Higgs and Neutralino Phenomenology of Peccei-Quinn NMSSM

K.J. Bae, KC, E.J. Chun, S.H. Im, C.B. Park, C.S. Shin, arXiv:1208.2555
KC, S.H. Im, K.S. Jeong, M. Yamaguchi, arXiv:1211.0875
KC, S.H. Im, K.S. Jeong, in preparation

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Outline

1) Introduction and motivation

2) Model: PQ-NMSSM

3) Higgs and neutralino phenomenology:

Singlet-like 98 GeV Higgs boson which may explain
the 2σ excess of Zbb events at LEP

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Introduction and motivation

* Low energy SUSY and QCD axion are compelling candidate for BSM physics:

  - **Gauge hierarchy problem:** Low energy SUSY around TeV
  - **Strong CP problem:** PQ-symmetry spontaneously broken at

    10^9 GeV < v_{PQ} < 10^{11} GeV ➔ QCD axion

* Potential difficulties with low energy SUSY

  Flavor/CP problem, μ-problem, Cosmological moduli/gravitino problem

* Puzzle about QCD axion:

  What is the dynamical origin of the intermediate scale v_{PQ} ?

Having SUSY and PQ-symmetry together can solve many of these puzzles!

- **Natural generation of an intermediate PQ scale**

Competition between SUSY breaking effects and Planck-scale suppressed effects: Murayama, Suzuki, Yanagida (1992)

$$V = -m_{soft}^2 |X|^2 + \frac{|X|^6}{M_{Planck}^2} \qquad v_{PQ} \equiv \langle X \rangle \sim \sqrt{m_{soft} M_{Planck}}$$

- **Attractive solution to the μ-problem**

$U(1)_{PQ}$ forbids a bare μ-term, but a correct size of μ can be generated as a consequence of spontaneous PQ breaking: Kim, Nilles (1984)

$$\Delta W = \frac{X^2}{M_{Planck}} H_u H_d \quad \rightarrow \quad \mu \sim \frac{v_{PQ}^2}{M_{Planck}} \sim m_{soft}$$

μ-problem in PQ-NMSSM:

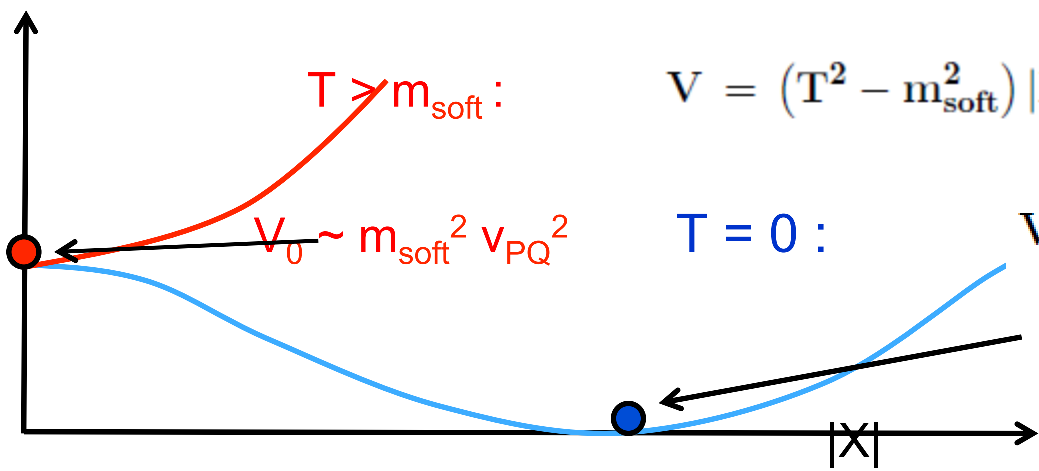
$$\Delta W = \lambda S H_u H_d + \mu_0 H_u H_d + \mu_1 S + \mu_2 S^2 + \kappa S^3$$

$$\mu_0 \sim \mu_1 \sim \mu_2 \sim \frac{v_{PQ}^2}{M_{Planck}} \sim m_{soft}, \quad \kappa \sim \left(\frac{v_{PQ}}{M_{Planck}}\right)^n \sim 0$$

- ## Late thermal inflation solving the cosmological moduli problem

Lyth, Stewart (1996); KC, Chun, Kim (1997)

(Nearly inevitable) thermal inflation at $m_{soft} < T < \sqrt{m_{soft}\, v_{PQ}}$ would dilute away all dangerous relics (moduli, gravitinos, ...)



$$V = \left(T^2 - m_{soft}^2\right)|X|^2 + \frac{|X|^6}{M_{Planck}^2}$$

$$V = -m_{soft}^2|X|^2 + \frac{|X|^6}{M_{Planck}^2}$$

$$v_{PQ} \equiv \langle X \rangle \sim \sqrt{m_{soft} M_{Planck}}$$

* With μ generated by spontaneous PQ-breaking, an attractive AD leptogenesis mechanism can operate after thermal inflation Stewart, Kawasaki, Yanagida (1997)

$$m_{LH_u}^2(\text{before}) < 0, \qquad m_{LH_u}^2(\text{after}) = m_{LH_u}^2(\text{before}) + |\mu|^2 + \delta m_{soft}^2 > 0$$

* **Axion dark radiation** from the decays of PQ-breaking field X (~ saxion)

KC, Chun, Kim (1997)

$$\Delta N_{\rm eff} = \frac{43}{7}\frac{B_a}{(1-B_a)}\left(\frac{43/4}{g_{RH}}\right) = 0.1 - 0.7 \quad \text{for} \;\; B_a \equiv Br(X \to aa) = 0.1 - 0.02$$

PLANCK: $\Delta N_{\rm eff} = 0.58 \pm 0.25 \;(\text{HST value of } H_0),\; 0.25 \pm 0.27 \;(\text{CMB value of } H_0)$

➔ Axion dark radiation with $\Delta N_{\rm eff} \sim 0.3$ solve the 2.5σ tension between PLANCK & HST measurements of H_0

- **Rich dark matter cosmology:** Axions, Neutralinos or Axinos

Diverse mechanism for DM production

* Freeze-out of thermal neutralinos

* Misalignment of axion field, axion emission by collapsing cosmic string/walls

* Production or dilution of DM by out of equilibrium decays of saxions/axinos

Taking into account the production by string/wall system, axions provide always a sizable part of DM for v_{PQ} > 5x10^9 GeV (< 10^{11} GeV). Hitamatsu et al (2012)

NMSSM

Interpretation of SM-like 126 GeV Higgs boson:

* **MSSM** with multi-TeV m_{stop} and/or maximal stop mixing

➔ Fine-tuning of O(0.1) % for EWSB (for mediation scale $\Lambda \sim M_{GUT}$)

* **NMSSM:** $\Delta W = \lambda S H_u H_d$

Additional contributions to m_{higgs}

- F-term quartic coupling

$$\Delta V = \lambda^2 |H_u H_d|^2 \qquad \Delta m^2_{higgs} = \frac{2\lambda^2 \sin^2 2\beta}{g_1^2 + g_2^2} M_Z^2$$

- Mixing with a lighter singlet ($m_s < m_{higgs}$ = 126 GeV)

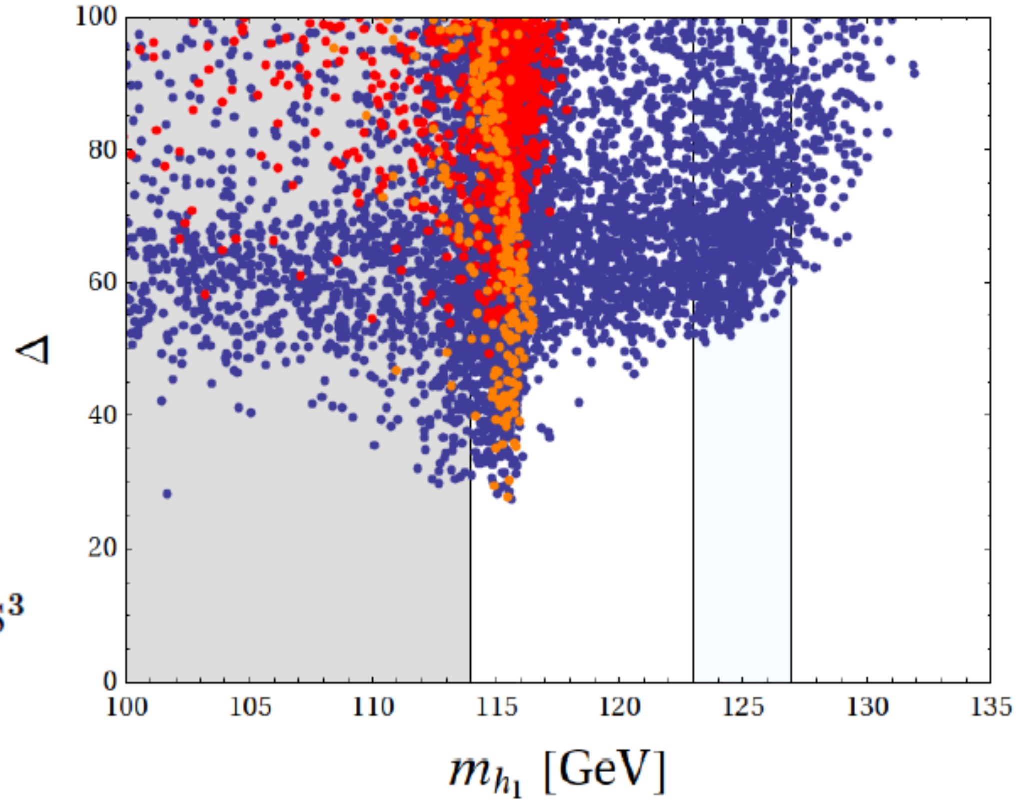
$$\Delta m^2_{higgs} \sim \left(m^2_{higgs} - m^2_s\right) \sin^2\theta$$

➔ Lighter (sub-TeV) stops, so significantly reduced fine-tuning:

O(few) % for $\lambda \leq 0.7$ and $\Lambda \sim M_{GUT}$ (for general NMSSM)

Fine-tuning in NMSSM ($\lambda \lesssim 0.7$, $\Lambda \sim M_{GUT}$)

Ross, Schmidt-Hoberg, Staub (2012)



* MSSM (Orange)

* Scale-invariant NMSSM (Red):

$$W_{Z_3 NMSSM} = \lambda S H_u H_d + \kappa S^3$$

(Z_3 symmetry)

* General NMSSM (Blue)

$$W_{GNMSSM} = \lambda S H_u H_d + \mu_1^2 S + \mu_2 S^2 + \kappa S^3$$

($\mu_1 \sim \mu_2 \sim m_{soft}$ with spontaneously broken discrete R-symmetry)

* PQ-NMSSM:

$$W_{PQ-NMSSM} = \lambda S H_u H_d + \mu_1^2 S + \mu_2 S^2$$

($\mu_1 \sim \mu_2 \sim m_{soft}$ with spontaneously broken PQ-symmetry)

PQ-NMSSM

NMSSM with a PQ-symmetry spontaneously broken at $v_{PQ} \sim \sqrt{m_{soft} M_{Planck}}$ by an interplay between m_{soft} and M_{Planck} :

Low energy realization of $U(1)_{PQ}$:

$$U(1)_{PQ}: \ A \to A + i\alpha v_{PQ}, \ \ H_u H_d \to e^{-i\alpha} H_u H_d, \ \ S \to e^{i\alpha} S, \ldots$$

($$A \equiv \text{axion superfield} = \sigma + ia + \theta \tilde{a} + \theta^2 F^A$$

Low energy effective lagrangian of generic PQ-NMSSM:

$$K = K_0(A + A^\dagger) + \sum_{\Phi} Z_\Phi(A + A^\dagger)\Phi^\dagger \Phi + \Delta K$$

$$\Delta K = \tilde{\mu}_4 e^{A^\dagger / v_{PQ}} S + \kappa_2 e^{2A^\dagger / v_{PQ}} S^2 + \kappa_3 e^{-2A^\dagger / v_{PQ}} H_u H_d + \ldots + \text{h.c.}$$

$$W = \lambda S H_u H_d + y_U H_u Q U^c + y_D H_d Q D^c + y_L H_d L E^c + \Delta W$$

$$\Delta W = \tilde{\mu}_i^2 e^{-A/v_{PQ}} S + \tilde{\mu}_2 e^{-2A/v_{PQ}} S^2 + \tilde{\mu}_3 e^{2A/v_{PQ}} H_u H_d + \kappa_1 e^{-3A/v_{PQ}} S^3 + \ldots$$

Generically $$\tilde{\mu}_i \sim v_{PQ} \left(\frac{v_{PQ}}{M_{Planck}} \right)^{n_i}, \qquad \kappa_i \sim \left(\frac{v_{PQ}}{M_{Planck}} \right)^{k_i} \qquad (n_i, k_i \geq 1)$$

➔ $$|\kappa_i| \sim 0 \qquad \text{Max}\,(\tilde{\mu}_i) \sim m_{soft}$$

For low energy particle phenomenology, one can replace the axion-superfield by its VEV.

Then, after an appropriate field redefinition $S \rightarrow S + \mu_0 + b_0\theta^2$ ıergy effective lagrangian of generic PQ-NMSSM takes the form:

$$\begin{aligned} K_{\rm eff} &= \sum_{\Phi}(1 - m_{\Phi}^2\theta^2\bar{\theta}^2)\Phi^\dagger\Phi \\ W_{\rm eff} &= \lambda(1 + A_\lambda\theta^2)SH_uH_d + \mu_1^2(1 + B_1\theta^2)S + \frac{1}{2}\mu_2(1 + B_2\theta^2)S^2 \\ &\quad + y_U(1 + A_U\theta^2)H_uQU^c + y_D(1 + A_D\theta^2)H_dQD^c + y_L(1 + A_L\theta^2)H_dLE^c \end{aligned}$$

Depending upon the UV model at scales > v_{PQ} , we have three possibilities:

1) $\mu_1 \sim \mu_2 \sim m_{\rm soft}$

2) $\mu_1 \sim m_{\rm soft}, \quad \mu_2 \sim m_{\rm soft}(v_{PQ}/M_{\rm Planck})^k \sim 0$

3) $\mu_1 \sim m_{\rm soft}(v_{PQ}/M_{\rm Planck})^k \sim 0, \quad \mu_2 \sim m_{\rm soft}$

It is straightforward to construct an explicit UV model realizing each of these three possibilities in the low energy limit, but the following model realizing $\mu_1 \sim m_{soft}$, $\mu_2 \sim 0$ seems to be **the simplest.**

(With a bit more complicate PQ-breaking sector, we can easily realize more general scenario having $\mu_1 \sim \mu_2 \sim m_{soft}$.)

Minimal PQ-NMSSM:

* PQ charges: $(S, H_uH_d, X, Y) = (1, -1, 1/2, -1/6)$

* Most general PQ-invariant Kahler potential and superpotential:

$$K = \sum_{\Phi} \Phi^*\Phi + \frac{1}{M_{Planck}} X^2 S^* + \ldots$$

$$W = \lambda S H_u H_d + \frac{1}{M_{Planck}} X^2 H_u H_d + \frac{1}{M_{Planck}} X Y^3 + \ldots$$

$$\rightarrow \quad v_{PQ} \sim \langle X \rangle \sim \langle Y \rangle \sim \sqrt{m_{soft} M_{Planck}} \;, \quad \frac{F^X}{X} \sim \frac{F^Y}{Y} \sim m_{soft}$$

$$\rightarrow \quad W_{eff} = \lambda S H_u H_d + \mu_1^2 S + \frac{1}{2}\mu_2 S^2 + \ldots$$

$$\mu_1 \sim \frac{v_{PQ}^2}{M_{Planck}} \sim m_{soft} \qquad \mu_2 \sim m_{soft} \left(\frac{v_{PQ}}{M_{Planck}}\right)^4 \sim 0$$

Stringy UV completion of PQ-NMSSM with $v_{PQ} \sim (m_{soft}M_{Planck})^{1/2}$?

* String compactifications generically involve multiple axions, one of which may correspond to the QCD axion solving the strong CP problem.

* Anomalous $U(1)_A$ gauge symmetry with $U(1)_A$-QCD-QCD anomaly (cancelled by the GS mechanism) is ubiquitous in string compactification:

$U(1)_A$:

$$A_\mu \to A_\mu + \partial_\mu \alpha(x), \quad a_{st} \to a_{st} + \delta_{GS}\alpha(x)$$

$$\phi_i \to e^{iq_i\alpha(x)}\phi_i \quad \left(\delta_{GS} = \frac{1}{8\pi^2}\sum_i q_i \mathrm{Tr}(T_a^2(\phi_i))\right)$$

$$\Rightarrow \quad \mathcal{L}_{eff} = M_{Pl}^2 \frac{\partial^2 K}{\partial t^2}(\partial_\mu a_{st} - \delta_{GS}A_\mu)^2 + \frac{1}{4}a_{st}G\tilde{G} - \frac{g_A^2}{2}\left(\xi_{FI} - q_i|\phi_i|^2\right)^2 + \ldots$$

a_{st} = stringy axion for the GS anomaly cancellation mechanism

t = modulus partner of **a_{st}**

* Quite often, H_uH_d is $U(1)_A$-charged, and generically the model involves multiple $U(1)_A$-charged SM-singlets $\{\varphi_i\}$ with

$$\Delta W = \lambda_i\varphi_i H_u H_d + \frac{\kappa_{ij}}{M_{Planck}}\varphi_i\varphi_j H_u H_d + \ldots$$

* Such models can allow a SUSY solution with vanishing Fayet-Iliopoulos term, and then $U(1)_A$ gauge boson gets a superheavy mass by the Stukelberg mechanism, **while leaving the global part of $U(1)_A$ unbroken**:

$$\mathcal{L}_{\rm eff} = M_{\rm Pl}^2 \frac{\partial^2 K}{\partial t^2} \left(\partial_\mu a_{\rm st} - \delta_{\rm GS} A_\mu\right)^2 + \frac{1}{4} a_{\rm st} G\tilde{G} - \frac{g_A^2}{2}\left(\xi_{\rm FI} - q_i|\phi_i|^2\right)^2 + \ldots$$

Low energy limit of models with stringy axion:

- Without anomalous $U(1)_A$: $\delta_{GS} = 0$

Physical QCD axion a_{st} with $v_{PQ} = \sqrt{\frac{\partial^2 K}{\partial t^2} \frac{M_{\rm Planck}}{8\pi^2}} \sim 10^{16}\ {\rm GeV}$

- With anomalous $U(1)_A$: KC, Jeong, Okumura, Yamaguchi (2011)

Stringy axion is eaten by the $U(1)_A$ gauge boson, leaving a global $U(1)_{PQ}$ symmetry (= global part of $U(1)_A$), which would be spontaneously broken at

$v_{PQ} \sim \sqrt{m_{\rm soft} M_{\rm Planck}} \sim 10^{10}\ {\rm GeV}$ JSY breaking effects are turned on.

Higgs and neutralino phenomenology

(General, PQ, Z3) NMSSM can have interesting Higgs and/or neutralino phenomenology if the singlet scalar and/or singlino are light:

m_S ~ sub-TeV, even < few 100 GeV.

* Mixing among CP-even Higgs bosons and its implication for the precision Higgs phenomenology:

Possibility of a singlet-like 98 GeV Higgs boson, together with SM-like 126 GeV Higgs boson

* Constraints on the light singlino in Minimal PQ-NMSSM

* Higgs mixing in general NMSSM

KC, Im, Jeong, Yamaguchi, arXiv:1211.0875; Cheung et al, arXiv:1302.0314; Barbieri et al, arXiv:1304.3670; Badziak et al, arXiv:1304.5437

General NMSSM with $W(S) = \lambda S H_u H_d + f(S)$

CP-even neutral Higgs:

: $\hat{h}$ Doublet fluctuation along the direction of VEV (SM Higgs in the decoupling limit)

: $\hat{H}$ Doublet fluctuation orthogonal to $\hat{h}$

= $\hat{s}$ Singlet fluctuation

Higgs mixing and mass eigenstate Higgs:

θ_1 = h-H mixing, θ_2 = h-s mixing, θ_3 = H-s mixing

$$h = c_{\theta_1} c_{\theta_2} \hat{h} - s_{\theta_1} \hat{H} - c_{\theta_1} s_{\theta_2} \hat{s}$$

$$s = (c_{\theta_2} c_{\theta_3} - s_{\theta_1} s_{\theta_2} s_{\theta_3}) \hat{s} + (s_{\theta_2} c_{\theta_3} + s_{\theta_1} s_{\theta_3} c_{\theta_2}) \hat{h} + s_{\theta_3} c_{\theta_1} \hat{H}$$

$$H = (c_{\theta_1} c_{\theta_3} - s_{\theta_3} c_{\theta_2}) \hat{H} + (s_{\theta_1} c_{\theta_2} c_{\theta_3} - s_{\theta_2} s_{\theta_3}) \hat{h} - (s_{\theta_3} c_{\theta_2} + s_{\theta_1} s_{\theta_2} c_{\theta_3}) \hat{s}$$

Lagrangian parameters vs Higgs mass/mixing in general NMSSM

$$(\mathbf{m_h}, \mathbf{m_s}, \mathbf{m_H}, \boldsymbol{\theta_1}, \boldsymbol{\theta_2}, \boldsymbol{\theta_3}) \quad \leftrightarrow \quad (\mathbf{m_0}, \mathbf{m_S}, \boldsymbol{\mu}, \boldsymbol{\mu}\mathbf{B}, \mathbf{A}, \boldsymbol{\lambda}, \mathbf{tan}\boldsymbol{\beta})$$

$$m_0^2 = m_Z^2 + \frac{3m_t^4}{4\pi^2 v^2}\left[\ln\left(\frac{m_{\tilde{t}}^2}{m_t^2}\right) + \frac{X_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12m_{\tilde{t}}^2}\right) + \cdots\right]$$

$$\mu = \lambda\langle S\rangle, \quad \mu B \ = \ A_\lambda \mu + \lambda\langle\partial_S f\rangle, \quad A \ = \ A_\lambda + \langle\partial_S^2 f\rangle \qquad m_A^2 = \frac{2\mu B}{\sin 2\beta}$$

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$$\lambda^2 v^2 = m_Z^2 + \frac{1}{\sin 4\beta}\Big((m_H^2 - m_s^2)s_{\theta_2}s_{2\theta_3} + 2(m_h^2 - m_H^2 c_{\theta_3}^2 - m_s^2 s_{\theta_3}^2)s_{\theta_1}c_{\theta_2}\Big)c_{\theta_1},$$

$$\begin{aligned}\lambda v \mu = & -\frac{1}{4}m_h^2 c_{\theta_1}^2 s_{2\theta_2} - \frac{1}{4}(m_H^2 - m_s^2)s_{\theta_1}c_{2\theta_2}s_{2\theta_3} \\ & + \frac{1}{4}\Big((m_H^2 - m_s^2 s_{\theta_1}^2)s_{\theta_3}^2 - (m_H^2 s_{\theta_1}^2 - m_s^2)c_{\theta_3}^2\Big)s_{2\theta_2} \\ & - \frac{\tan 2\beta}{4}\Big((m_H^2 - m_s^2)c_{\theta_2}s_{2\theta_3} - 2(m_h^2 - m_H^2 c_{\theta_3}^2 - m_s^2 s_{\theta_3}^2)s_{\theta_1}s_{\theta_2}\Big)c_{\theta_1},\end{aligned}$$

$$\lambda v\, A \ = -\frac{1}{2\cos 2\beta}\Big((m_H^2 - m_s^2)c_{\theta_2}s_{2\theta_3} - 2(m_h^2 - m_H^2 c_{\theta_3}^2 - m_s^2 s_{\theta_3}^2)s_{\theta_1}s_{\theta_2}\Big)c_{\theta_1}.$$

$$m_0^2 + (\lambda^2 v^2 - m_Z^2)\sin^2 2\beta = m_h^2 c_{\theta_1}^2 c_{\theta_2}^2 + m_H^2(s_{\theta_1}c_{\theta_2}c_{\theta_3} - s_{\theta_2}s_{\theta_3})^2 + m_s^2(s_{\theta_2}c_{\theta_3} + s_{\theta_1}c_{\theta_2}s_{\theta_3})^2,$$

$$m_A^2 - (\lambda^2 v^2 - m_Z^2)\sin^2 2\beta = m_h^2 s_{\theta_1}^2 + m_H^2 c_{\theta_1}^2 c_{\theta_3}^2 + m_s^2 c_{\theta_1}^2 s_{\theta_3}^2,$$

$$m_S^2 + \lambda^2 v^2 = m_h^2 c_{\theta_1}^2 s_{\theta_2}^2 + m_H^2(s_{\theta_1}s_{\theta_2}c_{\theta_3} + c_{\theta_2}s_{\theta_3})^2 + m_s^2(c_{\theta_2}c_{\theta_3} - s_{\theta_1}s_{\theta_2}s_{\theta_3})^2$$

Higgs boson couplings

SM-like Higgs boson h:

$$\frac{C^{h}_{W,Z}}{C^{hSM}_{W,Z}} = c_{\theta_1}c_{\theta_2}\,, \quad \frac{C^{h}_{t}}{C^{hSM}_{t}} = c_{\theta_1}c_{\theta_2} + s_{\theta_1}\cot\beta\,, \quad \frac{C^{h}_{b}}{C^{hSM}_{b}} = \frac{C^{h}_{\tau}}{C^{hSM}_{\tau}} = c_{\theta_1}c_{\theta_2} - s_{\theta_1}\tan\beta$$

$$\frac{\delta C^{h}_{\gamma}}{C^{hSM}_{\gamma}} \simeq 0.2\,\frac{\lambda v}{\mu}\tan\theta_2$$ the h-S mixing and charged-Higgsino loop

Singlet-like Higgs boson S:

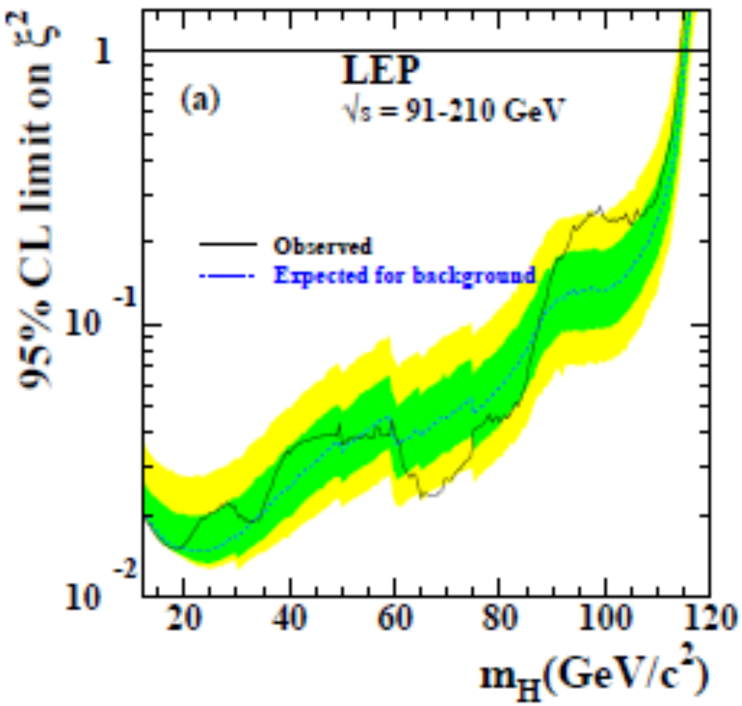
$$\frac{C^{s}_{W,Z}}{C^{hSM}_{W,Z}} = s_{\theta_2}c_{\theta_3} + s_{\theta_1}s_{\theta_3}c_{\theta_2}\,, \quad \frac{C^{s}_{t}}{C^{hSM}_{t}} = s_{\theta_2}c_{\theta_3} + s_{\theta_1}s_{\theta_3}c_{\theta_2} - s_{\theta_3}c_{\theta_1}\cot\beta$$

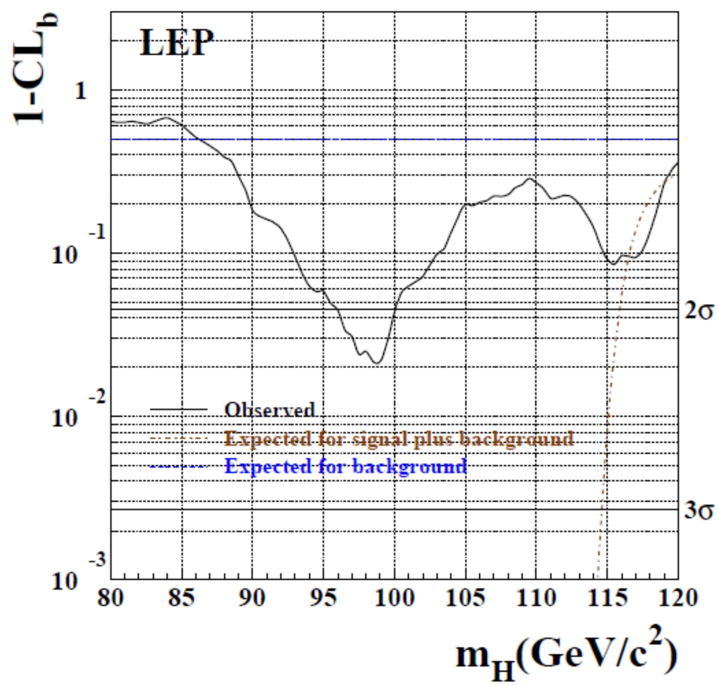
$$\frac{C^{s}_{b}}{C^{hSM}_{b}} = \frac{C^{s}_{\tau}}{C^{hSM}_{\tau}} = s_{\theta_2}c_{\theta_3} + s_{\theta_1}s_{\theta_3}c_{\theta_2} + s_{\theta_3}c_{\theta_1}\tan\beta$$

➔ $R(e^+e^- \to Z\,s \to Zb\bar{b}) \sim \sin^2\theta_2$ for m_s < 114 GeV

2σ excess in e+e- → Zbb at m_{bb} ~ 98 GeV in LEP data:

R(e+e- → Z s→ Zbb) = 0.1 - 0.25 with m_s ~ 98 GeV





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$(m_h, m_s) = (126, 98)$ GeV in general (PQ)NMSSM with

* $\lambda \leq 0.7$, $\mu > 105$ GeV, $m_H > 300$ GeV (constraints on B-physics)

* Not too heavy stop: 600 GeV < m_{stop} < 2 TeV

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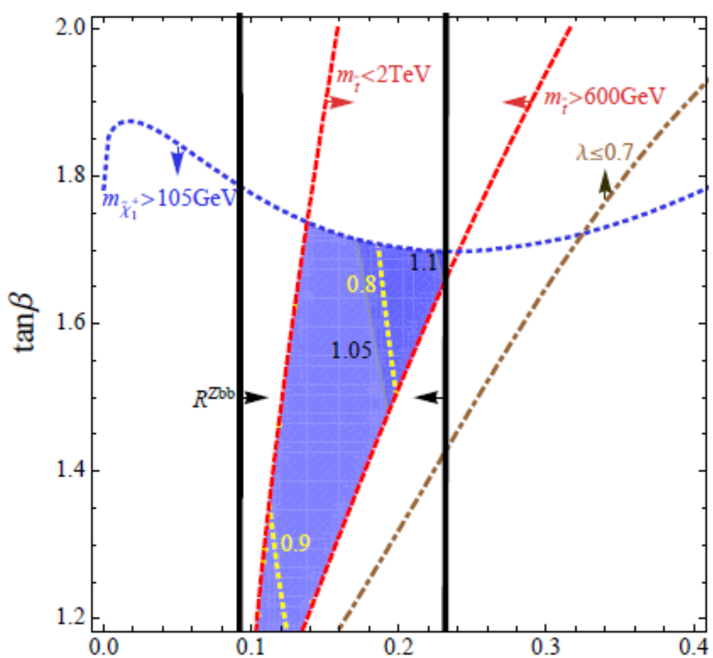
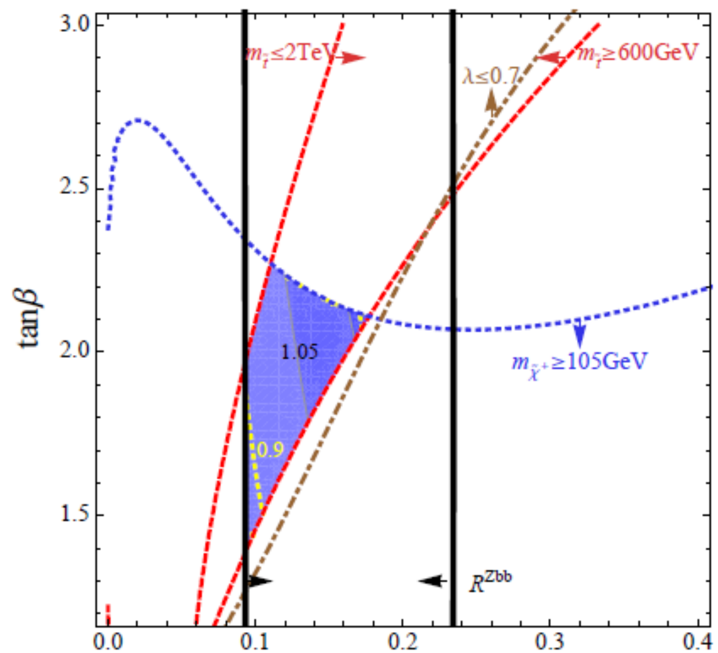




$\sin^2\theta_2$ (h-s) $\sin^2\theta_2$ (h-s)

m_H = 350 GeV, θ_3(H-s) = 0.1 m_H = 500 GeV, θ_3(H-s) = 0.07

B(pp → h → VV) = 1

Neutralinos in Minimal PQ-NMSSM: Light singlino-like neutralino

$$\mathcal{M}_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -g_1 v_d/\sqrt{2} & g_1 v_u/\sqrt{2} & 0 \\ & M_2 & g_2 v_d/\sqrt{2} & -g_2 v_u/\sqrt{2} & 0 \\ & & 0 & -\mu & -\lambda v_u \\ & & & 0 & -\lambda v_d \\ & & & & 0 \end{pmatrix}$$

$$W = \lambda S H_u H_d + \mu_1^2 S$$

nishing singlino

jorana mass

$$\rightarrow \quad m_{\tilde{\chi}_1^0} = \frac{\lambda^2 v^2 \mu \sin 2\beta}{\mu^2 + \lambda^2 v^2} + \mathcal{O}\left(\frac{\lambda^2 g^2 v^4 \cos^2 2\beta}{\mu^2 M_{\tilde{B},\tilde{W}}}\right)$$

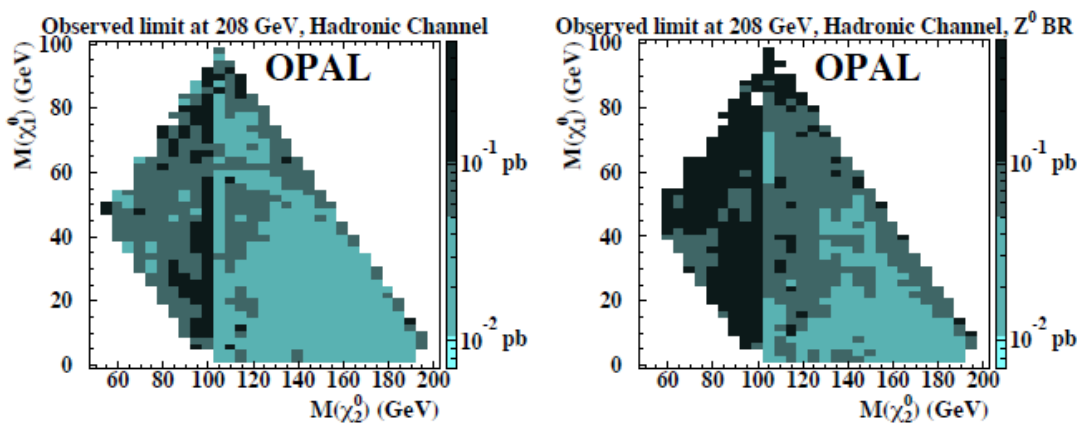
$$\leq \left[86\left(\frac{\lambda}{0.7}\right)\left(\frac{2}{1+\tan^2\beta}\right)^{1/2} + \mathcal{O}\left(\frac{\lambda^2 g^2 v^4 \cos^2 2\beta}{\mu^2 M_{\tilde{B},\tilde{W}}}\right)\right] \ \mathrm{GeV}$$

* To avoid a too large $\mathrm{Br}(h \to \tilde{\chi}_1^0 \tilde{\chi}_1^0)$ $\quad m_{\tilde{\chi}_1^0} > \frac{m_h}{2} \simeq 63\ \mathrm{GeV}$

* LEP bound:

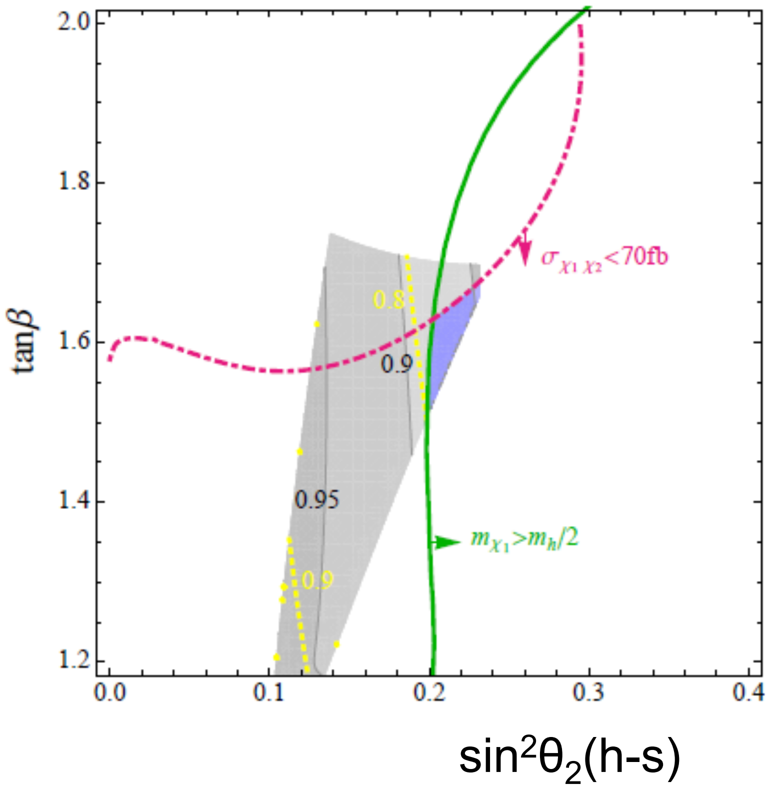
$$\sigma(e^+e^- \to \tilde{\chi}_1^0 \tilde{\chi}_2^0) < 70\ \mathrm{fb}$$

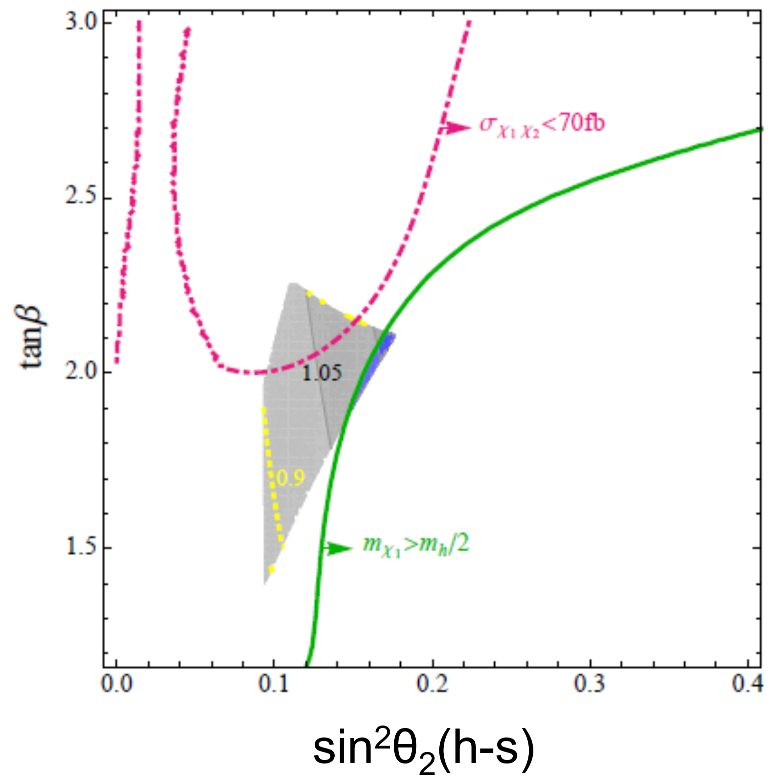
$$\left(\ m_{\tilde{\chi}_1^0} + m_{\tilde{\chi}_2^0} < 208\ \mathrm{GeV}\right.$$



(a) $\chi_2 \to q\bar{q}\chi_1$ (b) $\chi_2 \to Z^*\chi_1$

(m_h , m_s) = (126, 98) GeV in Minimal PQ-NMSSM





m_H = 350 GeV, θ_3(H-s) = 0.1

m_H = 500 GeV, θ_3(H-s) = 0.07

Conclusion

1) There are many virtues of having SUSY and PQ-symmetry together:

* Natural generation of an intermediate axion scale: $v_{PQ} \sim \sqrt{m_{soft} M_{Planck}}$
* Attractive solution to the μ-problem and cosmological moduli problem
* Axion dark radiation, Rich DM cosmology, …

2) These virtues, together with the SM-like 126 GeV Higgs boson, point towards PQ-NMSSM

3) (General, PQ, Z_3, …)NMSSM can give interesting Higgs and neutralino phenomenology associated with light singlet scalar and singlino, which can be tested at LHC and/or ILC, so is worth for a detailed study.