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Restrictions on the parameters of the minimal Supersymmetric Standard Model with CP-violation

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Motivations for researches of CP-violation

☞ the explanation of the baryon asymmetry

The Sakharov conditions [1]:

- the violation of baryon number;
- C-violation and CP-violation;
- the deviation from thermodynamic equilibrium.

[1] Sakharov A.D. Violation of CP invariance, C-asymmetry and baryon asymmetry of the Universe // Pisma v ZhETF, 1967, Vol. 5, Issue 1, pp. 32вЃ Y35. [in Russian].

CKM Matrix is not enough to describe the baryon asymmetry [2]!

The observed Higgs does not satisfy the strong electroweak phase transition

[2] Huet P, Sather E. Electroweak baryogenesis and standard model CP violation // Phys.Rev.D. - 1995. - V.51. - P.379.

HighLights

We can add CP-violation sources in extended the Higgs sector of a model beyond SM, and get Light CP-odd Higgs boson.

The field structure of the MSSM and NMSSM

	superfield	field	spin	superpartner	spin
quarks/	$\hat{Q}$	$Q = \begin{pmatrix} U_\alpha \\ D_\alpha \end{pmatrix}_L$	$\frac{1}{2}$	$\tilde{Q} = \begin{pmatrix} \tilde{U}_\alpha \\ \tilde{D}_\alpha \end{pmatrix}_L$	0
squarks	$\hat{U}$	$U_{\alpha R}$	$\frac{1}{2}$	$\tilde{U}_{\alpha R}$	0
	$\hat{D}$	$D_{\alpha R}$	$\frac{1}{2}$	$\tilde{D}_{\alpha R}$	0
leptons/	$\hat{L}$	$L_{\alpha L}$	$\frac{1}{2}$	$\tilde{L}_{\alpha L}$	0
sleptons	$\hat{E}$	$E_{\alpha R}$	$\frac{1}{2}$	$\tilde{E}_{\alpha R}$	0
the gauge	$\hat{G}$	G^a_μ	1	$\tilde{G}^a_\mu$	$\frac{1}{2}$
bosons /	$\hat{W}$	$W^\pm$, W^0	1	$\tilde{W}^\pm$, $\tilde{W}^0$	$\frac{1}{2}$
Gauge supermultiplets	$\hat{B}$	B^0	1	$\tilde{B}^0$	$\frac{1}{2}$
Higgs/	$\hat{H}_1$	$H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix}$	0	$\tilde{H}_1 = \begin{pmatrix} \tilde{H}_1^0 \\ \tilde{H}_1^- \end{pmatrix}$	$\frac{1}{2}$
Higgsino,	$\hat{H}_2$	$H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}$	0	$\tilde{H}_2 = \begin{pmatrix} \tilde{H}_2^+ \\ \tilde{H}_2^0 \end{pmatrix}$	$\frac{1}{2}$
S field / singlino	$\hat{S}$	S	0	$\tilde{S}$	$\frac{1}{2}$

α - generation ($\alpha = 1, 2, 3$), a - color combination ($a = 1 \ldots 8$).

Candidate for WIMPs: Neutralino

☞ MSSM: the superposition of states: $\tilde{B}^0$, $\tilde{W}^3$, $\tilde{H}_1^0$, $\tilde{H}_2^0$

NMSSM: the superposition of states: $\tilde{B}^0$, $\tilde{W}^3$, $\tilde{H}_1^0$, $\tilde{H}_2^0$, S

$\chi_1^0\chi_1^0 \to \gamma\gamma$ in the MSSM

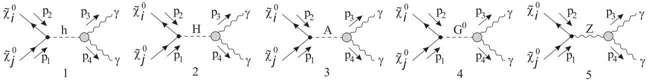


Fig.1. The system of Feynman diagrams determining the amplitude of the process $\chi_i^0\chi_j^0 \to \gamma\gamma$ in the MSSM.

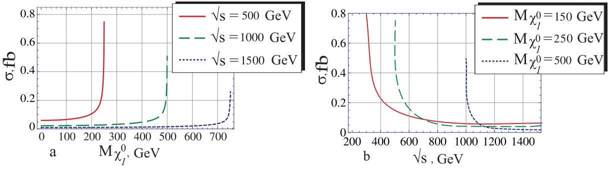


Fig.2. The total cross section: a) depending on the mass of the neutralino $\sigma(M_{\chi_1^0})$;

b) depending on the scale of energy $\sigma(\sqrt{s})$.

[3] Gurskaya, A.V. The annigilation cross-section of pair of the lightest neutralino of MSSM into two gamma quantum // MPA2012, Samara

Restrictions on the mass of the lightest superparticle on LHC

$\tilde{g} \to q\tilde{q}\tilde{\chi}_1^0$ $\qquad$ $\tilde{q} \to q\tilde{\chi}_1^0$

$\tilde{g} \to b\tilde{b}\tilde{\chi}_1^0$ $\qquad$ $\tilde{q}_L \to qW\tilde{\chi}_1^0$

$\tilde{g} \to t\tilde{t}\tilde{\chi}_1^0$ $\qquad$ $\tilde{q}_L \to qWZ\tilde{\chi}_1^0$

$\tilde{g} \to q\tilde{q}W\tilde{\chi}_1^0$ $\qquad$ $\tilde{q}, \tilde{b}, \tilde{t} \to q(\gamma/Z)\tilde{G}$ via $\tilde{\chi}_1^0$

$\tilde{g} \to q\tilde{q}WZ\tilde{\chi}_1^0$ $\qquad$ etc.

$$m_{\tilde{\chi}_1^0} > 1 \text{ TeV } (m_{\tilde{g}} > 1.6 \text{ TeV}), \qquad m_{\tilde{\chi}_1^0} > 500 \text{ GeV } (m_{\tilde{q}} > 0.6 - 1.8 \text{ TeV})$$

[4] https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2019-022/

Benchmark scenarios in the MSSM:

[5] M.Carena at el. // arXiv:hep-ph/9912223 [hep-ph]

[6] M. Carena at el.// Eur. Phys. J.C26(2003) 601–607

[7] M.Carena at el. // Eur. Phys. J.C73(2013)no. 9, 2552

[8] M.Carena at el.// Phys. Lett.B495(2000) 155–163

[9] M.Carena at el. // JHEP02(2016) 123

Effective potential of MSSM. Fields system

In two-doublet model there are two identical $SU(2)$ doublets of complex scalar fields Φ_1 and Φ_2

$$\Phi_1 = \left(\begin{array}{c} \phi_1^+(x) \\ \phi_1^0(x) \end{array} \right), \;\; \Phi_2 = \left(\begin{array}{c} \phi_2^+(x) \\ \phi_2^0(x) \end{array} \right)$$

with nonzero vacuum expectation values

$$\langle \Phi_1 \rangle = \frac{1}{\sqrt{2}} \left(\begin{array}{c} 0 \\ v_1 \end{array} \right), \qquad \langle \Phi_2 \rangle = \frac{1}{\sqrt{2}} \left(\begin{array}{c} 0 \\ v_2 \end{array} \right).$$

Neutral components of doublets

$$\phi_1^0(x) = \frac{1}{\sqrt{2}}(v_1 + \eta_1 + i\chi_1), \;\; \phi_2^0(x) = \frac{1}{\sqrt{2}}(v_2 + \eta_2 + i\chi_2).$$

Effective THDM potential of MSSM

The most general renormalizable hermitian $SU(2) \otimes U(1)$ invariant potential: [Akhmetzyanova E.N., M.V.D, Dubinin M.N. Soft SUSY Breaking and Explicit CP Violation in the THDM // CALC 2003 & SQS0́3 Proc.]

$$U(\Phi_1, \Phi_2) = -\mu_1^2(\Phi_1^\dagger \Phi_1) - \mu_2^2(\Phi_2^\dagger \Phi_2) - \mu_{12}^2(\Phi_1^\dagger \Phi_2) - \overset{*}{\mu}{}_{12}^2 (\Phi_2^\dagger \Phi_1) +$$

$$+\frac{\lambda_1}{2}(\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger \Phi_2)^2 + \lambda_3(\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4(\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) +$$

$$+\frac{\lambda_5}{2}(\Phi_1^\dagger \Phi_2)(\Phi_1^\dagger \Phi_2) + \frac{\overset{*}{\lambda}_5}{2}(\Phi_2^\dagger \Phi_1)(\Phi_2^\dagger \Phi_1) + \lambda_6(\Phi_1^\dagger \Phi_1)(\Phi_1^\dagger \Phi_2) +$$

$$+ \overset{*}{\lambda}_6 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_1) + \lambda_7(\Phi_2^\dagger \Phi_2)(\Phi_1^\dagger \Phi_2) + \overset{*}{\lambda}_7 (\Phi_2^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1)$$

with effective real parameters μ_1^2, μ_2^2, λ_1,...,λ_4 and complex parameters μ_{12}^2, λ_5, λ_6, λ_7.

Effective THDM potential of MSSM. Boundary conditions

In the tree approximation on the energy scale M_{SUSY}, the parameters λ_{1-7} are real and are expressed using the coupling constants g_1 and g_2 of electroweak group of the gauge symmetry $SU(2) \otimes U(1)$ as follows:

$$\lambda_1(M_{SUSY}) = \lambda_2(M_{SUSY}) = \frac{1}{4}\left(g_2^2(M_{SUSY}) + g_1^2(M_{SUSY})\right),$$

$$\lambda_3(M_{SUSY}) = \frac{1}{4}\left(g_2^2(M_{SUSY}) - g_1^2(M_{SUSY})\right),$$

$$\lambda_4(M_{SUSY}) = -\frac{1}{2}g_2^2(M_{SUSY}),$$

$$\lambda_5(M_{SUSY}) = \lambda_6(M_{SUSY}) = \lambda_7(M_{SUSY}) = 0.$$

Boundary conditions
On the scale of the superpartners M_{SUSY}

$$\text{————————}m_t\text{———}\Leftarrow\text{————————————}M_{SUSY}\text{————————}$$

The effective potential method,
the method of Feynman diagrams

$$\lambda_1^{SUSY} = \lambda_2^{SUSY} = \frac{g_1^2 + g_2^2}{8}, \qquad \lambda_3^{SUSY} = \frac{g_2^2 - g_1^2}{4},$$

$$\lambda_4^{SUSY} = -\frac{g_2^2}{2}, \qquad \lambda_5^{SUSY} = \lambda_6^{SUSY} = \lambda_7^{SUSY} = 0.$$

The deviation from the parameters

$$\lambda_{1,2,3,4} = \lambda_{3,4}^{SUSY} - \triangle\lambda_{1,2,3,4}, \qquad \lambda_{5,6,7} = -\triangle\lambda_{5,6,7},$$

The supersymmetric scalar potential of interaction of Higgs bosons with the third generation of quark superpartners on the tree level has the form

$$\mathcal{V}^0 = \mathcal{V}_M + \mathcal{V}_\Gamma + \mathcal{V}_\Lambda + \mathcal{V}_{\widetilde{Q}} \,,$$

$$\mathcal{V}_M = (-1)^{i+j} m_{ij}^2 \Phi_i^\dagger \Phi_j + M_{\widetilde{Q}}^2 \left(\widetilde{Q}^\dagger \widetilde{Q}\right) + M_{\widetilde{U}}^2 \widetilde{U}^* \widetilde{U} + M_{\widetilde{D}}^2 \widetilde{D}^* \widetilde{D} \,,$$

$$\mathcal{V}_\Gamma = \Gamma_i^D \left(\Phi_i^\dagger \widetilde{Q}\right) \widetilde{D} + \Gamma_i^U \left(i\Phi_i^T \sigma_2 \widetilde{Q}\right) \widetilde{U} + \overset{*}{\Gamma}{}_i^D \left(\widetilde{Q}^\dagger \Phi_i\right) \widetilde{D}^* - \overset{*}{\Gamma}{}_i^U \left(i\widetilde{Q}^\dagger \sigma_2 \Phi_i^*\right) \widetilde{U}^* \,,$$

$$\mathcal{V}_\Lambda = \Lambda_{ik}^{jl} \left(\Phi_i^\dagger \Phi_j\right) \left(\Phi_k^\dagger \Phi_l\right) + \left(\Phi_i^\dagger \Phi_j\right) \left[\Lambda_{ij}^Q \left(\widetilde{Q}^\dagger \widetilde{Q}\right) + \Lambda_{ij}^U \widetilde{U}^* \widetilde{U} + \Lambda_{ij}^D \widetilde{D}^* \widetilde{D}\right] +$$

$$+ \overline{\Lambda}{}_{ij}^Q \left(\Phi_i^\dagger \widetilde{Q}\right) \left(\widetilde{Q}^\dagger \Phi_j\right) + \frac{1}{2} \left[\Lambda \epsilon_{ij} \left(i\Phi_i^T \sigma_2 \Phi_j\right) \widetilde{D}^* \widetilde{U} + \text{h.c.}\right] , i, j, k, l = 1, 2 \,,$$

$\mathcal{V}_{\widetilde{Q}}$ denotes the terms of interaction of four scalar quarks.

Example Contributions to parameters of the Higgss potential

$$\Delta\lambda_1 = h_u^4 \lambda^4 v_3^4 I_2[m_Q, m_U] + h_d^4 A_d^4 I_2[m_Q, m_D] +$$

$$+ h_u^2 \lambda^2 v_3^2 \left(\left(\frac{g_2^2}{4} - \frac{g_1^2}{12} \right) I_1[m_Q, m_U] + \frac{1}{3} g_1^2 I_1[m_U, m_Q] \right) +$$

$$+ h_d^2 A_d^2 \left(\left(h_d^2 - \frac{g_1^2}{12} - \frac{g_2^2}{4} \right) I_1[m_Q, m_D] + \left(h_d^2 - \frac{g_1^2}{6} \right) I_1[m_D, m_Q] \right)$$

$$\Delta\lambda_2 = h_u^4 A_u^4 I_2[m_Q, m_U] + h_d^4 \lambda^4 v_3^4 I_2[m_Q, m_D] +$$

$$+ h_u^2 A_u^2 \left(\left(\frac{g_1^2}{12} - \frac{g_2^2}{4} \right) I_1[m_Q, m_U] + (h_u^2 - \frac{1}{3} g_1^2 I_1[m_U, m_Q] \right) +$$

$$+ h_d^2 \lambda^2 v_3^2 \left(\left(\frac{g_1^2}{12} + \frac{g_2^2}{4} \right) I_1[m_Q, m_D] + \frac{g_1^2}{6} I_1[m_D, m_Q] \right)$$

where I_1, I_2 define by Passarino–Veltman integrals (Nucl.Phys.B. (1979) 153. P.365–401.)

Physical States of Higgs bosons and Rotations

I. Transition into basis: H, h, A, G^0:

$$\begin{pmatrix} \phi_1^0 \\ \phi_2^0 \end{pmatrix} = \begin{pmatrix} cos\beta & -sin\beta \\ sin\beta & cos\beta \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}; \begin{pmatrix} \chi_1 \\ \chi_2 \end{pmatrix} = \begin{pmatrix} cos\beta & -sin\beta \\ sin\beta & cos\beta \end{pmatrix} \begin{pmatrix} G^0 \\ A \end{pmatrix}$$

II. Additional rotation with matrix A_{ij}.

$$\begin{pmatrix} h \\ H \\ A \end{pmatrix} = A \begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} \tag{1}$$

$$m_{ij} = \frac{\partial^2 U}{\partial\phi_i \partial\phi_j} (In\, the\, local\, minimum\, \frac{\partial U}{\partial \phi_i} = 0) \tag{2}$$

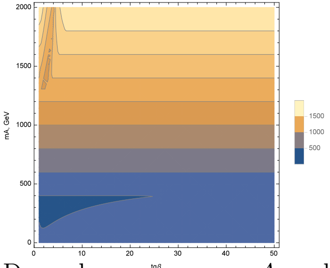
$$m_{11} = v^2 \lambda_1 Cos^2\beta + mA^2 Sin^2\beta + v^2 Sin2\beta Re(\lambda_6) + Sin^2\beta v^2 Re(\lambda_5) \tag{3}$$

$$\mathcal{M}_D = (h_i)^T (A^{-1})^T m\, A^{-1} h_i \tag{4}$$

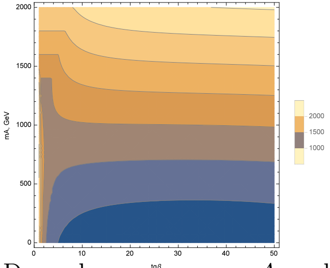
$$\mathcal{M}_D = \begin{pmatrix} M_{h_1}^2 & 0 & 0 \\ 0 & M_{h_2}^2 & 0 \\ 0 & 0 & M_{h_3}^2 \end{pmatrix}, \tag{5}$$

Restrictions on the parameters of the MSSM

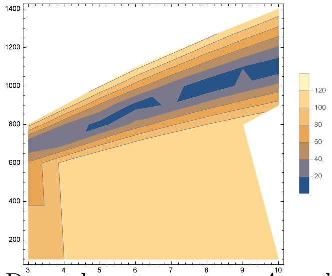
Parameters	Values
μ	$500(\text{GeV})$
$A_{t,b}$	$-1000 \div 1000(\text{GeV})$
M_{SUSY}	$500(\text{GeV})$
m_A	$100 \div 500(\text{GeV})$
$\tan\beta$	$3 \div 50$



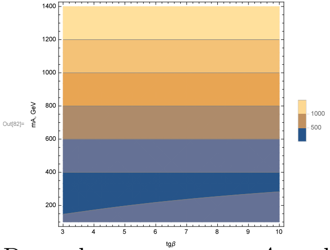
Dependence $\tilde{m}_1$ on mA and $tg\beta$



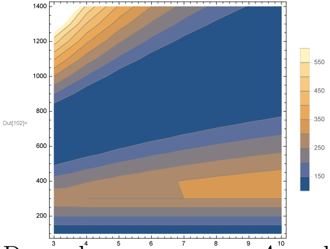
Dependence $\tilde{m}_2$ on mA and $tg\beta$



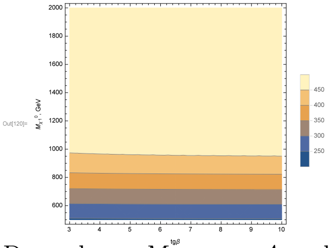
Dependence m_1 on mA and $tg\beta$



Dependence m_2 on mA and $tg\beta$



Dependence m_3 on mA and $tg\beta$



Dependence $M_{\chi_1^0}$ on mA and $tg\beta$

Conclusions

- Corrections to the Higgs potential parameters lead to explicit CP-violation and also give more possibilities for variation of the MSSM parameters.
- The masses of Higgs bosons at small $tg\beta$ values have a complex dependence on the model parameters. There is a possibility of an unobservable light Higgs boson.
- At small values $tg\beta$ the mass of the lightest stable particle must be more than ~ 250 GeV.
- μ–problem! $\mu H_1 H_2$: $\mu = \, ? \rightarrow \mu = \frac{1}{\sqrt{2}}\lambda < S >$
  We have more opportunities in NMSSM.