Electroweak Baryogenesis and Dark Matter from a Complex Singlet

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Motivation

➢ In spite of the great success of the Standard Model (SM) of particle physics, there are still many puzzles needing to be explained. Among others, two important questions are

- Dark Matter : In the SM, there is no DM candidate.
- Matter-Antimatter Asymmetry in our Universe

➢ Both problems require the physics beyond the SM.

Motivation

- ➢ Observed Baryon Asymmetry: Planck Collaboration, arXiv: 1502.01589

$$\boxed{\eta_B \equiv \frac{n_B}{s} = (8.61 \pm 0.09) \times 10^{-11}}$$

- ➢ Three Sakharov criteria for baryogenesis:

A. D. Sakharov, 1967

- ✓ B violation
- ✓ C and CP violation
- ✓ Thermal non-equilibrium

- ➢ Situation in the SM:

F. R. Klinkhamer & N.S. Manton 1984

M. E. Shaposhnikov, 1987

- ✓ B violation: weak sphaleron process
- ✓ The CP violation due to CKM phase is inadequate
- ✓ EW phase transition is actually a cross-over, rather than being of strongly first-order.

K. Kajantie et al, hep-ph/9605288

Motivation

- EW Baryogenesis:

V. A. Kuzmin, V.A. Rubakov, M.E. Shaposhnikov, 1985;
A. G. Cohen, D. B. Kaplan and A. E. Nelson, 1990

✓ new CPV sources

✓ adding new particles with masses of EW scale in order to make the EWPT of strongly first-order, which provides the necessary deviation from an equilibrium.

- Problem: The new CPV source required by the baryogenesis is strongly constrained by the EDMs of electrons and neutrons.

ACME Collaoration, 1310.7534; PDG 2016;

- Possible solution: If the CP is spontaneously broken at high temperatures before the EWPT while restored afterward, then the CPV constraint can be evaded!

J. McDonald, 1994; W. Chao, 1706.01041

The Model

- Extend the SM by an EW singlet complex scalar

$$S = (s+ia)/\sqrt{2}.$$

with a Z_2 symmetry: $S \leftrightarrow -S$ and CP symmetry related to S

J. McDonald, 1994, 1995; G.C. Branco et al, 9805302; S. Profumo et al, 0705.2425; …

- The scalar potential at zero temperature:

$$\boxed{H = (0, h/\sqrt{2})^T}$$

$$\begin{aligned}
V_0(H,S) = {} & \lambda_H \left(|H|^2 - \frac{v_0^2}{2}\right)^2 - \mu_1^2 (S^* S)^2 - \frac{\mu_2^2}{2}(S^2 + S^{*2}) \\
& + \lambda_1 (S^* S)^2 + \frac{\lambda_2}{4}(S^2 + S^{*2})^2 + \frac{\lambda_3}{2}|S|^2 (S^2 + S^{*2}) \\
& + |H|^2 \left[\kappa_1 (S^* S) + \frac{\kappa_2}{2}(S^2 + S^{*2})\right] \\
= {} & -\frac{1}{2}\lambda_H v_0^2 h^2 + \frac{1}{4}\lambda_H h^4 - \frac{1}{2}(\mu_1^2 + \mu_2^2) s^2 - \frac{1}{2}(\mu_1^2 - \mu_2^2) a^2 \\
& + \frac{1}{4}(\lambda_1 + \lambda_2 + \lambda_3)\, s^4 + \frac{1}{4}(\lambda_1 + \lambda_2 - \lambda_3)\, a^4 \\
& + \frac{1}{4}(\kappa_1 + \kappa_2) h^2 s^2 + \frac{1}{4}(\kappa_1 - \kappa_2) h^2 a^2 + \frac{1}{2}(\lambda_1 - \lambda_2) s^2 a^2 + \text{const.}\,.
\end{aligned}$$

REAL couplings

The Model

- Leading-order finite-temperature corrections at high-T expansion

$$\boxed{V_T = \frac{1}{2}c_h T^2 h^2 + \frac{1}{2}c_s T^2 s^2 + \frac{1}{2}c_a T^2 a^2}$$

where

$$c_h = \frac{3g^2}{16} + \frac{g'^2}{16} + \frac{y_t^2}{4} + \frac{\lambda_H}{2} + \frac{\kappa_1}{12}$$
$$c_s = \frac{1}{6}(2\lambda_1 + \kappa_1 + \kappa_2) + \frac{\lambda_3}{4},$$
$$c_a = \frac{1}{6}(2\lambda_1 + \kappa_1 - \kappa_2) - \frac{\lambda_3}{4}.$$

- Total Potential:

$$V_{\rm tot} = V_0 + V_T$$

EW Phase Transition

- Rewrite the total scalar potential $\boxed{\langle S\rangle = w_c e^{i\alpha}/\sqrt{2}}$

$$V_{\rm tot} = \frac{\lambda_{hs}}{4}\left(h^2 - v_c^2 + \frac{v_c^2 s^2}{w_c^2\cos^2\alpha}\right)^2 + \frac{\lambda_{ha}}{4}\left(h^2 - v_c^2 + \frac{v_c^2 a^2}{w_c^2\sin^2\alpha}\right)^2$$
$$+\frac{\lambda_{sa}}{4}\left(s^2\sin^2\alpha - a^2\cos^2\alpha\right)^2 + \frac{\kappa_{hs}}{4}h^2 s^2 + \frac{\kappa_{ha}}{4}h^2 a^2$$
$$+\frac{1}{2}(T^2 - T_c^2)[c_h h^2 + c_s s^2 + c_a a^2]$$

- Two vacua: (h, s, a) = (v_c, 0, 0) and (0, w_c cosα, w_c sinα)

- Critical Temperature:

$$\boxed{T_c^2 = \lambda_H(v_0^2 - v_c^2)/c_h}$$

EW Phase Transition

- ➢ Further Consistency Constraints:

✓ Strongly First-Order EWPT:

$$\boxed{v_c/T_c > 1}$$

G. D. Moore, hep-ph/9805264

✓Potential Stability: assume positive couplings

✓ Correct EWPT direction from (0, w_c cosα, w_c sinα) to (v_c, 0, 0)

$$c_h v_c^2 > c_s w_c^2 \cos^2\alpha + c_a w_c^2 \sin^2\alpha$$

✓ Z_2 symmetry: $\alpha \in (-\pi/2, \pi/2)$

✓Perturbativity: $|\lambda_{1,2,3}, \kappa_{1,2}| \leqslant 5$ M. Nebot et al, 0711.0483

Dark Matter Physics

- Depending the mass ordering, either s or a can be DM candidate X

- The DM pheno. only depends on Higgs portal coupling

$$\boxed{\lambda_{hX} h^2 X^2/4}$$

J. M. Cline & K. Kainulainen, 1210.4196

with

$$\lambda_{hX} = \begin{cases} \kappa_{hs} + \dfrac{2\lambda_{hs} v_c^2}{w_c^2 \cos^2\alpha}, & X = s \\ \kappa_{ha} + \dfrac{2\lambda_{ha} v_c^2}{w_c^2 \sin^2\alpha}, & X = a \end{cases}$$

- The DM relic density is obtained by the freeze-out mechanism, and is calculated with MicrOMEGAs code.
- In order to consider the case with subdominant DM, we define the DM fraction: $f_X = \dfrac{\Omega_X h^2}{\Omega_{\rm DM,obs} h^2}$ with $\Omega_{\rm DM,obs} h^2 = 0.1186$

Dark Matter Physics

➢ DM Constraints:

- ✓ DM direct detection: XENON1T
- ✓ DM Indirect detection: Fermi-LAT, Planck, and AMS-02
- ✓ SM Higgs Invisible Decay: $\mathrm{Br}(h \to XX) \leqslant 0.24$ PDG 2016
- ✓ Monojet searches: CMS

High-T CP Violation

- Introduction of the following dim-6 operaor

$$\boxed{\mathcal{O}_6 = \frac{S^2}{\Lambda^2}\bar{Q}_{3L}\tilde{H}t_R + \mathrm{H.c.}}$$

J. R. Espinosa et al., 1110.2876;
J.M. Cline & K. Kainulainen, 1210.4196;
V. Vaskonen, 1611.02073

- When S acquires a complex VEV at high T

$$\langle S\rangle = w_c e^{i\alpha}/\sqrt{2}$$

- Together with top Yukawa, we have a complex top-quark mass

$$m_t(z) = \frac{y_t}{\sqrt{2}}h(z)\left(1 + \frac{S(z)^2}{y_t\Lambda^2}\right) \equiv |m_t(z)|e^{i\theta(z)}$$

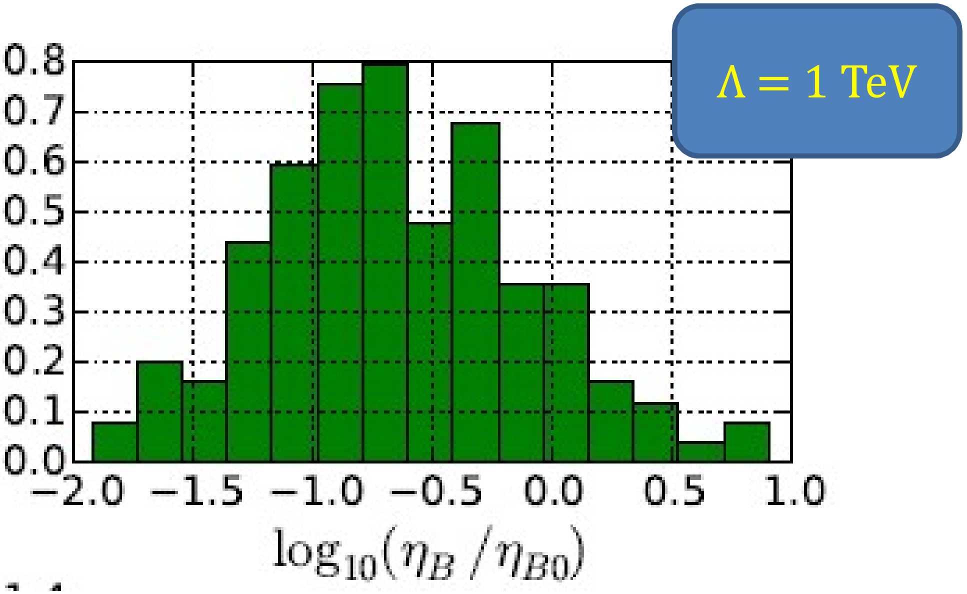
- This top mass would generate CPV force that acts on tops and anti-tops differently when they pass through the wall.

$$\boxed{F_z = -\frac{(m^2)'}{2E_0} \pm s\frac{(m^2\theta')'}{2E_0E_{0z}} \mp s\frac{\theta' m^2(m^2)'}{4E_0^3E_{0z}}}$$

L. Fromme & S.J. Huber, hep-ph/0604159

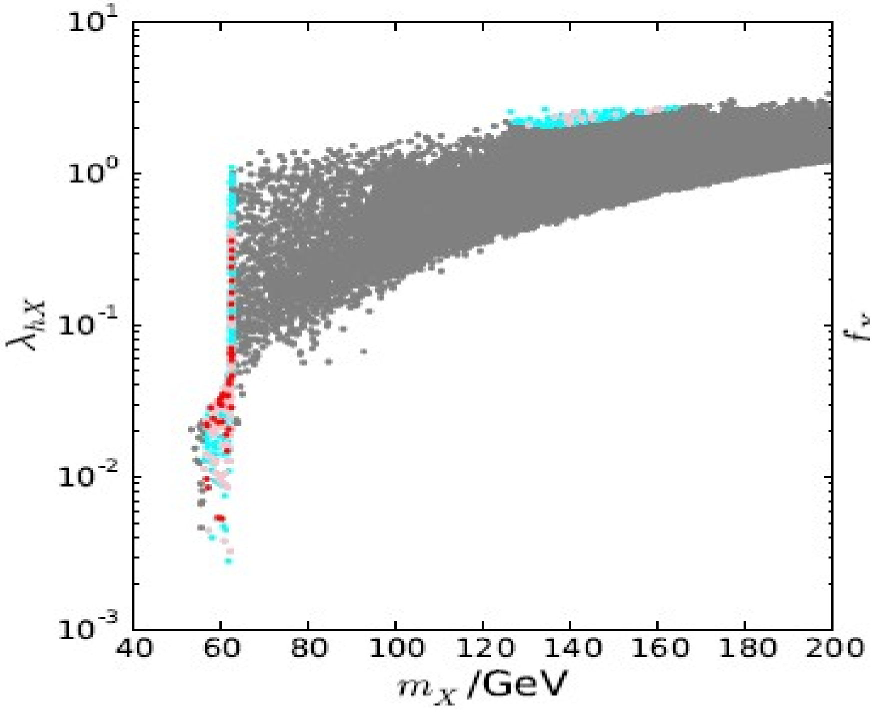
First-Order EWPT

- The CP violation created around the bubble wall would transport to the EW symmetric phase deeply, where it biases the EW sphaleron processes to generate baryon asymmetry.



Scanning Results

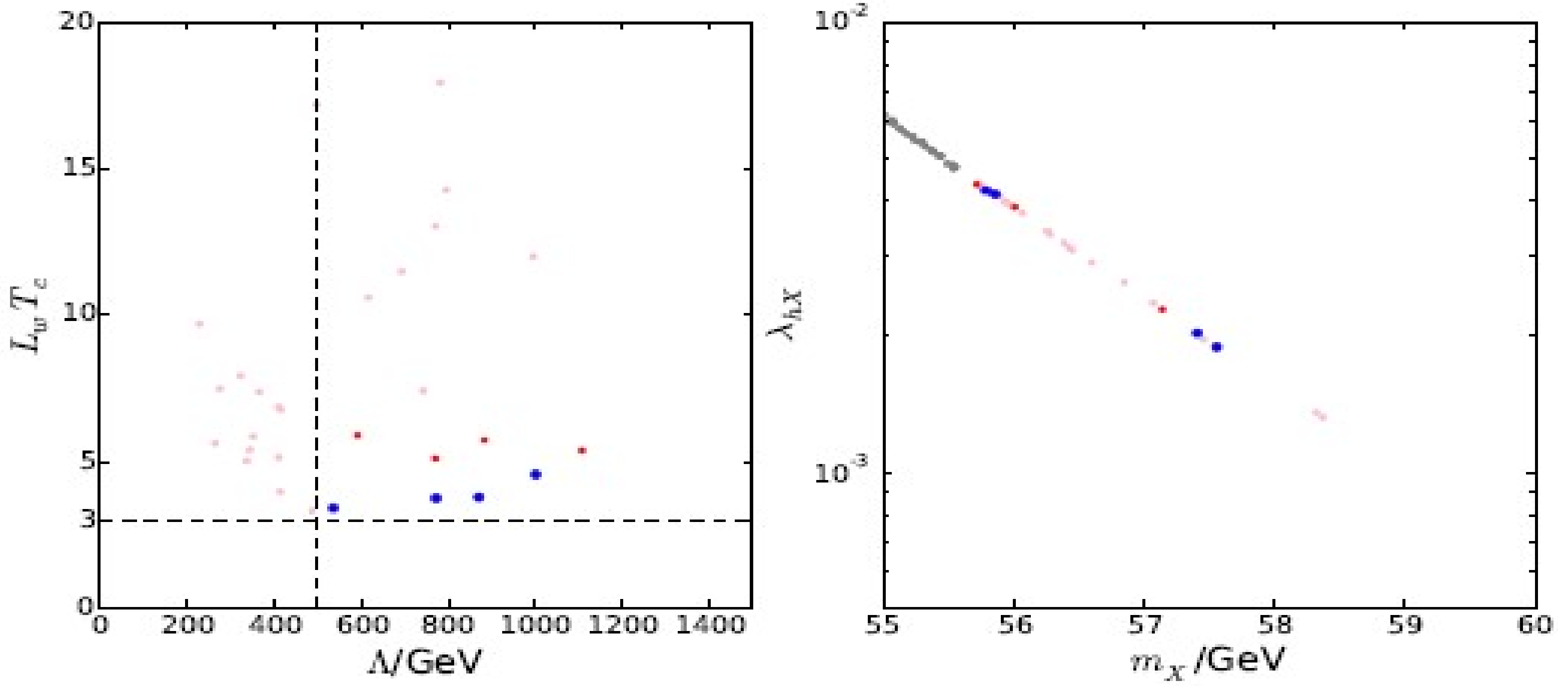
- Implications of EWBG on the DM properties



- Only SM Higgs resonance region can generate the enough cosmological baryon asymmetry without violating any bounds.

Models with Correct DM Density

- ➢ Question: Can this simple model explain the DM relic density and baryon asymmetry simultaneously?
- ➢ Zoom-in Scan near SM Higgs Resonance



Red: $w_c^2/\Lambda^2 < 0.5$

Blue: $w_c^2/\Lambda^2 < 0.2$

Summary

- We explored a new connection between DM and EWBG in a simple complex EW singlet extension of the SM.

- The model is appealing in that the CPV necessary for the EWBG is only spontaneously generated at temperatures higher than the EWPT, while the CP symmetry is restored at present time, so that the low-energy electron and neutron EDM constraints can be evaded.

- We show that the model can generate the DM relic density and baryon asymmetry with the DM mass near the SM Higgs resonance.

Thanks for your attention!