The EWPT in a non minimal SM effective-field theory

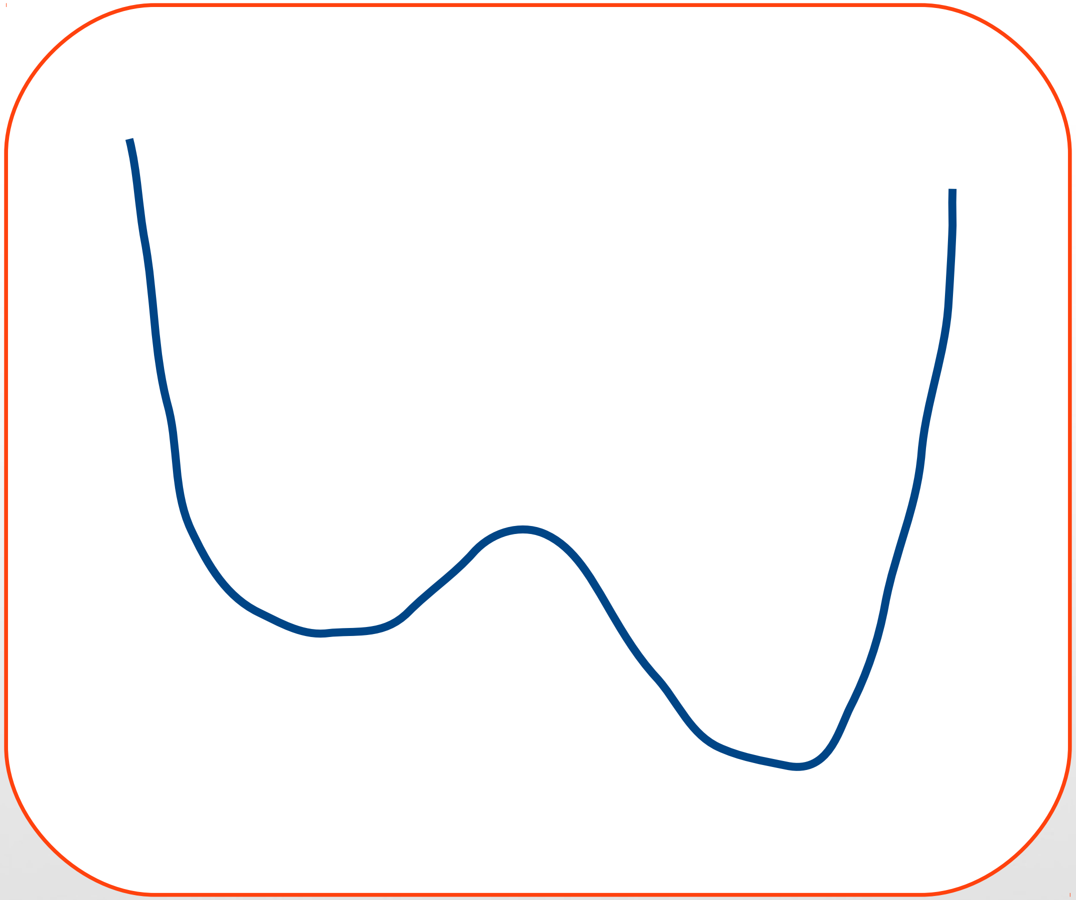
Mikael Chala (IPPP)

With **C. Krause** and **G. Nardini.** Based on *1802.xxxx.*

The dynamics of the EWPT

(crossover in the SM)

- Shape of the Higgs potential unknown
- No clue on the nature of the EWPT
- Order? Strength? Observables?
- Role of double Higgs production?



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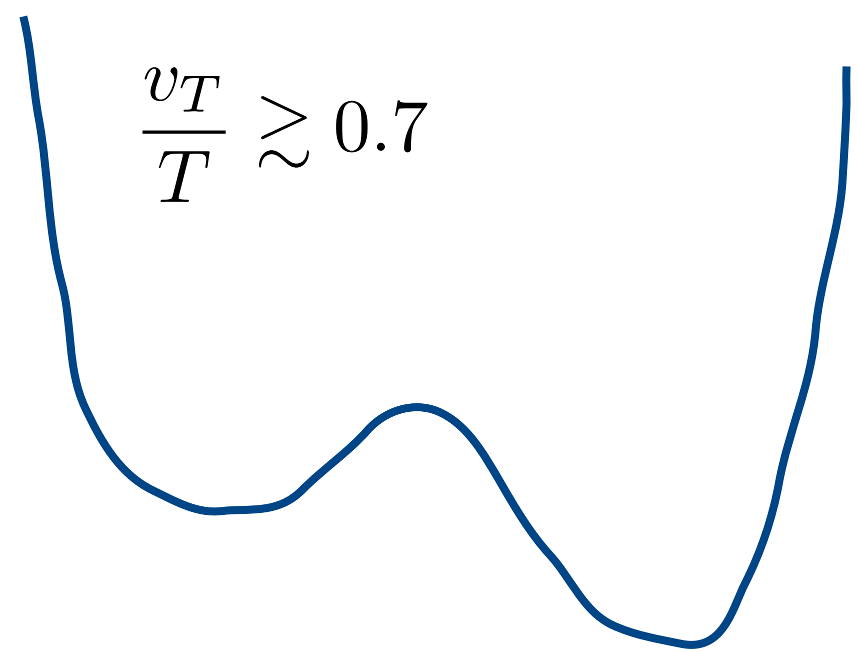

Could new physics modify the EWPT

(yes, but weird that we have seen no signal)

- Simple way to modify the EWPT. It is experimentally unconstrained, and agrees with the lack of observation of beyond the SM physics:

$$L = L_{\mathrm{SM}} + \frac{c_6}{f^2}(\phi^\dagger \phi)^3 + \cdots$$

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weakly coupled?

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(Simple) scalar extensions of the SM

(only tree-level dimension-6 operators)

- EW doublet with $Y = 1/2$ and vanishing couplings to the SM fermions

- EW quadruplets with $Y = 1/2,\ 3/2$

$$\mathcal{O}_6 = (\phi^\dagger \phi)^3 \ , \qquad \mathcal{O}_{d6} = \frac{1}{2}\partial_\mu(\phi^\dagger\phi)\partial^\mu(\phi^\dagger\phi) \ ,$$

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What if several fields are involved?

(an example from composite Higgs models)

- Consider *SU(5)/SO(5) [Vecchi, '15]*. Complex enough, UV completable *[Ferretti and Karateev, '13]*. It involves an additional singlet, and two triplets (real and complex)

$$\frac{c_{d6}}{f^2} = \frac{1}{M^4}\left[\kappa_{\mathcal{S}}^2 - \kappa_{\Xi_0}^2 - 4|\kappa_{\Xi_1}|^2\right], \qquad \frac{c_{\phi D}}{f^2} = -\frac{2}{M^4}\left[\kappa_{\Xi_0}^2 - 2|\kappa_{\Xi_1}|^2\right],$$

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[1412.8480]

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Actually, we can go further and show that *there is no weakly-coupled renormalizable extension of the Higgs sector contaning singlets or triplets with non-vanishing couplings to the SM in which the effective operators produced after integrating out all new scalars at tree level modify only the scalar potential.* [I feel that a split of this sentence in two sentences might be helpful for the reader.]

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Most "elegant" scenario: custodial quadruplet extension of SM

Custodial quadruplet extension of the SM

(phenomenology at high energies)

- It involves two quadruplets, with $Y = 1/2$ and $Y = 3/2$. Same VEVs; couplings related by custodial symmetry

$$\frac{c_6}{f^2} = \frac{1}{2}\frac{\lambda_\Theta^2}{M^2} + \frac{9}{2}\frac{\lambda_\Theta^2}{M^2} = 5\frac{{\lambda_\Theta}^2}{M^2}$$

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$$\mathrm{Br}(\Theta^{\pm\pm} \to W^{\pm}W^{\pm}) = 1, \quad \mathrm{Br}(\Theta^{\pm} \to W^{\pm}Z) = 1, \quad \mathrm{Br}(\Theta^{0} \to W^{+}W^{-} + ZZ) = 1\ .$$

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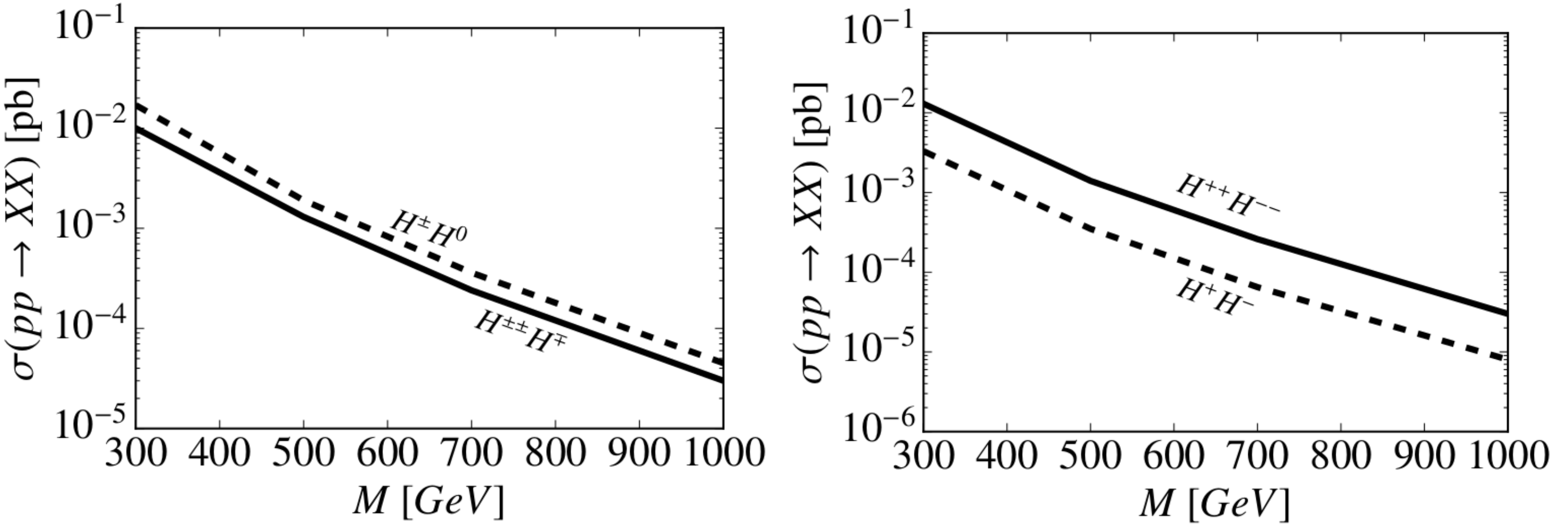

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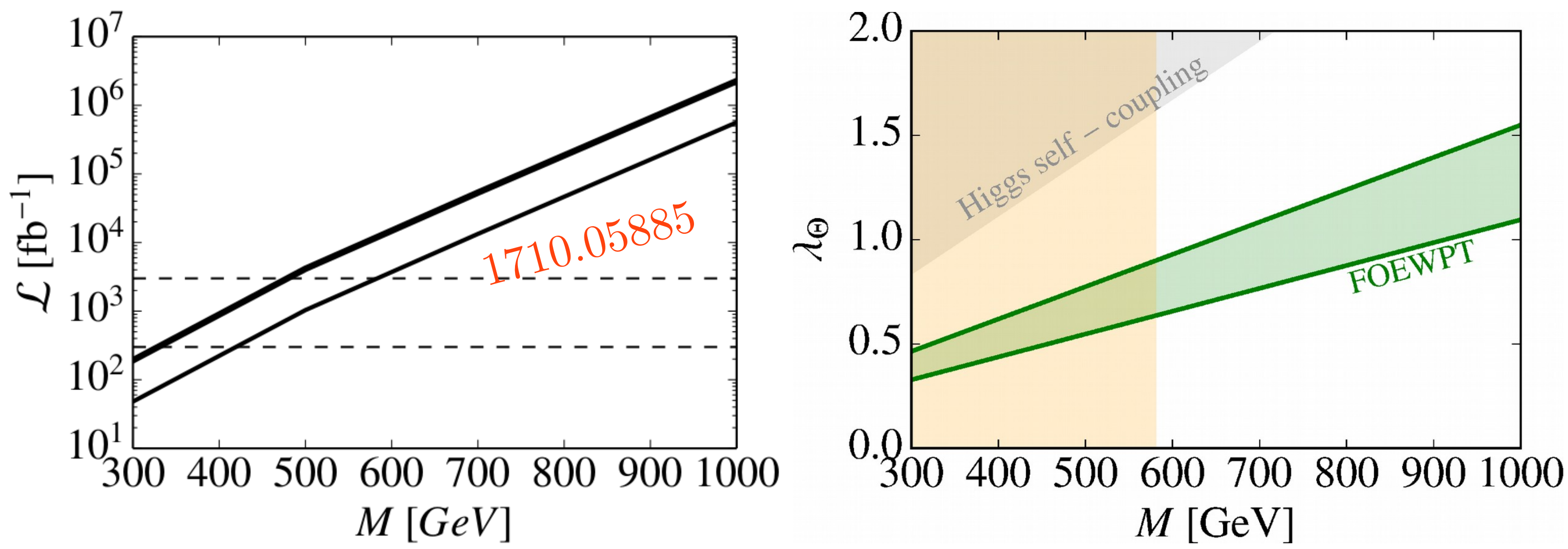

Beyond the dimension-6 EFT
(break down due to small gap)

- The SFOEWPT needs low masses in the weakly coupled case, dimension-8 operators are necessary,
- Dimension-8 operators are also necessary in strongly coupled theories

$$L = L_{\mathrm{SM}} + \frac{c_6}{f^2}(\phi^\dagger\phi)^3 + \frac{c_8}{f^4}(\phi^\dagger\phi)^4$$

The effective potential

(three classes of behaviour)

- Tree level barrier between the minima (left), barrier due to one-loop effects (center); unbounded potential (right)

$$V = V_{\rm tree} + V_{1l,T=0} + V_{1l,T\neq 0} \ ,$$

$$V_{1l,T\neq 0} \sim T^4 J_i(m_i^2(h)/T^2)$$

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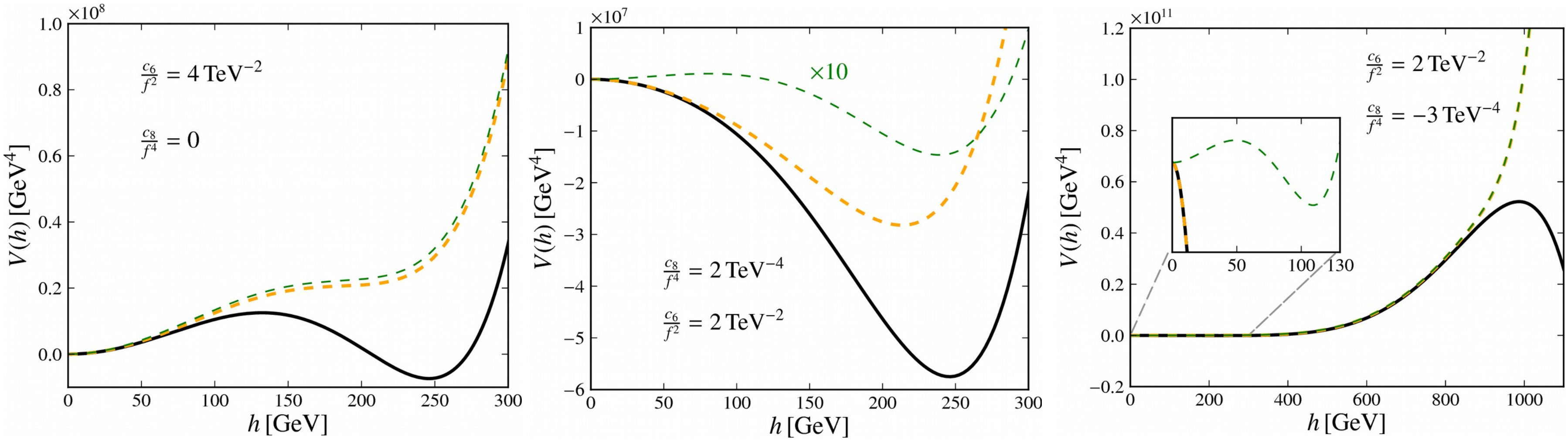

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(analytical results can be obtained)

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$$V_{1l,T\neq 0} \rightarrow \sim \pi^2 T^2/12$$

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- The thermal contribution can only rise the potential at values $h \neq 0$. So, $Vmean(v, T) < Vmean(0, 0)$:

$$V_{\text{mean}} = \frac{-\mu^2 + a_T T^2}{2} h^2 + \frac{\lambda}{4} h^4 + \frac{c_6}{8 f^2} h^6 + \frac{c_8}{16 f^4} h^8$$

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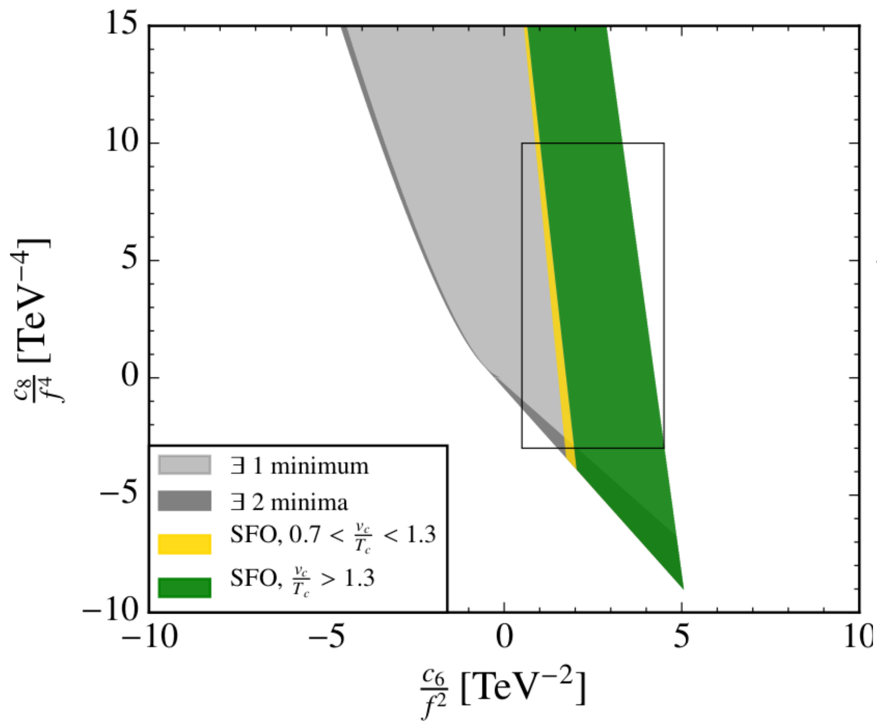

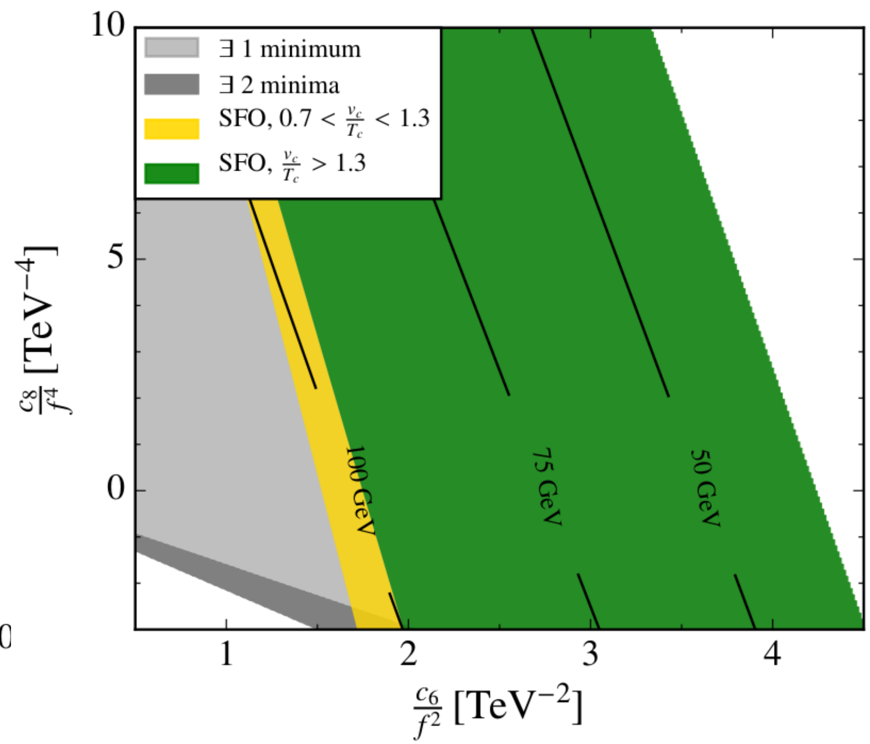

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(the right computation)

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- At very high temperature the **bounce** solution has O(3) symmetry.

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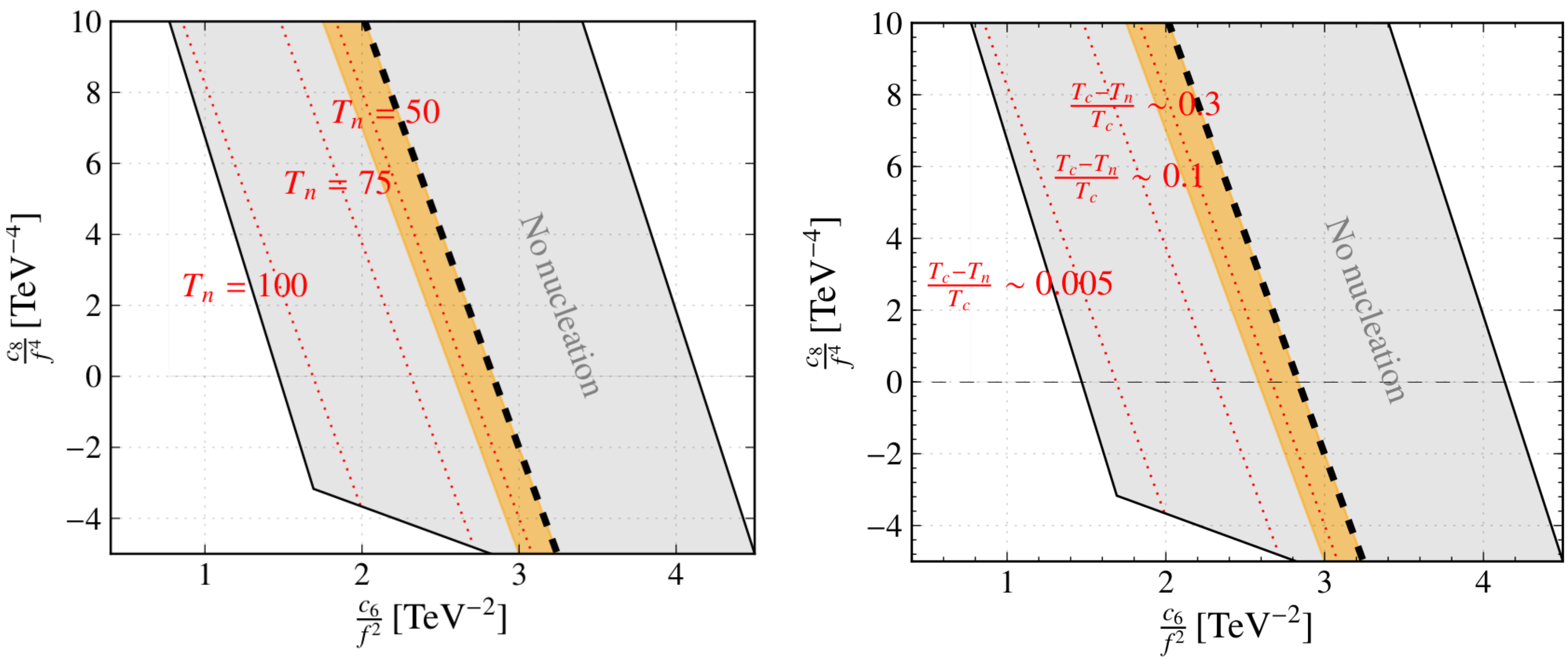
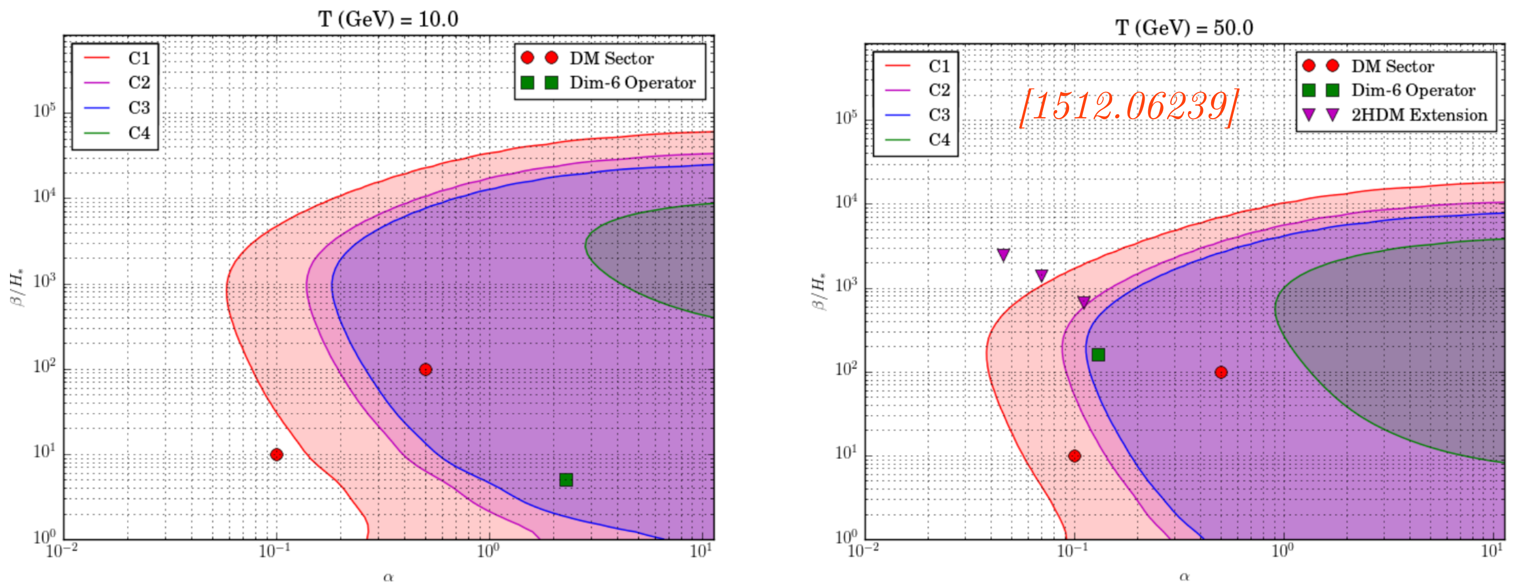


Other parameters relevant for the EWPT

(and for gravitational waves)

- Inverse duration time of the EWPT: $\beta/H = T_n \frac{d}{dT}(S_3/T)$
- Normalized latent heat: $\alpha = \epsilon(T_n)/(35T_n^4)$



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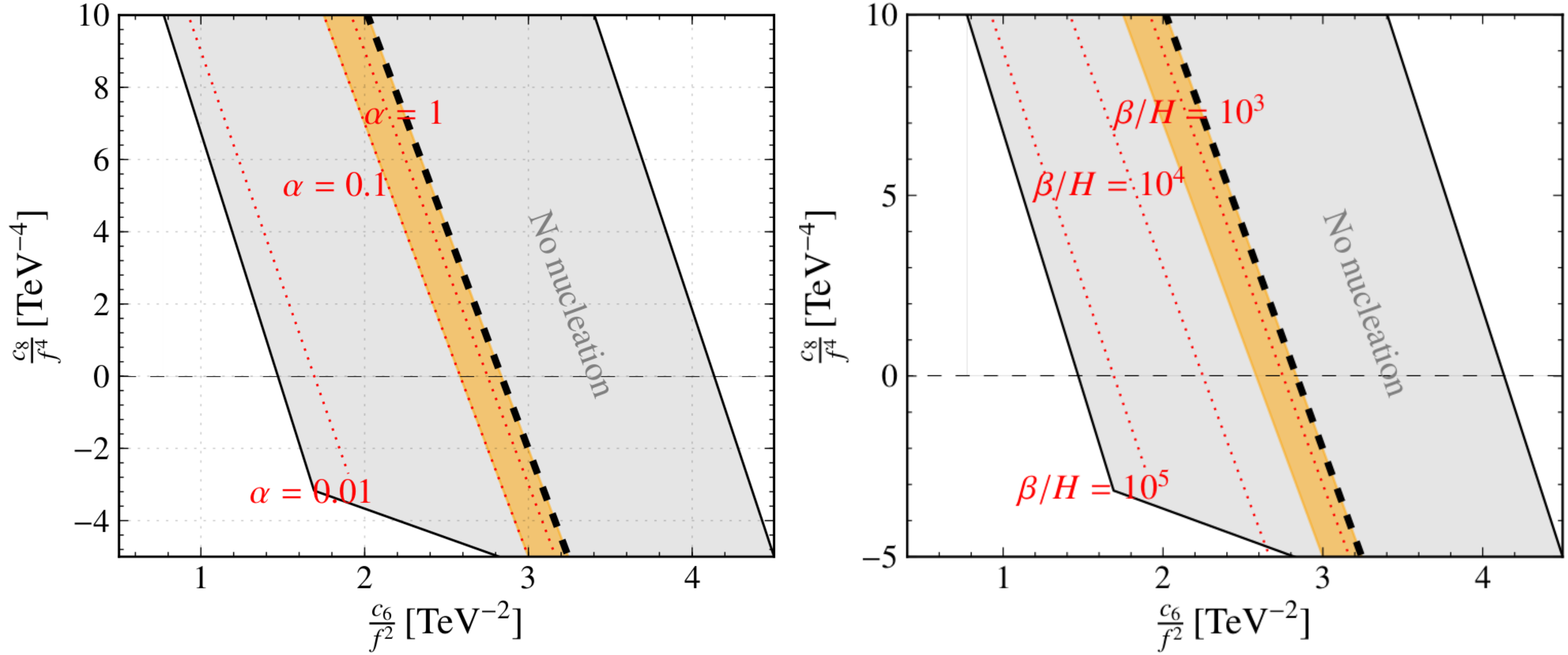

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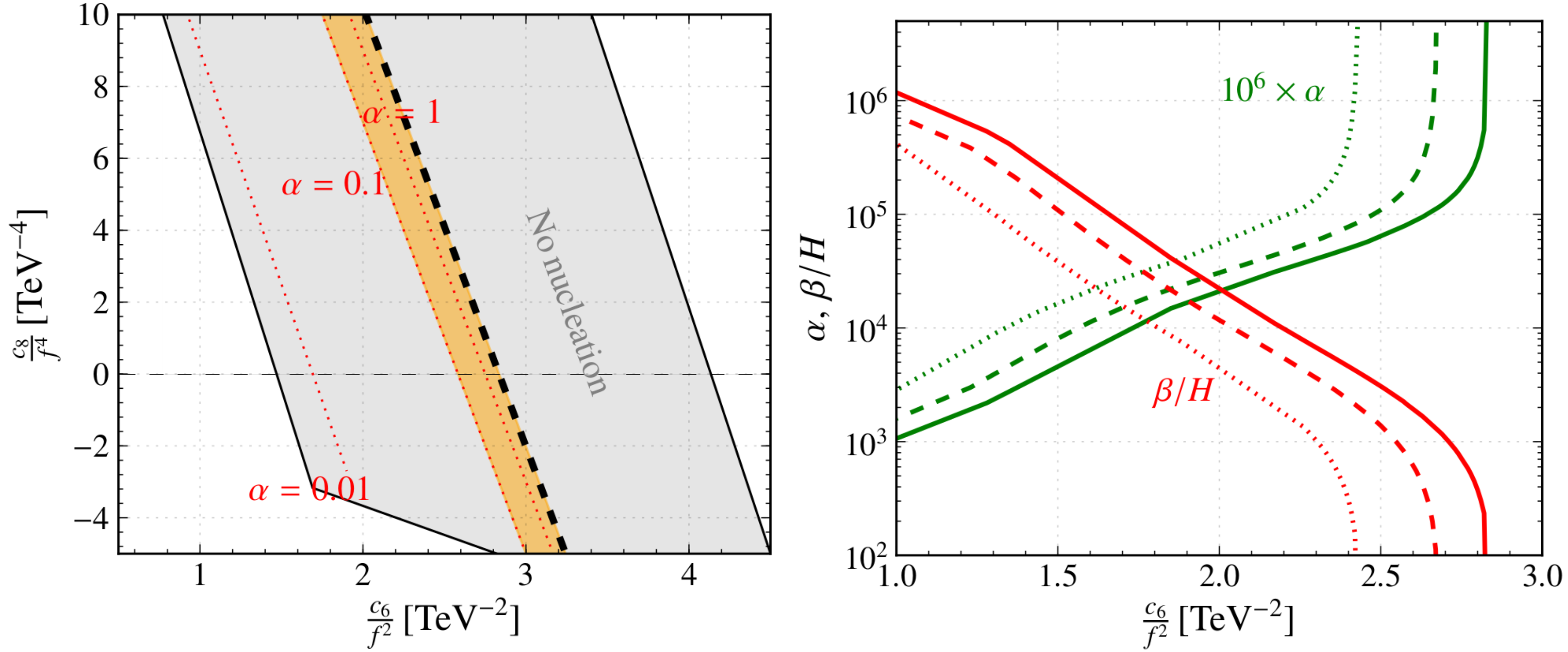
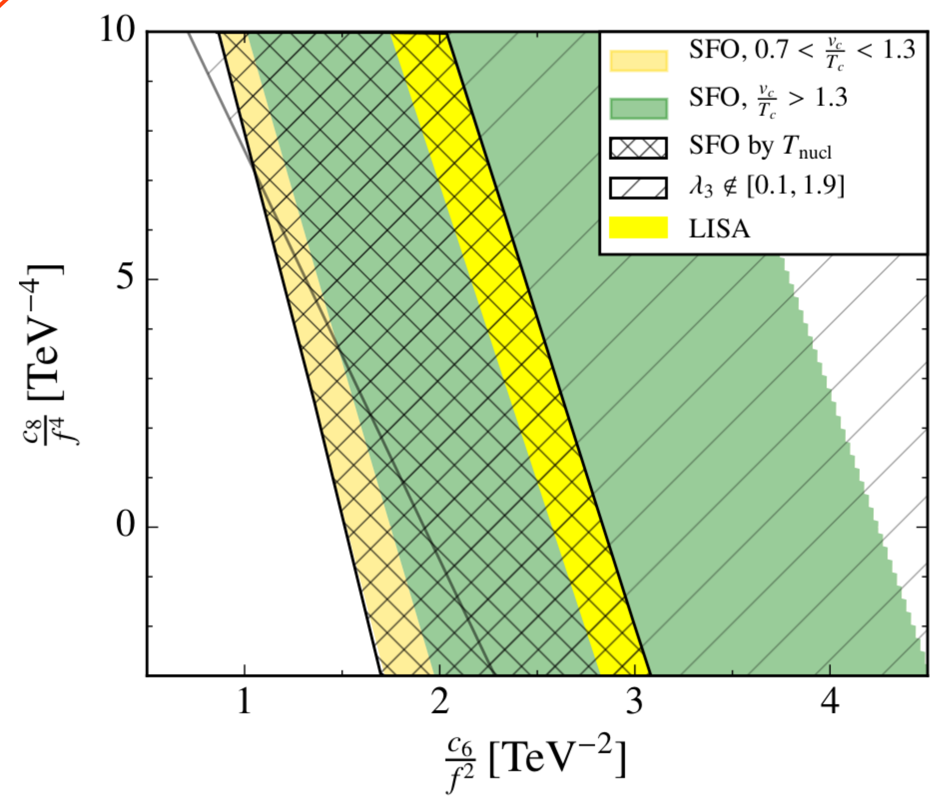


Interplay between different searches

(LISA versus doublet Higgs production)

$$\lambda_3 = 1 + \frac{v^2}{f^2}\left(2c_6\frac{v^2}{m_h^2}\right) + \frac{v^4}{f^4}\left(4\frac{v^2}{m_h^2}c_8\right)$$

- HL-LHC reach in double Higgs production: *[-0.7, 7.1]* 1704.01953
- FCC-ee reach in double Higgs production: *[0.1, 1.9]* 1711.03978
- Triple Higgs production also important at FCC-hh; *[1508.06524]*



Conclusions

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- The simplest non-tuned scenario involves a custodial quadruplet. In most cases, the EFT approach should contain also dimension-8 operators
- We have computed, for the first time in this context, Tc, Tn, v/Tn, α, β, and the LHC/FCC/LISA reach
- The effects of these operators might show up first as gravitational wave signatures

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Thank you very much for your attention!

Backup

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What is the role of Higgs self-coupling measurements in unraveling the new physics responsible for modifying the EWPT?

Quantum field theory at finite temperature

- Correlation functions must be computed in the thermal bath
- In practice, modified Feynman rules dependent on T [see Matsubara, '55; Quirós, '99]

$$\langle \mathcal{O} \rangle = \mathrm{Tr}[\rho \mathcal{O}], \;\; \rho = \frac{e^{-\beta H}}{\mathrm{Tr}[e^{-\beta H}]}$$