Exploring Thermally Induced First Order Phase Transitions in a Higgs-Yukawa Model with a Dimension-6 Operator

David Y. -J. Chu (Department of Electrophysics, NCTU)
Karl Jansen (NIC, DESY Zeuthen)
Bastian Knippschild (HISKP, Bonn)
C. -J. David Lin (Institute of Physics, NCTU)
Attila Nagy (Humboldt University at Berlin; NIC, DESY Zeuthen)

Workshop of recent developments in QCD and Quantum Field Theories
November 10, 2017, NTU

Motivation -- Electroweak Baryogenesis

A testable mechanism for observed baryon asymmetry in the universe.

A strong first-order electroweak phase transition is required.

Not realisable in the SM alone, with Higgs mass ~ 125 GeV

K. Kajantie *et al.*, PRL77, 1996

Alternatives are being considered -- MSSM, 2HDM, Beyond SM theories…

Our approach -- dimension-6 operator with lattice simulation.

F. P. Huang *et al.*, PRD 93, 2016
C. Grojean *et al.*, PRD 71, 2005

The Higgs-Yukawa Model

$$S_{HY}\left[\Phi,\Psi,\bar{\Psi}\right] = \int \mathrm{d}^4x \left\{ \frac{1}{2}\partial_\mu \Phi^\dagger \partial^\mu \Phi + \frac{1}{2} M_b^2 \Phi^\dagger \Phi + \lambda_b \left(\Phi^\dagger \Phi\right)^2 + \frac{\lambda_6}{\Lambda^2}\left(\Phi^\dagger \Phi\right)^3 \right\}$$

$$+ \int \mathrm{d}^4x \left\{ \bar{\Psi} \partial\!\!\!/ \Psi + y_b \left(\bar{\Psi}_L \Phi b_R + \bar{\Psi}_L \tilde{\Phi} t_R + h.c. \right) \right\},$$

$$\Phi = \begin{pmatrix} \phi_2 + i\phi_1 \\ \phi_0 - i\phi_3 \end{pmatrix}, \; \Psi = \begin{pmatrix} t \\ b \end{pmatrix}, \; \tilde{\Phi} = i\tau_2 \Phi^*.$$

τ_2 : Second Pauli matrix.

Dim-6 operator : proxy of BSM physics.

$$y_b = 175/246$$

Phase transition : Breaking of scalar **O(4)** symmetry.

Conditions

2-nd order non-thermal phase transition : continuum limit ⇨ $\langle\varphi\rangle \ll 1$ (broken phase)[1]

Separation of high and low energy physics.

Finite temperature study : reducing temporal extent of lattice. $T = \frac{1}{aN_t} = \frac{\Lambda}{N_t}$

Temperature induced 1-st order phase transition.

Strong enough less the effect is washed out. ⇨ $\frac{\Delta\langle\varphi\rangle}{T_c} = \Delta\langle\varphi\rangle N_t \gtrsim 1$[2]

Phenomenology connection : in zero temperature simulations,

$$\frac{\langle\varphi\rangle}{m_H} \sim \frac{246\,GeV}{125\,GeV} \sim 2.$$[3]

(Exp. known values)

Tool -- Constraint Effective Potential

R. Fukuda, E. Kyriakopoulos, Nucl. Phys. B85 (1975)
D. Chu *et al.* PLB744, 2015

The *vev.* is used as order parameter,

$$\langle\varphi\rangle = \frac{vev.}{\Lambda} = \left\langle \left| \frac{1}{V}\sum_{V} a\Phi \right| \right\rangle .$$

The constraint effective potential as a tool to probe phase structure,

$$e^{-VU(\hat{v})} = \int \mathcal{D}\Phi\mathcal{D}\psi\mathcal{D}\bar{\psi}\delta(\hat{v}-\varphi)e^{-S[\Phi,\psi,\bar{\psi}]},$$

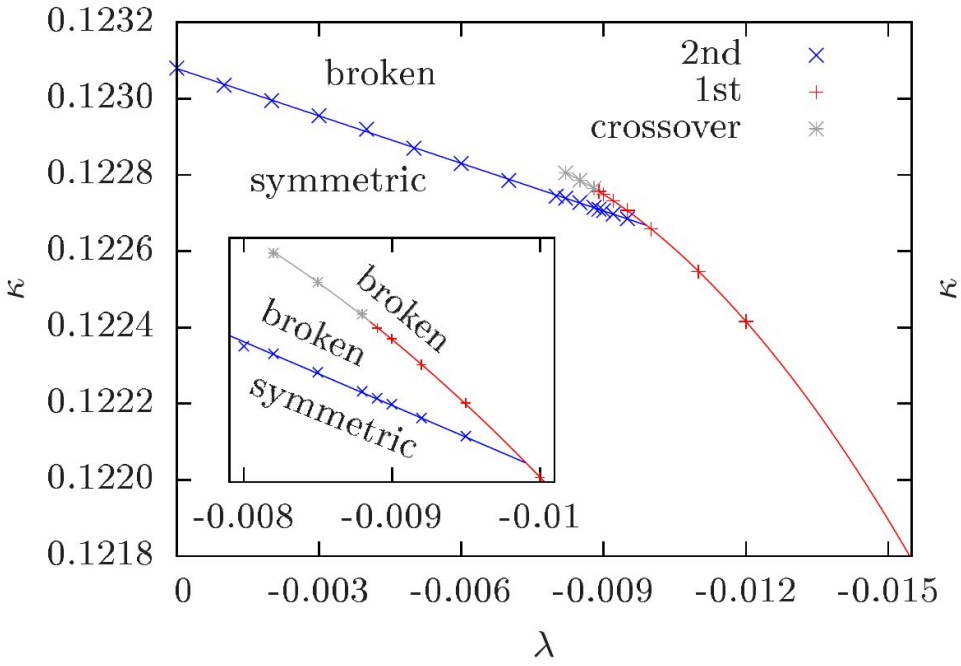
Analytically calculated in perturbation theory.

Numerically extracted by taking histograms of φ.

Return to effective potential at infinite volume.

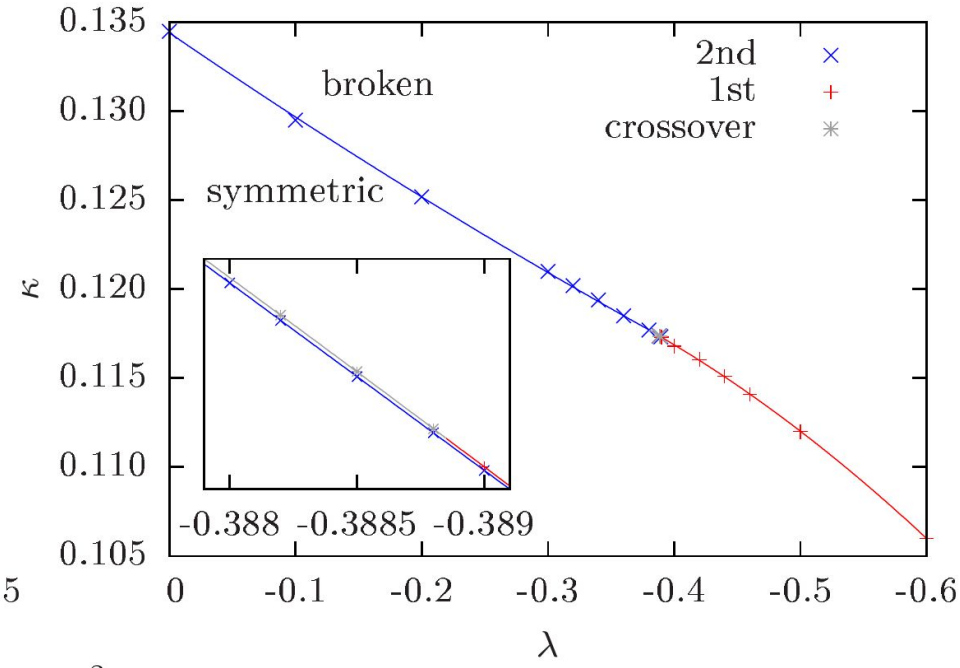
Phase structure of HY Model

Studied using CEP in D. Chu *et al.*, PLB744, 2015



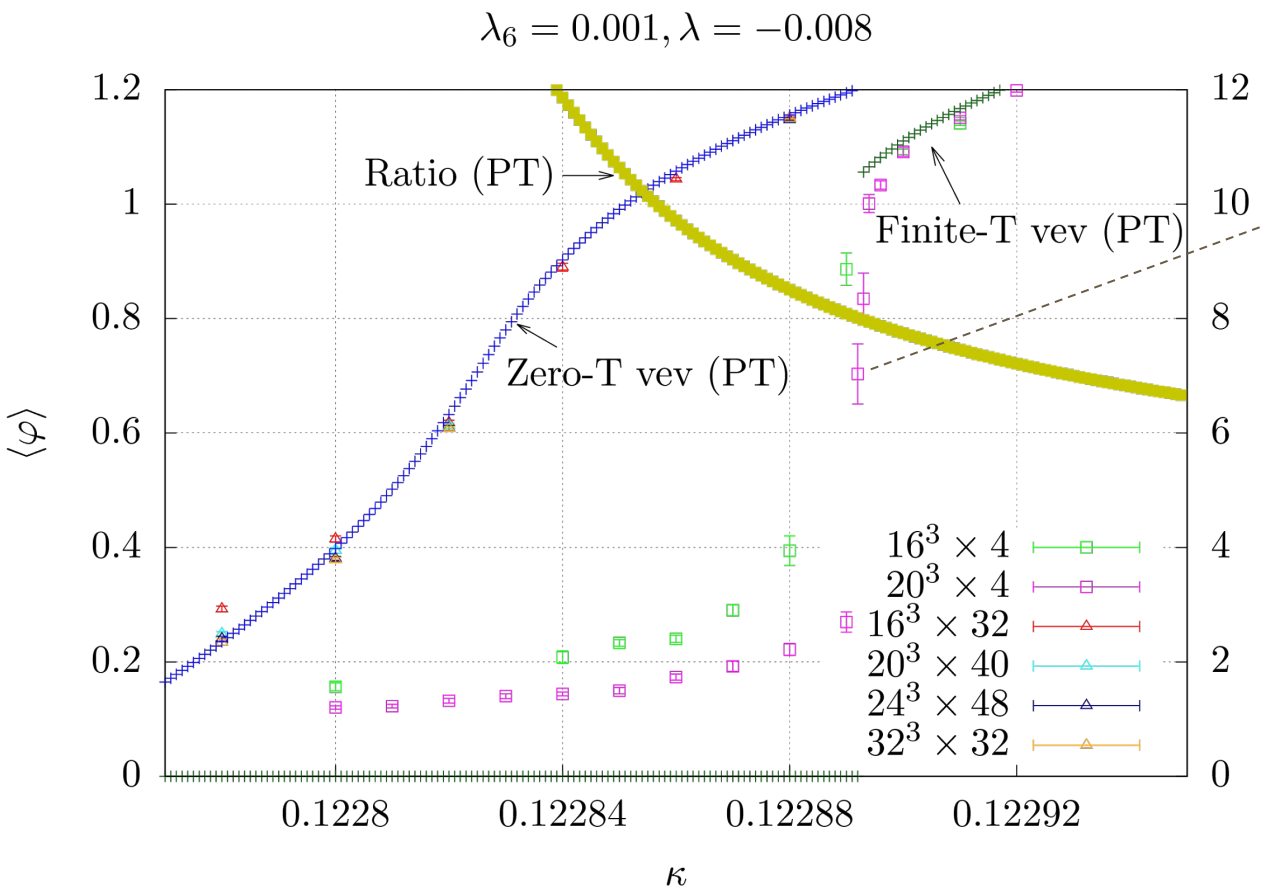
(a) $\lambda_6 = 0.001$

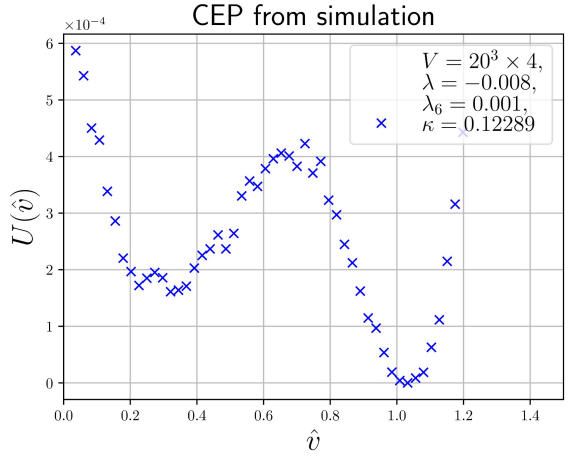
$$M_b^2 = \frac{1 - 8\kappa^2\lambda_b - 8\kappa}{\kappa}$$



(b) $\lambda_6 = 0.1$

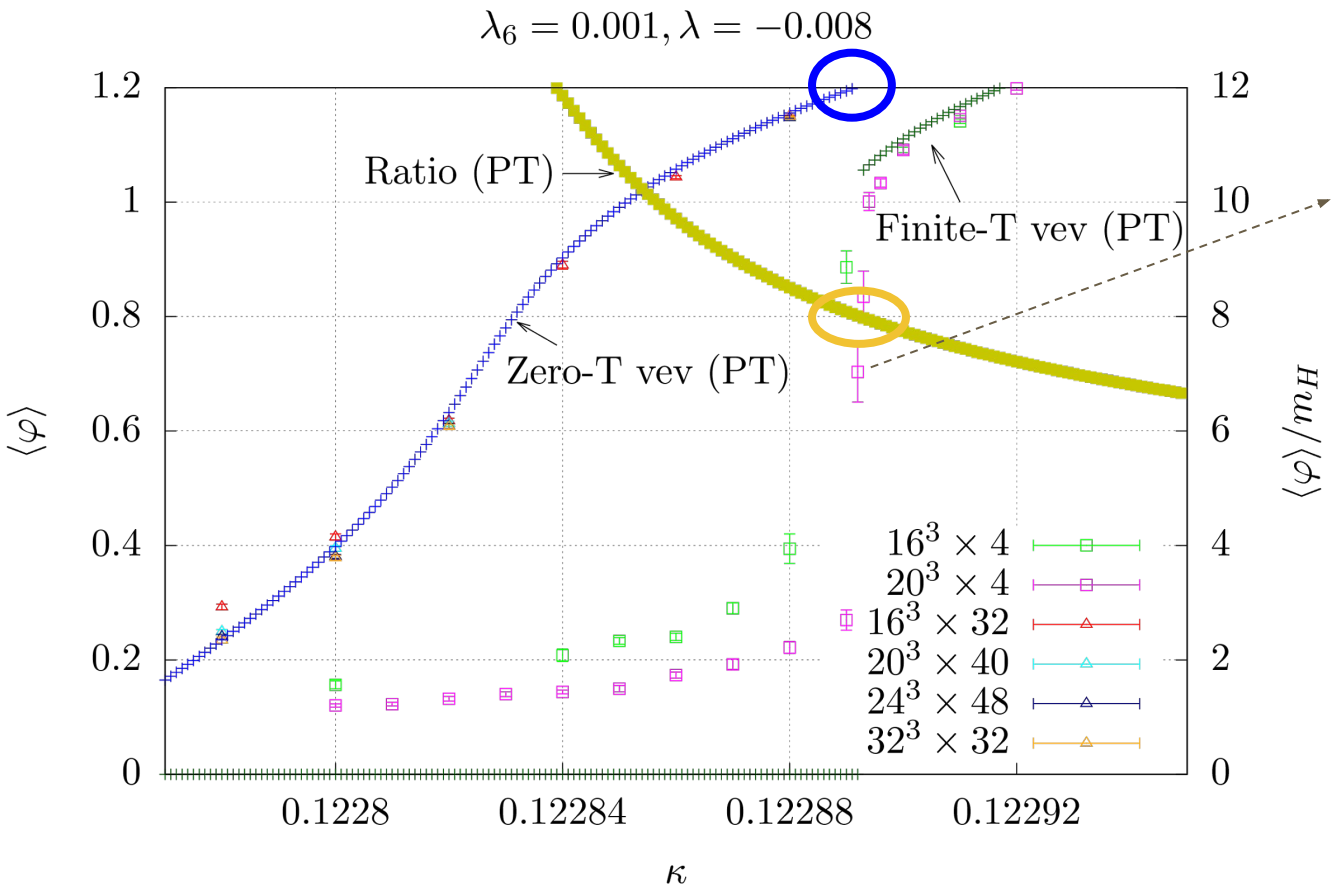
Result (perturbative regime)

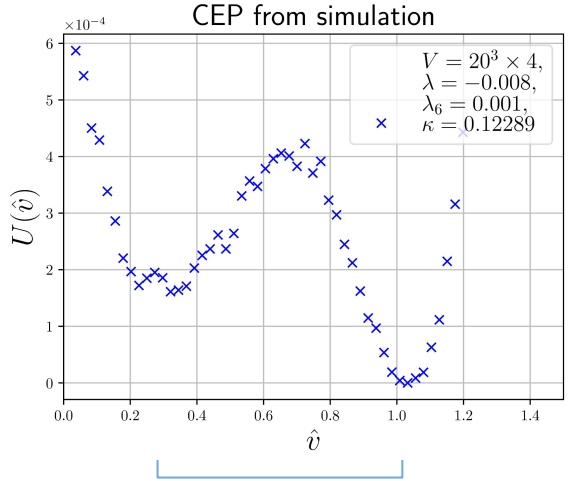




Temperature induced First-order phase transition found!

Conditions?





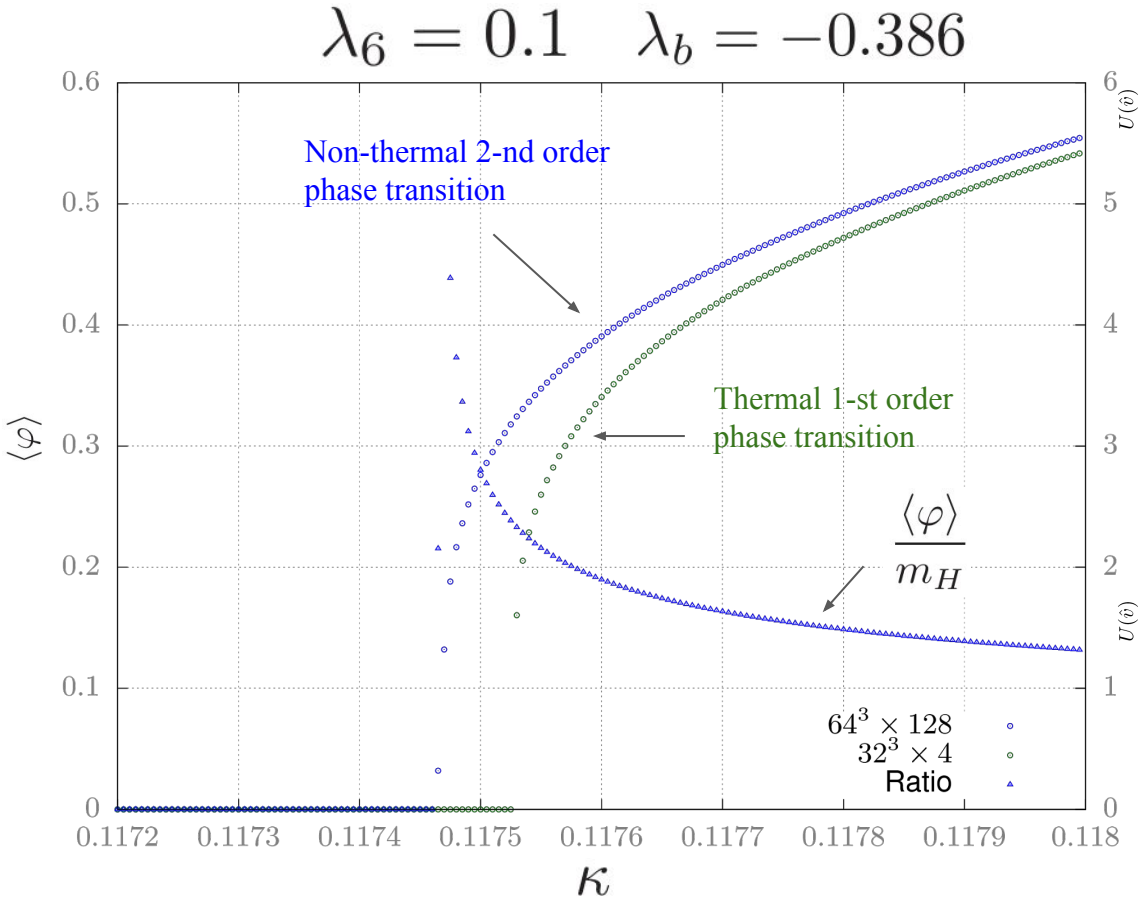
NO $\langle\varphi\rangle \ll 1$

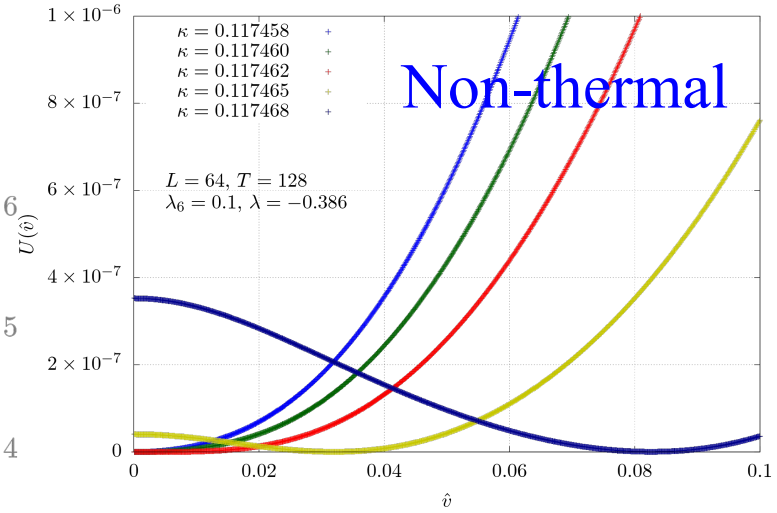
NO $\dfrac{\langle\varphi\rangle}{m_H} \sim 2$

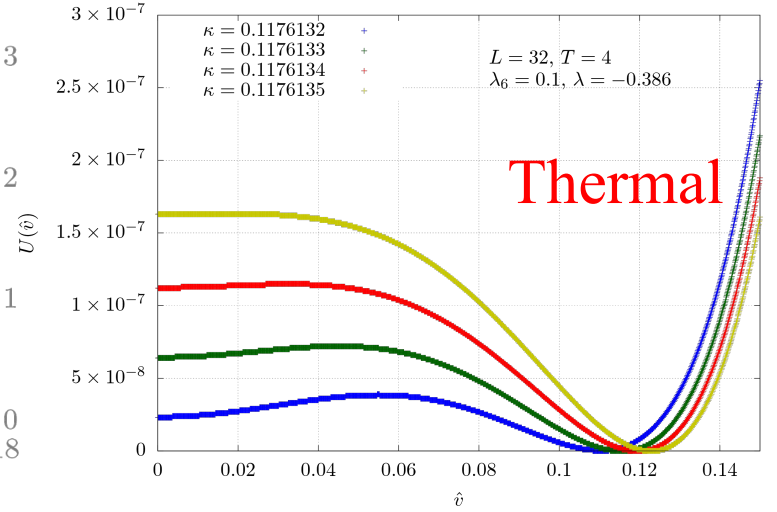
YES $\Delta\langle\varphi\rangle N_t \gtrsim 1$

Ruled out!

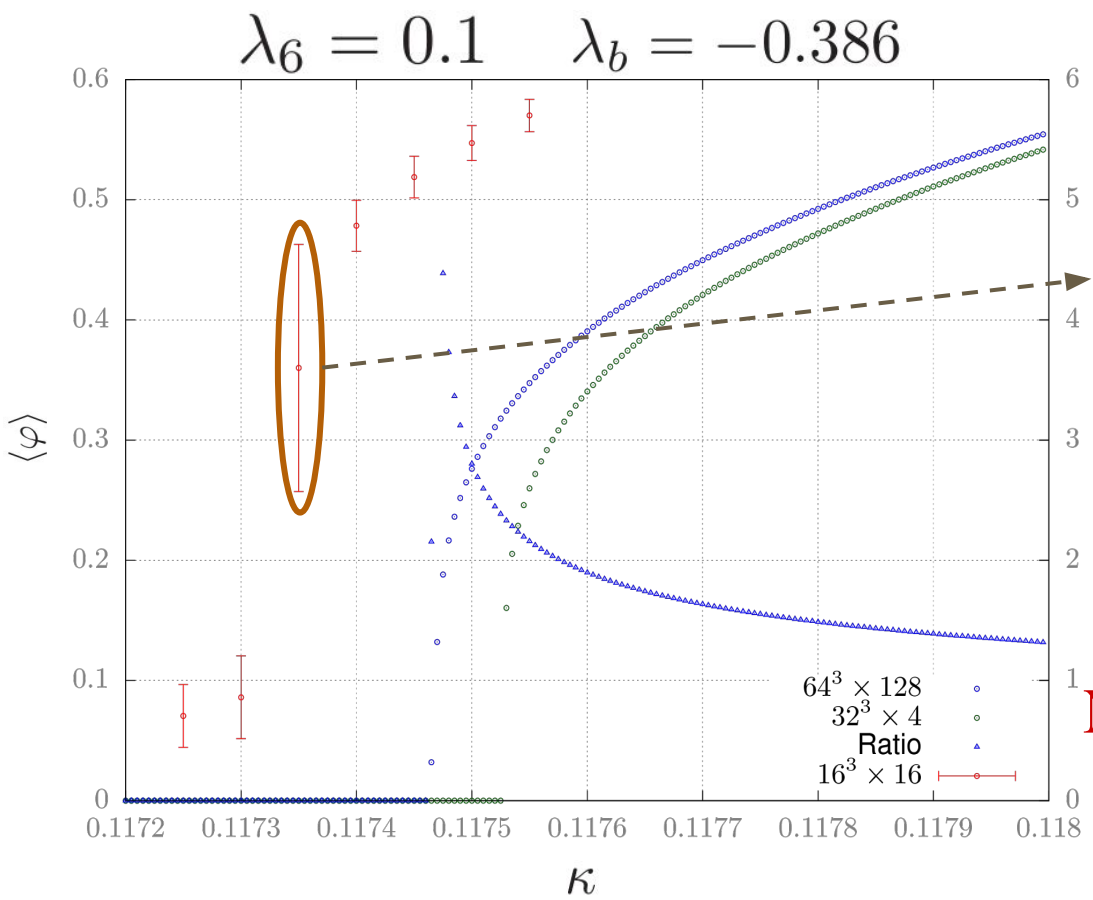
CEP scan (strong coupling)

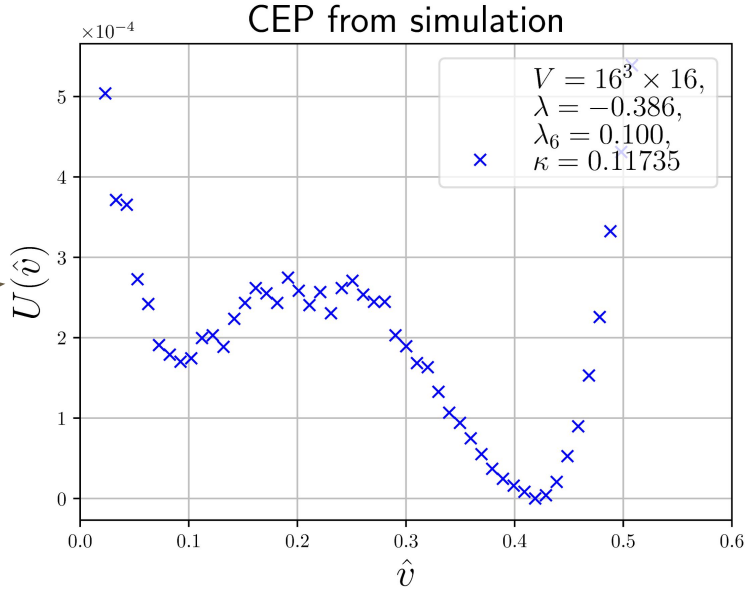






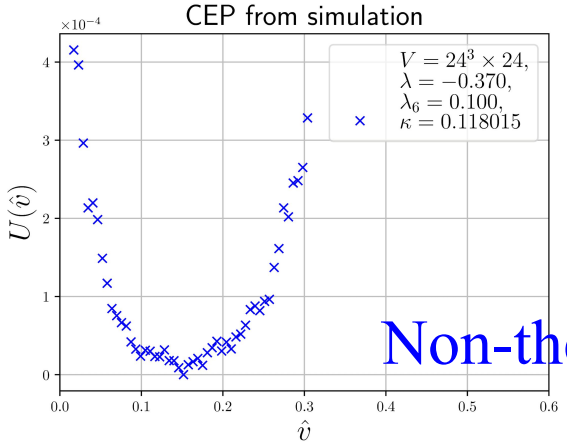
Numerical Result

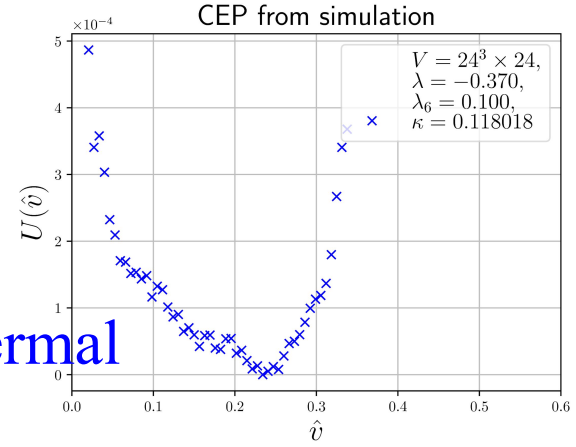




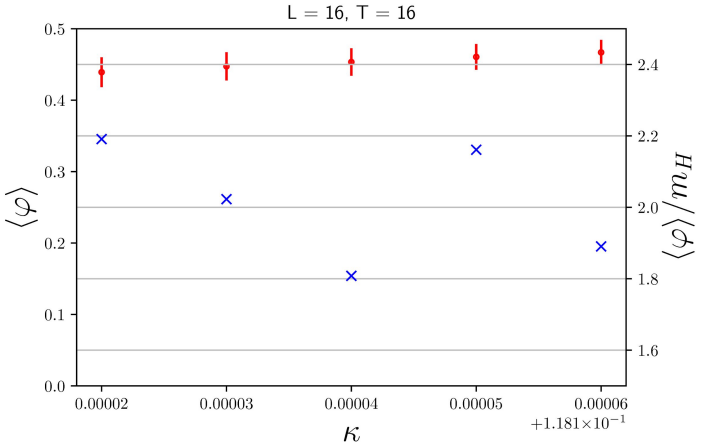
Non-thermal first-order PT!!
Not continuum.

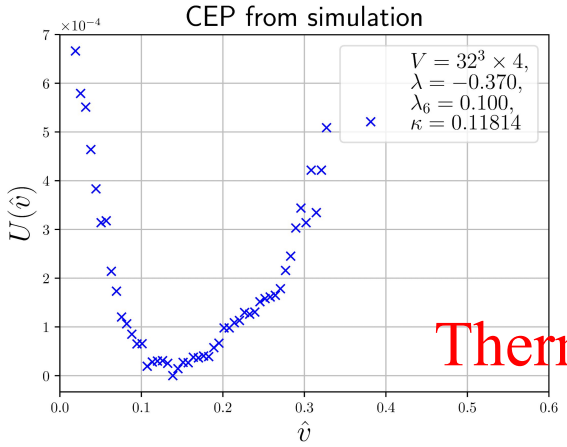
Proceed with more scanning…

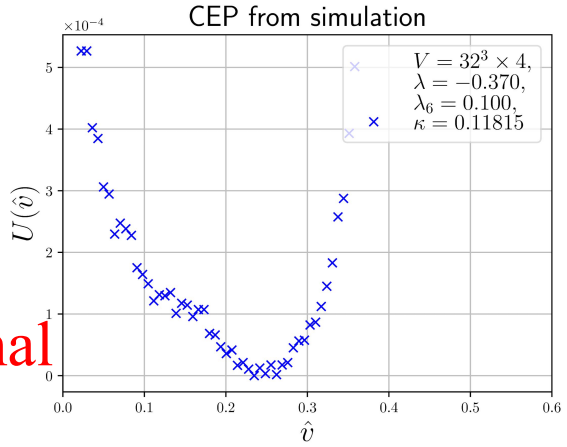




Non-thermal







Thermal

Conditions?

...YES? $\langle\varphi\rangle \ll 1$

YES $\dfrac{\langle\varphi\rangle}{m_H} \sim 2$

NO $\Delta\langle\varphi\rangle N_t \gtrsim 1$

Ruled out!

Summary and outlook

Higgs-Yukawa model with a dim-6 operator studied using lattice simulations.

Temperature induced first-order phase transitions (with the help of fermions).

Current results not compatible with phenomenology.

Include gauge couplings effectively (simulating at stronger yukawa coupling)?

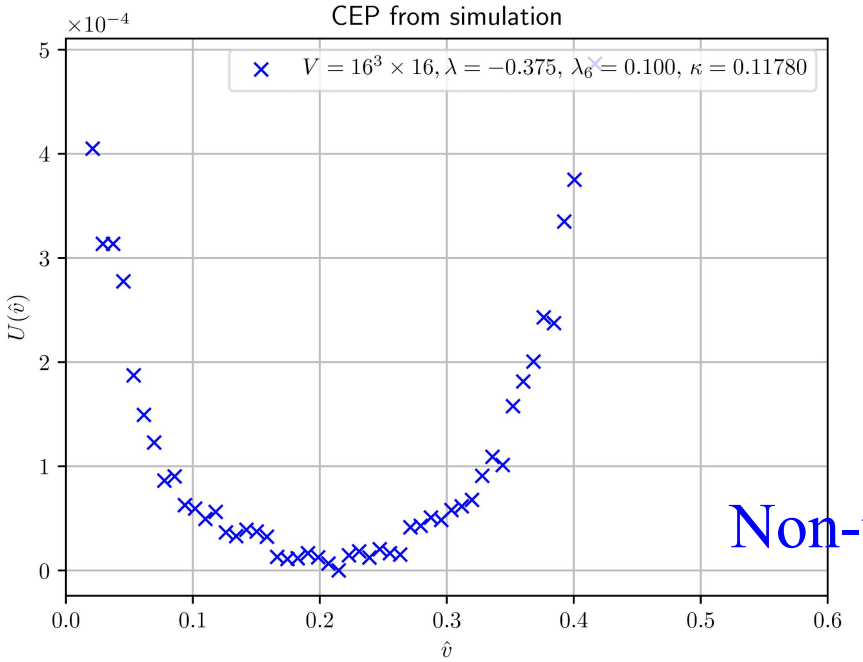
C. Grojean *et al.*, PRD 71 (2005) 036001
F. P. Huang *et al.*, PRD 93, 103515 (2016)

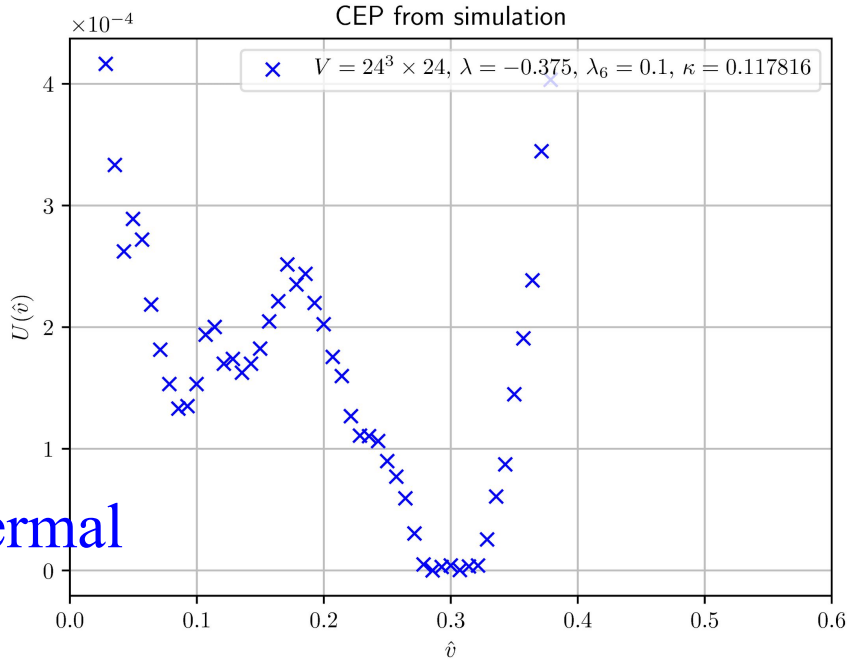
BSM physics not fully captured by the dim-6 operator alone?

M. Reichert *et al.*, arXiv:1711.00019 [hep-ph]

Thank you.

Proceed with more scanning…





Non-thermal

No strong first-order phase transition?