Electroweak phase transition: recent results

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Abstract

Recent results of four-dimensional (4d) lattice simulations on the finite temperature electroweak phase transition (EWPT) are discussed. The phase transition is of first order in the SU(2)-Higgs model below the end point Higgs mass 66.5±1.4 GeV. For larger masses a rapid cross-over appears. This result completely agrees with the results of the dimensional reduction approach. Including the full Standard Model (SM) perturbatively the end point is at 72.1±1.4 GeV. Combined with recent LEP Higgs mass lower bounds, this excludes any EWPT in the SM. A one-loop calculation of the static potential makes possible a precise comparison of the lattice and perturbative results. Recent 4d lattice studies of the Minimal Supersymmetric SM (MSSM) are also mentioned.

1. Introduction

The observed baryon asymmetry of the universe was eventually determined at the EWPT [1]. The understanding of this asymmetry needs a quantitative description of the phase transition. Unfortunately, the perturbative approach breaks down for the physically allowed Higgs-boson masses (e.g. $m_H > 70$ GeV) [2]. In order to understand this nonperturbative phenomenon a systematically controllable technique is used, namely lattice Monte-Carlo (MC) simulations. Since merely the bosonic sector is responsible for the bad perturbative features (due to infrared problems) the simulations are done without the inclusion of fermions. The first results dedicated to this questions were obtained on 4d lattices [3]. Soon after, simulations of the reduced model in three-dimensions were initiated, as another approach [4].

Recently, it became clear that for large Higgs masses the EWPT does not take place, i.e. there is an end point Higgs mass above which the first order EWPT goes over to a rapid crossover. Since the end point mass is smaller than the experimental LEP lower limit of the SM Higgs mass, baryogenesis can not be explained in the SM. One has to explore beyond the SM scenarios, the most natural choice is the MSSM.

2. End point of the electroweak phase transition in the Standard Model

The end point of the EWPT has been studied in the SU(2)-Higgs model in 4d simulations [5, 6]. The effects of fermions and the U(1) part of the SM have been taken into account perturbatively. The action in standard notation reads in case of an isotropic lattice:

$$S = \beta \sum \left(1 - \tfrac{1}{2}\mathrm{Tr}\, U_{pl}\right) - \kappa \sum \mathrm{Tr}\,(\varphi^+_{x+\hat{\mu}} U_{x,\mu}\, \varphi_x) + \sum \left\{ \tfrac{1}{2}\mathrm{Tr}\,(\varphi^+_x \varphi_x) + \lambda \left[\tfrac{1}{2}\mathrm{Tr}\,(\varphi^+_x \varphi_x) - 1\right]^2 \right\} \quad (1)$$

For larger time direction lattice extensions anisotropic lattices have been used. The method of Lee-Yang zeros of the partition function has been applied to determine the presence or absence of a first order phase transition at a given value of the parameters β and λ. Fig. 1 shows the values of the imaginary part κ_0 of the position of the first Lee-Yang zeros extrapolated to infinite (space) volume. For first order phase transitions the value is consistent with zero. This condition determines λ_c, which in turn determines (through T=0 simulation) the end point value of the Higgs mass.

An extrapolation to the continuum limit along the end point line of constant physics has been performed. The result is shown in fig. 2. The critical Higgs mass is 66.5 ± 1.4GeV in the SU(2)-Higgs model, in perfect agreement with the results of 3d simulations [7].

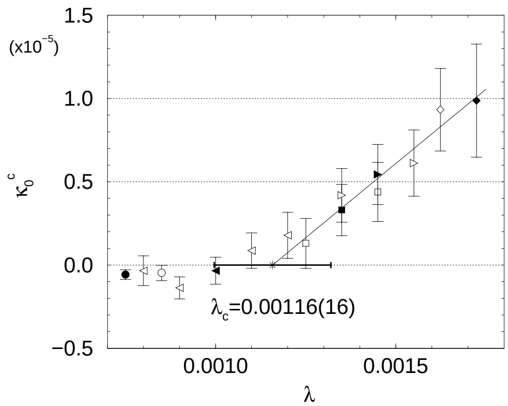

Figure 1. Imaginary part of first Lee-Yang zero at infinite-volume as a function of Higgs self coupling.

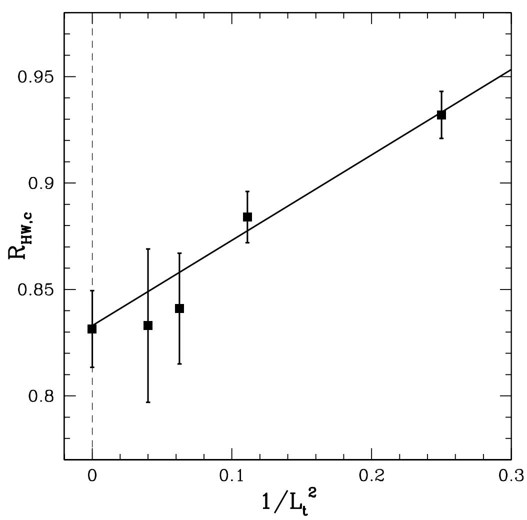

Figure 2. Dependence of $R_{HW,c}$, i.e. $R_{HW} = M_H/M_W$ corresponding to the endpoint of first order phase transitions on $1/L_t^2$ and extrapolation to the infinite volume limit.

Using published data of the DESY group [8] the phase diagram can also be drawn (cf. fig. 3).

3. Renormalized gauge coupling

To determine the SM value of the end point Higgs mass the relation of the lattice renormalized gauge coupling and the continuum $\overline{\text{MS}}$ coupling should be clarified. This connecion has been established in [9] calculating the static potential in the continuum theory at one loop level and defining the lattice analogue of the renormalized gauge coupling. The approach of the second paper in [9] has been followed in correcting the end point Higgs mass of the SU(2)-Higgs model to the full to SM case. The result is $M_{H_{critical}}$ =72.1±1.4GeV.

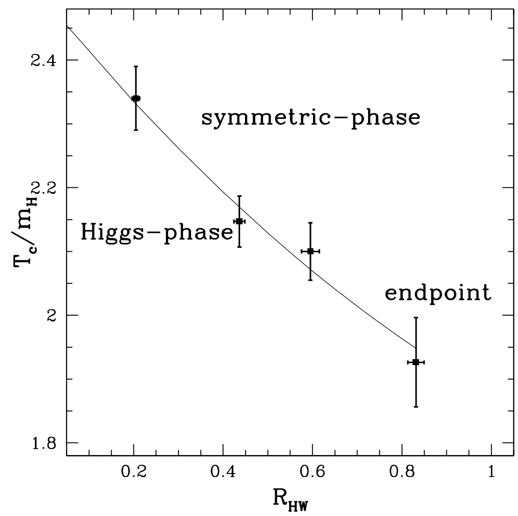

Figure 3. Phase diagram of the SU(2)-Higgs model in the $(T_c/m_H - R_{HW})$ plane. The continuous line – representing the phase-boundary – is a quadratic fit to the data points.

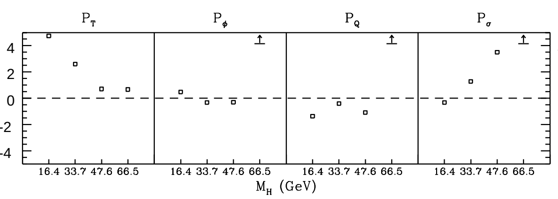

Figure 4. The pull for T_c/m_H, φ/T_c, $\Delta Q/T_c^4$ and σ/T_c^3 as function of the Higgs mass.

Incorporation of the precise relation between the two renormalized gauge coupling definitions also allows for a better comparison of the two-loop perturbative [10] and the lattice results [8]. The pull for the critical temperature over Higgs mass (T_c/m_H), jump of the order parameter over critical temperature (φ/T_c), normalized latent heat $(\Delta Q/T_c^4)$ and normalized surface tension (σ/T_c^3) as function of the Higgs mass is shown in fig. 4. Since the perturbative approach does not show the end point the pulls are large for large Higgs masses.

4. MSSM 4d simulations

As the SM does not have a first order EWPT, the explanation of baryogenesis requires extended models. The MSSM has been studied perturbatively [11] and at two-loop order seems to yield much stronger EWPT than the SM. Lattice studies in a 3d reduced model also show quite a strong EWPT [12].

A 4d lattice study of the bosonic part of the MSSM has been performed in [13]. Both Higgs doublets, the stop, sbottom and SU(2) and SU(3) gauge fields have been included. The simulations have been performed at different time extentions making possible a continuum extrapolation along a line of constant physics. The simulation corresponds to $\tan\beta(T=0) \approx 6$ and the mass of the lighter Higgs boson is around 35 GeV. For the physical value of α_s $v/T_c \approx 1.5$, while for a smaller value of α_s a larger value was obtained.

According to the standard scenario the generated baryon asymmetry is proportional to $< v^2/T^2 > \Delta\beta(T_c)$, where $v^2 = v_1^2 + v_2^2$ and $< v^2 >$ denotes an integral over the bubble wall and $\tan\beta = v_2/v_1$. The β parameter is measured in both phases and the difference turns out to be $\Delta\beta$=0.0045(7). This is far below the perturbative prediction $\Delta\beta(pert.)$=0.017.

5. Conclusions

The end point of hot EWPT with the technique of Lee-Yang zeros from simulations in 4d SU(2)-Higgs model was determined. The phase transition is first order for Higgs masses less than 66.5 ± 1.4 GeV, while for larger Higgs masses only a rapid cross-over is expected. The phase diagram of the model was given.

It was shown non-perturbatively that for the bosonic sector of the SM the dimensional reduction procedure works within a few percent. This indicates that the analogous perturbative inclusion of the fermionic sector results also in few percent error. In the full SM we get 72.1 ± 1.4 GeV for the end point, which is below the lower experimental bound. This fact is a clear sign for physics beyond the SM.

Based on a one-loop calculation of the static potential in the SU(2)-Higgs model a direct comparison between the perturbative and lattice results was performed.

The MSSM is more promising for a succesfull baryogenesis. Some 4d results were shown, indicating a strong first order phase transition.

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