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Electroweak baryogenesis in the $\mathbb{Z}_3$-invariant NMSSM

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Table of contents

Electroweak Baryogenesis

Sakharov Conditions

- B number violation
- departure from equilibrium
- C and CP violation

The Electroweak mechanism

At high temperature EW symmetry is restored before the EWPT.
Result in terms of Sakharov conditions

- EW sphalerons lead to unsuppressed B number violation in symmetric phase
- The EWPT proceeds by bubble nucleaution (SFOEWPT)
- C and CP violating interactions with the bubble wall lead bias the sphalerons

Shortcomings of SM

- EWPT is crossover for $m_h \sim 125$
- not enough CP violation

Shortcomings of MSSM

Pheno shortcomings

- little heirachy problem
- μ problem

EWBG shortcomings

- stops need to be light enough for SFOEWPT
- either stops need to be near degenerate for BAU or Higgsino and a gaugino need to be light and near degenerate
- EDMs and LHC constraints suffucate the MSSM

Phase transitions in NMSSM

Two types of phase transitions

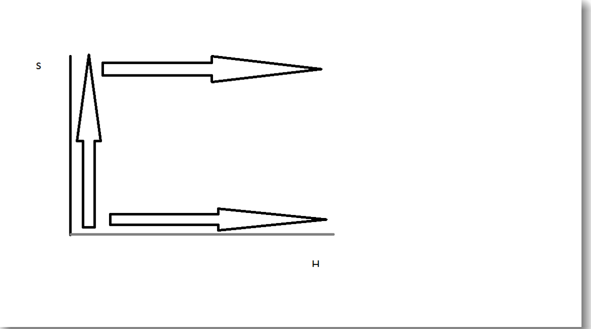


Figure 1: (Type I vs Type II)

- stops can be heavy if singlet catalyze SFOPT
- $\Delta\beta \propto$ BAU can be an order of magnitude larger.

New CP violating Source

New rephasing invariant: Higgsino-Singlino interactions with space time varying vevs

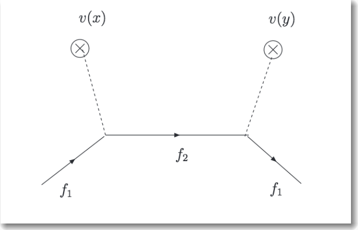


Figure 2: (Higgsino-Singlino interactions)

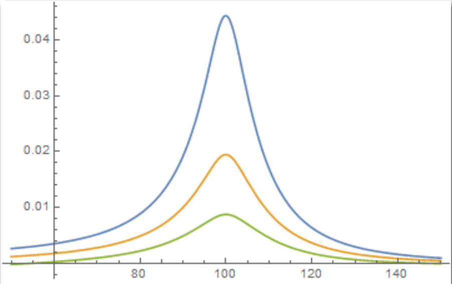
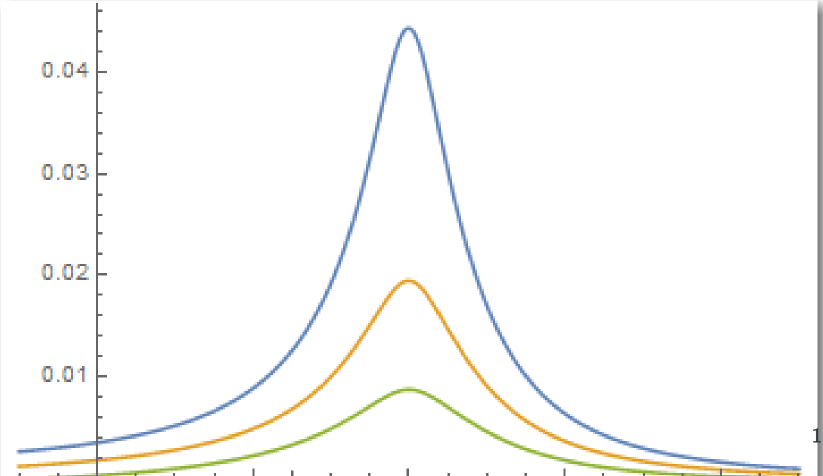


Figure 3: (Singlino source strength)

Thermal widths

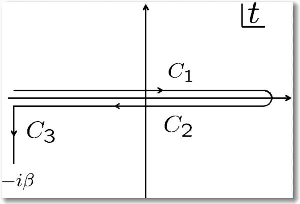
$$\Gamma_{\tilde{S}} = b(m_H^*)0.01(\lambda^2 + \kappa^2) \tag{1}$$



Baryon Asymmetry in the NMSSM

CTP formalism

Use CTP Formalism



- Doubles the number of Greens functions
- Use techniques from

C. Lee, V. Cirigliano, and M. J. Ramsey-Musolf, Phys. Rev. D **71** no 7 075010 (2005)

G. A. White, Phys. Rev. D **93**, no. 4, 043504 (2016) [arXiv:1510.03901 [hep-ph]].

VEV Insertion Approximation

"The VIA assumes that the particle-antiparticle asym- metry generation is dominated by the region near the phase boundary, where the vevs are small compared to both T and the (mass) difference"

S. Inoue, G. Ovanesyan and M. J. Ramsey-Musolf, Phys. Rev. D **93** .1 015013 (2016).

- Calculating vev insertion diagrams using the VIA is invalid if the mass difference is large

Other Approximations and assumptions

- local equilibrium between quarks and squarks
- Ficks diffusion law $\vec{J} \to \vec{\nabla} n$
- ignore bubble wall curvature and solve system in bubble wall rest frame z
  - This means $\partial_t \to v_w \partial_z$
  - the transport equations are inhomogenious coupled ODEs in a single space time variable

Transport equations

Type I phase transitions have no chemical potential for the fluctuations around the singlet vev.
Total list of number densities

$$\begin{aligned}
n_{H_1} &= n_{H_u^+} + n_{H_u^0} \\
n_{H_2} &= n_{H_d^-} + n_{H_d^0} \\
n_{\tilde{H}} &= n_{\tilde{H}_u^+} + n_{\tilde{H}_u^0} - n_{\tilde{H}_d^-} - n_{\tilde{H}_d^0} \\
n_t &= n_{t_R} + n_{\tilde{t}_R} \\
n_Q &= n_{t_L} + n_{b_L} + n_{\tilde{t}_R} + n_{\tilde{b}_L} \\
n_S &= n_S
\end{aligned} \tag{2}$$

Baryon Asymmetry

The baryon number density, ρ_B, satisfies the equation

$$D_Q \rho_B''(z) - v_W \rho_B'(z) - \Theta(-z)\mathcal{R}\rho_B = \Theta(-z)\frac{n_F}{2}\Gamma_{ws} n_L(z)$$

Which can be solved to get

$$Y_B = -\frac{n_F \Gamma_{ws}}{2\kappa_+ D_Q S}\int_{-\infty}^{0} e^{-\kappa_- x}\, n_L(x)\,\mathrm{d}x$$

Results

qualitative conditions

- Higgsino and Singlino masses in symmetric phase must be $\lesssim 4T_N$
  - this implies zero temperature singlet mass should be $<<1$ TeV
- Higgsino and Singlino masses must be within a factor of 2 of each other
- Correct zero-temperature Higgs sector (higgs mass and vev)

Type I vs Type II

- If the Higgs is tachyonic at $S = H = 0$, $\forall T < 200$ it must be a type I phase transition
- Tree level mass terms at $S = H = 0$ tend to be larger than 200 GeV.
- Nearly all points are Type I

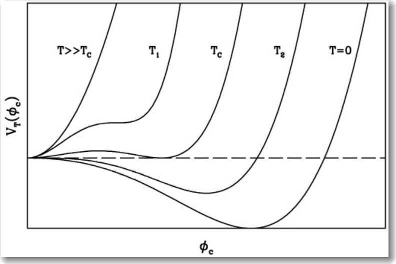


Figure 5

Preliminary (no pheno! Scan running: new results comingg soon!)

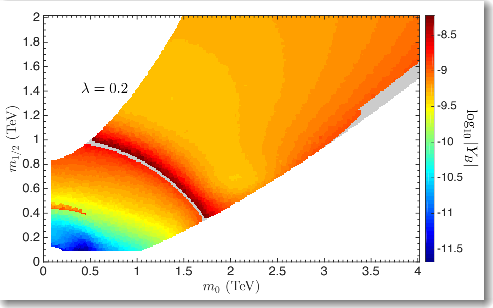


Figure 6: Singlino Higgsino 3 body rates

Effects of three body rates

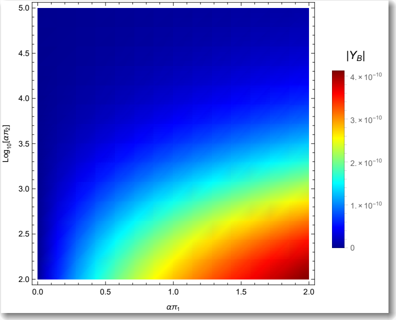
- Three body rates involving Singlinos and Higgsinos:

$$\mu_{H_i} + \mu_{\tilde{H}} \approx 0 \tag{3}$$

whereas supergauge relaxes combination

$$\mu_{H_i} - \mu_{\tilde{H}} \approx 0 \tag{4}$$

- But BAU $\propto \mu_{\tilde{H}}$!



Summary

Electroweak baryogenesis in the NMSSM overcomes some problems the MSSM has. Some parts of the parameter space can produce the BAU

Questions?