Baryogenesis in the extended Standard Model with a Complex Singlet and Iso-Doublet Vector Quarks

Neda Darvishi

In collaboration with Prof. Maria Krawczyk

Department of Physics, University of Warsaw
Warsaw, Poland

24^{th} June
PLANCK 2017, Warsaw

Outline

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- The Model
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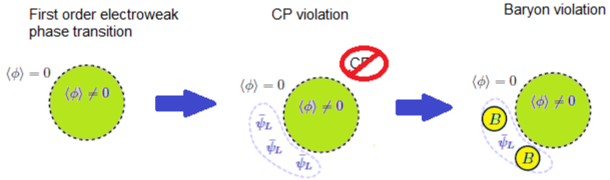
A Universe of matter

The observations from WMAP experiment:

$$\frac{\eta}{7.04} = \frac{n_B - n_{\bar{B}}}{s} \approx \frac{n_B}{s} = 8.7 \pm 0.3 \times 10^{-11}$$

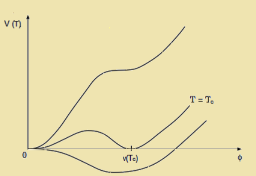
Sakharov conditions:

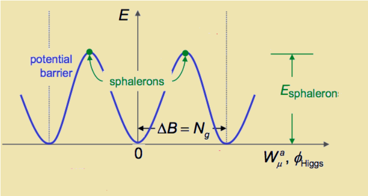
- Baryon number violation
- C and CP violation
- Departure from thermal equilibrium



Baryogenesis at the electroweak phase transitions

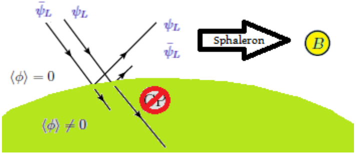
- Baryon-number can be generated during the first order EW phase transition





- Sphaleron rate at high temperature $(T > T_{EW})$, $\Gamma_{sph} = K(\alpha_W T)^4$
- Baryon violation- reactions must be strongly suppressed in $T < T_{EW} \sim 100GeV$, $\Gamma_{sph} = K(\alpha_W T)^4 exp(\frac{-E_{sph}}{T})$
- The out of thermal equilibrium $\rightarrow$ strong enough first order phase transition
- Strong enough first order $\rightarrow$ $\frac{E_{sph}(T_c)}{T_c} \geq 46$ or $\frac{v(T_c)}{T_c} \geq 1$
- SM problem: $\frac{v(T_c)}{T_c} \geq 1$ requires $m_{Higgs} < 72GeV$ while $m_{Higgs} \simeq 125GeV$

- Baryon generation dominated over the conjugate process through CP-violation.



- In the SM the amount of CP violation $\rightarrow$ J_{CP} invariant from CKM matrix
- The magnitude of the baryon asymmetry of the Universe in SM related to J_{CP}.

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx \frac{n_B}{n_\gamma} \sim \frac{\prod_u^{i>j}(m^i - m^j)\prod_d^{i>j}(m^i - m^j)J_{CP}}{T_{EW}^{12}}$$

- $J_{CP} \sim O(10^{-5})$
- SM problem: This gives a baryon asymmetry $O(10^{-17})$ much much below than the observed value of $O(10^{-11})$.

- The CP violation of SM is insufficient to explain the baryon asymmetry in the universe.
- Additional sources of CP-violation is needed.
  - Explicit : like in the SM, CP is not the symmetry of the original Lagrangian.
  - Spontaneous : via VEV
    - CP is the symmetry of the original Lagrangian
    - CP is not the symmetry of the vacuum
- Extension of the SM with a complex singlet and complex VEV $\rightarrow$ spontaneous CP violation.
- We will consider an extension of the SM with a complex singlet scalar field and Iso-doublet Vector quark (cSMCS).

The Model

- The model contains SM-like doublet Φ and a complex singlet χ and Iso-doublet vector quark
- Lagrangian

$$\mathcal{L} = \mathcal{L}_{gf}^{SM} + \mathcal{L}_Y(\psi_f, \Phi) + \mathcal{L}_Y(V_q, \chi) + \mathcal{L}_{scalar}, \quad \mathcal{L}_{scalar} = T - V$$

  - $\mathcal{L}_{gf}^{SM} \quad \rightarrow \quad$ gauge boson-fermion interaction as in the SM.
  - $\mathcal{L}_Y(\psi_f, \Phi) \quad \rightarrow \quad$ interaction of Φ to SM fermions.
  - $\mathcal{L}_Y(V_q, \chi) = \lambda_v \chi \bar{Q}_L V_R + M \bar{V}_L V_R + h.c.$
    - Iso-doublet vector quarks $\rightarrow V_L + V_R$
    - Have the same transformation as Q_L under the SM gauge group.

The scalar fields

$$\Phi = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}(\phi_1 + i\phi_4) \end{pmatrix}, \qquad \chi = \frac{1}{\sqrt{2}}(\phi_2 + i\phi_3).$$

$$\langle \Phi \rangle = \frac{1}{\sqrt{2}} v \quad \text{and} \quad \langle \chi \rangle = \frac{1}{\sqrt{2}} w e^{i\xi}$$

Potential

$$V = V_\Phi + V_\chi + V_{\Phi\chi}$$

- SM term

$$V_\Phi = -\frac{1}{2} m_{11}^2 \Phi^\dagger \Phi + \frac{1}{2} \lambda \left(\Phi^\dagger \Phi \right)^2 .$$

- Singlet term

$$V_S = -\frac{m_s^2}{2} \chi^* \chi - \frac{m_4^2}{2} (\chi^{*2} + \chi^2)$$

$$+\lambda_{s1} (\chi^* \chi)^2 + \lambda_{s2} (\chi^* \chi)(\chi^{*2} + \chi^2) + \lambda_{s3} (\chi^4 + \chi^{*4})$$

$$+\kappa_1 (\chi + \chi^*) + \kappa_2 (\chi^3 + \chi^{*3}) + \kappa_3 (\chi (\chi^* \chi) + \chi^* (\chi^* \chi)).$$

- Singlet and Doublet interaction

$$V_{\Phi\chi} = \Lambda_1 (\Phi^\dagger \Phi)(\chi^* \chi) + \Lambda_2 (\Phi^\dagger \Phi)(\chi^{*2} + \chi^2)$$

$$+\kappa_4 (\Phi^\dagger \Phi)(\chi + \chi^*).$$

Constrained Potential

To simplify the model we use U(1) symmetry

$$U(1): \quad \Phi \to \Phi,\, \chi \to e^{i\alpha}\chi.$$

$<\chi>$ spontaneous breaking symmetry $\to$ To avoid having massless Nambu-Goldstone scalar keep $U(1)$-soft-breaking terms

1. $U(1)$-symmetric terms: $m_{11}^2, m_s^2, \lambda, \lambda_{s1} \to \lambda_s, \Lambda_1 \to \Lambda$
2. $U(1)$-soft-breaking terms: $m_4^2, \kappa_{2,3}, \kappa_4$
3. $U(1)$-hard-breaking terms: $\lambda_{s2}, \lambda_{s3}, \Lambda_2$

$$V = -\frac{1}{2}m_{11}^2\Phi^\dagger\Phi + \frac{1}{2}\lambda\left(\Phi^\dagger\Phi\right)^2 - \frac{m_s^2}{2}\chi^*\chi + \lambda_s(\chi^*\chi)^2 + \Lambda(\Phi^\dagger\Phi)(\chi^*\chi)$$

$$-\frac{m_4^2}{2}(\chi^{*2} + \chi^2) + \kappa_2(\chi^3 + \chi^{*3}) + \kappa_3[\chi(\chi^*\chi) + \chi^*(\chi^*\chi)] + \kappa_4\Phi^\dagger\Phi(\chi + \chi)$$

Constrained Potential

$$V = -\frac{1}{2}m_{11}^2\Phi^\dagger\Phi + \frac{1}{2}\lambda\left(\Phi^\dagger\Phi\right)^2 - \frac{m_s^2}{2}\chi^*\chi + \lambda_s(\chi^*\chi)^2 + \Lambda(\Phi^\dagger\Phi)(\chi^*\chi)$$

$$-\frac{m_4^2}{2}(\chi^{*2} + \chi^2) + \kappa_2(\chi^3 + \chi^{*3}) + \kappa_3[\chi(\chi^*\chi) + \chi^*(\chi^*\chi)] + \kappa_4\Phi^\dagger\Phi(\chi + \chi)$$

- Parameters $\rightarrow$ $m_{11}^2,\ m_s^2,\ m_4^2,\ \lambda_s,\ \lambda,\ \Lambda,\ \kappa_2,\ \kappa_3,\ \kappa_4.$
  If real $\rightarrow$ No explicit CP violation
- Vacua with spontaneous CP violation
  $\langle\Phi\rangle = \frac{1}{\sqrt{2}}v$ and $\langle\chi\rangle = \frac{1}{\sqrt{2}}we^{i\xi} = \frac{1}{\sqrt{2}}(w_1 + iw_2)$
- Spontaneous CP violation $\rightarrow$ relevant parameters $m_4^2,\ \kappa_2,\ \kappa_3,\ \kappa_4$
- Positivity conditions

$$\lambda > 0, \qquad \lambda_s > 0, \qquad \Lambda + \sqrt{2\lambda\lambda_s} > 0.$$

Mass matrix

The mass matrix that describes the singlet-doublet mixing, in the basis of natural fields ϕ_1, ϕ_2, ϕ_3:

$$M = \begin{pmatrix} M_{11} & M_{12} & M_{13} \\ M_{21} & M_{22} & M_{23} \\ M_{31} & M_{32} & M_{33} \end{pmatrix}$$

- The mass elements for mass matrix

$$\begin{aligned}
M_{11} &= v^2\lambda, \\
M_{12} &= v(w_1\Lambda + \sqrt{2}\kappa_4), \\
M_{13} &= v w_2 \Lambda, \\
M_{22} &= \frac{w^2}{\sqrt{2}w_1}\Big(3\kappa_2 + \kappa_3(1 + 2(w_1^2 - w_2^2)/w^2) \\
&\quad -\kappa_4 v^2/w^2\Big) + 2w_1^2\lambda_s, \\
M_{23} &= w_2(2w_1\lambda_s + \sqrt{2}(-3\kappa_2 + \kappa_3)), \\
M_{33} &= 2w_2^2\lambda_s.
\end{aligned}$$

Mass eigenstate

- Diagonalization of M^2_{mix} gives the physical mass

$$RM^2_{mix}R^T = diag(M^2_{h_1}, M^2_{h_2}, M^2_{h_3})$$

- The rotation matrix R :

$$R = \begin{pmatrix} c_1c_2 & c_3s_1 - c_1s_2s_3 & c_1c_3s_2 + s_1s_3 \\ -c_2s_1 & c_1c_3 + s_1s_2s_3 & -c_3s_1s_2 + c_1s_3 \\ -s_2 & -c_2s_3 & c_2c_3 \end{pmatrix}$$

  R depends on the mixing of α_1, α_2 and α_3 angles vary over an interval of length π, $c_i = \cos\alpha_i, s_i = \sin\alpha_i$

- Physical higgs masses

$$M^2_{h_1} \simeq v^2\lambda \qquad \rightarrow \text{The SM-like Higgs boson mass, 125 GeV}$$

$$M^2_{h_{2,3}} = \frac{1}{2}(M_{22} + M_{33} \mp \sqrt{(M_{22} + M_{33})^2 + 4M^2_{23}})$$

$$m_{h_3} \gtrsim m_{h_2} > 150\,\text{GeV}.$$

Extremum conditions

From the potential we extract three extremum conditions:

1.
$$-m_{11}^2 + v^2\lambda + 2\sqrt{2}w_1\kappa_4 + \Lambda w^2 = 0,$$

2.
$$w_1(-\mu_1^2 + v^2\Lambda + 2w^2\lambda_s) + \sqrt{2}[3(w_1^2 - w_2^2)\kappa_2 + (3w_1^2 + w_2^2)\kappa_3] + v^2\sqrt{2}\kappa_4 = 0,$$

3.
$$w_2[-\mu_2^2 + v^2\Lambda + 2w^2\lambda_s + 2\sqrt{2}w_1(-3\kappa_2 + \kappa_3)] = 0,$$

When $w_1, w_2 \neq 0$ (i.e. CP violating vacuum) $\rightarrow$

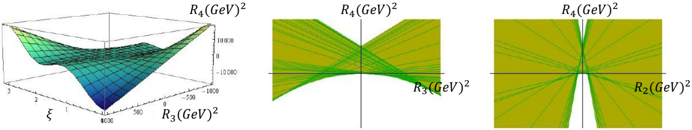
$$\underbrace{-8m_4^2\cos^2\xi + 6R_2\cos\xi(1 + 2\cos 2\xi) + 2R_3\cos\xi + R_4 = 0,}_{\text{CP-violation condition}}$$

The parameters (R_2, R_3, R_4) with dimension $[M]^2$ are:

$$R_2 = \sqrt{2}w\kappa_2,\ R_3 = \sqrt{2}w\kappa_3,\ R_4 = \frac{2\sqrt{2}v^2\kappa_4}{w}\cos\xi.$$

Region for possible CP violation

$$-8m_4^2\cos^2\xi + 6R_2\cos\xi(1+2\cos 2\xi) + 2R_3\cos\xi + R_4 = 0$$



(a) (b) (c)

Figure: (R_2, R_3, R_4, ξ), CP violation region for fix value of m_4^2

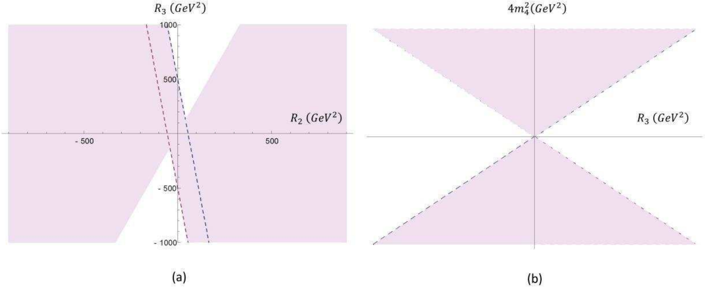
Region for possible CP violation

If $R_4 = 0 \to m_4^2, R_2, R_3, \xi$

$$-4m_4^2 \cos\xi + 3R_2(1 + 2\cos 2\xi) + R_3 = 0$$

If $R_4 = R_2 = 0 \to -4m_4^2 \cos\xi + R_3 = 0$

Figure: (R_2, R_3, ξ), CP violation region for fix value of m_4^2



Numerical Analysis

A numerical analysis of the parameters of the cSMCS model

- On the allowed regions for CP violation
- In accordance with the extremum conditions
- Under the positivity and the pertubativity conditions
- In accordance with mass constraints

$$m_{h_1} \sim 125\text{GeV}, \quad M_{h_3} \geq M_{h_2} > 150\text{GeV}$$

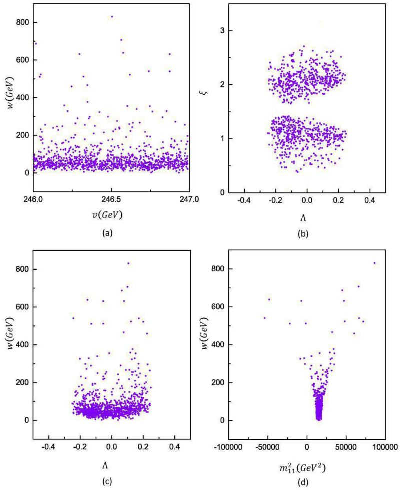
The relevant ranges of scanning:

$$-1 < \Lambda < 1, \quad 0 < \lambda_s < 1, \quad 0.2 < \lambda < 0.3, \quad 0 < \xi < \pi, \quad -1 < \rho_{2,3} < 1,$$

ρ's are dimensionless parameters of κ's

$$-90000\text{GeV}^2 < \mu_1^2,\ \mu_2^2 < 90000\text{GeV}^2,$$
$$\mu_1^2 = m_s^2 + 2m_4^2, \quad \mu_2^2 = m_s^2 - 2m_4^2.$$

Numerical Analysis



$$246\text{GeV} < v < 247\text{GeV}$$

Numerical Analysis

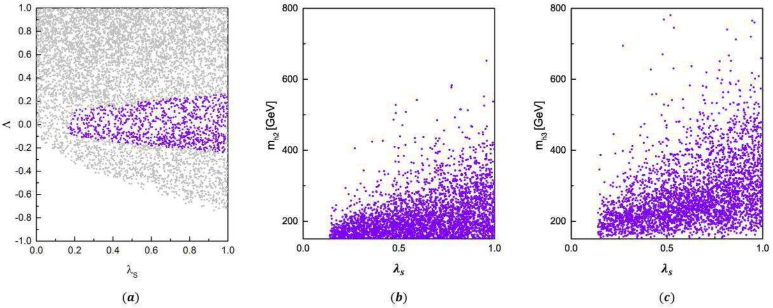


Figure: $-0.2 < \Lambda < 0.2$.

Numerical Analysis

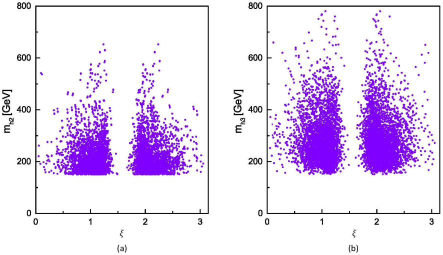


Figure: The correlation between masses M_{h_2} and M_{h_3} with ξ

$$M_{h_3} > M_{h_2} > 150$$

Numerical Analysis

B	α_1	α_2	α_3	M_{h_1}	M_{h_2}	M_{h_3}	S	T	$R^{h_1}_{\gamma\gamma}$
$A1$	-0.047	-0.053	1.294	124.64	652.375	759.984	-0.072	-0.094	0.98
$A2$	-0.048	0.084	0.084	124.26	512.511	712.407	-0.001	-0.039	0.98
$A3$	0.078	0.297	0.364	124.27	582.895	650.531	0.003	-0.046	0.98
$A4$	0.006	-0.276	0.188	125.86	466.439	568.059	-0.013	-0.169	0.92
$A5$	0.062	-0.436	0.808	125.21	303.545	582.496	0.002	-0.409	0.81
$A6$	-0.210	0.358	0.056	124.92	181.032	188.82	0.003	-0.010	0.82
$A7$	-0.205	0.403	0.057	125.01	175.45	178.52	0.002	-0.020	0.81

Table: Benchmark points $A1 - A7$. Masses are given in GeV and α are the mixing angles

These are in agreement with current data for S and T parameters,

$$S = 0.05 \pm 0.11, \quad T = 0.09 \pm 0.13,$$

and in agreement with $R_{\gamma\gamma}$ from ATLAS and CMS,

$$R_{\gamma\gamma} = 1.14^{+0.27}_{-0.25}(\text{ATLAS}) \quad \text{and } R_{\gamma\gamma} = 1.14^{+0.27}_{-0.25}(\text{CMS})$$

M. Krawczyk and ND,“CP violation in the Standard Model with a complex singlet”, arXiv:1603.00598

M.R. Masouminia and ND,“A phenomenological study on the production of Higgs bosons in the cSMCS model at the LHC," arXiv:1611.03312v1

The Electroweak Phase Transition

$$
\begin{aligned}
V(T_0) = \quad & -\frac{1}{2}m_{11}^2\Phi^\dagger\Phi + \frac{1}{2}\lambda_1\left(\Phi^\dagger\Phi\right)^2 - \frac{\mu_1^2}{4}\phi_2^2 \\
& -\frac{\mu_2^2}{4}\phi_3^2 + \frac{1}{2}\Lambda(\Phi^\dagger\Phi)(\phi_2^2+\phi_3^2) \\
& +\frac{1}{4}\lambda_s(\phi_2^2+\phi_3^2)^2 + \frac{1}{\sqrt{2}}\kappa_2(\phi_2^3 - 3\phi_2\phi_3^2) \\
& +\frac{1}{\sqrt{2}}\kappa_3(\phi_2^3+\phi_2\phi_3^2) + \sqrt{2}\kappa_4(\Phi^\dagger\Phi)\phi_2.
\end{aligned}
$$

The one-loop thermal corrections to the effective potential at finite temperature T

$$
\Delta V_{thermal} = \sum_i \frac{n_i T^4}{2\pi^2} I_{B,F}\left(\frac{m_i^2}{T^2}\right),
$$

with

$$
I_{B,F}(y) = \int_0^\infty dx\ x^2\ ln\left[1 \mp e^{-\sqrt{x^2+y}}\right].
$$

The potential at finite temperature T

$$V(v(T),T) = V(v_0) + \Delta V_{thermal}$$

The high temperature approximation

$$\begin{aligned} V(T) = \quad & \frac{1}{2}\overline{m}_{11}^2\Phi^\dagger\Phi + \frac{1}{2}\lambda(\Phi^\dagger\Phi) + \frac{\overline{\mu}_1^2}{4}\phi_2^2 + \frac{\overline{\mu}_2^2}{4}\phi_3^2 \\ & \frac{1}{2}\Lambda(\Phi^\dagger\Phi)(\phi_2^2+\phi_3^2) + \frac{1}{4}\lambda_s(\phi_2^2+\phi_3^2)^2 \\ & +\kappa_2\frac{1}{\sqrt{2}}(\phi_2^3 - 3\phi_2\phi_3^2) + \kappa_3\frac{1}{\sqrt{2}}(\phi_2^3+\phi_2\phi_3^2) \\ & +\sqrt{2}\kappa_4(\Phi^\dagger\Phi)\phi_2 + \overline{\kappa}_{34}\frac{T^2}{3}\phi_2, \end{aligned}$$

$$\begin{aligned} \overline{m}_{11}^2 &= -m_{11}^2 + (3\lambda \ + \Lambda + \frac{2m_W^2 + m_Z^2 + 2m_t^2}{2v^2})\frac{T^2}{3}, \\ \frac{1}{2}\overline{\mu}_1^2 &= -\frac{1}{2}\mu_1^2 + (\Lambda + 2\lambda_s)\frac{T^2}{3}, \\ \frac{1}{2}\overline{\mu}_2^2 &= -\frac{1}{2}\mu_2^2 + (\Lambda + 2\lambda_s)\frac{T^2}{3}, \\ \overline{\kappa}_{34} &= \sqrt{2}(\kappa_3+\kappa_4). \end{aligned}$$

Extermum conditions of the effective potential

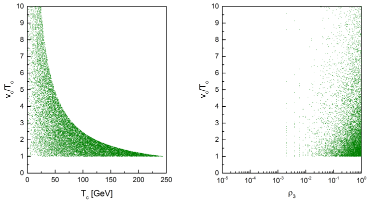
$$
\begin{aligned}
V(T) = \quad & \frac{1}{2}\overline{m}_{11}^2\Phi^\dagger\Phi + \frac{1}{2}\lambda(\Phi^\dagger\Phi) + \frac{\overline{\mu}_1^2}{4}\phi_2^2 + \frac{\overline{\mu}_2^2}{4}\phi_3^2 \\
& \frac{1}{2}\Lambda(\Phi^\dagger\Phi)(\phi_2^2+\phi_3^2) + \frac{1}{4}\lambda_s(\phi_2^2+\phi_3^2)^2 \\
& +\kappa_2\frac{1}{\sqrt{2}}(\phi_2^3 - 3\phi_2\phi_3^2) + \kappa_3\frac{1}{\sqrt{2}}(\phi_2^3+\phi_2\phi_3^2) \\
& +\sqrt{2}\kappa_4(\Phi^\dagger\Phi)\phi_2 + \overline{\kappa}_{34}\frac{T^2}{3}\phi_2,
\end{aligned}
$$

- $\overline{m}_{11}^2 + \lambda v^2 + \Lambda w^2 + 2\sqrt{2}\kappa_4 w_1 = 0,$
- $w_1(\overline{\mu}_1^2 + \Lambda v^2 + 2\lambda_s w^2) + \sqrt{2}\left[3\kappa_2(w_1^2 - w_2^2) + \kappa_3(3w_1^2 + w_2^2) + \kappa_4 v^2\right] + \frac{2}{3}\overline{\kappa}_{34}T^2 = 0,$
- $w_2[\overline{\mu}_2^2 + \Lambda v^2 + 2\lambda_s w^2 + 2\sqrt{2}(-3\kappa_2+\kappa_3)w_1] = 0.$

Numerical solution for strong enough first order EWPT

Conditions for strong enough first order EWPT:

- $V_{eff}(v(T_c), T_c) = V_{eff}(0, T_c)$
- $\frac{v(T_c)}{T_c} \geq 1$



(a) (b)

$$
\begin{gathered}
-0.2 < \Lambda < 0.2, \\
0.2 < \lambda_s < 1, \\
-1 < \rho_{2,3,4} < 1, \\
0 < \xi < \pi, \\
-90000\text{GeV}^2 < \mu_i^2 < 90000\text{GeV}^2, \\
M_{h_1}^2 \approx m_{11}^2 \approx \lambda v^2 (M_{h_1} \approx 125\text{GeV}), \\
0.2 < \lambda < 0.3.
\end{gathered}
$$

- This model provides a strong enough first order EWPT.

Baryon Generation

Baryon asymmetry resulting from a mixing of the SM quarks and heavy vector quarks at high temperature [McDonald 1995] (low temperature [Branco 1998])

- $\mathcal{L}_Y(V_q, \chi) = \lambda_v \chi \bar{Q_L} V_R + M \bar{V_L} V_R + h.c.$

$$\begin{aligned}
\begin{bmatrix} Q'_L \\ V'_L \end{bmatrix} &= \begin{bmatrix} a & b \\ -b^* & a^* \end{bmatrix} \begin{bmatrix} Q_L \\ V_L \end{bmatrix} \\
a &= \left[1 + \left(\frac{\lambda_v w}{M}\right)^2\right]^{-1/2} \\
b &= \left(\frac{\lambda_v w}{M}\right) \left[1 + \left(\frac{\lambda_v w}{M}\right)^2\right]^{-1/2} e^{-i\xi}
\end{aligned}$$

Diagonalizing the mass terms results in some non-diagonalized kinetic terms.

$$\overline{Q}_L i\gamma^\mu \partial_\mu Q_L + \overline{V}_L i\gamma^\mu \partial_\mu V_L \to \overline{Q'}_L i\gamma^\mu \partial_\mu Q'_L + \overline{V'}_L i\gamma^\mu \partial_\mu V'_L + \Delta\mathcal{L}_k + const$$

$$\Delta\mathcal{L}_k = -\frac{\lambda_V^2 w^2}{M^2} \dot{\xi} (\overline{Q'}_L \gamma^0 Q'_L - \overline{V'}_L \gamma^0 V'_L)$$

The phase of singlet should be time-dependent.

Baryon Generation

The amount of baryon asymmetry:

$$n_B = -N_f \int \frac{\Gamma_{sph}(T)}{2T} \mu_B dt$$

N_f is the number of flavors in the model
The sphaleron rate $\Gamma_{sph} \to \Gamma_{sph} = K(\alpha_W T)^4$ at high temperature

$$\mu_B = -\frac{5}{6} \frac{\lambda_V^2 w^2}{M^2} \dot{\xi}$$

$$s = \frac{2\pi^2}{45} g^* T^3$$

$g^* \sim 100$ the effective number of degrees of freedom
therefore,

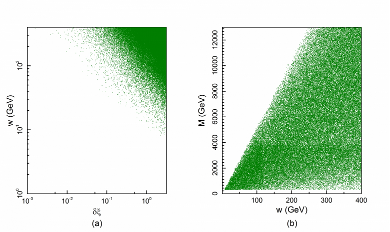
$$\frac{n_B}{s} = \frac{225 K \alpha_W^4}{4\pi^2 g^*} \frac{\lambda_V^2 w^2}{M^2} \delta\xi$$

The observations from WMAP $\to$ $\frac{n_B}{s} = 8.7 \pm 0.3 \times 10^{-11}$

Baryon Generation

$$\frac{n_B}{s} = \frac{225K\alpha_W^4}{4\pi^2 g^*}\frac{\lambda_V^2 w^2}{M^2}\delta\xi = 8.7 \pm 0.3 \times 10^{-11}$$

$$K\frac{\lambda_V^2 w^2}{M^2}\delta\xi = 1.14 \pm 0.3 \times 10^{-3}$$



$$0.3 \text{ TeV} < M < 13 \text{ TeV}$$

$$2\text{GeV} \; < w < 400 \text{ GeV}$$

$$0 < \lambda_V < 1$$

$$0 < \delta\xi < \pi$$

- This model provides an acceptable number for the generation of baryons in the Universe.

ND, "Baryogenesis of the Universe in cSMCS Model plus Iso-Doublet Vector Quark", arXiv:1608.02820

Summery and Conclusion

- This model contains a SU(2) doublet as in the SM and a complex singlet with a complex VEV and iso-doublet vector quark.
- This model provides a source of spontaneous CP violation.
- This model provides a strong first order phase transition and an acceptable number for the generation of baryons in the Universe.
- The analysis of this model was performed as a part of full analysis of the cIDMS (Inert Doublet Model plus Complex Singlet) which was confronted with LHC data for 125 GeV, precision data STU as well as astro data on dark matter. Bonilla, Sokolowska, Diaz-Cruz, Krawczyk and ND, "IDMS: Inert Dark Matter Model with a complex singlet," arXiv:1412.8730.