THE 125 GeV (FAT) HIGGS FROM HIGGS LOOPS

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w/ A Menon
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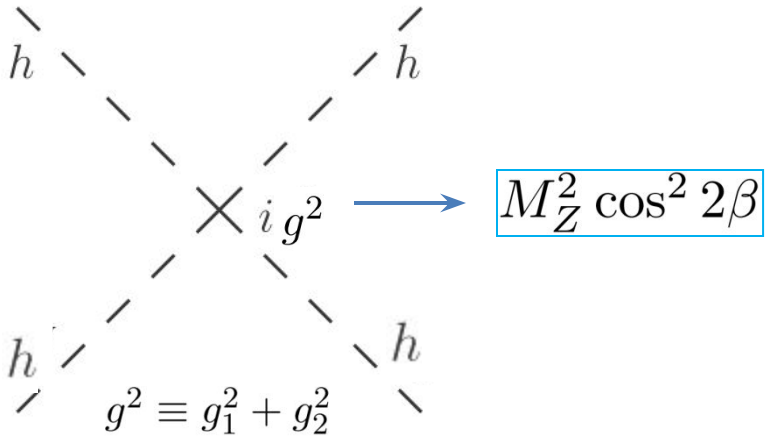
Higgs and Supersymmetry

Minimal Supersymmetric SM

$$m_h^{\max}(\text{tree}) = M_Z \sim 91 \text{ GeV}$$



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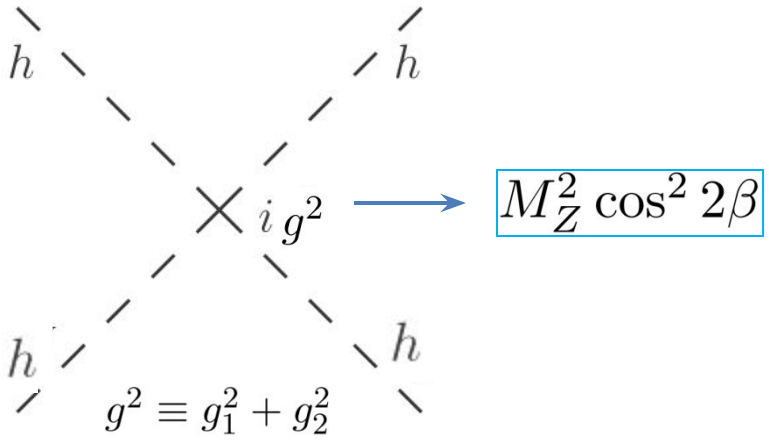

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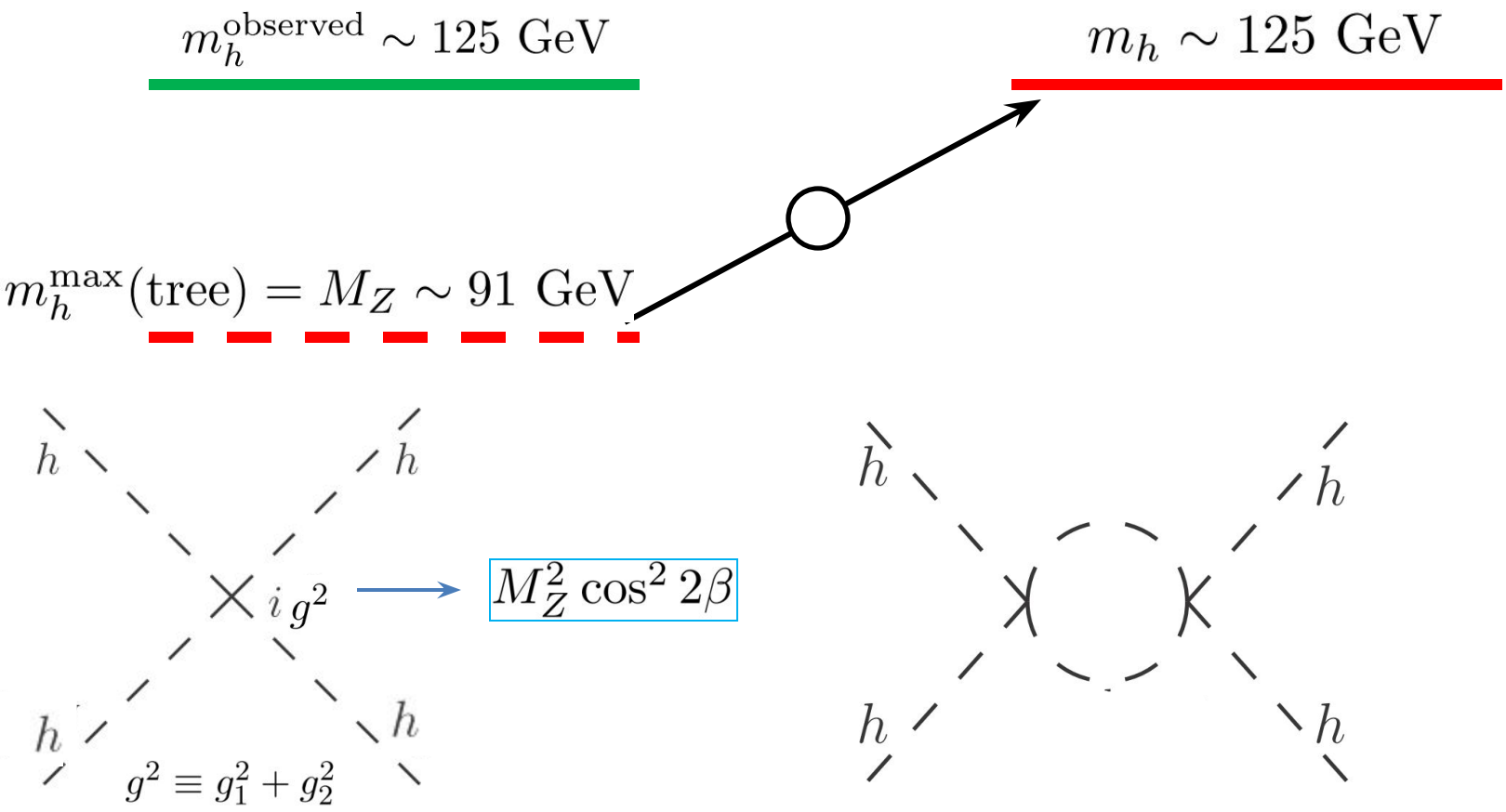

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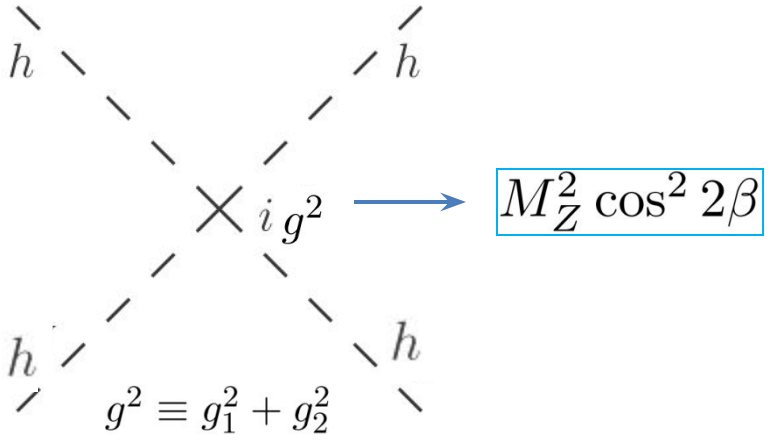
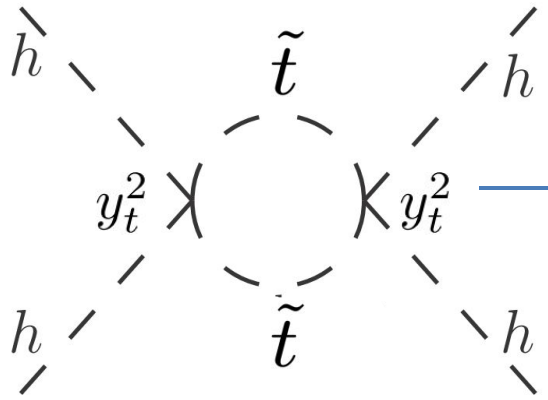


$M_Z^2 \cos^2 2\beta$



$\frac{3y_t^4}{4\pi^2} v^2 \log\left(\frac{m_{\tilde{t}}^2}{M_Z^2}\right)$

Higgs and Supersymmetry

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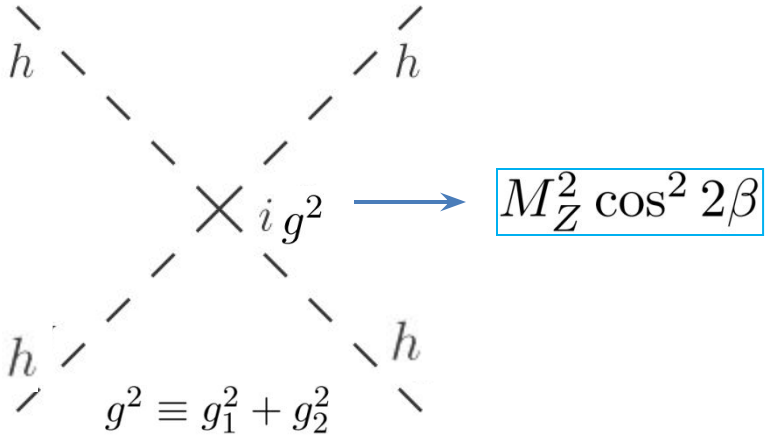
Generally need heavy stops, mixing



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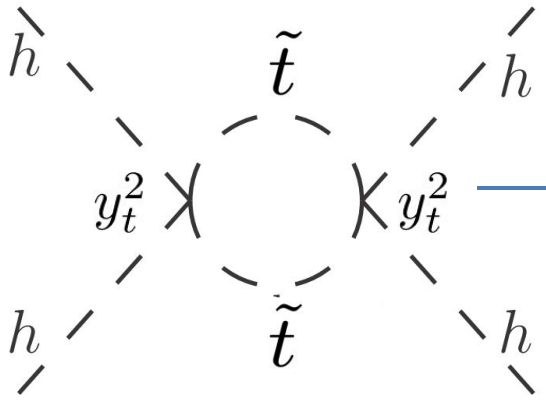

$\frac{3y_t^4}{4\pi^2} v^2 \log\left(\frac{m_{\tilde{t}}^2}{M_Z^2}\right)$

Tree-level quartic contribution

Next-to-Minimal Supersymmetric SM

Extend MSSM with a gauge singlet, S :

$$W \supset \lambda S H_u H_d$$

Tree-level quartic contribution

Next-to-Minimal Supersymmetric SM

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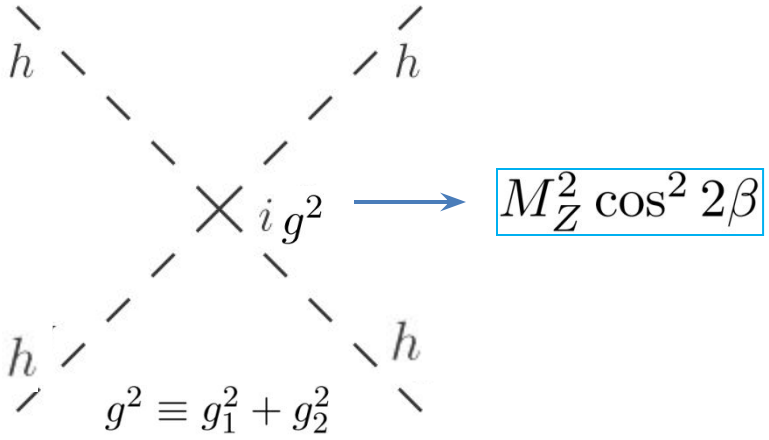
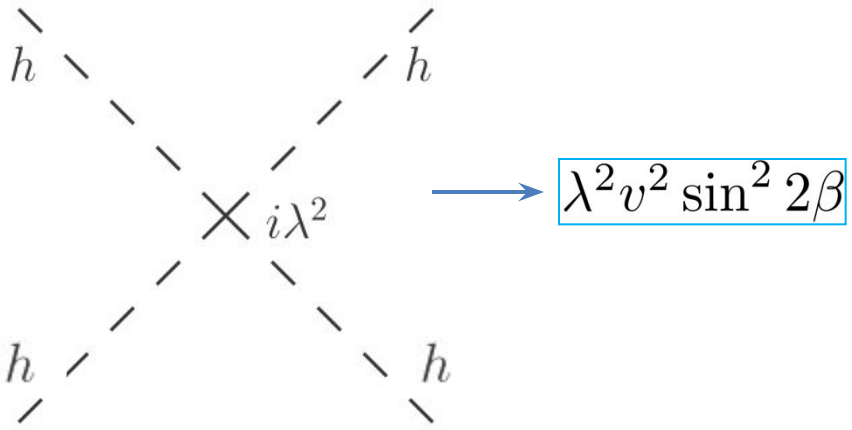
$m_h \sim 125$ GeV

$m_h^{\max}(\text{tree}) = M_Z \sim 91$ GeV





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Next-to-Minimal Supersymmetric SM

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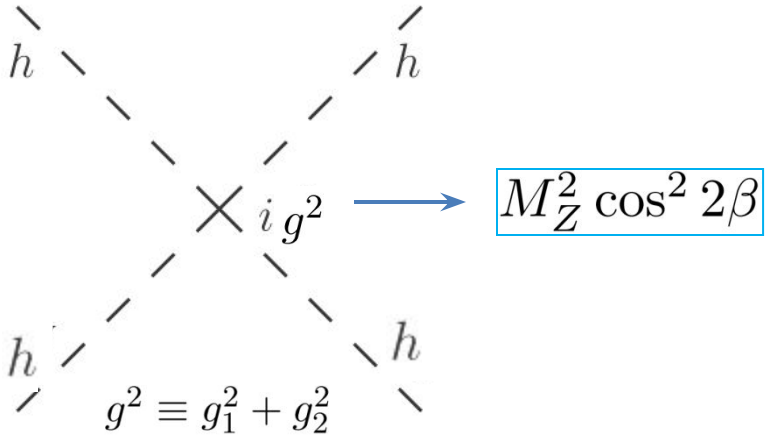
Advantage: stops can be light; discoverable @ LHC Run II



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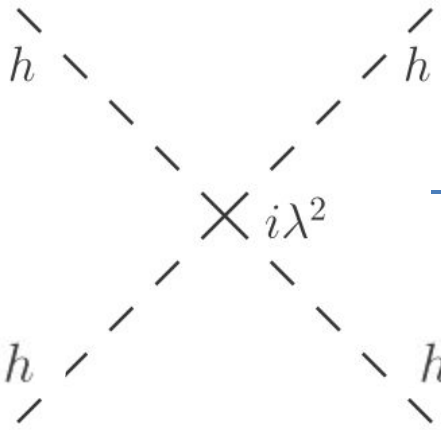


$\lambda^2 v^2 \sin^2 2\beta$

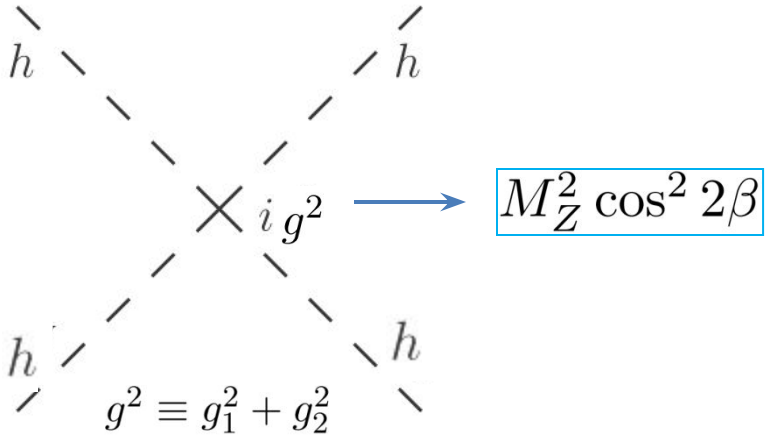
Large tanβ: Back to MSSM problem

Next-to-Minimal Supersymmetric SM

$m_h^{\text{observed}} \sim 125$ GeV

$\tan\beta \gg 1$

$m_h^{\max}(\text{tree}) = M_Z \sim 91$ GeV $\longrightarrow$ $m_h \sim 91$ GeV



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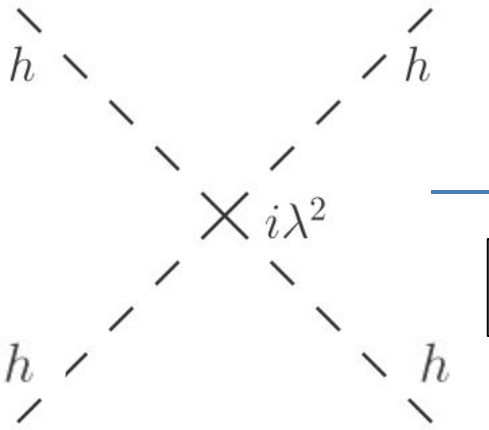

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suppressed

Large tanβ: This Talk

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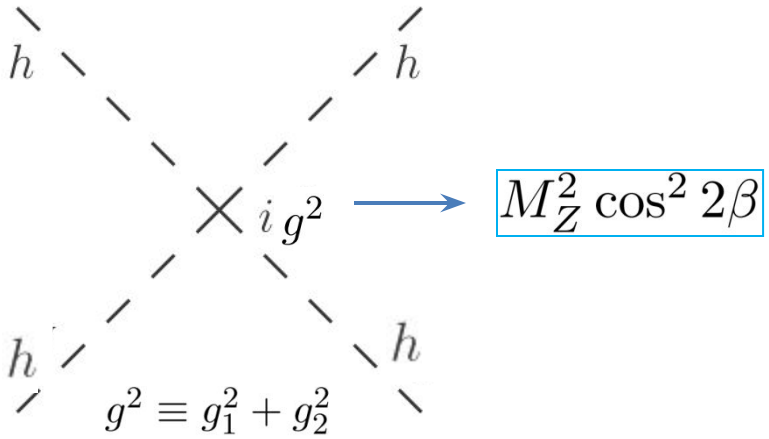

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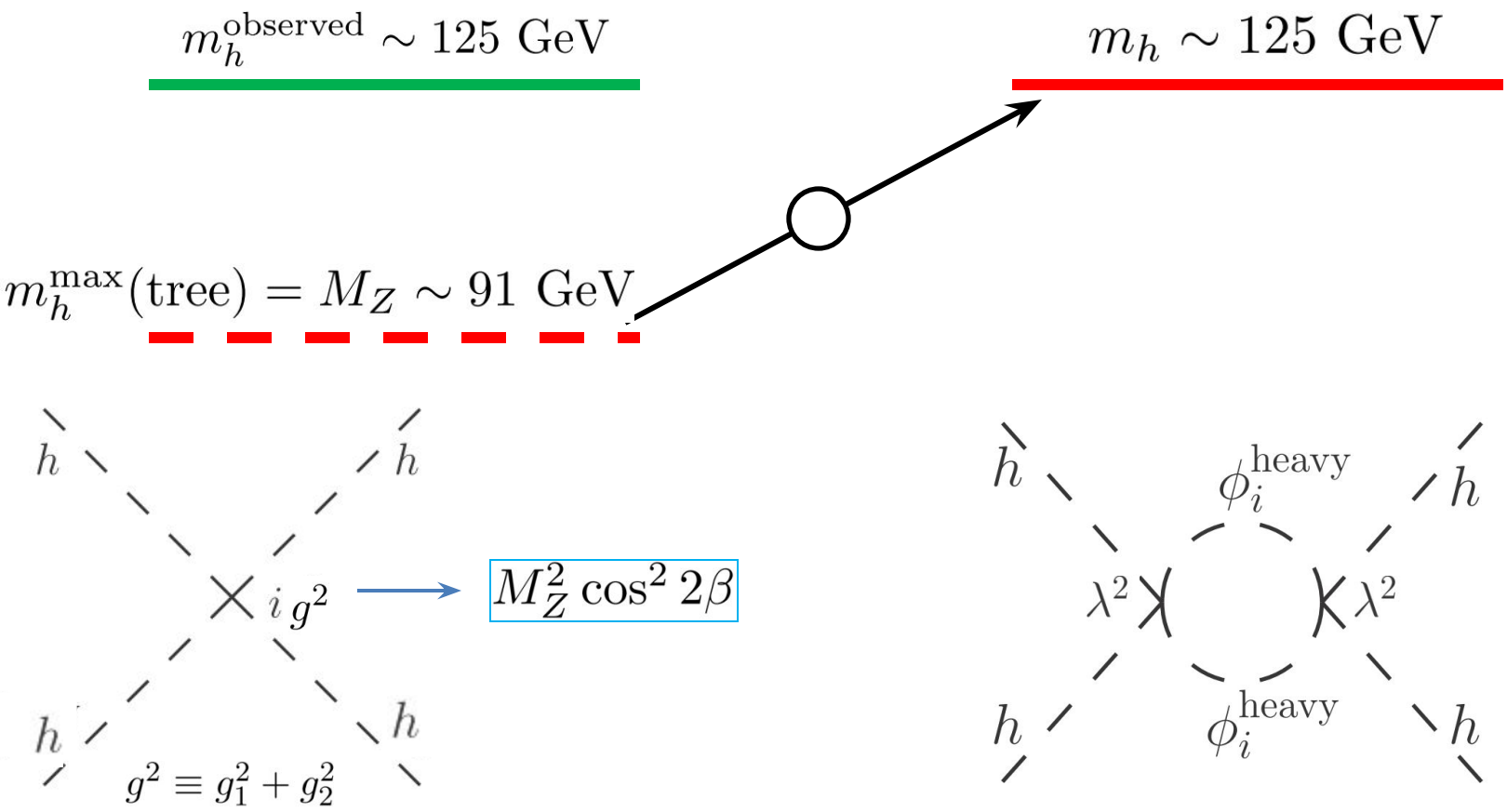
Large tanβ: This Talk

Quartic raised by loops of *non-standard Higgs*es



Back-of-the-envelope: $\lambda >> g$, $\tan\beta$ large

$$H_u \xrightarrow{\beta\to\pi/2} \begin{pmatrix} G^+ \\ v + \frac{1}{\sqrt{2}}(h + iG^0) \end{pmatrix} \qquad H_d \xrightarrow{\beta\to\pi/2} \begin{pmatrix} \frac{1}{\sqrt{2}}(H + iA_D^0) \\ H^- \end{pmatrix} \qquad S \xrightarrow{\beta\to\pi/2} \frac{1}{\sqrt{2}}(s + h_s^0 + iA_S^0)$$

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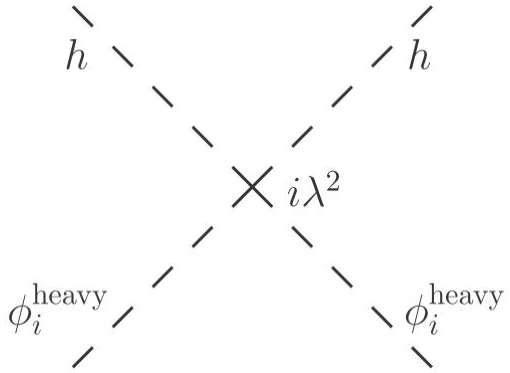

$$\phi_i^{\text{heavy}} = \underbrace{H,\ A_D^0}_{M_{A_D}},\ \underbrace{h_s^0,\ A_S^0}_{M_{A_S}}$$

(neglecting mixing)

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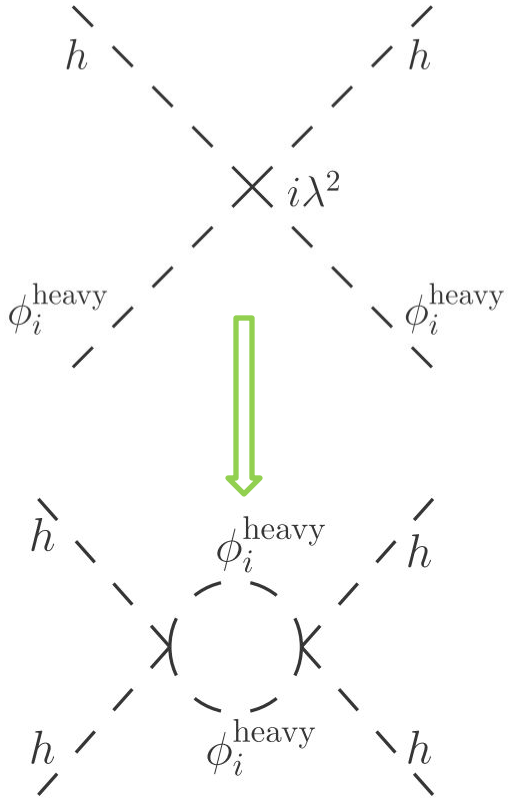


$$\phi_i^{\text{heavy}} = \underbrace{H,\ A_D^0}_{M_{A_D}},\ \underbrace{h_s^0,\ A_S^0}_{M_{A_S}} \quad \text{(neglecting mixing)}$$

two fields for each mass

$$\Pi_{hh} = v^2 \frac{\cdot 2 \cdot \lambda^4}{16\pi^2}\left[\log\left(\frac{M_{A_D}^2}{M_Z^2}\right) + \log\left(\frac{M_{A_S}^2}{M_Z^2}\right)\right]$$

$$\sim (\lambda^2/2)^2 \text{ x } 250^2 \ (M_A = 4 \text{ TeV})$$

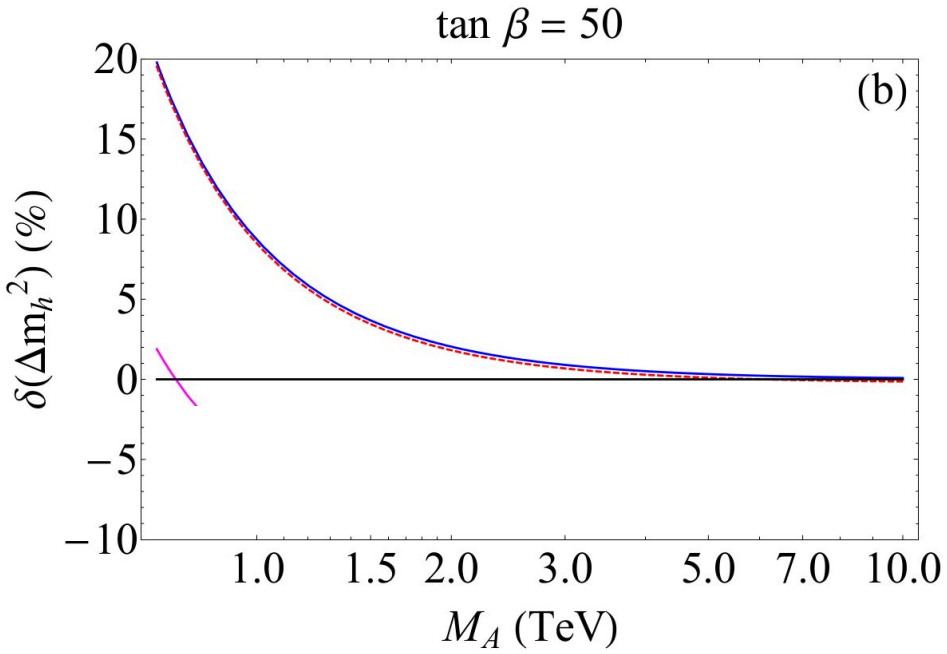
$$\sim 125^2$$

One-loop effective potential

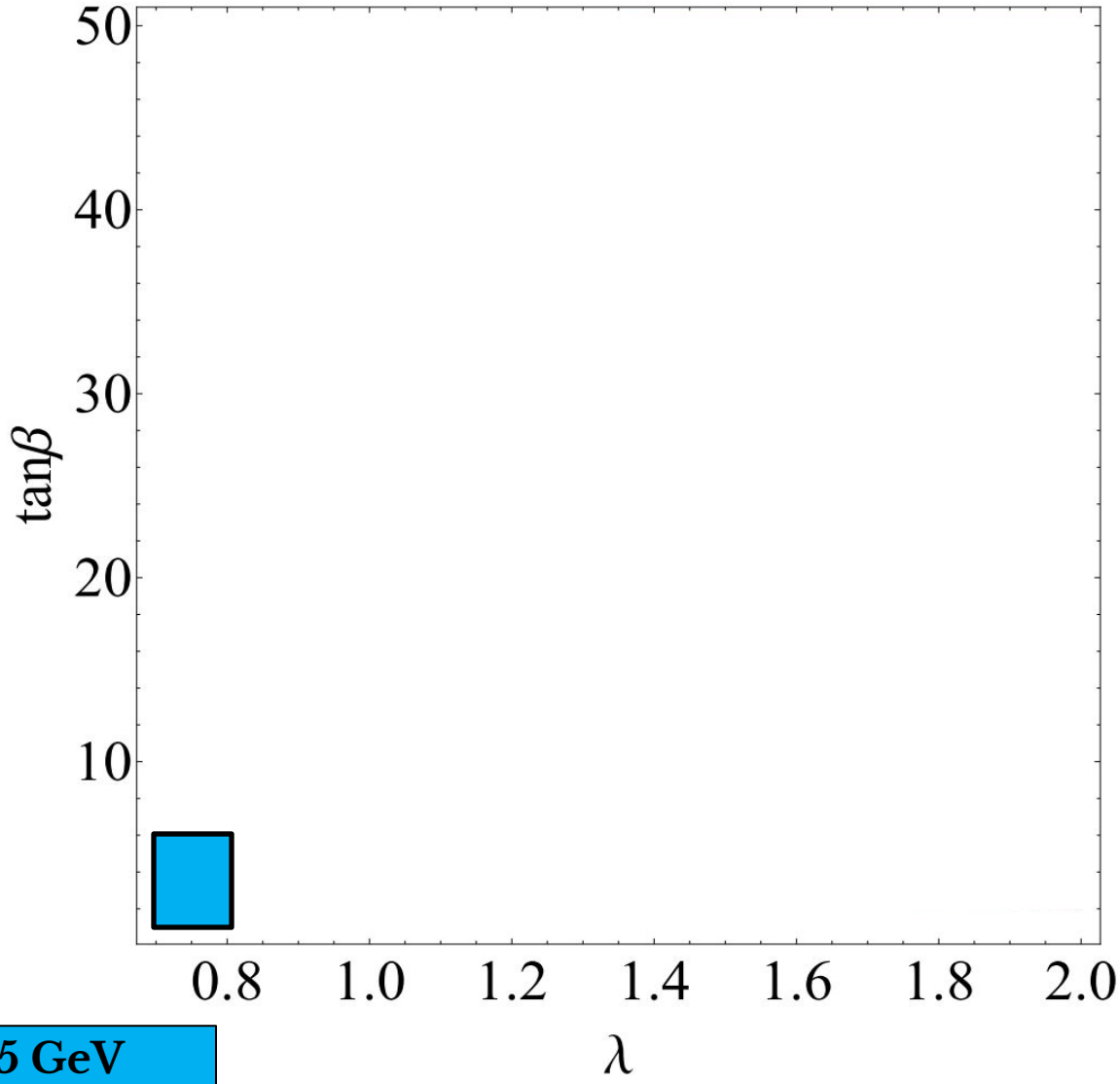
For full calculation (include effects of tanβ and mixing),

$$\Delta V^a = \sum_i \left(M_{ia}^2(\phi_k)\right)^2 \left(\log \frac{M_{ia}^2(\phi_k)}{Q^2} - \frac{3}{2}\right) \approx \sum_{i=\text{heavy}} \left(M_{ia}^2(\phi_k)\right)^2 \left(\log \frac{M_{ia}^2}{Q^2} - \frac{3}{2}\right)$$

field-dependent eigenvalues



Literature v Us - I



m(higgs) ~ 125 GeV from tree level quartic

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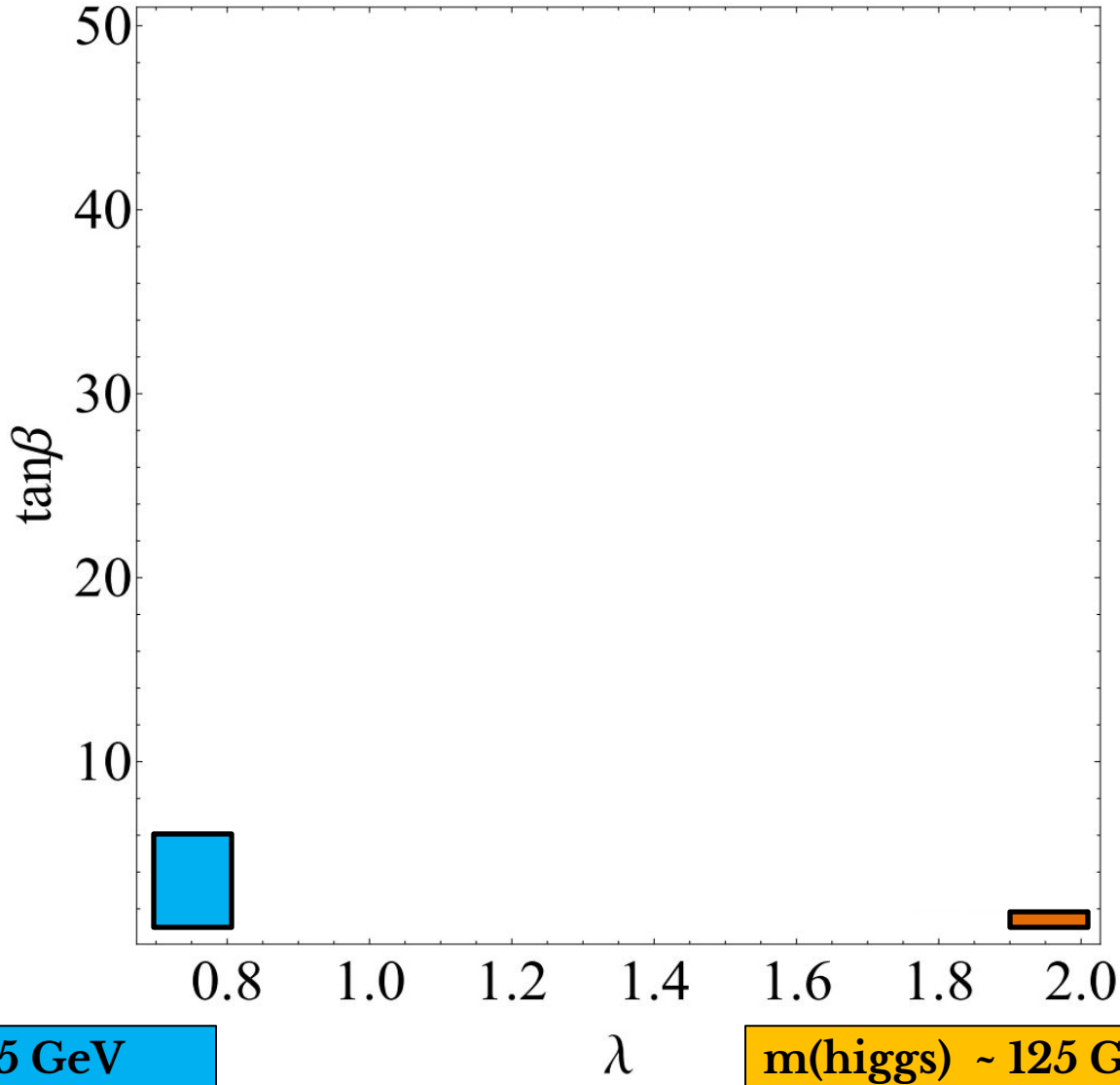

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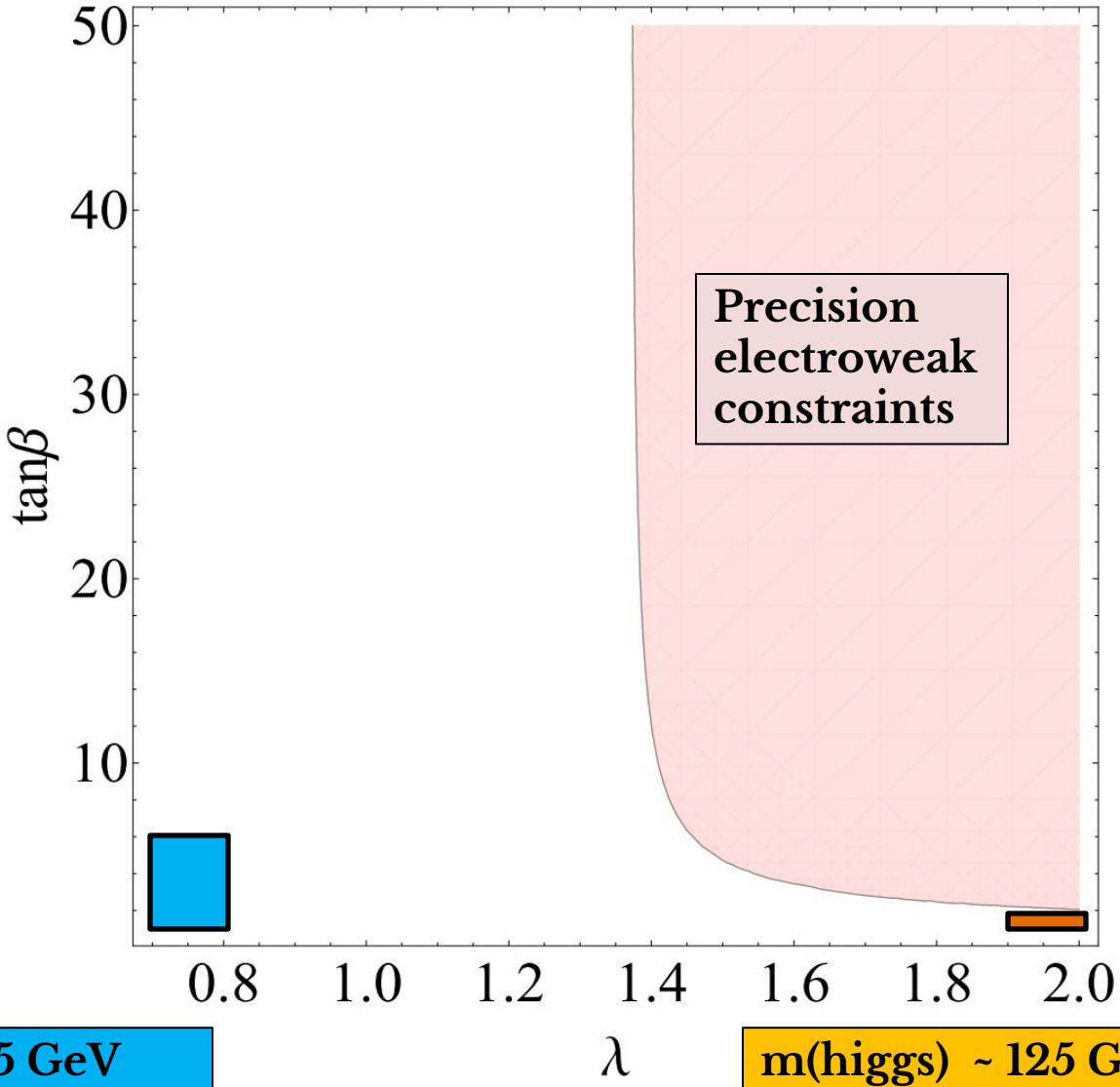
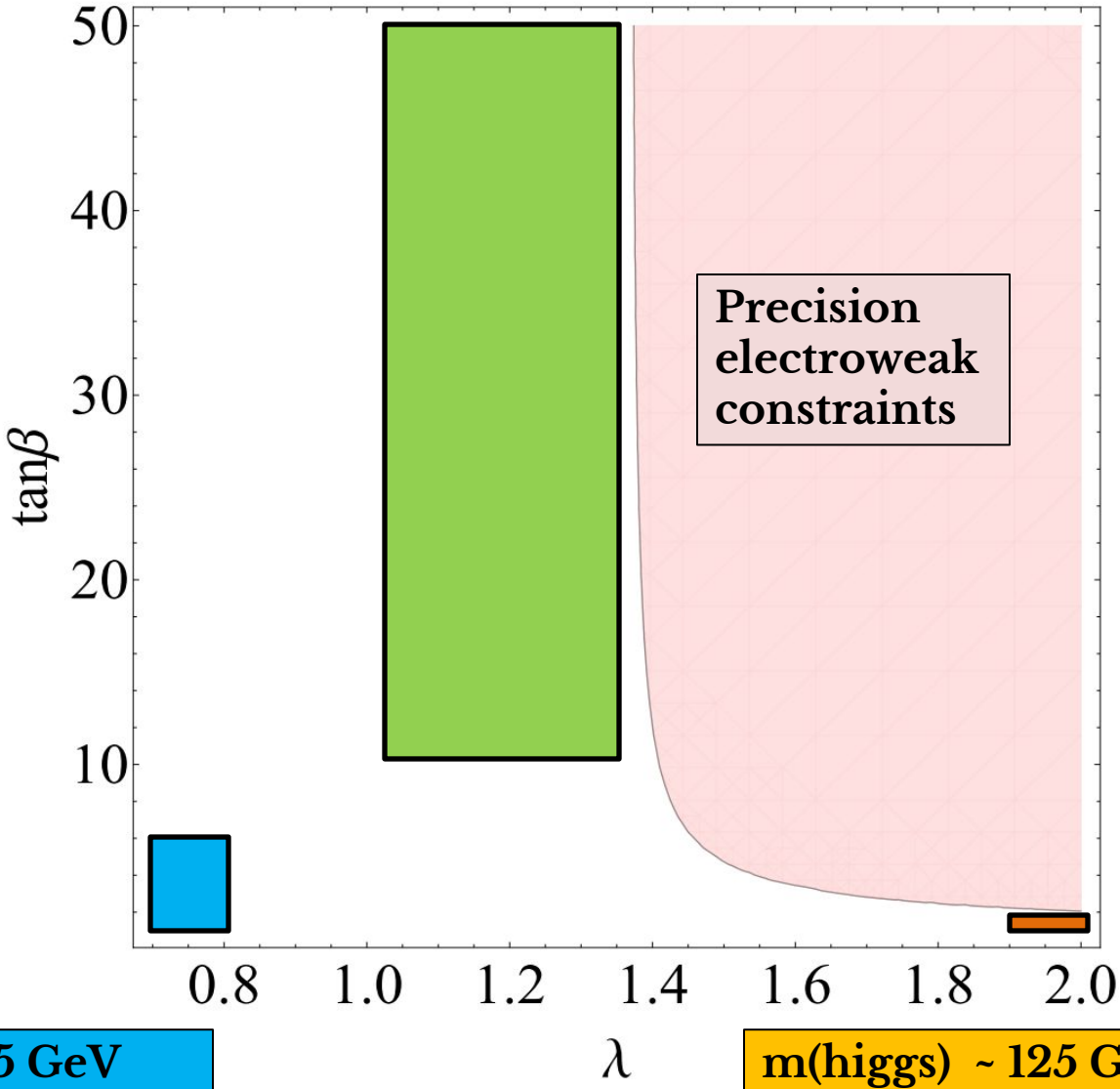


m(higgs) ~ 125 GeV from tree level quartic

m(higgs) ~ 125 GeV from singlet-doublet mixing

Literature v Us - I

m(higgs) ~ 125 GeV
from loop corrections ~ λ^4



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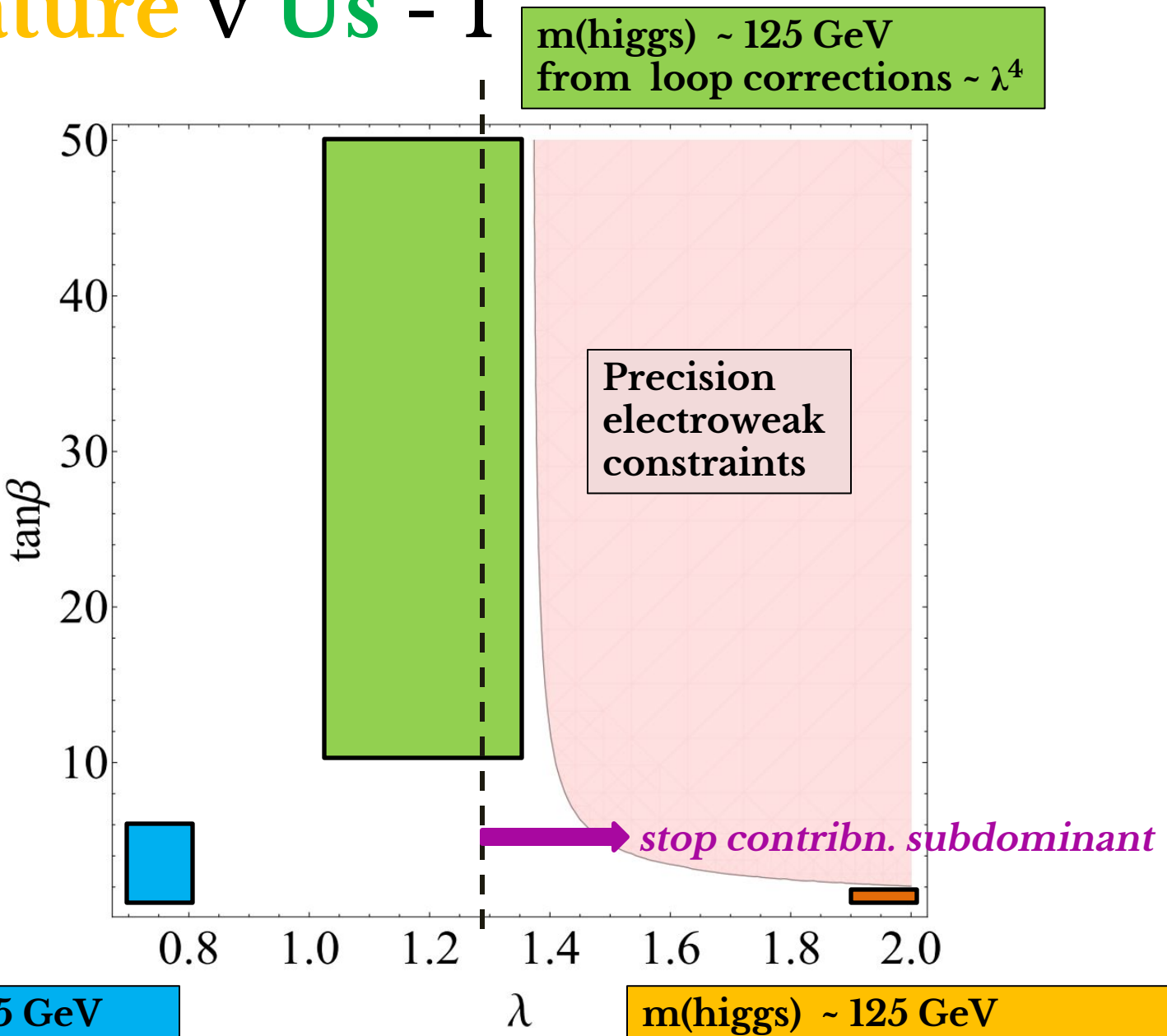


Literature v Us - II

Incorporation of radiative corrections

* Ellwanger & Hugonie (hep-ph/0504269) assumed large hierarchy in heavy higgs scalars

- Result implemented in *NMSSMTools*

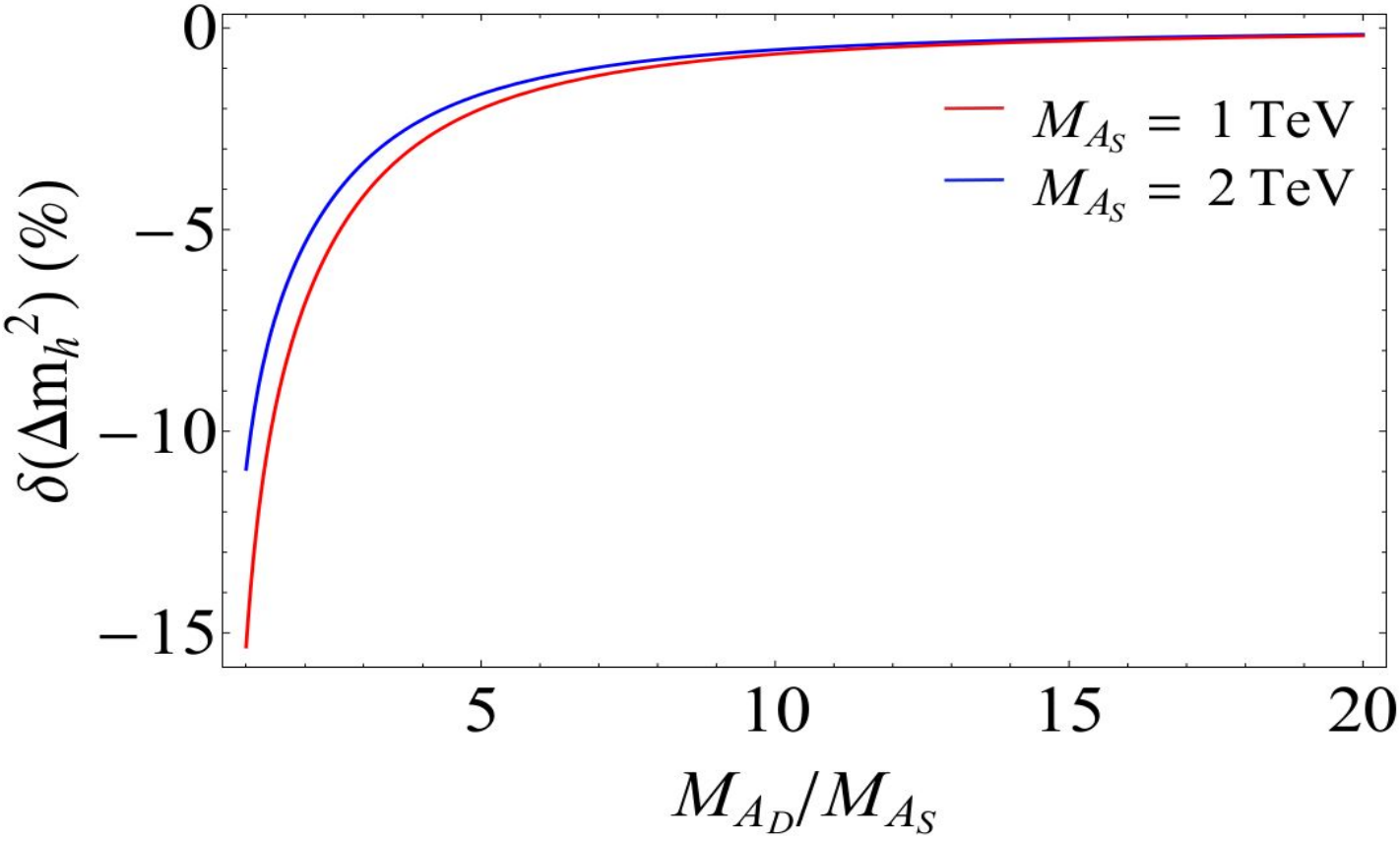
* Gherghetta, et al (1212.5243), Perelstein, et al (1310.0459)

- Scans, but used *NMSSMTools*

* A. Menon & NR solved characteristic equations analytically by expanding in $1/M_A$

- General result, applicable to any spectrum with large nonstandard higgs masses

Discrepancy with NMSSMTools



Agreement reached when heavy higgses are split.

Phenomenology

Low-energy theory

$$\mathcal{W}^{\text{eff}}_{\text{NMSSM}} = \mathcal{W}_{\text{Yukawa}} + \lambda \hat{S} \hat{H}_u \hat{H}_d + \frac{1}{2}\mu' \hat{S}^2 + \xi_F \hat{S}$$

$$\begin{aligned} -\mathcal{L}^{\text{eff}}_{\text{soft}} &= -\mathcal{L}^{\tilde{f}}_{\text{soft}} + m^2_{H_u}|H_u|^2 + m^2_{H_d}|H_d|^2 + m^2_S|S|^2 \\ &\quad + \left(\lambda A_\lambda S H_u H_d + m^2_3 H_u H_d + \frac{1}{2} m'^2_S + \xi_S S + \text{h.c.} \right) \end{aligned}$$

Phenomenology

Assumptions

$$m^{1,2}_{\text{squarks}} = m^{1,2,3}_{\text{sleptons}} = M_2 = 10 \text{ TeV}$$

$$M_A = M_{A_D} = M_{A_S} \in [4, 8] \text{ TeV}$$

Only independent parameters:

$$\lambda, \ \tan\beta, \ M_A, \ \mu_{\text{eff}}, \ \mu', \ M_1$$

$$\mu_{\text{eff}}, \mu', M_1 \leq 1 \text{ TeV}$$

$$m_{\tilde{t}} = 800 \text{ GeV}$$

Phenomenology: general comments

Constraints

* Higgs couplings -- weak (nonstandard higgses heavy)
* EWPT -- weak ($\lambda < 1.4$ => higgsino-singlino mixing small)
* Dark matter -- strong (generically, large rates)

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* Higgs couplings -- weak (nonstandard higgses heavy)
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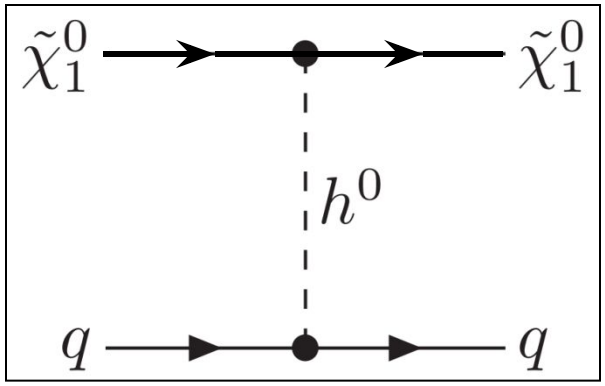
* Dark matter -- strong (generically, large scattering rates)

Higgs-DM-DM coupling

$$g_{h\chi\chi} = \frac{\lambda}{\sqrt{2}}(\zeta_{H_u} N_{\tilde{\psi}_d^0} N_{\tilde{\psi}_s^0} + \zeta_{H_d} N_{\tilde{\psi}_u^0} N_{\tilde{\psi}_s^0} + \zeta_S N_{\tilde{\psi}_u^0} N_{\tilde{\psi}_d^0}) - \frac{g_1}{2} N_{\tilde{B}} (\zeta_{H_u} N_{\tilde{\psi}_d^0} - \zeta_{H_d} N_{\tilde{\psi}_u^0})$$



ζ : components in LHC higgs

N : components in LSP

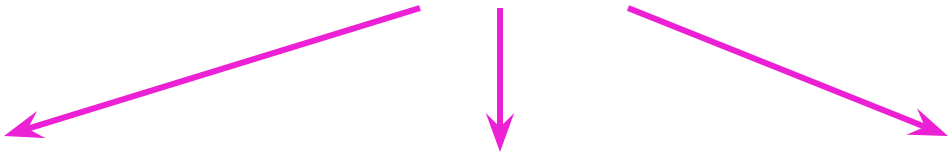
Dark matter phenomenology

$$g_{h\chi\chi} = \frac{\lambda}{\sqrt{2}}(\zeta_{H_u} N_{\widetilde{\psi}_d^0} N_{\widetilde{\psi}_s^0} + \zeta_{H_d} N_{\widetilde{\psi}_u^0} N_{\widetilde{\psi}_s^0} + \zeta_S N_{\widetilde{\psi}_u^0} N_{\widetilde{\psi}_d^0}) - \frac{g_1}{2} N_{\widetilde{B}} (\zeta_{H_u} N_{\widetilde{\psi}_d^0} - \zeta_{H_d} N_{\widetilde{\psi}_u^0})$$

ζ : components in LHC higgs, N : components in LSP

To evade bounds from direct detection (and $\Gamma(h \to \widetilde{\chi}_1^0 \widetilde{\chi}_1^0)$):

$$g_{h\chi\chi} \to 0$$



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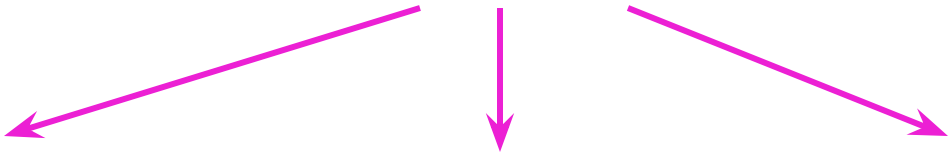

"Well-tempered" (e.g., mix of bino, higgsino, singlino)

Dark matter phenomenology

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higgsino DM

$$N_{\tilde{\psi}_s}, N_{\tilde{B}} \simeq 0$$

$$N^2_{\tilde{\psi}_u} = N^2_{\tilde{\psi}_d} \simeq 1/2$$

Dark matter phenomenology

$$g_{h\chi\chi} = \frac{\lambda}{\sqrt{2}}(\zeta_{H_u} N_{\tilde{\psi}_d^0} N_{\tilde{\psi}_s^0} + \zeta_{H_d} N_{\tilde{\psi}_u^0} N_{\tilde{\psi}_s^0} + \zeta_S N_{\tilde{\psi}_u^0} N_{\tilde{\psi}_d^0}) - \frac{g_1}{2} N_{\tilde{B}} (\zeta_{H_u} N_{\tilde{\psi}_d^0} - \zeta_{H_d} N_{\tilde{\psi}_u^0})$$

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bino/singlino DM

$$N_{\tilde{\psi}_u}, N_{\tilde{\psi}_d} \simeq 0$$

$$N^2_{\tilde{B}} + N^2_{\tilde{\psi}_s^0} \simeq 1$$

Dark matter phenomenology

$$g_{h\chi\chi} = \frac{\lambda}{\sqrt{2}}(\zeta_{H_u} N_{\tilde{\psi}_d^0} N_{\tilde{\psi}_s^0} + \zeta_{H_d} N_{\tilde{\psi}_u^0} N_{\tilde{\psi}_s^0} + \zeta_S N_{\tilde{\psi}_u^0} N_{\tilde{\psi}_d^0}) - \frac{g_1}{2} N_{\tilde{B}} (\zeta_{H_u} N_{\tilde{\psi}_d^0} - \zeta_{H_d} N_{\tilde{\psi}_u^0})$$

ζ : components in LHC higgs, N : components in LSP

To evade bounds from direct detection (and $\Gamma(h \to \tilde{\chi}_1^0 \tilde{\chi}_1^0)$):

$$g_{h\chi\chi} \to 0$$

This talk

"Well-tempered" (e.g., mix of bino, higgsino, singlino)

higgsino DM

$$N_{\tilde{\psi}_s}, N_{\tilde{B}} \simeq 0$$

$$N^2_{\tilde{\psi}_u} = N^2_{\tilde{\psi}_d} \simeq 1/2$$

bino/singlino DM

$$N_{\tilde{\psi}_u}, N_{\tilde{\psi}_d} \simeq 0$$

$$N^2_{\tilde{B}} + N^2_{\tilde{\psi}_s^0} \simeq 1$$

Singlino/ bino dark matter

If the abundance is set thermally,

$$g_{h\chi\chi} \to 0$$ => naively, DM overproduced

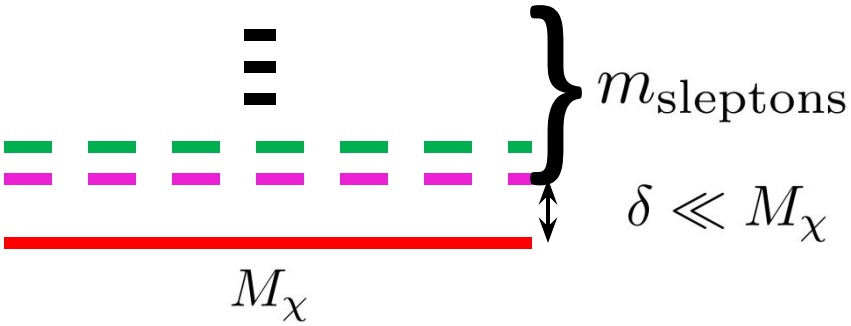
Singlino/ bino dark matter

If the abundance is set thermally,

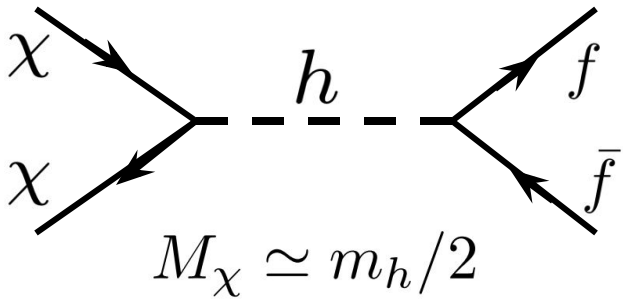
$$g_{h\chi\chi} \to 0 \quad \Rightarrow \text{ naively, DM overproduced}$$

Exceptions [Griest & Seckel, PRD 43 (1991)]:

Assisted annihilation
("co-annihilation")



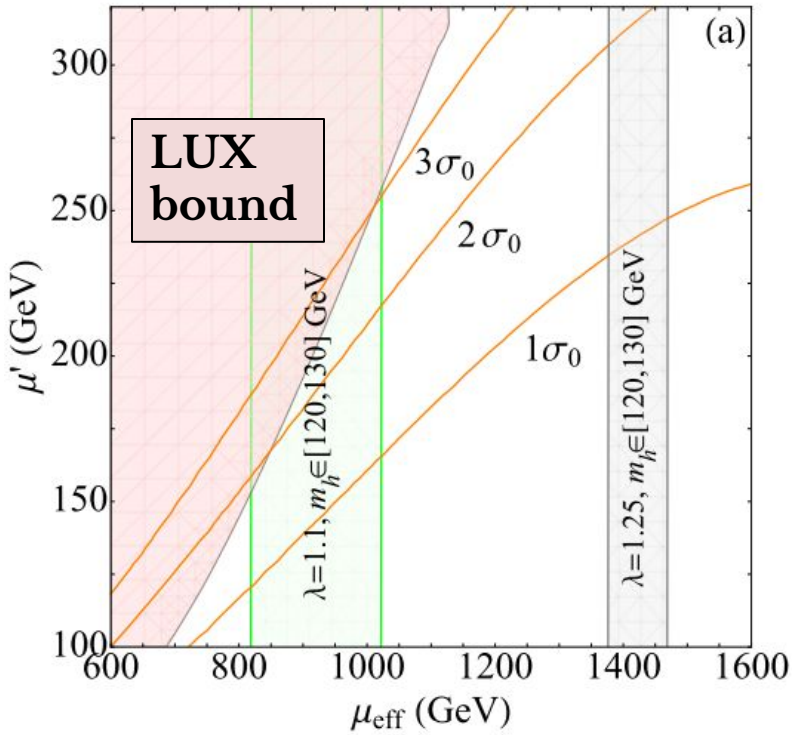
Annihilation at pole
("resonant annihilation")



Singlino/bino DM: (possibly) co-annihiln.

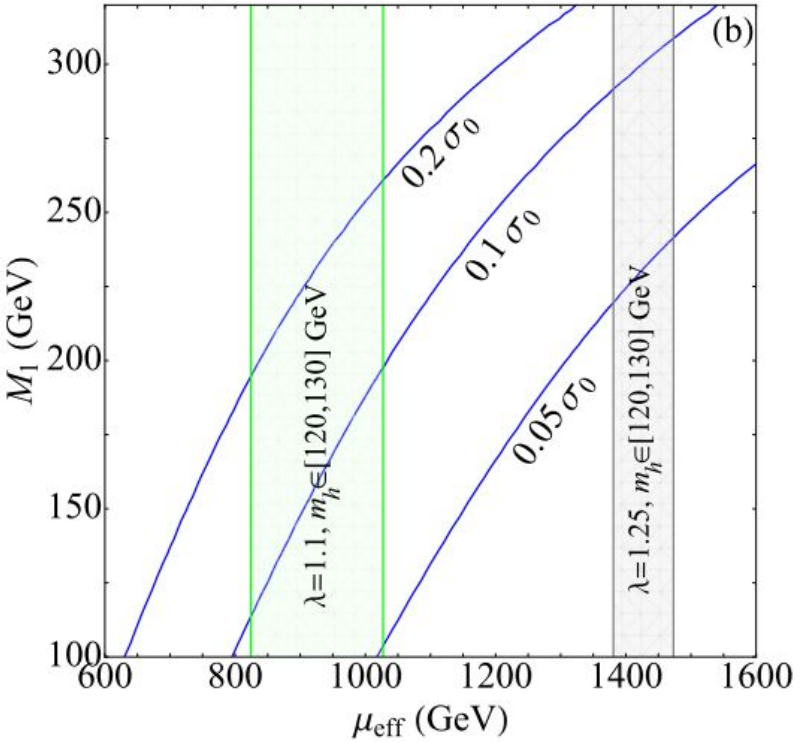
$N^2_{\widetilde{\psi}^0_s} \simeq 1$

(NMSSM-like)



$N^2_{\widetilde{B}} \simeq 1$

(MSSM-like)



$\sigma_0 = 10^{-45}\ \mathrm{cm}^2$

Singlino/bino DM: (possibly) co-annihiln.

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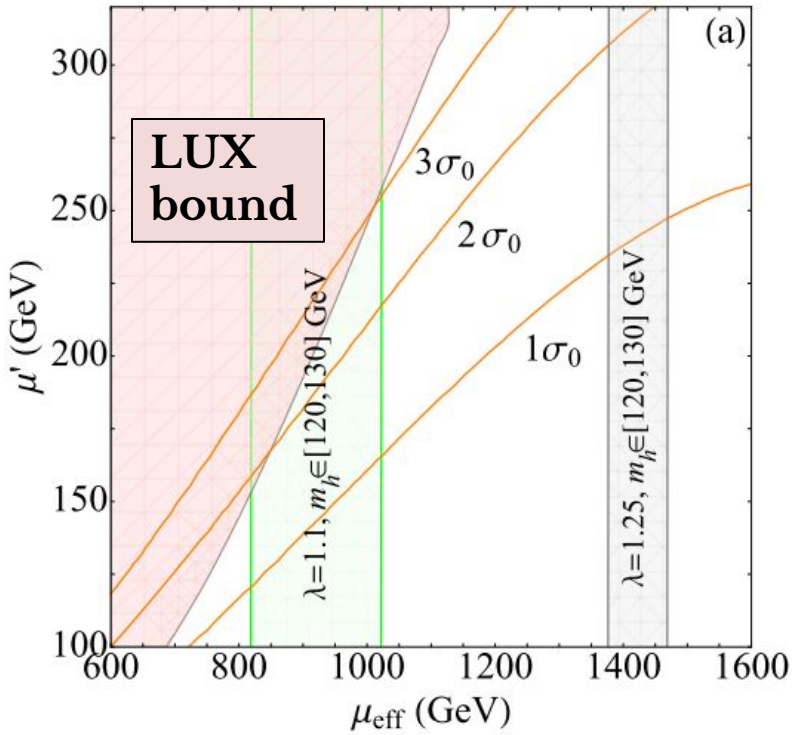
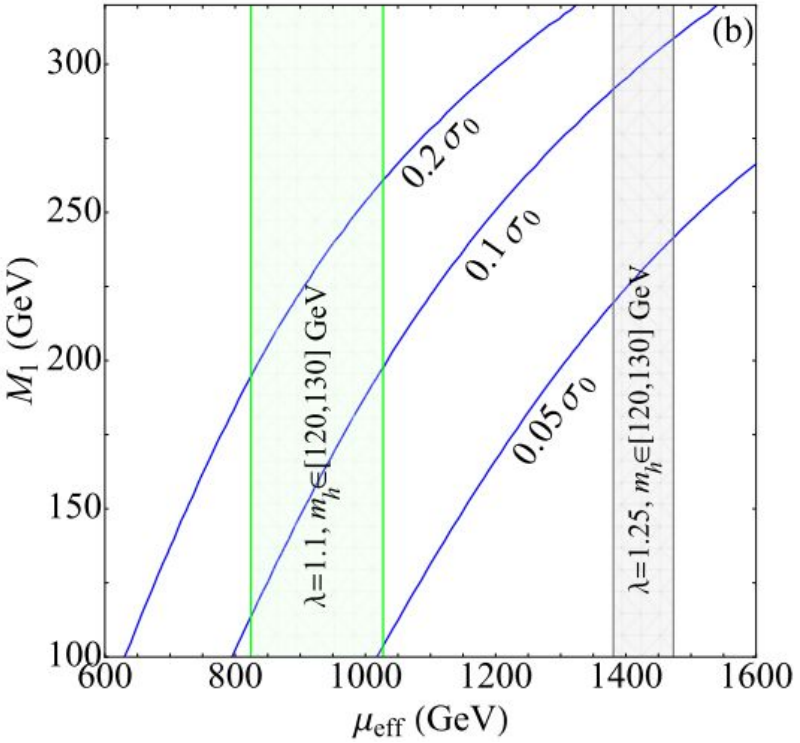


$N^2_{\widetilde{B}} \simeq 1$

(MSSM-like)



$\sigma_0 = 10^{-45}\ \mathrm{cm}^2$

XENON 1T reach: $\sigma_{SI} \sim 10^{-47}$ cm²
--> These regions probe-able

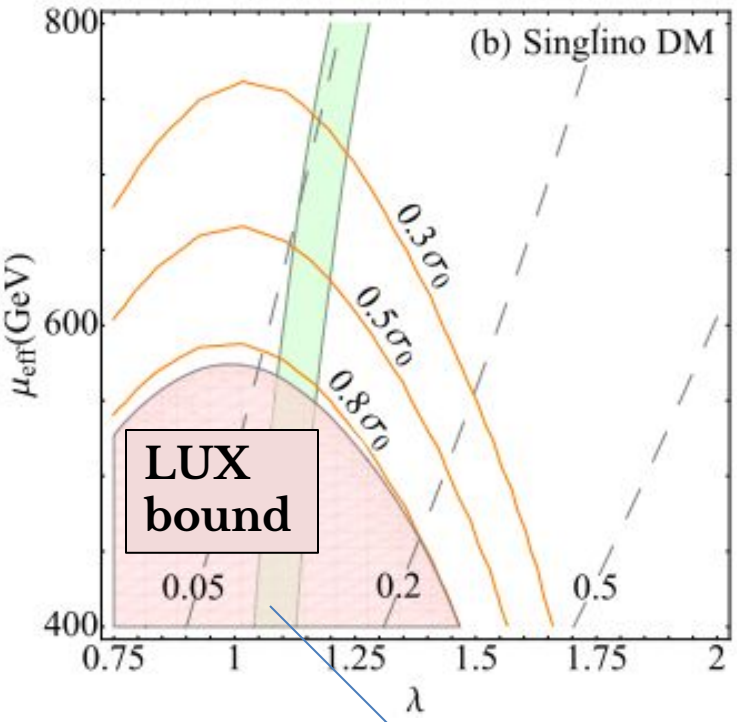
Singlino/bino DM: resonant annihiln.

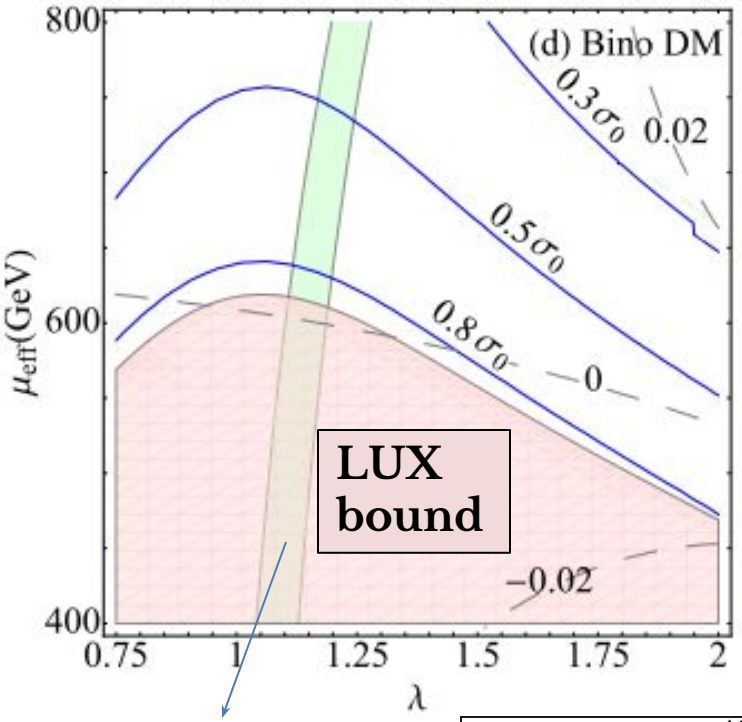
$N^2_{\widetilde{\psi}^0_s} \simeq 1$

(NMSSM-like)

$N^2_{\widetilde{B}} \simeq 1$

(MSSM-like)





$120\ \text{GeV} \leq m_h \leq 130\ \text{GeV}$

$\sigma_0 = 10^{-45}\ \text{cm}^2$

Probe-able by XENON 1T

Conclusions

• In NMSSM, 91 GeV --> 125 GeV achieved by raising SM-higgs quartic with non-SM higgs loops

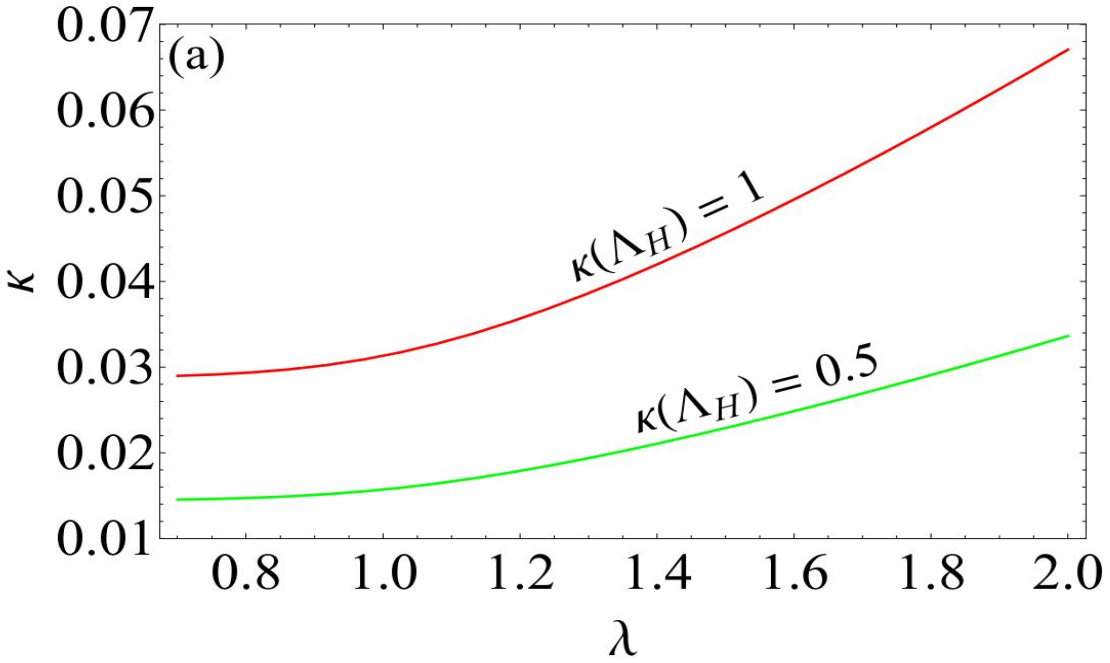
- Ingredients:
(a) Large λ (~ 1 – 1.5)
(b) heavy non-standard higgses

- Consequences:
* Opens up very large tanβ (= v_u/v_d), previously thought impossible due to precision electroweak limits.
* Third generation squarks within reach of LHC Run II.

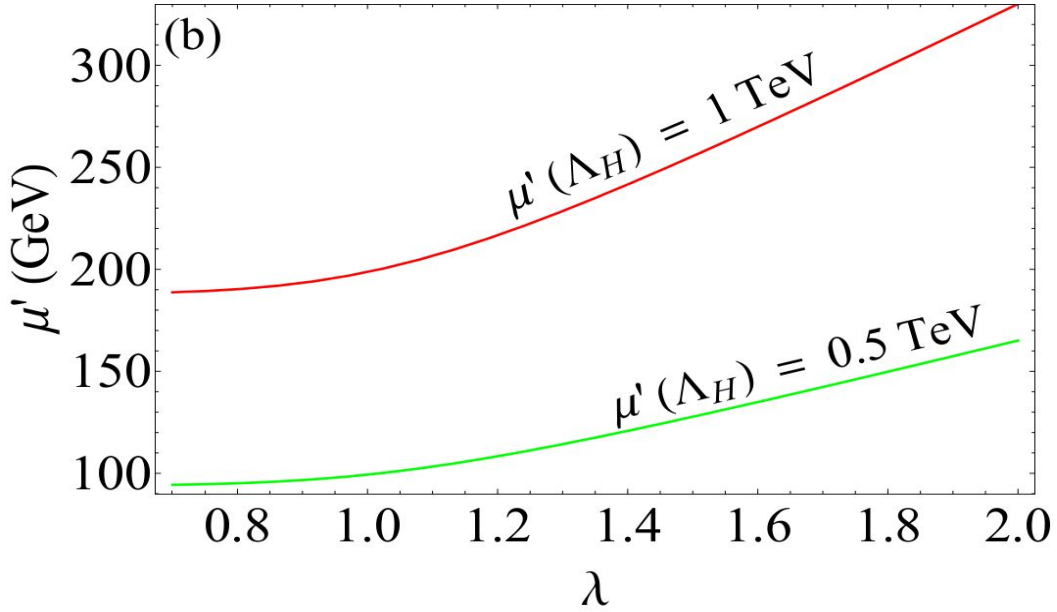
• LSP dark matter viability => bino and/or singlino
- If thermally produced, info about DM mass obtained
- XENON1T can probe this

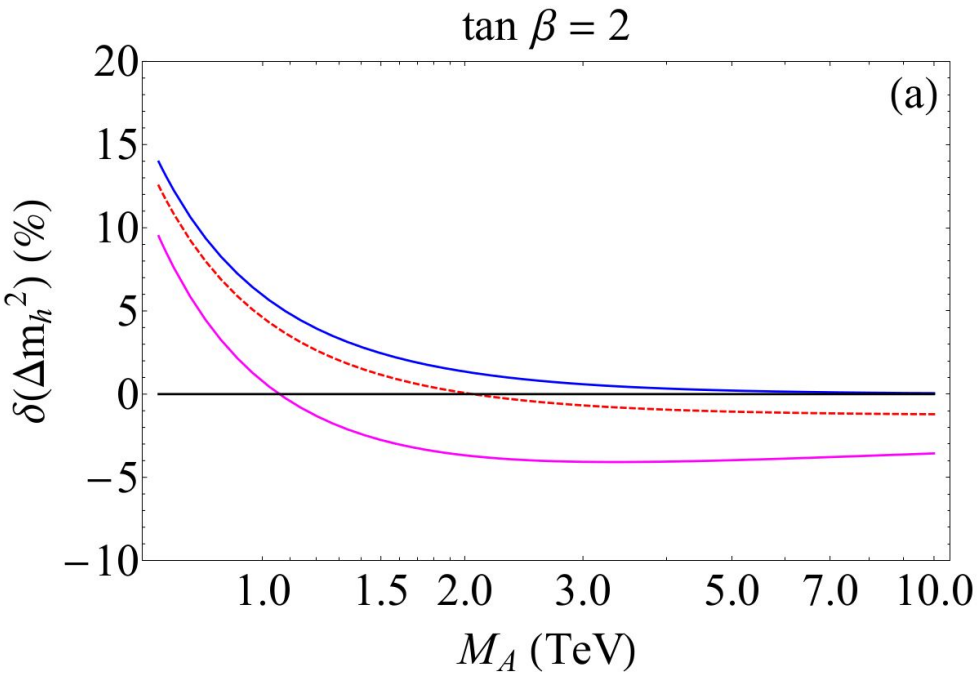
Thanks for your attention!

Backup Slides

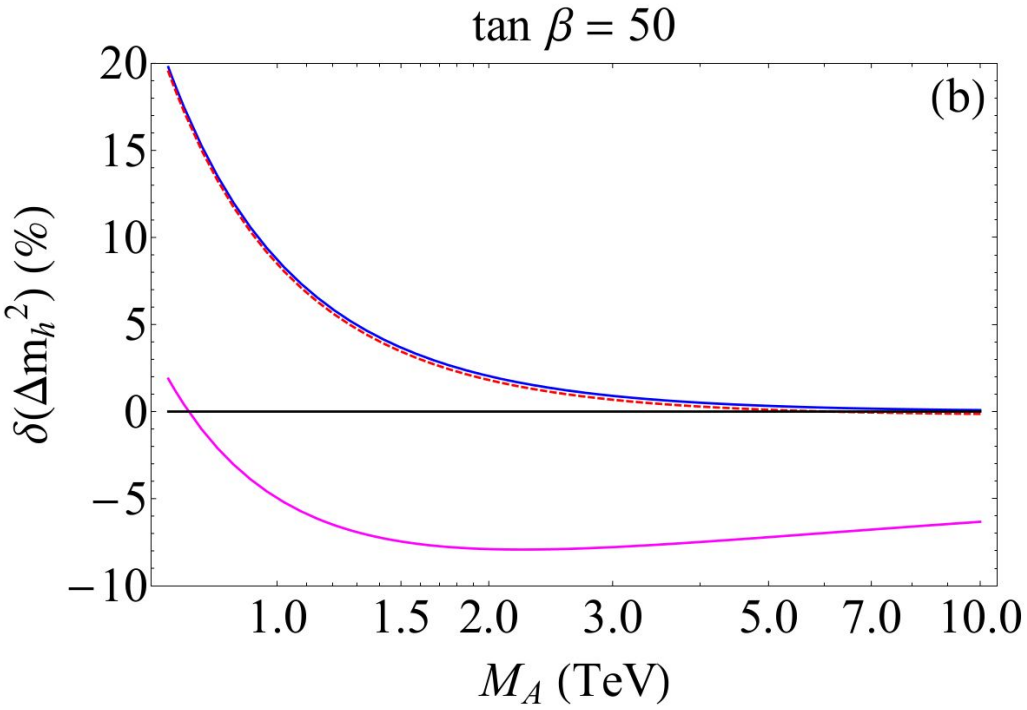


RG Suppression

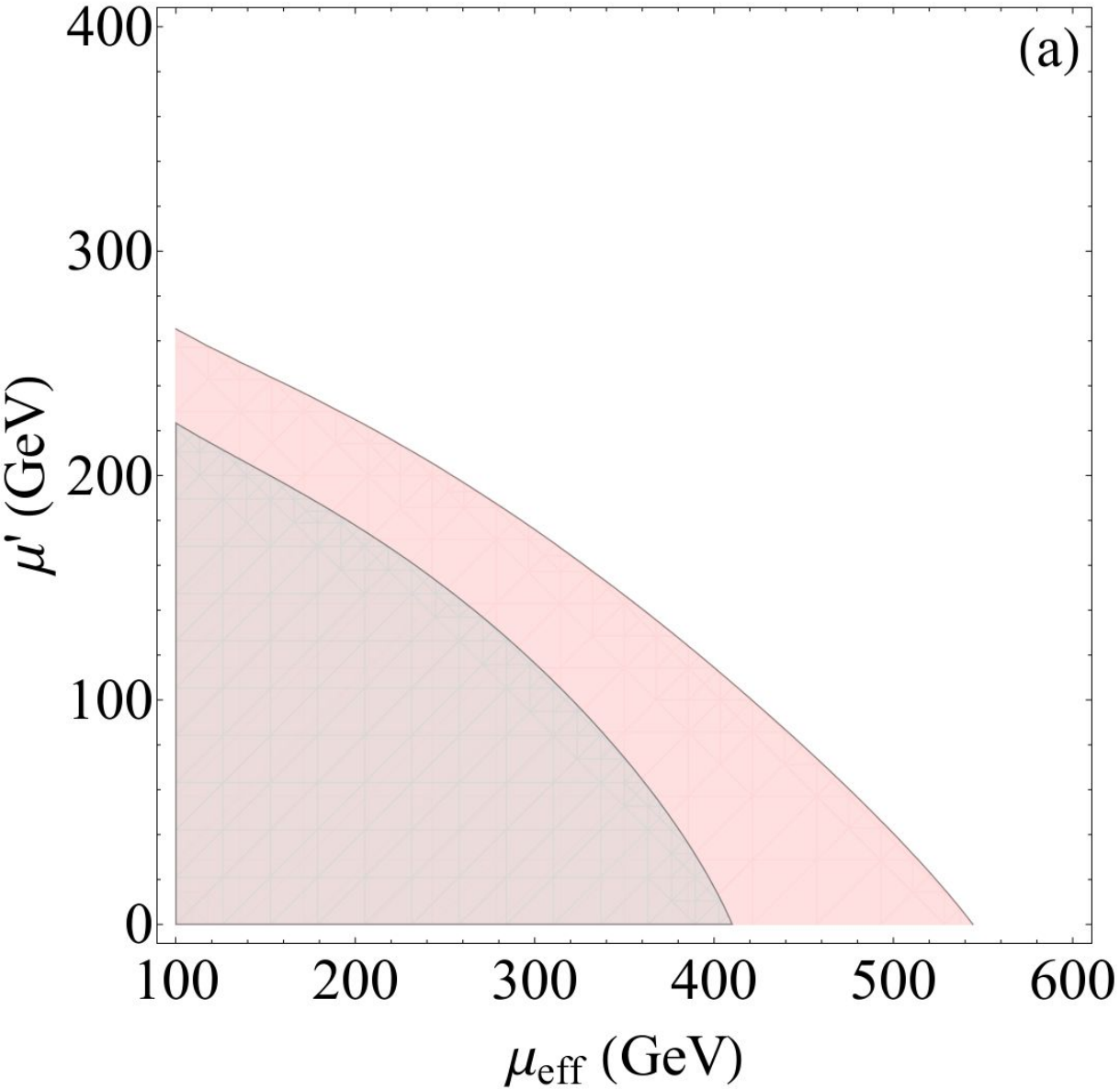




All Discrepancies



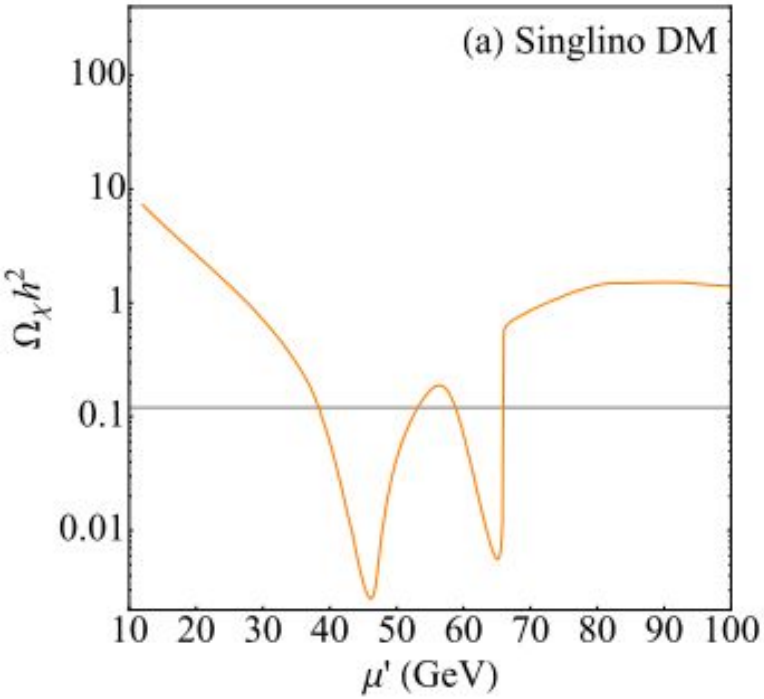
T Constraints



Resonant annihiln.

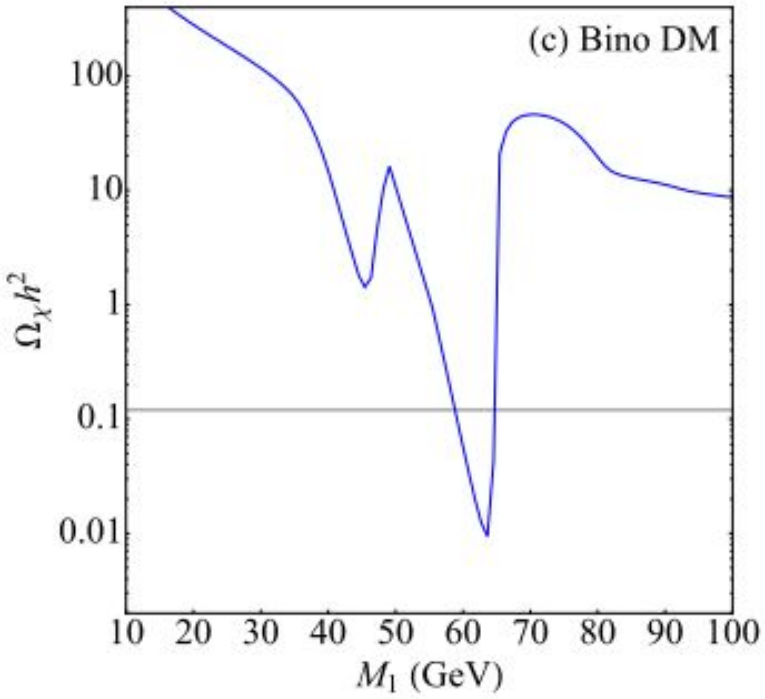
$N^2_{\widetilde{\psi}^0_s} \simeq 1$

(NMSSM-like)

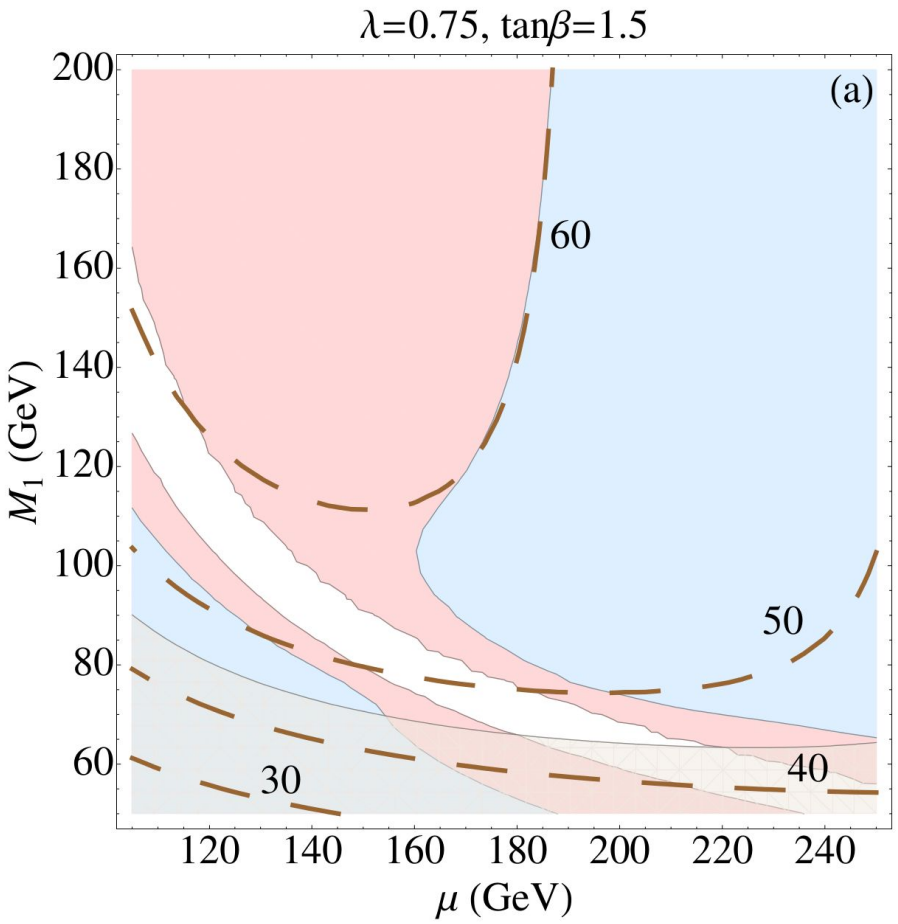


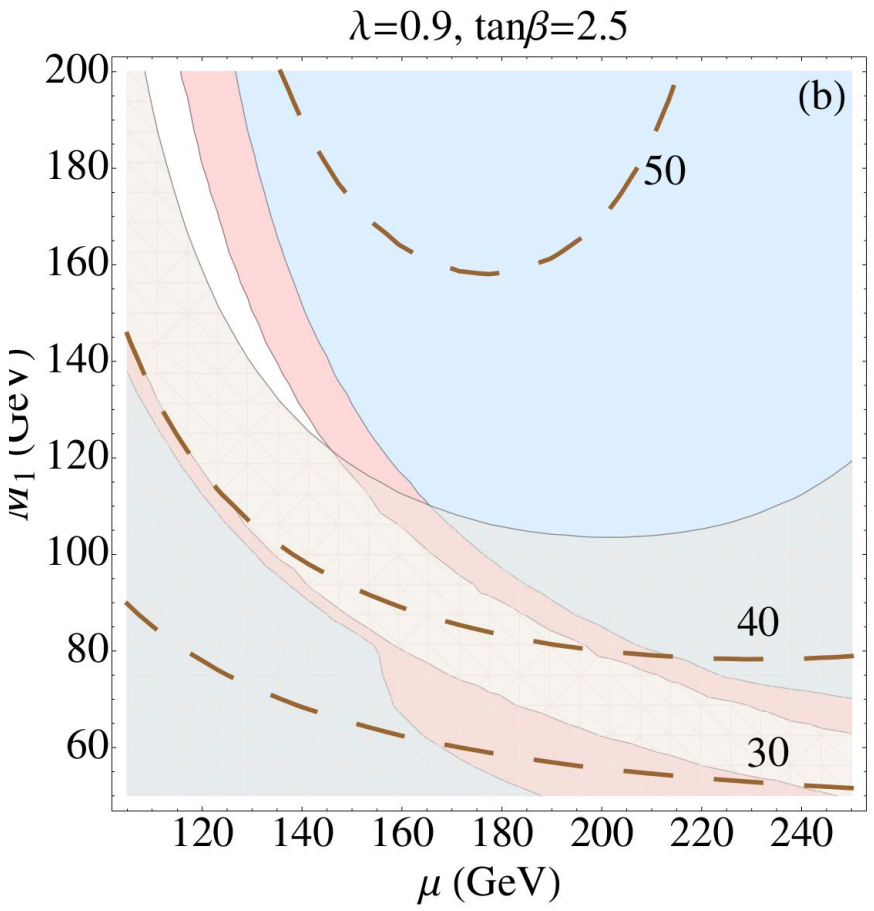
$N^2_{\widetilde{B}} \simeq 1$

(MSSM-like)



Well-tempered





$$\hat{S} \sim \hat{T}_5\hat{T}_6; \quad \begin{pmatrix} \hat{H}_u^+ \\ \hat{H}_u^0 \end{pmatrix} \sim \begin{pmatrix} \hat{T}_1\hat{T}_3 \\ \hat{T}_2\hat{T}_3 \end{pmatrix}; \quad \begin{pmatrix} \hat{H}_d^0 \\ \hat{H}_d^- \end{pmatrix} \sim \begin{pmatrix} \hat{T}_1\hat{T}_4 \\ \hat{T}_2\hat{T}_4 \end{pmatrix}$$

$$\lambda(\Lambda_H) \sim 4\pi; \qquad \kappa(\Lambda_H) \sim \left(\frac{\Lambda_H}{4\pi\Lambda_0}\right)^3$$

$$\mu \sim \frac{\Lambda_H^2}{(4\pi)^2\Lambda_0} \sim \mu'; \qquad \xi_F \sim \frac{m\Lambda_H}{4\pi},$$

$$\frac{\kappa(Q)}{\kappa(\Lambda_H)} = \left(\frac{\mu'(Q)}{\mu'(\Lambda_H)}\right)^3$$

$$\mathcal{W}^{\text{eff}}_{\text{NMSSM}} = \mathcal{W}_{\text{Yukawa}} + \lambda\hat{S}\hat{H}_u\hat{H}_d + \frac{1}{2}\mu'\hat{S}^2 + \xi_F\hat{S}$$

$$-\mathcal{L}^{\text{eff}}_{\text{soft}} = -\mathcal{L}^{\hat{f}}_{\text{soft}} + m^2_{H_u}|H_u|^2 + m^2_{H_d}|H_d|^2 + m^2_S|S|^2 + \left(\lambda A_\lambda S H_u H_d + m_3^2 H_u H_d + \frac{1}{2}m_S'^2 + \xi_S S + \text{h.c.}\right)$$

$$V_F = \left|\lambda\left(H_u^+ H_d^- - H_u^0 H_d^0\right) + \mu' S + \xi_F\right|^2 + |\lambda S|^2 \ \left(|H_u|^2 + |H_d|^2\right),$$

$$V_D = \frac{g^2}{8}\left(\left|H_u^0\right|^2 + \left|H_u^+\right|^2 - \left|H_d^0\right|^2 - \left|H_d^-\right|^2\right) + \frac{g^2}{2}\cos^2\theta_W \left|H_u^+ H_d^{0*} + H_u^0 H_d^{-*}\right|^2,$$

$$V_S = m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_S^2 |S|^2 +$$

$$(\lambda A_\lambda (H_u^+ H_d^- - H_u^0 H_d^0) S + m_3^2 (H_u^+ H_d^- - H_u^0 H_d^0) + \frac{1}{2} m_S'^2 S^2 + \xi_S S + \text{h.c.}),$$

$$\begin{aligned}
\left(M_H^2\right)_{11} &= M_Z^2 s_\beta^2 + r\ t_\beta^{-1}; & \left(M_H^2\right)_{12} &= (2\lambda^2 v^2 - M_Z^2) s_\beta c_\beta - r; \\
\left(M_H^2\right)_{22} &= M_Z^2 c_\beta^2 + r\ t_\beta; & \left(M_H^2\right)_{13} &= \lambda v (2\mu_{\text{eff}} s_\beta - (A_\lambda + \mu') c_\beta); \\
\left(M_H^2\right)_{23} &= \lambda v (2\mu_{\text{eff}} c_\beta - (A_\lambda + \mu') s_\beta); & \left(M_H^2\right)_{33} &= \left(\lambda v^2 (A_\lambda + \mu') - (\xi_S + \xi_F \mu')\right)/s,
\end{aligned} \tag{13}$$

$$\left(M_A^2\right)_{11} = 2r/s_{2\beta}; \qquad \left(M_A^2\right)_{12} = \lambda v (A_\lambda - \mu');$$

$$\left(M_A^2\right)_{22} = \tfrac{1}{s}\left(\lambda v^2 (A_\lambda + \mu') s_\beta c_\beta - (\xi_F \mu' + \xi_S)\right) - 2 m_S'^2,$$

$$M_\pm^2 = 2r/s_{2\beta} - (\lambda^2 - g_2^2/2) v^2$$

$$
\begin{aligned}
\left(M_H^2\right)_{hh} &= M_Z^2 c_{2\beta}^2 + \lambda^2 v^2 s_{2\beta}^2; \qquad \left(M_H^2\right)_{hH} = (\lambda^2 v^2 - M_Z^2) s_{4\beta}/2; \\
\left(M_H^2\right)_{HH} &= M_{A_D}^2 - (\lambda^2 v^2 - M_Z^2) s_{2\beta}^2; \qquad \left(M_H^2\right)_{hS} = 2\lambda v(\mu_{\text{eff}} - A_\lambda s_{2\beta}); \qquad (17) \\
\left(M_H^2\right)_{HS} &= -2\lambda v A_\lambda c_{2\beta}; \qquad \left(M_H^2\right)_{SS} = M_{A_S}^2 + 2{m'_S}^2 + \frac{\lambda^2 v^2}{\mu_{\text{eff}}} A_\lambda (2 - s_{2\beta} c_\beta),
\end{aligned}
$$

$$
\Delta V \propto \sum_i \left[a_i M_{A,i}^4 + 2 b_i M_{A,i}^2 + (b_i^2 + 2c_i)\right] \left(\log \frac{M_{A,i}^2}{Q^2} - \frac{3}{2}\right)
$$

$$
M_Z^2 = \frac{t_\beta^2 + 1}{t_\beta^2 - 1} \left(m_{H_d}^2 - m_{H_u}^2\right) - \left(m_{H_u}^2 + m_{H_d}^2\right) - 2\left|\mu_{\text{eff}}\right|^2,
$$

$$
\frac{1}{2} M_Z^2 \approx -m_{H_u}^2 - \left|\mu_{\text{eff}}\right|^2 \qquad \Delta(a^2) = \left|\frac{a^2}{M_Z^2/2}\right|
$$

$$
\frac{g_{tth_1}}{g_{tth_{\text{SM}}}} = \cos\gamma \left(\cos\delta + \frac{\sin\delta}{\tan\beta}\right),
$$

$$
\frac{g_{bbh_1}}{g_{bbh_{\text{SM}}}} = \cos\gamma(\cos\delta - \sin\delta\tan\beta)
$$

$$
\frac{g_{VVh_1}}{g_{VVh_{\text{SM}}}} = \cos\gamma\cos\delta,
$$

$$
\frac{g_{tth_1}}{g_{tth_{\text{SM}}}} = \frac{g_{bbh_1}}{g_{bbh_{\text{SM}}}} = \frac{g_{VVh_1}}{g_{VVh_{\text{SM}}}} = \cos\gamma. \qquad h_1 = (-h_u^0 \ \sin\alpha + h_d^0 \ \cos\alpha)\cos\gamma + h_s^0 \ \sin\gamma
$$

$$T_\chi \approx \left(\frac{t_\beta^2-1}{t_\beta^2+1}\right)^2 F(\mu_{\rm eff},\mu',\lambda), \quad T_{\rm st-sb} \approx 0.05\left(\frac{500\ {\rm GeV}}{m_{\tilde{t}_L}}\right)^2 \quad M_{\chi_1^0} \approx \mu' + \lambda^2 v^2 \mu_{\rm eff} s_{2\beta}/(\mu_{\rm eff}^2+\lambda^2 v^2)$$

$$\Pi_{11} = \frac{\lambda^4 v^2}{16\pi^2} s_\beta^2 \left[-(4c_{2\beta}+c_{4\beta}+1)\log\left(\frac{M_{A_D}^2}{M_Z^2}\right) + 2\log\left(\frac{M_{A_S}^2}{M_Z^2}\right)\right],$$

$$\Pi_{12} = \frac{2\lambda^4 v^2}{16\pi^2} s_\beta c_\beta (2+c_{4\beta}) \log\left(\frac{M_{A_D}^2}{M_Z^2}\right),$$

$$\Pi_{22} = \frac{\lambda^4 v^2}{16\pi^2} c_\beta^2 \left[-(-4c_{2\beta}+c_{4\beta}+1)\log\left(\frac{M_{A_D}^2}{M_Z^2}\right) + 2\log\left(\frac{M_{A_S}^2}{M_Z^2}\right)\right],$$

$$\Pi_{13} = \frac{\lambda^3 v \mu_{\rm eff}}{16\pi^2} s_\beta \left[-(1+3c_{2\beta})\log\left(\frac{M_{A_D}^2}{M_Z^2}\right) + 4\log\left(\frac{M_{A_S}^2}{M_Z^2}\right)\right],$$

$$\Pi_{23} = \frac{\lambda^3 v \mu_{\rm eff}}{16\pi^2} c_\beta \left[-(1-3c_{2\beta})\log\left(\frac{M_{A_D}^2}{M_Z^2}\right) + 4\log\left(\frac{M_{A_S}^2}{M_Z^2}\right)\right],$$

$$\Pi_{33} = \frac{4\lambda^2 \mu_{\rm eff}^2}{16\pi^2} \log\left(\frac{M_{A_D}^2}{M_Z^2}\right).$$