Light Sparticles from a light Singlet in Gauge Mediation

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The legacy of LHC Run 1:

A 125 GeV Higgs, no new physics

Much too early to give up on Hierarchy Problem: best candidate to protect weak scale is still low-energy **Supersymmetry**

While waiting for next LHC Run, we can use information on Higgs mass as input for SUSY model building

Why is the Higgs so heavy ?

In **MSSM** tree-level Higgs mass bounded by Z mass: need large radiative corrections from stops, of the same order as tree-level mass

$$\Delta m_h^2 \approx \frac{3m_t^4}{4\pi^2 v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right)+\frac{X_t^2}{M_S^2}\left(1-\frac{X_t^2}{12M_S^2}\right)\right)$$

Need heavy stops and large stop mixing

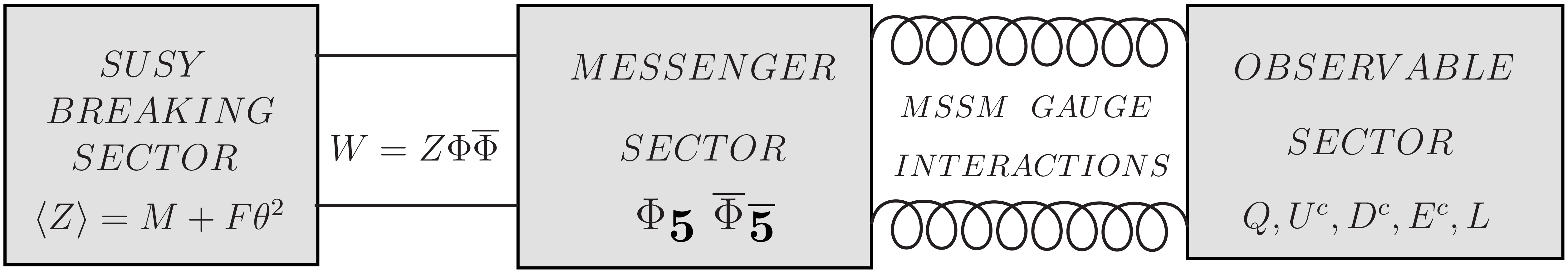
Can alternatively raise tree-level Higgs mass in non-minimal realizations like **NMSSM**

How is SUSY broken?

In MSSM underlying SUSY breaking sector parametrized in terms of most general soft SUSY breaking terms: ~ 100 new parameters

A successful mechanism of SUSY breaking should drastically **reduce the fundamental parameter space** and **explain the protection of new flavor and CP structure**

Minimal Gauge Mediation



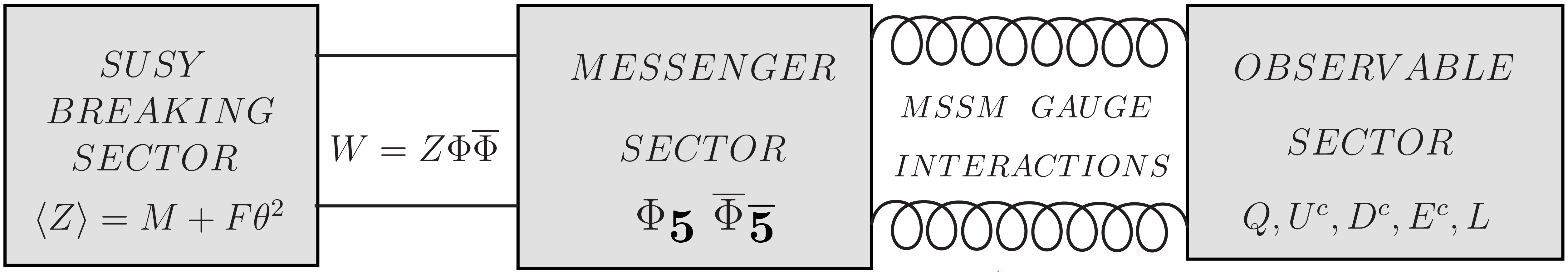
Very predictive (5 parameters)

Solves SUSY Flavor Problem (MFV)

But problems with Higgs mass due to small A-terms:
need heavy SUSY spectrum beyond LHC reach

e.g. Shafi & al '12

Minimally modify minimal model!



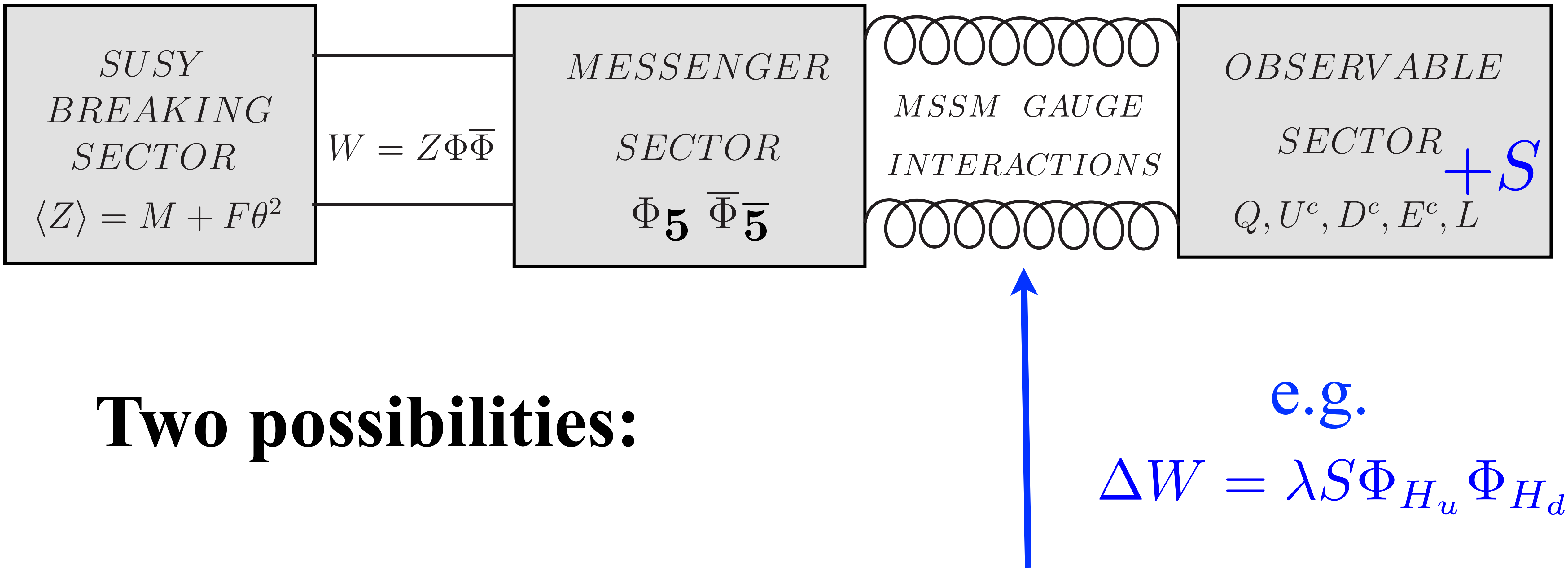
e.g.

$$\Delta W = \lambda_{ij} Q_i U_j \Phi_{H_u}$$

Two possibilities:

1) additional source of A-terms
with direct messenger - matter couplings

Minimally modify minimal model!



Two possibilities:

2) raise tree-level Higgs mass in NMSSM with direct messenger - singlet couplings

① New messenger-matter couplings generate large A-terms: but **need to take care of flavor structure**

$$\Delta W = \lambda_{ij} Q_i U_j \Phi^5_{H_u}$$

MFV

$$\lambda_{ij} = c\, y^u_{ij}$$

Yanagida & al. '11

FGM

$$\lambda_{ij} \sim y^u_{ij}$$

Shadmi & Szabo '11

New couplings controlled by underlying flavor model: same parametric suppression as Yukawas

In both cases SUSY spectrum controlled by single new parameter and easily in LHC reach, only flavor pheno different: **FGM can realize flavor patterns beyond MFV**

Sflavor Structure in U(1) Model

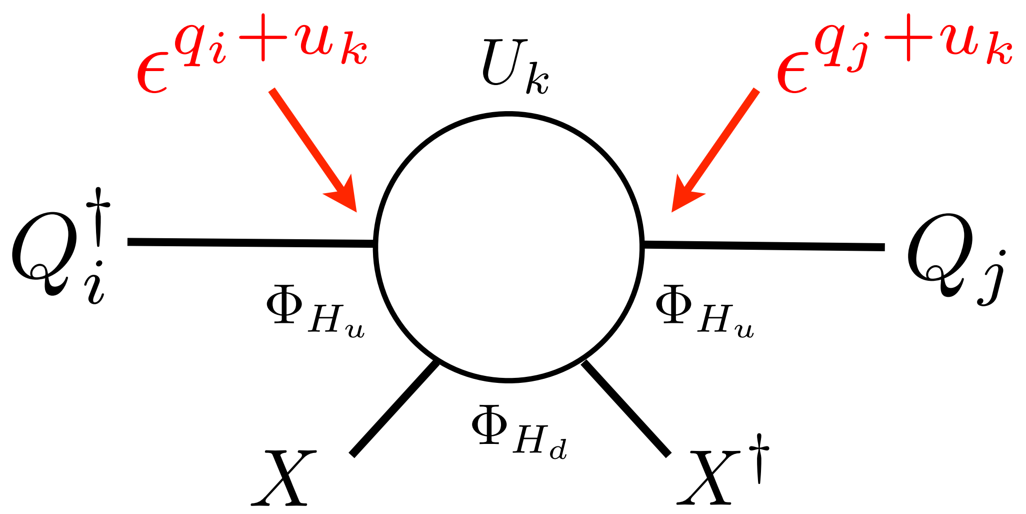
Calibbi, Paradisi, RZ, '13

In U(1) flavor model can estimate couplings in terms of masses and mixing through charges

$$(\lambda_U)_{ij} \sim \epsilon^{q_i+u_j}$$

Loop origin leads to **suppression of flavor violation as in SUSY PC + 3rd gen Yukawa**

$$(\delta^u_{LL})_{ij} \sim (\lambda_U)_{ik}(\lambda_U)^*_{jk} \sim \epsilon^{q_i+q_j+2u_k} \sim V_{i3}V_{j3}y_t^2$$



Gravity Mediation:

$\sim V_{i3}/V_{j3}$

Flavor violation under control

	MFV	PC	$U(1)$	$\mathrm{FGM}_{U,D}+U(1)$	$\mathrm{FGM}_U+U(1)$
$(\delta^u_{LL})_{ij}$	$V_{i3}V^*_{j3}y_b^2$	$(\epsilon_3^q)^2 V_{i3}V^*_{j3}$	$\frac{V_{i3}}{V_{j3}}\vert_{i\leq j}$	$V_{i3}V^*_{j3}y_t^2$	$V_{i3}V^*_{j3}y_t^2$
$(\delta^d_{LL})_{ij}$	$V^*_{3i}V_{3j}y_t^2$	$(\epsilon_3^q)^2 V_{i3}V^*_{j3}$	$\frac{V_{i3}}{V_{j3}}\vert_{i\leq j}$	$V^*_{3i}V_{3j}y_t^2$	$V^*_{3i}V_{3j}y_t^2$
$(\delta^u_{RR})_{ij}$	$y_i^U y_j^U V_{i3}V^*_{j3}y_b^2$	$\frac{y_i^U y_j^U}{V_{i3}V^*_{j3}}\frac{(\epsilon_3^u)^2}{y_t^2}$	$\frac{y_i^U V_{j3}}{y_j^U V_{i3}}\vert_{i\leq j}$	$\frac{y_i^U y_j^U}{V_{i3}V^*_{j3}}$	$\frac{y_i^U y_j^U}{V_{i3}V^*_{j3}}$
$(\delta^d_{RR})_{ij}$	$y_i^D y_j^D V^*_{3i}V_{3j}y_t^2$	$\frac{y_i^D y_j^D}{V_{i3}V^*_{j3}}\frac{(\epsilon_3^u)^2}{y_t^2}$	$\frac{y_i^D V_{j3}}{y_j^D V_{i3}}\vert_{i\leq j}$	$\frac{y_i^D y_j^D}{V_{i3}V^*_{j3}}$	$y_i^D y_j^D V^*_{3i}V_{3j}y_t^2$
$(\delta^u_{LR})_{ij}$	$y_j^U V_{i3}V^*_{j3}y_b^2$	$y_j^U\frac{V_{i3}}{V^*_{j3}}$	$y_j^U\frac{V_{i3}}{V^*_{j3}}$	$y_j^U V_{i3}V^*_{j3}y_t^2 + y_i^U\frac{y_i^U y_j^U}{V_{i3}V^*_{j3}}$ $y_j^U\frac{V_{i3}}{V^*_{j3}}y_t^6$	$y_j^U V_{i3}V^*_{j3}y_t^2 + y_i^U\frac{y_i^U y_j^U}{V_{i3}V^*_{j3}}$ $y_j^U\frac{V_{i3}}{V^*_{j3}}y_t^6$
$(\delta^d_{LR})_{ij}$	$y_j^D V^*_{3i}V_{3j}y_t^2$	$y_j^D\frac{V_{i3}}{V^*_{j3}}$	$y_j^D\frac{V_{i3}}{V^*_{j3}}$	$y_j^D V^*_{3i}V_{3j}y_t^2 + y_i^D\frac{y_i^D y_j^D}{V_{i3}V^*_{j3}}$ $y_j^D\frac{V^*_{3i}}{V_{3j}}y_t^4 y_b^2$	$y_j^D V^*_{3i}V_{3j}y_t^2$

and similar to SUSY Partial Compositeness (dominantly in LR sector)

Application to Slepton Sector

Calibbi, Paradisi, RZ, '14

New couplings just in lepton sector,
controlled by underlying U(1) model

$$\Delta W = (\lambda_e)_{ij} L_i E_j \Phi_{H_d} \qquad (\lambda_e)_{ij} \sim (y_e)_{ij} \sim \epsilon_i^L \epsilon_j^E$$

Get less suppression from mixing angles, but
LFV and eEDM under control for small tanβ

$$(\delta^e_{LL})_{ij} \sim V_{i3}^{\rm PMNS} V_{j3}^{\rm PMNS} y_\tau^2 \qquad A_E \sim y_e \lambda_e^\dagger \lambda_e$$

exploit 3rd gen. Yukawa
suppression: small tanβ!

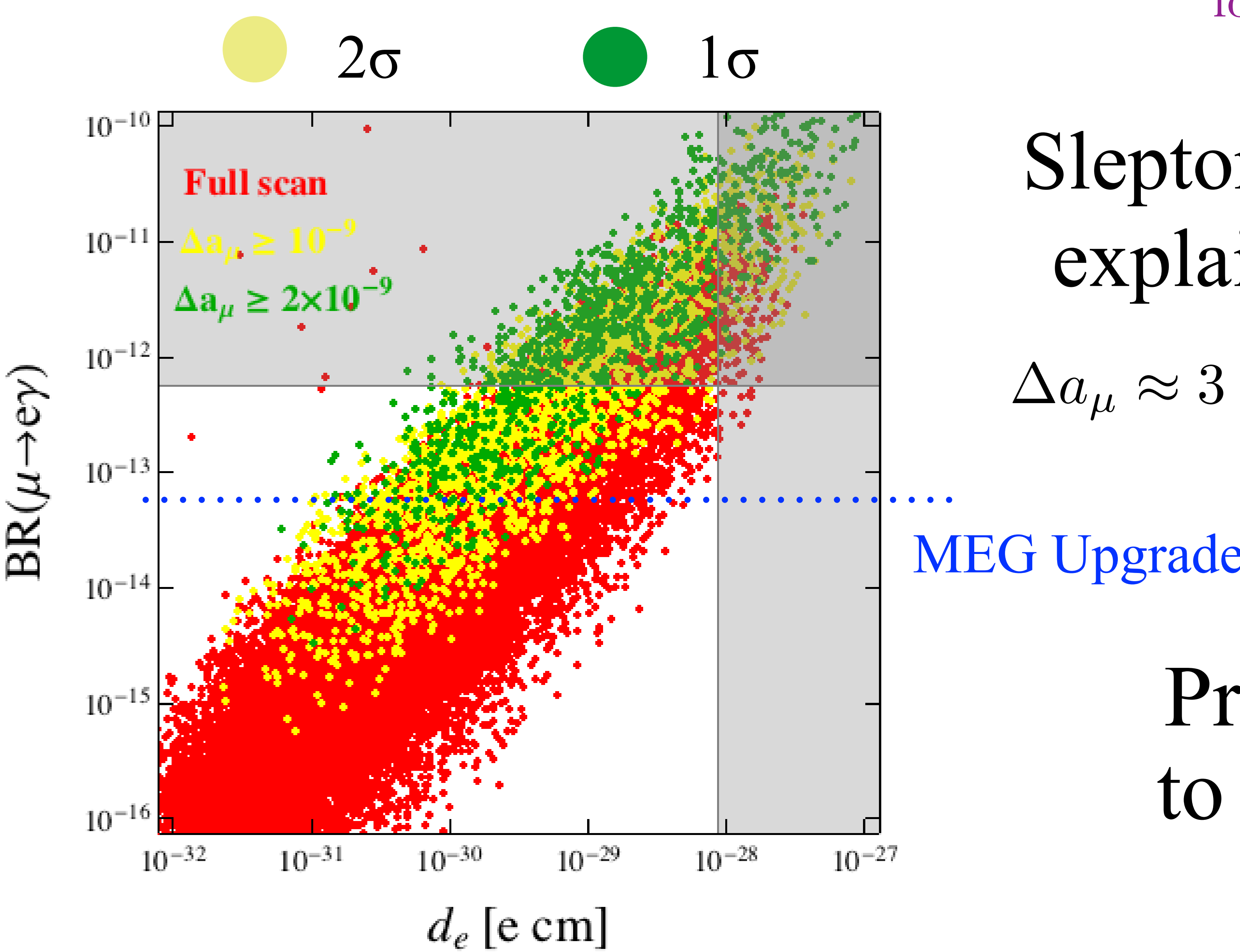
leading order term in LR
has no diagonal phases!

For given U(1) flavor model get prediction for LFV and eEDM, viable even for light sleptons

$$\mathrm{BR}(\mu \to e\gamma) \approx 7 \times 10^{-13}\ (\tan\beta/3)^6\ (200\,\mathrm{GeV}/\tilde{m})^4$$

$$|d_e| \approx 8 \times 10^{-29}\ (\tan\beta/6)^5\ (200\,\mathrm{GeV}/\tilde{m})^2\, e\,\mathrm{cm}$$

for U(1) model from Altarelli & al ’12



Slepton mass can be fixed to explain muon g-2 anomaly

$$\Delta a_\mu \approx 3 \times 10^{-10}\ (200\,\mathrm{GeV}/\tilde{m})^2 \tan\beta$$

Predicts $\mu \to e\gamma$ to be found soon

② Raise tree-level Higgs with mixing

$$\begin{pmatrix} m_h^2 & m_{hs}^2 \\ m_{hs}^2 & m_s^2 \end{pmatrix} \xrightarrow{m_h^2 > m_s^2} m_{h_2}^2 \approx m_h^2 + \frac{m_{hs}^4}{m_h^2}$$

can realize in NMSSM $\Delta W = \lambda S H_u H_d + \frac{\kappa}{3} S^3$

Mixing angles constrained by LEP and LHC: maximal contribution to tree-level Higgs mass for

$m_{h_1} \approx 94\,\mathrm{GeV}$ $\cos\theta \approx 0.88$

Badziak, Olechowski, Pokorski '13

Can realize NMSSM mixing scenario in Gauge Mediation?

Besides predictivity NMSSM provides simplest solution for μ-B_μ problem of gauge mediation:

μ and B_μ typically generated at same loop order, therefore B_μ too large for correct EWSB; in NMSSM both terms dynamically related to soft SUSY breaking through singlet potential

However: NMSSM + Minimal Gauge Mediation does not work since soft singlet mass too small!

Simplest Model to couple NMSSM to Gauge Mediation: Delgado, Giudice, Slavich '07

Minimal GM with two pairs of messengers
and direct couplings to singlet

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

generates NMSSM A-terms at one-loop
and singlet masses at two-loop

very predictive model with only 4 parameters

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

soft SUSY breaking scale ($\tilde{m}$)

messenger scale (M)

We re-analyzed this model, concentrating on the singlet-Higgs mixing region

Allanach, Badziak, Hugonie, RZ '15

$\cos\theta \approx 0.88$
$m_{h_1} \approx 94\,\mathrm{GeV}$
$m_{h_2} \approx 125\,\mathrm{GeV}$

↓

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

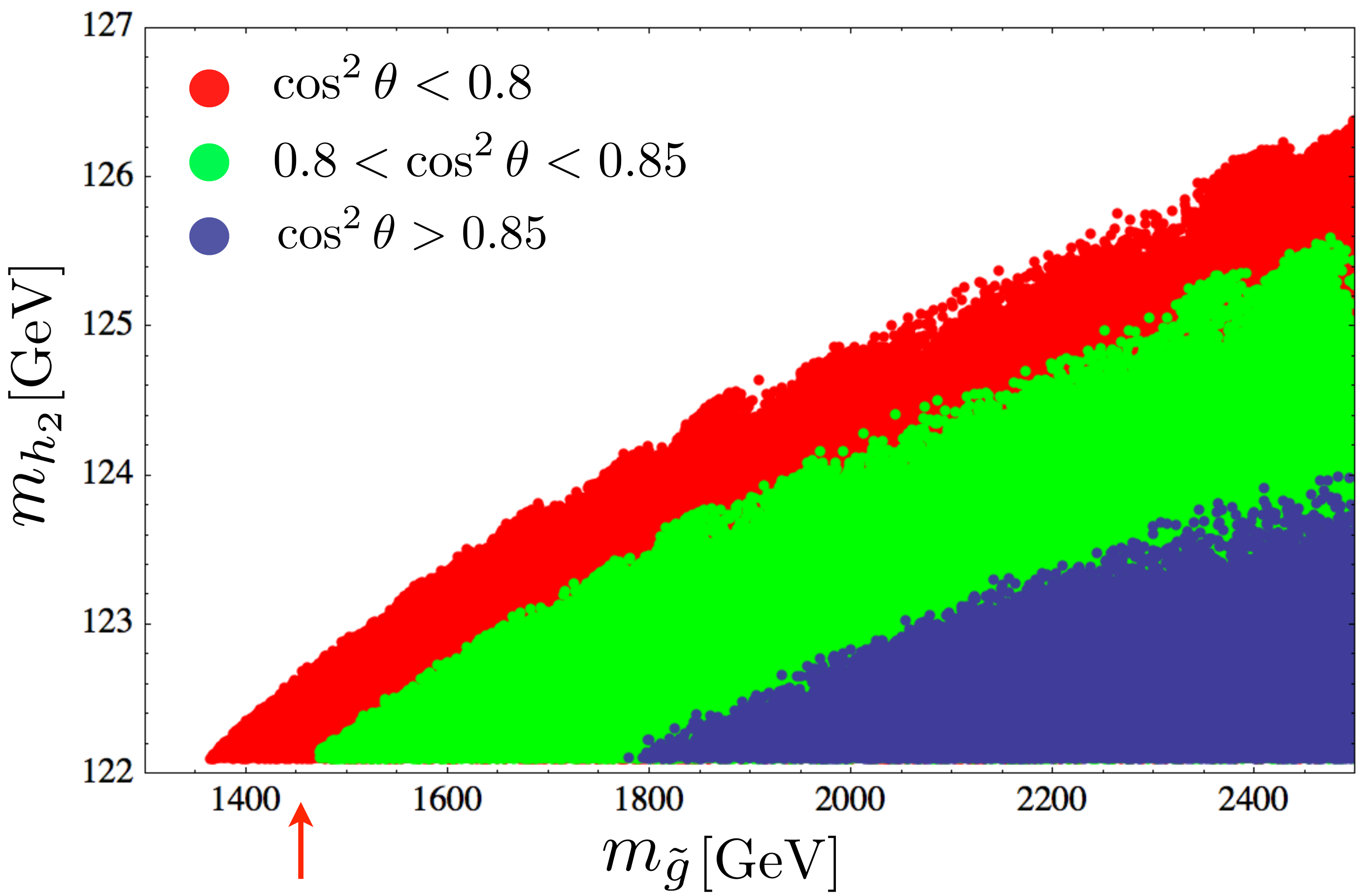
↓

$\lambda \sim \xi \sim 10^{-2}$
$\tilde{m} \sim 1\,\mathrm{TeV}$

Maximizing the tree-level Higgs contribution from mixing essentially fixes all model parameters

Only the messenger scale remains free and determines collider phenomenology

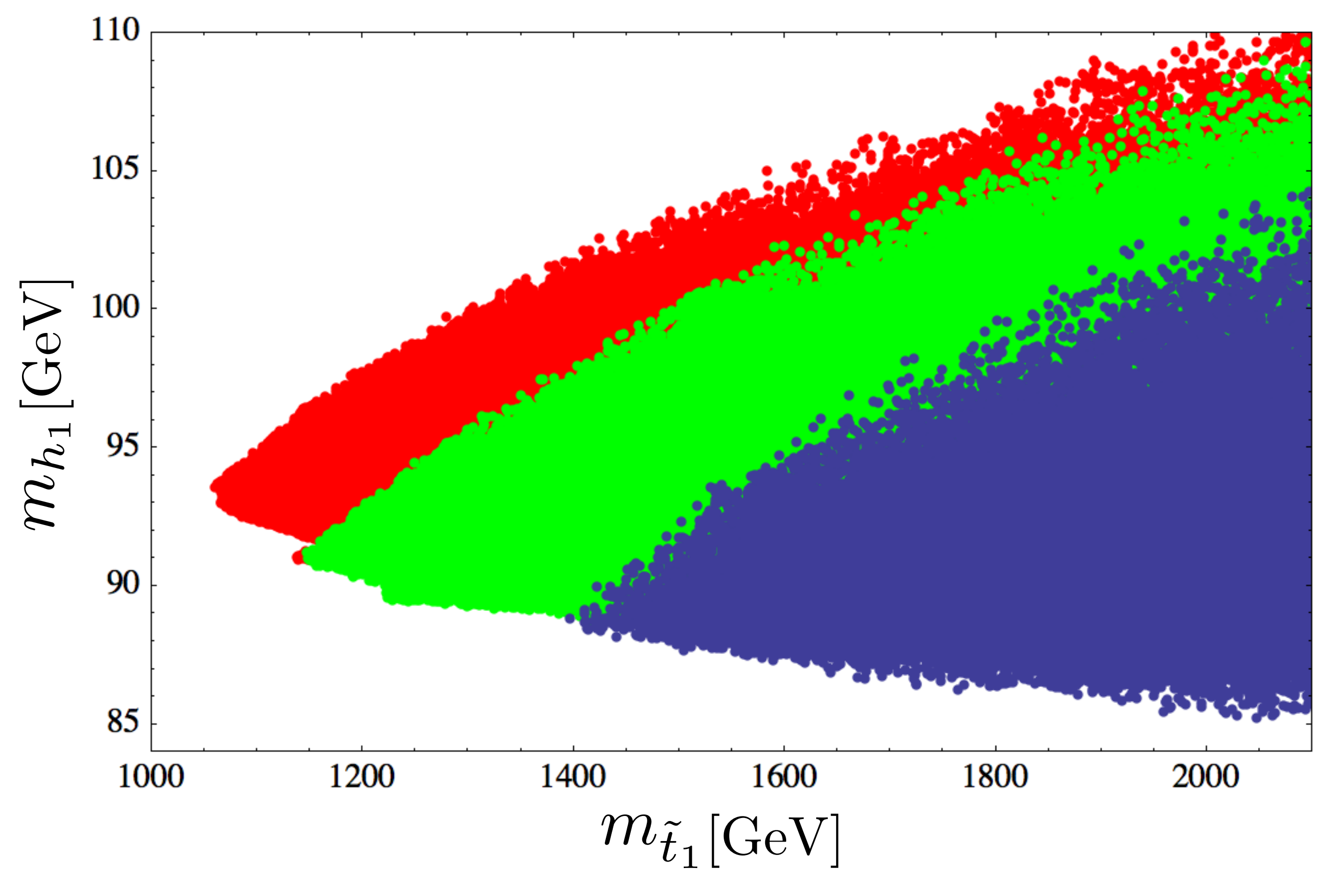
Sparticle masses can be close to direct exclusion bounds



Allows for 1.4 TeV Gluinos

← small Higgs-singlet mixing

↑ large Higgs-singlet mixing



and 1.1 TeV stops

Phenomenology

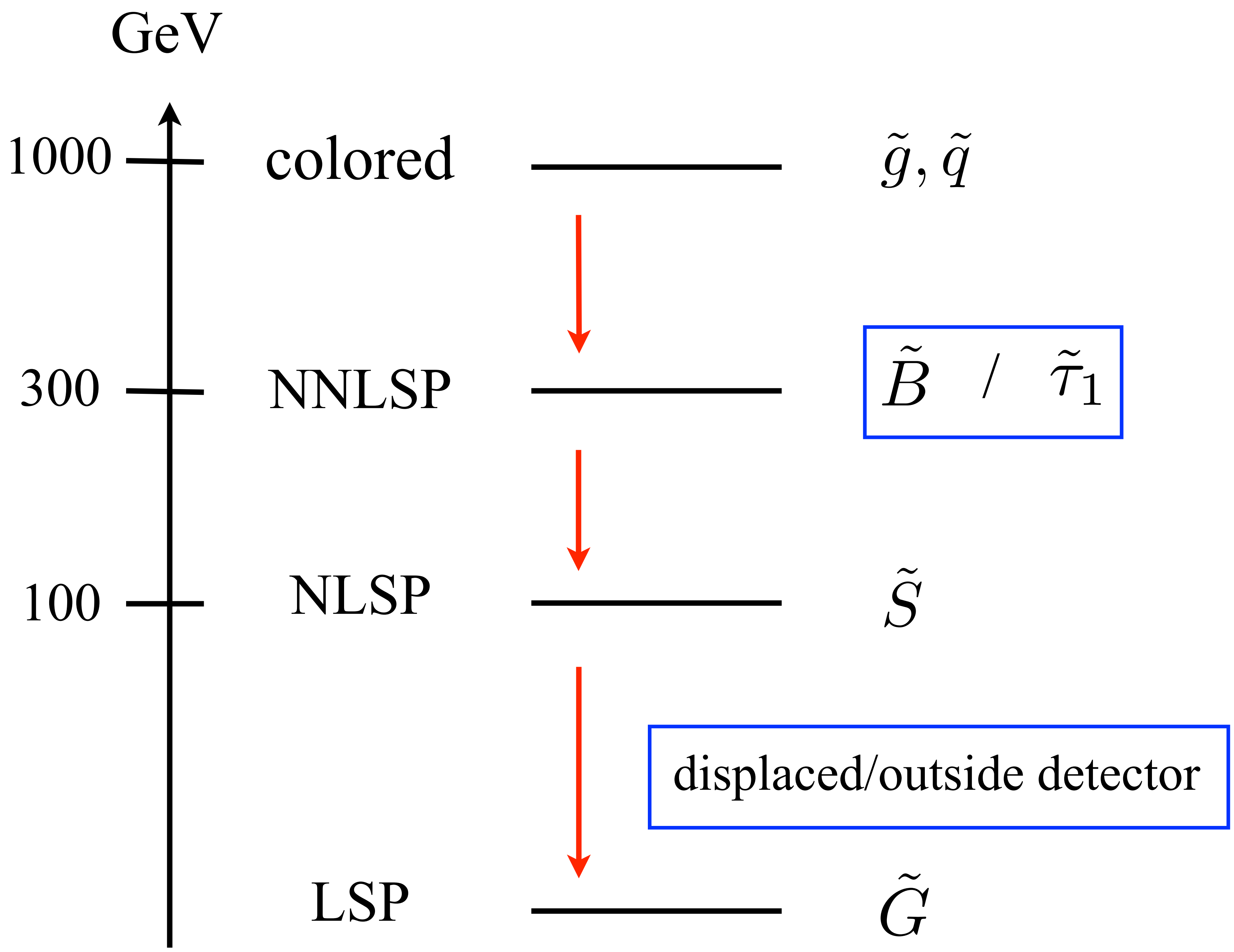
new feature is Singlino NLSP & Gravitino LSP

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

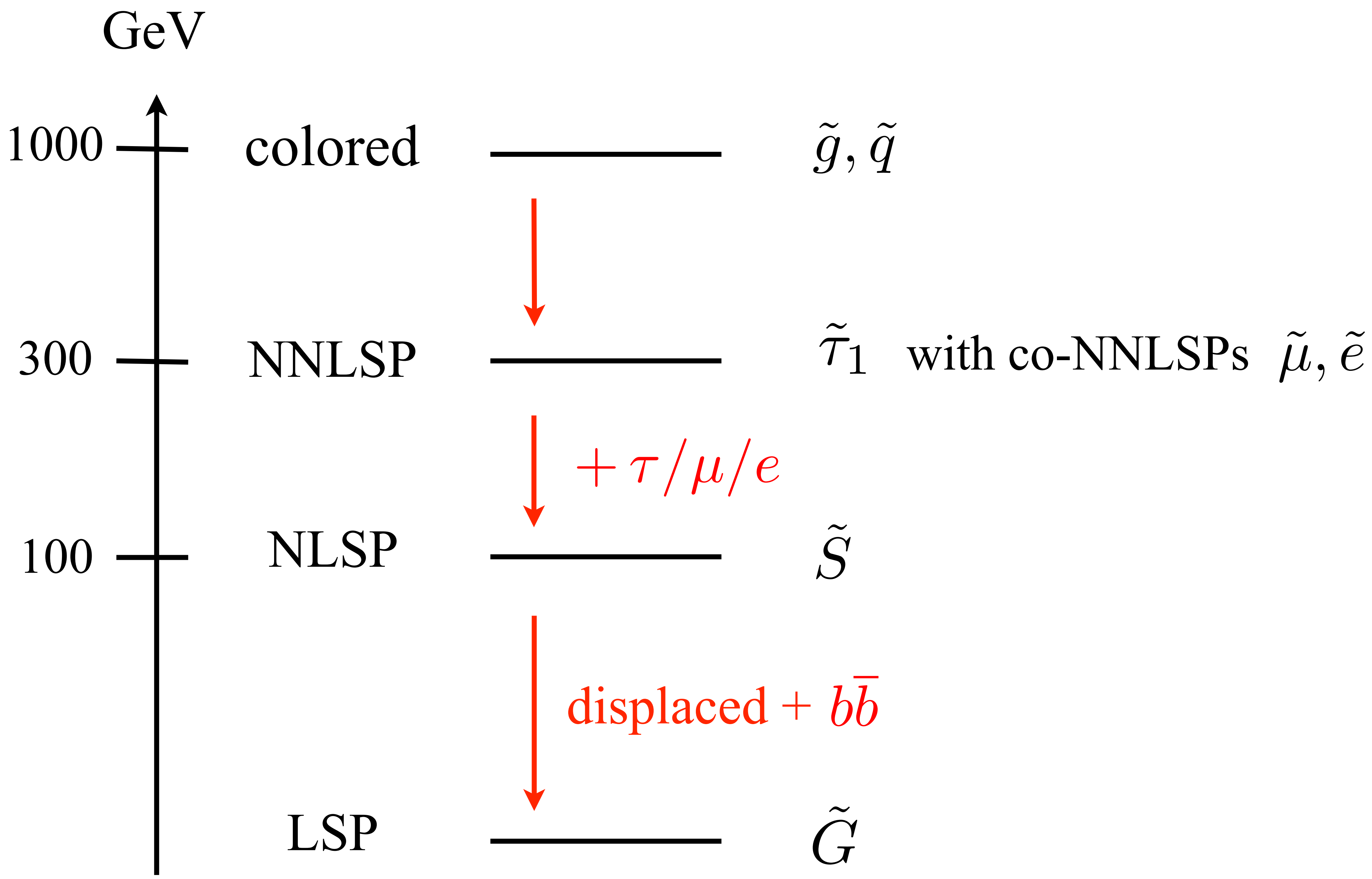
$$c\tau_{\tilde{N}_1} \approx 2.5\,\mathrm{cm}\,\left(\frac{100\,\mathrm{GeV}}{M_{\tilde{N}_1}}\right)^5 \left(\frac{M}{10^6\,\mathrm{GeV}}\right)^2 \left(\frac{\tilde{m}}{\mathrm{TeV}}\right)^2$$

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

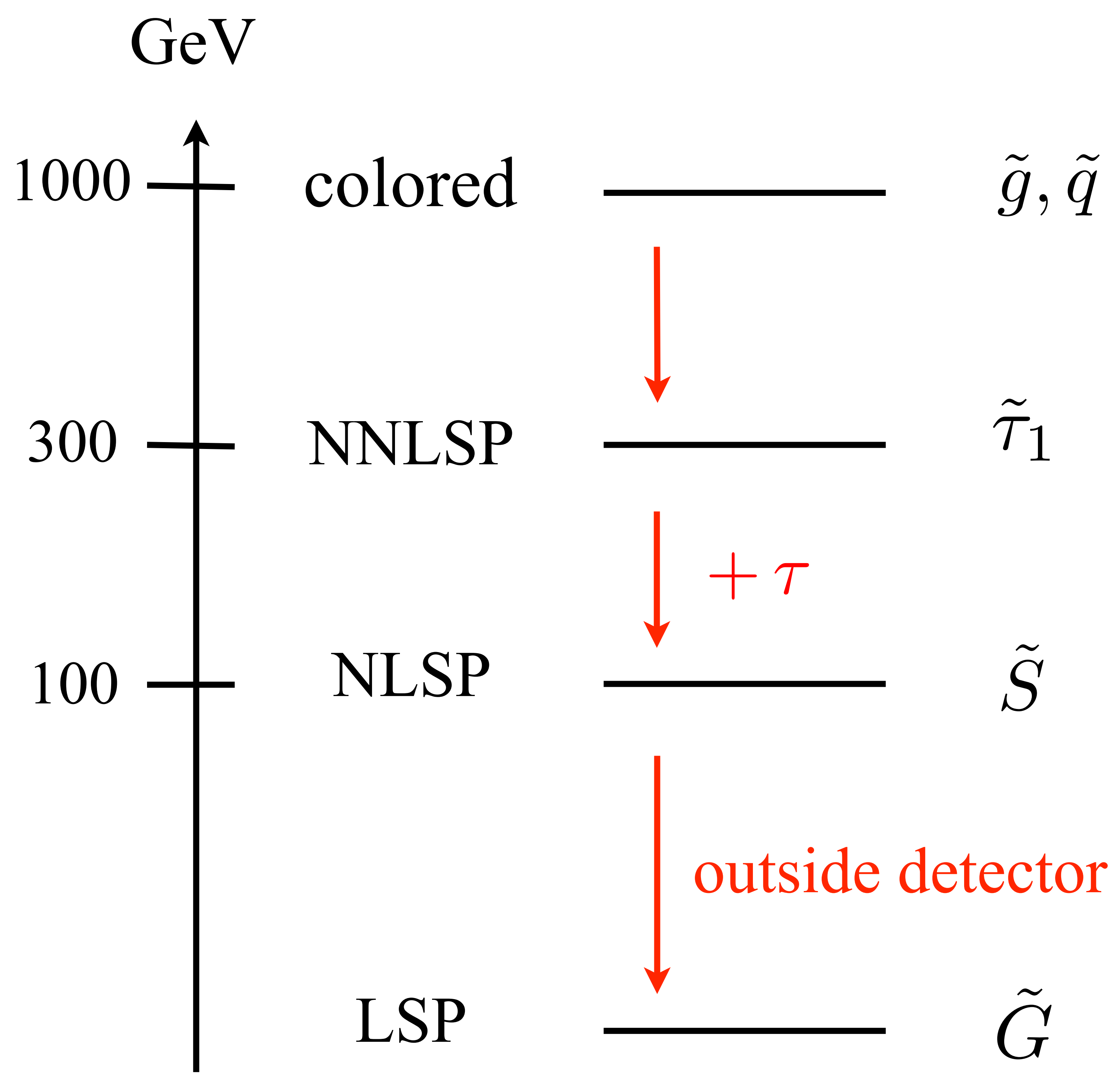
Signals depend on NNLSP nature and singlino decay length



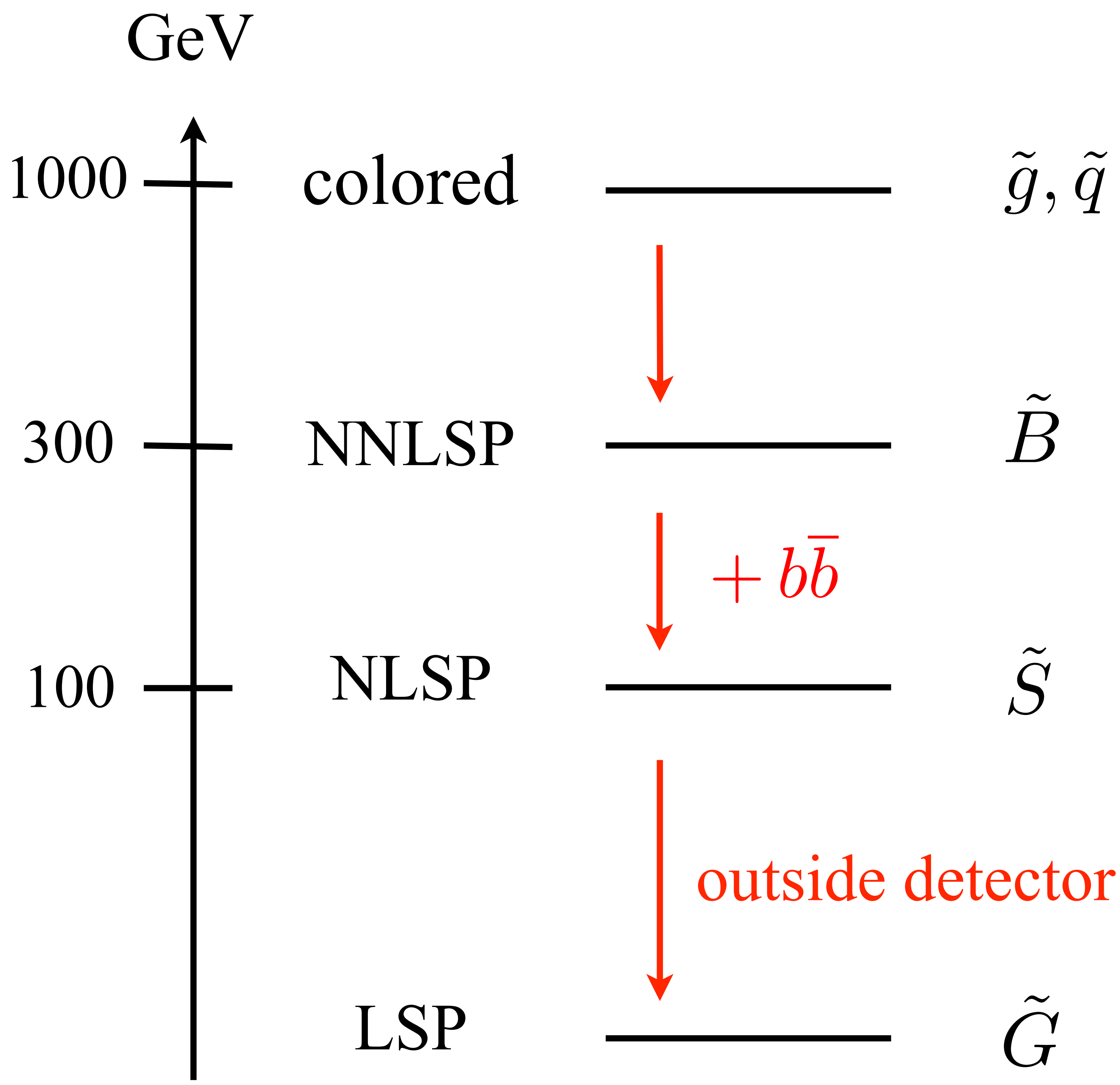
Low-M region: M < 10^7 GeV



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



Large-M region: M > 10^9 GeV



Summary

- A 125 GeV Higgs in Minimal Gauge Mediation requires sparticles out of LHC reach: motivates extensions of minimal model

- Flavored messenger matter-couplings generate large A-terms: leads to rich (but viable) flavor phenomenology that allows to test flavor models

- Minimal model for NMSSM + Gauge Mediation allows for light sparticles thanks to Higgs-singlet mixing: very predictive framework with new collider signatures

Backup

High-energy Soft Terms

(on top of MGM)

- Non-zero squark A-terms

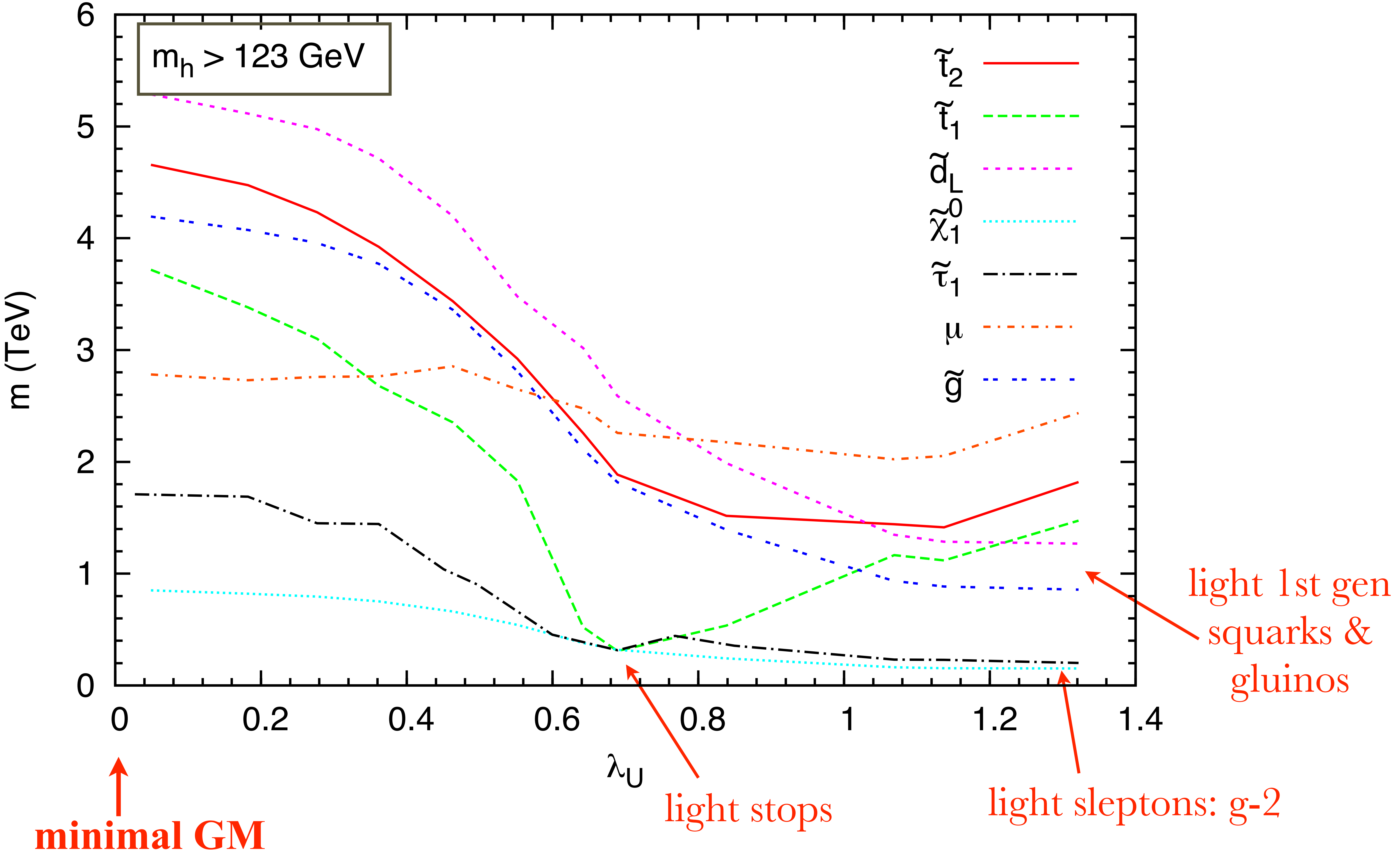
$$A_U = -\frac{\Lambda}{16\pi^2}\left(\lambda_U \lambda_U^\dagger y_U + 2\, y_U \lambda_U^\dagger \lambda_U\right) \qquad A_D = -\frac{\Lambda}{16\pi^2}\lambda_U \lambda_U^\dagger y_D$$

- New contribs to 2-loop squark masses

$$\Delta m_{Q(U)}^2 \sim \frac{\Lambda^2}{256\pi^4}\left(\lambda_U \lambda_U^\dagger - g_3^2\right)\lambda_U \lambda_U^\dagger \qquad \Delta m_D^2 \sim \frac{\Lambda^2}{256\pi^4} y_D^\dagger \lambda_U \lambda_U^\dagger y_D$$

Only 1 new parameter relevant for spectrum

Low-energy Spectrum



	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	$1.9 \cdot 10^{16}$	$6.0 \cdot 10^{15}$
$\sigma_{\tilde{q}\tilde{q}}^{13\text{TeV}}$	9.35	2.99	1.98	59.7	2.63
$\sigma_{\tilde{q}\tilde{g}}^{13\text{TeV}}$	11.9	3.30	2.01	91.1	2.48
$\sigma_{\text{tot}}^{13\text{TeV}}$	25.2	7.28	4.58	190	5.95
$\sigma_{\text{tot}}^{8\text{TeV}}$	0.51	0.07	0.03	10.1	0.05

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 (obtained with `PROSPINO` [16]) 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 $\cos\theta \approx 0.88$.