Peccei-Quinn NMSSM in the light of 125 GeV Higgs

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Contents

- PQ NMSSM
  - Higgs mass
  - Neutralino sector
- Phenomenological constraints
  - Z invisible decay
  - χ_1^0, χ_2^0 production in LEP II
  - Higgs invisible decay
  - DM relic density, XENON100 bound on direct detection
- Small $\tan\beta$ ($1 < \tan\beta < 2$) region
- Large $\tan\beta$ ($\tan\beta > 2$) region

PQ NMSSM

$$W_{\rm eff} = (\mu_0 + \lambda S) H_u H_d + \mu_S^2 S + \frac{1}{2}\mu'_S S^2 + \frac{1}{3}\kappa S^3$$

- NMSSM : SM singlet superfield S coupled to the Higgs fields through the renormalizable term $\lambda S H_u H_d$ which can give a solution to the "mu problem" in the MSSM by the VEV of S.
- PQ symmetry : Global U(1) symmetry that can give the axion solution to the "strong CP problem".
- Assume $\lambda S H_u H_d$ is allowed in the PQ symmetric phase with $q_S = -(q_{Hu} + q_{Hd})$.
- The other terms are generated by spontaneous PQ symmetry breaking below the PQ scale v_{PQ} with the PQ sector like

$$W_{\rm PQ} = \frac{\kappa_{\rm PQ}}{M_{\rm Pl}} X_1^n X_2^{4-n} \qquad K = \frac{\kappa_{XS}}{M_{\rm Pl}} X_1^{*2} S + {\rm h.c.}$$

PQ NMSSM

$$W_{\text{eff}} = (\mu_0 + \lambda S) H_u H_d + \mu_S^2 S + \frac{1}{2}\mu'_S S^2 + \frac{1}{3}\kappa S^3$$

- It can be shown that the dimensionful parameters can be given by the soft SUSY breaking scale and the S^3 term is generally suppressed in the PQ NMSSM
  $\mu_0 \sim \mu_S \sim \mu_S' \sim v_{PQ}^2/M_{Pl} \sim m_{soft}$
- The μ_0 term can be rotated away by the field redefinition $S \to S - \mu_0/\lambda$
- The μ_S' term needs more complex field contents and charge assignments to be obtained in the PQ sector.
- So the simplest and easiest possibility of PQ symmetric NMSSM realized in low energy scale is

$$W_{\text{eff}} = \lambda S H_u H_d + \mu_S^2 S.$$

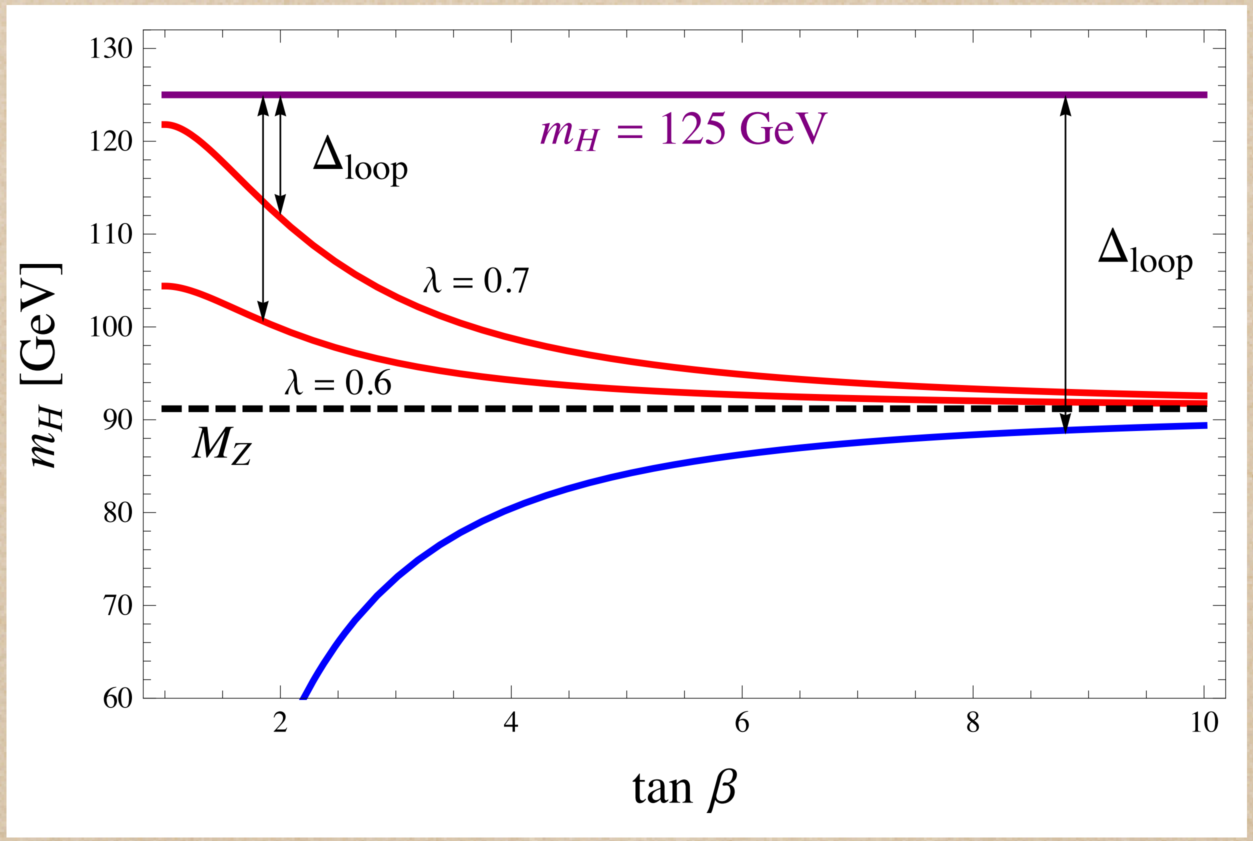
which we will call Minimal PQ NMSSM.

Higgs mass in the NMSSM

$$m_{h,\mathrm{tree}}^2 \simeq m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \left(\sin^2 2\beta - \frac{(2\mu_{\mathrm{eff}} - A_\lambda \sin 2\beta)^2}{m_S^2} \right)$$

Usual MSSM contribution

NMSSM-specific contribution



- The new Higgs quartic coupling induced by the F_S term raises the tree level Higgs mass which can ameliorate the fine-tuning for the 125 GeV Higgs mass with lower stop mass compared to the MSSM.
- Since it is proportional to sin2β~2/tanβ, small tanβ is favored in the NMSSM for the naturalness purpose.

Neutralino sector

$$\mathcal{M}_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -g_1 v_d/\sqrt{2} & g_1 v_u/\sqrt{2} & 0 \\ & M_2 & g_2 v_d/\sqrt{2} & -g_2 v_u/\sqrt{2} & 0 \\ & & 0 & -\mu_{\rm eff} & -\lambda v_u \\ & & & 0 & -\lambda v_d \\ & & & & 0 \end{pmatrix} \quad \text{in the basis } (-i\widetilde{\lambda}_1,\ -i\widetilde{\lambda}_2^3,\ \widetilde{H}_d^0,\ \widetilde{H}_u^0,\ \widetilde{S})$$

$$\Rightarrow \quad m_{\tilde{\chi}_1^0} \simeq \frac{\lambda^2 v^2}{\mu_{\rm eff}} \left[\sin 2\beta - \frac{\lambda^2 v^2}{\mu_{\rm eff}^2} \sin 2\beta - \left(\frac{g_1^2 v^2}{2\mu_{\rm eff} M_1} + \frac{g_2^2 v^2}{2\mu_{\rm eff} M_2} \right) \cos^2 2\beta + \mathcal{O}(\frac{v^4}{\mu_{\rm eff}^4}) \right]$$

- The fermion component in the S superfield, called singlino, constitutes for the lightest neutralino, mixing with neutral Higgsinos and gauginos.
- Since there is no supersymmetric mass term ($W_{\rm eff} \not\ni \mu_S' S^2$) for the singlino in the minimal PQ NMSSM, it can obtain its mass only by mixing.
- So the mass of the lightest neutralino in the minimal PQ NMSSM turns out to be quite small in general parameter space.

Phenomenological constraints

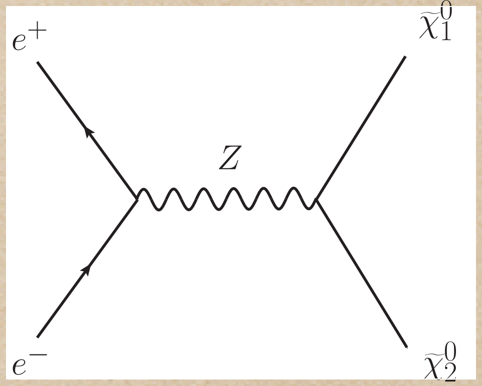
- Due to the light lightest neutralino, the minimal PQ NMSSM suffers several important phenomenological constraints.

- Z invisible decay in LEP II

$$\Gamma(Z \to \widetilde{\chi}_1^0 \widetilde{\chi}_1^0) = \frac{g_2^2}{4\pi} \frac{(N_{13}^2 - N_{14}^2)^2}{24\cos^2\theta_W} m_Z \left[1 - \left(\frac{2M_{\widetilde{\chi}_1^0}}{m_Z}\right)^2\right]^{3/2} < 3 \text{ MeV}$$

- X_1^0, X_2^0 pair production in LEP II

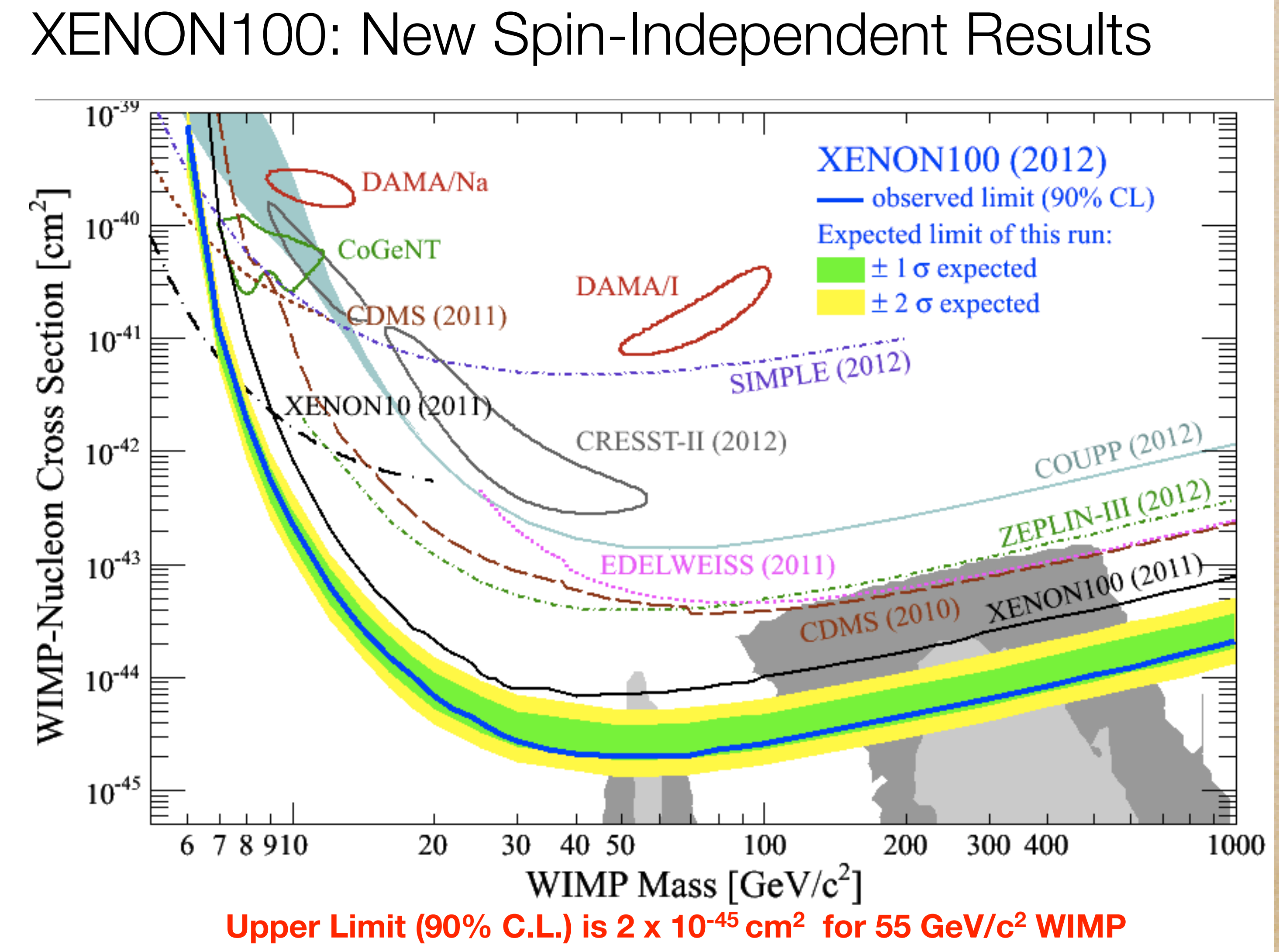
$$\sigma(e^+e^- \to \widetilde{\chi}_1^0 \widetilde{\chi}_2^0) < 10\,\text{fb}$$



- Higgs invisible decay : small tanβ (kinematically forbidden), large tanβ (nontrivial coupling suppression needed)

- Due to the enhanced Higgs-neutralino-neutralino coupling by $\lambda S H_u H_d$, the direct detection cross section of the lightest neutralino LSP is rather larger than MSSM.

- Recent XENON100 bound thus restricts the viable parameter space considerably.



Small tanβ (1 < tanβ < 2) region

- In small tanβ region, the lightest neutralino mass can be larger than the half of the Higgs mass.
- So the Higgs invisible decay as well as the Z invisible decay is kinematically forbidden.
- Also small tanβ gives large λ-proportional contribution to the tree level Higgs mass, which is favored by the naturalness perspective.

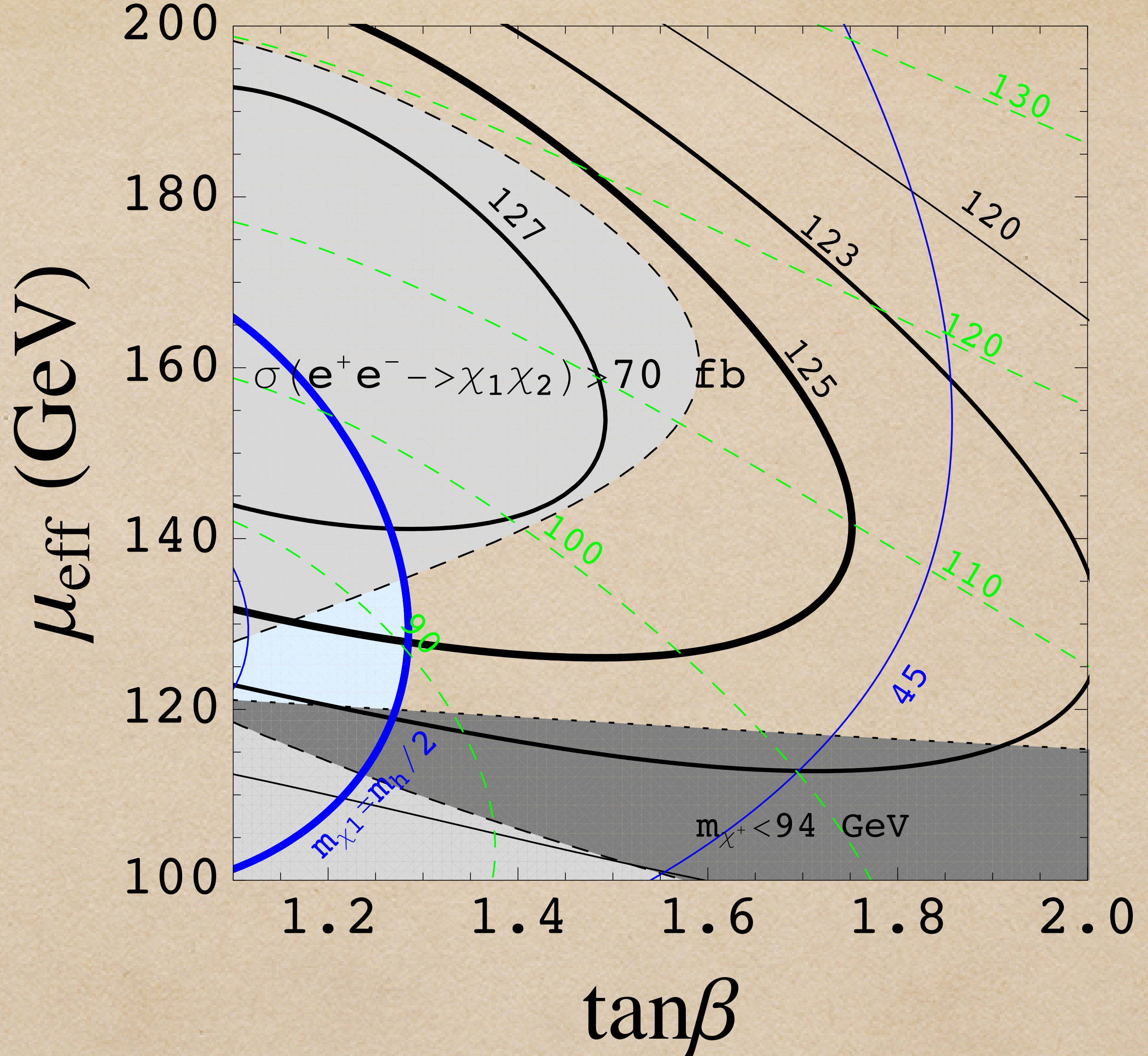
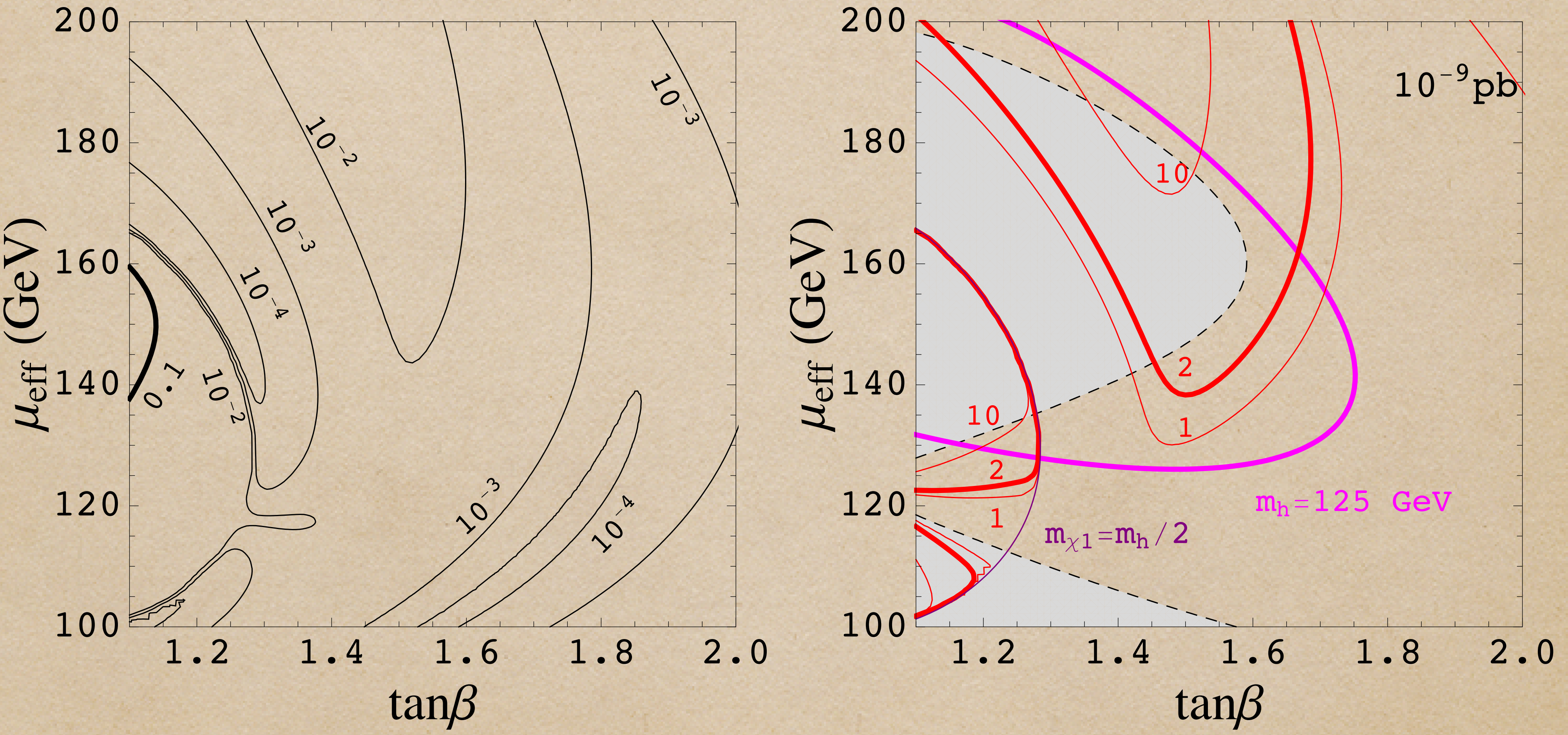


Figure 2: Plot for small $\tan\beta$. Here we set $6M_1 = 3M_2 = M_3 = 1$ TeV, $m_A = 350$ GeV, $m_{\tilde{Q}_3} = m_{\tilde{t}^c} = 500$ GeV, $A_t = 0$, and $\xi_S = -7 \times 10^7$ GeV^3. Black curves denote Higgs mass in GeV, blue curves denote $m_{\tilde{\chi}_1^0}$. in GeV, and green dashed curves denote $m_{\tilde{\chi}_2^0}$. The gray-shaded region is excluded by the OPAL [17].

- However, the small tanβ region is severely constrained by the recent XENON100 bound on the direct detection cross section of DM
- We find that the lightest neutralino LSP heavier than the half of the Higgs mass cannot satisfy the XENON100 bound without fine-tuning of the LSP mass to give resonant cross section.

$$m_{\tilde{\chi}_1^0} - \frac{m_h}{2} \lesssim 0.1 \text{ GeV}$$



(a) $\Omega^{\rm TH}_{\tilde{\chi}_1^0} h^2$ (b) $(\Omega^{\rm TH}_{\tilde{\chi}_1^0}/\Omega_{\rm DM})\,\sigma_{{\rm SI},\tilde{\chi}_1^0}$

- However, the PQ sector can cure this problem.

- The entropy dumping by late saxion decay with lower reheating temperature than the LSP freeze-out temperature can dilute the thermal LSP relic density enough.

$$\begin{aligned}\Delta &= \frac{S(T_{\rm RH})}{S(T_f)} \simeq \frac{g_*(T_f)}{g_*(T_{\rm RH})}\left(\frac{T_f}{T_{\rm RH}}\right)^5 \\ &\simeq 0.9\times 10^5\left(\frac{g_*(T_f)}{80}\right)\left(\frac{70}{g_*(T_{\rm RH})}\right)\left(\frac{T_f}{3\ {\rm GeV}}\right)^5\left(\frac{500\ {\rm MeV}}{T_{\rm RH}}\right)^5\end{aligned}$$

- Then the DM relic density can be explained by the axion CDM.

$$\Omega_a h^2 \simeq 0.23\left(\frac{v_{\rm PQ}}{10^{12}\ {\rm GeV}}\right)^{7/6}\langle\theta^2\rangle$$

Large tanβ (tanβ >2) region

- In large tanβ region, the LSP mass becomes smaller than the half of the Higgs mass, and the Higgs invisible decay channel opens.
- However, suppressing the h-X_1^0-X_1^0 coupling turns out to be difficult.

$$g_{h\tilde{\chi}_1^0\tilde{\chi}_1^0} = -g_2\Big(N_{12} - \tan\theta_W N_{11}\Big)\Big(S_{11}N_{13} - S_{12}N_{14}\Big) + \sqrt{2}\lambda\Big(S_{13}N_{13}N_{14} + N_{15}(S_{12}N_{13} + S_{11}N_{14})\Big)$$

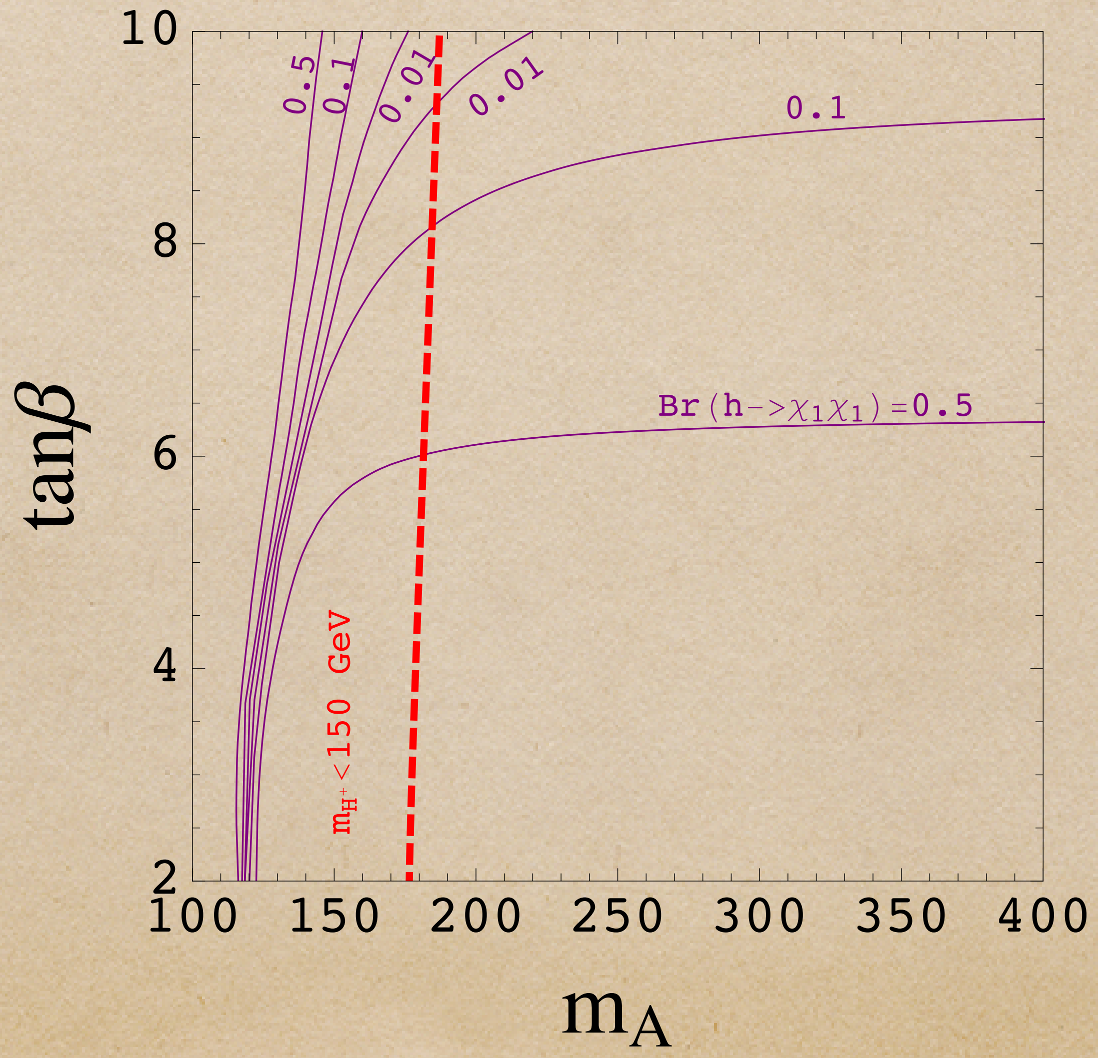
↓ $g_{hXX} = 0$

$$\frac{1}{\tan\beta} \simeq -\left(c - c\frac{9m_W^4}{4M_2^2\mu_{\rm eff}^2} - \frac{3m_W^2}{M_2\mu_{\rm eff}}\right)\left(1 - c\frac{3m_W^2}{2M_2\mu_{\rm eff}}\right)\left(1 + \frac{3\sqrt{2}\lambda^2v^2}{\mu_{\rm eff}^2}\right)$$

$$= \left[\frac{3m_W^2}{M_2\mu_{\rm eff}} - c\left(1 + \frac{9m_W^4}{4M_2^2\mu_{\rm eff}^2}\right) - c^2\frac{3m_W^2}{2M_2\mu_{\rm eff}}\left(1 - \frac{9m_W^4}{4M_2^2\mu_{\rm eff}^2}\right)\right]\left(1 + \frac{3\sqrt{2}\lambda^2v^2}{\mu_{\rm eff}^2}\right).$$

where $c \equiv S_{11}/S_{12},\ g_2 \simeq 2g_1$

- With $M_A{}^2 \equiv 2b_{eff}/\sin 2\beta$ (Not physical CP-odd Higgs mass in the NMSSM),
- For small $M_A \lesssim 170$ GeV, the parameter space is ruled out by the ATLAS bound on the charged Higgs mass (for $\tan\beta < 4$), or disfavored by non SM-like Higgs due to the CP-even Higgs mixing.
- For large $M_A \gtrsim 170$ GeV, the parameter space is disfavored by the large $\tan\beta$ needed to suppress the coupling. It requires $\tan\beta \gtrsim 10$ where the NMSSM specific contribution to the Higgs mass is negligible.



Conclusions

- The minimal PQ NMSSM is the simplest low energy consequence of the PQ symmetrized NMSSM which incorporates solutions to the mu problem and strong CP problem.

- This model is strongly disfavored by the Higgs invisible decay induced by the light lightest neutralino and the recent XENON100 bound on the DM direct detection cross section.

- Still, the thermal LSP dilution by the saxion decay in the PQ sector leaves the space for this model to be viable.

back-up

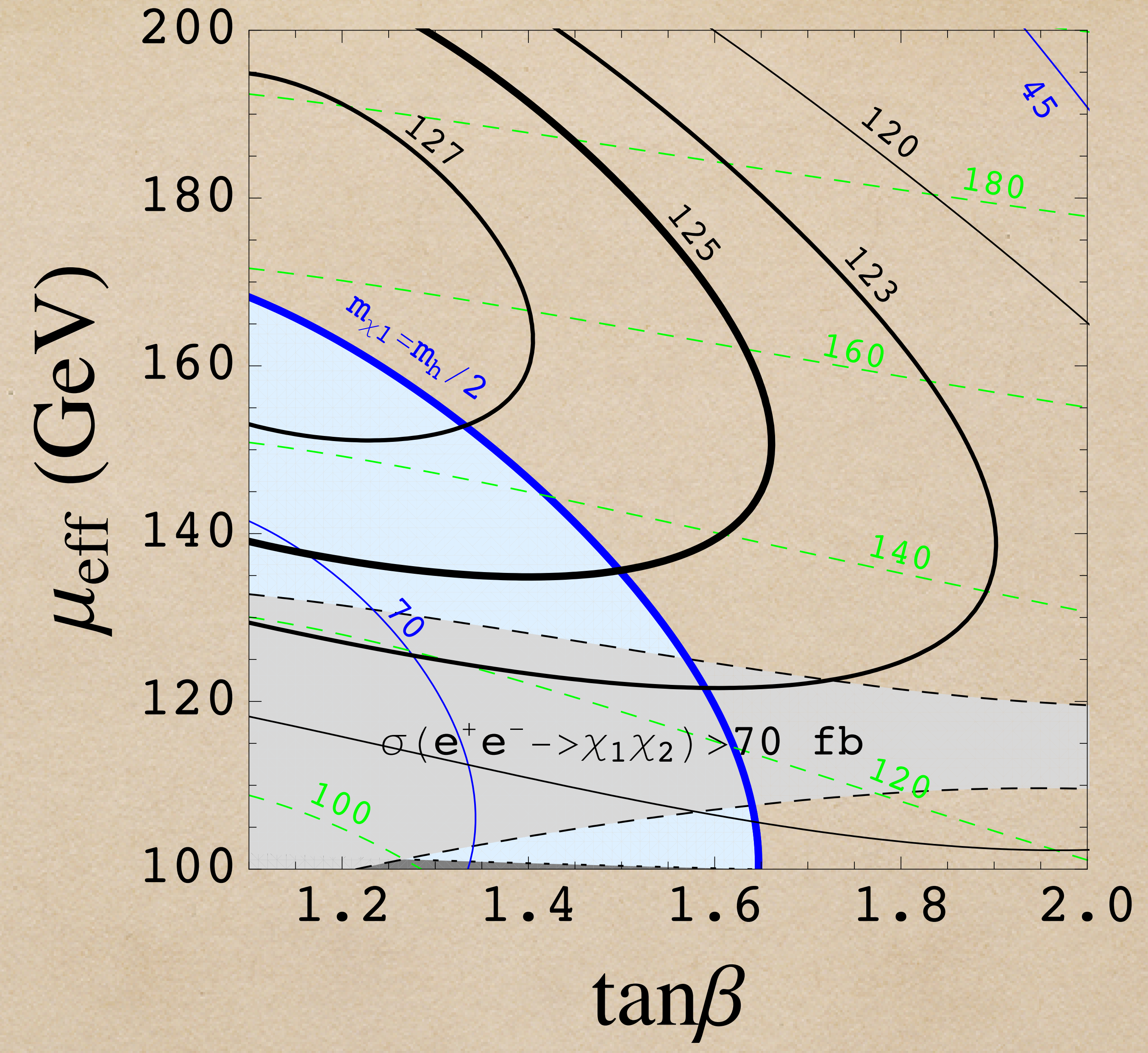
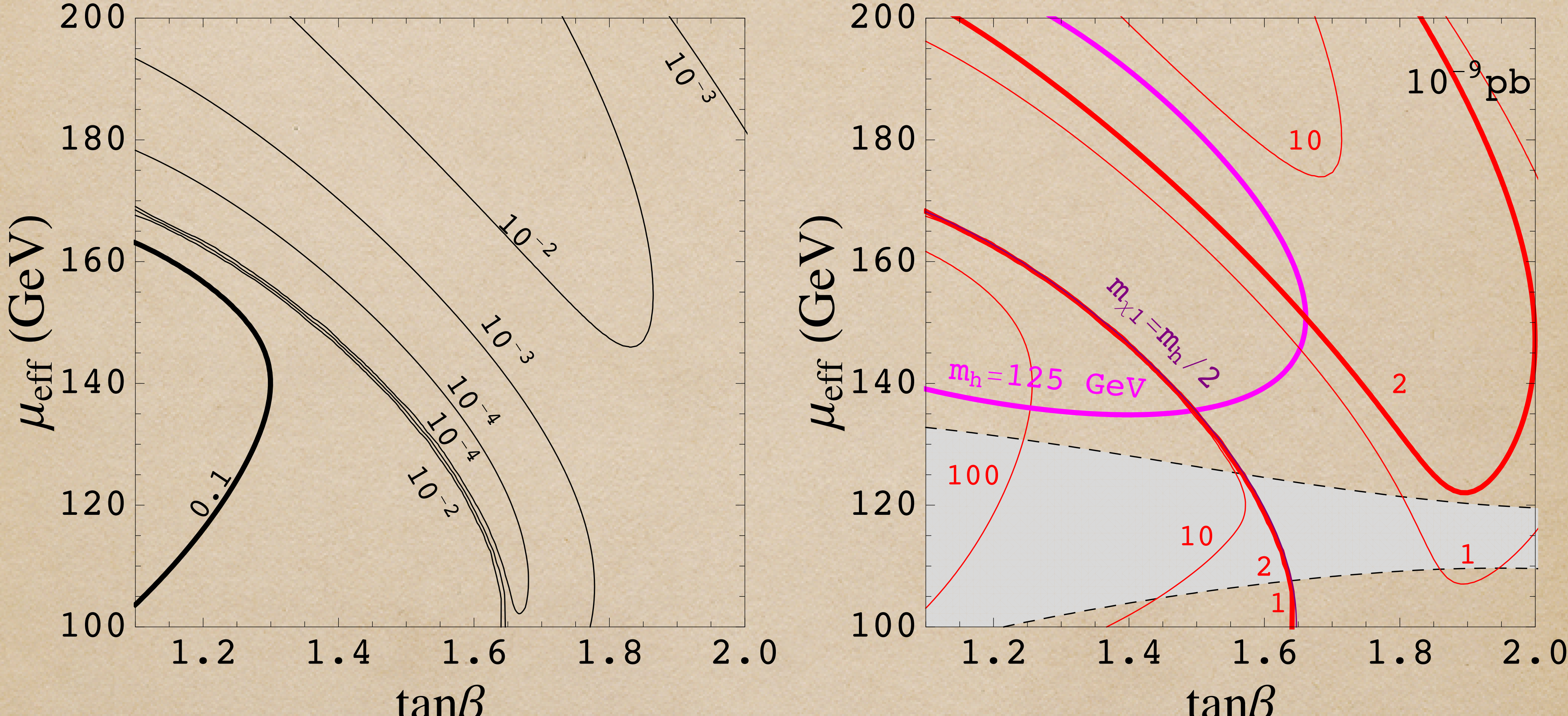


Figure 3: Plot for small $\tan\beta$. Here we set $M_1 = M_2 = M_3 = 1$ TeV, $m_A = 350$ GeV, $m_{\widetilde{Q}_3} = m_{\widetilde{t}^c} = 500$ GeV, $A_t = 0$, and $\xi_S = -7 \times 10^7$ GeV^3. Black curves denote Higgs mass in GeV, blue curves denote $m_{\widetilde{\chi}^0_1}$. in GeV, and green dashed curves denote $m_{\widetilde{\chi}^0_2}$. The gray-shaded region is excluded by the OPAL [17].



(a) $\Omega^{\rm TH}_{\widetilde{\chi}^0_1} h^2$

(b) $(\Omega^{\rm TH}_{\widetilde{\chi}^0_1}/\Omega_{\rm DM})\,\sigma_{{\rm SI},\widetilde{\chi}^0_1}$