} \simeq 1$ perturbatively

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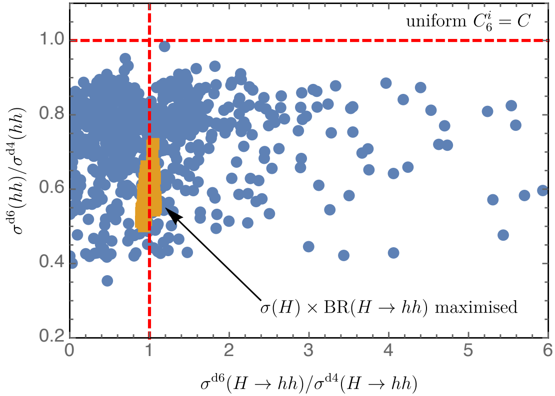
- *uniform* Wilson coefficient scan for $\xi_c^{\mathrm{d4}} > 0.3$ and enhanced $BR(H \to hh)$ sample



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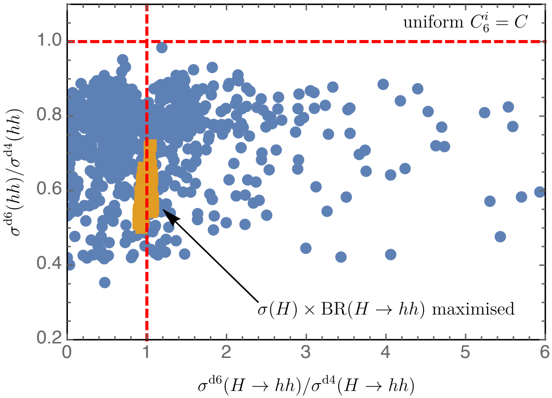

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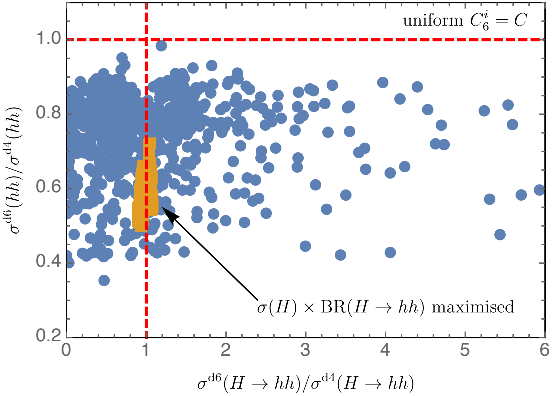

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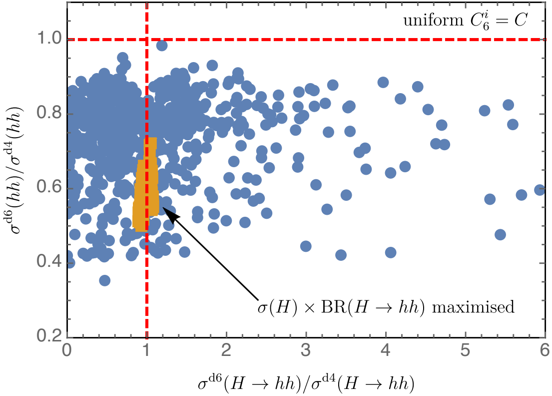

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- **Higgs-philic points**: 5-10% modification in resonance contribution, up to -50% in continuum

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Thanks for Your attention!