Higgs boson self-coupling as a probe of the sphaleron property

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S. Kanemura, M Tanaka: PLB 809 135711 (2020)

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Introduction

Standard model(SM) consistents with the collider experiments

The problem in Higgs sector

- The structure of the Higgs potential
- The dynamics of the spontaneous electroweak symmetry breaking

Phenomena beyond the SM(BSM)

- Baryon Asymmetry of the Universe
- Dark Matter
- Tiny mass of neutrino

The extension of the Higgs sector ↔ New Physics

Baryon asymmetry of the Universe

[PDG 2019]

$$\frac{n_b - n_{\bar{b}}}{n_\gamma} = (5.8 - 6.6) \times 10^{-10}$$

Sakharov's conditions: [Sakharov 1967]

① Baryon violation

② C, CP violation

③ Departure from thermal equilibrium

Electroweak baryogenesis,
Leptogenesis,
GUT baryogenesis,
etc···

We focus on the scenario of the electroweak baryogenesis

Electroweak baryogenesis: [Kuzmin, et al. : PLB155 (1985)]

① Sphaleron process

② The effects on the new physics ← Electric dipole moment

③ 1st Order Phase Transition(1stOPT) ← hhh coupling, GW specturm

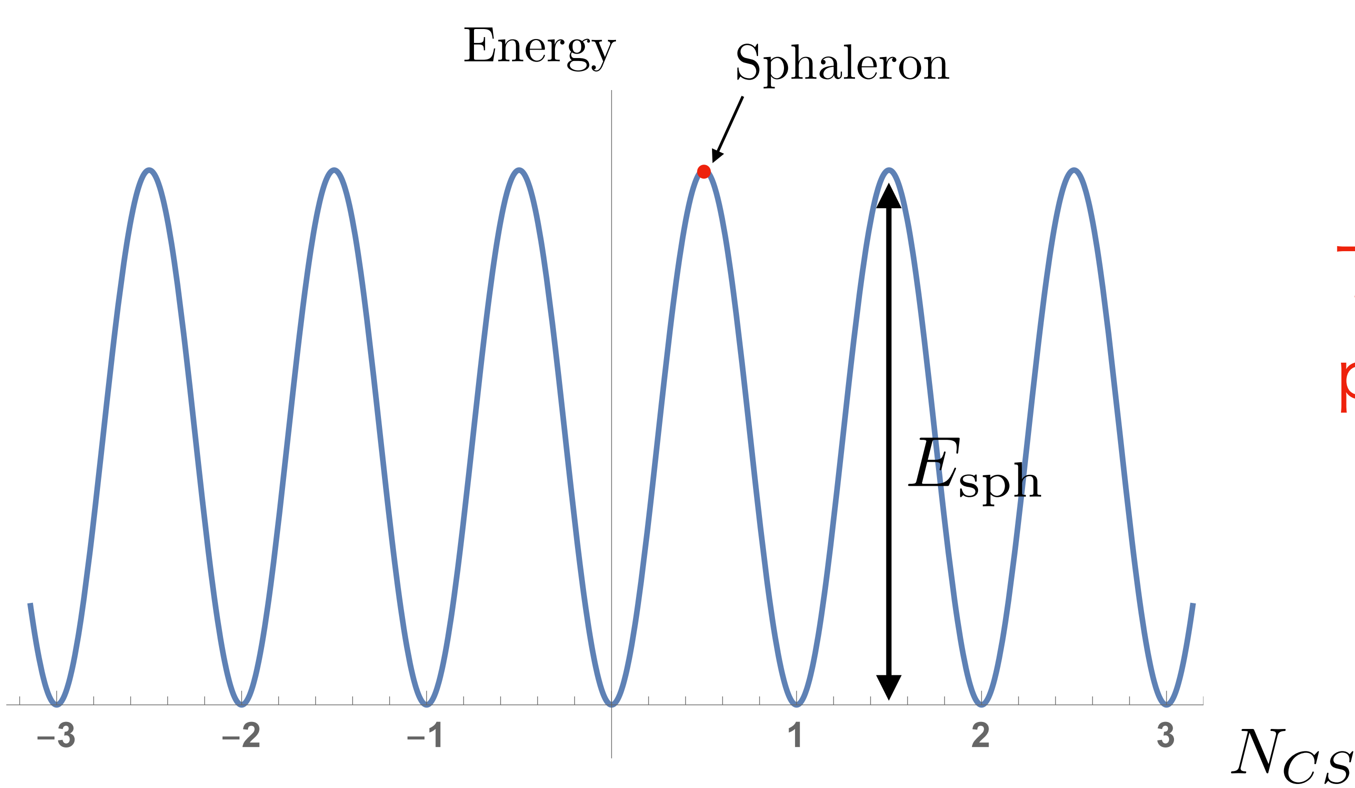
Can we determine the sphaleron property by experiments？

Sphaleron

Sphaleron "ready to fall"

[Klinkhamer, Manton: PRD.30 (1984)]

- Non-perturbative solution in field equations(static and unstable)
- Saddle point field configuration
- B+L violation process: sphaleron process



Field configuration

$$\Delta(B+L) = 6\Delta N_{\rm CS}$$

The process is important to produce the baryon asymmetry.

Sphaleron in the SM

- Energy functional $(g' = 0)$ [Manton: PRD28 (1983)]

$$E[W_i^a, \Phi] = \int d^3x \left[\frac{1}{4g^2} W_{ij}^a W_{ij}^a + (D_i\Phi)^\dagger D_i\Phi + V(\Phi) \right] \qquad V^{\rm SM}(\Phi) = \frac{m_h^2}{2v^2}\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)^2$$

[Akiba et al. : PRD38 (1988)]
[Spannowsky, Tamarit : PRD95 (2017)]

- Ansatz

$$W_i^a(\vec{r}) = m_W \left[\epsilon_{aij} n_j \frac{1 - R(r)\cos\theta(r)}{r} + (\delta_{ai} - n_a n_i) \frac{R(r)\sin\theta(r)}{r} \right], \quad n_a = x^a/r$$

$$\Phi(\vec{r}) = \frac{v}{\sqrt{2}} S(r) e^{i n_a \sigma^a \phi(r)} \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

From a symmetry,

$$\theta = \pi, \ \phi = \frac{\pi}{2}$$

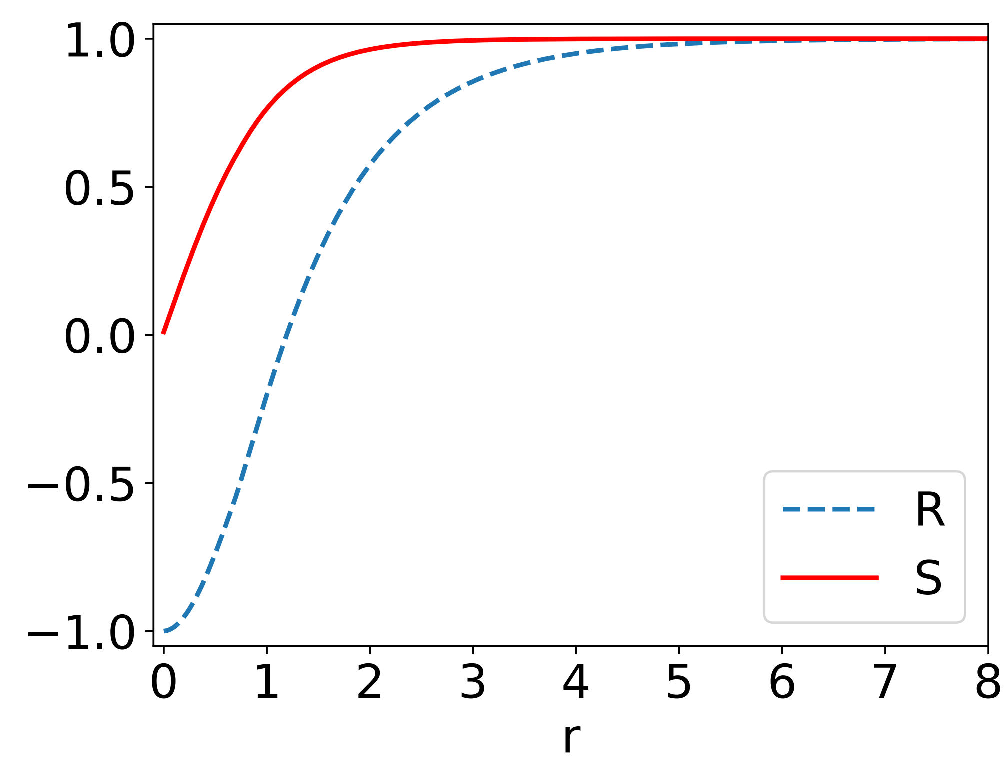
- Field equation

$$r^2 R'' - R^3 + R\left(1 - r^2 S^2\right) + r^2 S^2 = 0$$

$$S'' + \frac{2}{r} S' - \frac{1}{2r^2} S (1 - R)^2 - \frac{4}{g^2 v^4} \frac{\partial V(S)}{\partial S} = 0$$

$$E_{\rm sph}^{\rm SM} = 9.08 \ \rm TeV$$

[Kanemura, Tanaka: PLB 809 (2020)]



Gauge field: R, Higgs field:S

Triple Higgs coupling and sphaleron

- Triple Higgs coupling

$$\left.\frac{\partial^3 V(h)}{\partial h^3}\right|_{h=0} = \lambda_{hhh}^{\rm SM}\left(1+\boxed{\frac{\Delta\lambda_{hhh}^{\rm new}}{\lambda_{hhh}^{\rm SM}}}\right) \quad \lambda_{hhh}^{\rm SM} = \frac{3m_h^2}{v} \quad \Delta\lambda_{hhh}^{\rm new} = \lambda_{hhh}^{\rm new} - \lambda_{hhh}^{\rm SM}$$

Eg) 2HDM [Kanemura et al.: PRD 70 (2004)]

$$m_\Phi^2 \simeq M^2 + \lambda_\Phi v^2$$

$$\frac{\Delta\lambda_{hhh}^{\rm 2HDM}}{\lambda_{hhh}^{\rm SM}} \simeq \frac{m_\Phi^4}{12\pi^2 m_h^2 v^2}\left(1-\frac{M^2}{m_\Phi^2}\right)^3 \xrightarrow{M\to 0} \frac{m_\Phi^4}{12\pi^2 m_h^2 v^2}$$

Non-Decoupling

[Kanemura et al.: PLB606 (2005)]

The strong 1stOPT demands $\Delta\lambda_{hhh}/\lambda_{hhh}$ >O(10)% in 2HDM

- Sphaleron energy ↔ Higgs potential ↔ hhh coupling

$$\Rightarrow \boxed{\Delta E_{\rm sph}^{\rm new} \simeq -A^{\rm new}\frac{\Delta\lambda_{hhh}^{\rm new}}{\lambda_{hhh}^{\rm SM}}}$$

$$E_{\rm sph}^{\rm new} = E_{\rm sph}^{\rm SM} + \Delta E_{\rm sph}^{\rm new}$$

$A^{\rm new}$ can be determined theoretically

[Kanemura, Tanaka: PLB 809 (2020)]

Today’s theme

hhh coupling → Sphaleron energy at the early Universe

Sphaleron at the early Universe

- SMEFT added a dim. 6 operator to Higgs potential [Grojean et al.: PRD71 (2005)] [Zhou et al.: PRD101 (2020)]
- SM with additional N singlet scalars model

$$V_0(\Phi, \vec{S}) = -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2 + \frac{\mu_S^2}{2}|\vec{S}|^2 + \frac{\lambda_S}{4}|\vec{S}|^4 + \lambda_{\Phi S}\Phi^\dagger\Phi|\vec{S}|^2$$

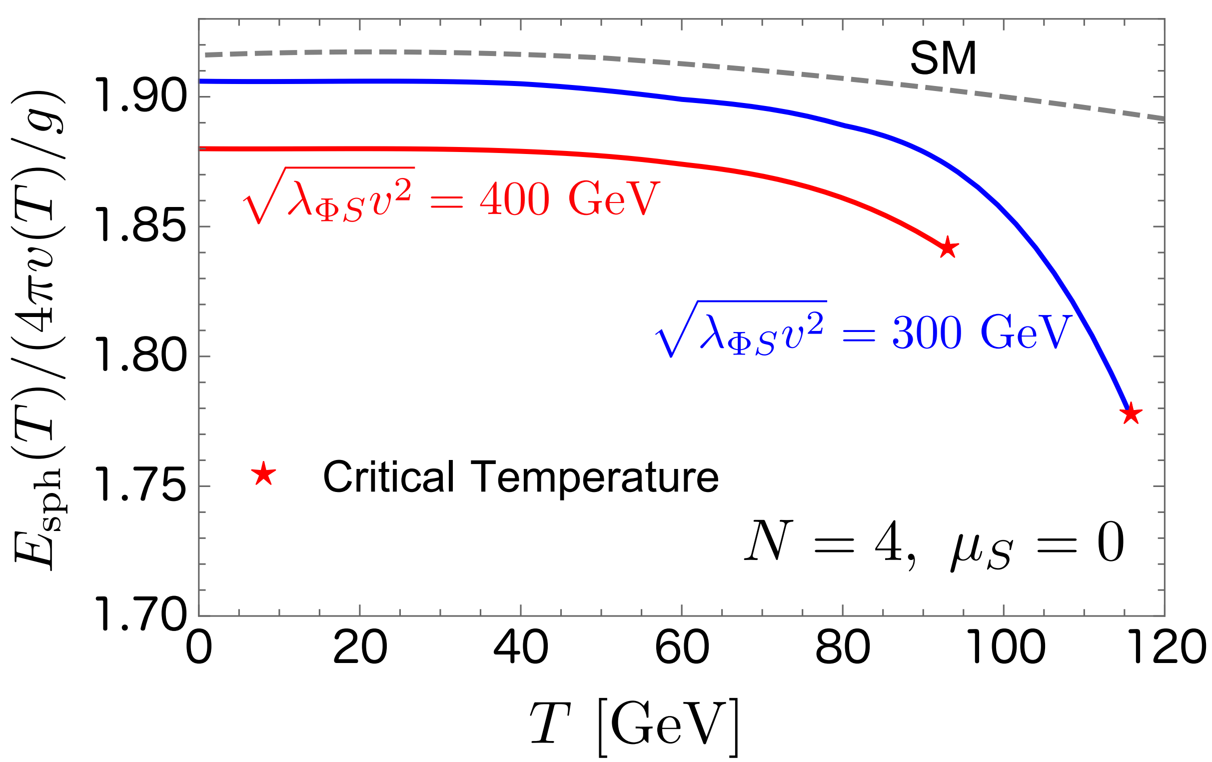
$$\vec{S} = (S_1, S_2, \cdots, S_N)$$
$$\mu_S^2 > 0$$
$$M_S(v)^2 = \mu_S^2 + \lambda_{\Phi S}v^2$$

The effective potential

$$V_{\rm eff}(\Phi, T) = V_0(\Phi) + \underline{V_1(\Phi)} + \underline{V_T(\Phi, T)} + \underline{\Delta V_T(\Phi, T)}$$

1loop at T=0　1loop at T≠0　Daisy resummation

[Kanemura, Tanaka: Preliminary]



$$\Delta E_{\rm sph}^{\rm new} \simeq -A^{\rm new}\frac{\Delta\lambda_{hhh}^{\rm new}}{\lambda_{hhh}^{\rm SM}}$$

$$\Delta\lambda_{hhh}^{\rm new} \leftrightarrow \Delta E_{\rm sph}^{\rm new}(T=0) \leftrightarrow \Delta E_{\rm sph}^{\rm new}(T=T_C)$$

We can determine the sphaleron energy at the early Universe via the measurements of future colliders

Sphaleron decoupling condition

- Departure from thermal equilibrium [Kuzmin, et al. : PLB155 (1985)]

$$\Gamma_{\rm sph}(T_C) < H(T_C) \quad \Rightarrow \quad \boxed{\frac{v_C}{T_C} > \zeta_{\rm sph}(T_C) \;\; \text{or} \;\; \frac{E_{\rm sph}(T_C)}{T_C} > B(T_C)} \qquad \Gamma_{\rm sph}(T) = A(T)e^{-E_{\rm sph}(T)/T}$$

- $\zeta_{\rm sph}(T_C)$ and $E_{\rm sph}(T_C)/T_C$ are determined by measurements of λ_{hhh}

$$\boxed{\Delta\lambda_{hhh}^{\rm new} \;\; \leftrightarrow \;\; \Delta E_{\rm sph}^{\rm new}(T=0) \;\; \leftrightarrow \;\; \Delta E_{\rm sph}^{\rm new}(T=T_C)}$$

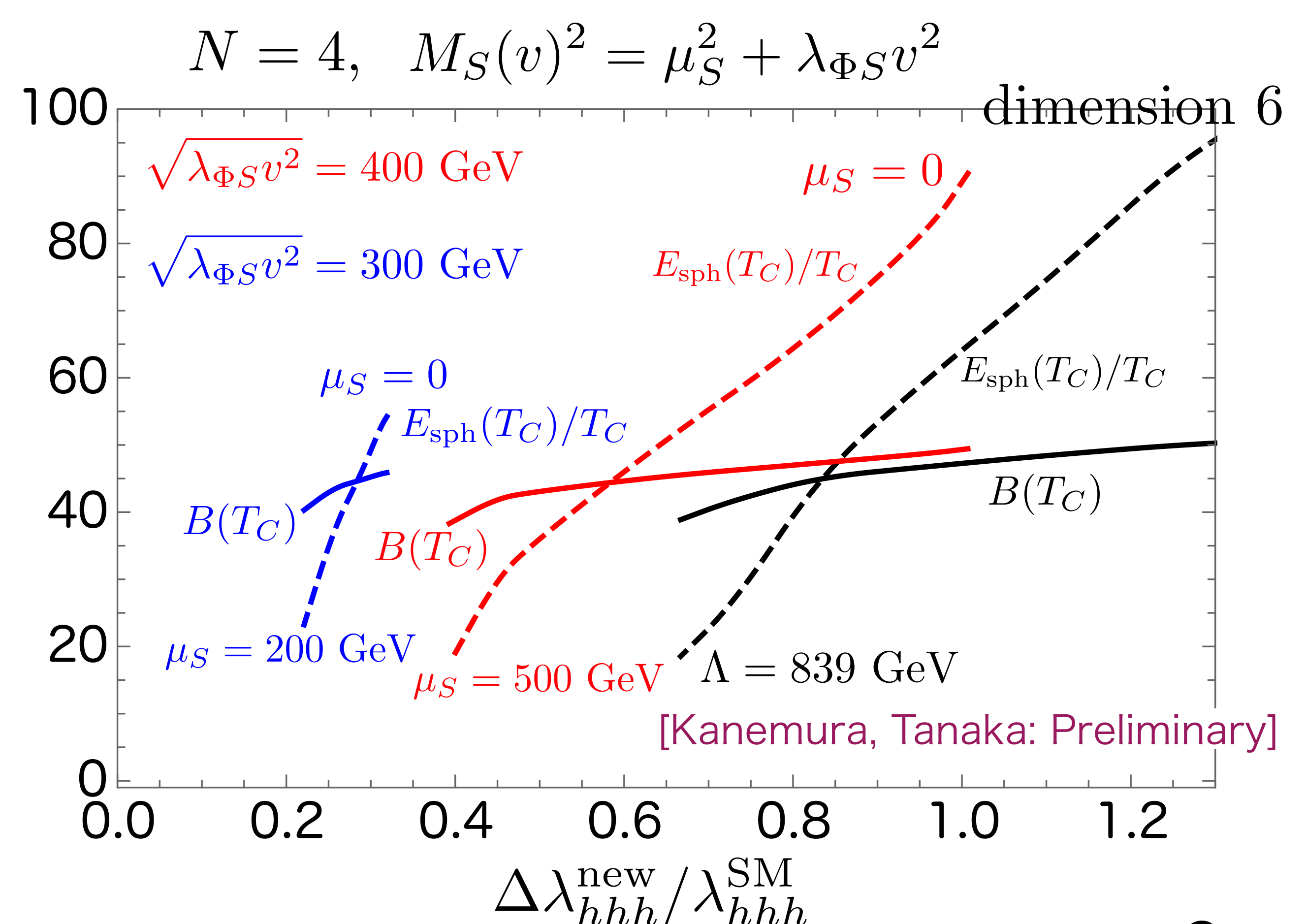
We can verify the validity of the electroweak baryogenesis at ILC

- SM with additional N singlet scalars

$\Delta\lambda_{hhh}^{N\rm scalar}/\lambda_{hhh}^{\rm SM} > 22\,\%$ (N=4) is needed

← Update of previous work

[Kanemura et al.: PLB606 (2005)]



Summary

① Although the sphaleron is important in explaining the baryon asymmetry, the property of the sphaleron has not been determined by experiments.

② Sphaleron and triple Higgs coupling are both associated with Higgs potentials

→ Sphaleron energy is determined via the measurement of λ_{hhh} at future colliders

$$\Delta E_{\rm sph}^{\rm new} \simeq -A^{\rm new} \frac{\Delta\lambda_{hhh}^{\rm new}}{\lambda_{hhh}^{\rm SM}}$$

③ Sphaleron energy at the early Universe is determined the measurement of λ_{hhh}

→ $\zeta_{\rm sph}(T_C)$ and $E_{\rm sph}(T_C)/T_C$ are also determined

$$\frac{v_C}{T_C} > \zeta_{\rm sph}(T_C) \quad \text{or} \quad \frac{E_{\rm sph}(T_C)}{T_C} > B(T_C)$$

→ We can verify the scenario of the electroweak baryogenesis

④ In order to realize the strong 1stOPT, λ_{hhh} should satisfy $\Delta\lambda_{hhh}^{N\rm scalar}/\lambda_{hhh}^{\rm SM} > 22\,\%$ in the model with additional four scalar singlets(i.e. 2HDM)

Back Up

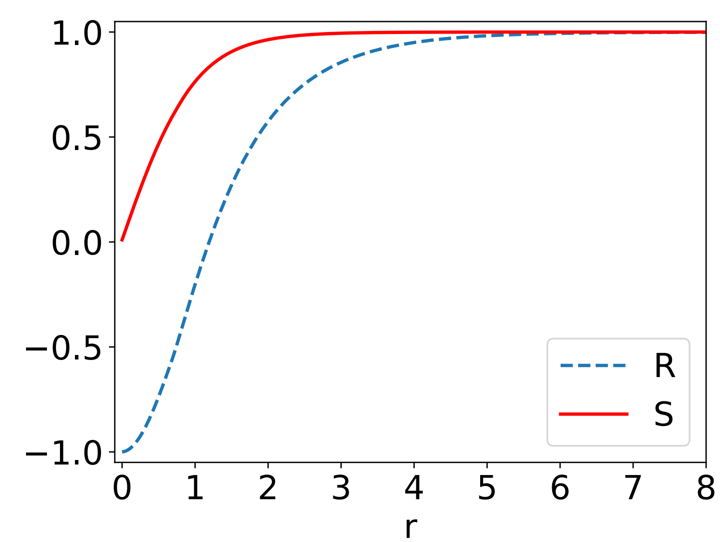
次元6演算子を加えた有効場の理論

[Grojean et al.: PRD71 (2005)] [Gan et al.: PRD96 (2017)]

- ヒッグスポテンシャル: $V(\Phi) = \frac{m_h^2}{2v^2}\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)^2 + \underline{\frac{1}{\Lambda^2}\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)^3}$

- スファレロンエネルギー: $\Delta E_{\rm sph}^{\rm dim6} \simeq -\frac{\pi v^2 m_h^2}{4m_W^3}\frac{2v^4}{m_h^2\Lambda^2}\int_0^\infty dr[1-S(r)]^3$

- ヒッグス3点結合: $\frac{\Delta\lambda_{hhh}^{\rm dim6}}{\lambda_{hhh}^{\rm SM}} = \frac{2v^4}{m_h^2\Lambda^2}$



⇨ $\Delta E_{\rm sph}^{\rm dim6} \simeq -A^{\rm dim6}\frac{\Delta\lambda_{hhh}^{\rm dim6}}{\lambda_{hhh}^{\rm SM}}$

$$A^{\rm dim6} = \frac{\pi v^2 m_h^2}{4m_W^3}\int_0^\infty [1-S(r)]^3 = 0.149\ {\rm TeV}$$ ←Λに依存しない

Eg) $\Delta\lambda_{hhh}^{\rm dim6}/\lambda_{hhh}^{\rm SM} = 96\,\%$ ($\Lambda = 700$ GeV)では $\Delta E_{\rm sph}^{\rm dim6}/E_{\rm sph}^{\rm SM} = -1.54\,\%$

ヒッグス3点結合 ↔ スファレロンエネルギー

スカラー一重項をN個追加したモデル

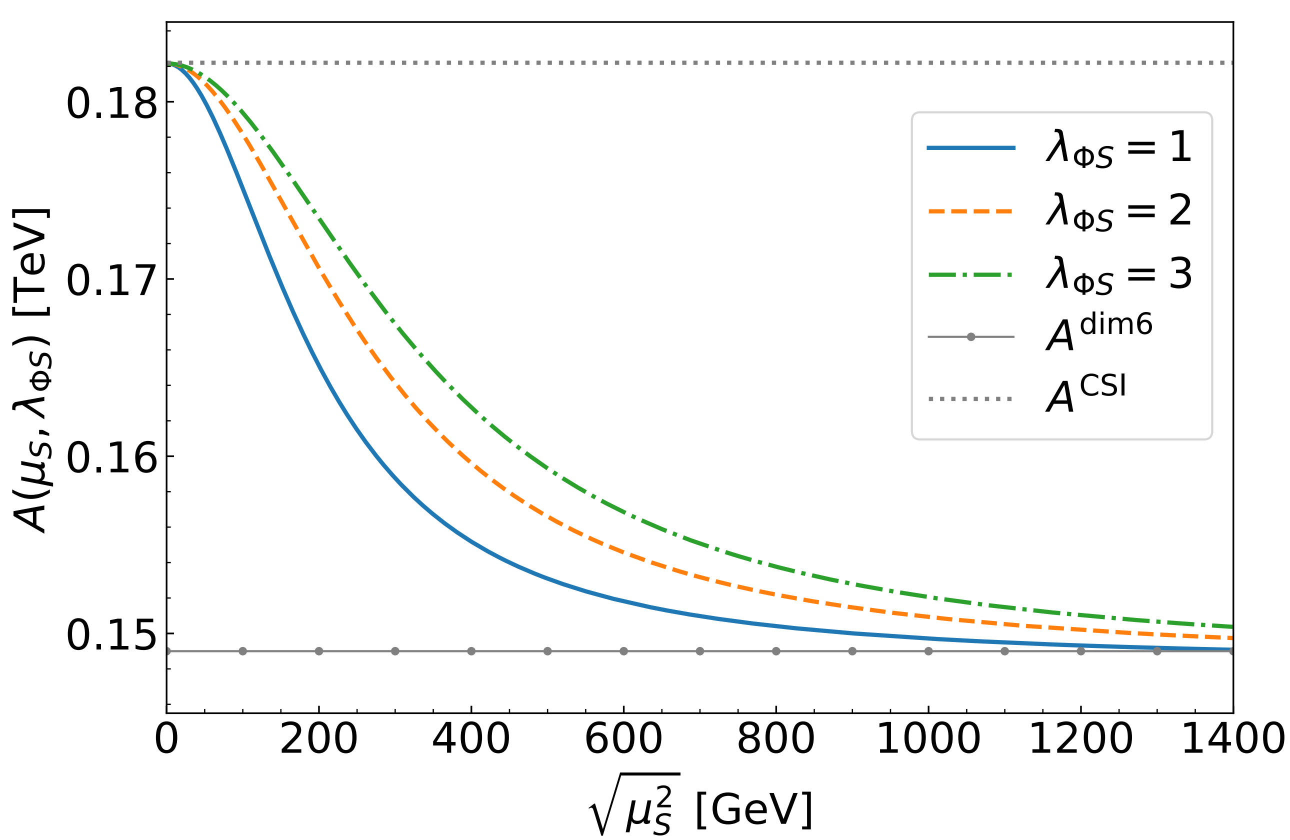
- ヒッグスポテンシャル(tree)　$\vec{S} = (S_1, S_2, \cdots, S_N)$　$\mu_S^2 > 0$

$$V_0(\Phi, \vec{S}) = -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2 + \frac{\mu_S^2}{2}|\vec{S}|^2 + \frac{\lambda_S}{4}|\vec{S}|^4 + \lambda_{\Phi S}\Phi^\dagger\Phi|\vec{S}|^2 \qquad M_S(v)^2 = \mu_S^2 + \lambda_{\Phi S}v^2$$

- 1ループ効果を含む有効ポテンシャルで$E_{\rm sph}$を評価　[Coleman, Weinberg.: PRD7 (1973)]

$$\Delta E_{\rm sph}^{N\,\rm scalar} = -A(\mu_S^2, \lambda_{\Phi S})\frac{\Delta\lambda_{hhh}^{N\,\rm scalar}}{\lambda_{hhh}^{\rm SM}} \qquad \frac{\Delta\lambda_{hhh}^{N\,\rm scalar}}{\lambda_{hhh}^{\rm SM}} = \frac{NM_S^4}{12\pi^2 m_h^2 v^2}\left(1 - \frac{\mu_S^2}{M_S^2}\right)^3$$

[Kanemura, Tanaka: PLB 809 (2020)]



係数Aはモデルの間で対応関係がある

$$A(\mu_S^2, \lambda_{\Phi S}) \to \begin{cases} A^{\dim 6} & (\mu_S^2 \gg v^2), \\ A^{\rm ND} & (\mu_S^2 \to 0) \end{cases}$$

Eg) Non-decouplingの場合 $(\mu_S^2 = 0)$

$$\frac{\Delta\lambda_{hhh}^{N\,\rm scalar}}{\lambda_{hhh}^{\rm SM}} = \frac{3}{2} \quad \Rightarrow \quad \frac{\Delta E_{\rm sph}^{N\rm scalar}}{E_{\rm sph}^{\rm SM}} = -1.2\%$$

スファレロンの直接検証

- 加速器でB+Lの破れを引き起こす方法

$$\Delta(B+L) = +6 \quad qq \to lllqqqqqqqqq$$

[Aoyama, Goldberg, PLB 188 (1987)]
[J. Ellis, K. Sakurai, JHEP 086 (2016)]

$\sqrt{s} > E_{\rm sph} \simeq 9\ \mathrm{TeV}$の高エネルギー加速器実験でB+Lの破れが起きるのか？

[Tye, Wong, PRD 92 (2015)]　[Funakubo, Fuyuto, Senaha, arXiv: 1612.05431]

B+Lを破る過程の散乱断面積の計算で現れる主要な問題点

① トンネリング因子は効くのか？

② Ncsを変化させるには，大量のWボソンとヒッグス粒子の生成が必要であるが，その過程は指数関数的に抑制される．この抑制を相殺するような機構は存在するのか？

[Tye, Wong, PRD 96 (2017)]

肯定的な推定では$\sqrt{s} > 25\ \mathrm{TeV}$ならば見える可能性が指摘されている

← QMを用いた推定で，QFTによる基礎づけは行われていない

議論が決着しておらず，B+Lの破れを加速器実験で直接観測できるかは未知