Peccei-Quinn NMSSM in the light of 125 GeV Higgs

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work in progress

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Outline

- Motivation
- PQ-NMSSM and Phenomenology
- Collider perspective
- Summary

Peccei-Quinn Symmetry

U(1) anomalous global symmetry that gives the most plausible solution of strong CP problem.

In QCD

$$\mathcal{L}_\theta = \theta \frac{g^2}{32\pi^2} G^a_{\mu\nu} \widetilde{G}^{\mu\nu a} \longrightarrow |D_n| \lesssim 10^{-24}\ \mathrm{cm} \quad \Rightarrow \quad |\theta| \lesssim 10^{-9}$$

Anomaly of $U(1)_{PQ}$ generates $aG\widetilde{G}$ term and

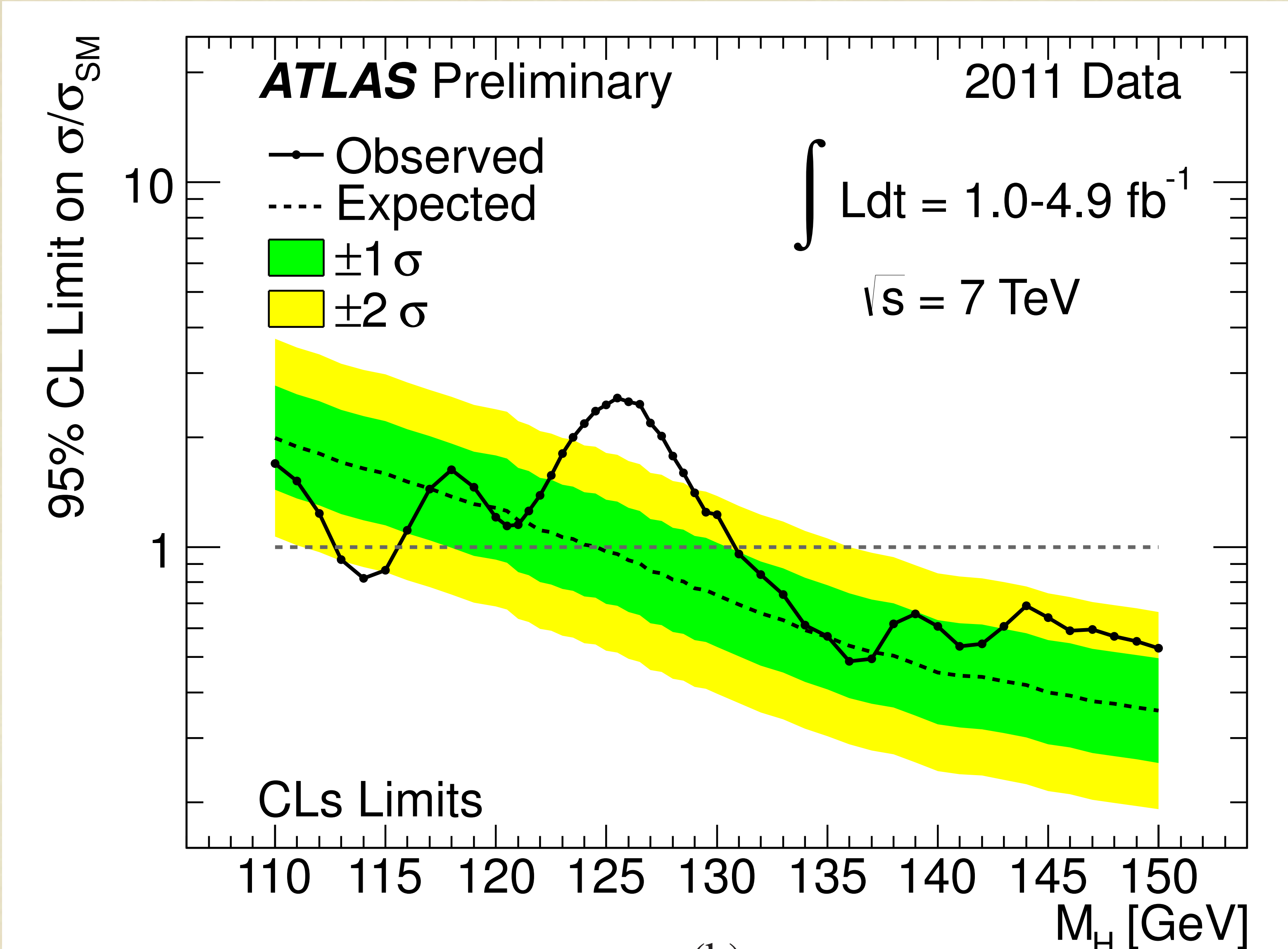
$$-\frac{g^2}{32\pi^2}\left(\theta - \frac{a}{f_a}\right) G\widetilde{G} \longrightarrow \bar{\theta} \equiv \theta - \frac{a}{f_a}$$

$$E(\theta) = \langle\theta|H|\theta\rangle = -|K|^2 \cos\theta$$

Vafa-Witten showed that energy minimum is always at $\langle\bar{\theta}\rangle = 0$.

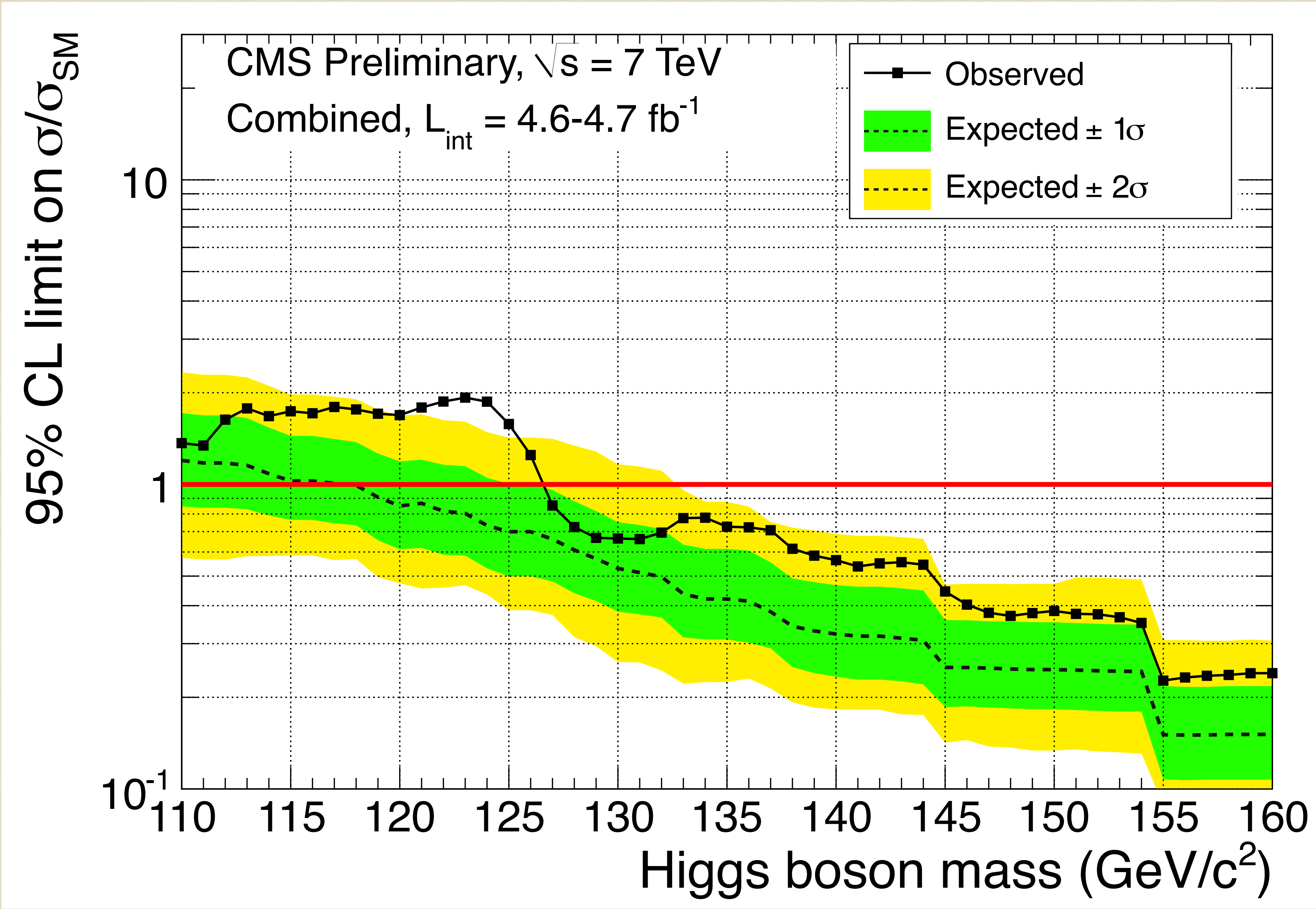
Phys.Rev.Lett. 53 (1984) 535

125 GeV Higgs at the LHC



(b)

125 GeV Higgs at the LHC



125 GeV Higgs in MSSM

In MSSM, tree-level Higgs mass is bounded from above by M_Z. We need radiative corrections...

$$m_h^2 = M_Z^2 \cos 2\beta + \frac{3G_F m_t^4}{\sqrt{2}\pi^2}\left\{\log\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12m_{\tilde{t}}^2}\right)\right\} + \cdots$$

To make Higgs mass 125 GeV, large stop mass is needed.

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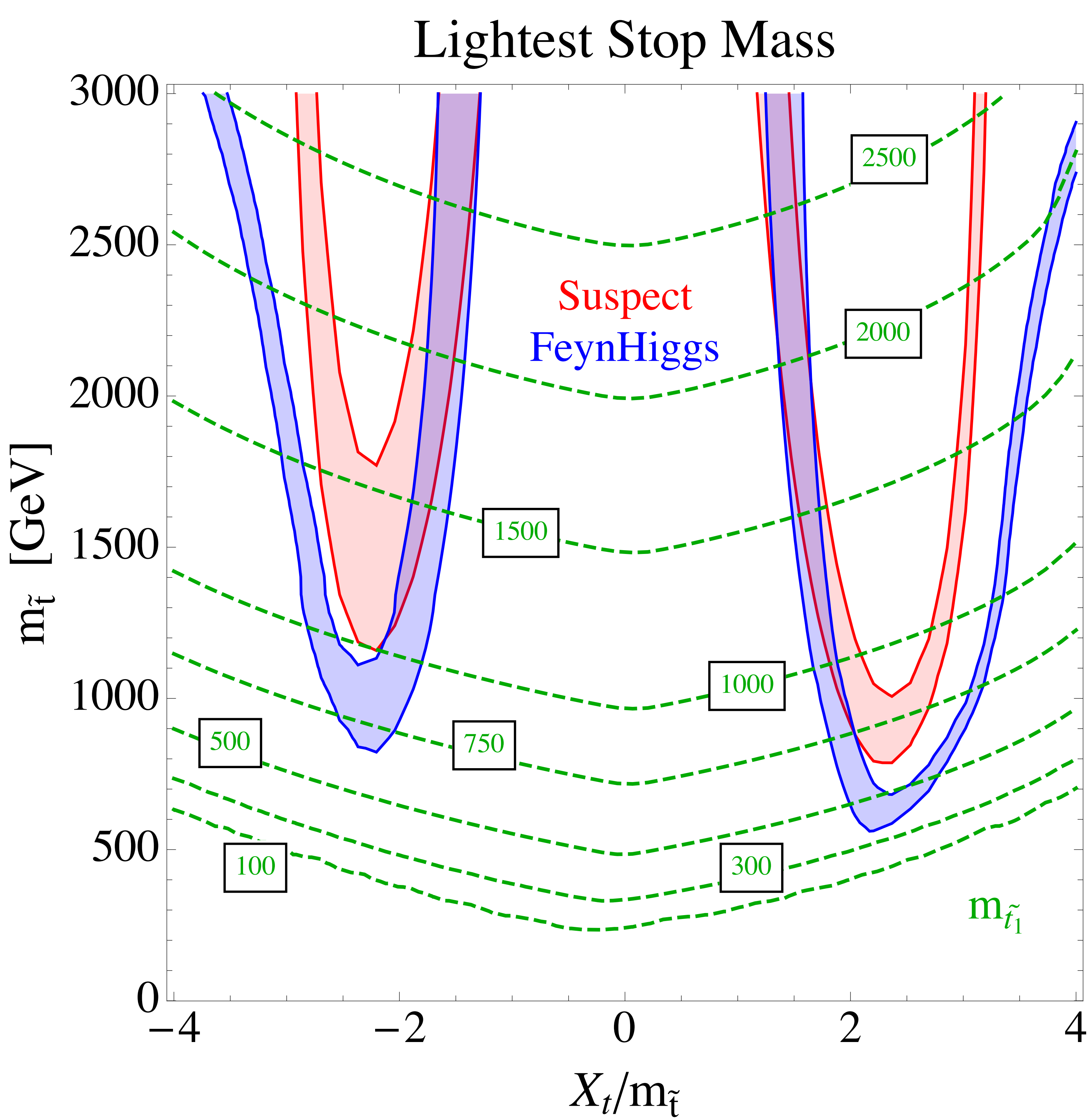

taken from Hall, Pinner, Ruderman

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To make Higgs mass 125 GeV, large stop mass is needed.

↓

Naturalness prob. is on rise to obtain weak scale.

Need some extensions to make more natural model for 125 GeV Higgs

Raising the Higgs mass

We can add Higgs quartic couplings by some ways...

- New gauge symmetry that gives additional D-term quartic potential, e.g. $U(1)_X$
- Singlet extension that gives additional F-term potential, e.g. NMSSM: $\lambda S H_u H_d$

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we focus on this possibility

PQ-NMSSM and Phenomenology

PQ-NMSSM: Model I

We introduce axion superfield X other than singlet superfield S.

Jeong, Shoji, Yamaguchi

$$\mathcal{L} = \int d^2\theta \lambda S H_u H_d + \int d^4\theta \kappa \frac{X^{*2}}{M_p} S + \text{h.c.}$$

with PQ-charge $(X, S, H_u, H_d) = (1, 2, -1, -1)$.

PQ symmetry breaking can be generated by SUSY breaking ($f_a \sim \sqrt{m_{\text{soft}} M_p}$).

$$X = F_a(1 + m_{\text{soft}}\theta^2), \quad \kappa \to \kappa(1 + m_{\text{soft}}\theta^2 + m_{\text{soft}}\bar{\theta}^2 + m_{\text{soft}}^2\theta^4)$$

We obtain effective superpotential

$$\xi_F = \kappa m_{\text{soft}} \frac{f_a^2}{M_p}$$

$$\xi_S = \kappa m_{\text{soft}}^2 \frac{f_a^2}{M_p}$$

$$W_{\text{eff}} = \lambda S H_u H_d + (\xi_F + \theta^2 \xi_S) S$$

similar to nMSSM

Panagiotakopoulos, Tamvaki;
Panagiotakopoulos, Pilaftsis

PQ-NMSSM: Model I

Higgs sector

$$
\begin{aligned}
\mathcal{M}^2_{S,11} &= m_Z^2 \cos^2\beta + m_A^2 \sin^2\beta, \\
\mathcal{M}^2_{S,22} &= m_Z^2 \sin^2\beta + m_A^2 \cos^2\beta, \\
\mathcal{M}^2_{S,12} &= (2\lambda^2 v^2 - m_A^2 - m_Z^2)\sin\beta\cos\beta, \\
\mathcal{M}^2_{S,33} &= m_S^2 + \lambda^2 v^2, \\
\mathcal{M}^2_{S,13} &= 2\lambda\mu_{\rm eff} v\cos\beta - \lambda A_\lambda v\sin\beta, \\
\mathcal{M}^2_{S,23} &= 2\lambda\mu_{\rm eff} v\sin\beta - \lambda A_\lambda v\cos\beta,
\end{aligned}
$$

$$
\begin{aligned}
m_A^2 &= \frac{\mu_{\rm eff} B_{\rm eff} + \widehat{m}_3^2}{\sin\beta\cos\beta} \\
m_S^2 &= \lambda^2 v^2 \left(\frac{A_\lambda \sin\beta\cos\beta}{\mu_{\rm eff}} - 1\right) - \frac{\lambda\xi_S}{\mu_{\rm eff}} \\
\mu_{\rm eff} &= \lambda s \\
B_{\rm eff} &= A_\lambda \\
\widehat{m}_3^2 &= \lambda\xi_F.
\end{aligned}
$$

PQ-NMSSM: Model I

Higgs sector

2x2 doublet part
rotated by angle β

$$\boxed{\begin{aligned}\mathcal{M}^2_{S,11} &= m_Z^2\cos^2\beta + m_A^2\sin^2\beta,\\ \mathcal{M}^2_{S,22} &= m_Z^2\sin^2\beta + m_A^2\cos^2\beta,\\ \mathcal{M}^2_{S,12} &= (2\lambda^2v^2 - m_A^2 - m_Z^2)\sin\beta\cos\beta,\end{aligned}}$$

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Tree-level Higgs mass

$$m_h^2 \lesssim m_Z^2\cos^2 2\beta + \lambda^2v^2\sin^2 2\beta$$

$$\begin{aligned}m_A^2 &= \frac{\mu_{\text{eff}}B_{\text{eff}} + \widehat{m}_3^2}{\sin\beta\cos\beta}\\ m_S^2 &= \lambda^2v^2\left(\frac{A_\lambda\sin\beta\cos\beta}{\mu_{\text{eff}}} - 1\right) - \frac{\lambda\xi_S}{\mu_{\text{eff}}}\\ \mu_{\text{eff}} &= \lambda s\\ B_{\text{eff}} &= A_\lambda\\ \widehat{m}_3^2 &= \lambda\xi_F.\end{aligned}$$

PQ-NMSSM: Model I

Higgs sector

2x2 doublet part rotated by angle β

$$\boxed{\begin{aligned}
\mathcal{M}^2_{S,11} &= m_Z^2 \cos^2\beta + m_A^2 \sin^2\beta, \\
\mathcal{M}^2_{S,22} &= m_Z^2 \sin^2\beta + m_A^2 \cos^2\beta, \\
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\mu_{\rm eff} &= \lambda s \\
B_{\rm eff} &= A_\lambda \\
\widehat{m}_3^2 &= \lambda \xi_F .
\end{aligned}$$

Tree-level Higgs mass

$$m_h^2 \lesssim m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta$$

We can have 125 GeV Higgs for moderate $1<\tan\beta<3$ and O(100) GeV stop

We take $\lambda=0.7$ because it is maximum value allowed by Landau pole constraint

Neutralino sector

$$\mathcal{M}_0 = \begin{pmatrix} M_1 & 0 & -g_1 v_d/\sqrt{2} & g_1 v_u/\sqrt{2} & 0 \\ & M_2 & g_2 v_d/\sqrt{2} & -g_2 v_u/\sqrt{2} & 0 \\ & & 0 & -\mu_{\rm eff} & -\lambda v_u \\ & & & 0 & -\lambda v_d \\ & & & & 0 \end{pmatrix} .$$

Neutralino sector

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Zero Mass → **generated by mixing**

$$m_{\chi_1} = \frac{\lambda^2 v^2 \sin 2\beta}{\mu_{\text{eff}}} \left(1 - \frac{\lambda^2 v^2}{\mu_{\text{eff}}^2} + \mathcal{O}\left(\frac{\lambda^4 v^4}{\mu_{\text{eff}}^4} \right) \right)$$

Neutralino sector

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Zero Mass ⟶ generated by mixing

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Relatively light (singlino-like) neutralino induces invisible decays of Z boson and Higgs boson,

constrains the model and reduces Higgs signals at collider.

Relic neutralinos are overproduced but it can be diluted by late-time entropy production. Or it can decay to light axinos.

LEP constraints

Z boson invisible decay

$$\Gamma(Z \to \chi_1 \chi_1) \approx \frac{g_2^2}{4\pi} \frac{(N_{13}^2 - N_{14}^2)^2}{24 \cos^2 \theta_W} M_Z$$

From LEPI, Γ_{inv}<3 MeV,

$$|N_{13}^2 - N_{14}^2| \approx \frac{\lambda^2 v^2}{\mu_{\text{eff}}^2} |\cos 2\beta| < 0.13$$

From LEPII (s=(208 GeV)^2),

$$\sigma(e^+ e^- \to \chi_1 \chi_2) \approx \frac{1}{128\pi s} \frac{g_2^4}{\cos^4 \theta_W} (N_{13} N_{23} - N_{14} N_{24})^2 < 70 \text{ fb}$$

$$|N_{13} N_{23} - N_{14} N_{24}| \lesssim 0.2$$

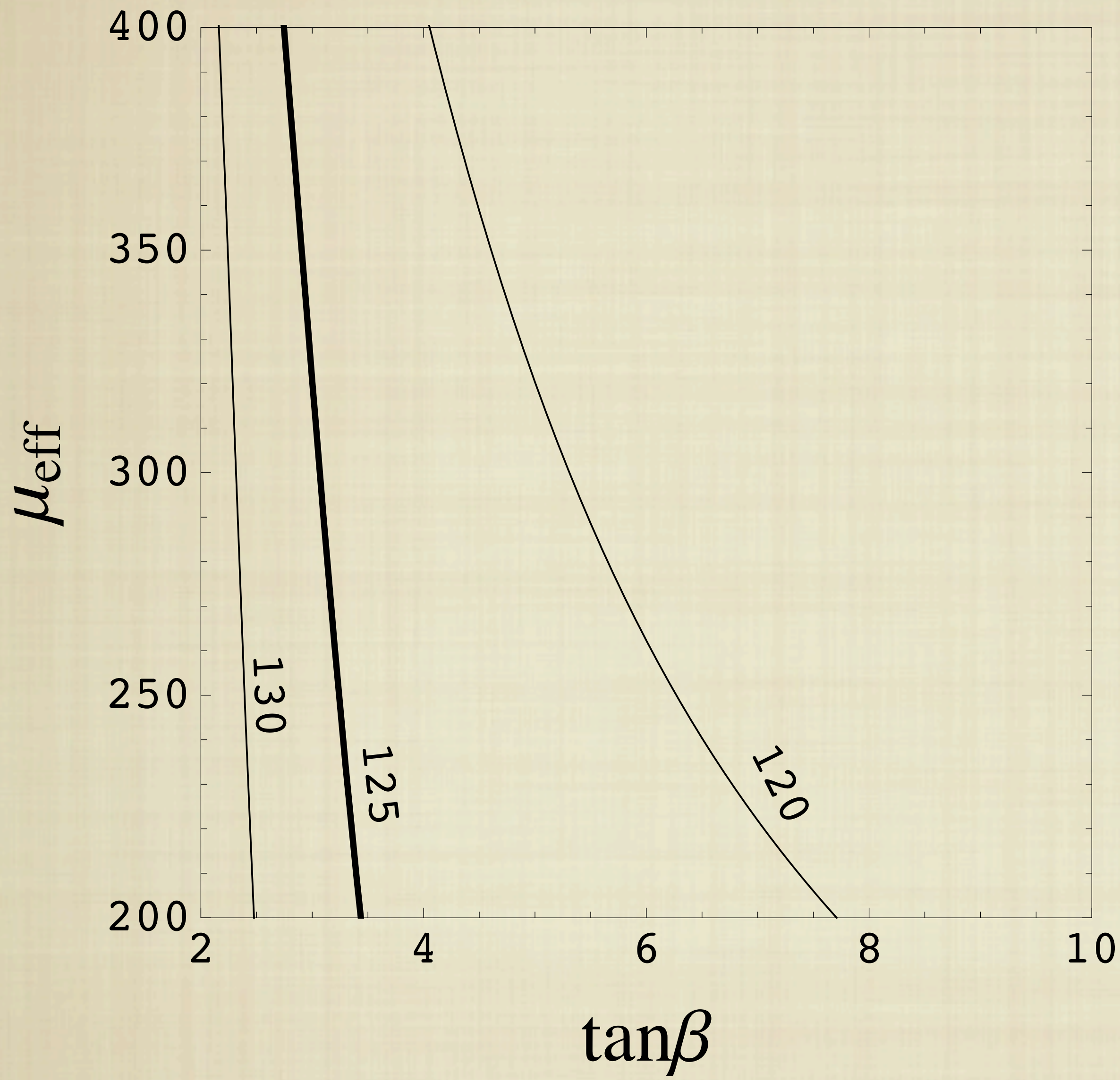
Higgs invisible decay

2 possible ways to avoid Higgs invisible decay

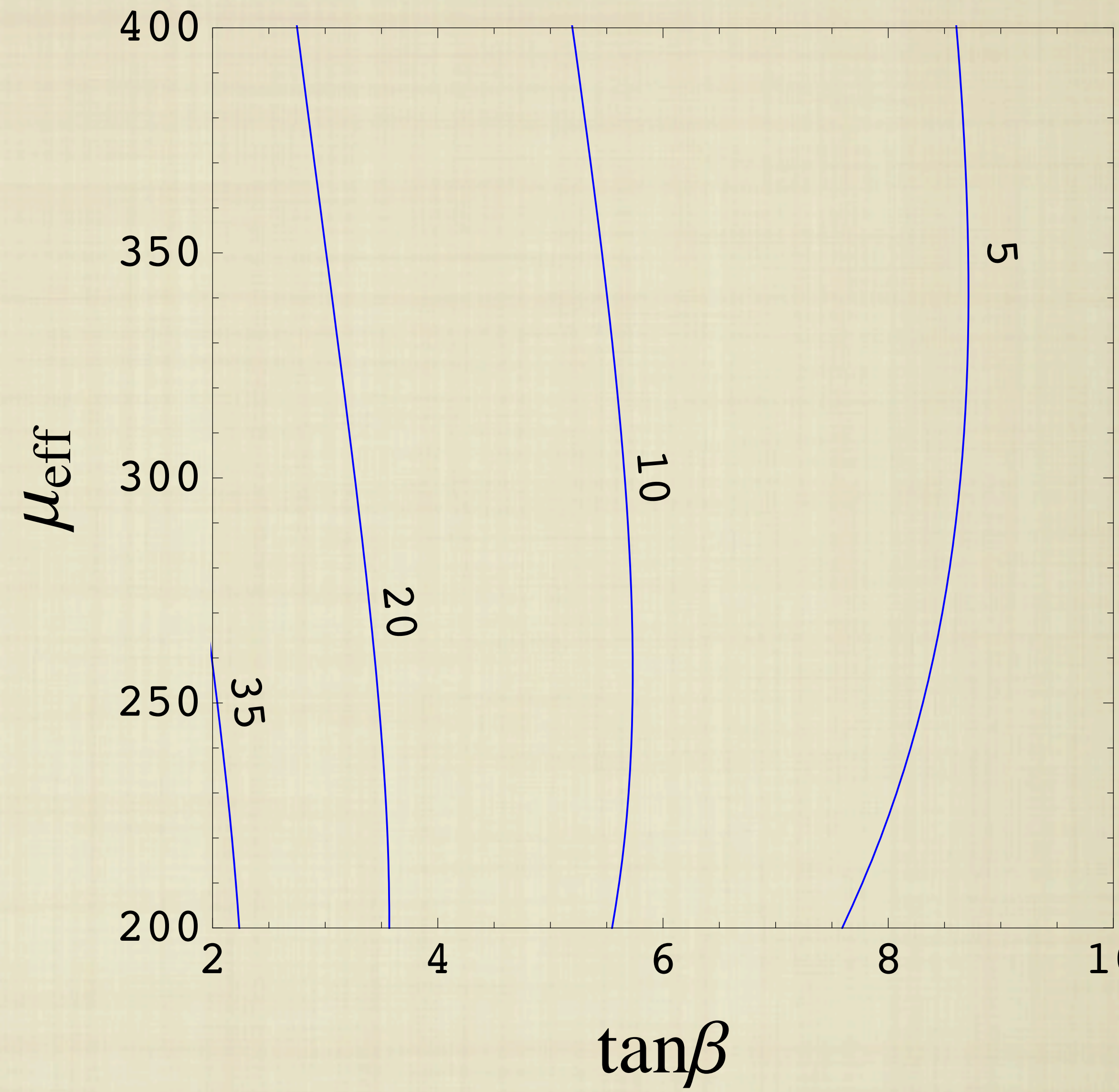
- Large singlino-Higgsino mixing can make neutralino mass above $M_H/2$.
  However, $e^+e^- \to \chi_1\chi_2$ in LEPII constrains this since μ should be small($\sim$ 110 GeV) for large mixing.

- Even for light neutralino, $g_{H\chi_1\chi_1}$ can **vanish** in the parameter region that **gaugino part and Higgsino part cancel**.
  - If H_U-H_D mixing vanishes, $H\to\gamma\gamma$ signal is enhanced for small invisible decay region.
  - If H_U-H_D mixing is sizable, $H\to\gamma\gamma$ signal is at most SM one for vanishing invisible decay region.

Results: no H_U-H_D mixing



Higgs Mass

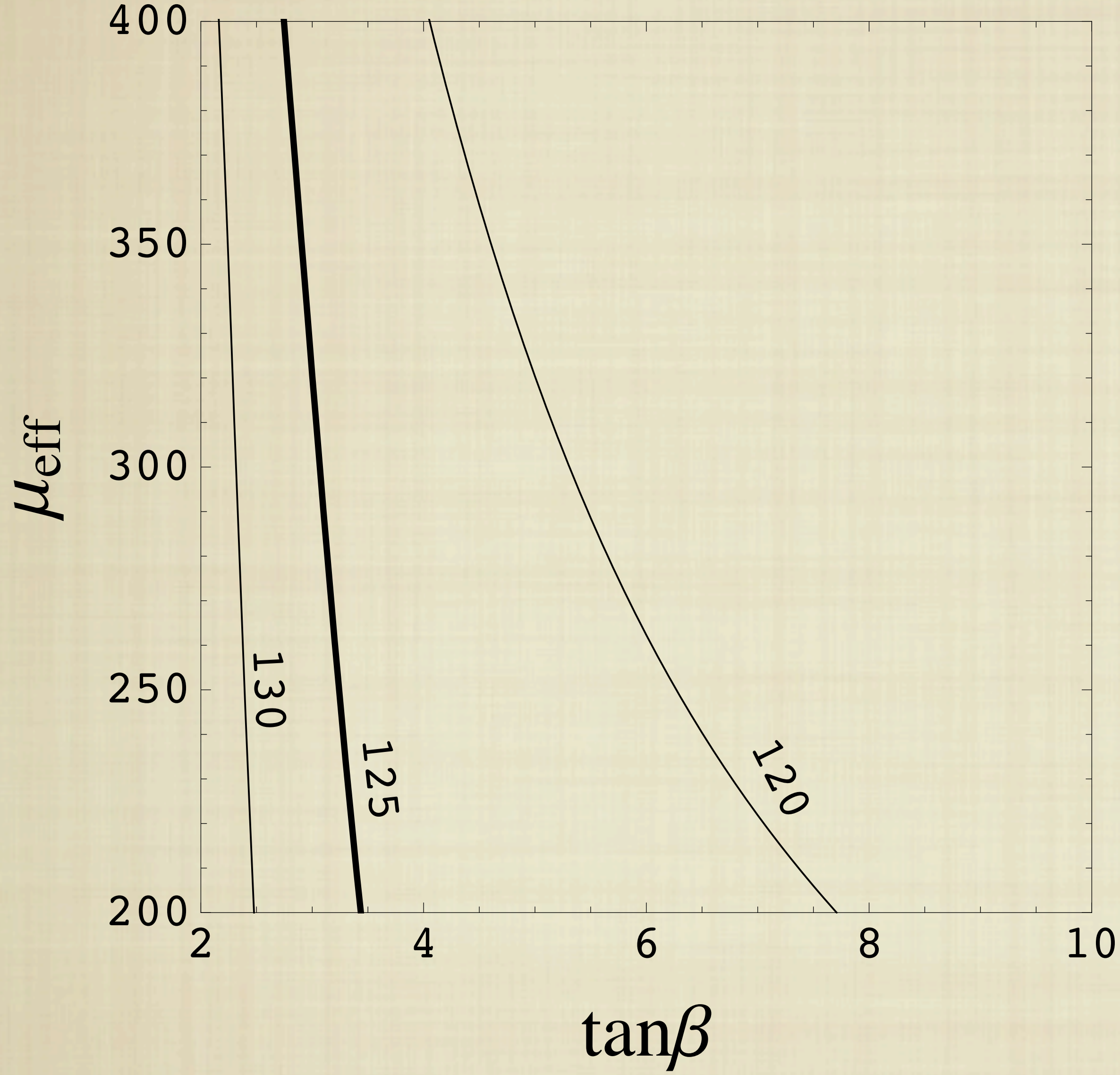


Neutralino Mass

$m_A = 146$ GeV, $\quad M_3 = 3M_2 = 6M_1 = 900$ GeV,

$m_{\tilde{Q}3} = m_{\tilde{u}3} = 500$ GeV, $\quad X_t = -1$ TeV

Results: no H_U-H_D mixing



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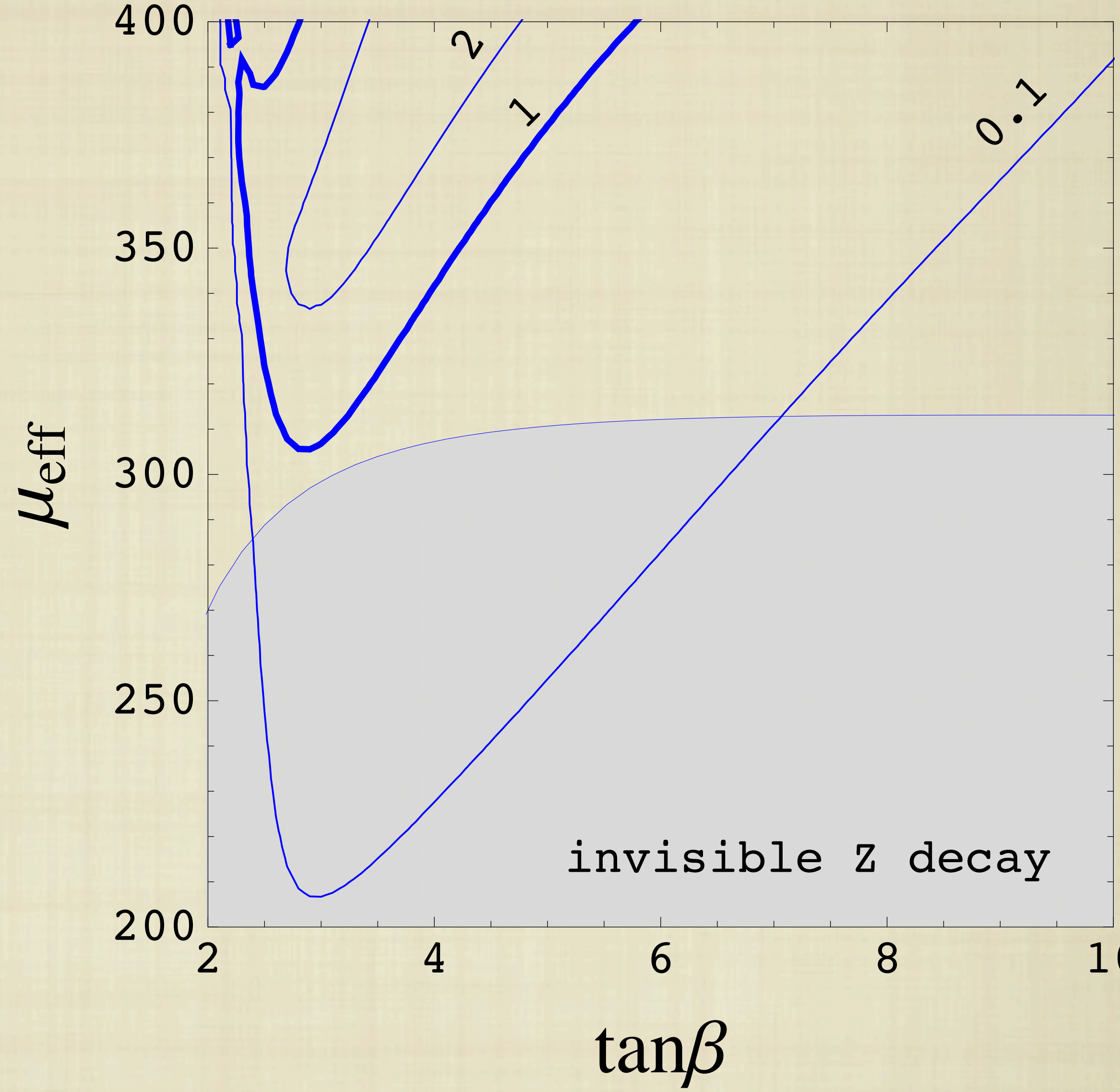

σ(gg->H->γγ)/σ_SM

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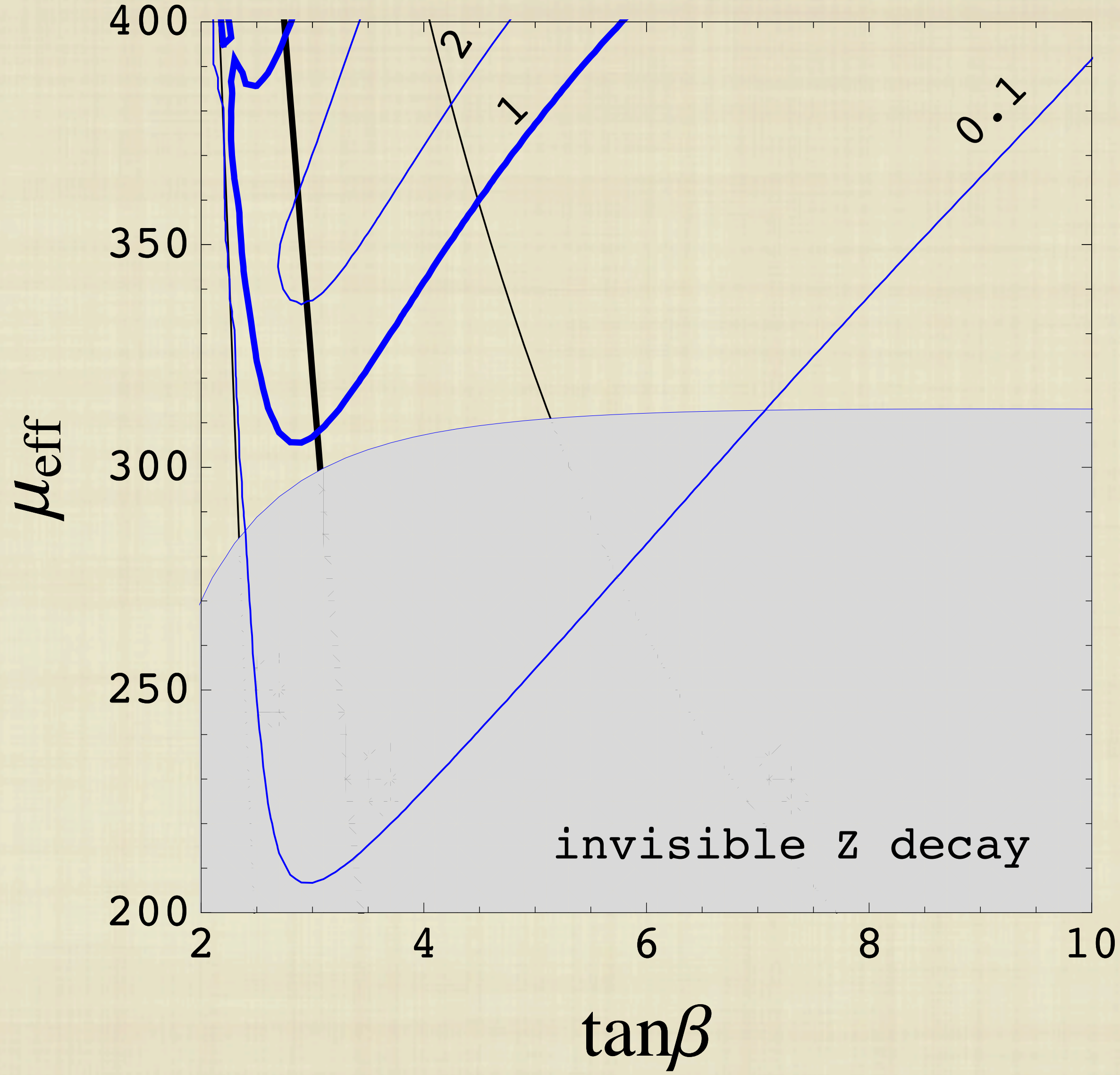

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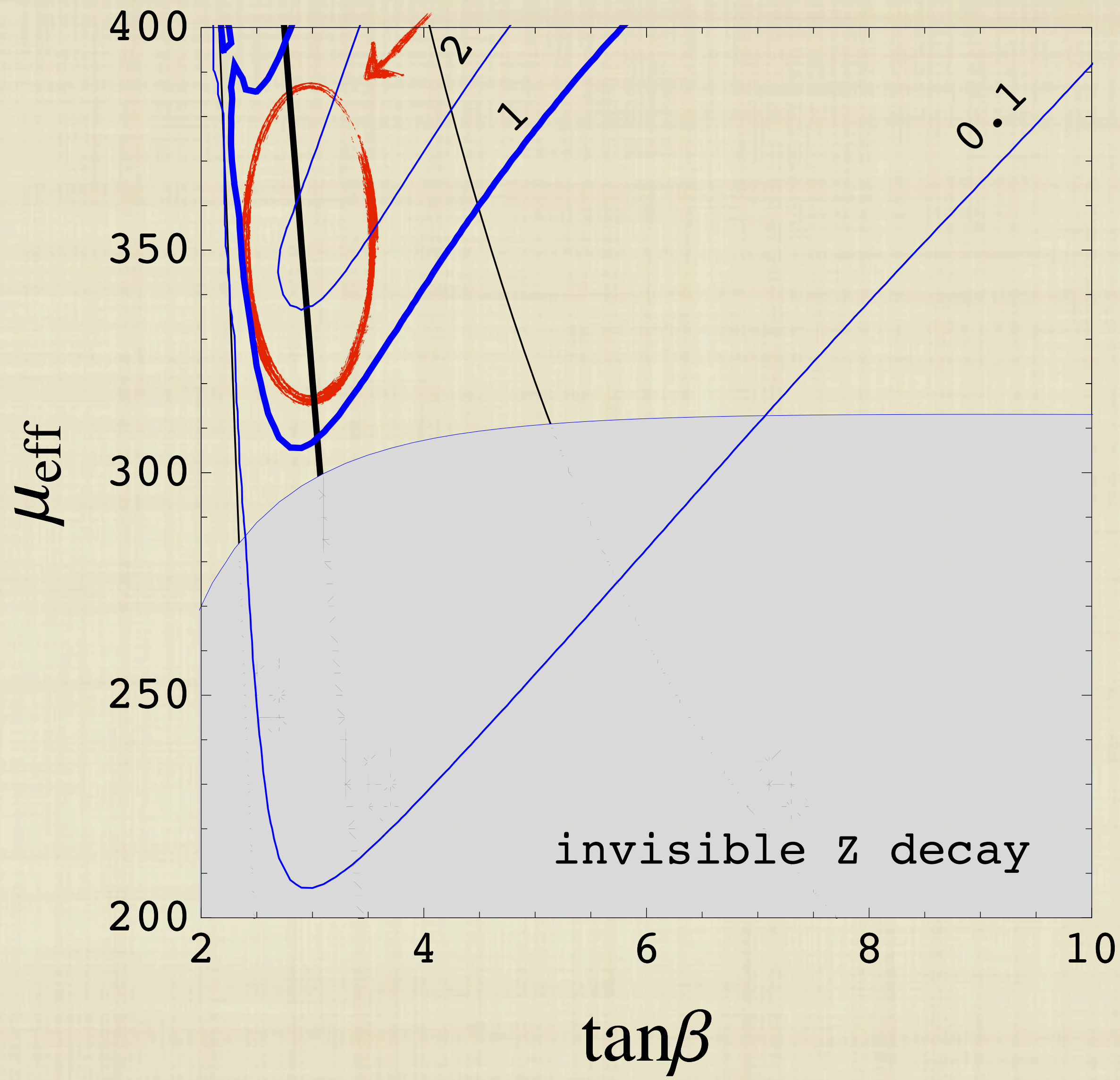
Results: no H_U-H_D mixing

We prefer this region!



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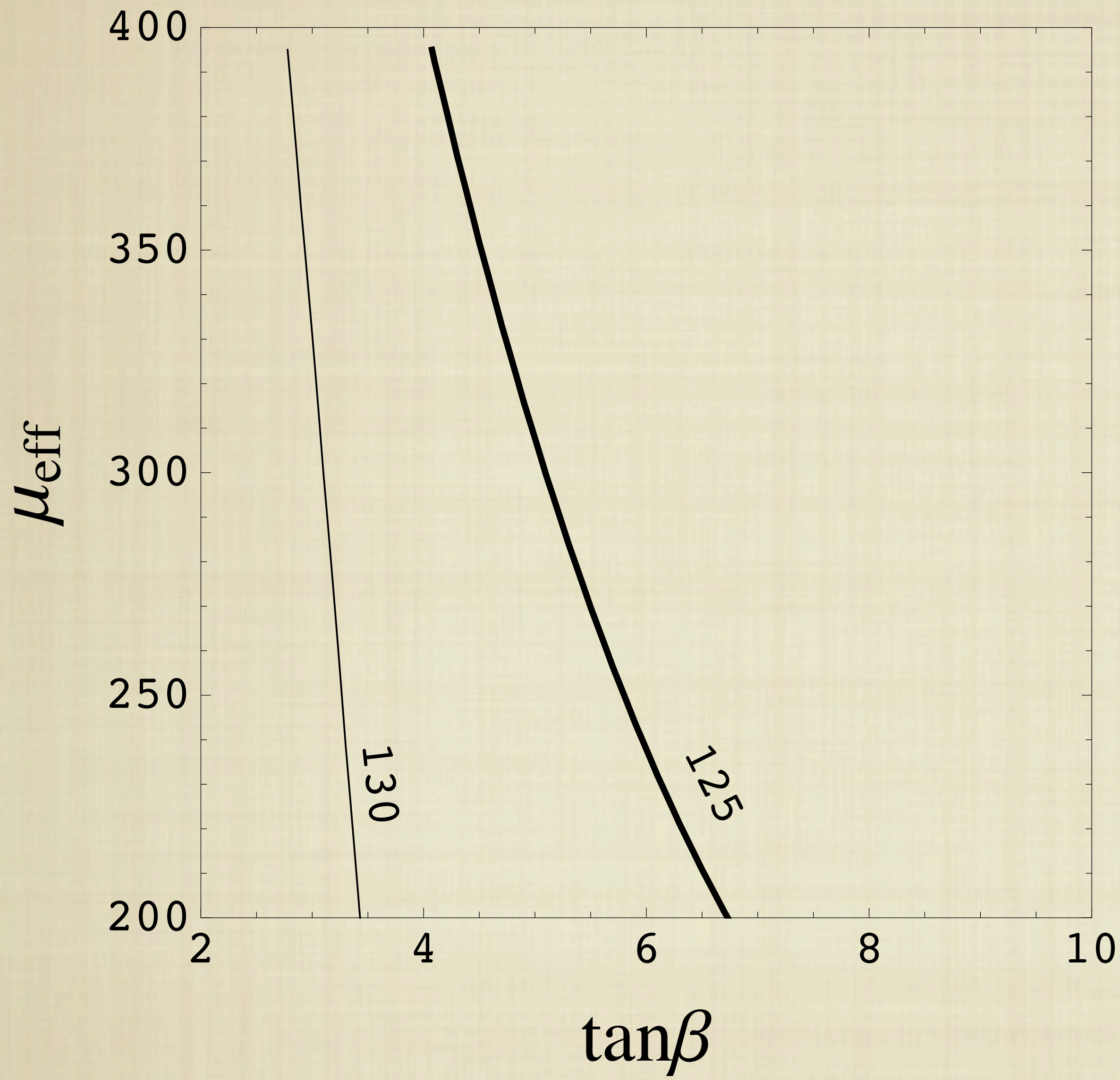
Results: H_U-H_D mixing



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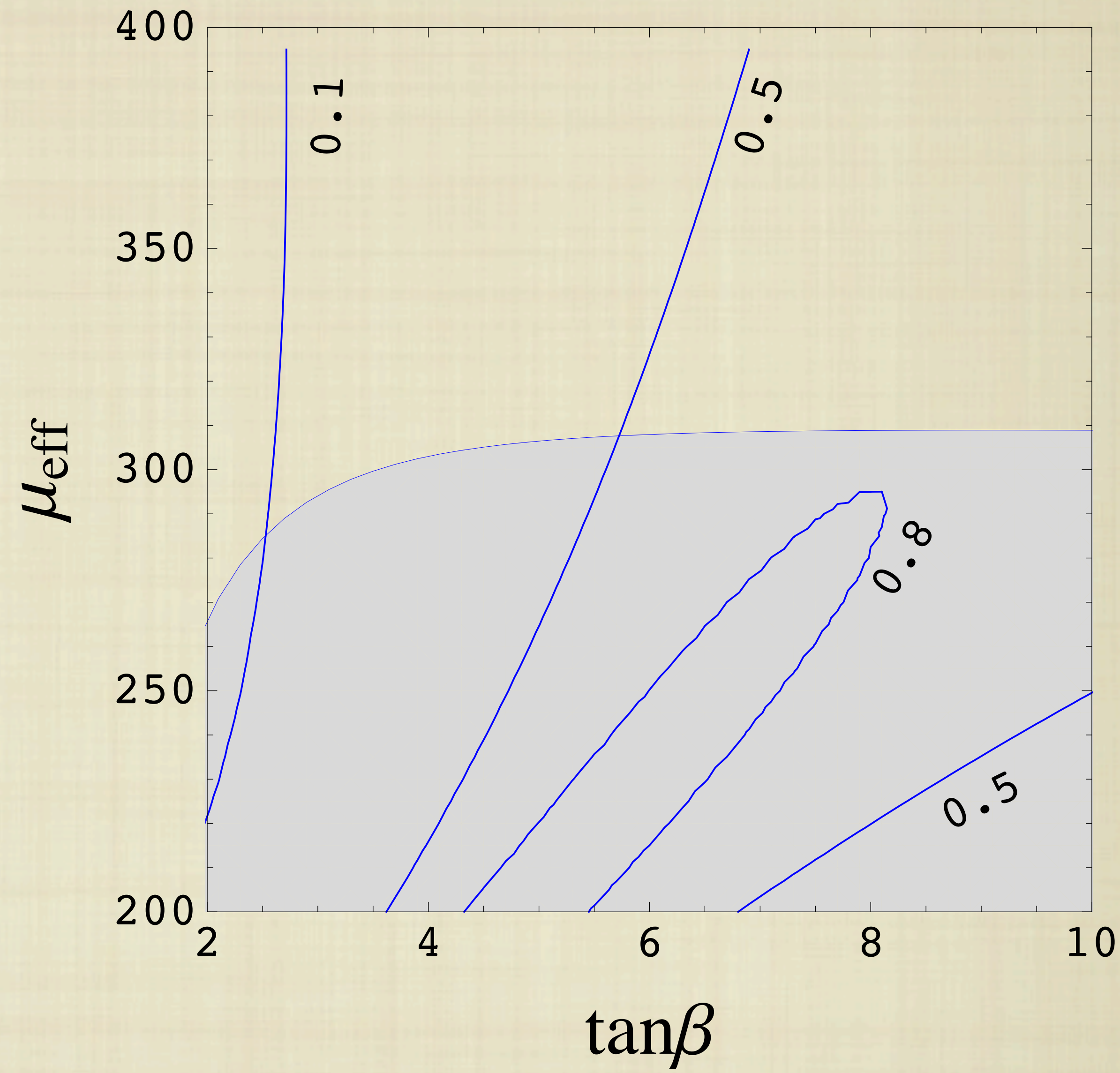
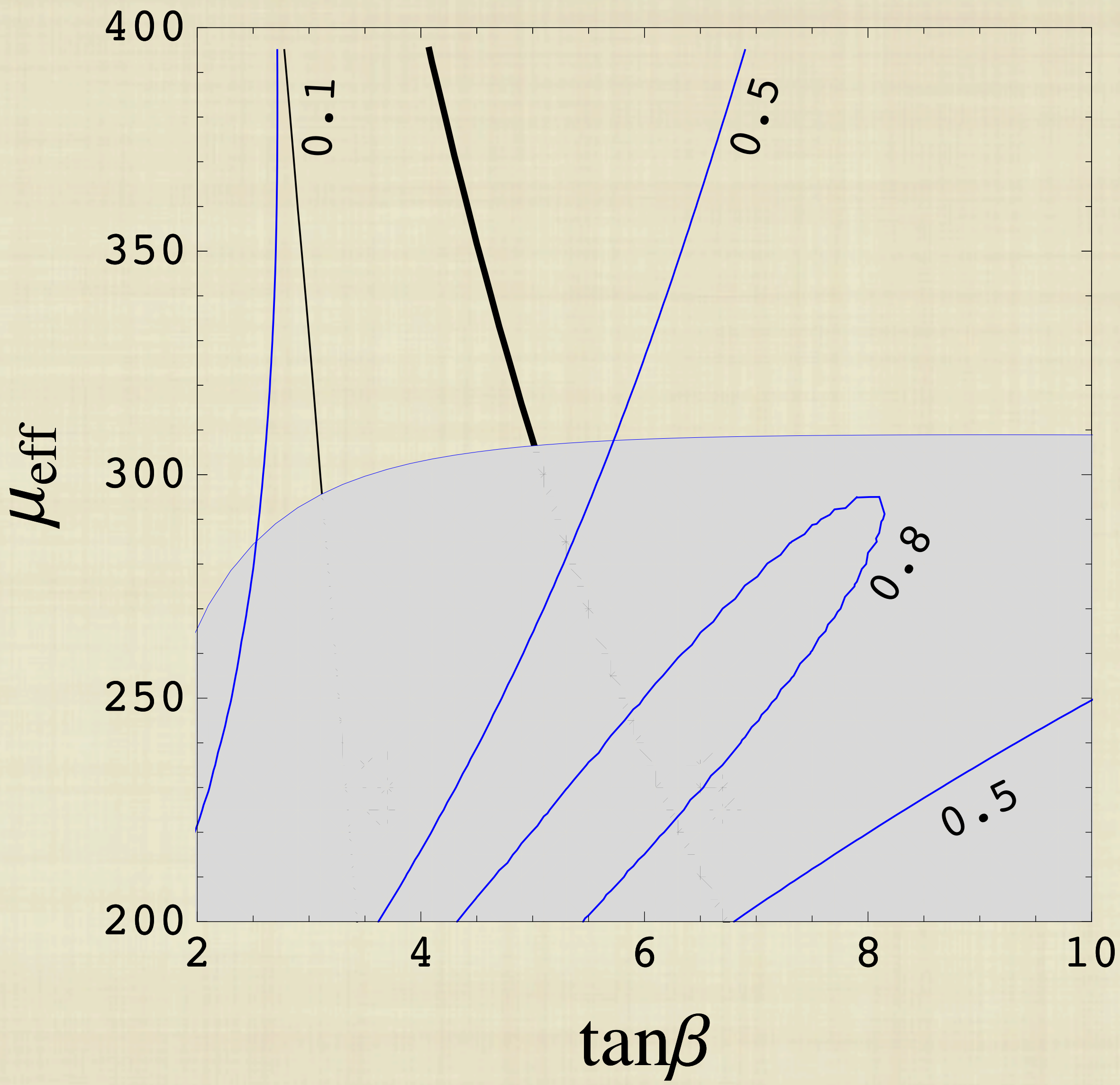


σ(gg->H->$\gamma\gamma$)/σ_{SM}

$m_A = 500$ GeV, $\quad M_3 = 3M_2 = 6M_1 = 900$ GeV,

$m_{\tilde{Q}3} = m_{\tilde{u}3} = 1$ TeV, $\quad X_t = -2$ TeV

Results: H_U-H_D mixing



$m_A = 500$ GeV, $\quad M_3 = 3M_2 = 6M_1 = 900$ GeV,

$m_{\tilde{Q}3} = m_{\tilde{u}3} = 1$ TeV, $\quad X_t = -2$ TeV

PQ-NMSSM: Model II

To avoid such parameter choice, we can extend the model.

$$W = \lambda S H_u H_d + Y T_1 T_2 + T_2 S^2 + \frac{X^3 T_1}{M_p} + \frac{X T_1 T_2 + Y^2 T_2}{M_p} S,$$

$$K = \frac{(X^\dagger)^2 + Y^\dagger T_1 + Y^2}{M_p} S^\dagger + \text{h.c.}$$

with charge assignment

fields	X	Y	T_1	T_2	S	$H_u H_d$
$U(1)_{\text{PQ}}$	-1	1	3	-4	2	-2
$\mathbb{Z}_2$	0	π	π	0	π	π

$$\langle X \rangle, \langle Y \rangle \gg \langle T_1 \rangle, \langle T_2 \rangle, \langle S \rangle$$

Integrating out heavy field T_1 and T_2,

$$\begin{aligned} W_{\text{eff}} =& \lambda S H_u H_d - \frac{X^3 Y}{M_p^2} S - \frac{X^3}{M_p Y} S^2 \\ =& \lambda S H_u H_d + \xi_F S + \frac{1}{2} \mu' S^2 \end{aligned}$$

PQ-NMSSM: Model II

Higgs sector is similar to model I.

Neutralino sector is

$$\mathcal{M}_0 = \begin{pmatrix} M_1 & 0 & -g_1 v_d/\sqrt{2} & g_1 v_u/\sqrt{2} & 0 \\ & M_2 & g_2 v_d/\sqrt{2} & -g_2 v_u/\sqrt{2} & 0 \\ & & 0 & -\mu_{\rm eff} & -\lambda v_u \\ & & & 0 & -\lambda v_d \\ & & & & \mu' \end{pmatrix}$$

Non-zero singlino mass

The χ_1 can be both singlino-like or Higgsino-like (also gaugino-like).

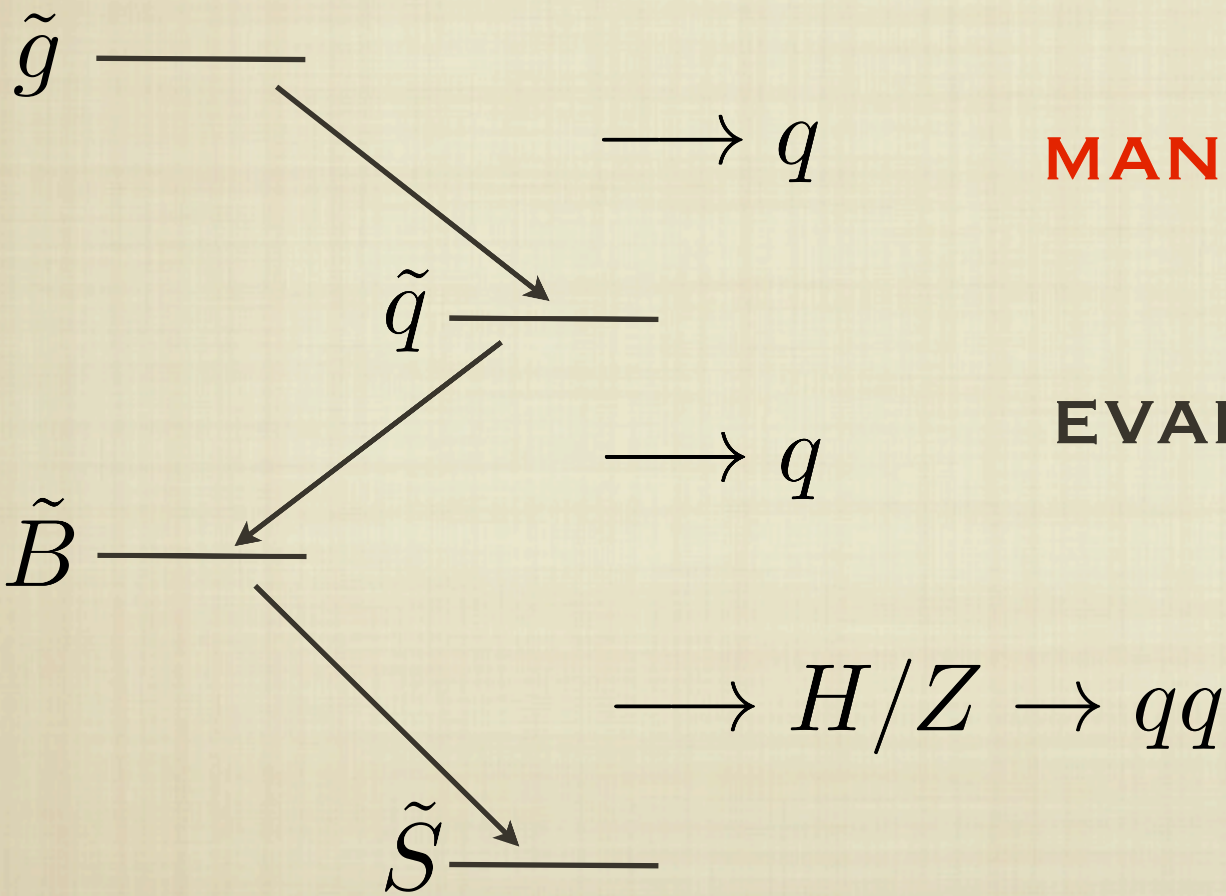
Invisible decay of Z and Higgs can be kinematically forbidden for sizable μ`.

Collider Perspective

PQ-NMSSM: Model I

Light singlino-like neutralino (~20 GeV)

heavy particles make long decay chain.



many jets and small MET

evade SUSY direct searches

PQ-NMSSM: Model II

Depending on the parameter space (size of μ`),

Singlino-like $(\mu' < M_1, M_2, \mu)$

Heavy singlino (~70 GeV) is possible.

MET is not much reduced.

↓

many jets from long cascade.

MSSM-like $(\mu' > M_1 \text{ or } M_2 \text{ or } \mu)$

Higgsino-like or gaugino-Like.

2,3,4 jets and MET can constrain the model.

↓

Similar to MSSM.

Now in progress...

Summary

- PQ symmetry can solve strong CP problem.
- To make 125 GeV Higgs in SUSY, singlet extension is needed.
- Simple PQ-NMSSM can satisfy all constraints only in special parameter space (doublet mixing vanishes).
- Including singlino mass term is needed to avoid special parameter choice.
- Light singlet of PQ-NMSSM can make many jets and small MET.