The Electroweak Phase Transition and Standard Model Effective Field Theory

Rikard Enberg

Physics Days / Particle Days, Lund, 15 June 2022

Based on work with E. Camargo-Molina and J. Löfgren

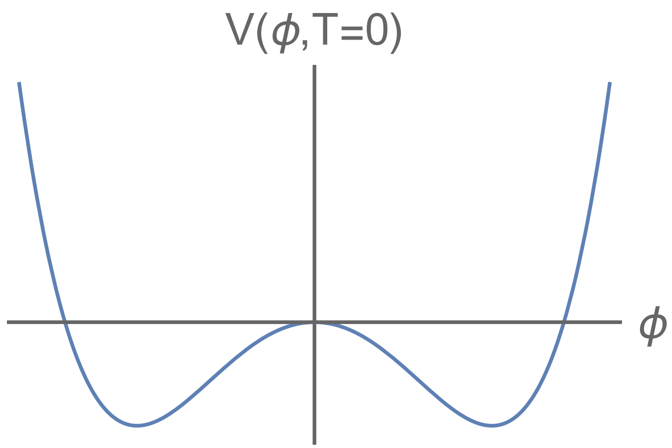
SHIFt
Knut och Alice Wallenbergs Stiftelse
CARL TRYGGERS STIFTELSE FÖR VETENSKAPLIG FORSKNING
UPPSALA UNIVERSITET

The scalar potential = energy density of Higgs field

$$V_{\rm SM} = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2 = -\frac{1}{2}\mu^2\phi^2 + \frac{\lambda}{4}\phi^4$$

ϕ = neutral component of Higgs doublet H

The minimum determines the ground state of the Universe



But why does it look like that? With a negative mass term?

We need to probe the scalar potential further:

- λ is the only SM param we haven't probed in expt
- μ is the only dimensionful parameter in the SM

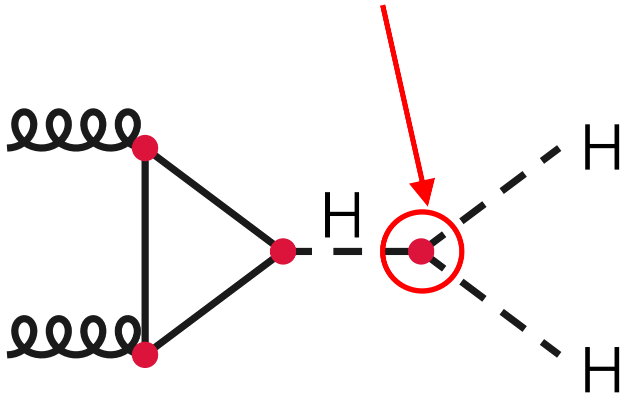
Probing the potential

How to test?

- Higgs pair production

- Electroweak phase transition

Triple Higgs self-coupling



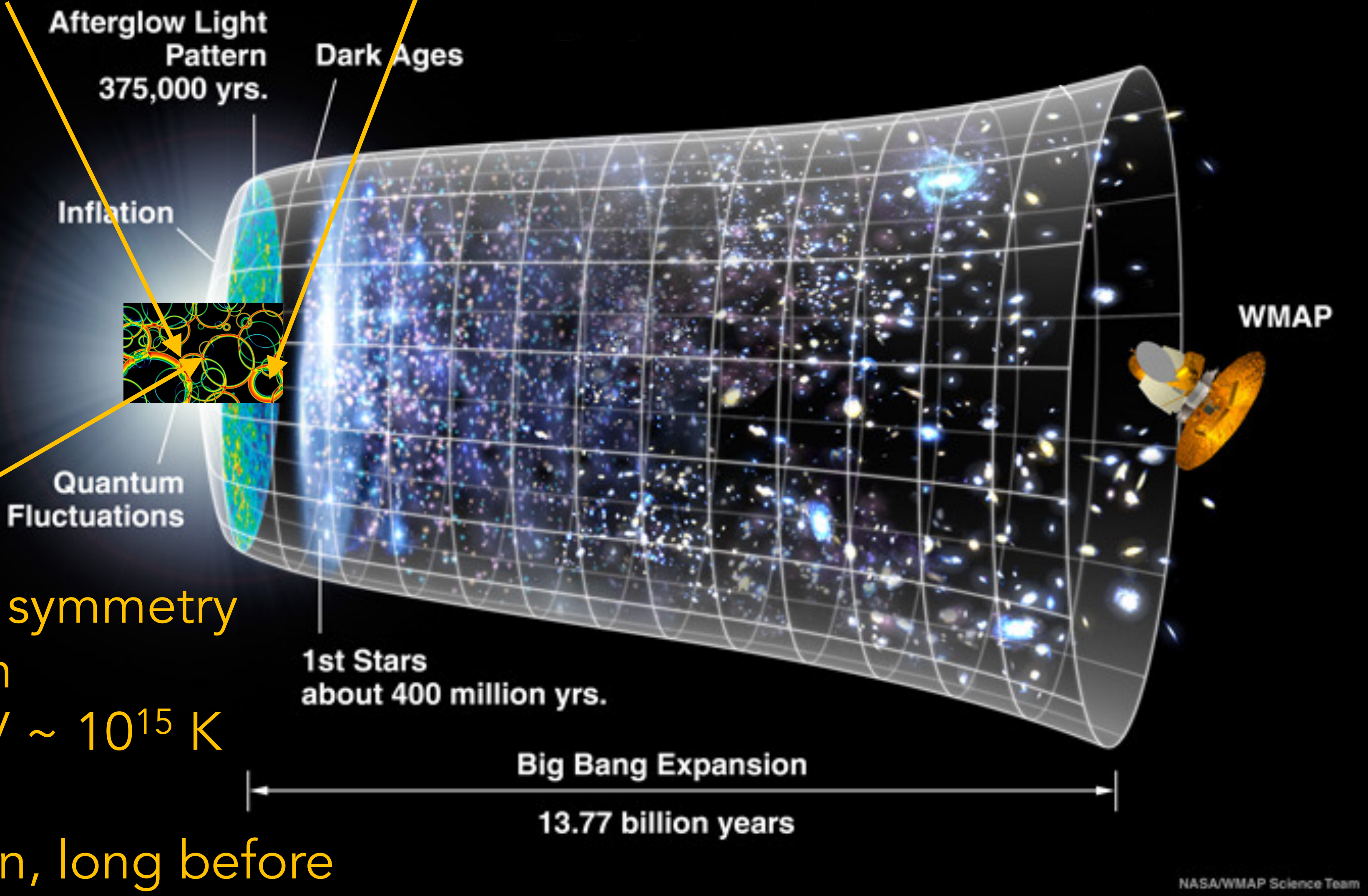
New BSM physics will often affect the Higgs self-coupling and the scalar potential

New physics can be heavy or light… We will consider SMEFT

UPPSALA UNIVERSITET

Before: $SU(2)_L \times U(1)_Y$ symmetry, no Higgs field, all particles massless

After: Only $U(1)_{EM}$ symmetry, Higgs field nonzero, particles massive



Electroweak symmetry broken when
T ~ 100 GeV ~ 10^{15} K
t ~ 10 ps
After inflation, long before nucleosynthesis and CMB

How did this electroweak phase transition occur?

There are different types of phase transitions:

- **First order**: abrupt transition with release of latent heat
- **Second order**: continuous transition, long range correlations, critical phenomena
- **Crossover**: not a phase transition at all (?) according to orthodox definition. Very smooth transition.

We want to know what the EW phase transition was in our Universe!

UPPSALA
UNIVERSITET

First order phase transitions are great

They are abrupt, violent affairs with energy released in the form of bubble nucleation of the new phase

The bubbles expand, collide, create sound waves, turbulence

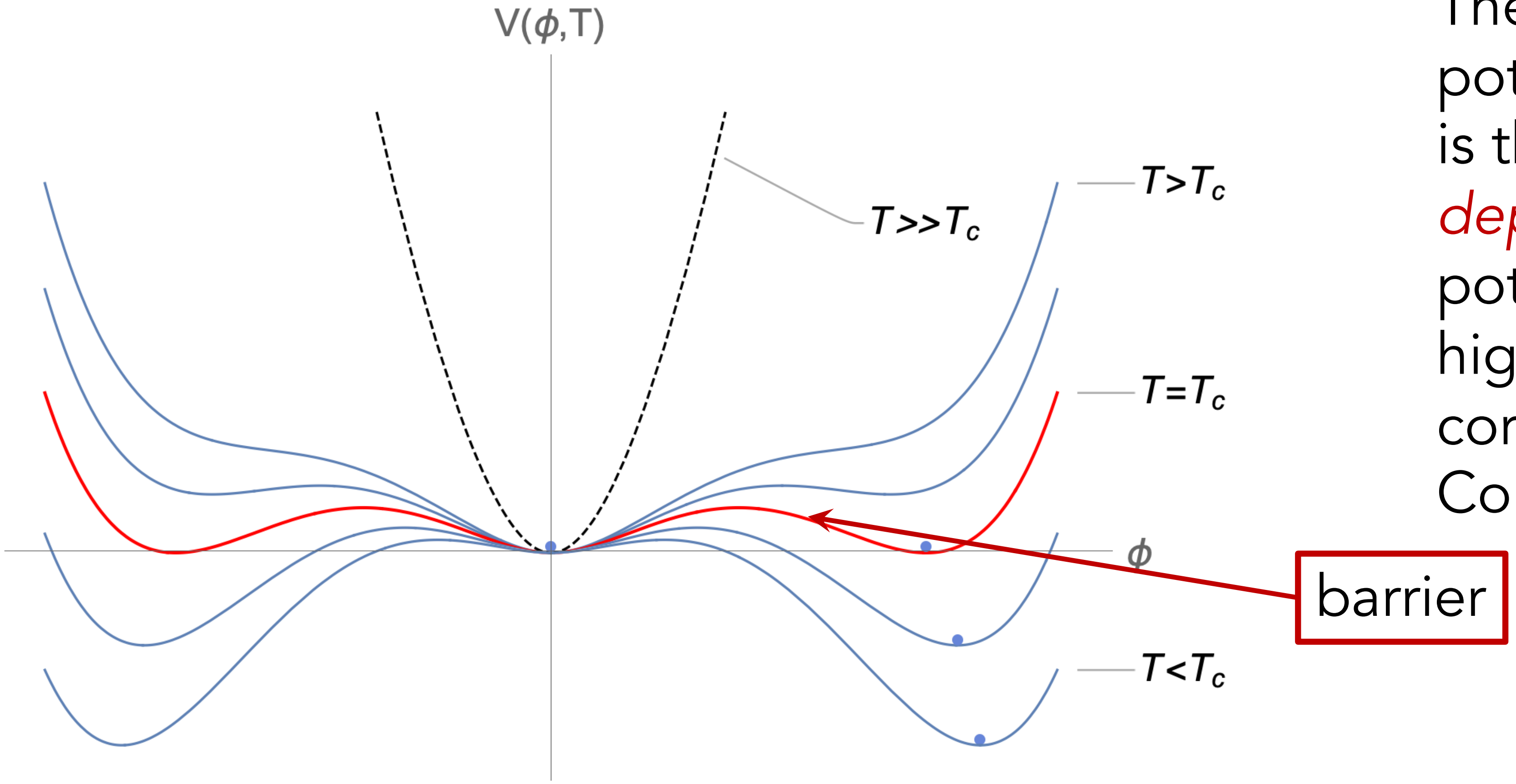
If the transition is "strongly first order"…

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

UPPSALA
UNIVERSITET

Free energy density = effective potential

The effective potential is equivalent to the free energy and determines the ground state of the theory

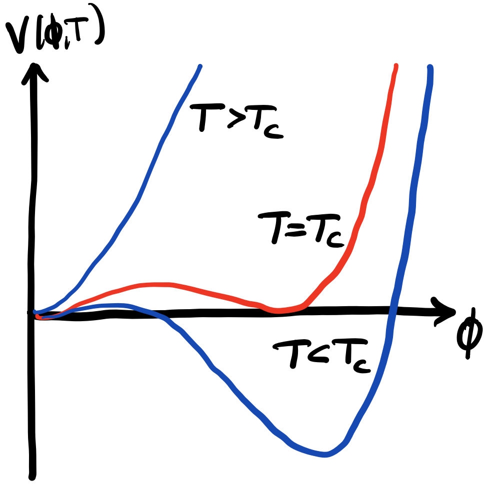


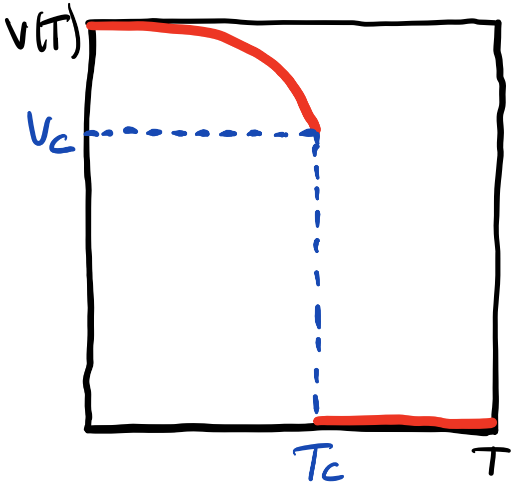
The effective potential $V_{eff}(\phi,T)$ is the *temperature-dependent* Higgs potential with higher order corrections (e.g. Coleman-Weinberg)

UPPSALA UNIVERSITET

Order of phase transition depends on V_{eff}

A barrier means tunneling to the new ground state
→
abrupt, discontinous 1^{st} order transition with **latent heat**

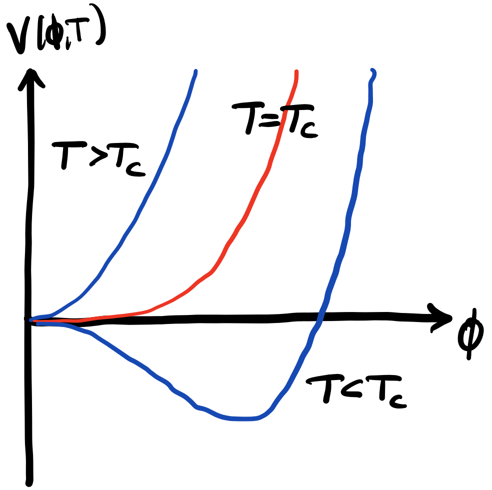


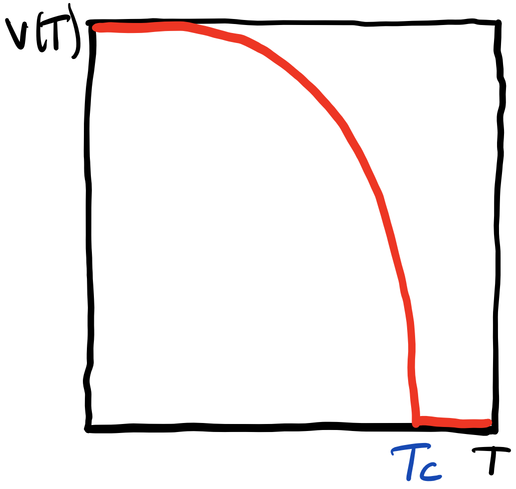


1st order transition

(order parameter is discontinuous)

No barrier
→
smooth, continuous 2^{nd} order or crossover



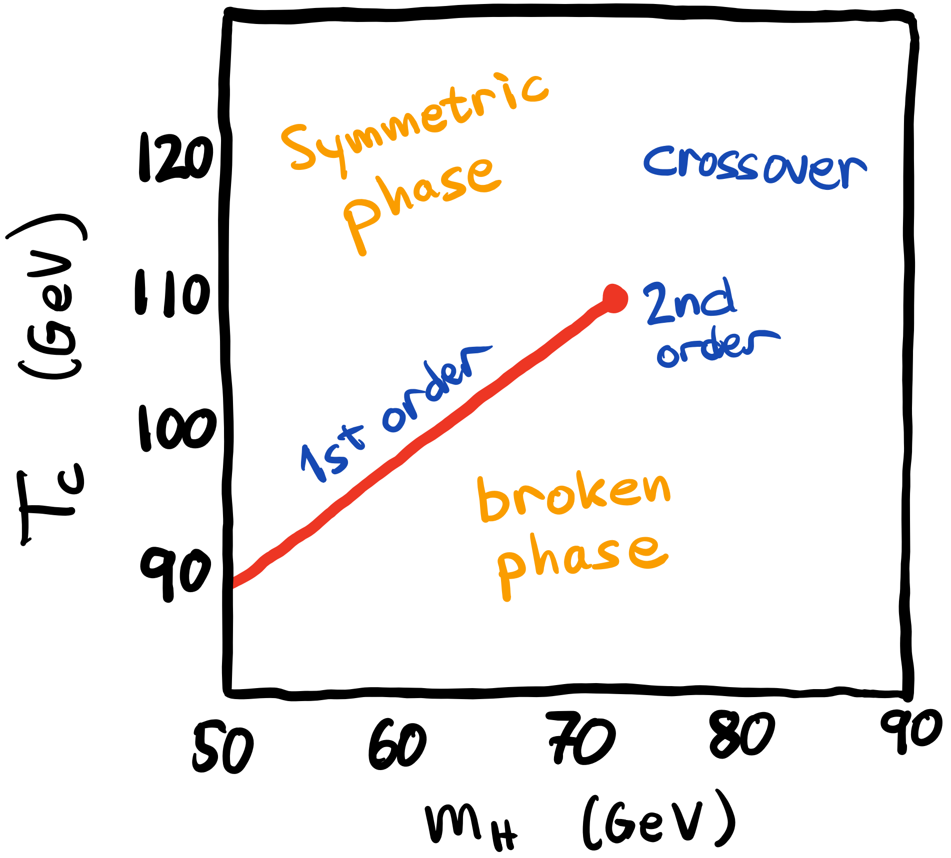


2nd order transition

Plots adapted from E. Senaha, Symmetry 2020, 12(5), 733 (CC BY 4.0)

UPPSALA UNIVERSITET

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

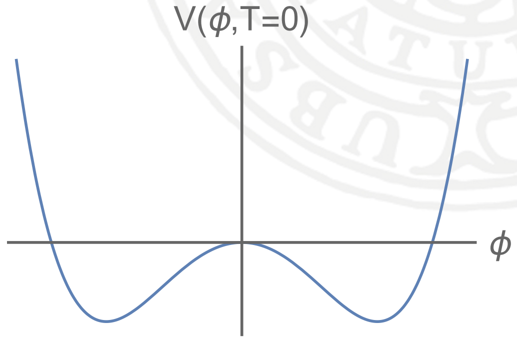
A first order phase transition is only possible if $m_H < 72$ GeV
– in our universe, it was a smooth crossover transition

UPPSALA UNIVERSITET

So how do you get a barrier?

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

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

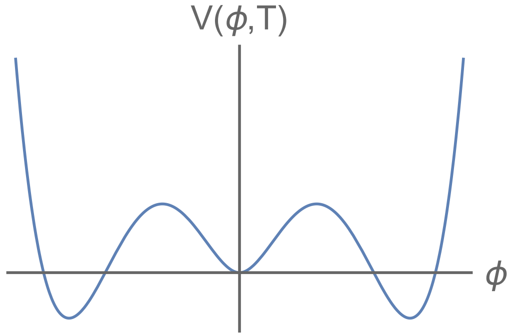


Gauge boson contributions at finite T give a cubic term:

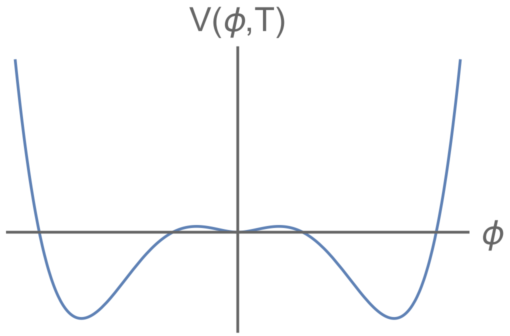
$$V_{\text{eff}}(\phi, T) = -\frac{1}{2}\mu^2_{\text{eff}}(T)\phi^2 - e^3\frac{T}{12\pi}\phi^3 + \frac{\lambda}{4}\phi^4,$$

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

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



or



?

UPPSALA UNIVERSITET

Why does m_H determine the barrier?

In order to have a large barrier, the cubic term must be about the same size as the quadratic and quartic terms:

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

Power counting (Arnold and Espinosa): **we need scaling $\lambda \sim e^3$**, which is not satisified in the SM: λ is ~5 times too large

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

UPPSALA UNIVERSITET

Use higher dimension operators to do this!

- Grojean, Servant, Wells (and others later) considered EWPT with dimension-6 operators
- They took $\lambda<0$ to get a barrier at tree-level with the ϕ^6 term providing the Mexican Hat-type potential
- This does not work so well because it requires a rather small cutoff scale ~ 700 GeV
- We will instead consider $\lambda>0$ as in SM but **small**. This makes a 1st order EWPT possible with correct Higgs mass, because we can get the right Higgs mass anyway

UPPSALA
UNIVERSITET

Standard Model Effective Field Theory (SMEFT)

Effective field theory with SM symmetries and dimension-6 operators built out of SM fields:

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

There are 59 such operators (with B and L conservation) but the ones relevant for the Higgs sector are

$$Q_H = (H^\dagger H)^3,$$
$$Q_{H\Box} = (H^\dagger H)\Box(H^\dagger H)\,,$$
$$Q_{HD} = (H^\dagger D_\mu H)^*(H^\dagger D^\mu H)$$

UPPSALA
UNIVERSITET

Phase transition in the SMEFT

SMEFT at T=0:

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

but power-counting at high T → dimension-6 term does not influence the phase transition!

Thus we can use the same EWPT calculation as in the SM* but for smaller λ! However:

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

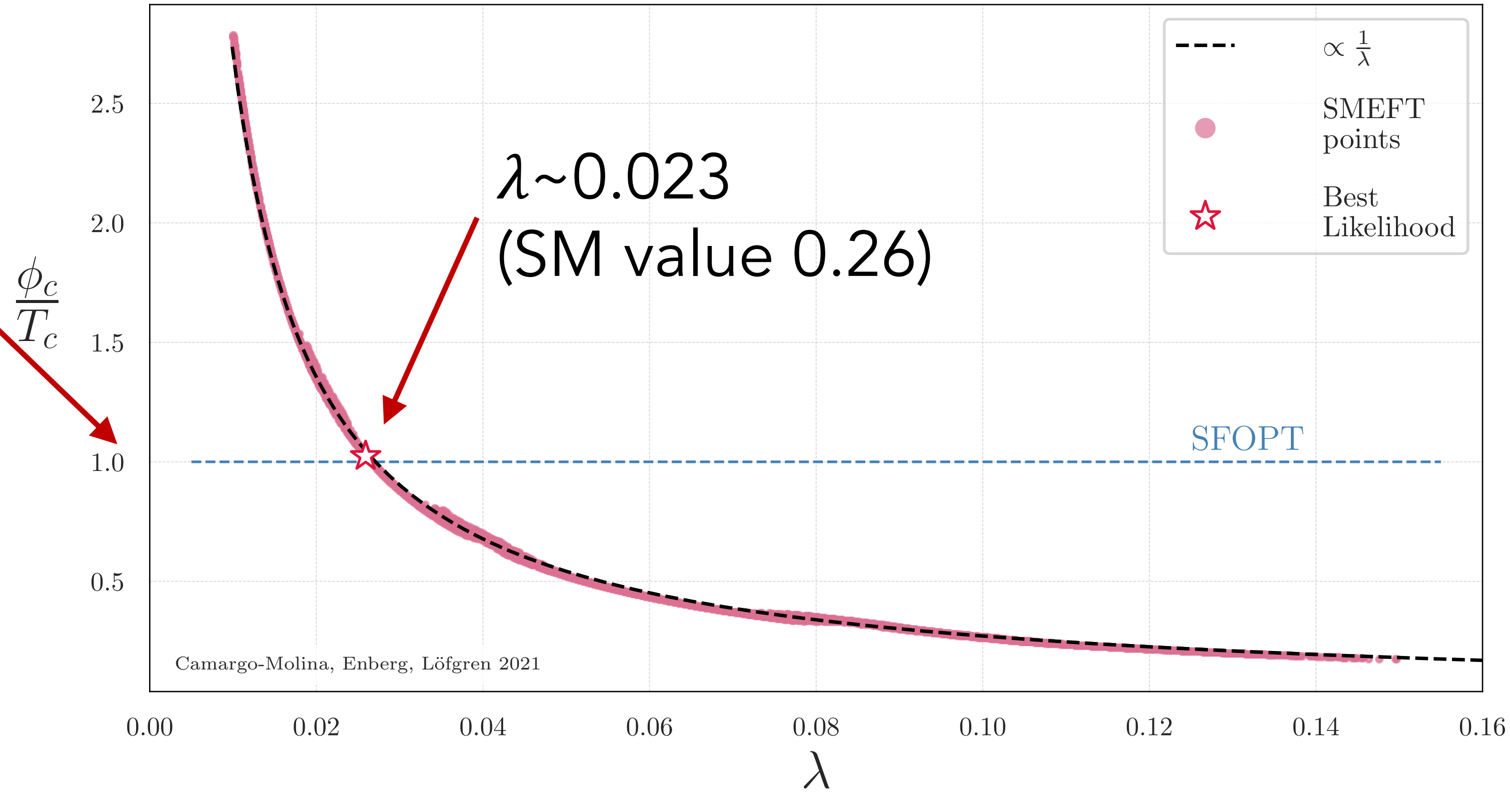
* μ_{eff} gets a contribution from SMEFT Wilson coefficients

UPPSALA UNIVERSITET

The scan and the results

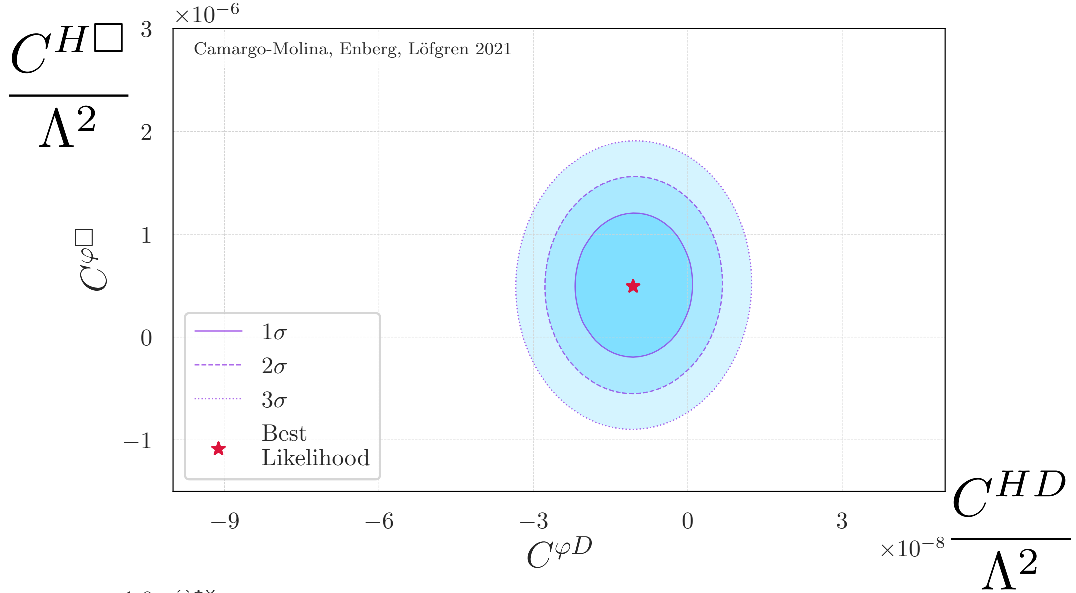
For small λ we can get a strong 1st order PT

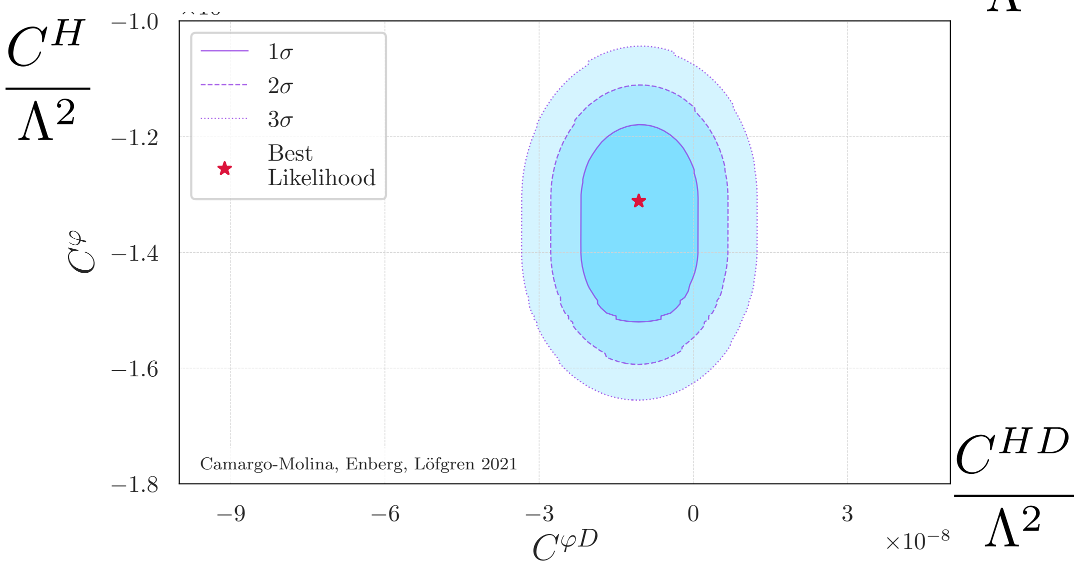
(The $1/\lambda$ dependence comes from the power counting in the potential)

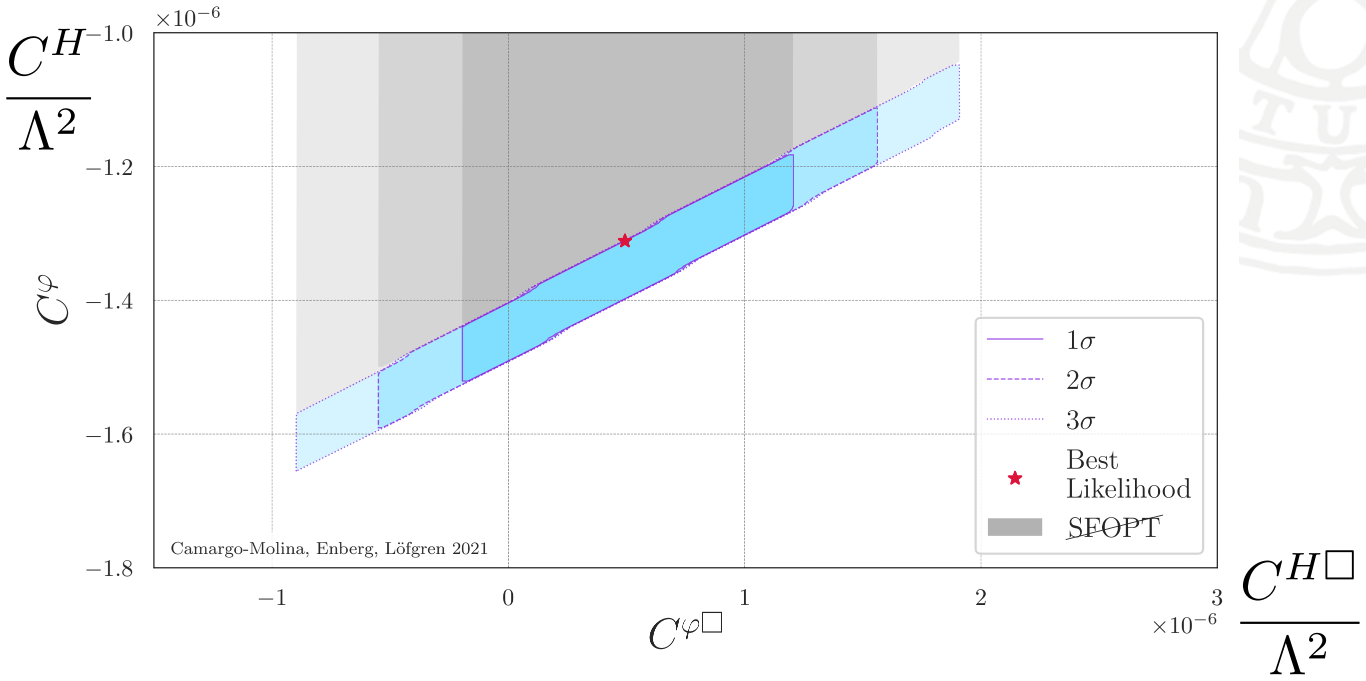


Camargo-Molina, RE, Löfgren, JHEP 10 (2021) 127, arXiv:2103.14022

Scan over Wilson coefficients: Λ~1 TeV







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

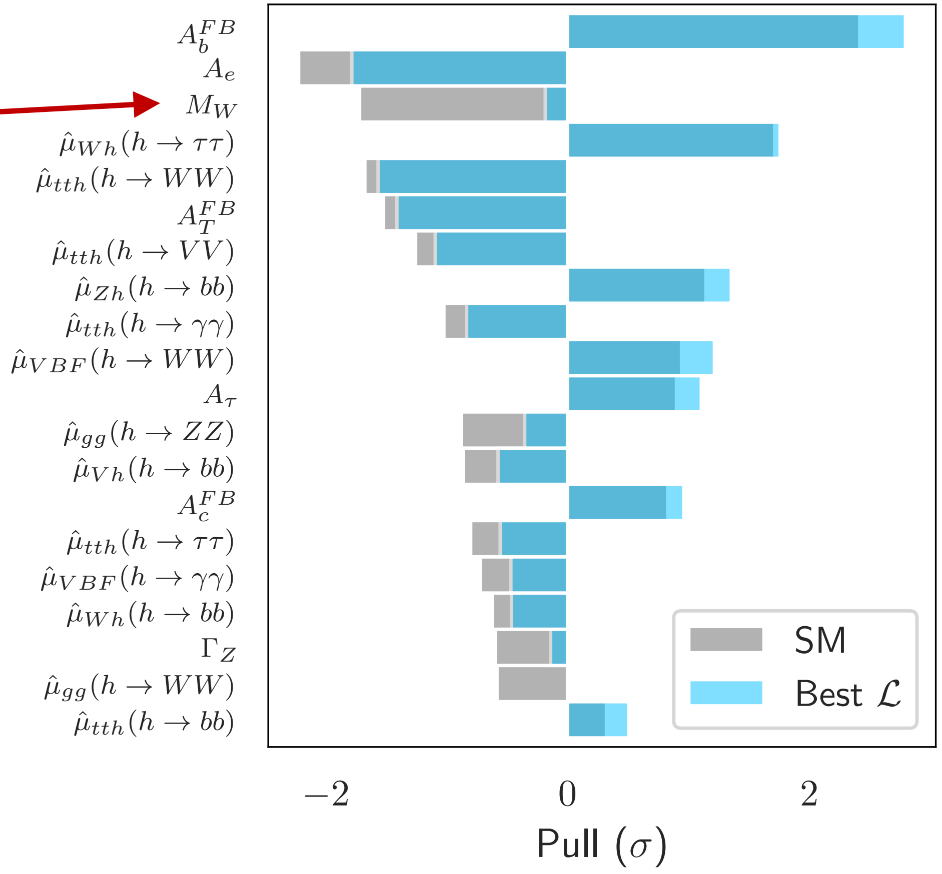
The fit uses the codes smelli, flavio and wilson (Aebischer, Kumar, Stangl, Straub)

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

UPPSALA UNIVERSITET

W mass!

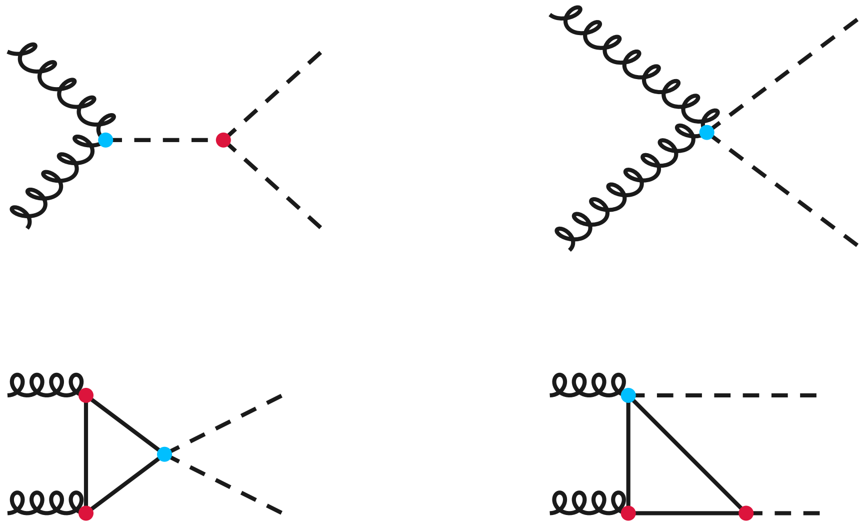
- In fact the fit gives a better fit to the W mass than the SM, because it predicts a slightly larger m_W
- The Wilson coefficients relax some of the parameter relations in the Standard Model



Higgs pair production in SMEFT

These exist in the SM but are modified in SMEFT by dim-6 operators, including a new *p*-dependence. But roughly

$$\frac{\lambda_{HHH}}{\lambda_{HHH}^{\mathrm{SM}}} \simeq 1 - \frac{2v^4}{m_h^2}\frac{C^H}{\Lambda^2}, \qquad \text{here: } C^H < 0$$



These are new diagrams that can modify the rate and the kinematical dependence of the cross section

UPPSALA UNIVERSITET

Next steps

- Investigate Higgs pair production in this small λ scenario
  Part of SHIFT activities; see related talks by Christina Dimitriadi and Elin Bergeås Kuutmann
- Gravitational waves?
  Best way: dimensional reduction, see next talk by Andreas Ekstedt
- Electroweak baryogenesis?
  Need to include CP-violation: more operators