First-order electroweak phase transition in the SMEFT

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Based on work with Eliel Camargo-Molina and Johan Löfgren,
2103.14022 [JHEP10(2021)127] and 240x.yyyyy

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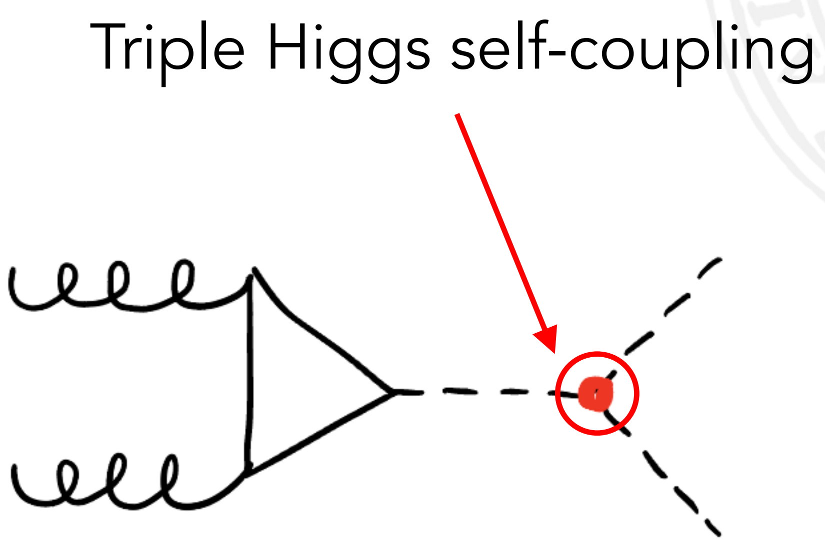
Probing the Higgs potential

$$V_{\rm SM} = -\frac{1}{2}\mu^2\phi^2 + \frac{\lambda}{8}\phi^4$$



How to test?

- Higgs pair production
- Electroweak phase transition

BSM physics will often affect the Higgs self-coupling and the scalar potential

- New physics can be ***light:*** new bosons at colliders [talk by Ramsey-Musolf]
- Or ***heavy:*** no new visible particles → (bottom up) EFTs → SMEFT

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Standard Model Effective Field Theory (SMEFT)

Effective field theory with SM symmetries and fields:

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_{\rm dim\ 6} \frac{C^i}{\Lambda^2} Q_i$$

59 operators at dim 6 with B&L [Grzadkowski et al (2010)]

$$Q_H = (H^\dagger H)^3,$$

In the Higgs sector: $$Q_{H\Box} = (H^\dagger H)\Box(H^\dagger H),$$

$$Q_{HD} = (H^\dagger D_\mu H)^* (H^\dagger D^\mu H)$$

Much EWPT pheno is done for extended scalar sectors

→ But we should know if we can get something interesting in EFTs too [talk by Kanemura]

Looking for possible first order phase transitions

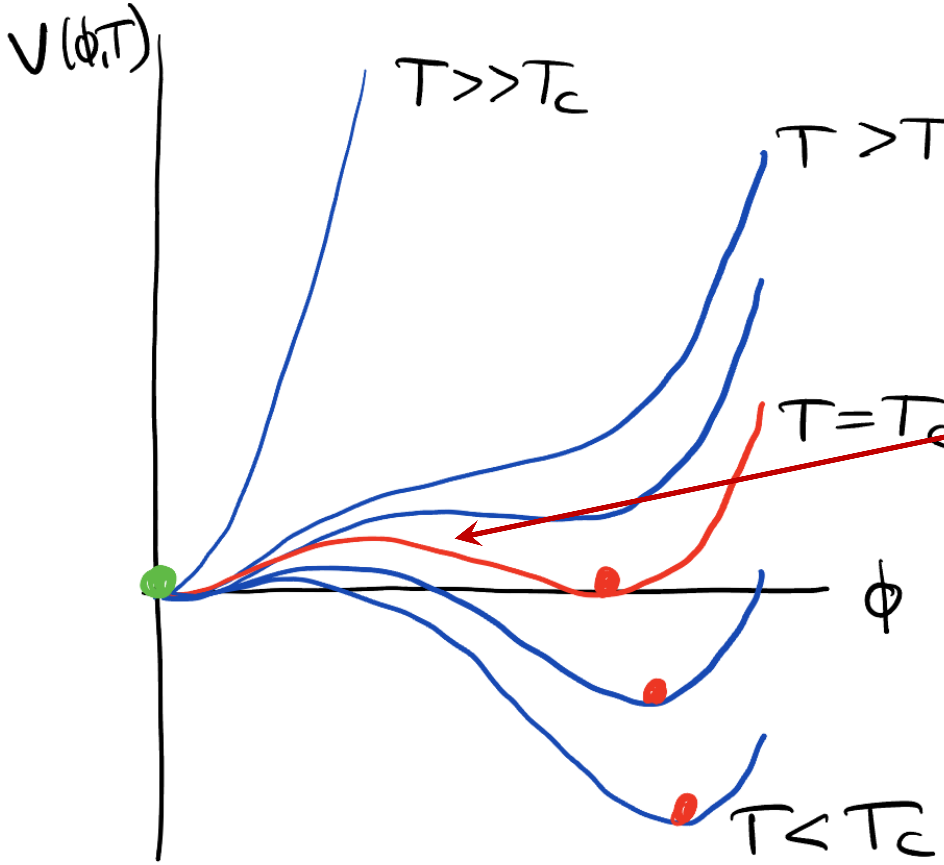
First order PT are abrupt with energy released in bubbles

The bubbles expand, collide, create sound waves, turbulence

- The bubble dynamics may generate observable ***gravitational waves*** (with space-based expts like LISA)
- Non-perturbative dynamics at the bubble walls may lead to ***electroweak baryogenesis***

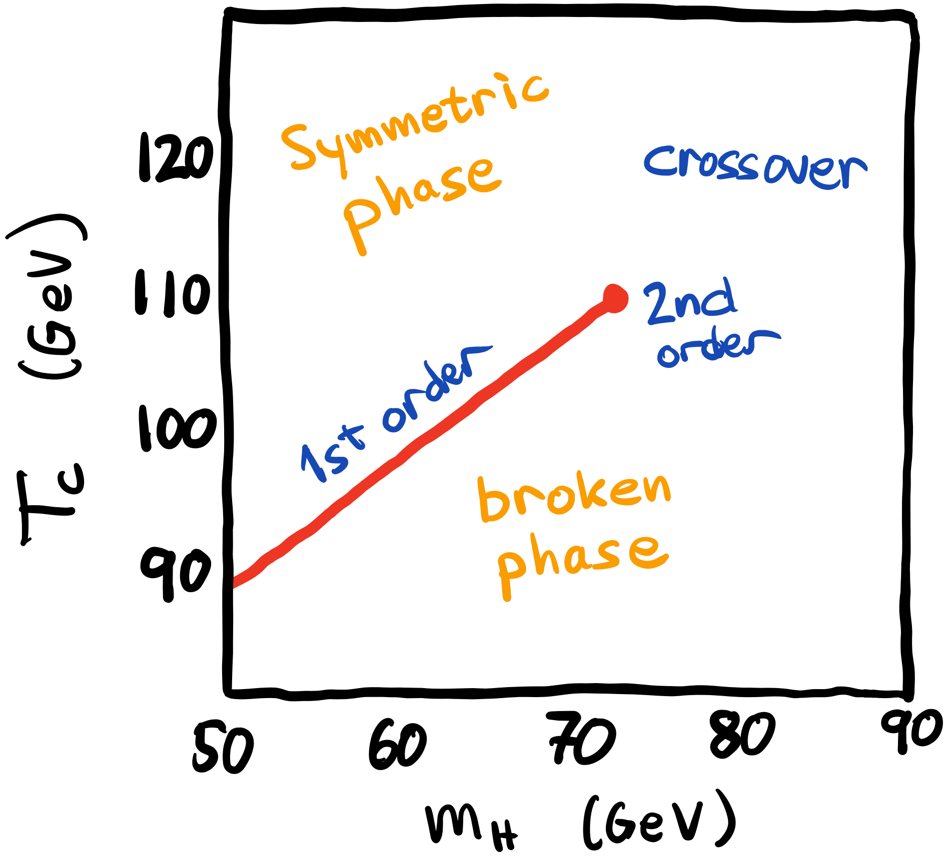
Energy density = effective potential

The effective potential $V_{eff}(\phi,T)$ determines the ground state of the theory



A ***barrier*** is needed for first order transition

Electroweak phase diagram of the SM



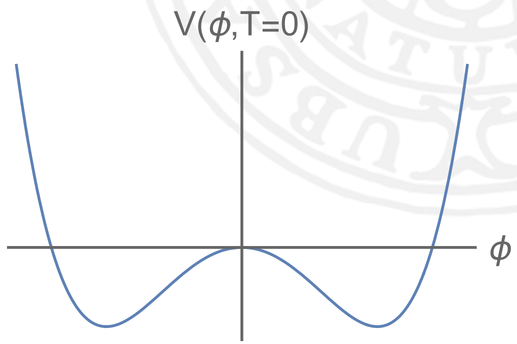
Plot adapted from Kajantie, Laine Rummukainen, Shaposhnikov (1996 and 1998)

Critical point at
$m_H = m_{Hc} = 72$ GeV
$T = T_c = 109$ GeV

A first order phase transition is only possible if $m_H < 72$ GeV – in the SM universe, it was a smooth crossover transition

So how do you get a barrier?

There is no barrier at T=0 so it must be created radiatively:



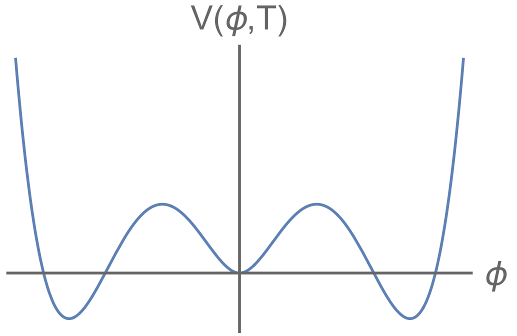
$$V_0(\phi) = -\frac{1}{2}\mu^2\phi^2 + \frac{\lambda}{8}\phi^4$$

Gauge boson contributions at high T give a cubic term:

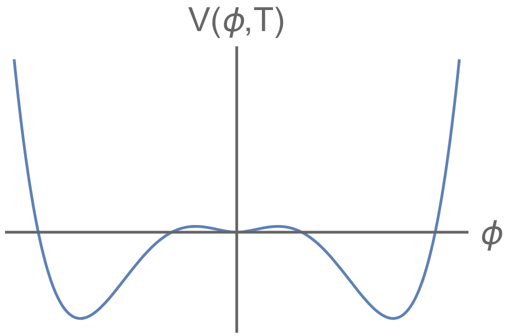
$$V_{\rm LO}(\phi) = -\frac{1}{2}\mu^2_{\rm eff}(T)\phi^2 - e^3\frac{T}{12\pi}\phi^3 + \frac{\lambda}{8}\phi^4$$

$$\mu^2_{\rm eff}(T) = \mu^2 - \alpha T^2/12$$
$$e^3 = \frac{1}{2}g^3 + \frac{1}{4}(g^2 + g'^2)^{3/2}$$

…but is it large enough to give a substantial barrier?



or



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Why does m_H determine the barrier?

To have a large barrier, the cubic term must be about the same size as the other terms:

$$V_{\mathrm{LO}}(\phi) = -\frac{1}{2}\mu_{\mathrm{eff}}^2(T)\phi^2 - e^3\frac{T}{12\pi}\phi^3 + \frac{\lambda}{8}\phi^4$$

Power counting (Arnold and Espinosa): **we need scaling $\lambda \sim e^3$**, not satisified in the SM: λ is much too large

The Higgs mass is given by $m_H^2 = 2\lambda v^2$:
Thus we need smaller λ and smaller m_H for a 1st order transition

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Use higher dimension operators to do this

- **EWPT with dim-6 operator ϕ^6** – Grojean, Servant, Wells (2004) and more recently e.g. Croon et al (2020) and Postma & White (2020)
- λ<0 to get barrier at tree-level with ϕ^6 term providing the Mexican Hat
- Requires a rather small cutoff scale

We will do two things:

I. **Instead consider λ>0 as in SM *but small*.**
Makes FOEWPT possible with correct Higgs mass, because we can get the right Higgs mass from dim-6 operators *(arXiv:2103.14022)*

II. **Catalog all options for barriers that give a FOEWPT in the SMEFT**
Use power counting and 3D EFT for proper calculation,
connect to 4D phenomenology *(in progress)*

Phase transition in the SMEFT

SMEFT at T=0:

$$V_0(\phi) = -\frac{\mu^2}{2}\phi^2 + \frac{\lambda}{8}\phi^4 - \frac{1}{8}\frac{C^H}{\Lambda^2}\phi^6$$

It turns out we can get a radiatively generated barrier like in the SM but for smaller λ with correct Higgs mass because

$$m_h^2 = \lambda v^2 - \left(3C^H - 2\lambda C^{H\Box} + \frac{\lambda}{2}C^{HD}\right)\frac{v^4}{\Lambda^2}$$

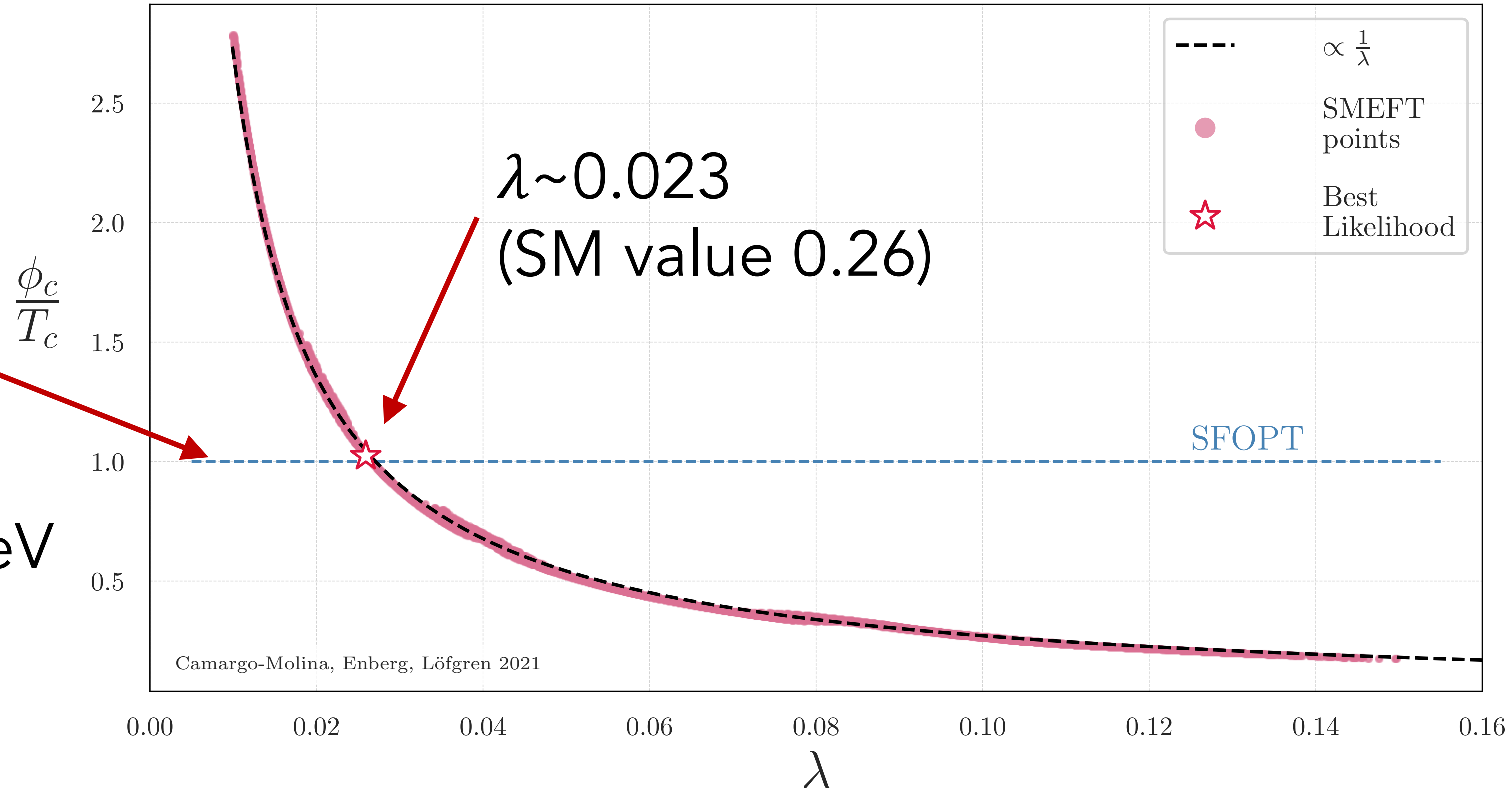
Power counting shows that dim-6 term is subleading at the phase transition → can use the same EWPT calculation as in the SM but for smaller λ!

Parameter scan

For small λ we can get a strong 1st order PT

These points have m_H=125 GeV and satisfy all constraints

(The roughly 1/ λ dependence comes from the power counting in the potential)



Camargo-Molina, RE, Löfgren, JHEP 10 (2021) 127, arXiv:2103.14022

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But maybe there are more possibilities

- The previous work was done at leading order following the gauge-invariant method of Ekstedt & Löfgren [2006.12614]
- But there are well-known problems with the EWPT calculation:
  - gauge dependence
  - renormalization scale dependence
  - IR divergences
  - perturbative breakdown at high T
  - …
- Basic problem: need to treat perturbation theory right
- Modern idea: don’t just resum, use (top-down) EFT

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How to compute?

Stop comparing resummation methods

Johan Löfgren

I argue that the consistency of any resummation method can be established if the method follows a power counting derived from a hierarchy of scales. I.e., whether it encodes a top-down effective field theory. This resolves much confusion over which resummation method to use once an approximation scheme is settled on. And if no hierarchy of scales exists, you should be wary about resumming. I give evidence from the study of phase transitions in thermal field theory, where adopting a consistent power-counting scheme and performing a strict perturbative expansion dissolves many common problems of such studies: gauge dependence, strong renormalization scale dependence, the Goldstone boson catastrophe, IR divergences, imaginary potentials, mirages (illusory barriers), perturbative breakdown, and linear terms.

Johan Löfgren [2301.05197]

How to compute?

Dimensionally reduced 3D EFT can agree quite well with lattice, and is gauge invariant, if the perturbative expansion is strictly done

– and if there's a hierarchy of separated scales with the Higgs at an intermediate softer ("supersoft") scale, above the non-pert scale

Important demonstration in triplet extension example:
Gould & Tenkanen [2309.01672]

See also e.g:

Gould et al [1903.11604]
Ekstedt and Löfgren [2006.12614]
Croon et al [2009.10080]
Ekstedt [2104.11804]
Gould and Hirvonen [2108.04377]
Löfgren et al [2112.05472]
Hirvonen et al [2112.08912]
Ekstedt [2205.05145]
Hirvonen [2205.02687]
Ekstedt, Gould and Löfgren [2205.0724]
Löfgren [2301.05197]

3D EFT for thermal transitions

- Dimensional reduction: Integrate out non-zero Matsubara modes
- Get Euclidean 3D EFT at "soft scale" with only bosons, and potential

$$V_3(\phi_3) = \frac{1}{2} m_3^2\, \phi_3^2 + \frac{1}{4}\lambda_3\, \phi_3^4 + \frac{1}{6} C_3^H\, \phi_3^6$$

- Wilson coefficients from matching to full theory – contain T-dependence
  Automated by **DRalgo** [Ekstedt, Schicho, Tenkanen 2205.08815]
- Additional ϕ_3^3 term from integrating out gauge bosons
  if the scale hierarchies allow it ($m_H \ll m_{gauge}$) [Gould & Hirvonen 2108.04377]
- This potential determines the properties of phase transitions
- Follow phase as T changes – coefficients depend on 4D parameters

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Catalog of SMEFT phase transitions

Characterize phase transitions with different scale hierarchies in 3D:

- ➢ Barriers (tree-level or radiative), or radiative symmetry breaking (CW)
- ➢ Supercooled transitions

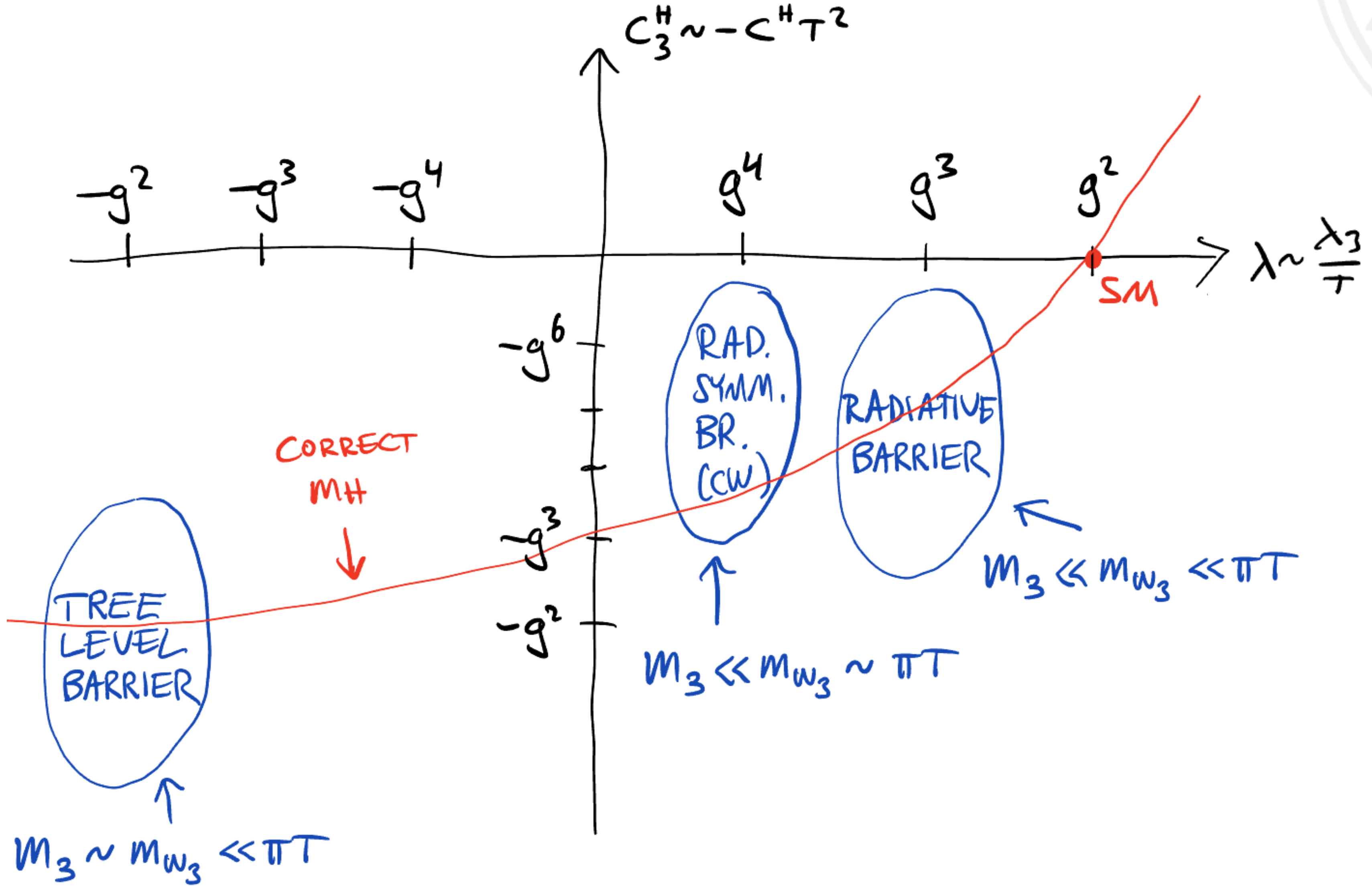
This must be related to the physical parameters of the 4D theory

➔ Work in progress: scan parameter space, matching 3D ⟷ 4D

➔ Will evaluate prospects for first order transitions

➔ Global fit using EW precision, which scenarios allowed or excluded

Sketch of parameter space in 3D theory



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Conclusions

- SMEFT is a general model-independent approach to heavier BSM physics
- Important to know if a first-order EWPT is allowed in the SMEFT
- It is

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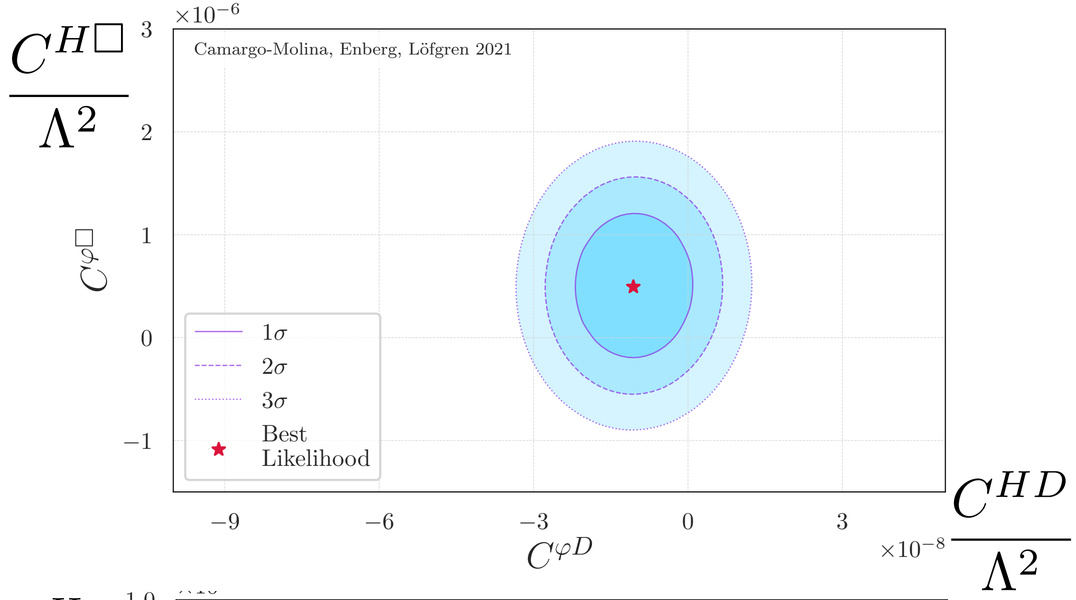
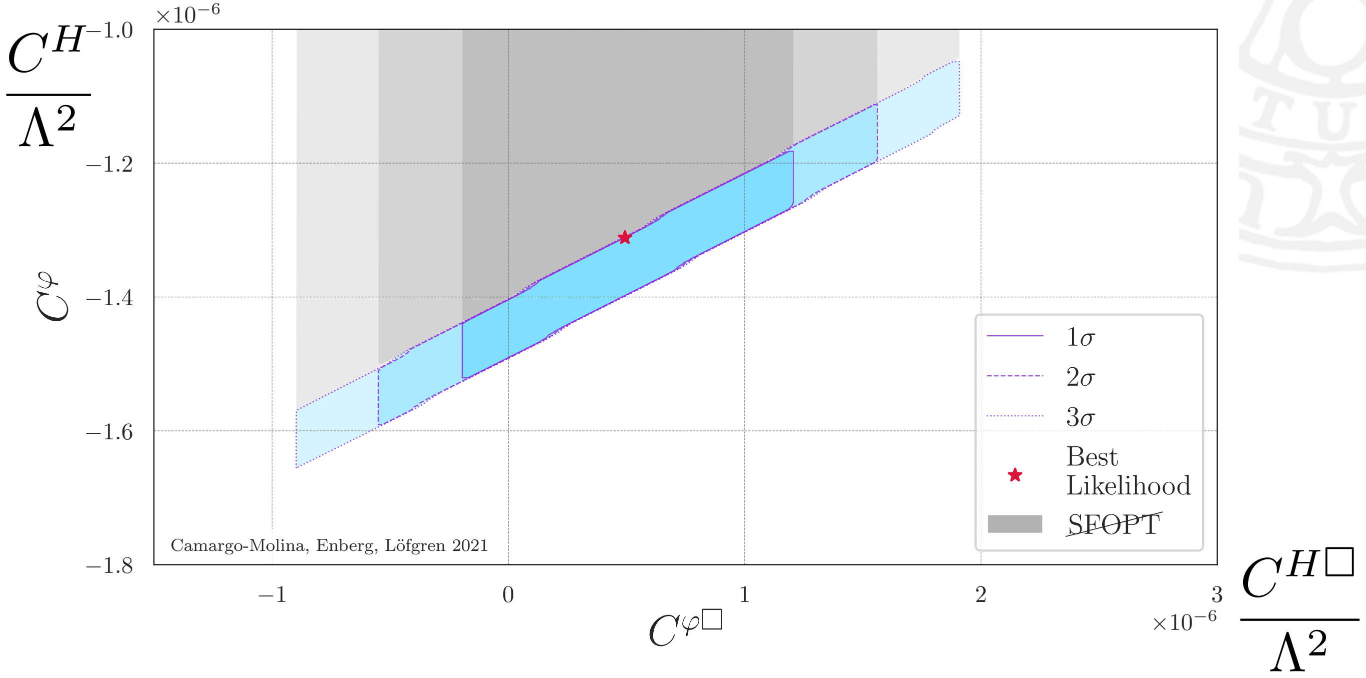
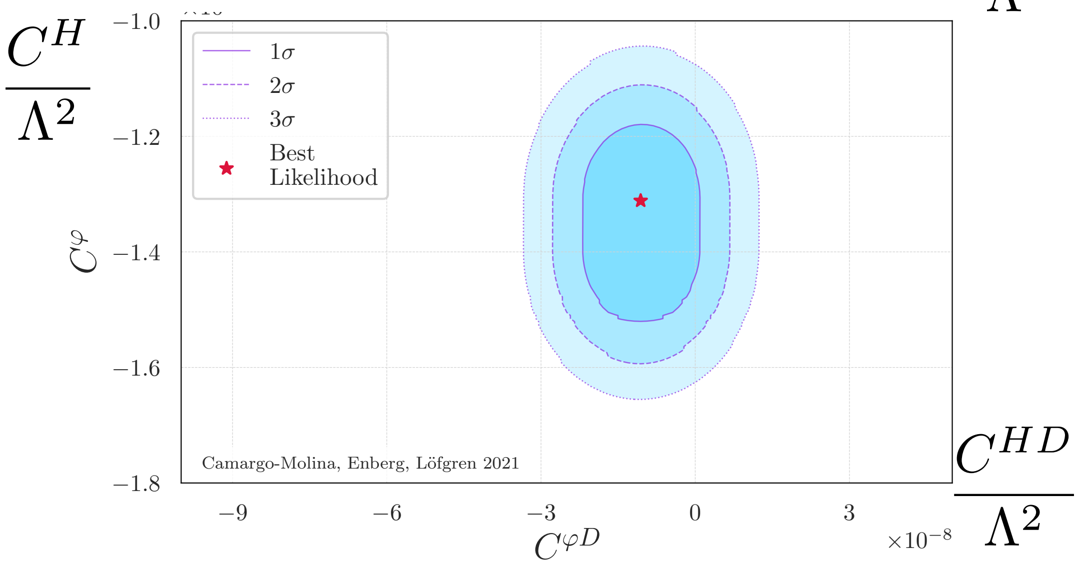
Backup

Scan Wilson coefficients: reference scale Λ~1 TeV







The best fit to data is a point with a strongly 1st order phase transition

The fit uses the codes `smelli`, `flavio` and `wilson` (Aebischer, Kumar, Stangl, Straub)

Camargo-Molina, RE, Löfgren, JHEP 10 (2021) 127, arXiv:2103.14022

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Example of power counting & scale hierarchies

3D EFT at "supersoft" scale: $V_{LO} = \frac{1}{2} m_3^2 \phi_3^2 - \frac{1}{8\pi} g_3^3 \phi_3^3 + \frac{1}{4}\lambda_3 \phi_3^4 + \frac{1}{6} C_3^H \phi_3^6$

Scaling:
$$\begin{cases} m_3^2 \sim g^{n_m} T^2 \\ \lambda_3 \sim g^{n_\lambda} T \\ \phi_3 \sim g^{n_\phi} \sqrt{T} \\ C_3^H \sim g^{n_c} \\ g_3 \sim g\sqrt{T} \end{cases}$$

Taking all terms to be important for the barrier, and take perturbativity into account:

$$\begin{cases} n_m = 3 + n_\phi \\ n_\lambda = 3 - n_\phi \\ n_c = 3 - 3n_\phi \end{cases}$$

$$\Longrightarrow -1 < n_\phi < 1$$

Thus, for a radiative barrier:

$$\begin{cases} m_3^2 \sim g^3 T^2 \\ \lambda_3 \sim g^3 T \\ \phi_3 \sim \sqrt{T} \\ C_3^H \sim g^3 \end{cases}$$

Scales

$$\underbrace{\pi T}_{\text{hard scale}} \gg \underbrace{\left(\frac{g}{4\pi}\right)^{\frac{1}{2}} \pi T}_{\text{semisoft scale}} \gg \underbrace{\left(\frac{g}{4\pi}\right)^{1} \pi T}_{\text{soft scale}} \gg \underbrace{\left(\frac{g}{4\pi}\right)^{\frac{3}{2}} \pi T}_{\text{supersoft scale}} \gg \underbrace{\left(\frac{g}{4\pi}\right)^{2} \pi T}_{\text{ultrasoft scale}}$$

Non-perturbative

Dimensional reduction

Radiative barrier: Higgs is here
(cancellation in mass between thermal and tree-level contributions)

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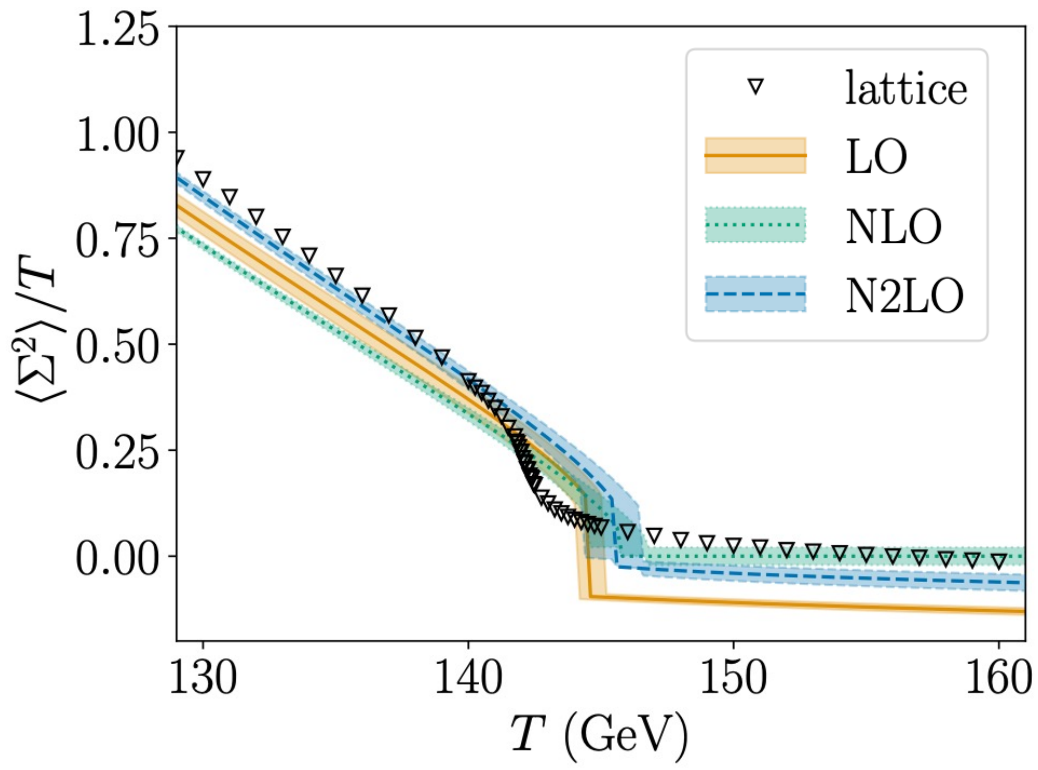
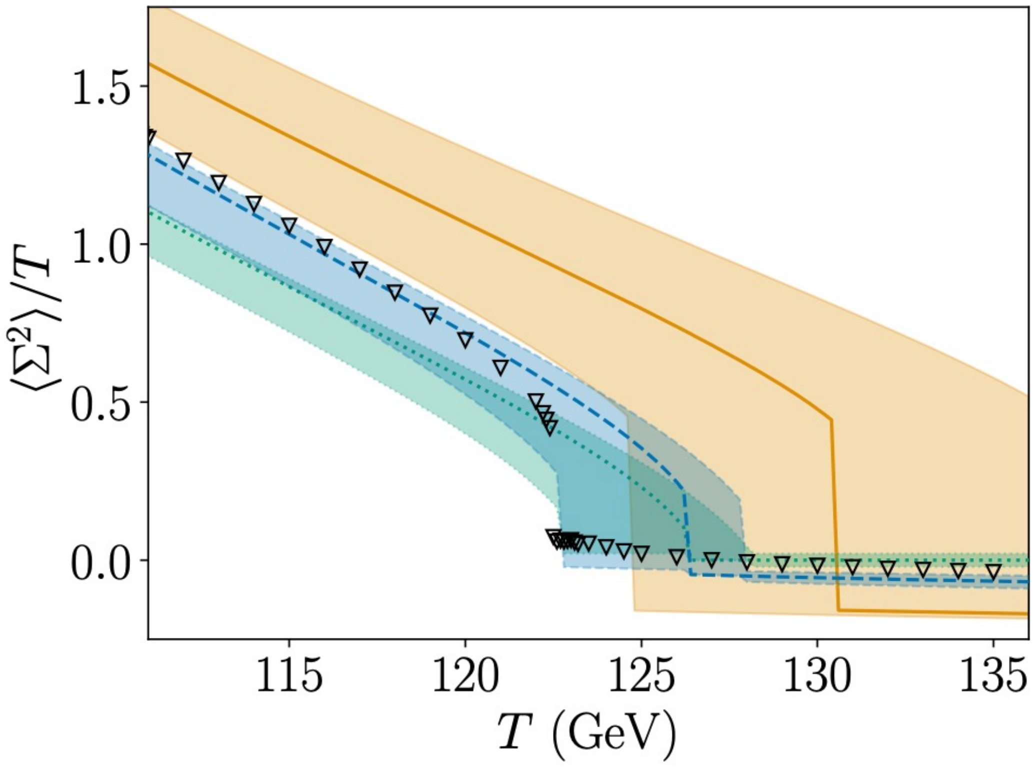
Gould & Tenkanen: triplet condensate





[2309.01672]

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