Z′-ino driven electroweak baryogenesis

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Baryon Asymmetry of the Universe (BAU)

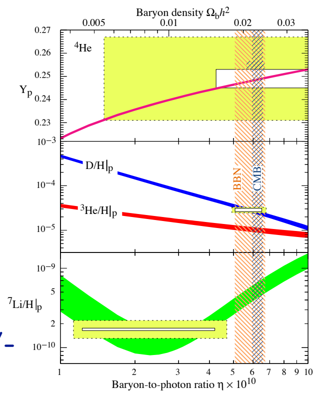
❒ Our Universe is baryon-asymmetric.

$$\eta \equiv \frac{n_B}{n_\gamma} = \frac{n_b - n_{\bar b}}{n_\gamma} = (5.1-6.5)\times 10^{-10}\ (95\%\ \mathrm{CL})$$

▪ If the BAU is generated before T≃1 MeV, the light element abundances (D,^{3}He,^{4}He,^{7}Li) can be explained by the standard Big-Bang cosmology.

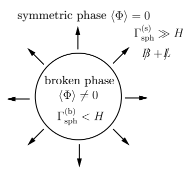
baryogenesis = to generate right η $\quad Y_B = \frac{n_B}{s},\quad s/n_\gamma = 7.04.$

❒ We consider electroweak baryogenesis (EWBG) in the U(1)′-extended MSSM.



[PDG2012]

Electroweak Baryogenesis



[Kuzmin, Rubakov, Shaposhnikov, PLB155,36 ('85)]

Baryogenesis can occur if the EW phase transition (EWPT) is strongly 1st-order.

B violation: anomalous process at finite temperature (sphaleron)

C violation: chiral gauge interactions

CP violation: CP phase in the CKM matrix and/or other sources beyond the SM

Out of equilibrium: 1st-order EWPT with expanding bubble walls

well-known fact: SM EWBG was ruled out.
∵ KM phase is too small to generate the BAU, and EWPT is NOT 1st-order for m_h=126 GeV.

U(1)′-extended MSSM (UMSSM)

$$W_{\rm UMSSM} \ni \epsilon_{ij}\lambda S H_u^i H_d^j,$$

M.Cvetic et al, PRD56:2861 ('97).
D.Suematsu et al, Int.J.Mod.Phys.A10 ('95) 4521.

2 Higgs doublets (H_d, H_u) + 1 Higgs singlet (S)

Higgs potential

$$V_0 = V_F + V_D + V_{\rm soft},$$
$$V_F = |\lambda|^2\{|\epsilon_{ij}\Phi_d^i\Phi_u^j|^2 + |S|^2(\Phi_d^\dagger\Phi_d + \Phi_u^\dagger\Phi_u)\},$$
$$V_D = \frac{g_2^2+g_1^2}{8}(\Phi_d^\dagger\Phi_d - \Phi_u^\dagger\Phi_u)^2 + \frac{g_2^2}{2}(\Phi_d^\dagger\Phi_u)(\Phi_u^\dagger\Phi_d) + \frac{g_1'^2}{2}(Q_{H_d}\Phi_d^\dagger\Phi_d + Q_{H_u}\Phi_u^\dagger\Phi_u + Q_S|S|^2)^2,$$
$$V_{\rm soft} = m_1^2\Phi_d^\dagger\Phi_d + m_2^2\Phi_u^\dagger\Phi_u + m_S^2|S|^2 - (\epsilon_{ij}\lambda A_\lambda S\Phi_d^i\Phi_u^j + {\rm h.c.}).$$

$$\Phi_d = \begin{pmatrix} \frac{1}{\sqrt2}(v_d+h_d+ia_d) \\ \phi_d^- \end{pmatrix},\quad \Phi_u = e^{i\theta}\begin{pmatrix} \phi_u^+ \\ \frac{1}{\sqrt2}(v_u+h_u+ia_u) \end{pmatrix},\quad S = \frac{1}{\sqrt2}(v_S+h_S+ia_S).$$

Q's: U(1)′ charges,
Q_{Hd} + Q_{Hu} + Q_S = 0. $g_1' = \sqrt{5/3}g_1$

After imposing the minimum condition, one gets $I_\lambda \equiv \frac{|\lambda||A_\lambda|}{\sqrt2}\sin(\delta_{A_\lambda}+\delta_\lambda+\theta) = 0.$ no CP violation

Higgs boson masses (tanβ=1, Q_{Hd}=Q_{Hu}=Q)

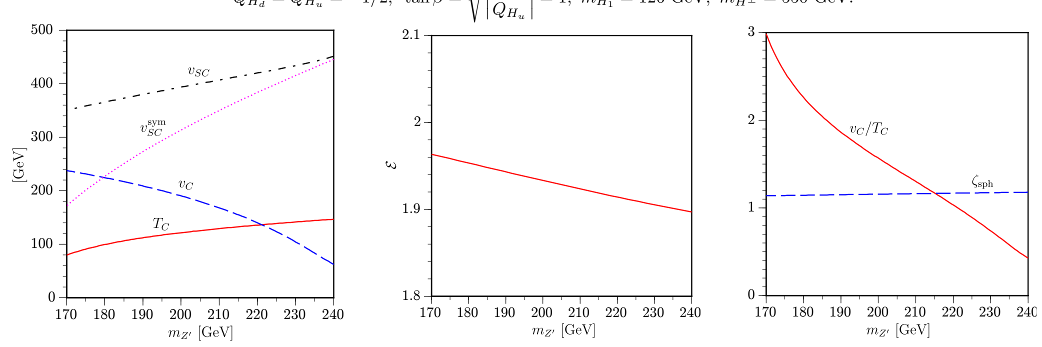
$$m_{H_{1,2}}^2 = \frac12\left[m_S^2 + |\lambda|^2v^2 + 6g_1'^2Q^2v_S^2 \mp \sqrt{\{m_S^2+2g_1'^2Q^2(3v_S^2-v^2)\}^2 + 4v^2\{R_\lambda - (|\lambda|^2-2g_1'^2Q^2)v_S\}^2}\right],$$
$$m_{H_3}^2 = m_Z^2 - \frac{|\lambda|^2}{2}v^2 + 2R_\lambda v_S,$$
$$m_A^2 = \frac{R_\lambda v_S}{v_d v_u}\left(v^2 + \frac{v_d^2v_u^2}{v_S^2}\right),\quad m_{H^\pm}^2 = m_W^2 + \frac{2R_\lambda v_S}{\sin 2\beta} - \frac{|\lambda|^2}{2}v^2,\quad R_\lambda = \frac{|\lambda||A_\lambda|}{\sqrt2}\cos(\delta_{A_\lambda}+\delta_\lambda+\theta).$$

EWPT and sphaleron decoupling condition

T_C : T at which $V_{\rm eff}$ has the two degenerate minima.

$$v_C = \lim_{T\uparrow T_C}\sqrt{v_d^2(T_C)+v_u^2(T_C)},\ v_{SC} = \lim_{T\uparrow T_C} v_S(T_C),\ v_{SC}^{\rm sym} = \lim_{T\downarrow T_C} v_S(T_C)$$

$$Q_{H_d} = Q_{H_u} = -1/2,\ \tan\beta = \sqrt{\left|\frac{Q_{H_d}}{Q_{H_u}}\right|} = 1,\ m_{H_1} = 126\ {\rm GeV},\ m_{H^\pm} = 550\ {\rm GeV}.$$



❒ In the light Z′ (small v_S) region, the EWPT can be strong 1st-order due to the doublet-singlet Higgs mixing effects.
❒ In such a case, Z′ must be leptophobic.

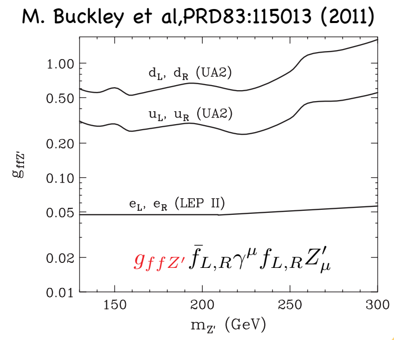
Experimental constraints on light Z′ boson

❒ Electroweak precision tests (see e.g. Umeda, Cho, Hagiwara, PRD58 (1998) 115008) -> In our case, the Z-Z′ mixing is assumed to be sufficiently small.

❒ All dijet-mass searches at Tevatron/LHC are limited to M_{jj}>200 GeV.

❒ Z′ boson (<200 GeV) is constrained by the UA2 experiment. (see UA2 Collaborations,NPB400: (1993) 3)

M. Buckley et al,PRD83:115013 (2011)



CP violating source term

$$\frac{\partial n_\psi(X)}{\partial t_X} + \nabla_X\cdot j_\psi(X) = i\int_{-\infty}^{t_X}dz^0\int_{-\infty}^{\infty}d^3z\ {\rm tr}\Big[\Sigma^>(X,z)S^<(z,X) - \Sigma^<(X,z)S^>(z,X) - S^>(X,z)\Sigma^<(z,X) + S^<(X,z)\Sigma^>(z,X)\Big].$$

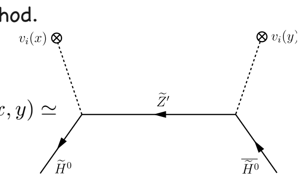
$$S^>_{\alpha\beta}(x,y) = \langle\psi_\alpha(x)\bar\psi_\beta(y)\rangle,\quad S^<_{\alpha\beta}(x,y) = -\langle\bar\psi_\beta(y)\psi_\alpha(x)\rangle.$$

CPV source term is calculated from the r.h.s. using the VEV insertion method. (perturbation from symmetric phase)

Z′-ino-Higgsino inetractions

$$\mathcal{L} \ni -g_1'\Big[\overline{\tilde H^0}(Q_{H_d}v_d(x)e^{-i\delta_{M_1'}/2}P_L - Q_{H_u}v_u(x)e^{i(\delta_\lambda'+\delta_{M_1'}/2)}P_R)\tilde Z' + \overline{\tilde Z'}(-Q_{H_u}v_u(x)e^{-i(\delta_\lambda'+\delta_{M_1'}/2)}P_L + Q_{H_d}v_d(x)e^{i\delta_{M_1'}/2}P_R)\tilde H^0\Big]$$

$$-i\Sigma^{<,>}_{\tilde H^0}(x,y) \simeq$$



$$S_{\tilde Z'\tilde H^0}(X) = -4g_1'^2Q_{H_d}Q_{H_u}|M_1'||\mu_{\rm eff}(X)|v^2(X)\partial_{t_X}\beta(X)\sin(\delta_\lambda+\delta_{M_1'})\mathcal{I}^f_{\tilde Z'\tilde H^0}.$$

Baryon asymmetry

supergauge equilibrium is assumed

$$Q = n_{t_L} + n_{\tilde t_L} + n_{b_L} + n_{\tilde b_L},$$
$$T = n_{t_R} + n_{\tilde t_R},$$
$$B = n_{b_R} + n_{\tilde b_R},$$
$$H = n_{H_u^+} + n_{H_u^0} + n_{H_d^+} + n_{H_d^0} + n_{\tilde H^+} + n_{\tilde H^0},$$

$$n_{b,f} = g\int\frac{d^3k}{(2\pi)^3}\left[\frac{1}{e^{(\omega-\mu)}\mp1} - \frac{1}{e^{(\omega+\mu)}\mp1}\right] = \frac{T^2\mu}{6}k_{b,f}\left(\frac{m}{T}\right)$$

g: d.o.f., μ: chemical potential

$$\frac{\partial Q(X)}{\partial t_X} + \nabla_X\cdot j_Q(X) = -\Gamma_M^+\left(\frac{T}{k_T}+\frac{Q}{k_Q}\right) + \Gamma_M^-\left(\frac{T}{k_T}-\frac{Q}{k_Q}\right) + \Gamma_Y\left(\frac{T}{k_T}-\frac{H}{k_H}-\frac{Q}{k_Q}\right) - 2\Gamma_{ss}\left(\frac{2Q}{k_Q}-\frac{T}{k_T}+\frac{9(Q+T)}{k_B}\right) - S_{\tilde t},$$
$$\frac{\partial T(X)}{\partial t_X} + \nabla_X\cdot j_T(X) = \Gamma_M^+\left(\frac{T}{k_T}+\frac{Q}{k_Q}\right) - \Gamma_M^-\left(\frac{T}{k_T}-\frac{Q}{k_Q}\right) - \Gamma_Y\left(\frac{T}{k_T}-\frac{H}{k_H}-\frac{Q}{k_Q}\right) + \Gamma_{ss}\left(\frac{2Q}{k_Q}-\frac{T}{k_T}+\frac{9(Q+T)}{k_B}\right) + S_{\tilde t},$$
$$\frac{\partial H(X)}{\partial t_X} + \nabla_X\cdot j_H(X) = -\Gamma_h\frac{H}{k_H} + \Gamma_Y\left(\frac{T}{k_T}-\frac{H}{k_H}-\frac{Q}{k_Q}\right) + S_{\tilde H},$$

$\Gamma_M^\pm$: particle # changing rate by VEVs,
Γ_Y: particle # changing rate by Yukawa int.,
Γ_{ss}: axial # changing rate

$$\dot H - \bar D\nabla^2 H + \bar\Gamma H - \bar S = 0\qquad \Gamma_Y, \Gamma_{ss} \gg \Gamma_M^\pm\qquad \boldsymbol{j} = -D\nabla n$$
$$n_L = 5Q + 4T = -r_1 H + \mathcal{O}(1/\Gamma_{Y,ss})$$
$$D_q n_B''(\bar z) - v_w n_B'(\bar z) - \theta(-\bar z)\mathcal{R}n_B(\bar z) = \theta(-\bar z)\frac{N_g}{2}\Gamma_B^{(s)}n_L(\bar z),\quad {\rm B.C.}\ n_B(\bar z\to-\infty) = 0,\quad n_B(\bar z>0) = {\rm constant}$$

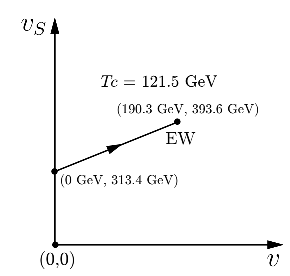
baryon number

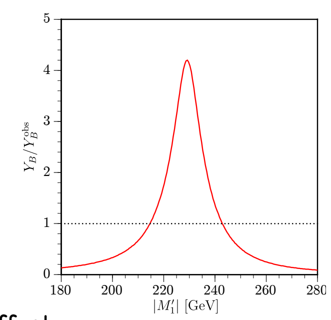
$$n_B = \frac32\Gamma_{ws}^{(s)}\mathcal{A}\Big[r_1 + \mathcal{O}(1/\Gamma_{ss})\Big]\qquad \mathcal{A} \propto \frac{S_{\tilde Z'\tilde H^0}}{\sqrt{\Gamma_M^- + \Gamma_h}},\qquad \Gamma_{ws}^{(s)}:\ \text{weak sphaleron rate in the sym. phase.}$$

NOTE: If all squarks are thermally decoupled, $k_Q = 6$ and $k_T = k_B = 3$,
$r_1 \propto 9k_Qk_T - 5k_Qk_B - 8k_Tk_B = 9\cdot6\cdot3 - 5\cdot6\cdot3 - 8\cdot3\cdot3 = 0.$ [Huet and Nelson, PRD53, 4578 ('96)]

Z′-ino driven EWBG

$$\tan\beta = 1,\ m_{H_1} = 126\ {\rm GeV},\ m_{H^\pm} = 550\ {\rm GeV},\ m_{Z'} = 200\ {\rm GeV},$$
$$\delta_{M_1'} = \pi/2,\ \delta_\lambda = 0,\ \Delta\beta = 0.01,\ v_w = 0.4$$





❒ If $|M'_1|$≃$|\mu_{\rm eff}|$, BAU can be explained by the Z′-ino effect.

Conclusions

We have considered the EWBG in the UMSSM.

❒ EWPT can be strongly 1st-order due to the doublet-singlet Higgs mixing effects.

❒ In such a case, the Z′ boson has to be less than (150-300) GeV and thus leptophobic.

❒ Z′-ino can provide the CP-violating source for the sufficient BAU.

Next step

❒ Model building and experimental constraints