Extension of the Standard Model with a Doublet and a Complex Singlet and Heavy Vector Quarks

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Scalar 2017

In memory of

Professor Maria Krawczyk

Motivation

Baryogenesis

$$\frac{n_B}{s} = 8.7 \pm 0.3 \times 10^{-11}$$

Sakharov conditions:

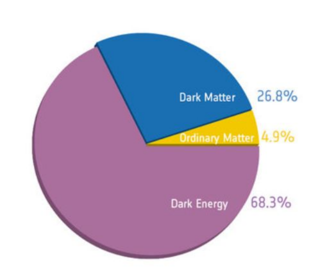
- Baryon number violation
- C and CP violation
- Departure from thermal equilibrium

• Baryogenesis at the electroweak phase transitions:

- CP violation in the Standard Model is insufficient to explain Baryogenesis.
- The out of thermal equilibrium would require $m_{Higgs} < 72GeV$ while $m_{Higgs} \simeq 125GeV$

Dark matter

• Dark matter is one of the main ingredients of our universe.



- Dark Matter should be neutral, stable, weakly interacting.
- There is no Dark Matter in the Standard Model.

The Model

- We consider a model that contains two doublet Φ_1(SM- like), Φ_2(with zero vev) and a complex singlet χ and heavy iso-doublet vector quark VQ

$$Z_2 \,\text{transformation} \;:\; \Phi_1 \to \Phi_1,\; \Phi_2 \to -\Phi_2,\; \chi \to \chi,$$
$$\text{VQ} \to \text{VQ}, \;\; \text{SM fields} \to \text{SM fields}.$$

- Lagrangian

$$\mathcal{L} = \mathcal{L}_{gf}^{SM} + \mathcal{L}_Y(\psi_f, \Phi_1) + \mathcal{L}_Y(V_q, \chi) + \mathcal{L}_{scalar}, \quad \mathcal{L}_{scalar} = T - V$$

  - $\mathcal{L}_{gf}^{SM} \;\to\;$ gauge boson-fermion interaction as in the SM.
  - $\mathcal{L}_Y(\psi_f, \Phi_1) \;\to\;$ interaction of Φ_1 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 $\to V_L + V_R$
    - Have the same transformation as Q_L under the SM gauge group.

The scalar fields

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(\phi_1 + i\phi_6) \end{pmatrix} \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(\phi_4 + i\phi_5) \end{pmatrix} \quad \chi = \frac{1}{\sqrt{2}}(\phi_2 + i\phi_3)$$

$$\langle\Phi_1\rangle = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}v \end{pmatrix} \quad \langle\Phi_2\rangle = \begin{pmatrix} 0 \\ 0 \end{pmatrix} \quad \langle\chi\rangle = \frac{1}{\sqrt{2}}we^{i\xi} = \frac{1}{\sqrt{2}}(w_1 + iw_2)$$

Potential

$$V = V_{IDM} + V_S + V_{DS}$$

- Doublet interaction

$$V_{IDM} = -\frac{1}{2}(m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2) + \frac{1}{2}(\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \lambda_2(\Phi_2^\dagger\Phi_2)^2)$$
$$+\lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}((\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2).$$

- Singlet term

$$V_S = -\frac{m_3^2}{2}\chi^*\chi - \frac{m_4^2}{2}(\chi^{*2} + \chi^2)$$
$$+\lambda_{s1}(\chi^*\chi)^2 + \lambda_{s2}(\chi^*\chi)(\chi^{*2} + \chi^2) + \lambda_{s3}(\chi^4 + \chi^{*4})$$
$$+\kappa_1(\chi + \chi^*) + \kappa_2(\chi^3 + \chi^{*3}) + \kappa_3(\chi(\chi^*\chi) + \chi^*(\chi^*\chi)).$$

- Singlet and Doublet interaction

$$V_{DS} = \Lambda_1(\Phi_1^\dagger\Phi_1)(\chi^*\chi) + \Lambda_2(\Phi_2^\dagger\Phi_2)(\chi^*\chi) + \Lambda_3(\Phi_1^\dagger\Phi_1)(\chi^{*2} + \chi^2)$$
$$+\Lambda_4(\Phi_2^\dagger\Phi_2)(\chi^{*2} + \chi^2) + \kappa_4(\Phi_1^\dagger\Phi_1)(\chi + \chi^*) + \kappa_5(\Phi_2^\dagger\Phi_2)(\chi + \chi^*).$$

Constrained Potential

To simplify the model we impose U(1) symmetry

$$U(1): \quad \Phi_1 \to \Phi_1,\ \Phi_2 \to \Phi_2,\ \chi \to e^{i\alpha}\chi$$

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

1. $U(1)$-symmetric terms: $m_{11}^2, m_{22}^2, m_3^2, \lambda_{1,2,3,4,5}, \lambda_{s1}, \Lambda_1,$
2. $U(1)$-soft-breaking terms: $m_4^2, \kappa_{2,3}, \kappa_4$
3. $U(1)$-hard-breaking terms: $\lambda_{s2}, \lambda_{s3}, \Lambda_{3,5} \quad \to \quad 0$

$$\begin{aligned}
V &= -\frac{1}{2}[m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2] + \frac{1}{2}\left[\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \lambda_2(\Phi_2^\dagger\Phi_2)^2\right] \\
&+ \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}\left[(\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2\right] \\
&- \frac{m_s^2}{2}\chi^*\chi + \lambda_{s1}(\chi^*\chi)^2 + \Lambda_1(\Phi_1^\dagger\Phi_1)(\chi^*\chi) \\
&- \frac{m_4^2}{2}(\chi^{*2} + \chi^2) + \kappa_2(\chi^3 + \chi^{*3}) + \kappa_3[\chi(\chi^*\chi) + \chi^*(\chi^*\chi)] + \kappa_4(\Phi_1^\dagger\Phi_1)(\chi + \chi^*).
\end{aligned}$$

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- Positivity conditions

$$\lambda_1, \lambda_2, \lambda_{s1} \geq 0,$$

$$\bar{\lambda}_{12} = \lambda_3 + \theta[-\lambda_4 + |\lambda_5|](\lambda_4 - |\lambda_5|) + \sqrt{\lambda_1\lambda_2} > 0,$$

$$\bar{\lambda}_{1S} = \Lambda_1 + \sqrt{2\lambda_1\lambda_{s1}} > 0, \;\; \bar{\lambda}_{2S} = \sqrt{2\lambda_2\lambda_{s1}} > 0,$$

$$\frac{1}{2}\sqrt{\lambda_1\lambda_2\lambda_{s1}} + [\lambda_3 + \theta[-\lambda_4 + |\lambda_5|](\lambda_4 - |\lambda_5|)]\sqrt{\lambda_{s1}} + \Lambda_1\sqrt{\lambda_2/2} + \sqrt{\bar{\lambda}_{12}\bar{\lambda}_{1S}\bar{\lambda}_{2S}} > 0.$$

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 $w_{1,2} \neq 0$ (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:

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

$$\mu_1^2 = m_s^2 + 2m_4^2, \quad \mu_2^2 = m_s^2 - 2m_4^2.$$

Region for possible CP violation

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

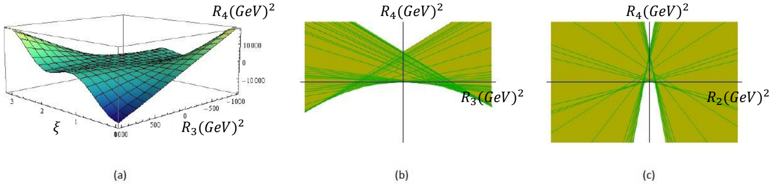


Figure: (R_2, R_3, R_4, ξ), CP violation region for $m_4^2 = 500\text{GeV}^2$

- N. Darvishi, "Baryogenesis of the Universe in cSMCS Model plus Iso-Doublet Vector Quark," arXiv:1608.02820, JHEP 1611 (2016) 065, DOI: 10.1007/JHEP11 (2016)065.

Mass eigenstate

•The mass of Higgs sector:

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

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

• The Mass of charged sector:

$$M_{H^\pm}^2 = \frac{1}{2}(-m_{22}^2 + v^2\lambda_3).$$

• The Mass of the inert sector (Z_2-odd sector):

$$M_H^2 = \frac{1}{2}(-m_{22}^2 + v^2\lambda_{345}), \quad \lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5$$

$$M_A^2 = \frac{1}{2}(-m_{22}^2 + v^2\lambda_{345}^-), \quad \lambda_{345}^- = \lambda_3 + \lambda_4 - \lambda_5,$$

The Electroweak Phase Transition

The one-loop thermal corrections to the effective potential at finite temperature T [Branco 1998]

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

with

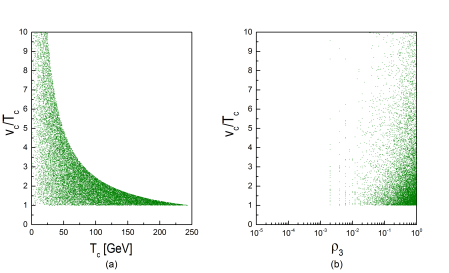
$$I_{B,F}(y) = \int_0^\infty dx\; x^2\; ln\left[1 \mp e^{-\sqrt{x^2+y}}\right].$$

The potential at finite temperature T:

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

Conditions for strong enough first order EWPT:

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



- This model provides a strong enough first order EWPT.

Baryon Generation

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

- $\mathcal{L}_Y(V_q,\chi) = \lambda_V \chi \bar{Q}_L V_R + M\bar{V}_L V_R + h.c.$

$$\begin{bmatrix} Q'_L \\ V'_L \end{bmatrix} = \begin{bmatrix} a & b \\ -b^* & a^* \end{bmatrix} \begin{bmatrix} Q_L \\ V_L \end{bmatrix}$$

$$a = \left[1 + \left(\frac{\lambda_V w}{M}\right)^2\right]^{-1/2}$$

$$b = \left(\frac{\lambda_V w}{M}\right)\left[1 + \left(\frac{\lambda_V w}{M}\right)^2\right]^{-1/2} e^{-i\xi}$$

When we diagonolize the mass matrix the kinetic terms give:

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

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

The phase of singlet vev should be time-dependent.

Baryon Generation

The baryon asymmetry [McDonald 1995]:

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

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,

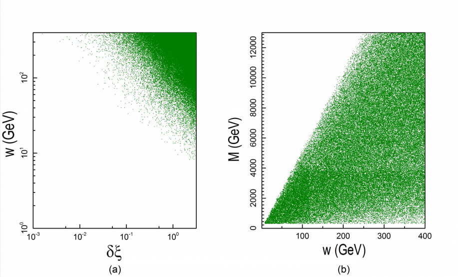
$$\frac{n_B}{s} = \frac{225 K \alpha_W^4}{4\pi^2 g^*} \frac{\lambda_V^2 w^2}{M^2} \delta\xi$$

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 value for baryon asymmetry $\frac{n_B}{s}$.

- N. Darvishi, "Baryogenesis of the Universe in cSMCS Model plus Iso-Doublet Vector Quark," arXiv:1608.02820, JHEP 1611 (2016) 065, DOI: 10.1007/JHEP11 (2016)065.
- N. Darvishi, "Extension of Standard Model with a Complex Singlet and Iso-Doublet Vector Quarks," Journal of Physics: Conference Series (IOP).

Experimental constraints

- **LEP bounds** No decay of $W^\pm$ or Z into inert particles

$$M_{H^\pm} + M_{H,A} > M_{W^\pm}, \quad M_H + M_A > M_Z, \quad 2M_{H^\pm} > M_Z$$

$$\text{excluded} : M_A - M_H > 8 \text{ GeV if } M_H < 80 \text{ GeV} \wedge M_A < 100 \text{ GeV}$$

- **Electroweak Precision Tests (EWPT)**

$$S_{exp} = 0.05 \pm 0.11, \quad T_{exp} = 0.09 \pm 0.13, \quad U_{exp} = 0.01 \pm 0.11.$$

- **LHC constraints**
  - Higgs mass: $M_{h_1} \sim 125$ GeV
  - Higgs signal strength:

$$\mathcal{R}_{XX} = \frac{\sigma(gg \to h_1)}{\sigma(gg \to \phi_{SM})} \frac{\text{BR}(h_1 \to XX)}{\text{BR}(\phi_{SM} \to XX)} \simeq \frac{\Gamma(h_1 \to gg)}{\Gamma(\phi_{SM} \to gg)} \frac{\text{BR}(h_1 \to XX)}{\text{BR}(\phi_{SM} \to XX)}.$$

$$\mathcal{R}_{\gamma\gamma} = 1.14^{+0.27}_{-0.25}(\text{ATLAS}) \; \mathcal{R}_{\gamma\gamma} = 1.11^{+0.25}_{-0.23}(\text{CMS})$$

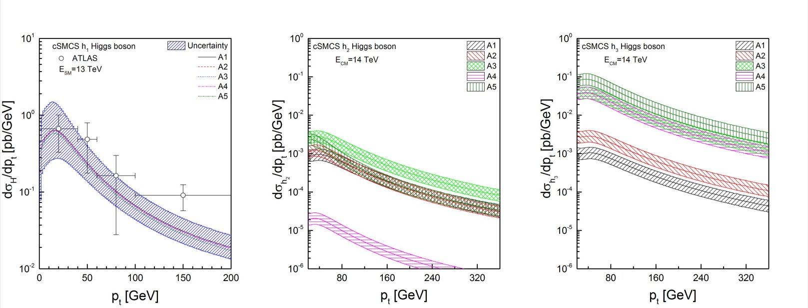
  - Invisible Higgs decays : $\Gamma(h_1 \to \varphi\varphi) \sim \lambda_{345}^2 (\varphi = A, H)$
    - LHC:$Br(h_1 \to inv) < 0.37 \to |\lambda_{345}| \lesssim 0.02$

- **DM constraints: Planck results on DM relic density**

Within 3σ bound: $0.1118 < \Omega_{DM} h^2 < 0.128$ $\quad \lambda_{345}^{min}, \lambda_{345}^{max}$

Benchmarks

B	M_{h_1}	M_{h_2}	M_{h_3}	S	T	$R^{h_1}_{\gamma\gamma}$
$A1$	124.64	652.375	759.984	-0.072	-0.094	0.98
$A2$	124.26	512.511	712.407	-0.001	-0.039	0.98
$A3$	124.27	582.895	650.531	0.003	-0.046	0.98
$A4$	125.86	466.439	568.059	-0.013	-0.169	0.92
$A5$	125.21	303.545	582.496	0.002	-0.409	0.81

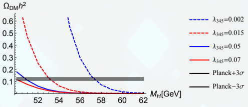


- Our results are in relative agreement with the experimental data within the uncertainty bounds.

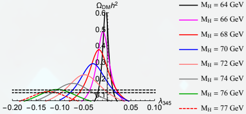
N. Darvishi, M.R. Masouminia, "A phenomenological study on the production of Higgs bosons in the cSMCS model at the LHC," arXiv:1611.03312v1, Nuclear Physics B 923 (2017) 491-507, DOI: 10.1016/j.nuclphysb.2017.08.013

Results for the DM

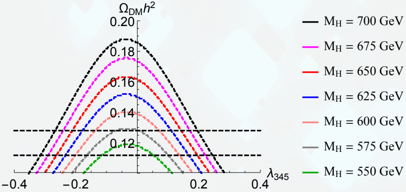
- **Low DM mass:** $53GeV < M_H < 62GeV$
- **Medium DM mass:** $62GeV < M_H < 80GeV$
  with $M_A = M_H + 50GeV, M_{H\pm} = M_H + 55GeV$
- **High DM mass:** $M_H \gtrsim 500GeV$ with $M_A = M_{H\pm} = M_H + 1GeV$



(a) Low DM mass



(b) Medium DM mass



(c) High DM mass

This model Provides good candidate for dark matter in agreement (within 3σ) with Planck limits $\Omega_{DM}h^2 = 0.1199 \pm 0.002$.

- C. Bonilla, D. Sokolowska, N. Darvishi, J.L. Diaz-Cruz, M. Krawczyk, "IDMS: Inert Dark Matter Model with a complex singlet," 2016, Journal of Physics G, Volume 43 Number 065001.

Summary and Conclusion

- The extension of SM with SU(2) doublet with zero vev and a complex singlet and heavy vector quark is considered.
- 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.
- This model Provides good candidate for dark matter in agreement (within 3σ) with Planck limits.

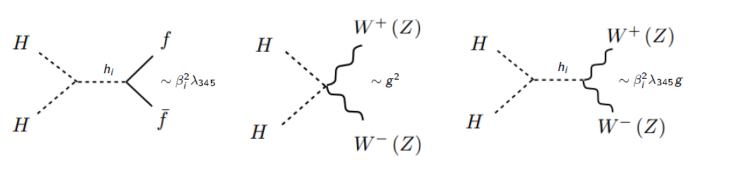
Back up

Relic density constraints

The relic density of DM From Planck data to be in agreement with

$$\Omega_{DM} h^2 = 0.1199 \pm 0.0027,$$

The important processes for the cIDMS are:



$$HH \to h_i \to f\bar{f}, \quad HH \to h_i \to WW(ZZ),$$
$$HH \to WW,$$
$$HA(H^\pm) \to Z(W^\pm) \to ff',$$

$$g_{h_i HH} = \beta_i \lambda_{345}, \quad g_{h_i f\bar{f}} = \beta_i g^{\mathrm{IDM}}_{hf\bar{f}},$$

$$\phi_1 = \beta_i h_i = r_{11} h_1 + r_{21} h_2 + r_{31} h_3$$

$$\sum_{i=1}^{3} g^2_{h_i HH} = (g^{\mathrm{IDM}}_{hHH})^2 = \lambda^2_{345}, \quad \sum_{i=1}^{3} g_{h_i f\bar{f}} = (g^{\mathrm{IDM}}_{hf\bar{f}})^2.$$

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- M. Krawczyk, N. Darvishi and D. Sokolowska, "The Inert Doublet Model and its extensions," Acta Phys. Polon. B 47 (2016) 183 doi:10.5506/APhysPolB.47.183, arXiv:1512.06437[hep-ph].