Lattice study of the Higgs-Yukawa model with a dimension-6 operator

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Outline

- Motivation.
- The Higgs-Yukawa model with $\lambda_6 \left(\varphi^\dagger \varphi\right)^3$.
- Bulk phase structure and the continuum limit.
- Constraint Effective Potential and Lattice simulations.
- The Higgs boson mass and bounds on λ_6.
- Outlook.

Motivation

- No obvious deviation from the SM hitherto.
- The SM must be replaced by its UV completion.
- The scale for new physics is unknown.
- Triviality of the quartic coupling means higher-dim operators may play a role.

Motivation
Possible forms of the Higgs potential

- Textbook thingy

$$V(H) = -\mu^2|H|^2 + \lambda|H|^4$$

- How about a toy model....

$$\tilde{V}(H) = -\lambda|H|^4 + c_6|H|^6$$

$$v^2 = \frac{4}{3}\frac{\lambda}{c_6}\,, \quad \frac{m_h^2}{v^2} = 2\lambda \quad \Longrightarrow \quad c_6 v^2 \sim 0.17$$

- Better data in the Higgsicion era.
- Lattice computation can play a role.

The continuum theory

$$
\begin{aligned}
S^{\mathrm{cont}}[\bar{\psi},\psi,\varphi] = \int d^4x \left\{ \frac{1}{2}\left(\partial_\mu\varphi\right)^\dagger\left(\partial^\mu\varphi\right) + \frac{1}{2} m_0^2 \varphi^\dagger\varphi + \lambda\left(\varphi^\dagger\varphi\right)^2 + \lambda_6\left(\varphi^\dagger\varphi\right)^3 \right\} \\
+ \int d^4x \left\{ \bar{t}\partial\!\!\!/ t + \bar{b}\partial\!\!\!/ b + y\left(\bar{\psi}_L \varphi\, b_R + \bar{\psi}_L \tilde{\varphi}\, t_R\right) + h.c. \right\},
\end{aligned}
$$

$$
\psi = \begin{pmatrix} t \\ b \end{pmatrix}, \quad \varphi = \begin{pmatrix} \varphi^2 + i\varphi^1 \\ \varphi^0 - i\varphi^3 \end{pmatrix}, \quad \tilde{\varphi} = i\tau_2\varphi^* .
$$

Note: degenerate Yukawa couplings

The lattice theory

- Bosonic component:

$$S_B[\Phi] = -\kappa \sum_{x,\mu} \Phi_x^{\dagger} \left[\Phi_{x+\mu} + \Phi_{x-\mu}\right] + \sum_x \left(\Phi_x^{\dagger}\Phi_x + \hat{\lambda} \left[\Phi_x^{\dagger}\Phi_x - 1\right]^2 + \hat{\lambda}_6 \left[\Phi_x^{\dagger}\Phi_x\right]^3 \right).$$

$$a\,\varphi = \sqrt{2\kappa} \begin{pmatrix} \Phi^2 + i\Phi^1 \\ \Phi^0 - i\Phi^3 \end{pmatrix}, a^2 m_0^2 = \frac{1 - 2\hat{\lambda} - 8\kappa}{\kappa}, \lambda = \frac{\hat{\lambda}}{4\kappa^2}, \quad a^{-2}\lambda_6 = \frac{\hat{\lambda}_6}{8\kappa^3}.$$

$a = 1$ in this talk.

- Fermionic component: the overlap fermions.

→ Exact lattice chiral cymmetry.

The continuum limit

$a \to 0$ and $\Lambda \to \infty$

- Computing with "pure numbers (dim-less couplings)".
- Tune these couplings to reach the continuum limit.
- For a theory with asymptotic freedom, e.g., QCD:

$$g_0^2(a) \stackrel{a\to 0}{\longrightarrow} 0 \quad \text{while} \quad g_{\rm R}^2(\mu, a) \stackrel{a\to 0}{=} \text{finite}.$$

- For a trivial theory,

$$g_0^2(a) \stackrel{a\to 0}{\longrightarrow} \text{finite} \quad \text{while} \quad g_{\rm R}^2(\mu, a) \stackrel{a\to 0}{=} 0.$$

- Work very close to vanishing renormalised coupling.

The continuum limit

$a \to 0$ and $\Lambda \to \infty$

- The key point is the separation of the scales.
- It can be achieved at 2nd-order bulk phase transitions:

$$\xi / a \longrightarrow \infty.$$

- Condensed matter physics:

  At fixed a, take $\xi \to \infty$.

- For our purpose:

  At fixed ξ, take $a \to 0$.

The constraint effective potential

Fukuda and Kyriakopoulos, 1985

- Phase structure is probed using the Higgs vev,

$$vev = a\varphi_c = \langle \hat{m} \rangle = \left\langle \frac{1}{V} \left| \sum_x \Phi_x^0 \right| \right\rangle .$$

- The constraint effective potential is a useful tool,

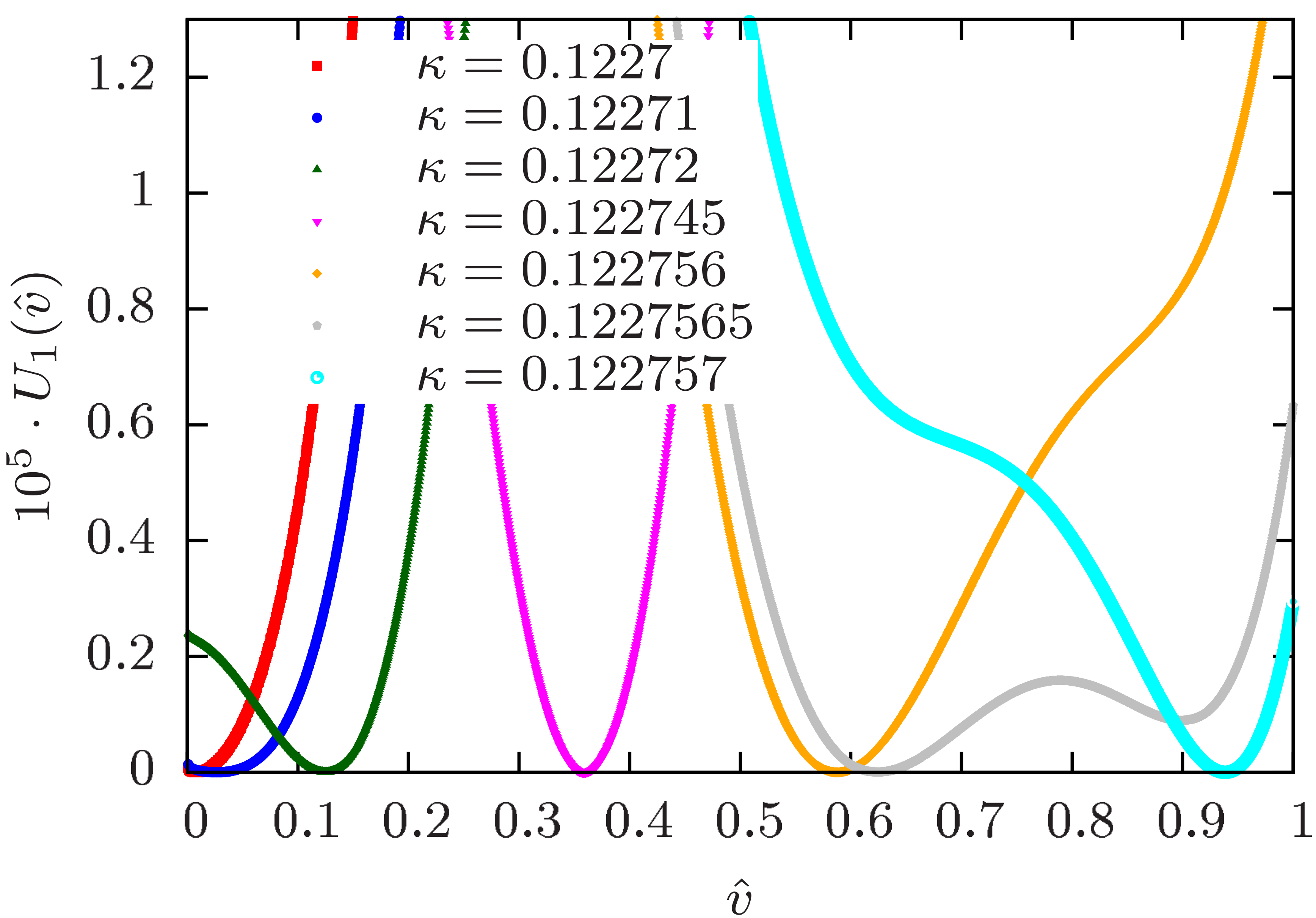
$$\mathrm{e}^{-V U(\hat{v})} \sim \int \mathcal{D}\varphi \mathcal{D}\bar{\psi} \mathcal{D}\psi \ \delta\left(\hat{v} - \varphi_c\right) \ \mathrm{e}^{-S[\varphi, \bar{\psi}, \psi]},$$

where $\hat{v}$ is the zero mode.

- Analytically calculated in perturbation theory.
- Numerically obtained by histogram of $\hat{m}$.

Using the CEP for the phase structure

y tuned to have $m_t \sim 173$ GeV.

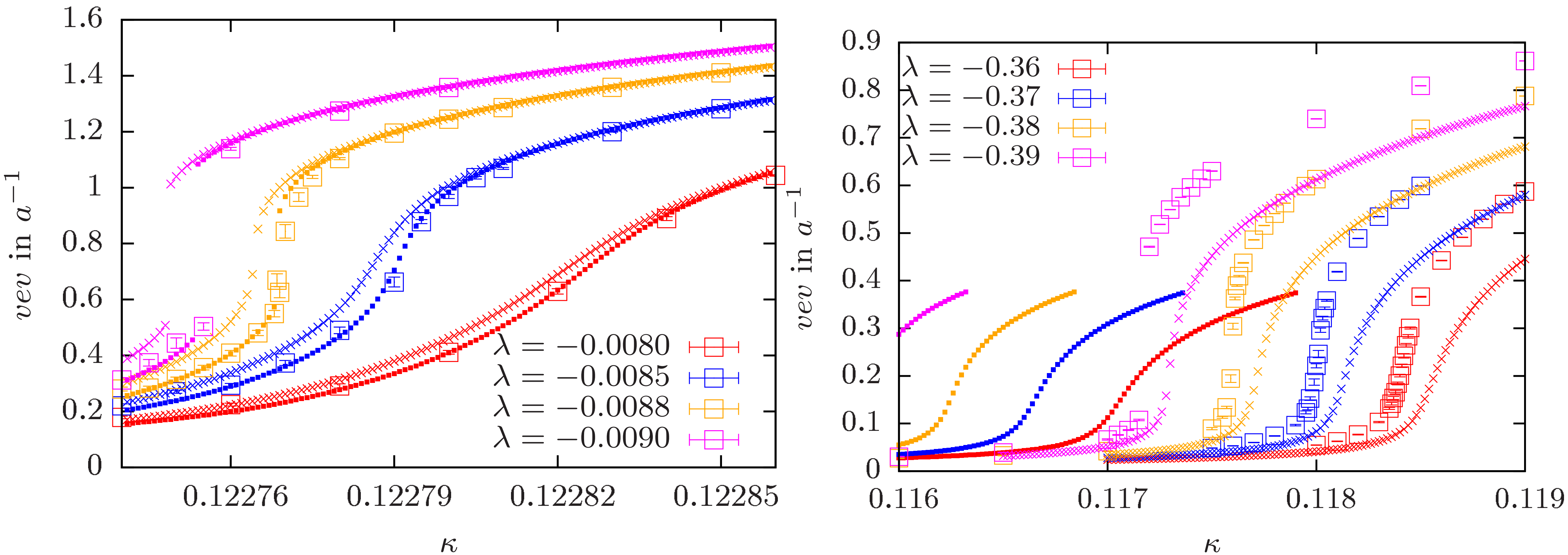


$$\lambda_6 = 0.001, \lambda = -0.0089$$

Two ways for perturbative expansion

The CEP can only serve as a guide

y tuned to have $m_t \sim 173$ GeV.

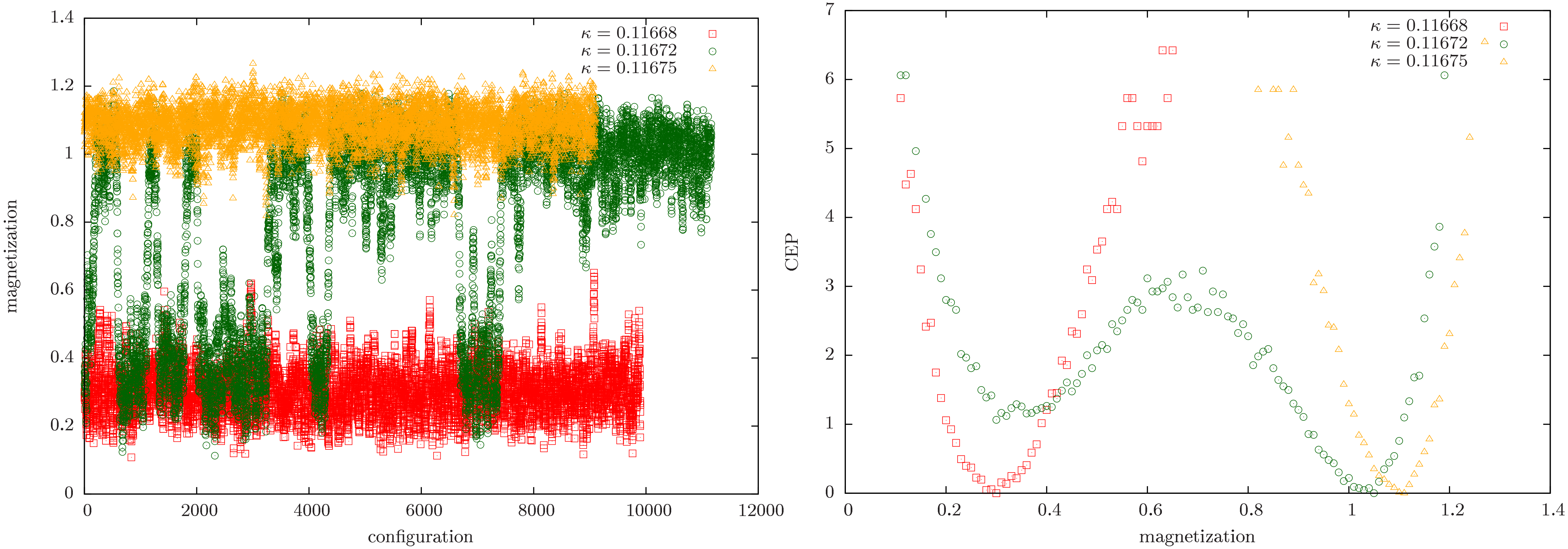


(a) $\lambda_6 = 0.001$ (b) $\lambda_6 = 0.1$

Lattice simulation for the phase structure

y tuned to have $m_t \sim 173$ GeV.

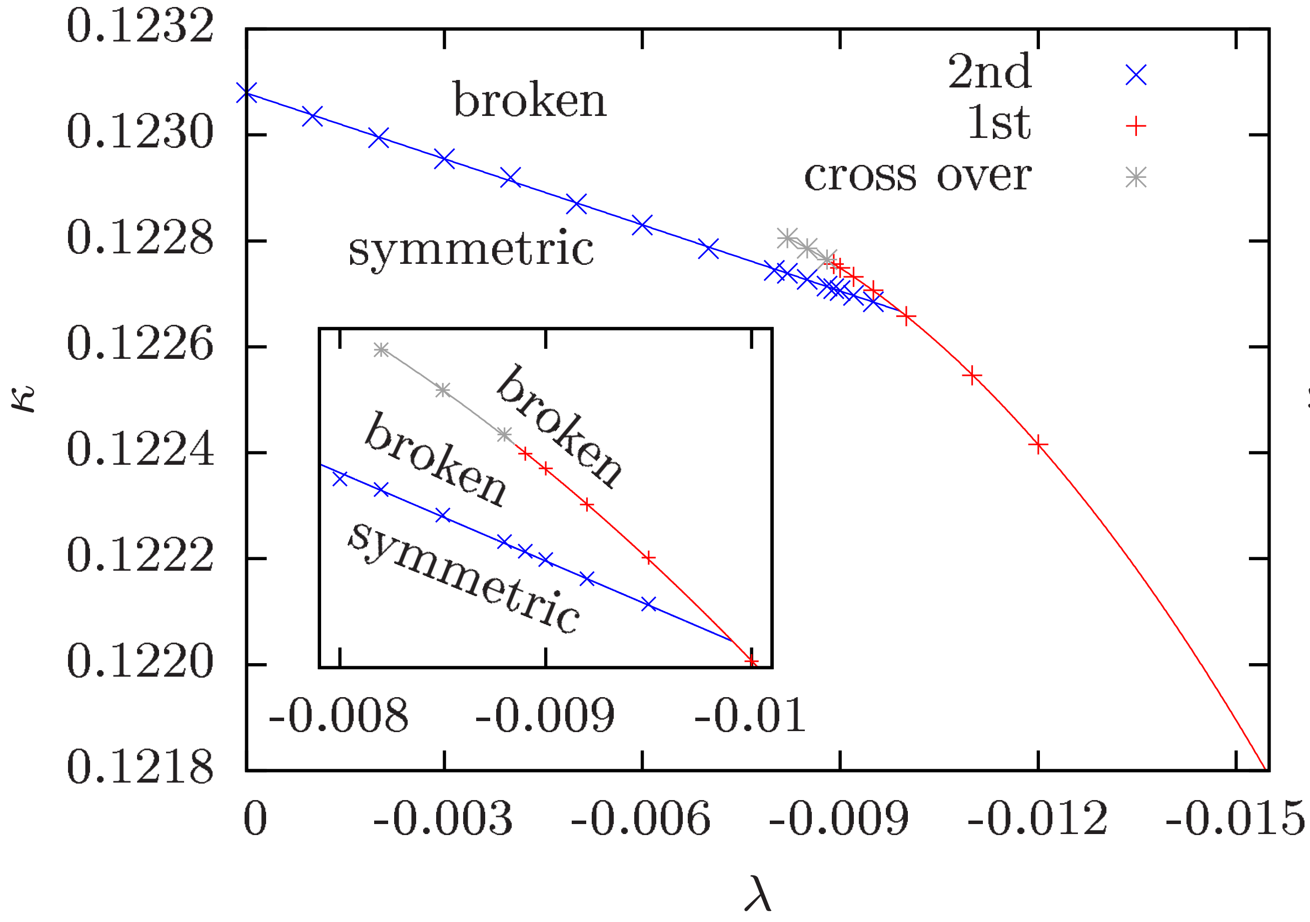
$\lambda_6 = 0.1$ and $\lambda = -0.40$



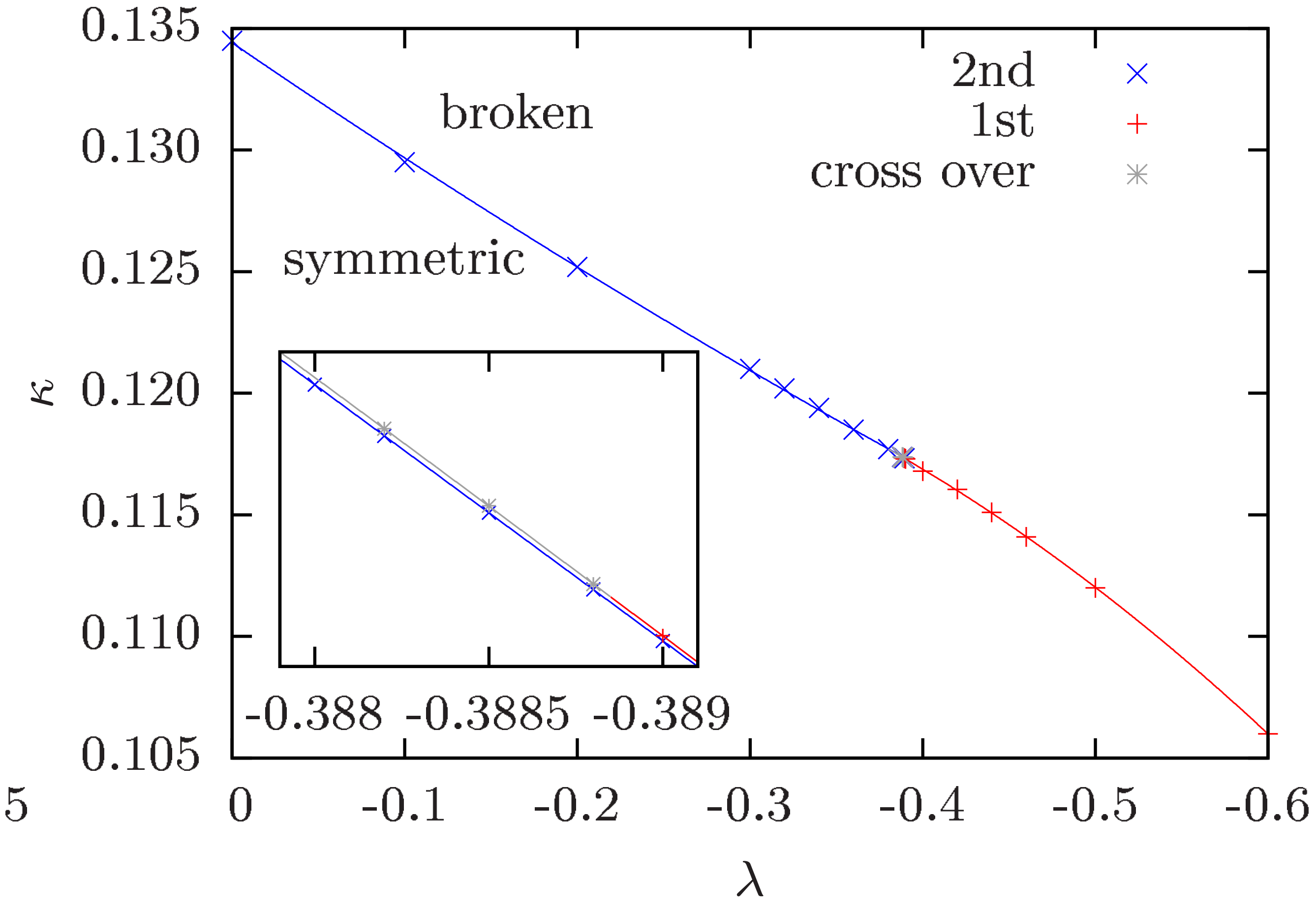
First-order phase transition expected and observed.

The phase structure

y tuned to have $m_t \sim 173$ GeV.

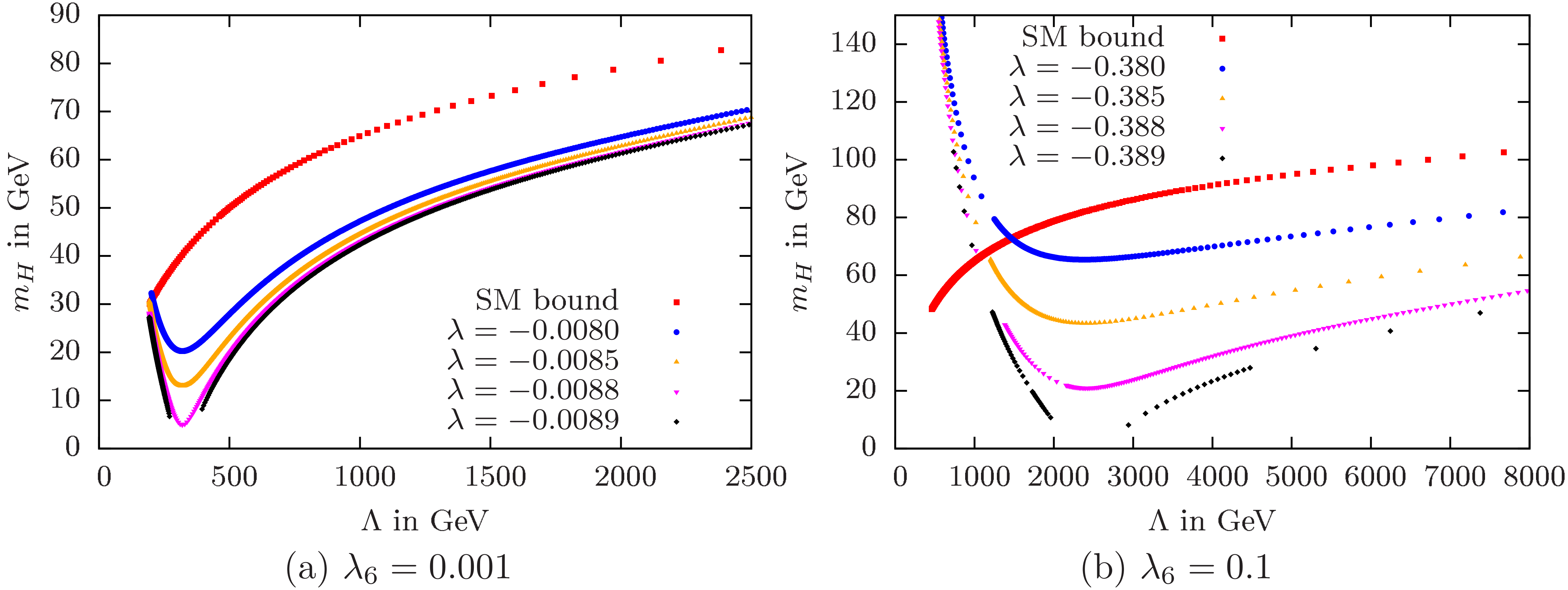


$\lambda_6 = 0.001$



$\lambda_6 = 0.1$

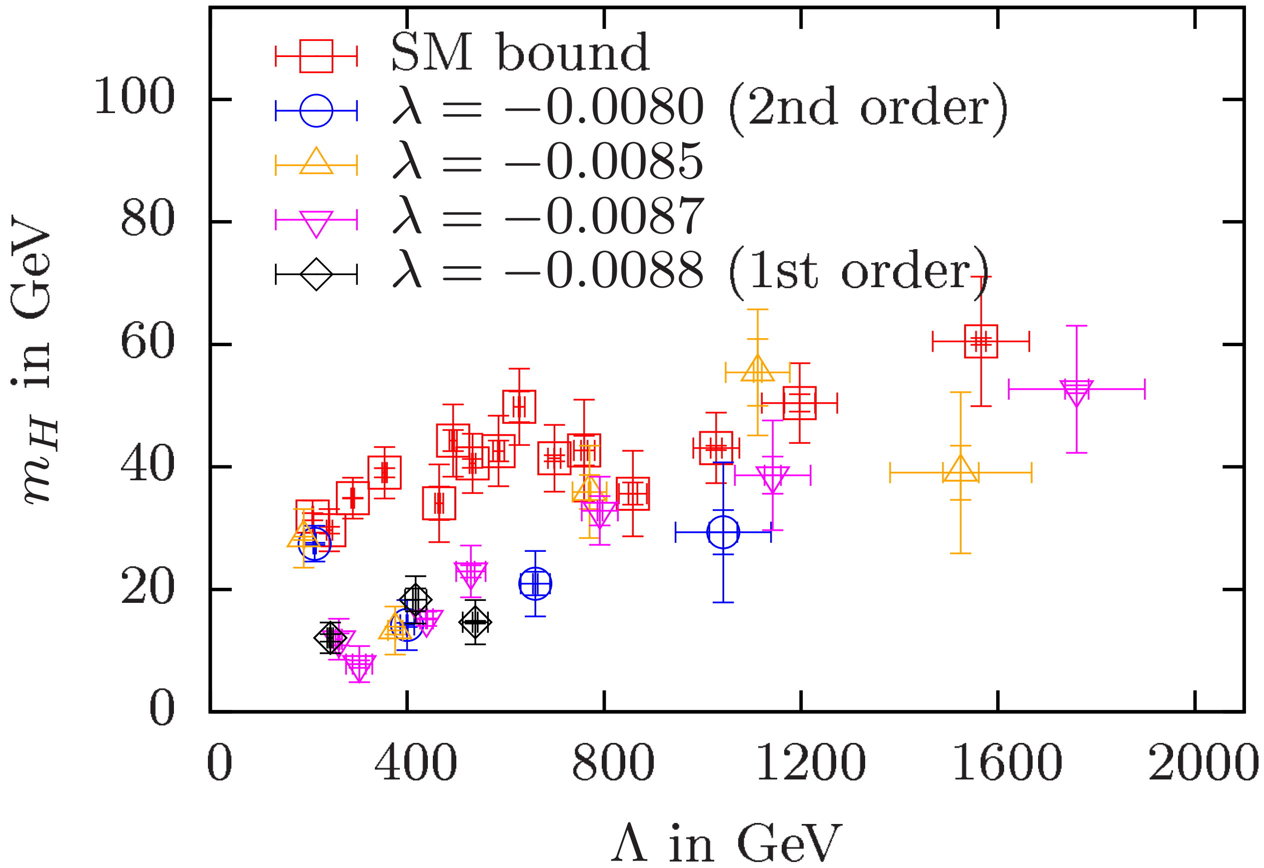
The Higgs mass lower bounds from the CEP



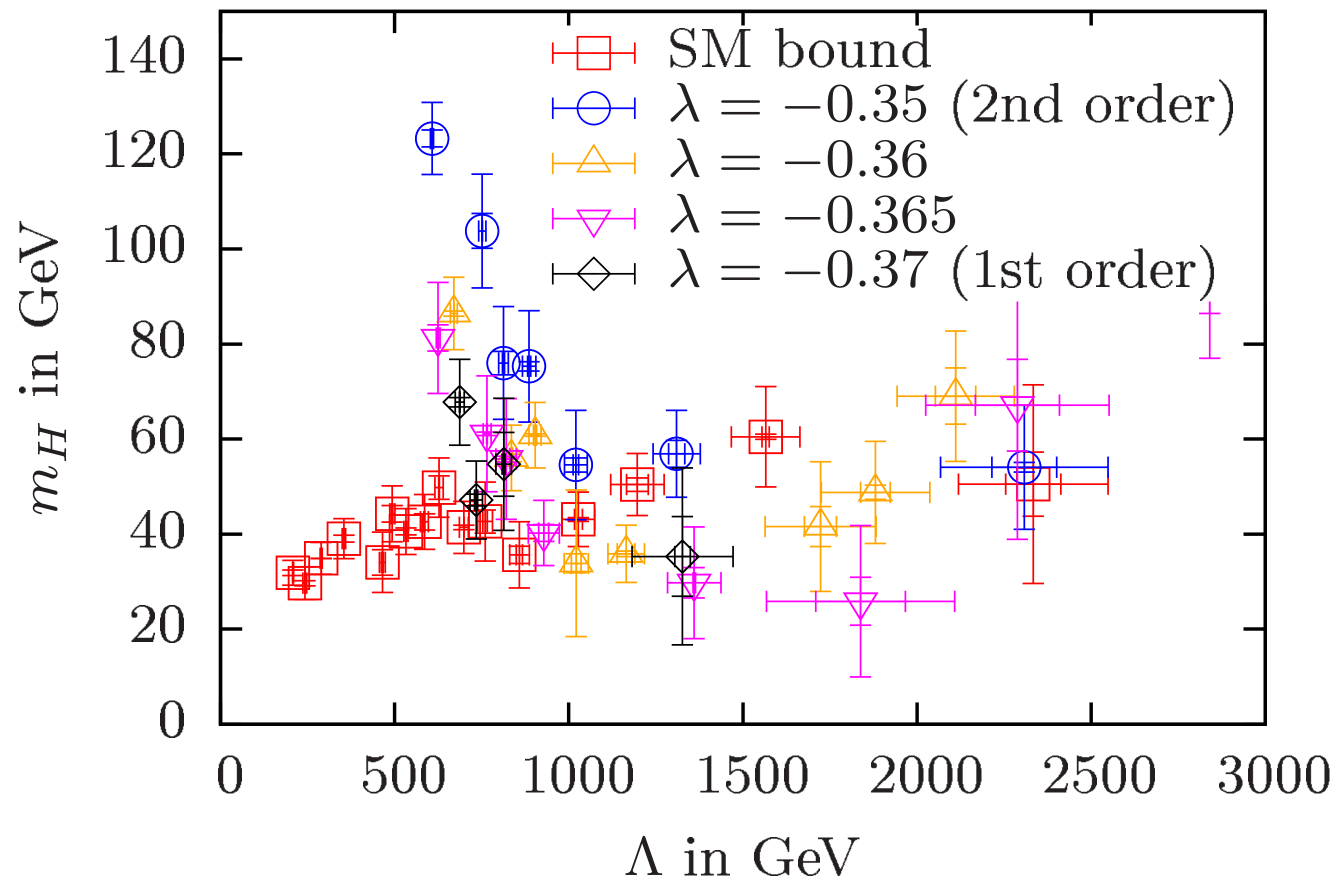
The Higgs mass lower bounds

Preliminary results from lattice simularions

y tuned to have $m_t \sim 173$ GeV.



$\lambda_6 = 0.001$



$\lambda_6 = 0.1$

Remarks and outlook

- The extended Higgs-Yukawa model contains rich phase structure.
- Adding a dimension-6 operator can alter the spectrum significantly.
- Simulations for larger λ_6 are being performed.
- Finite-temperature study is on-going.