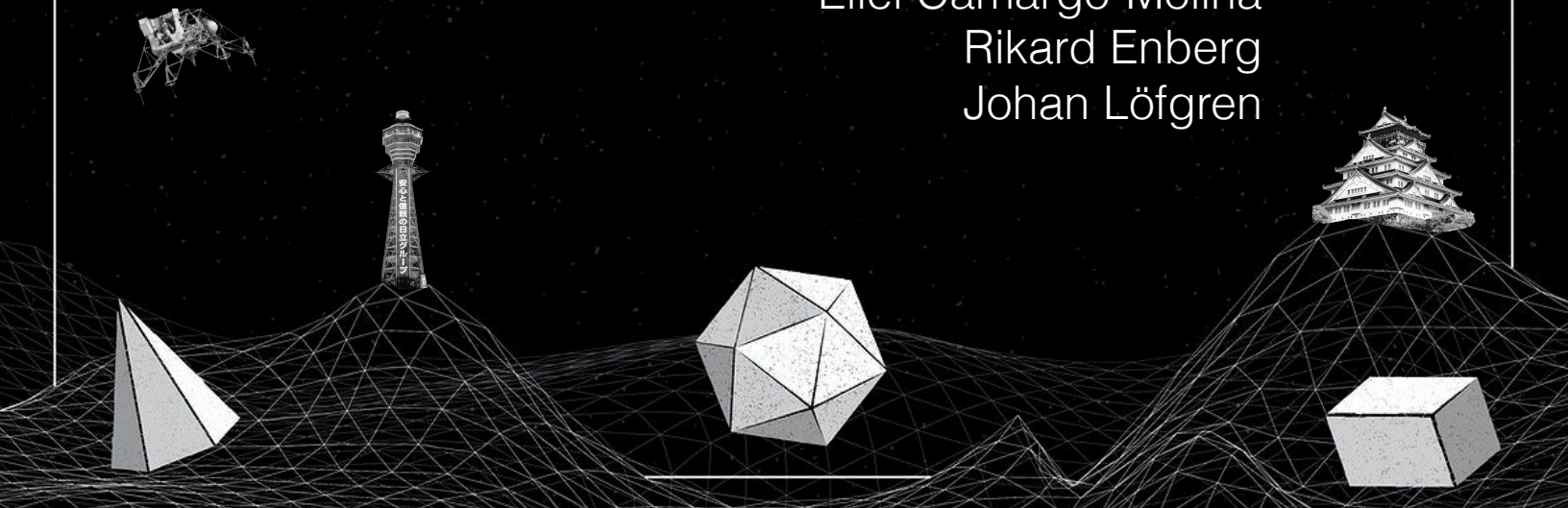


arXiv:2103.14022

First order phase transitions in the SMEFT: **A new perspective**

Eliel Camargo-Molina
Rikard Enberg
Johan Löfgren



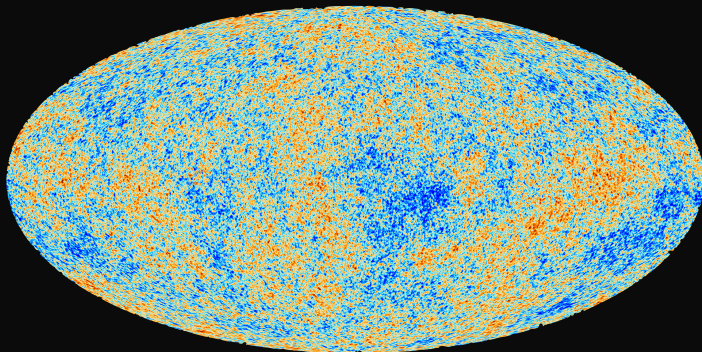
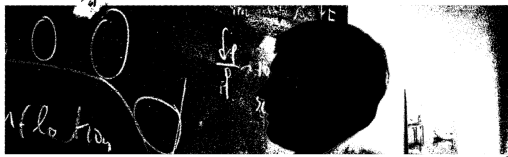
Beyond the Standard Models: Probing the intersection of cosmology and particle physics

At first sight, one might think that these sciences of the very small and of the very large would have very little to say to each other. However, in the past few years the dialogue between particle physics and cosmology has been developing very rapidly.

While some particle theorists are now very concerned about observations of light element abundances in distant gas clouds, cosmologists wait with bated breath to know the decay rate of the Z^0 boson. In this article we outline the reasons for this developing symbiosis between microphysics and macrophysics, and trace some of the development in this rapidly changing field.

Particle physics and cosmology

by John Ellis and Dimitri Nanopoulos 1983



- Connecting the very small and the very large has been in the sight of physicists for a while. GUTs started paving the road
- We knew first from Cosmology that there were ~ 3 Neutrinos. Still only have an upper bound on neutrinos' masses from Cosmology
- Nuclear physics is crucial for star formation, abundances

THE STANDARD MODEL Of Particle Physics

No Dark Matter

No Inflation

Predicted vacuum energy is huge!

No reason for so much more
matter than anti-matter

Origin of its very special parameter values

No gravity

Why is the Higgs so light?

Vacuum Stability

THE STANDARD MODEL Of Cosmology

What is Dark Matter?

Flatness problem: Initial conditions for a present-day
flat universe are $< O(10^{-60})$

Inflation?

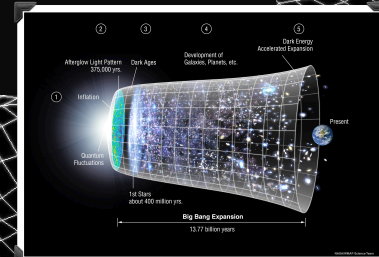
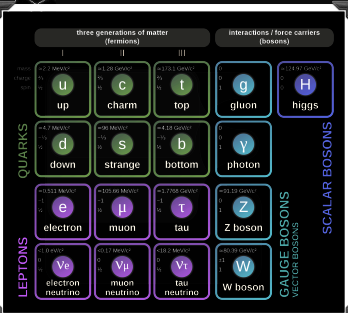
Vacuum energy is tiny!

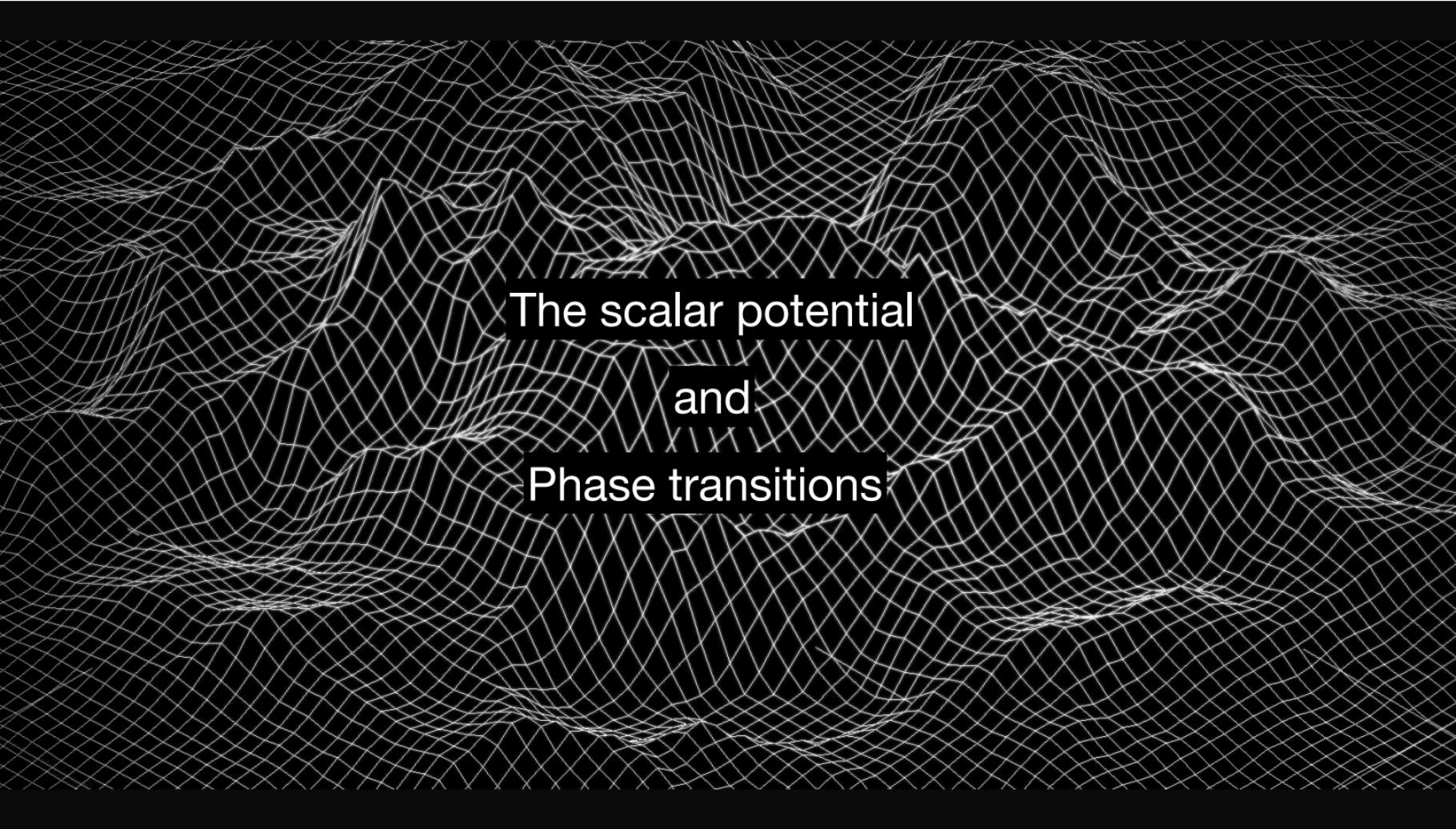
CC, is it constant?

Missing Baryon problem (maybe solved)

Hubble constant disagreement

6 free parameters, too much?



The background of the slide is a 3D wireframe plot of a scalar potential landscape. The plot is rendered in white lines on a black background, showing a complex surface with several prominent peaks and valleys. The lines form a grid-like pattern that follows the contours of the potential, giving it a mesh-like appearance. The overall shape suggests a landscape with multiple local minima and maxima, typical of a potential energy surface in physics.

The scalar potential
and
Phase transitions

Phase transitions

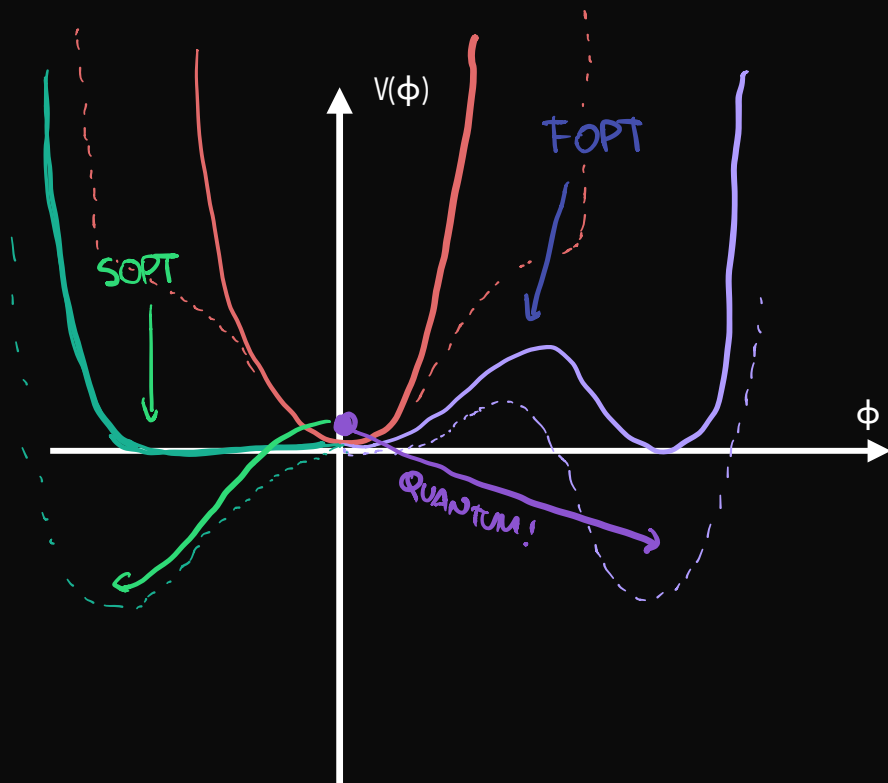
Transition from one vacuum (+symmetries) to another broken phase (+other symmetries).

First order > STRONG

Second order > SOFT

Necessary for generating baryon asymmetry:

- 1) Baryon number violation
- 2) Charge and Charge-Parity violation
- 3) Departure from thermal equilibrium



A 3D wireframe mesh of a mountain range, rendered in white lines against a black background. The mesh is composed of a grid of lines that form the peaks and valleys of the terrain. The perspective is from a low angle, looking across the range.

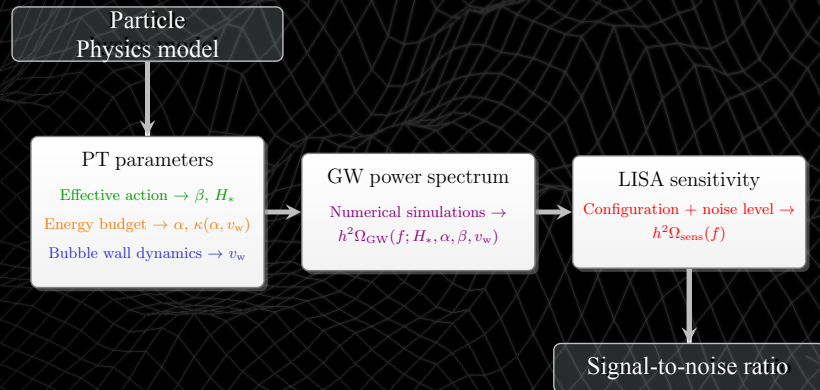
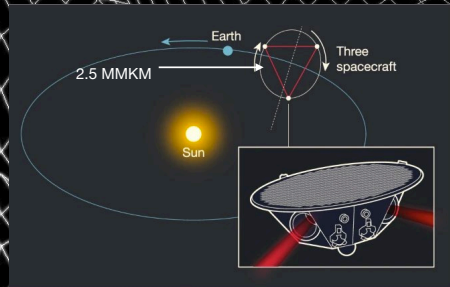
Can we measure that?

Prospects for measurements, Part I

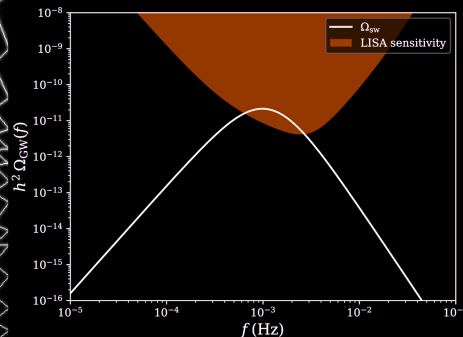
The early universe was transparent to GWs!

A first-order PT means bubbles. Bubbles collide and disturb spacetime massively.

First order phase transitions from EW to TeV Scales predict stochastic GW backgrounds accessible by the Laser Interferometer Space Antenna (LISA).



From 1910.13125, Caprini et al.



Prospects for measurements, Part I

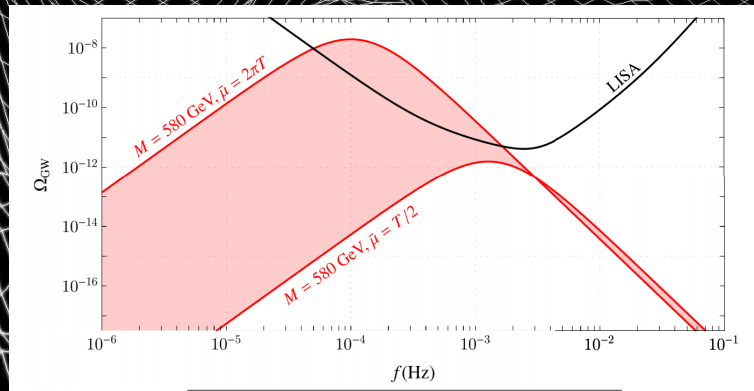
Early days of GW predictions

Formalism, uncertainties and tool ecosystem in lively development

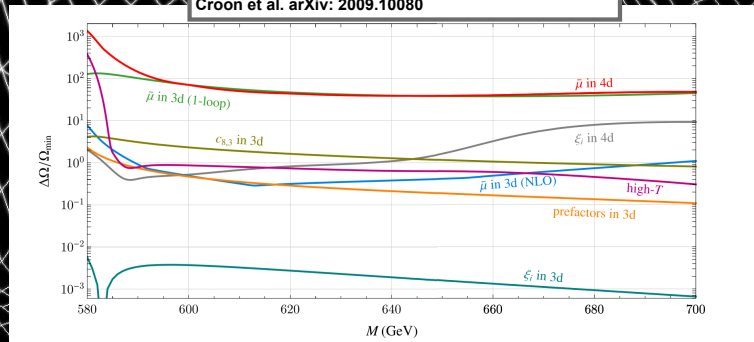
LISA will probe "some" region, maybe it picks up the EWPT if we are lucky

For a given model/assumption still large discrepancy in predictions

Is there a complementary way?



Theo. Uncertainties of cosmological phase transitions
Croon et al. arXiv: 2009.10080



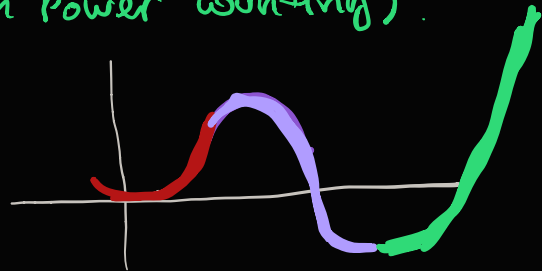


Can we probe the EWPT in another way?
EWPT in the SM and the SMEFT

FOPT in the SM (schematically)

the LO potential (Being careful with power counting).

$$V_{LO} = -m_{\text{eff}}^2(T) \frac{\varphi^2}{2} + \frac{\lambda}{8} \varphi^4 - \frac{T e^3}{12\pi} \varphi^3$$



for this to work out, we need a certain scaling of lagrangian parameters (Arnold + Espinosa, 9212235)

$$\text{FOPT} \rightarrow \lambda \sim e^3 \quad \phi \sim T \quad m_{\text{eff}}^2 \sim e^3 T^2 \quad T \sim \frac{\sqrt{m^2}}{e}$$

$$\rightarrow m_h \sim \lambda v^2 \Rightarrow$$

If FOPT then
 $m_h < 125 \text{ GeV}$

Want to know more?
Check Johan Löfgren talk
Session 8-C

FOPT in the SMEFT

← what if the SM is an EFT?
write down all high dim. ops.

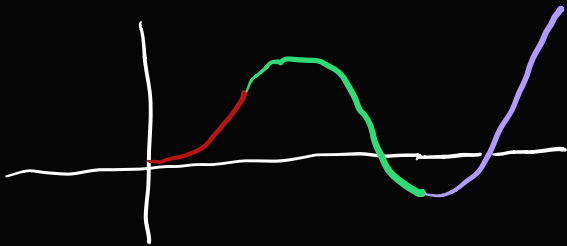
$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + C^{\varphi} (\phi\phi^\dagger)^3 + C^{\varphi\Box} \phi\phi^\dagger \Box \phi\phi^\dagger + C^{\varphi D} (\phi D_\mu \phi^\dagger)^* (\phi^\dagger D^\mu \phi) + \sum_i C_i \mathcal{O}_i + \mathcal{O}\left(\left(\frac{v}{\Lambda}\right)^4\right)$$

$[\text{GeV}]^{-2} \nearrow$

$$V(T=0) = -\frac{m^2}{2} \varphi^2 + \frac{\lambda}{8} \varphi^4 - \frac{C^\varphi}{8} \varphi^6$$

$$\boxed{\lambda < 0}$$

$T \neq 0$

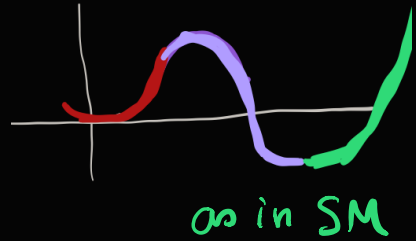


Leads to small $\Lambda_{\text{NP}} < \text{TeV}$ \rightarrow EFT?

what about $\lambda > 0$

FOPT in the SMEFT

$$\boxed{\lambda > 0} \quad V_{LO} \approx -m_{\text{eff}}^2(\tau) \frac{\varphi^2}{2} + \frac{\lambda}{8} \varphi^4 - \frac{T e^3}{12\pi} \varphi^3$$



We still need $\lambda \sim e^3$, and a careful Gauge invariant calculation of $\langle \phi \rangle / T_c$.

Can we have $m_H \sim 125 \text{ GeV}$? YES!

$$m_H^2 = \lambda v^2 - (3C^e - 2\lambda C^{eD} + \frac{\lambda}{2} C^{eD}) v^2 \Rightarrow C^e \sim \frac{\lambda}{v^2} \quad C, C^D \sim \frac{1}{v^2}$$

A 3D wireframe mesh of a mountain range, rendered in white lines against a black background. The mesh is composed of a grid of lines that form the peaks and valleys of the terrain. The text "What about all other experiments?" is centered over the middle of the image.

What about all other experiments?

Finding allowed regions with $\lambda > 0$ and FOPT

Pick a point within a reasonable slice of parameter space

Find λ and m^2

$$\begin{aligned} C^{\varphi} &\in [-1 \cdot 10^{-5}, 0] \\ C^{\varphi D} &\in [-1 \cdot 10^{-7}, 0.5 \cdot 10^{-7}] \\ C^{\varphi \square} &\in [-1.5 \cdot 10^{-6}, 3 \cdot 10^{-6}], \end{aligned}$$

~ Scaling for FOPT
EWPT, rho par, ...
EWPT ...
NP ~ 1 - 3 TeV

Calculate the $\Delta \log$ likelihood given experimental data using **smelli**

Check if it leads to a FOPT

Find points in agreement with data and a FOPT

Finding v/T_c :
Numerical implementation of a binary search by first placing lower and upper bound on the critical temperature and minimising the potential.

$v/T_c > 1$, FOPT

README.md

build passing coverage 90%

smelli – a global likelihood for precision constraints

smelli is a Python package providing a global likelihood function in the space of dimension-six Wilson coefficients in the Standard Model Effective Field Theory (SMEFT). The likelihood includes contributions from quark and lepton flavour physics, electroweak precision tests, and other precision observables.

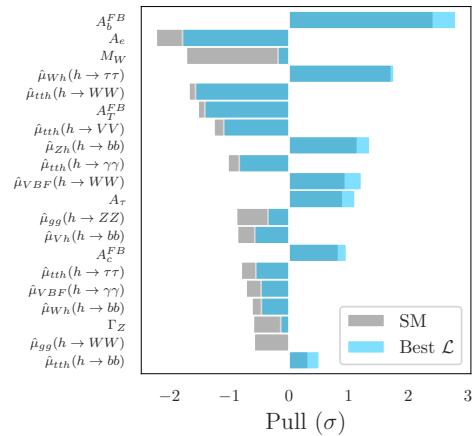
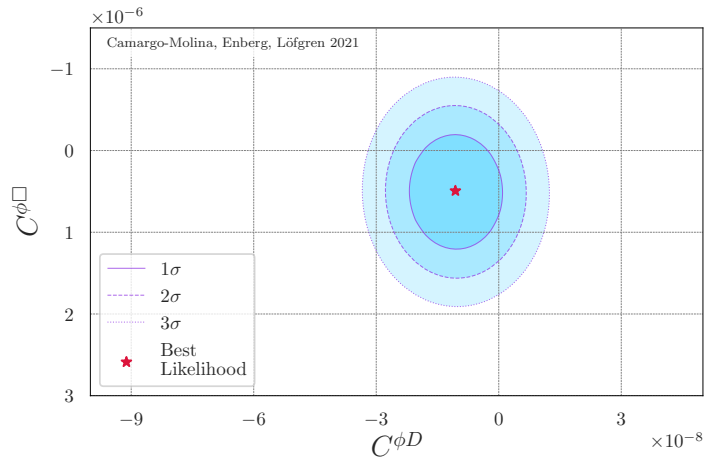
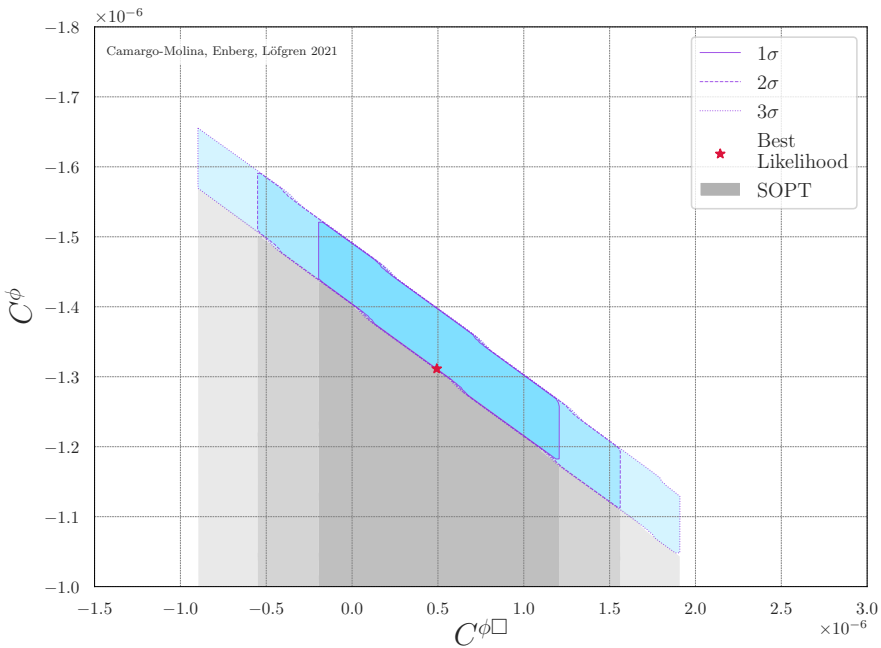
The package is based on [flavio](#) for the calculation of observables and statistical treatment and [wilson](#) for the running, translation, and matching of Wilson coefficients.

Installation

The package requires Python version 3.6 or above. It can be installed with

```
python3 -m pip install smelli --user
```

Allowed regions with $\lambda > 0$ and FOPT

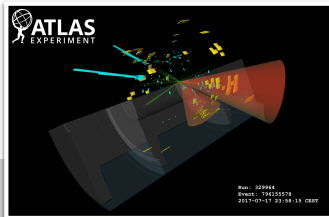


Cosmology @ Colliders

Search for Higgs boson pair production in the two bottom quarks plus two photons final state in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

ATLAS Collaboration
Mar 31, 2021

Report number: ATLAS-CONF-2021-016
Experiments: CERN-LHC-ATLAS
View in: [CERN Document Server](#)



$$\frac{\lambda_{HHH}}{\lambda_{HHH}^{\text{SM}}} = 1 - 2 \frac{C^\varphi v^4}{m_h^2}$$

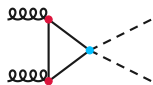
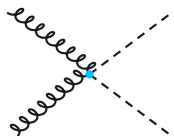
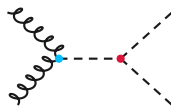
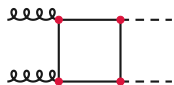
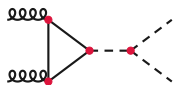
$$-1.2 \cdot 10^{-5} < C_{\text{LHC}}^\varphi < 5.3 \cdot 10^{-6}$$

$$-2.8 \cdot 10^{-6} < C_{\text{HL-LHC}}^\varphi < 1.7 \cdot 10^{-6}$$

Kim, Sakaki, Son
[1801.06093]

$$-1.65 \cdot 10^{-6} \lesssim C_{\text{FOPT}}^\varphi \lesssim -1.05 \cdot 10^{-6}$$

If C^φ is constrained to be outside this region, then the EWPT can not be first-order driven by new physics beyond the TeV scale.



● Modified vertex
● New vertex

Conclusions

- First order phase transitions are the (most promising) link between observations, cosmology and particle physics.
- SMEFT a good “agnostic” proxy that captures heavy NP.
- So far, only $\lambda < 0$ has been seriously thought about. But that means scale of NP maybe too low
- Proper power counting and care for gauge invariance surprisingly opens up $\lambda > 0$.
- It is also allowed by measurements so far!

A roadmap for the future

The particle physics community refreshes the roadmap for the field in Europe, taking into account the worldwide context, in the so-called European Strategy for Particle Physics update, which happens every seven years.

Fabiola Gianotti and Gian Francesco Giudice

The focus of particle physics has thus evolved towards addressing structural questions about spacetime, fundamental interactions and the origin of the Universe. Some of these are as old as civilization itself and it is fascinating that we have today reached the maturity and developed the technologies to address them. The urge to seek answers to such questions is part of what defines us as humans. The ambitious task that lies ahead entails global collaboration on a courageous experimental venture, involving high-energy colliders, low-energy precision tests, observational cosmology, cosmic rays, dark-matter searches, gravitational waves, terrestrial and cosmic neutrinos, and much more.