Gauge Mediation in NMSSM: Light Sparticles from a Light Singlet

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Based on:
B. Allanach, MB, C. Hugonie, R. Ziegler, PRD **92**, 015006 [arXiv:1502.05836]
MB, M. Olechowski, S. Pokorski, JHEP 1306 (2013) 043 [arXiv:1304.5437]

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FNP
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Outline

- Implications of the Higgs discovery for MSSM spectrum
- The Higgs mass in NMSSM
- Enhancing the Higgs mass in NMSSM by mixing effects with a light singlet-like scalar
- Next-to-minimal gauge mediation with light singlet
- Predictions for the 13 TeV LHC

Motivation

LHC found the 125 GeV Higgs boson which is in the ball-park of the prediction of many supersymmetric models

Supersymmetry remains one of the best candidate for new physics

However, 125 GeV Higgs mass implies heavy SUSY spectrum in standard gauge mediation models (providing e.g. elegant solution to SUSY flavor problem)

In this talk:

Minimal gauge mediation in NMSSM with a light singlet:

- Sparticles discoverable at the LHC Run II
- Novel LHC phenomenology

The Higgs mass in MSSM

SUSY models predict the Higgs mass:

$$m_h^2 \approx M_Z^2 \cos^2 2\beta + \frac{3g^2 m_t^4}{8\pi^2 m_W^2}\left[\ln\left(\frac{M_{\tilde{t}}^2}{m_t^2}\right) + \frac{X_t^2}{M_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12 M_{\tilde{t}}^2}\right)\right]$$

$$M_{\tilde{t}} = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}} \quad X_t = A_t - \mu/\tan\beta$$

- For small stop mixing $X_t = 0 \longrightarrow$ heavy stops $M_{\tilde{t}} \gtrsim 5\,\mathrm{TeV}$
- $\mathcal{O}(1\,\mathrm{TeV})$ stops only for large stop mixing $X_t/M_{\tilde{t}} \sim \sqrt{6}$

The Higgs mass in MSSM extensions

$$m_h^2 = M_Z^2 \cos^2 2\beta + (\delta m_h^2)^{\rm loop} + (\delta m_h^2)^{\rm non-MSSM}$$

If non-MSSM contribution accounts for 5 GeV of the Higgs mass:

$M_{\tilde{t}} \gtrsim \mathcal{O}(2-3)\,\mathrm{TeV}$ for small stop mixing

$M_{\tilde{t}} \gtrsim \mathcal{O}(500)\,\mathrm{GeV}$ for large stop mixing

5 GeV non-MSSM contribution to the Higgs mass may allow for substantially lighter stops (less fine tuning, better discovery prospects)

Higgs sector in NMSSM

NMSSM is MSSM extended by a singlet superfield S that couples to H_u and H_d generating effective μ-term:

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

$$-\mathcal{L}_{\rm soft}^{\rm NMSSM} = m_S^2 |S|^2 + (A_\lambda \lambda H_u H_d S + \frac{1}{3}\kappa A_\kappa S^3 + {\rm h.c.})$$

(for the scale-invariant case)

Higgs sector in NMSSM

$$\hat{M}^2 = \begin{pmatrix} \hat{M}^2_{hh} & \frac{1}{2}(m_Z^2 - \lambda^2 v^2)\sin 4\beta & \lambda v(2\mu - \Lambda \sin 2\beta) \\ \frac{1}{2}(m_Z^2 - \lambda^2 v^2)\sin 4\beta & \hat{M}^2_{HH} & \lambda v \Lambda \cos 2\beta \\ \lambda v(2\mu - \Lambda \sin 2\beta) & \lambda v \Lambda \cos 2\beta & \hat{M}^2_{ss} \end{pmatrix}$$

$$\Lambda = A_\lambda + 2\kappa \langle S \rangle$$

The mass of the SM-like Higgs:

$$m_h^2 = M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + m_{h,\mathrm{mix}}^2 + m_{h,\mathrm{loop}}^2$$

The NMSSM contributions:

- tree-level contribution due to $\lambda H_u H_d$ interaction
- contribution due to mixing among h, s and H states (mainly h-s mixing)

The Higgs mass in NMSSM

$$m_h^2 = M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + m_{h,\mathrm{mix}}^2 + m_{h,\mathrm{loop}}^2$$

The most popular strategy to get big enough Higgs boson mass is to use the NMSSM tree-level contribution

- sin2β cannot be small ⟶ tanβ close to 1 (usually <3)
- λ must be big in order to overcompensate the decrease of the tree-level MSSM term $M_Z^2 \cos^2 2\beta$

The Higgs in NMSSM with large tanβ

$$m_h^2 = M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + m_{h,\mathrm{mix}}^2 + m_{h,\mathrm{loop}}^2$$

For large tanβ the Higgs mass can be increased only using the mixing contribution

The mixing always pushes away the eigenvalues

$$m_{h,\mathrm{mix}}^2 > 0 \qquad \text{if} \qquad m_s < m_h$$

Large h-s mixing ⟶ large "push-up effect"

How large can the singlet-doublet mixing can be?

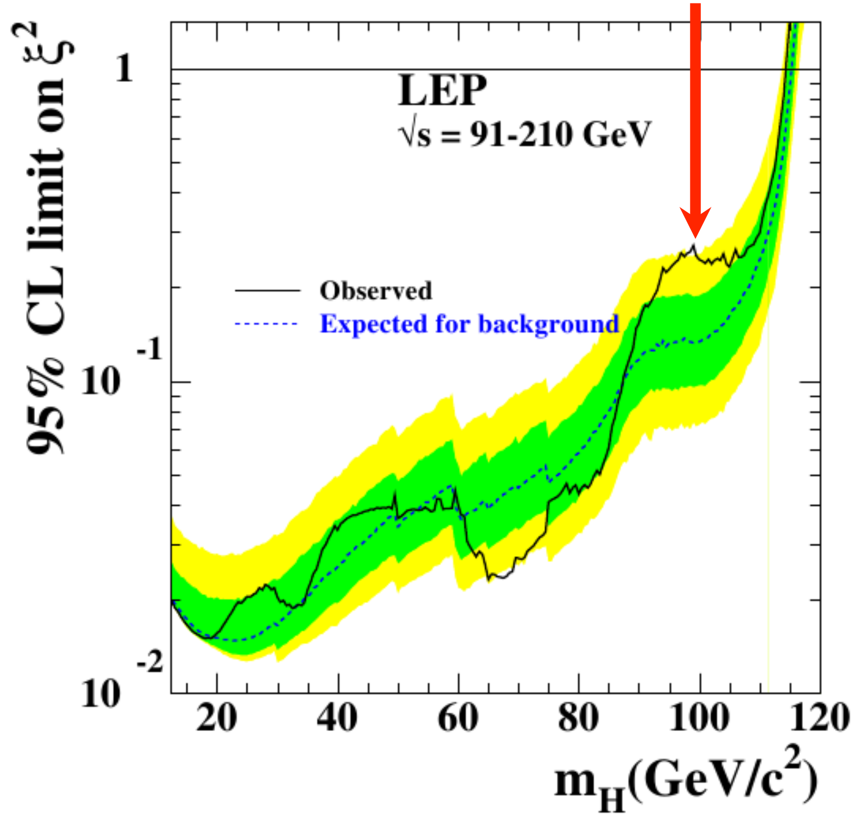
The main constraint on mixing comes from LEP

$$\xi^2_{b\bar{b}} \equiv \bar{g}_s^2 \times \overline{BR}(s \to b\bar{b})$$

$\cos\theta$

$$\overline{BR}(s \to b\bar{b}) \equiv \frac{\mathrm{BR}(s \to b\bar{b})}{\mathrm{BR}(h^{\mathrm{SM}} \to b\bar{b})}$$

the LEP excess



How large the mixing contribution to the Higgs mass can be?

$$M^2 = \begin{pmatrix} M^2_{hh} & M^2_{hs} \\ M^2_{hs} & M^2_{ss} \end{pmatrix}$$

MSSM Higgs mass

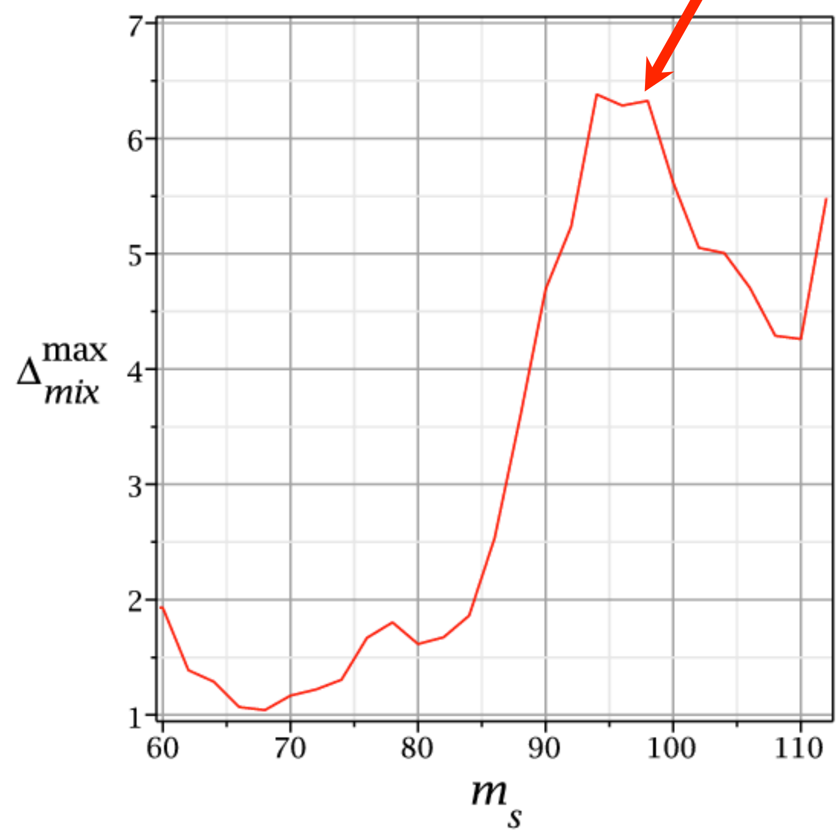
$$m_h \equiv M_{hh} + \Delta_{\rm mix}$$

$$\Delta_{\rm mix} \approx \frac{\bar{g}_s^2}{2}\left(m_h - \frac{m_s^2}{m_h}\right)$$

5-6 GeV correction to the Higgs mass is possible when m_s close to the LEP excess

MB, Olechowski, Pokorski ’13

the LEP excess



The LEP constraints on the singlet can be relaxed at large tanβ

MB, Olechowski, Pokorski '13

- If H is heavy but not totally decoupled the singlet coupling to bottom quarks is modified

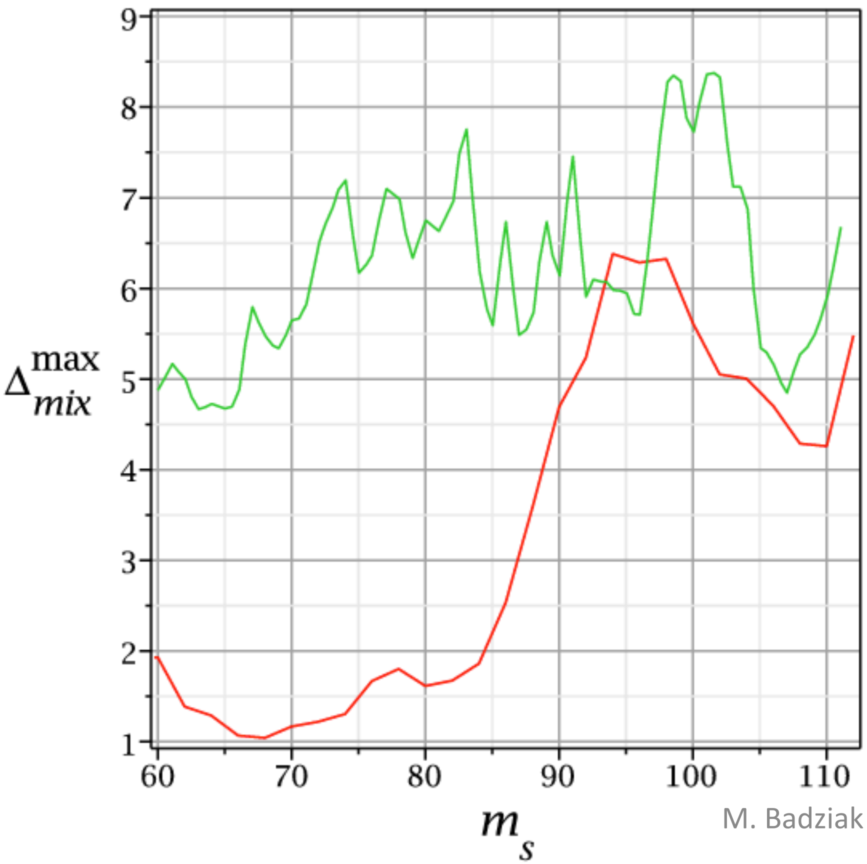
$$C_{b_s} = C_{\tau_s} = \overline{g}_s + \beta_s^{(H)} \tan\beta$$

H-component of the singlet

- For large tanβ the singlet-bottom coupling can be strongly suppressed
- $\xi_{b\bar{b}}^2 \ll \overline{g}_s^2$ can be obtained relaxing the constraints from the b-tagged LEP searches!

LEP constraints for singlet with suppressed singlet-bottom coupling

- Singlet decays mainly to cc and gg
- LEP constraints for s → jj weaker than s → bb



Larger corrections to the Higgs mass from mixing are consistent with the LEP data if the singlet-bottom coupling is suppressed

Singlet with suppressed sbb coupling is constrained by the LHC Higgs data

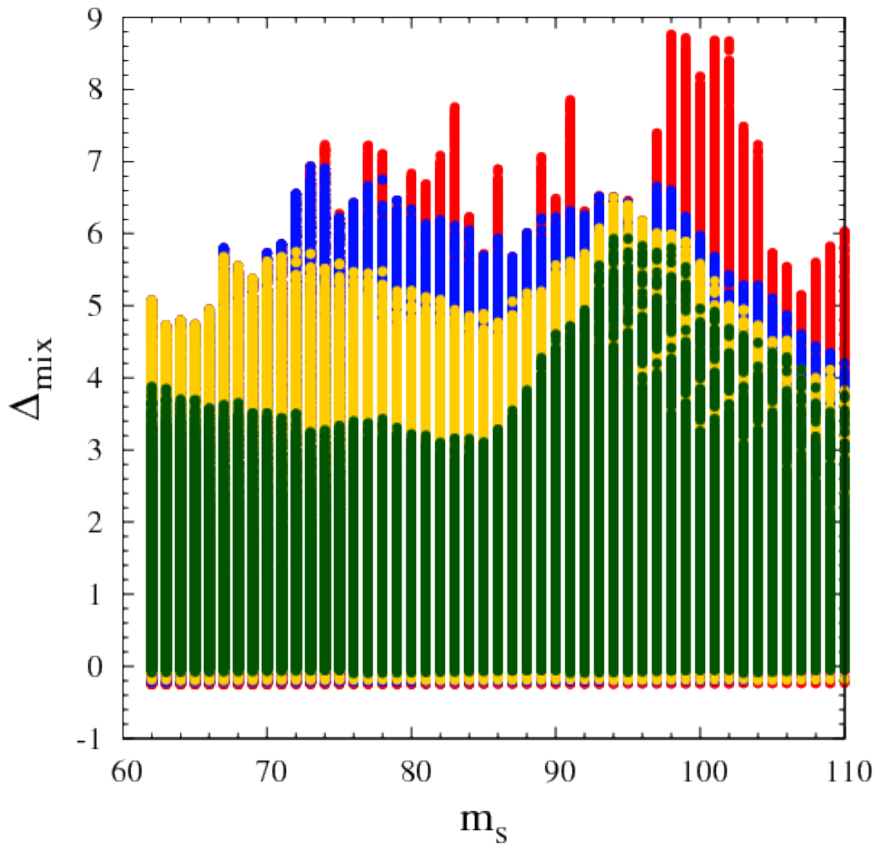
$$R_i^{(h)} \equiv \frac{\sigma(pp \to h) \times \mathrm{BR}(h \to i)}{\sigma^{\mathrm{SM}}(pp \to h) \times \mathrm{BR}^{\mathrm{SM}}(h \to i)}$$

$$C_g \approx C_\gamma \approx C_{t_h} \approx C_{V_h} = \sqrt{1 - \bar{g}_s^2} \qquad \Rightarrow \qquad \frac{\sigma(pp \to h)}{\sigma^{\mathrm{SM}}(pp \to h)} \approx 1 - \bar{g}_s^2$$

- Suppressed sbb coupling implies enhanced hbb coupling (BRs to gauge bosons reduced)

$$\mathbf{\overline{BR}(s \to b\bar{b})\ \ suppressed \Rightarrow R_{\gamma\gamma}^{(h)} \approx R_{VV}^{(h)} < 1 - \bar{g}_s^2}$$

Singlet with suppressed sbb coupling is constrained by the LHC Higgs data



excluded at 3σ

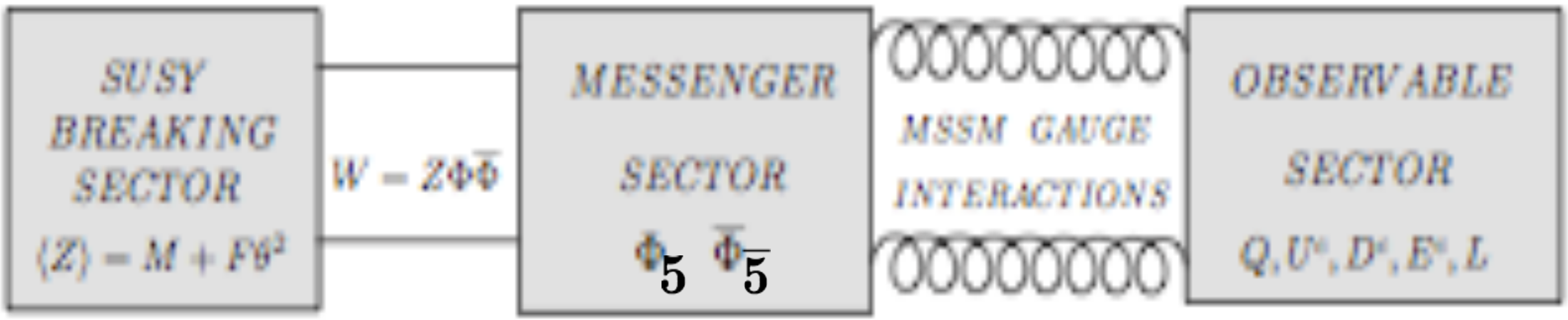
consistent within 3σ

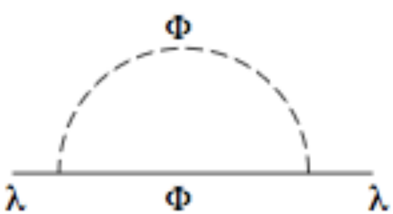
consistent within 2σ

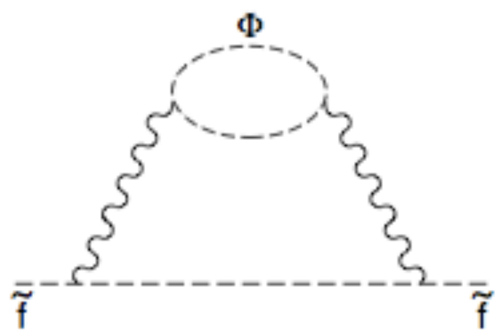
consistent within 1σ

5-6 GeV correction to the Higgs mass for a range of m_s between 60 and 100 GeV allowed by LHC

Minimal Gauge Mediation







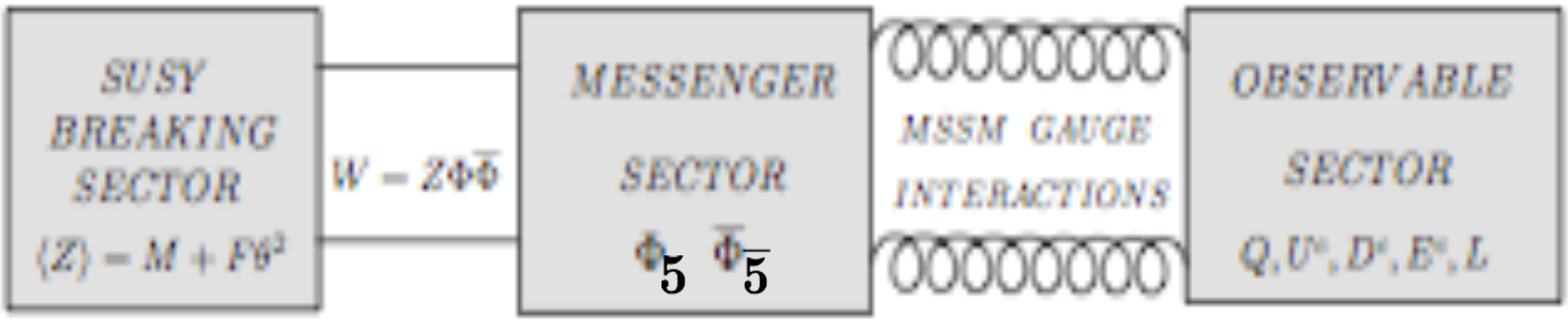
Gaugino masses

Soft scalar masses

$$M_i = 2g_i^2 \tilde{m}\,,$$

$$m_{\tilde{f}}^2 = 4 \sum_{i=1}^{3} C_i(f)\; g_i^4 \tilde{m}^2 \quad \tilde{m} \;\equiv\; 1/(16\pi^2)F/M$$

Minimal Gauge Mediation

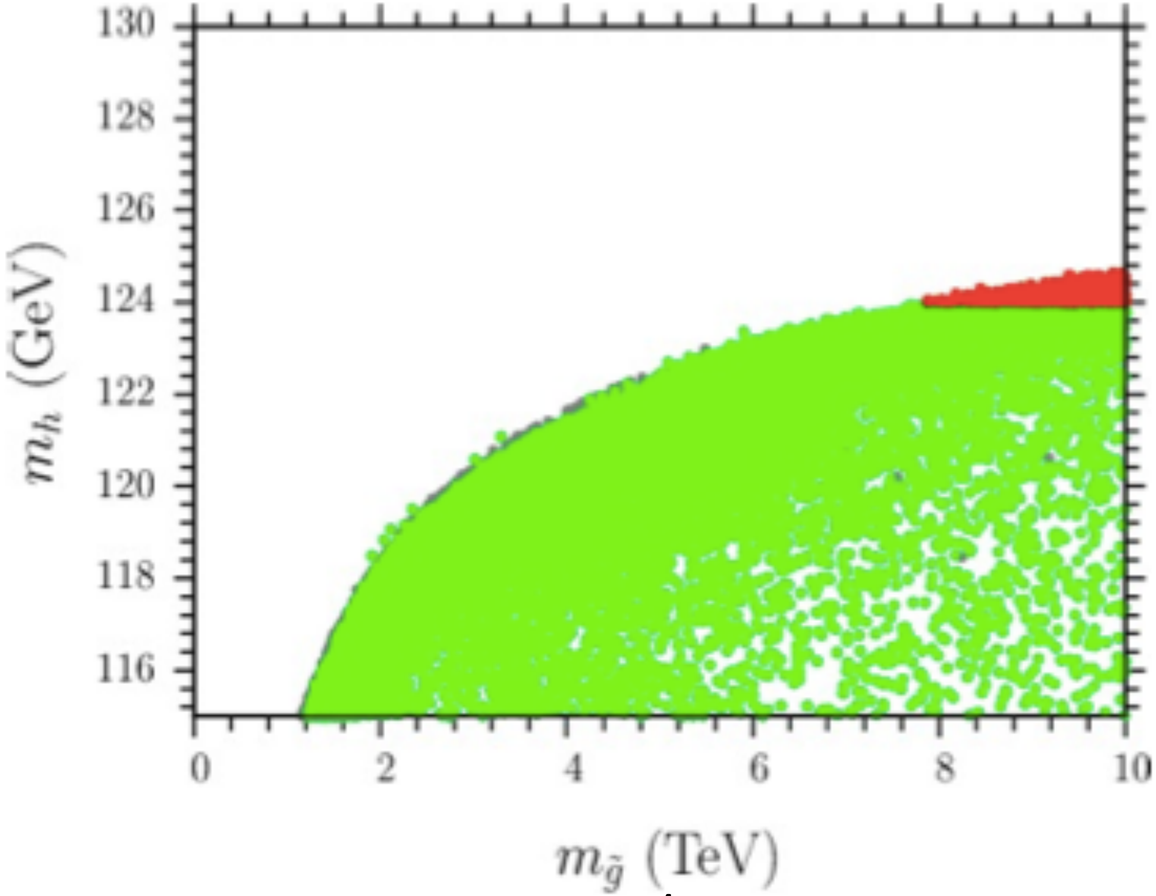


Very predictive framework that solves SUSY flavor problem

But with other problems:

- μ and B_μ typically generated at same loop order, therefore B_μ too large for correct EWSB (μ-B_μ problem)
- A-terms suppressed: very unnatural sparticle spectrum with no chance to be probed at the LHC

Minimal GM with 125 GeV Higgs

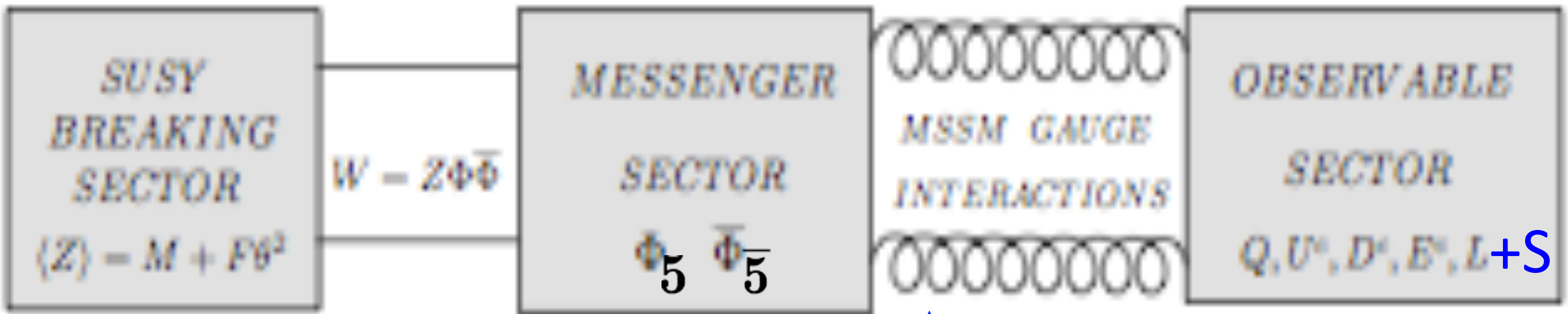


e.g. Shafi et al. '12

125 GeV Higgs implies gluino/squark masses above 5 TeV

Need to go to non-minimal models of gauge mediation $\longrightarrow$ NMSSM

Next-to-minimal gauge mediation



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

- New contributions to the Higgs mass
- μ and B_μ generated dynamically:

$$\mu \sim \langle S \rangle \sim m_{\text{soft}} \quad B_\mu \sim \langle F_S \rangle \sim m_{\text{soft}}^2 \sim \mu^2$$

However: naive combination NMSSM + minimal GM does not provide correct EWSB (because singlet soft mass too small)

The minimal model of gauge mediation in NMSSM:

Delgado, Giudice, Slavich ' 07

Main ingredient:

direct coupling of the singlet to (two pairs) of messengers

$$W_{\rm DGS} = S\left(\xi_D \bar{\Phi}_1^D \Phi_2^D + \xi_T \bar{\Phi}_1^T \Phi_2^T\right) \qquad \xi_D(M_{\rm GUT}) = \xi_T(M_{\rm GUT}) \equiv \xi$$

generates NMSSM A-terms and soft singlet mass (correct EWSB):

$$A_\lambda = \frac{A_\kappa}{3} = -\tilde{m}\left(2\xi_D^2 + 3\xi_T^2\right)$$

soft SUSY breaking scale

$$\begin{aligned}\tilde{m}_S^2 = {} & \tilde{m}^2\left[8\xi_D^4 + 15\xi_T^4 + 12\xi_D^2\xi_T^2\right] \\ & - \tilde{m}^2\left[4\kappa^2\left(2\xi_D^2 + 3\xi_T^2\right)\right] \\ & - \tilde{m}^2\left[\xi_D^2\left(\frac{6}{5}g_1^2 + 6g_2^2\right) + \xi_T^2\left(\frac{4}{5}g_1^2 + 16g_3^2\right)\right]\end{aligned}$$

The minimal model of gauge mediation in NMSSM:

Delgado, Giudice, Slavich ’07

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generates NMSSM A-terms and soft singlet mass (correct EWSB)

very predictive model with only 4 parameters:

$$\lambda, \xi, \tilde{m}, M$$

soft SUSY breaking scale

messenger scale

Note: $\tan\beta$ is NOT a free parameter

The minimal model of gauge mediation in NMSSM

Delgado, Giudice, Slavich ' 07

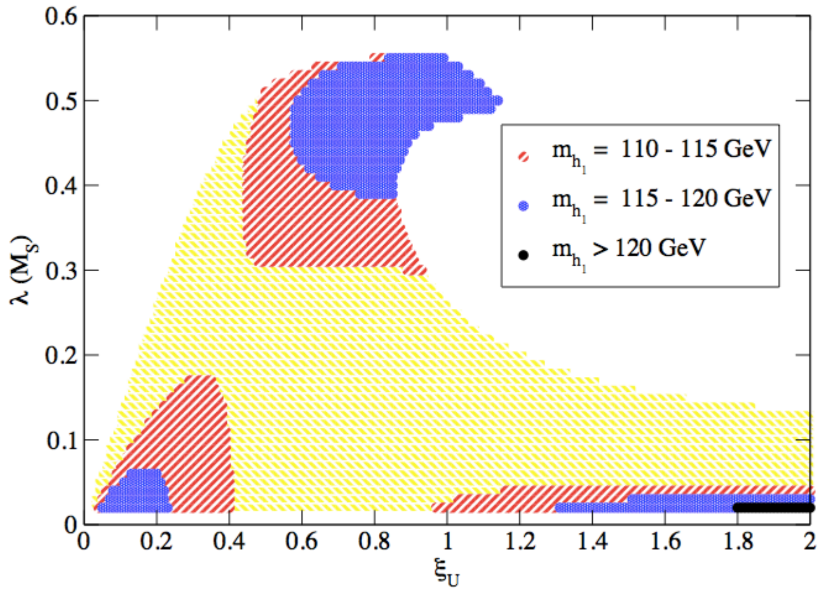


Figure 2: Mass of the lightest CP-even Higgs boson h_1 in the $\xi_U - \lambda(M_S)$ plane, for $M = 10^{13}$ GeV and $F/M = 1.72 \times 10^5$ GeV.

Conclusion of the original DGS paper: sparticles are never lighter (for a given Higgs mass) than in Minimal Gauge Mediation in MSSM

Stop masses about 2 TeV
The Higgs mass at most 120 GeV

We revisited that statement concentrating on the light singlet region with sizable singlet-doublet mixing

Allanach, MB, Hugonie, Ziegler ' 15

Light singlet scenario in DGS model

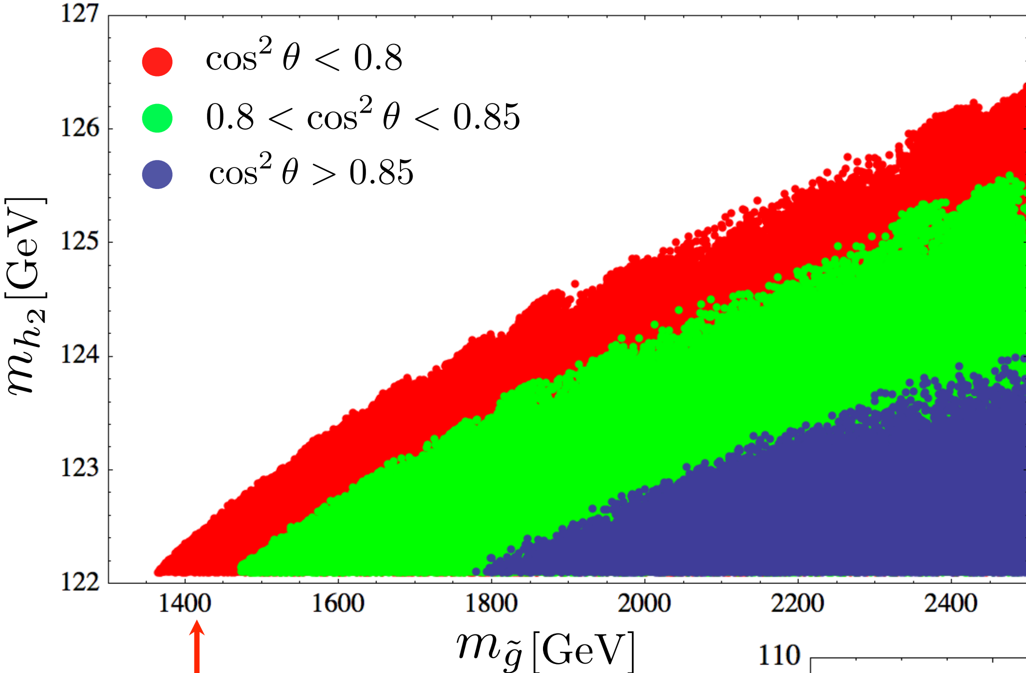
Allanach, MB, Hugonie, Ziegler '15

Maximizing the contribution to the Higgs mass from mixing essentially fixes most model parameters

$$\cos\theta \approx 0.9 \longrightarrow \lambda \sim 10^{-2}$$
$$m_{h_1} \approx 90 - 100\,\mathrm{GeV} \longrightarrow \xi \sim 10^{-2}$$
$$\longrightarrow \text{100 GeV Singlino NLSP, 20-40 GeV pseudoscalar}$$
$$m_{h_2} \approx 125\,\mathrm{GeV} \longrightarrow \tilde{m} \sim 1\,\mathrm{TeV}$$

Only the messenger scale remains free and determines collider phenomenology

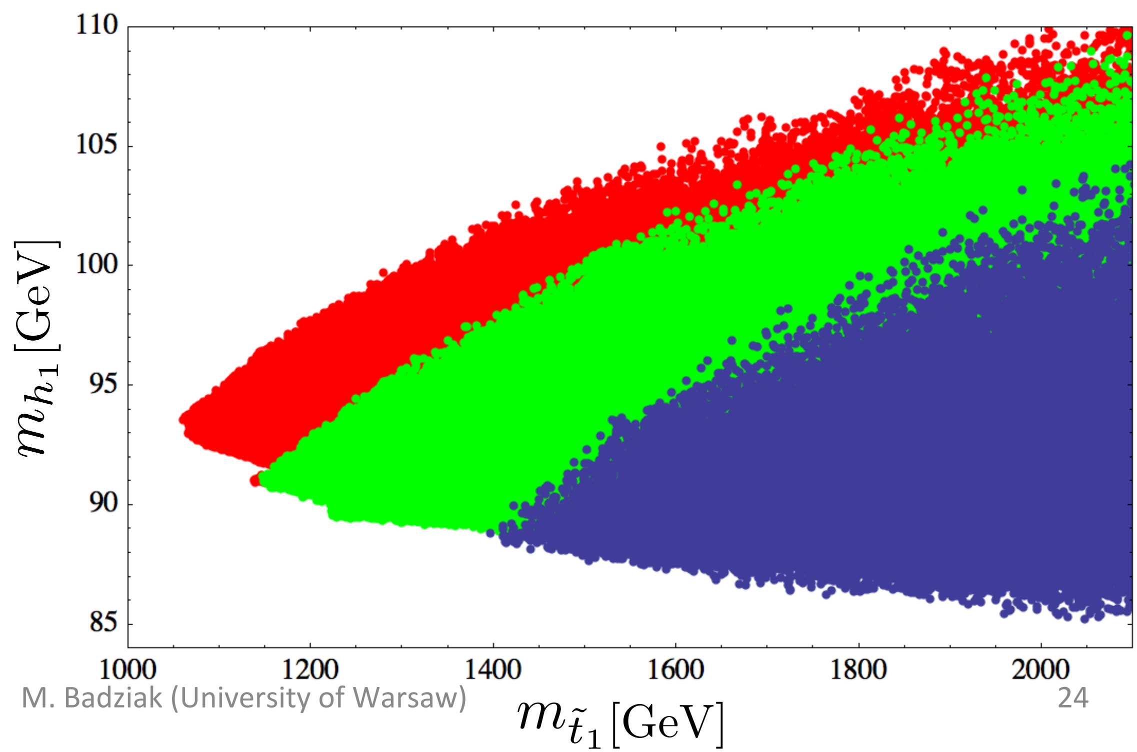
Sparticle masses close to direct exclusion bounds



Allows for 1.4 TeV Gluinos

small Higgs-singlet mixing

large Higgs-singlet mixing



and 1.1 TeV stops

Small λ

Large tanβ

Squarks/gluinos below 2 TeV

Large LHC x-sec at 13 TeV

	P1	P2	P3	P4	P5
$\tilde{m}$	$7.5 \cdot 10^2$	$8.7 \cdot 10^2$	$9.3 \cdot 10^2$	$5.9 \cdot 10^2$	$9.3 \cdot 10^2$
M	$1.4 \cdot 10^6$	$2.8 \cdot 10^6$	$3.3 \cdot 10^7$	$8.3 \cdot 10^{14}$	$3.4 \cdot 10^{14}$
λ	$1.0 \cdot 10^{-2}$	$9.3 \cdot 10^{-3}$	$6.7 \cdot 10^{-3}$	$9.2 \cdot 10^{-3}$	$6.9 \cdot 10^{-3}$
ξ	$1.2 \cdot 10^{-2}$	$1.1 \cdot 10^{-2}$	$1.3 \cdot 10^{-2}$	$3.2 \cdot 10^{-2}$	$2.0 \cdot 10^{-2}$
$\tan\beta$	25	28	24	26	21
m_{h_1}	92	93	98	94	94
m_{h_2}	122.1	123.4	122.9	122.1	125.0
m_{a_1}	26	26	28	40	32
$m_{\tilde{N}_1}$	101	102	106	104	104
$m_{\tilde{N}_2}$	322	377	400	251	379
$m_{\tilde{e}_1}$	303	358	406	449	676
$m_{\tilde{\tau}_1}$	284	333	376	432	637
$m_{\tilde{g}}$	1.73	1.98	2.09	1.37	2.06
$m_{\tilde{u}_R}$	1.79	2.06	2.15	1.36	2.07
$m_{\tilde{t}_1}$	1.64	1.87	1.90	1.06	1.63
$c\tau_{\tilde{N}_1}$	$6.4 \cdot 10^{-2}$	0.34	48	$1.9 \cdot 10^{16}$	$6.0 \cdot 10^{15}$
$\sigma^{13\text{TeV}}_{\tilde{q}\tilde{q}}$	9.35	2.99	1.98	59.7	2.63
$\sigma^{13\text{TeV}}_{\tilde{g}\tilde{g}}$	11.9	3.30	2.01	91.1	2.48
$\sigma^{13\text{TeV}}_{\text{strong}}$	25.2	7.28	4.58	190	5.95
$\sigma^{8\text{TeV}}_{\text{strong}}$	0.51	0.07	0.03	10.1	0.05
$\sigma^{13\text{TeV}}_{\text{EW}}$	27	12	7.5	6.7	5.6
$\sigma^{8\text{TeV}}_{\text{EW}}$	5.5	2.1	1.2	1.3	0.7

TABLE I: List of benchmark points. All masses are in GeV except colored sparticle masses in TeV, the neutralino decay length $c\tau_{\tilde{N}_1}$ in m and cross-sections in fb. All points have reduced effective Higgs couplings, with Higgs signal strenghts about 0.75, as a result of a Higgs-singlet mixing angle with $\cos\theta \approx 0.88$.

Small λ

Large tanβ

	P1	P2	P3	P4	P5
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$\tan\beta$	25	28	24	26	21

Sparticle masses just above the exclusion limits from the LHC RunI

Squarks/gluinos below 2 TeV

Large LHC x-sec at 13 TeV

	P1	P2	P3	P4	P5
$m_{\tilde{g}}$	1.73	1.98	2.09	1.37	2.06
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LHC Phenomenology

new feature is Singlino NLSP & Gravitino LSP

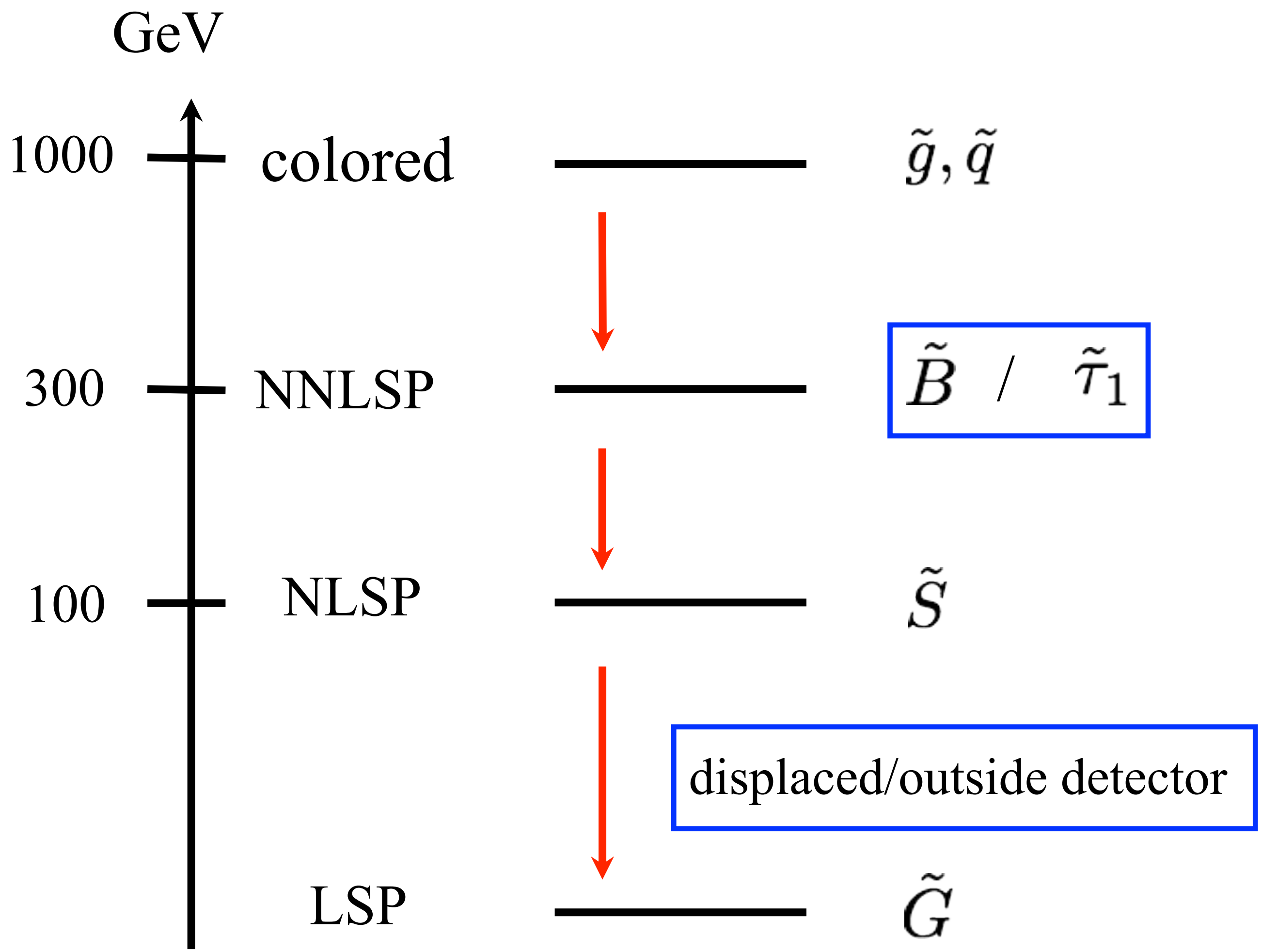
$$\tilde{N}_1 \to a_1 \tilde{G} \to b\bar{b}\tilde{G}$$

Messenger scale determines NNLSP (bino or stau) and singlino decay length

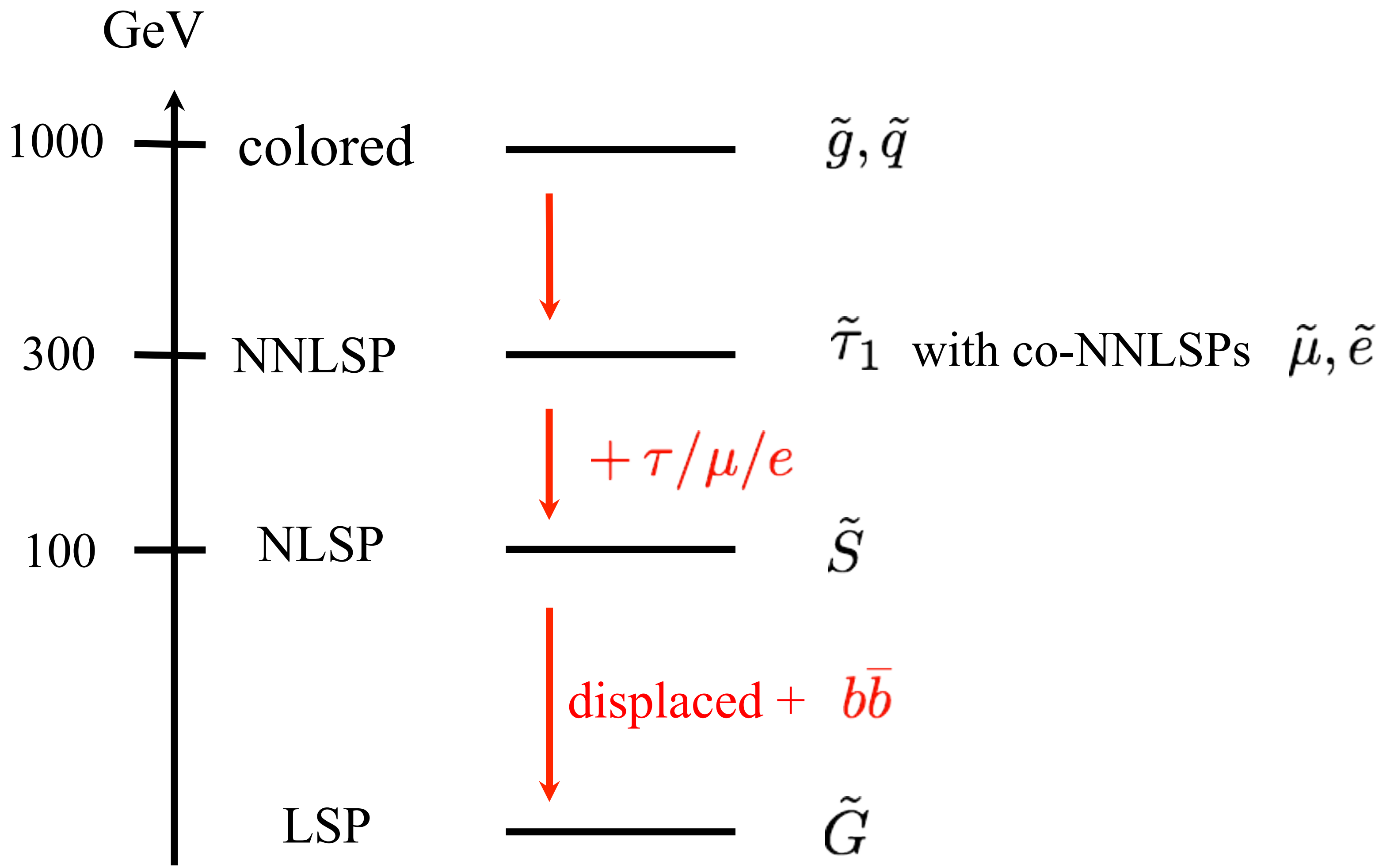
$$c\tau_{\tilde{N}_1} \approx 2.5\,\mathrm{cm}\,\left(\frac{100\,\mathrm{GeV}}{M_{\tilde{N}_1}}\right)^5 \left(\frac{M}{10^6\,\mathrm{GeV}}\right)^2 \left(\frac{\tilde{m}}{\mathrm{TeV}}\right)^2$$

Singlino and Gravitino essentially decoupled: all SUSY decay chains to LSP proceed through NNLSP and NLSP

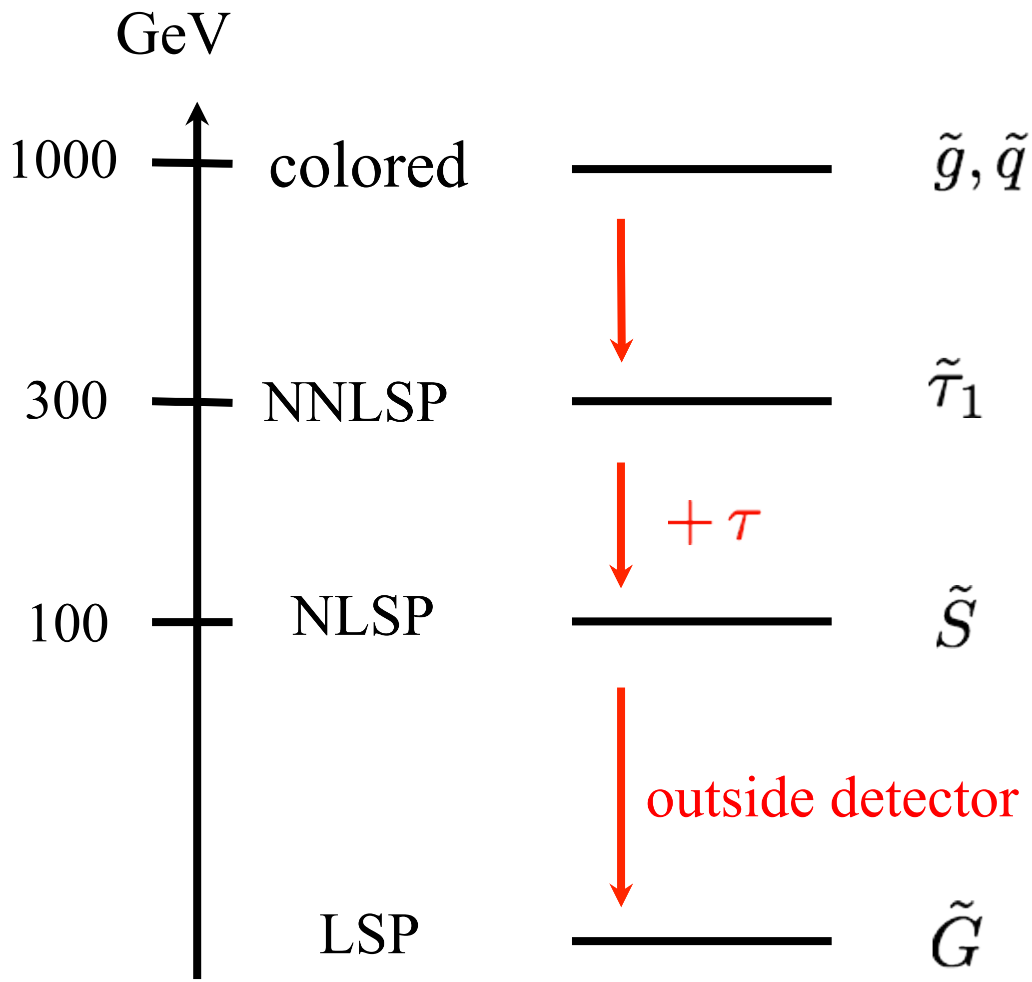
Signals depend on NNLSP nature and singlino decay length



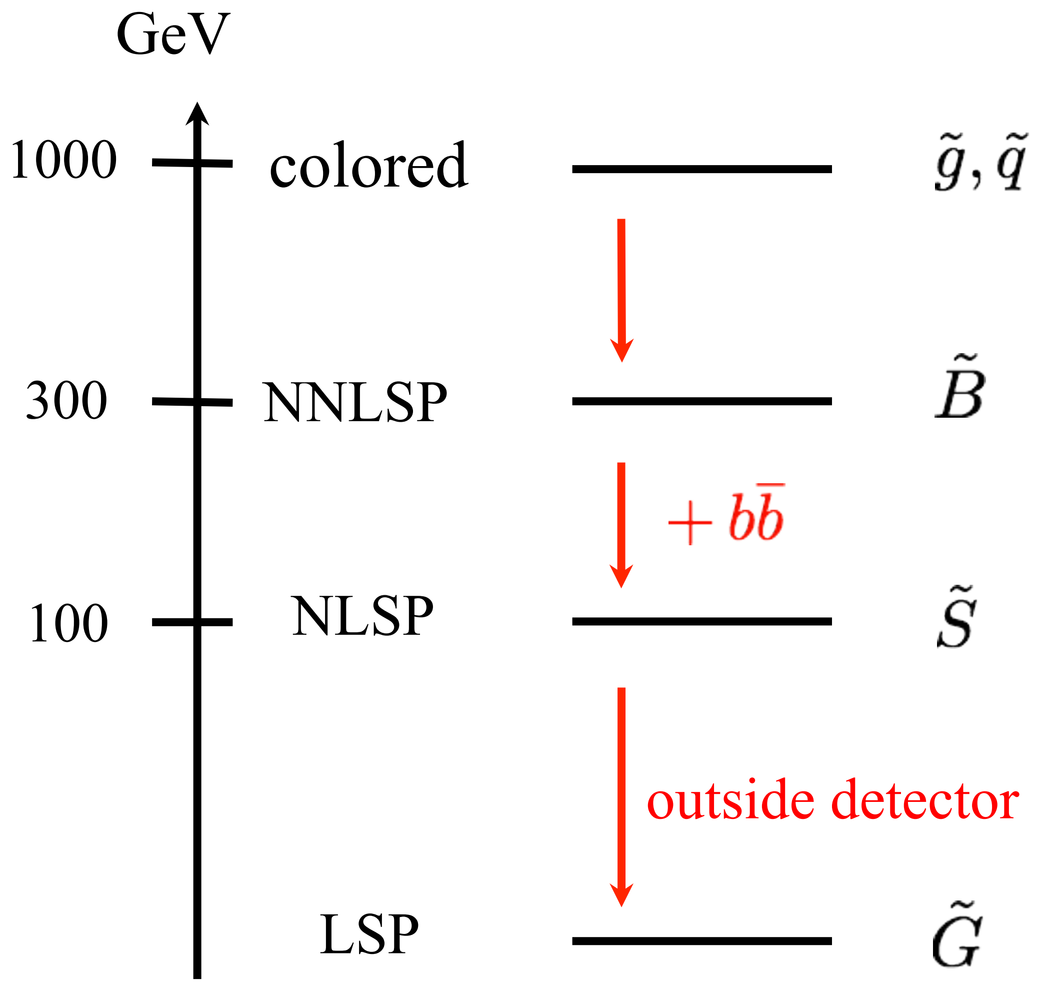
Low-M region: M < 10^7 GeV



Medium-M region: M ~ $10^{7\text{-}9}$ GeV



Large-M region: M > 10^9 GeV



Conclusions

- Higgs-singlet mixing in NMSSM can enhance the Higgs mass by up to about 6 GeV
- Light NMSSM singlet (which explains the LEP excess) solves the problems of minimal gauge mediation in MSSM
- Direct singlet-messenger couplings is crucial for correct EWSB
- Very predictive NMSSM scenario with small λ and large tanβ
- The simplest extension of minimal GM predicting light sparticles discoverable in the early stage of the LHC run II

$$\sigma^{13\mathrm{TeV}} \sim \mathcal{O}(10-100)\mathrm{fb}$$

- Novel LHC signature with singlino NLSP decaying to gravitino and displaced b-jets