CP violation in 2HDM+singlet

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CP violating IDMS

Reference: The Inert Doublet Model and its extensions, M.Krawczyk, N.Darvishi, D. Sokolowska, 10.5506/*APhysPolB*.47.183

- IDMS is a Z_2 symmetric model containing a SM-like Higgs doublet Φ_1, inert doublet Φ_2
- Φ_2 has a vev 0 and is odd under a Z_2 symmetry
- Also a neutral complex singlet χ $(Y = 0, < \chi >= we^{i\epsilon})$

Φ_1 and χ obtain vaccuum expectation values and the field decomposition around the vaccuum $(v,\ 0,\ we^{i\epsilon})$ where $v, w, \epsilon \in \mathbf{R}$ is:

$$\Phi_1 = (\phi_1^\dagger \qquad \frac{1}{\sqrt{2}}(v + \phi_1 + i\phi_6))^T,$$
$$\Phi_2 = (\phi_2^\dagger \qquad \frac{1}{\sqrt{2}}(\phi_4 + i\phi_5))^T$$

$$\chi = \frac{1}{\sqrt{2}}(we^{i\epsilon} + \phi_2 + i\phi_3))$$

Scalar potential

$$V = -\frac{1}{2}\left[m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2\right] + \frac{1}{2}\left[\lambda_1\left(\Phi_1^\dagger\Phi_1\right)^2 + \lambda_2\left(\Phi_2^\dagger\Phi_2\right)^2\right]$$

$$+\lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \lambda_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right) + \frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger\Phi_2\right)^2 + \left(\Phi_2^\dagger\Phi_1\right)^2\right]($$

$$-\frac{m_3^2}{2}\chi^*\chi + \lambda_{s1}(\chi^*\chi)^2 + \Lambda_1(\Phi_1^\dagger\Phi_1)(\chi^*\chi)$$

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

- Three higgs sector particles h_1, h_2 and h_3 having CP-even and CP-odd parts.

$$h_1 = c_1 c_2 \phi_1 + (c_3 s_1 - c_1 s_2 s_3)\phi_2 + (c_1 c_3 s_2 + s_1 s_3)\phi_3,$$

- Couplings of h_1 modified by a factor of $R_{11} = c_1 c_2$
- Possible enhancement in $R_{\gamma\gamma}$, $R_{Z\gamma}$ and R_{ZZ}.

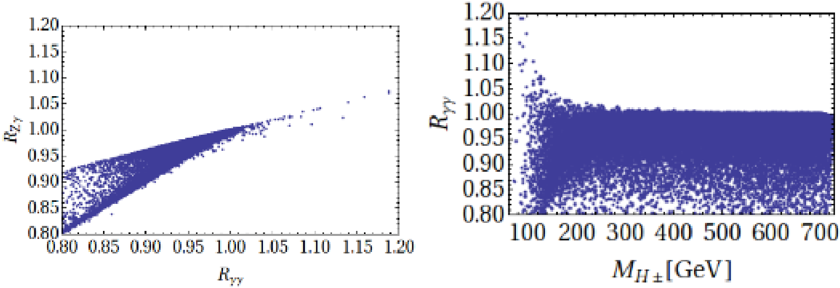


Figure: Correlation between $R_{\gamma\gamma}$ and $R_{Z\gamma}$ (left) and $M_{H^\pm}$ (right).

Dark matter phenomenology

- The inert sector consists of $H, A, H^{\pm}$ of which the lightest H is chosen to be the DM candidate.
- Two representative benchmarks:

$$\mathbf{A1}:\ M_{h_1} = 124.83\text{GeV},\ M_{h_2} = 194.46\text{GeV},\ M_{h_3} = 239.99\text{GeV},$$
$$\mathbf{A4}:\ M_{h_1} = 125.36\text{GeV},\ M_{h_2} = 149.89\text{GeV},\ M_{h_3} = 473.95\text{GeV}.$$

A4 has two lighter higgs states $< 2M_W$ leading to additional resonant annihilation channels.

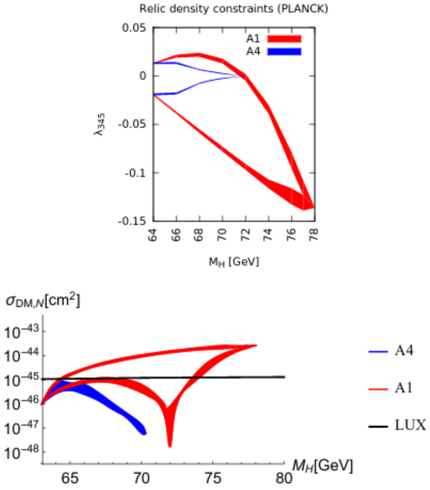


Figure: Relic density and direct detection cross-section plots for **A1** and **A2**.

SM+complex singlet

Scalar Potential V:

$$V = -\frac{1}{2}m_{11}^2\Phi_1^\dagger\Phi_1 + \frac{1}{2}\lambda_1\left(\Phi_1^\dagger\Phi_1\right)^2 - \frac{m_s^2}{2}\chi^*\chi + \lambda_{s1}(\chi^*\chi)^2 + \Lambda_1(\Phi_1^\dagger\Phi_1)(\chi^*\chi)$$

$$-\frac{m_4^2}{2}(\chi^{*2}+\chi^2) + \kappa_2(\chi^3+\chi^{*3}) + \kappa_3[\chi(\chi^*\chi)+\chi^*(\chi^*\chi)]. \qquad (14)$$

Positivity and extremum conditions:

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

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

where $R_2 = \sqrt{2}w^2\kappa_2$ and $R_3 = \sqrt{2}w^2\kappa_3$.

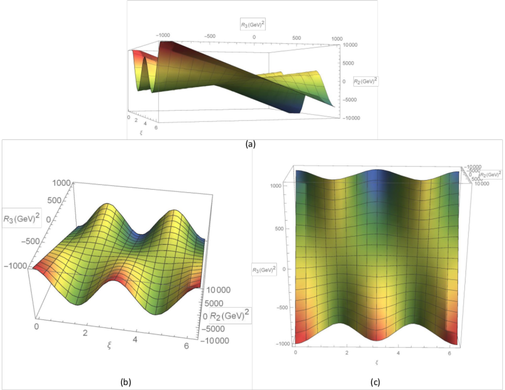


Figure: Regions depicting CP violation in SM+complex singlet model where $R_2 = \sqrt{2}w^2\kappa_2$ and $R_3 = \sqrt{2}w^2\kappa_3$.

CP violation due to non-zero phase of χ ($w \neq 0$) realised by quadratic and cubic parameters of V.

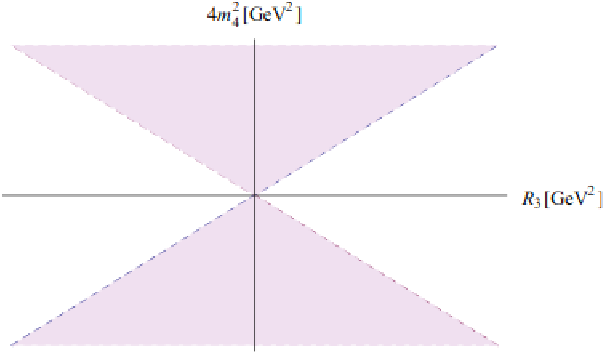


Figure: (R_3, m_4^2) for $R_2 = 0$, $\cos\epsilon \in$ (-1,1).

Baryogenesis

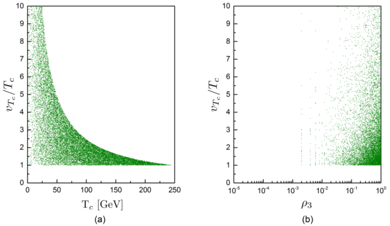


Figure 2.10: The allowed regions of critical temperature T_c, v_{T_c} and $|\rho_3|$ for strongly first-order phase transition. (a) (T_c,v_{T_c}/T_c) and (b) ($|\rho_3|$, v_{T_c}/T_c). The scatter points are selected to satisfy the criterion, $(v_{T_c}/T_c) \geq 1$ (see text for details).

Extension of the Standard Model with a Doublet and a complex singlet (Thesis: N.Darvishi)

Baryogenesis and 2HDM

Issues faced by this model:

- second order phase transition possible
- loop contributions may give rise to first order phase transitions but only a small fraction of the observed baryon asymmetry of the Universe (above the SM contributions)

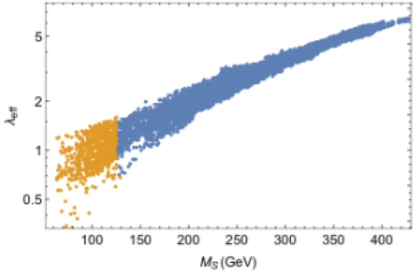
Baryogenesis and 2HDM+singlet(2HSDM)

Baryogenesis in the two doublet and inert singlet extension of the Standard Model, JCAP08 (2016) 057

Attractive features of the model:

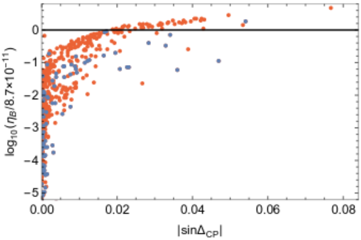
- Strongly first order phase transition
- gives rise to observed baryon asymmetry of the Universe
- Consistent with all experimental constraints
- Caveat: DM underabundant (0.001 of observed thermal relic density)
  Can look into multicomponent DM, candidate: a axions, gravitinos, axinos ?

Electroweak phase transitions



where λ_{eff} is the coupling of the higgs to a pair of DM particles and M_S is the mass of the DM candidate.

Baryon−to−entropy ratio (η_B) and electron dipole moments



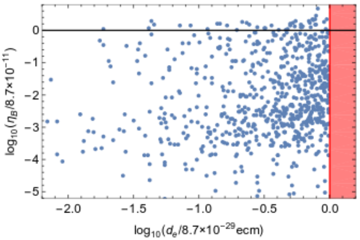


Figure: Correlation between the baryon-to-entropy (η_B) ratio and the mixing matrix element $\sin\Delta$ CP (left) and with electric dipole moment d_e (right). $\sin\Delta CP$ encodes the projection of the higgs to the second higgs doublet.

Summary and future directions

- The IDMS addresses the theoretical and experimental constraints satisfactorily, a detailed analyses of the baryogenesis aspect could be done in more detail.
- For the general 2HDM model, although baryogenesis is acheieved, DM underabundant!

  Axinos, Gravitinos as WDM could address part of the issue: Multicomponent DM

Other directions

A second Higgs doublet in the early universe:baryogenesis and gravitational waves G.C. Dorsch et al JCAP05(2017)052

Thank you!