Baryogenesis in non-minimal split Supersymmetry model

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Setup of non-minimal split SUSY model (split NMSSM)

$$\text{CMB (PDG 2013):} \quad 6.1 \times 10^{-10} < \frac{n_B}{n_\gamma} < 6.9 \times 10^{-10}. \qquad (1)$$

$$\text{Higgs discovery (ATLAS, CMS 2012):} \quad m_H = 125.6 \pm 0.3 \ \text{GeV}.$$

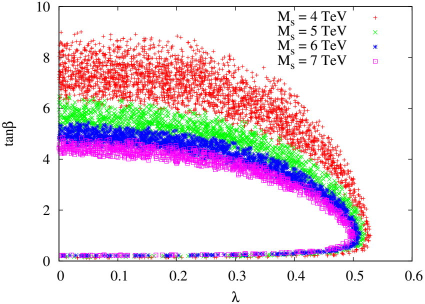
D. Gorbunov and S. Demidov 2006:

- Additional sinlet field N non-minimal coupled to Higgs $W = \lambda \hat{N} \hat{H}_u \epsilon \hat{H}_d + \frac{1}{3} k \hat{N}^3 + \mu \hat{H}_u \epsilon \hat{H}_d + r \hat{N}$.
- Spectrum of the particles is splitted:

  (1) $\tilde{l}$, $\tilde{q}$, A and $H^{\pm}$ decouple from the spectrum at $Q < M_S$.

  (2) SM + ($\tilde{H}_{u,d}$, $\tilde{W}$, $\tilde{B}$, $\tilde{g}$, N , $\tilde{n}$) have masses near $\mathcal{O}(M_{EW})$
- Soft trilinear couplings $\sim H^2 N$ and $\sim N^3$ provide the mechanism of strengthen the first order EWPT.
- N-H mass squared mixing is absent at electroweak scale, $Q < M_S$.

Scaninng over dimensionless couplings at M_S scale



Allowed regions of $\tan\beta$ and λ at M_S scale.

$$(g', g, g_s, y_t), \quad (\tilde{g}_{u,d}, \tilde{g}'_{u,d}, \lambda_{u,d}, \kappa, \kappa_{1,2}k, \lambda_N, \tilde{\lambda}, \xi, \eta).$$

$$\tilde{\lambda}(M_S) = \frac{\bar{g}^2}{4}\cos^2 2\beta + \frac{\lambda^2}{2}\sin^2 2\beta.$$

$$m_H = \sqrt{\tilde{\lambda}(M_{EW})}v : \qquad 125.3\text{ GeV} < m_H < 125.9\text{ GeV}, \quad v = 246\,\text{GeV}$$

Dimensionful parameters:

$$-\mathcal{L}_{trilinear} = +i\tilde{A}_1 H^\dagger H\left(N - N^*\right) + \tilde{A}_2 H^\dagger H\left(N + N^*\right) +$$
$$+\frac{1}{3}\tilde{A}_k\left(N^3 + N^{*3}\right) + \tilde{A}_r\left(N + N^*\right) + \left(\frac{1}{2}\tilde{A}_3 N^2 N^* + h.c.\right),$$

Higgs-scalar ($H - S$) and Higgs-pseudoscalar ($H - P$) squared mass mixings are absent at EW energies. This implies the appropriate electroweak fine-tuning for trilinear couplings A_1 and A_2.

$$N = (S + iP)/\sqrt{2}, \quad \langle S\rangle = v_S, \quad \langle P\rangle = v_P,$$

There are only seven independent dimensionful parameters of the model at EW scale

$$(v_S, \quad v_P, \quad M_1, \quad M_2, \quad \tilde{A}_k, \quad \tilde{A}_3, \quad \tilde{A}_r). \tag{2}$$

$$\tilde{A}_3 = \tilde{A}_r = 0, \quad \tilde{A}_k = -1.1 \text{ GeV}. \tag{3}$$

Strong first order EWPT

Three necessary conditions (Sakharov conditions) must be fulfilled in the early Universe to produce the baryon asymmetry:

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

Departure from thermodynamic equilibrium is induced by the rapidly-expanding bubble walls through the cosmological plasma.

Violation of baryon number comes from the rapid sphaleron transitions in the symmetric phase.

C- and CP-violating scattering processes are needed at the phase boundaries to create the particle number asymmetries that bias the sphalerons to create more baryons than antibaryons.

Strong first order EWPT

We define T_c as a temperature at which one bubble of the broken phase begin to nucleate within a casual space-time volume of the Universe. The last one is defined by the Hubble parameters $\mathcal{H}(T)$ as

$$\mathcal{H}^{-4}(T) = (M^*_{PL}/T^2)^4. \tag{4}$$

The bubble nucleates with the rate

$$\Gamma(T) \simeq (\text{prefactor}) \times T^4 \exp(-S_3/T). \tag{5}$$

where S_3 is a free energy of the critical bubble

$$S_3(T) = 4\pi \int_0^\infty dr\, r^2 \left[\frac{1}{2}\left(\frac{dh}{dr}\right)^2 + \frac{1}{2}\left(\frac{dS}{dr}\right)^2 + \frac{1}{2}\left(\frac{dP}{dr}\right)^2 + V_T^{eff}(h, S, P)\right]$$

Here $h(r), S(r)$ and $P(r)$ are the radial configurations of the scalar field, which minimize S_3.

Strong first order EWPT

The probability of bubble nucleation inside a casual volume is given by

$$P \sim \frac{M_{PL}^{*4}}{T^4} \exp(-S_3/T). \tag{6}$$

The first bubble nucleates when $P \sim 1$, so that, one can obtain a rough nucleation criteria

$$S_3(T)/T \sim 4 \ln\left(\frac{M_{PL}^{*}}{T}\right) \sim 150,$$

where T is a typical temperature of order the electroweak energy scale, $T = 100$ GeV. More stringent result gives (Anderson et al. 1991)

$$S_3(T_c)/T_c \simeq 140. \tag{7}$$

Strong first order EWPT

By using the iterative procedure for anzats configurations, we find the absolute minimum of the functional

$$\mathcal{F}(h,S,P) = 4\pi \int_0^\infty dr\, r^2 \left[E_h^2(r) + E_S^2(r) + E_P^2(r)\right], \qquad (8)$$

where $E_h(r)$, $E_S(r)$ and $E_P(r)$ are the equations of motion for bubble wall profiles

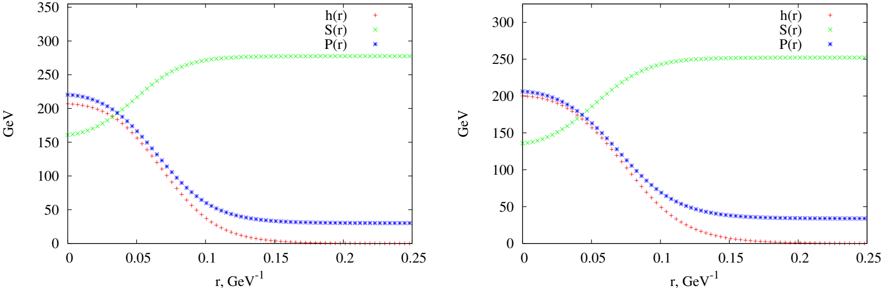
$$E_h(r) = \frac{d^2h}{dr^2} + \frac{2}{r}\frac{dh}{dr} - \frac{\partial V_T^{eff}}{\partial h} = 0, \qquad E_S(r) = \frac{d^2S}{dr^2} + \frac{2}{r}\frac{dS}{dr} - \frac{\partial V_T^{eff}}{\partial S} = 0,$$

$$E_P(r) = \frac{d^2P}{dr^2} + \frac{2}{r}\frac{dP}{dr} - \frac{\partial V_T^{eff}}{\partial P} = 0.$$

Note that the critical bubble obey the following boundary conditions

$$(h(r), S(r), P(r))\Big|_{r=\infty} = (0, S_s, P_s), \quad \left(\frac{dh}{dr}, \frac{dS}{dr}, \frac{dP}{dr}\right)\Big|_{r=0} = (0,0,0).$$

Strong first order EWPT

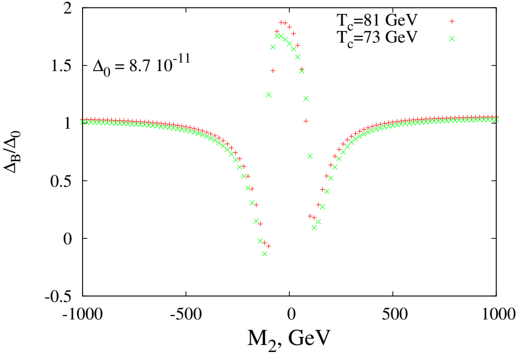


The critical bubbles. Left panel: $T_c = 73$ GeV. Right panel $T_c = 81$ GeV.

	v_S	v_P	T_c	v_c	S_c	P_c	S_s	P_s	S_3/T_c
(1)	53	242	81.0	218.8	53.7	252.2	240.4	33.8	139.6
(2)	72	263	73.0	229.5	72.4	261.9	277.5	30.1	141.2

All dimensionful parameters are in GeV.

Baryogenesis



Baryon asymmetry ratio Δ_B/Δ_0 versus gaugino mass parameter M_2.

$$M_{ch} = \begin{pmatrix} M_2 & \frac{1}{\sqrt{2}}\tilde{g}_u h(z) \\ \frac{1}{\sqrt{2}}\tilde{g}_d h(z) & \tilde{\mu}(z) \end{pmatrix}, \qquad (9)$$

EDM constraints

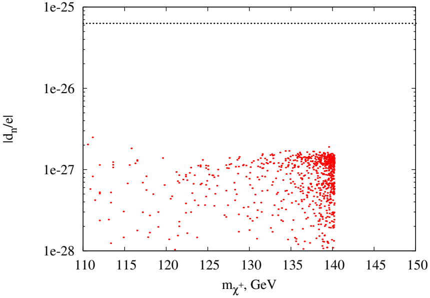
There are three terms which contribute to EDM of fermion

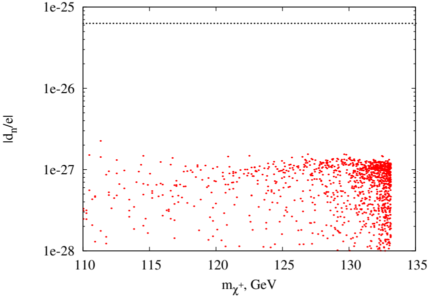
$$d_f = d_f^{H\gamma} + d_f^{HZ} + d_f^{WW},$$

where $d_f^{H\gamma}$, d_f^{HZ} and d_f^{WW} are the partial EDMs related to the exchange of $H\gamma$, HZ^0 and W^+W^- bosons in chargino-neutralino sector.

The most stringent upper limit on EDM of the electron $|d_e/e| < 8.7 \cdot 10^{-29}$ cm was obtained by ACME collaboration at 90% CL (Baron et al. 2013).

The current bound on neutron's EDM is $|d_n/e| < 3.0 \cdot 10^{-26}$ cm at 90 % CL (Baker et al. 2006).

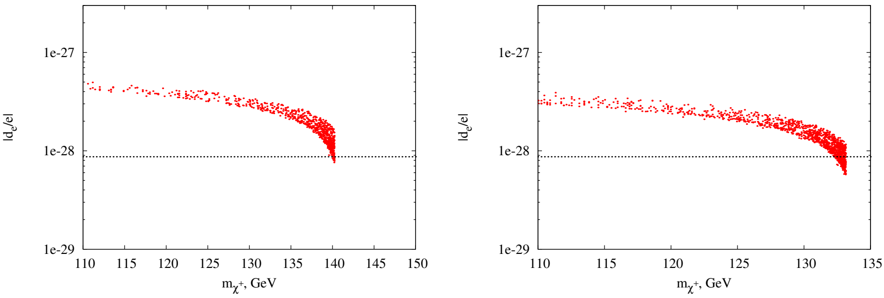




The numerical results for neutron EDM. One can see that predictions for the neutron EDMs satisfy the current experimental bound

$$|d_n/e| < 3.0 \cdot 10^{-26}\, cm.$$

Scanning over the region $0 < M_1, M_2 < 1000$GeV.



The EDM of electron versus the lightest chargino mass $m_{\chi_1^+}$. Current experimental bound is $|d_e/e| < 8.7 \cdot 10^{-29}$ cm. Predicted chargino masses, $m_{\chi_1^+} = 140$ GeV and $m_{\chi_1^+} \simeq 132.5$ GeV, in agreement with CMS and ATLAS limits on chargino-neutralino production at LHC without light sleptons and squarks.

- Right pane: $M_S = 4.0$ TeV, $\tan\beta = 6.59$, $\lambda = 0.4$, $k = -0.5$,
- Left panel: $M_S = 4.72$ TeV, $\tan\beta = 4.91$, $\lambda = 0.4$, $k = -0.5$.

Summary

- Successful baryogenesis is considered in Split NMSSM for Higgs favored ($m_H = 125$ GeV) parameter space.
- Light charginos are predicted, $m_{\chi_1^+} = 140$ GeV and $m_{\chi_1^+} = 132.5$ GeV, from the experimental bound on electron EDM, $|d_e/e| < 8.7 \cdot 10^{-29}$ cm.
- TeV split scale and large $\tan\beta$ are reqiured, $M_S = 4$ TeV and $\tan\beta = 7$, to explain the observed asymmetry between baryon and antibaryon in the Universe.
- Very narrow region in parameter space of Split NMSSM can be probed in *pp* collision at LHC 14.

Thank You!