Higgs self-coupling at a $\sqrt{s}$ = 10 TeV Muon Collider

Muon4Future

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on behalf of IMCC

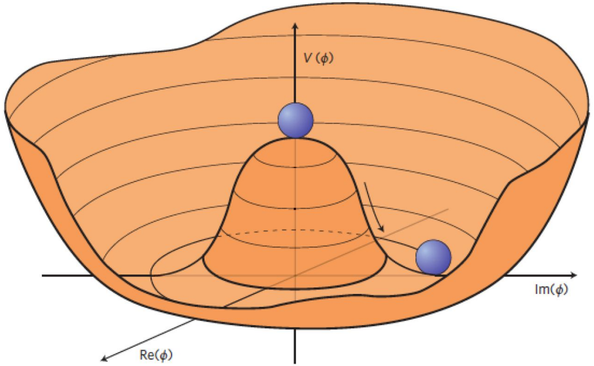
FLASH TALKS session

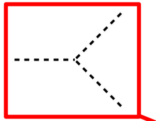
Why the Higgs self coupling?

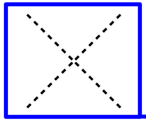
The spontaneous symmetry breaking in the SM gives masses to fermions and W/Z bosons

↳ only possible if the Higgs potential has a non-trivial vacuum

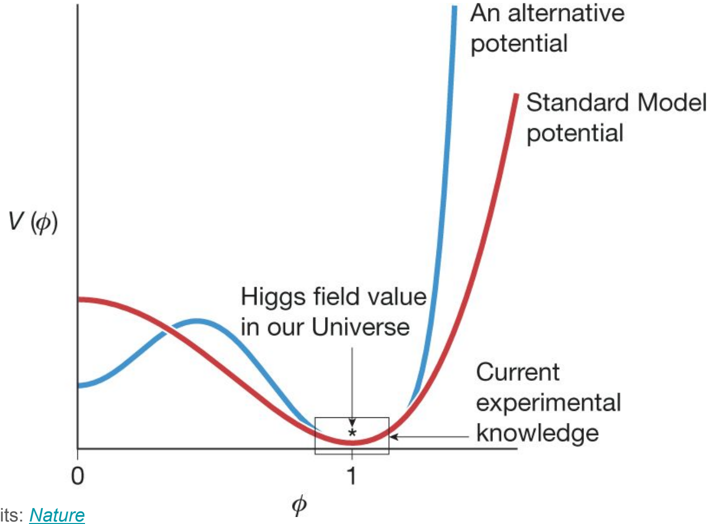
↳ self-interaction terms in the Higgs Lagrangian







$$\mathcal{L}_H^{ug} = (\partial_\mu h\, \partial^\mu h)/2 - m_h h^2 + \boxed{\lambda_3 h^3} + \boxed{\lambda_4 h^4}$$



Credits: Nature

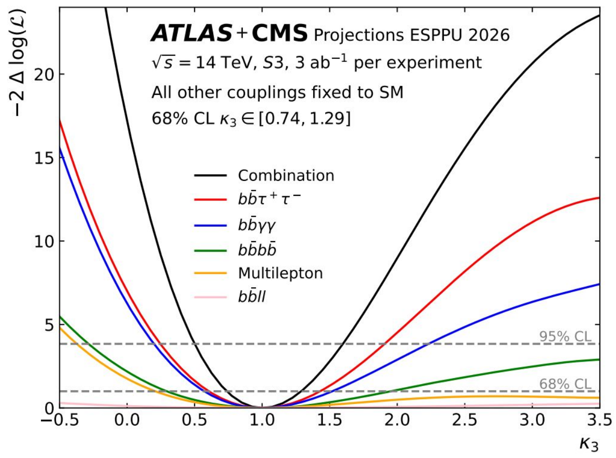
The direct measurement of λ_3 and λ_4 would help determine the shape of the Higgs potential

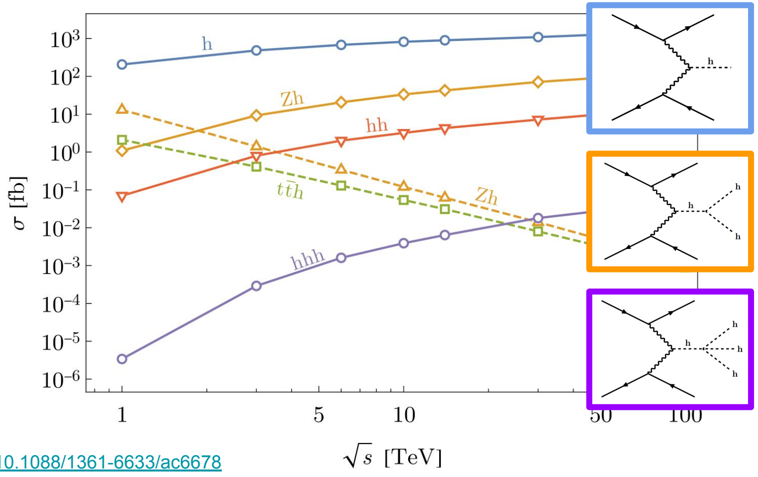
- ✓ stability of the SM vacuum state
- ✓ first order / continuous transition in the early universe
- ✓ possible new physics in quantum corrections

The quest for two Higgses

- ➡ LHC is not set to observe double Higgs events
- ➡ HiLumi LHC with L = 3 ab^{-1} will constrain the $\kappa_3 = \lambda_3/\lambda_3(\mathrm{SM})$ with uncertainty ~ 30% at 68% CL
  - ↳ ATLAS + CMS all-channels combination
- ➡ To get a <10% constraint we must wait the next future collider at the Energy Frontier

CMS+ATLAS ESPPU input





doi.org/10.1088/1361-6633/ac6678

- ➡ A multi-TeV Muon Collider is *de facto* a Higgs factory
- ➡ >10^4 double-Higgs production events at $\sqrt{s}$ = 10 TeV assuming L = 10 ab^{-1} / 5 years (one experiment)
- ➡ Lepton collider → small physics backgrounds
  → high-precision measurements

The MUSIC detector study

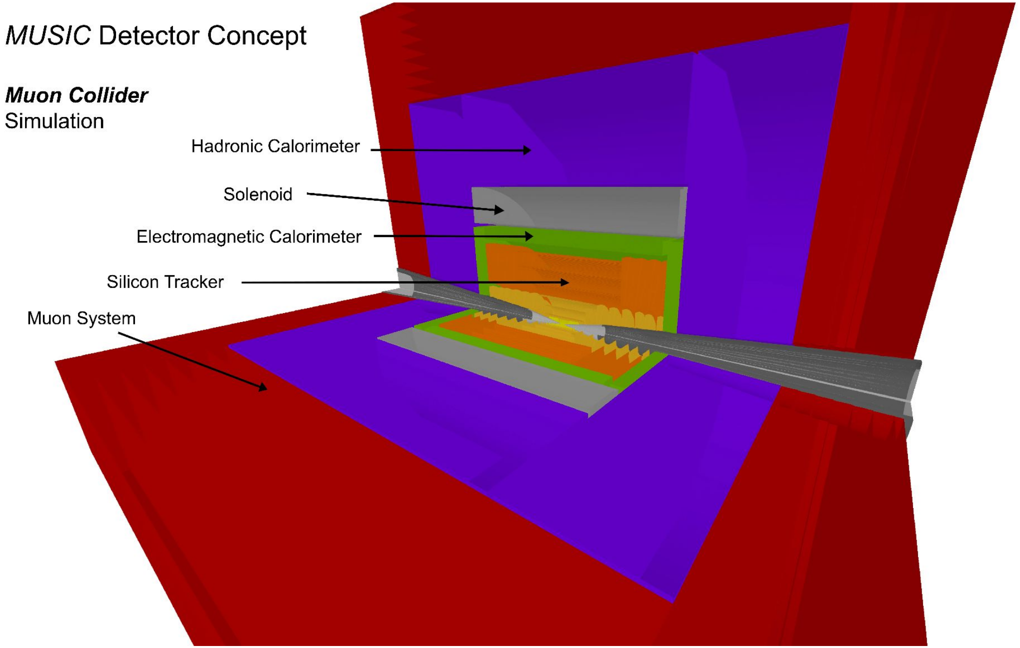
MUon System for Interesting Collisions: detector concept for a $\sqrt{s}$ = 10 TeV Muon Collider, designed in view of ESPPU 2025.

→ detailed simulation studies for benchmark single and double Higgs processes

The detector study included:

- ✓ Tracking efficiency and p_T resolution
- ✓ ECal efficiency and energy resolution
- ✓ Jets reconstruction efficiency and p_T resolution
- ✓ Muon reconstruction efficiency and p_T resolution
- ✓ Jet flavour tagging performance

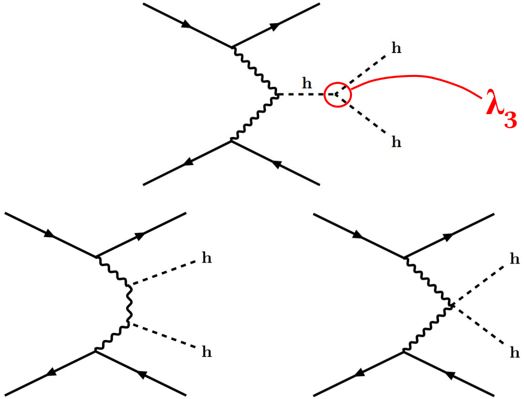
All results are summed up in an input report for ESPPU: MUSIC performance study

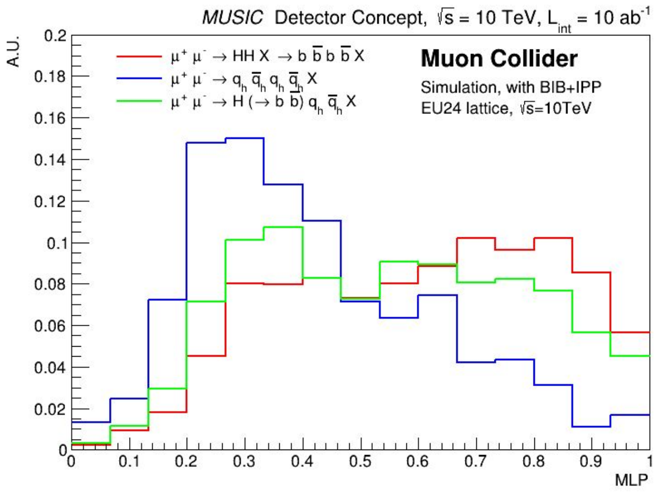


Benchmark analysis: hh $\rightarrow$bbbb

- ➡ Decay mode with largest Branching Ratio (~34%)
- ➡ Final state: at least 4 reconstructed jets
  - ↳ jet p_T > 20 GeV/c, η < 2.5
  - ↳ Higgs candidates by minimizing the figure of merit

    $\sqrt{[(m_{jj,1} - m_h)^2 + (m_{jj,1} - m_h)^2]}$
  - ↳ at least one b-tagged jet per Higgs candidate
- ➡ Dominant backgrounds: $\mu\mu \rightarrow 4q_hX$, hq_hq_hX with $h \rightarrow bb$ (q_h = b, c and X = $\nu\nu$, $\mu\mu$)
- ➡ MultiLayer Perceptron (MLP) to discriminate between double Higgs events and backgrounds
- ➡ Binned maximum likelihood fit of the MLP score to extract the statistical sensitivity
- ➡ **$\Delta(\sigma$ BR$)/(\sigma$ BR$)$ = 6% (stat), L = 10ab $^{-1}$, 5 years, 1 experiment**

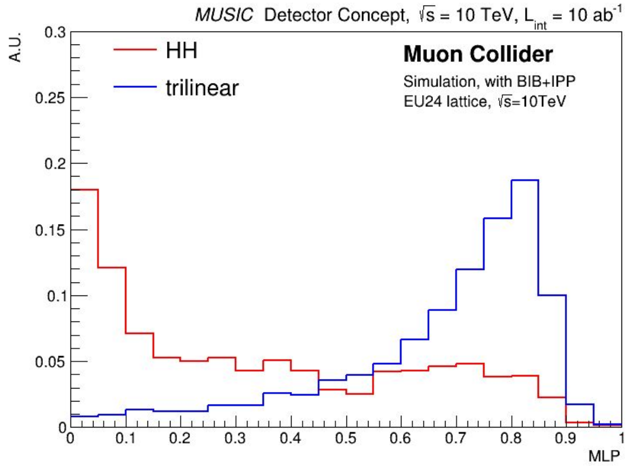


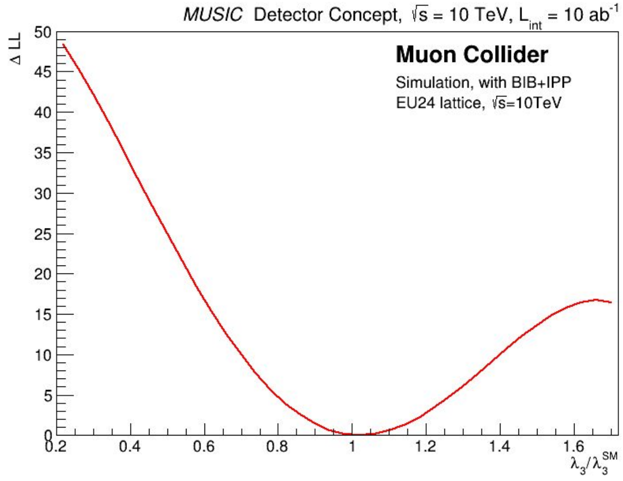


Trilinear Higgs coupling

- ➡ MLP to discriminate between events from a trilinear vertex and other double-Higgs production modes
- ➡ 2D binned maximum likelihood fit of the two MLP scores
  - ↳ hh / background discrimination
  - ↳ trilinear / other hh modes discrimination
- ➡ Analysis on different samples generated varying $0.2 < \kappa_3 < 1.8$
  - ↳ extract the log-likelihood difference profile
- ➡ **$\delta\lambda_3$ (hh→4b) = [-6, +8]% (stat), L = 10ab^{-1}, 5 years, 1 experiment**
- ➡ A $\sqrt{s}$ = 10 TeV Muon Collider is the only Future Collider at the energy frontier able to reach a O(%) precision on the trilinear coupling in such a short period of time

MUSIC Higgs physics ESPPU input





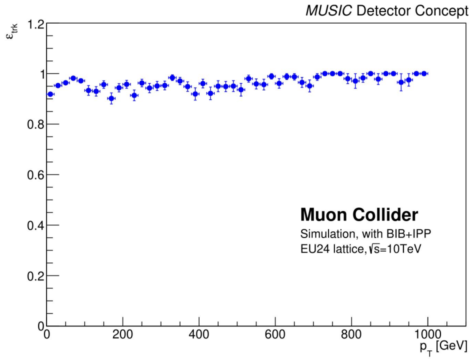
Conclusions

- ➡ A $\sqrt{s}$ = 10 TeV Muon Collider can provide a sample of $>10^4$ double Higgs events with L = $10ab^{-1}$ / 5 years
- ➡ A single experiment is able to achieve a $\Delta(\sigma\ BR)/(\sigma\ BR)$ = 6% (stat) on the process $hh\to bbbb$
- ➡ The trilinear Higgs coupling can be constrained with $\delta\lambda_3$ ($hh\to 4b$) = [-6, +8]% (stat)
  - ↳ single channel, single experiment
  - ↳ unmatched precision-to-runtime among Future Colliders at the energy frontier
- ➡ MUSIC performance in Higgs physics benchmarks analyses is summed up in the ESPPU input
  - ↳ other processes will be added (e.g. $hh\to bbWW$)
  - ↳ paper in progress!
- ➡ Phenomenological studies are exploring the possibility of studying the Higgs quartic coupling at the $\sqrt{s}$ = 10 TeV Muon Collider via the $hhh\to 6b$ process

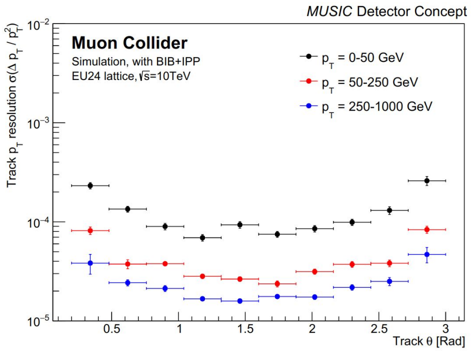
Thank you!

Backup

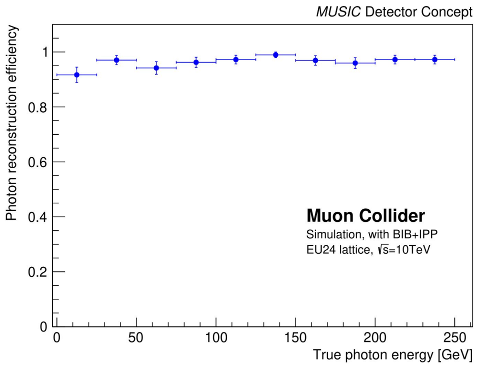
MUSIC reconstruction performance (1)



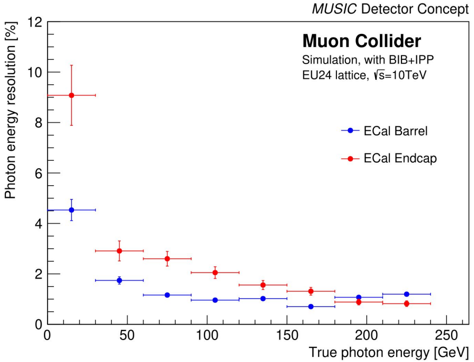
Tracking efficiency



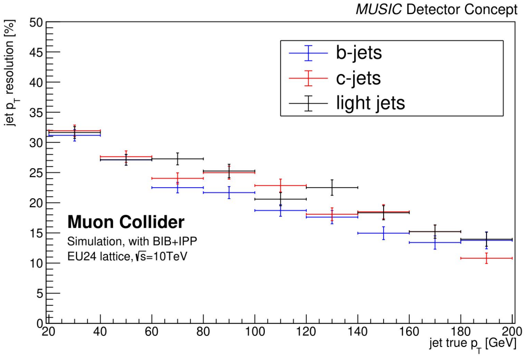
Track pT resolution



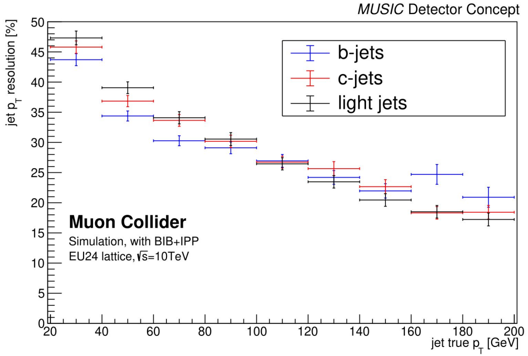
ECal efficiency



ECal energy resolution

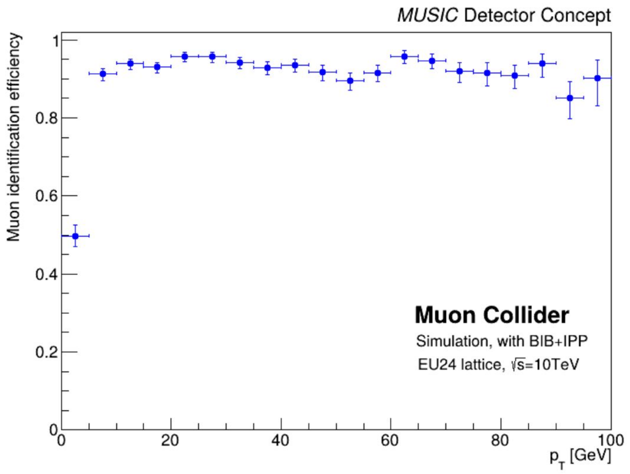


Jet pT resolution (transition)

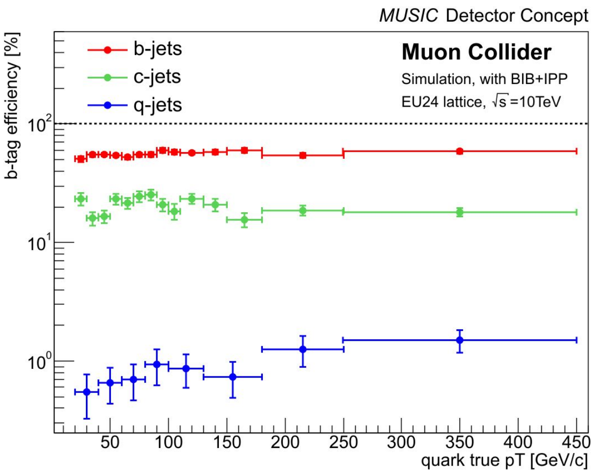


Jet pT resolution (endcap)

MUSIC reconstruction performance (2)

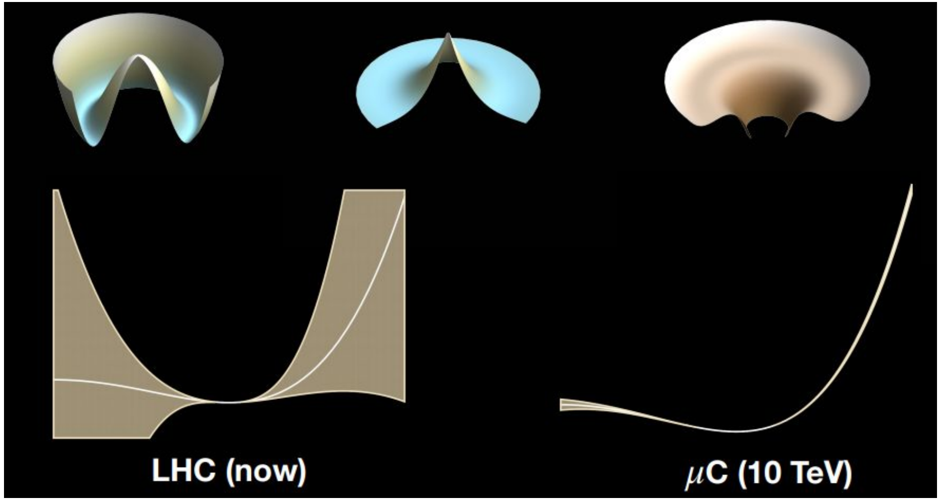


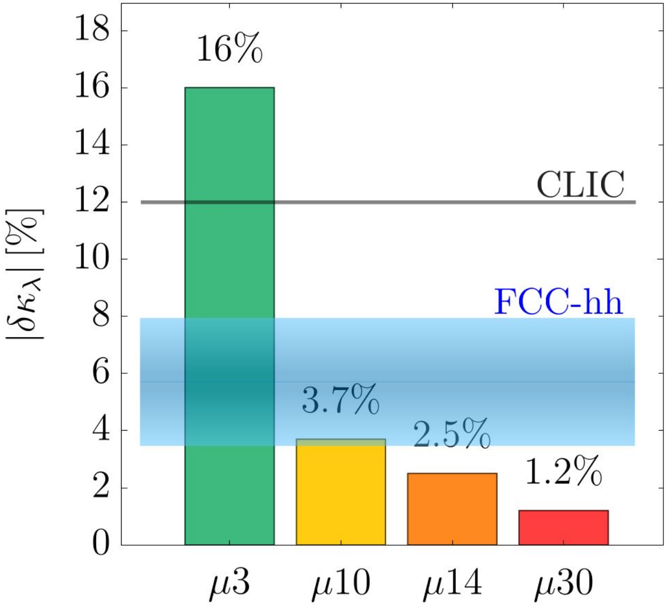
Muon reconstruction efficiency



b-jet tagging efficiency and mis-ID

Pheno predictions on the trilinear coupling sensitivity



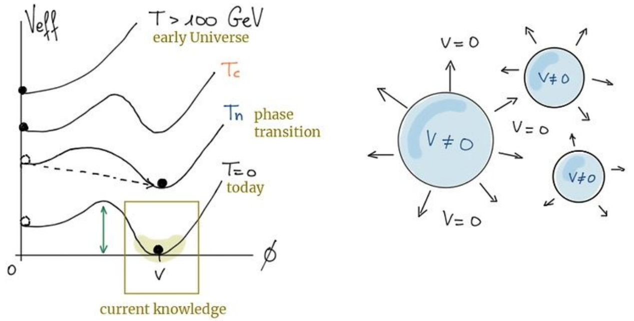


EW phase transition and the early Universe

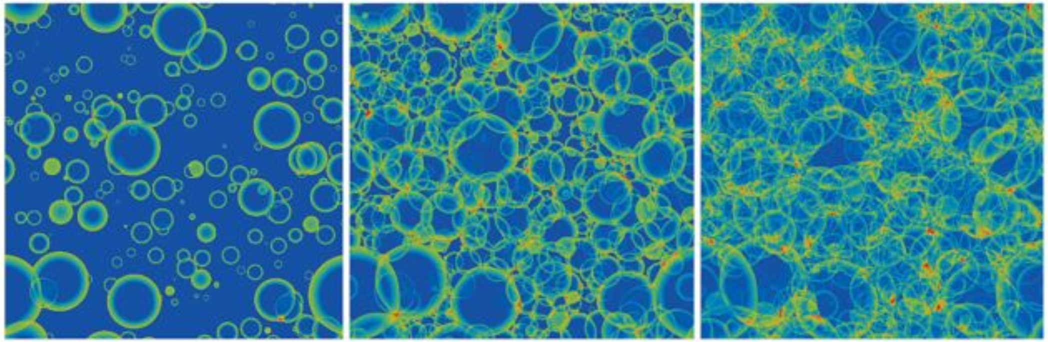
The SM predicts a smooth crossover (“continuous” / second order) → adiabatic

Higgs compositeness or extended Higgs sector can modify the potential = first order transition (“vacuum boiling”):

- electroweak baryogenesis hypothesis, possible explanation of the baryon asymmetry in the Universe
  - ↳ given a source of CPV and a first order EW transition, it matches all Sakharov conditions
- would produce a strongly peaked gravitational waves background
  - ↳ “echo” of the vacuum bubbles



Credits: Quantum Universe



Credits: CERN Courier