高次元演算子を持つ複素シングレットスカラー拡張模型における電気双極子モーメントと電弱バリオン数生成

論文準備中　共同研究者：瀬名波栄問

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1. Introduction

Baryon Asymmetry of the Universe (BAU)

from bigbang nucleosynthesis $\eta^{\rm BBN} = \dfrac{n_B}{n_\gamma} = (5.8-6.5)\times 10^{-10}(95\%{\rm CL})$

from cosmic microwave background $\eta^{\rm CMB} = \dfrac{n_B}{n_\gamma} = (6.105\pm 0.055)\times 10^{-10}(95\%{\rm CL})$

One hypothesis to explain BAU is **electroweak baryogenesis**

Sakharov conditions : The conditions necessary to generate baryon numbers

1. Baryon number violation : Sphaleron process
2. C symmetry and CP symmetry violation : Chiral gauge interaction, CKM matrix
3. Departure from thermal equilibrium : Strong 1st order phase transition

EWBG w/ SM

・CKM phase cannot fully explain the CP asymmetry

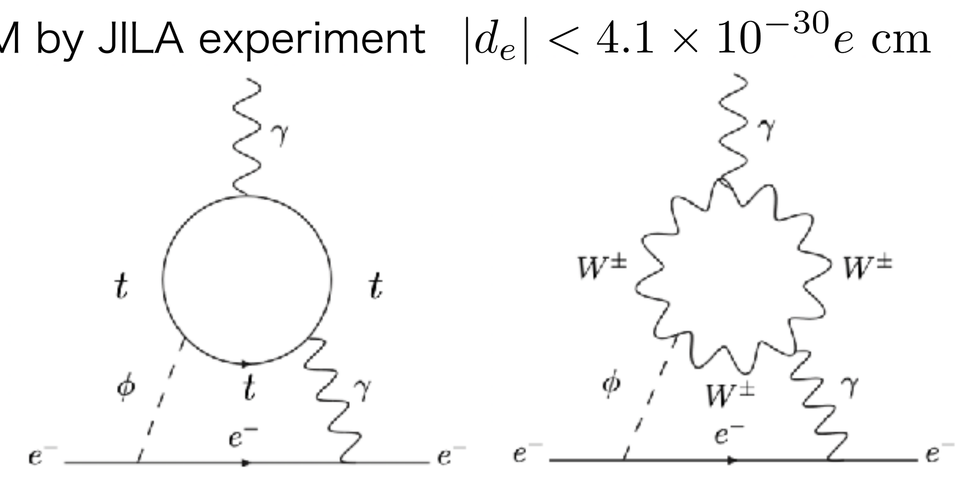
・Strong 1st order phase transition gives an upper limit for the Higgs mass

→ the SM must be extended

Electric dipole moment (EDM)

Upper bound on the electron EDM by JILA experiment $|d_e| < 4.1\times 10^{-30} e$ cm

Two dominant Barr-Zee diagrams in which electron phase enters



top-loop　　W-loop

Our BSM model: Complex singlet extension of the SM (CxSM)

2. The Model

Scalar potential

$$V_0(H,S) = \frac{m^2}{2}H^\dagger H + \frac{\lambda}{4}\left(H^\dagger H\right)^2 + \frac{\delta_2}{2}H^\dagger H|S|^2 + \frac{b_2}{2}|S|^2 + \frac{d_2}{4}|S|^4 + \left(a_1 S + \frac{b_1}{4}S^2 + {\rm H.c.}\right),$$

where $a_1 = a_1^r + i a_1^i,\ b_1 = b_1^r + i b_1^i$

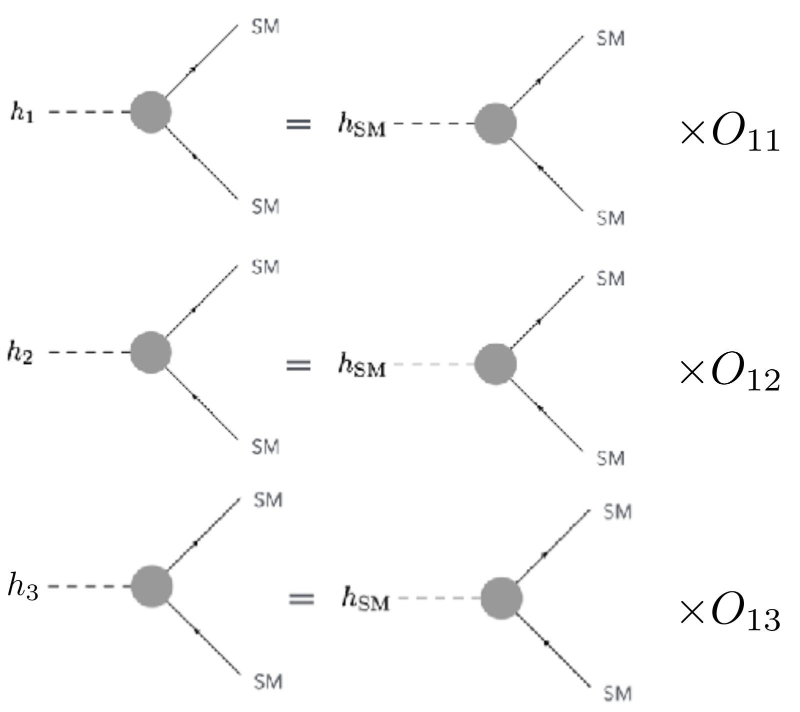
$$H(x) = \begin{pmatrix} G^+(x) \\ \frac{1}{\sqrt{2}}\left(v + h(x) + iG^0(x)\right)\end{pmatrix}$$

$$S(x) = \frac{1}{\sqrt{2}}\left(v_S^r + i v_S^i + s(x) + i\chi(x)\right). = \frac{1}{\sqrt{2}}\left(|v_S|e^{i\theta_S} + s(x) + i\chi(x)\right)$$

$$\underbrace{(h,s,\chi)^T}_{\text{Gauge eigenstates}} = O(\alpha_i)\underbrace{(h_1,h_2,h_3)^T}_{\text{Mass eigenstates}}$$

$$O(\alpha_i) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_3 & -s_3 \\ 0 & s_3 & c_3\end{pmatrix}\begin{pmatrix} c_2 & 0 & -s_2 \\ 0 & 1 & 0 \\ s_2 & 0 & c_2\end{pmatrix}\begin{pmatrix} c_1 & -s_1 & 0 \\ s_1 & c_1 & 0 \\ 0 & 0 & 1\end{pmatrix}\quad \begin{array}{l} s_i = \sin\alpha_i, \\ c_i = \cos\alpha_i \\ (i=1,2,3)\end{array}$$

3. Degenerate scalar scenario



$$h_1 = O_{11}h_{\rm SM} + O_{21}s + O_{31}\chi$$
$$h_2 = O_{12}h_{\rm SM} + O_{22}s + O_{32}\chi$$
$$h_3 = O_{13}h_{\rm SM} + O_{22}s + O_{33}\chi$$

Only $h_{\rm SM}$ couples to SM fermions and gauge bosons

$$\Gamma(h_1\to{\rm SM}) = \Gamma(h_{\rm SM}\to{\rm SM})(m_{h_1})\times O_{11}^2$$
$$\Gamma(h_2\to{\rm SM}) = \Gamma(h_{\rm SM}\to{\rm SM})(m_{h_2})\times O_{12}^2$$
$$\Gamma(h_3\to{\rm SM}) = \Gamma(h_{\rm SM}\to{\rm SM})(m_{h_3})\times O_{13}^2$$

The orthogonality of the mixing matrix

$$\Sigma_k O_{ik}O_{jk} = \delta_{ij}$$

e.g., $O_{11}^2 + O_{12}^2 + O_{13}^2 = 1$

In Higgs masses degenerate limit

$$\boxed{\Gamma(h_1\to{\rm SM}) + \Gamma(h_2\to{\rm SM}) + \Gamma(h_3\to{\rm SM}) \simeq \Gamma(h_{\rm SM}\to{\rm SM})\ \ {\rm for}\ m_{h_1}\simeq m_{h_2}\simeq m_{h_3}}$$

Degenerate scalar scenario

4. Higher dimensional operator

S couples to SM fermions only through the mixing angles α

⇒ pseudoscalar coupling $h_i \bar{f}\gamma_5 f$ does not arise

Even though the complex phases exist in the singlet scalar VEV, we do not induce CPV in the matter sector in the SM

One possible extension

adding new fermions that couple to S and a new contribution to the Yukawa interaction through a higher dimensional operator.

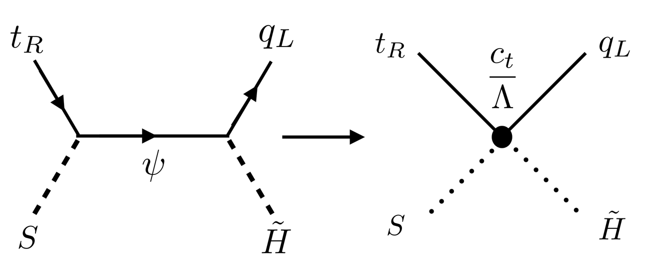
Dimension-5 operators contributing to the top quark and electron Yukawa coupling

$$\mathcal{L}_t^{\rm Yukawa} = -\bar{q}_L\tilde{H}\frac{c_t}{\Lambda}S t_R + {\rm H.c},$$
$$\mathcal{L}_e^{\rm Yukawa} = -\bar{l}_L H\frac{c_e}{\Lambda}S e_R + {\rm H.c},$$

$\tilde{H} = i\tau^2 H^*$ w/ Pauli matrix τ^2

c_i : arbitrary parameters

Λ: the scale of the integrated fermion ψ



(i) Real c_t case : EWBG-related CPV arises only from ${\rm Im}S$

(ii) Complex c_t case : EWBG-related CPV arises from both c_t and ${\rm Im}S$

Scalar field

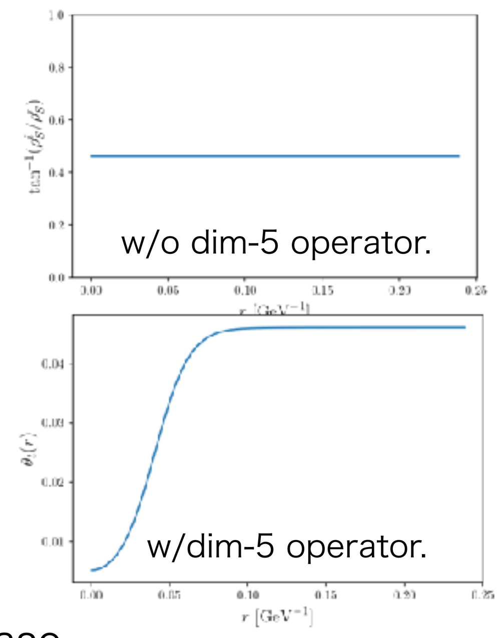
$$\langle H(r)\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ \rho(r)\end{pmatrix},\quad \langle S(r)\rangle = \frac{1}{\sqrt{2}}\left(\rho_S^r(r) + i\rho_S^i(r)\right)$$

The top mass during EWPT

$$m_t(r) = \frac{y_t\rho(r)}{\sqrt{2}} + \frac{c_t\rho(r)}{2\Lambda}\left(\rho_S^r(r) + i\rho_S^i(r)\right) \equiv |m_t(r)|\,e^{i\theta_t(r)}$$

Phase $\theta_t(r)$

$$\theta_t(r) = \tan^{-1}\left(\frac{\rho_S^i(r)}{\sqrt{2}\Lambda y_t/c_t + \rho_S^r(r)}\right).$$



the baryon number arises from the r derivative of the phase

5. Electron EDM and BAU

top-loop

$$(d_e^{h\gamma})_t/e = \frac{1}{3\pi^2}\left(\frac{\alpha_{\rm em}G_F v^2}{\sqrt{2}\pi m_t}\right)\sum_{i=1}^n\left[{\rm Im}\left(Y_{eeh_i}\right){\rm Re}\left(Y_{tth_i}\right)f\left(\frac{m_t^2}{m_{h_i}^2}\right) + {\rm Re}\left(Y_{eeh_i}\right){\rm Im}\left(Y_{tth_i}\right)g\left(\frac{m_t^2}{m_{h_i}^2}\right)\right]$$

W-loop

$$(d_e^{h\gamma})_W/e = -\sum_{i=1}^n\frac{\alpha_{\rm em}^2 v}{32\pi^2 s_W^2 m_W^2}{\rm Im}\left(Y_{eeh_i}\right)g_{h_iVV}\mathcal{J}_W^\gamma\left(m_{h_i}\right)$$

The couplings of scalar mass eigenstates h_i to top quark and electron

$$Y_{\bar{t}_L t_R h_i} = O_{1i}\frac{m_t}{v} + O_{2i}\frac{1}{2}\frac{c_t v}{\Lambda} + O_{3i}\frac{1}{2}\frac{i c_t v}{\Lambda}$$
$$Y_{\bar{e}_L e_R h_i} = O_{1i}\frac{m_e}{v} + O_{2i}\frac{1}{2}\frac{c_e v}{\Lambda} + O_{3i}\frac{1}{2}\frac{i c_e v}{\Lambda}$$

where

$$m_t = \frac{y_t v}{\sqrt{2}} + \frac{c_t v}{2\Lambda}\left(v_S^r + i v_S^i\right),\quad m_e = \frac{y_e v}{\sqrt{2}} + \frac{c_e v}{2\Lambda}\left(v_S^r + i v_S^i\right)$$

Benchmark point where strong 1st order EWPT occurs

Inputs	v [GeV]	v_S^r [GeV]	v_S^i [GeV]	m_{h_1} [GeV]	m_{h_2} [GeV]	m_{h_3} [GeV]	α_1 [rad]	α_2 [rad]
BP1	246.22	0.6	-0.3	125.0	124.0	124.5	$\pi/4$	0.0
Outputs	m^2	b_2 [GeV^2]	b_1^r [GeV^2]	λ	δ_2	d_2	a_1^r [GeV^3]	a_1^i [GeV^3]
BP1	$-(124.5)^2$	$-(121.2)^2$	-2.572×10^{-12}	0.511	1.51	1.111	$-(18.735)^3$	$-(14.870)^3$

(i) Real c_t, c_e case

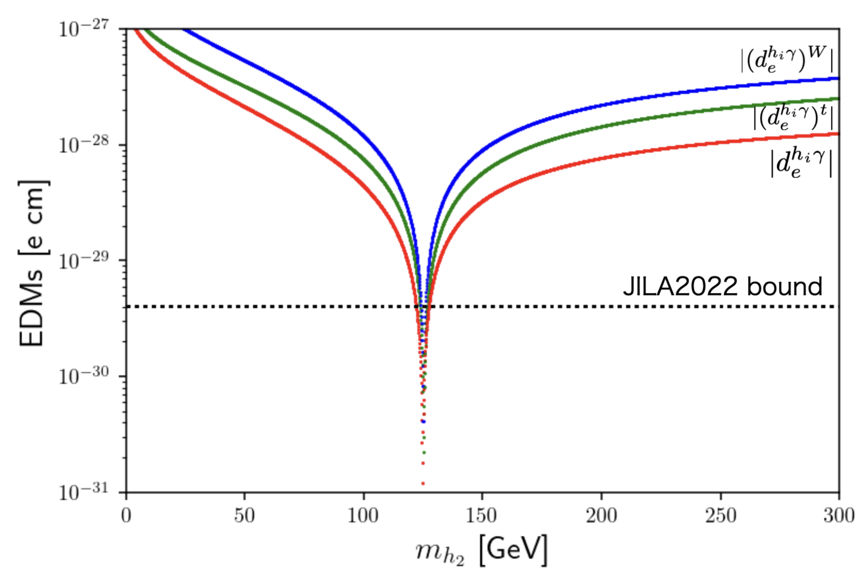
top-loop

$$(d_e^{h\gamma})_t/e = \frac{1}{3\pi^2}\left(\frac{\alpha_{\rm em}G_F v^2}{\sqrt{2}\pi m_t}\right)\sum_{i=1}^3\left\{\underbrace{\left(O_{3i}\frac{1}{2}\frac{c_e v}{\Lambda}\right)}_{{\rm Im}\left(Y_{eeh_i}\right)}\underbrace{\left(O_{1i}\frac{m_t}{v} + O_{2i}\frac{1}{2}\frac{c_t v}{\Lambda}\right)}_{{\rm Re}\left(Y_{tth_i}\right)}f\left(\frac{m_t^2}{m_{h_i}^2}\right) + \underbrace{\left(O_{1i}\frac{m_e}{v} + O_{2i}\frac{1}{2}\frac{c_e v}{\Lambda}\right)}_{{\rm Re}\left(Y_{eeh_i}\right)}\underbrace{\left(O_{3i}\frac{1}{2}\frac{c_t v}{\Lambda}\right)}_{{\rm Im}\left(Y_{tth_i}\right)}g\left(\frac{m_t^2}{m_{h_i}^2}\right)\right\}$$

$$\overset{\rm degenerate}{=} 0 \quad \because O_{1i}O_{3i} = O_{2i}O_{3i} = 0$$

W-loop

$$(d_e^{h\gamma})_W/e = -\frac{\alpha_{\rm em}}{32\pi^3 v}\sum_{i=1}^3\left\{O_{1i}\underbrace{O_{3i}\frac{c_e v}{2\Lambda}}_{{\rm Im}\left(Y_{eeh_i}\right)}\right\}\mathcal{J}_W^\gamma\left(m_{h_i}\right)\overset{\rm degenerate}{=} 0 \quad \because O_{1i}O_{3i} = 0$$



depending on the degree of degeneracy, cancellation of the top-loop and W-loop contributions may be necessary.

$\Lambda = 1000$ [GeV]　$\eta_B = 1.16\times 10^{-10}$

$\Lambda = 1500$ [GeV]　$\eta_B = 7.97\times 10^{-11}$

$\Lambda = 2000$ [GeV]　$\eta_B = 6.06\times 10^{-11}$

sufficiently BAU!

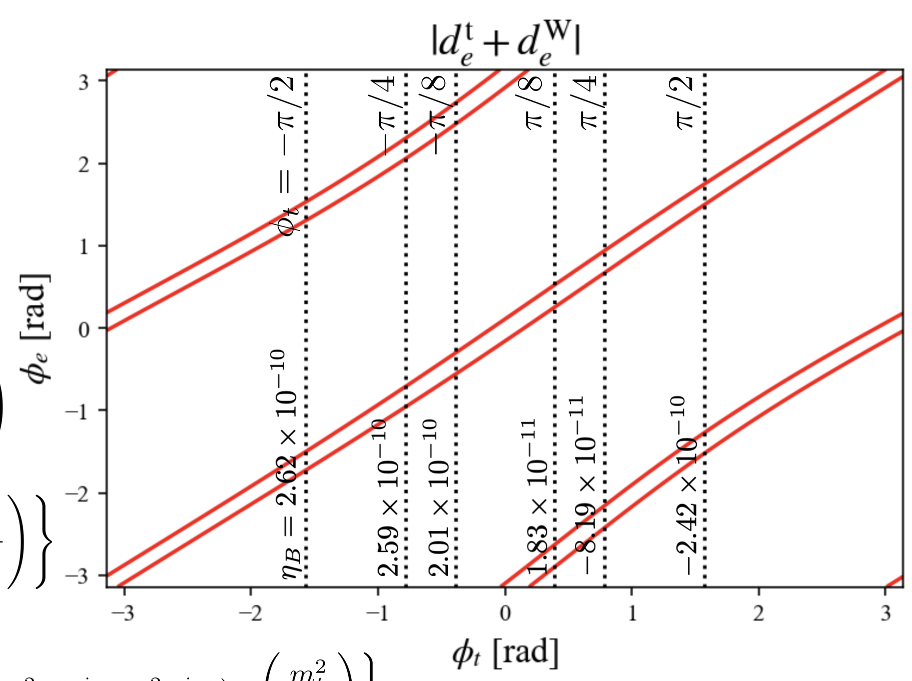
(ii) complex c_t, c_e case

$$c_t = c_t^r + i c_t^i = |c_t|\,e^{i\phi_t},\ c_e = c_e^r + i c_e^i = |c_e|\,e^{i\phi_e}$$

top-loop

$$\left(d_e^{h\gamma}\right)_t/e = \frac{1}{3\pi^2}\left(\frac{\alpha_{\rm em}G_F v^2}{\sqrt{2}\pi m_t}\right)\sum_{i=1}^3\left\{\underbrace{\left(O_{2i}\frac{1}{2}\frac{c_e^i v}{\Lambda} + O_{3i}\frac{1}{2}\frac{c_e^r v}{\Lambda}\right)}_{{\rm Im}\left(Y_{eeh_i}\right)}\underbrace{\left(O_{1i}\frac{m_t}{v} + O_{2i}\frac{1}{2}\frac{c_t^i v}{\Lambda} - O_{3i}\frac{1}{2}\frac{c_t^r v}{\Lambda}\right)}_{{\rm Re}\left(Y_{tth_i}\right)}f\left(\frac{m_t^2}{m_{h_i}^2}\right)\right.$$
$$\left. + \underbrace{\left(O_{1i}\frac{m_e}{v} + O_{2i}\frac{1}{2}\frac{c_e^r v}{\Lambda} - O_{3i}\frac{1}{2}\frac{c_e^i v}{\Lambda}\right)}_{{\rm Re}\left(Y_{eeh_i}\right)}\underbrace{\left(O_{2i}\frac{1}{2}\frac{c_t^i v}{\Lambda} + O_{3i}\frac{1}{2}\frac{c_t^r v}{\Lambda}\right)}_{{\rm Im}\left(Y_{tth_i}\right)}g\left(\frac{m_t^2}{m_{h_i}^2}\right)\right\}$$

$$\overset{\rm degenerate}{\simeq}\frac{1}{3\pi^2}\left(\frac{\alpha_{\rm em}G_F v^2}{\sqrt{2}\pi m_t}\right)\sum_{i=1}^3\frac{v^2}{4\Lambda^2}\left\{\left(O_{2i}^2 c_e^i c_t^r - O_{3i}^2 c_e^r c_t^i\right)f\left(\frac{m_t^2}{m_{h_i}^2}\right) + \left(O_{2i}^2 c_e^r c_t^i - O_{3i}^2 c_e^i c_t^r\right)g\left(\frac{m_t^2}{m_{h_i}^2}\right)\right\}$$



To suppress d_t/e $\dfrac{c_e^i}{c_e^r} = \dfrac{c_t^i}{c_t^r} \Longleftrightarrow \phi_t = \phi_e$ is needed

W-loop

$$(d_e^{h\gamma})_W/e = -\frac{\alpha_{\rm em}}{32\pi^3 v}\sum_{i=1}^3\left\{O_{1i}\underbrace{\left(O_{2i}\frac{c_e^i v}{2\Lambda} + O_{3i}\frac{c_e^r v}{2\Lambda}\right)}_{{\rm Im}\left(Y_{eeh_i}\right)}\right\}\mathcal{J}_W^\gamma\left(m_{h_i}\right)\overset{\rm degenerate}{=} 0$$

6. Conclusion

EDM

	top-loop Barr-Zee diagram	W-loop Barr-Zee diagram
Real $c_t,\ c_e$	Higgs mass degeneracy	Higgs mass degeneracy
Complex $c_t,\ c_e$	Higgs mass degeneracy and $\phi_t = \phi_e$	Higgs mass degeneracy

BAU　Singlet CPV alone is sufficient to explain the BAU.