Discerning Singlet and Triplet scalars at the electroweak phase transition and Gravitational Wave

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Anomalies 2021

Based on:[1] **Eur.Phys.J.C 80 (2020) 8, 715, arxiv:2111.03866**
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Outline

Introduction

If the minimum of $V_{eff}^{T=0}(\phi)$ ocuurs at $<\phi>=\sigma\neq 0$, for sufficiently high temperatures, the minimum of $V_{eff}^{\beta}(\phi)$ occurs at $<\phi(T)>=0$.

This phenomena is known as symmetry restoration at high temperature, and gives rise to the phase transition from $\phi(T)=0$ to $\phi=\sigma$.

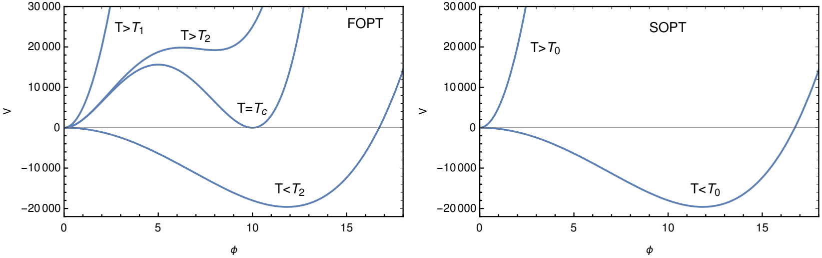
The phase transition may be first or second order.

- First-order phase transitions have out of equilibrium symmetric states when the temperature decreases and are used for baryogenesis process.
- Second-order phase transitions are used in the so-called new inflationary models.

First and second order phase transitions

$$V(\Phi, T) = D(T^2 - T_0^2)\Phi^2 + \lambda(T)\Phi^4 - ET(\Phi^3)$$

$$V(\Phi, T) = D(T^2 - T_0^2)\Phi^2 + \lambda(T)\Phi^4$$



(a) (b)

- Cubic term in effective potential is essential to generate a potential barrier between the symmetric and broken phases.
- It can provide the phase transition to be of the first order.

Electroweak phase transition in Standard Model

- In Standard Model, this cubic term, E, is contributed only by the electroweak gauge bosons.
- The parameter E is the cubic term of the effective potential of order of

$$E \sim \frac{2M_W^3 + M_Z^3}{4\pi v^3} \sim 0.01$$

- The Higgs self-coupling parameter has very small value

$$\lambda \sim 2E \sim 0.02 \rightarrow m_h = 49.2 GeV.$$

- This is incompatible with observed Higgs boson mass

$$M_h = \sqrt{2\lambda} v \sim 125.5 GeV \rightarrow \lambda \sim 0.13$$

In Standard Model the electroweak phase transition is a smooth crossover.

M. Gogberashvili,

Adv. High Energy Phys. 2018 (2018), 4653202

In BSM scenarios, additional contribution from bosons to the cubic term in effective potential can trigger the first order phase transition.

Why first order?

The first-order electroweak phase transition may solve some cosmological problems, like the generation of baryon asymmetry of the universe.

The Φ- dependent part of the effective potential can be written in the high-temperature expansion as

$$V_{eff}(\Phi, T) = V_{tree} + \Delta V_B + \Delta V_F$$

where

$$\Delta V_B = \sum_{i=h,\chi,W_L,Z_L,\gamma_L,W_T,Z_T,\gamma_T,T} g_i \Delta V_i$$

$$\Delta V_i = \frac{m_i^2(\Phi)T^2}{24} - \frac{\mathcal{M}_i^3(\Phi)T}{12\pi} - \frac{m_i^4(\Phi)}{64\pi^2}\left[log\frac{m_i^2(v)}{c_B T^2} - 2\frac{m_i^2(v)}{m_i^2(\Phi)} + \delta_{i\chi} log\frac{m_h^2(v)}{m_i^2(v)}\right],$$

and

$$\Delta V_F = g_t\left[\frac{m_{top}^2(\Phi)T^2}{48} + \frac{m_{top}^4(\Phi)}{64\pi^2}\left[log\frac{m_{top}^2(v)}{c_F T^2} - 2\frac{m_{top}^2(v)}{m_{top}^2(\Phi)}\right]\right]$$

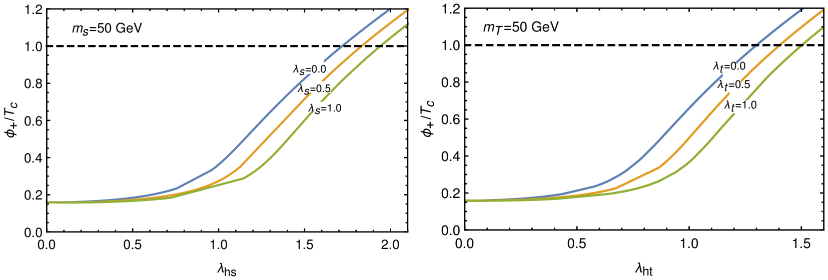
$$\mathcal{M}_i^2 = m_i^2(\Phi) + \Pi_i(\Phi, T)$$

S.Jangid, P. Bandyopadhyay,
Eur.Phys.J.C 80 (2020) 8, 715

The condition for a strongly first-order phase transition has typically taken to be

$$\frac{\Phi_+(T_C)}{T_C} \geq 1.$$

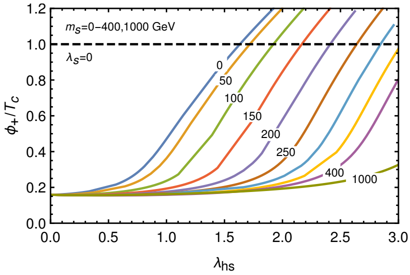
D. E. Morrissey, M. J. Ramsey-Musolf
New J. Phys. 14 (2012), 125003



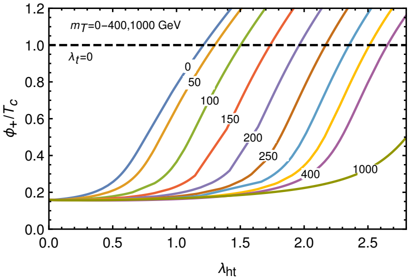
(a) Singlet (b) Triplet

$\frac{\Phi_+(T_C)}{T_C}$ is decreasing with increase in quartic coupling for particular value of soft mass parameter.

Variation with soft mass parameter



(a) Singlet



(b) Triplet

$\frac{\Phi_+(T_C)}{T_C}$ is decreasing with increase in soft mass parameter for particular value of quartic coupling.

Soft mass paramter and self quartic coupling are considered to be zero to maximize $\frac{\phi_+(T_c)}{T_c}$.

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arxiv:2111.03866

$\lambda_{hs}^{max}/\lambda_{ht}^{max}$ at a particular scale

For $\lambda_s/\lambda_t = 0$, we consider maximum allowed value of $\lambda_{hs}/\lambda_{ht}$ at the electroweak scale for which the theory remains perturbative at a particular scale.

	$\lambda_{hs} = \lambda_{hs}^{max}$		$\lambda_{ht} = \lambda_{ht}^{max}$	
	m_t (GeV)		m_t (GeV)	
Λ (GeV)	120.0	173.2	120.0	173.2
10^4	1.8350	1.6545	1.4190	1.3710
10^6	0.7672	0.7290	0.7435	0.7067
10^8	0.5420	0.5120	0.5171	0.4873
10^{11}	0.5010	0.4780	0.3685	0.3477
10^{16}	0.3112	0.3090	0.2566	0.2490
10^{19}	0.2480	0.2370	0.2202	0.2180

Λ is the perturbative scale where any of the coupling diverges.

λ_{ht}^{max} values at each perturbative scale are lower in case of triplet because of more number of scalars.

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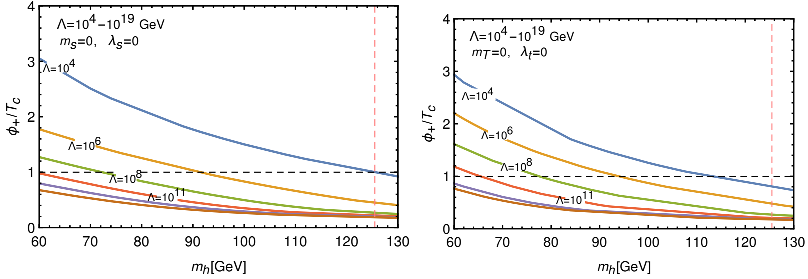
arxiv:2111.03866

Perturbative scale dependence of $\frac{\phi_+}{T_c}$

Only for 10^4 GeV, singlet can satisfy the strongly first-order phase transition condition consistent with current Higgs boson mass while triplet case fails to achieve.



(a) Singlet (b) Triplet

For Planck scale perturbativity, the condition for first-order phase transition is not consistent with current Higgs boson mass in both scenarios at one-loop level.

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Λ (GeV)	λ_{hs}^{max}	λ_{ht}^{max}
10^{19}	4.00	1.95

The two loop effect slows down the enhancement of the scalar quartic couplings via some negative contributions, as compared to one-loop.

These negative contributions, then allow much higher values of interaction quartic coupling $\lambda_{hs/ht}$ allowed from Planck scale perturbativity and correspondingly higher $\frac{\Phi_+(T_C)}{T_C}$.

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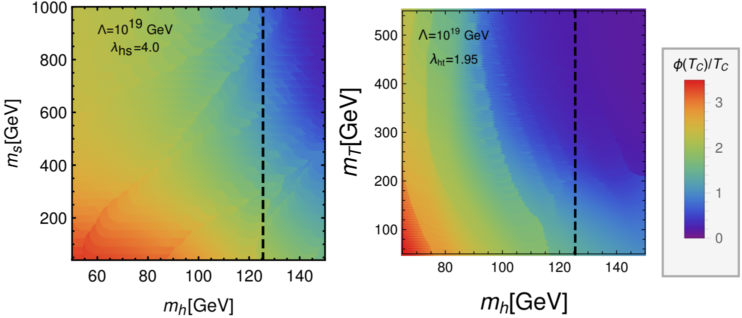

(a) Singlet (b) Triplet

The $\frac{\phi_+}{T_c}$ parameter decreses with the increase in soft mass parameter.

For lower values of soft mass parameter, first order phase transition is stronger.

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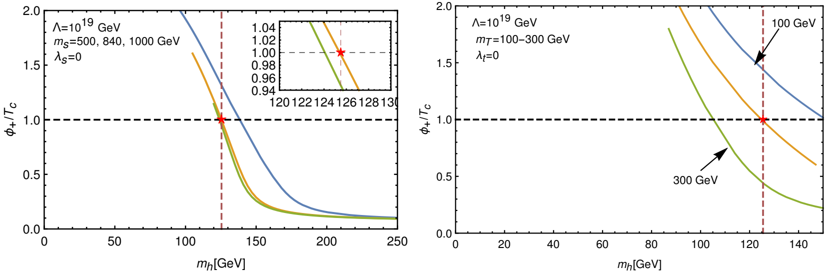
Bounds on soft mass pareameter



(a) Singlet (b) Triplet

For Planck scale perturbativity, the upper bound on the soft mass parameter is 840 GeV and 193 GeV for singlet and triplet satisfying the current Higgs mass and strongly first-order phase transition.

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The GWs are produced from the strong first-order electroweak phase transition maily by three mechanisms;

- Bubble collisions
- Sound waves in hot plasma
- Magnetohydrodynamic turbulence of bubbles in the early universe

Total GW intensity $\Omega_{GW}\mathrm{h}^2$ as a function of frequency is expressed as sum of

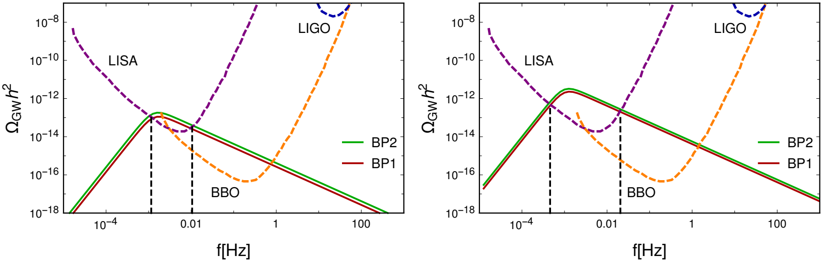
$$\Omega_{GW}h^2 = \Omega_{coll}h^2 + \Omega_{SW}h^2 + \Omega_{turb}h^2$$

C. Caprini, M. Hindmarsh, S. Huber,et al.
JCAP 04 (2016), 001

	m_S/m_T	λ_s/λ_t	$\lambda_{hs}/\lambda_{ht}$
BP1	150.23	0.10	0.10
BP2	120.23	0.01	0.01

Table: BPs for frequency analysis for singlet and triplet scenario.

Gravitational Wave intensity



(a) Singlet (b) Triplet

The detectable frequencies for singlet lie between $\sim 1.15 \times 10^{-3} - 1.06 \times 10^{-2}$ Hz, while for the triplet, the allowed ranges enhance to range $\sim 4.18 \times 10^{-4} - 1.99 \times 10^{-2}$ Hz, for the LISA experiment.

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Conclusions

- No consistent solutions have been found at one-loop from Planck scale perturbativity consistent with first order phase transition, and current Higgs boson and top quark masses.
- For Planck scale perturbativity at two-loop, the maximum mass values for the singlet field and the triplet field as $909, 310$ GeV respectively predicting first order phase transition, consistent with the current Higgs boson and top quark masses.
- The detectable frequency range by LISA is more for the triplet i.e. $\sim 4.18 \times 10^{-4} - 1.99 \times 10^{-2}$ Hz, in comparison to the singlet i.e. $\sim 1.15 \times 10^{-3} - 1.06 \times 10^{-2}$ Hz.
- Singlet model, constrained from perturbative unitarity and DM relic is in agreement with the sensitivity curves of LISA and BBO.
- For triplet case, the first-order phase transition predicts relatively lower mass i.e. 310 GeV, demanding additional multiplets to satisfy the DM relic.

- M. Gogberashvili, Adv. High Energy Phys. **2018** (2018), 4653202 doi:10.1155/2018/4653202 [arXiv:1702.08445 [gr-qc]].
- J. R. Espinosa and M. Quiros, Phys. Lett. B **305** (1993), 98-105 doi:10.1016/0370-2693(93)91111-Y [arXiv:hep-ph/9301285 [hep-ph]].
- D. E. Morrissey and M. J. Ramsey-Musolf, New J. Phys. **14** (2012), 125003 doi:10.1088/1367-2630/14/12/125003 [arXiv:1206.2942 [hep-ph]].
- C. Caprini, M. Hindmarsh, S. Huber, T. Konstandin, J. Kozaczuk, G. Nardini, J. M. No, A. Petiteau, P. Schwaller and G. Servant, *et al.* JCAP **04** (2016), 001 doi:10.1088/1475-7516/2016/04/001 [arXiv:1512.06239 [astro-ph.CO]].


Thank
you

Effective potential at zero temperature

- The effective potential for high field values is written as

$$V_{\text{eff}}(h,\mu) \simeq \lambda_{\text{eff}}(h,\mu)\frac{h^4}{4}, \quad \text{with } h \gg v,$$

- Where λ_{eff} is given by

$$\lambda_{\text{eff}}(h,\mu) \simeq \underbrace{\lambda_h(\mu)}_{\text{tree-level}} + \underbrace{\frac{1}{16\pi^2}\sum_{\substack{i=W^{\pm},Z,t,\\ h,\chi}} n_i\kappa_i^2\left[\log\frac{\kappa_i h^2}{\mu^2} - c_i\right]}_{\text{Contribution from SM}} + \underbrace{\frac{1}{16\pi^2}\sum_{i=T^0,T^{\pm}} n_i\kappa_i^2\left[\log\frac{\kappa_i h^2}{\mu^2} - c_i\right]}_{\text{Contribution from inert triplet}}.$$

where

$$C_W = C_Z = \frac{5}{6}$$

$$C_h = C_\chi = C_t = \frac{3}{2}$$

and n_i are the degrees of freedom

$$n_W = 6,\ n_Z = 3,\ n_h = 1,\ n_\chi = 3,\ n_t = -12$$

The Φ- dependent part of the effective potential can be written in the high-temperature expansion as

$$V_{eff}(\Phi, T) = V_{tree} + \Delta V_B + \Delta V_F$$

where

$$\Delta V_B = \sum_{i=h,\chi,W_L,Z_L,\gamma_L,W_T,Z_T,\gamma_T,T} g_i \Delta V_i$$

$$\Delta V_i = \frac{m_i^2(\Phi) T^2}{24} - \frac{\mathcal{M}_i^3(\Phi) T}{12\pi} - \frac{m_i^4(\Phi)}{64\pi^2} \left[log \frac{m_i^2(v)}{c_B T^2} - 2 \frac{m_i^2(v)}{m_i^2(\Phi)} + \delta_{i\chi} log \frac{m_h^2(v)}{m_i^2(v)} \right],$$

and

$$\Delta V_F = g_t \left[\frac{m_{top}^2(\Phi) T^2}{48} + \frac{m_{top}^4(\Phi)}{64\pi^2} \left[log \frac{m_{top}^2(v)}{c_F T^2} - 2 \frac{m_{top}^2(v)}{m_{top}^2(\Phi)} \right] \right]$$

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The number of degrees of freedom g_i are given by

$$g_h = 1,\ g_\chi = 3,\ g_T = 3,\ g_t = 12$$

$$g_{W_L} = g_{Z_L} = g_{\gamma_L} = 1,$$

$$g_{W_T} = g_{Z_T} = g_{\gamma_T} = 2$$

while the coefficients c_B and c_F are defined by: $\log c_B$=3.9076, $\log c_F$=1.1350.

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Debye masses

The Debye masses $\mathcal{M}_i^2(\Phi)$ for $i = h, \chi, T, W_L, W_T, Z_T, \gamma_T$ are

$$\mathcal{M}_i^2 = m_i^2(\Phi) + \Pi_i(\Phi, T)$$

where the self-energies $\Pi_i(\Phi, T)$ are given by

$$\begin{aligned}
\Pi_h(\Phi, T) &= \Big(\frac{3g^2 + 3g'^2}{16} + \frac{\lambda_1}{2} + \frac{y_t^4}{4} + \frac{\lambda_{ht}}{12}\Big) T^2 \\
\Pi_\chi(\Phi, T) &= \Big(\frac{3g^2 + 3g'^2}{16} + \frac{\lambda_1}{2} + \frac{y_t^4}{4} + \frac{\lambda_{ht}}{12}\Big) T^2 \\
\Pi_T(\Phi, T) &= \frac{2\lambda_t + \lambda_{ht}}{6} T^2 \\
\Pi_{W_L}(\Phi, T) &= \frac{11}{6} g^2 T^2 \\
\Pi_{W_T}(\Phi, T) &= \Pi_{Z_T}(\Phi, T) = \Pi_{\gamma T} = 0
\end{aligned}$$

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Cont...

$$\mathcal{M}_{ZL}^2 = \frac{1}{2}\left[m_Z^2(\Phi) + \frac{11}{6}\frac{g^2}{\cos^2\theta_W}T^2 + \Delta(\Phi, T)\right]$$

$$\mathcal{M}_{\gamma L}^2 = \frac{1}{2}\left[m_Z^2(\Phi) + \frac{11}{6}\frac{g^2}{\cos^2\theta_W}T^2 - \Delta(\Phi, T)\right]$$

with

$$\Delta^2(\Phi, T) = m_Z^4(\Phi) + \frac{11}{3}\frac{g^2\cos^2 2\theta_W}{\cos^2\theta_W}\left[m_Z^2(\Phi) + \frac{11}{12}\frac{g^2}{\cos^2\theta_W}T^2\right]T^2$$

Sef energy contribution to the transverse components of W, Z, γ is zero.

Photon is also contributing to the effective potential through non-zero self energy contribution in longitudinal component.

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arxiv:2111.03866