1st order thermal phase transition in MSSM with 126 GeV Higgs

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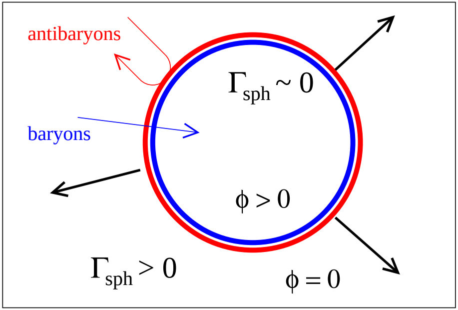
Lattice 2013, Mainz, 1.8.2013

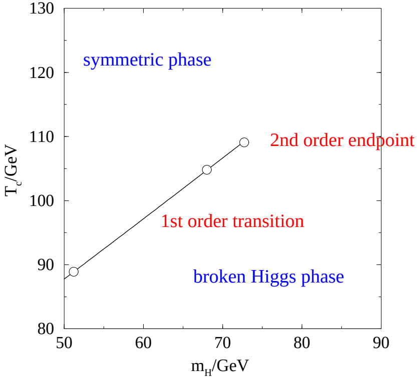
Electroweak baryogenesis

- Standard Model violates baryon number through *sphaleron* transitions
  - Strongly suppressed at $T \ll T_{\rm EW} \approx 100\,{\rm GeV}$
- *Electroweak baryogenesis* scenario: generation of baryons through *thermal* cosmological 1st order phase transition
- Need:
  - "Strong enough" first order transition
    - → out of thermal equilibrium: metastability, supercooling
    - → bubble nucleation & expansion
    - ★ $v/T \gtrsim 1$ in the broken phase to suppress sphalerons
  - Strong enough CP violation



Phase transition in the Standard Model

- Standard Model does *not* satisfy these conditions
  - After lots of activity on and off the lattice:
  - $\rightarrow$ No phase transition at all, smooth "cross-over" for $m_{\mathrm{Higgs}} \gtrsim 72\,\mathrm{GeV}$



[Kajantie,Laine,K.R.,Shaposhnikov,Tsypin 96–98]

see also

[Csikor,Fodor, Heitger]

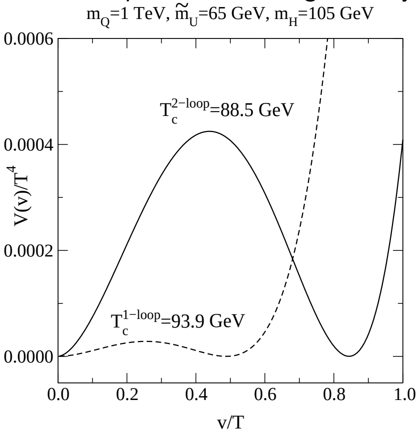
[Gürtler,Ilgenfritz,Schiller,Strecha]

MSSM

- Extensions of SM: EWBG is possible in many of them!
- MSSM: strongly constrained model
  - strong phase transition when right-handed stop is light
  - 1998–2002: works within LEP bound $m_H \gtrsim 115\,\mathrm{GeV}$
    Both perturbative and lattice studies
  - Carena, Nardini, Quiros, Wagner 2009-12: pushed the limits to include 126 GeV Higgs (in perturbation theory)
- Here: non-perturbative study of the strength of the phase transition
- ignore CP violation

Why non-perturbative?

- Physics is non-perturbative at ultrasoft scales $p \lesssim g^2 T$!
- Perturbative effective potential converges slowly:



[Laine, K.R. 2002]

- Perturbatively weak 1st order transitions may vanish altogether (this happens in the Standard Model)

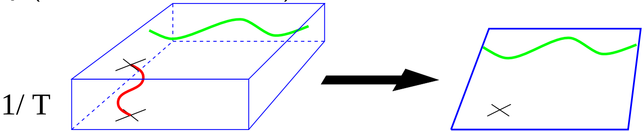
3d effective theory

Simulations of the full SM or MSSM are impossible. We proceed through *effective theories*

- Modes $p \gtrsim g^2 T$ are perturbative (at weak coupling): can be "integrated out" in stages:

1. Integrate $p \gtrsim T$: fermions, non-zero Matsubara frequencies

$\rightarrow$ 3d theory (dimensional reduction)

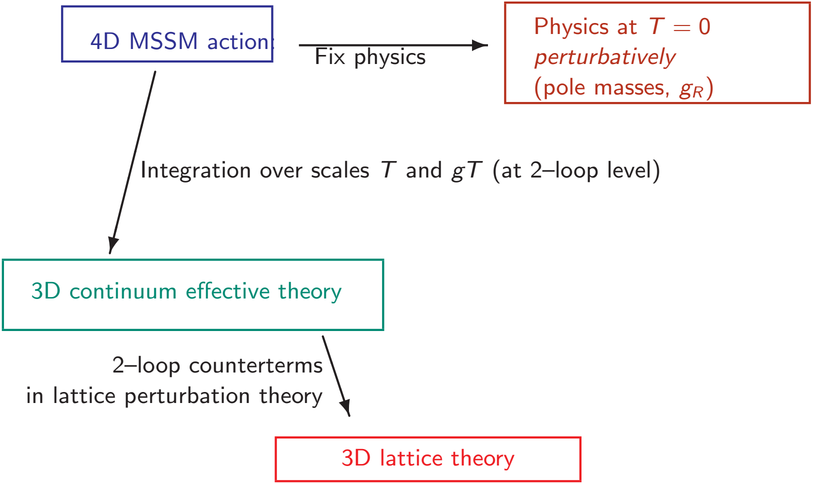


2. Integrate electric modes $p \sim gT$

$\Rightarrow$ Obtain a magnetic theory for modes $p \lesssim g^2 T$. Fully contains the non-perturbative thermal physics.

- Can be directly compared to perturbative results

3d effective theory

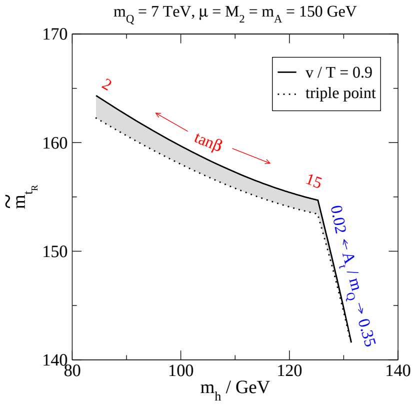


3d effective Lagrangian:

$$
\begin{aligned}
\mathcal{L}_{\rm 3d} &= \frac{1}{2}\,{\rm Tr}\,G_{ij}^2 + (D_i^s U)^\dagger (D_i^s U) + m_U^2(T) U^\dagger U + \lambda_U (U^\dagger U)^2 \\
&+ \gamma_1 U^\dagger U H_1^\dagger H_1 + \gamma_2 U^\dagger U H_2^\dagger H_2 + \left[\gamma_{12} U^\dagger U H_1^\dagger H_2 + {\rm H.c.}\right] \\
&+ \frac{1}{2}\,{\rm Tr}\,F_{ij}^2 + (D_i^w H_1)^\dagger (D_i^w H_1) + (D_i^w H_2)^\dagger (D_i^w H_2) \\
&+ m_1^2(T) H_1^\dagger H_1 + m_2^2(T) H_2^\dagger H_2 + \left[m_{12}^2(T) H_1^\dagger H_2 + {\rm H.c.}\right] \\
&+ \lambda_1 (H_1^\dagger H_1)^2 + \lambda_2 (H_2^\dagger H_2)^2 + \lambda_3 H_1^\dagger H_1 H_2^\dagger H_2 + \lambda_4 H_1^\dagger H_2 H_2^\dagger H_1 \\
&+ \left[\lambda_5 (H_1^\dagger H_2)^2 + \lambda_6 H_1^\dagger H_1 H_1^\dagger H_2 + \lambda_7 H_2^\dagger H_2 H_1^\dagger H_2 + {\rm H.c.}\right].
\end{aligned}
$$

G_{ij}: SU(3) gauge
U: right-handed stop
F_{ij}: SU(2) gauge
H_1, H_2: two SU(2) scalars (Higgses)
Parameters $g_W^2; g_S^2; m_i^2; m_{12}^2; \lambda_j; \gamma_i; \gamma_{12}$ depend on the 4d physical parameters (incl. temperature T).

Parameters:



Choose MSSM parameters
$\tilde{m}_U = 70.4\,\text{GeV}$
$m_Q = 7\text{TeV}$
$\mu = M_2 = m_A = 150\text{GeV}$
$\tan\beta = 15$
$A_t/m_Q = 0.02$

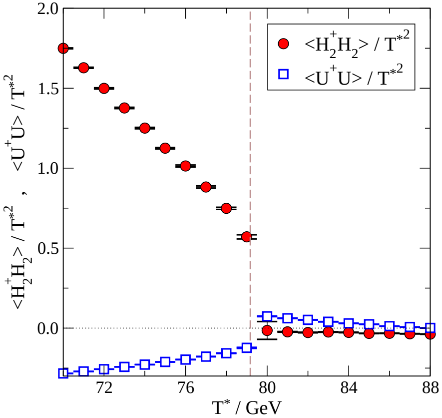
These correspond to
Higgs mass $m_h = 126\,\text{GeV}$ and
the right-handed stop mass
$m_{\tilde{t}_R} \approx 155\,\text{GeV}$

Due to large mass hierarchy $m_Q/m_{\tilde{t}_R}$ there appear possibly large 2-loop logs in dimensional reduction. These are not yet taken into account. These cause some uncertainty of a few GeV especially to the value of $m_{\tilde{t}_R}$.

Simulation volumes

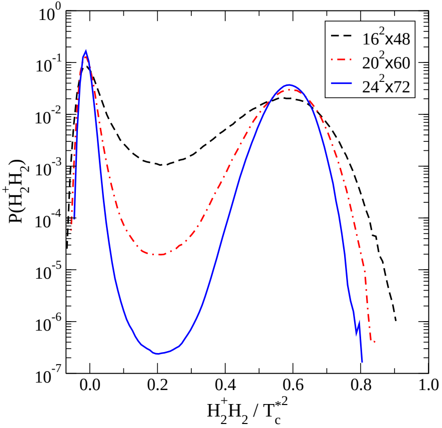
$\beta_w = 4/(g_W^2 Ta)$	volumes
8	12^3, 16^3
10	16^3
12	16^3, 20^3, 32^3, $12^2 \times 36$, $20^2 \times 40$
14	24^3, $14^2 \times 42$, $24^2 \times 48$
16	24^3, $16^2 \times 48$, $20^2 \times 60$, $24^2 \times 72$
20	32^3, $20^2 \times 60$, $26^2 \times 72$, $32^2 \times 64$
24	24^3, 32^3, 48^3, $24^2 \times 78$, $30^2 \times 72$
30	48^3

Results: Higgs field expectation value $\langle H_2^\dagger H_2 \rangle$

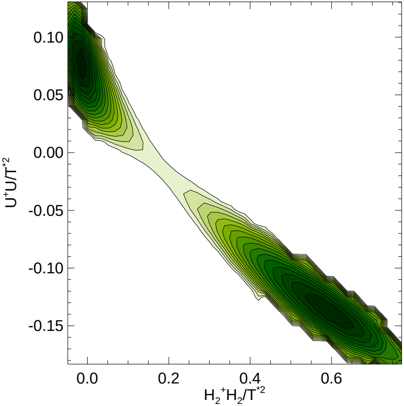


- Results extrapolated to continuum
- Strong transition
- Stop field U participates

Histograms

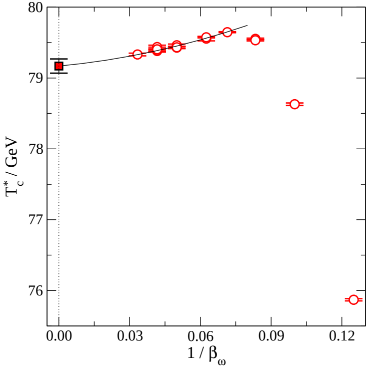


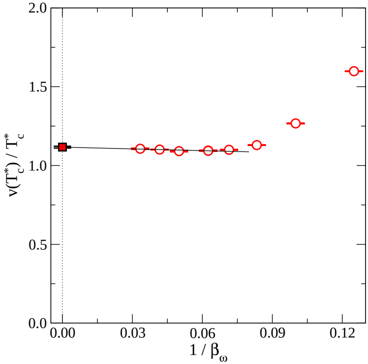
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
$P(H_2^+H_2)$
0.0
0.2
0.4
0.6
0.8
1.0
$H_2^+H_2 / T_c^{*2}$
16^2x48
20^2x60
24^2x72



0.10
0.05
0.00
-0.05
-0.10
-0.15
U^+U/T^{*2}
0.0
0.2
0.4
0.6
$H_2^+H_2/T^{*2}$

Results: continuum limits





$T_c = 79.17 \pm 0.10$ GeV

2-loop pert. theory ~ 84.4 GeV

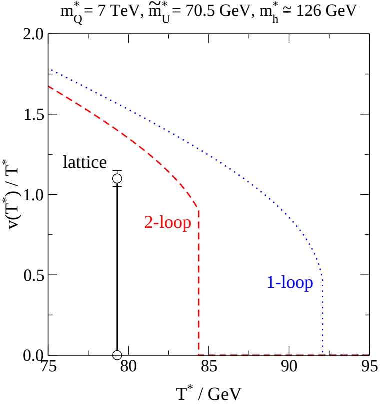
$v/T_c = 0.117 \pm 0.005$

pert. theory 0.9

Results compared with 2-loop perturbation theory

		lattice	perturbative (Landau gauge)
Transition temperature	T_c/GeV	79.17(10)	84.4
Higgs discontinuity	v/T_c	1.117(5)	0.9
Latent heat	L/T_c^4	0.443(4)	0.26
Surface tension	σ/T_c^3	0.035(5)	0.025

The transition is clearly stronger on the lattice.



Conclusions:

- Simulations give consistently stronger transition than pert. theory
- All relevant thermodynamical parameters under control
- Transition is strong enough for baryogenesis (but CP violation?)
- Requires light right-handed stop. Exclusion by LHC?
- Calculations can be generalized to extensions of MSSM or other theories with stop-like particles
- Effective dimensionally reduced theory is a very powerful tool for analysing high-temperature phase transitions in weakly coupled models!