Light Sparticles in NMSSM + Gauge Mediation

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GGI 2015: Gearing up for the LHC

Introduction

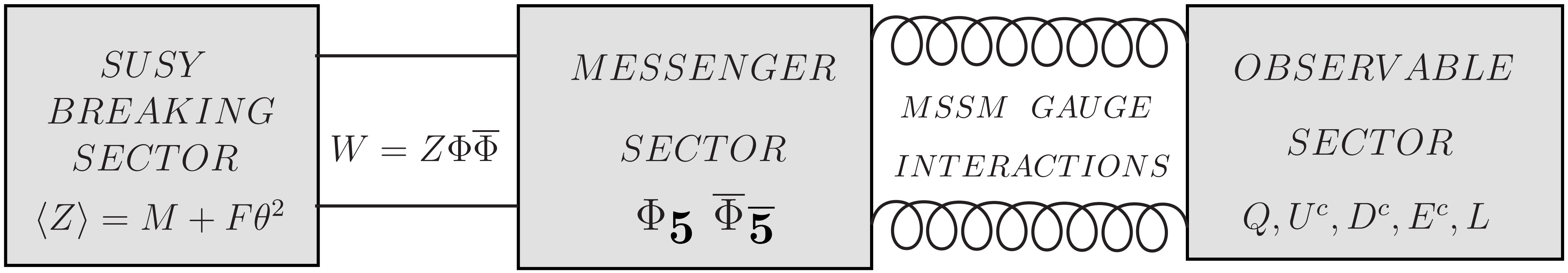
The legacy of LHC Run 1:
A 125 GeV Higgs, no new physics

Don’t give up yet: best candidate to protect
weak scale is still low-energy SUSY

Still room for light sparticles:
explore non-minimal models

For heavy SUSY indirect tests important:
explore non-minimal sflavor structures

Minimal Gauge Mediation



Very predictive (5 parameters) ✔

Solves SUSY Flavor Problem (MFV) ✔

Higgs mass problematic (small A-terms) ✘
need $m_{\tilde{g}} \gtrsim 3\,\mathrm{TeV}$

The Higgs mass in Gauge Mediation

How to increase Higgs mass?

- large radiative A_t

  → heavy gluino & squarks

- large boundary A_t

  → new couplings messenger - Q,U,H_u

- new tree-level Δm_h^2

  → D-terms, F-terms, mixing

  (F-terms, mixing: **NMSSM**)

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  Part I

- new tree-level Δm_h^2

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  Part II

  NMSSM

Part I: Messenger-Matter couplings

messengers have same quantum number as Higgs

$$W_{yuk} = y^u_{ij} Q_i U_j H_u \quad \rightarrow \quad \Delta W_{yuk} = \lambda^u_{ij} Q_i U_j \Phi^5_{H_u}$$

get new contributions to A-terms and soft masses

$$A_t \sim \frac{\Lambda}{16\pi^2} \lambda_U \lambda_U^\dagger y_U \qquad \Delta m^2_{Q(U)} \sim \frac{\Lambda^2}{256\pi^4} \left(\lambda_U \lambda_U^\dagger - g_3^2\right) \lambda_U \lambda_U^\dagger$$

need to take care of flavor structure: $\lambda_U \neq \mathcal{O}(1)_{ij}$

...but plausible since also $y_U \neq \mathcal{O}(1)_{ij}$

Flavored Gauge Mediation

2 possibilities to relate new couplings to up-Yukawas

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

aligned to Yukawas
through explicit mixing
(MFV)

controlled by same
underlying flavor model
("Flavored Gauge Mediation")

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

Evans, Ibe, Yanagida '11

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

Shadmi & Szabo '11
Abdullah, Galon, Shadmi, Shirman '12

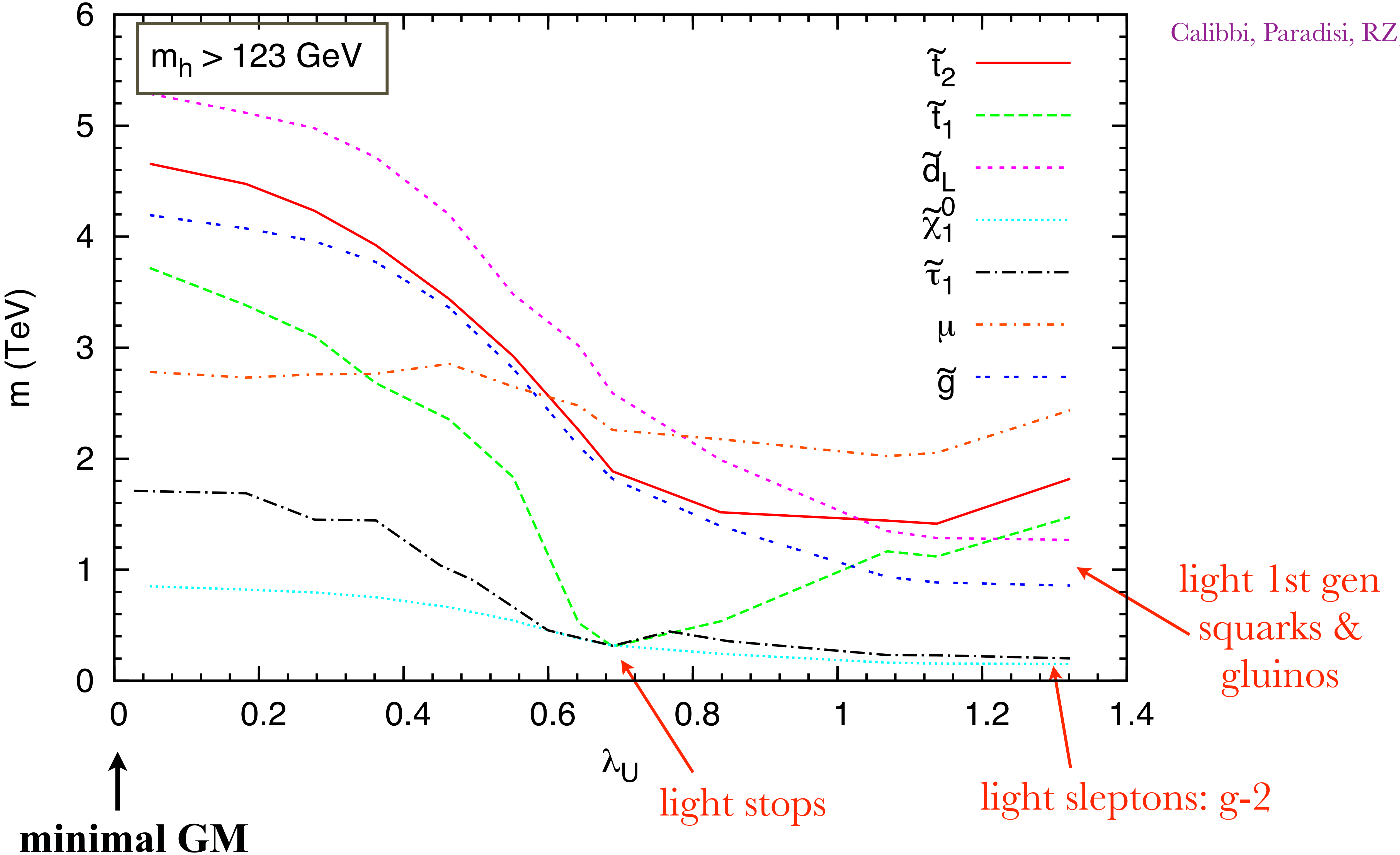
In both cases SUSY spectrum controlled by single new parameter λ^u_{33} and easily in LHC reach

only flavor pheno different: **FGM gives non-MFV sflavor**

Low-energy Spectrum

Evans, Ibe, Yanagida '11,'12

Calibbi, Paradisi, RZ, '13



Sflavor Structure in U(1) Flavor Model

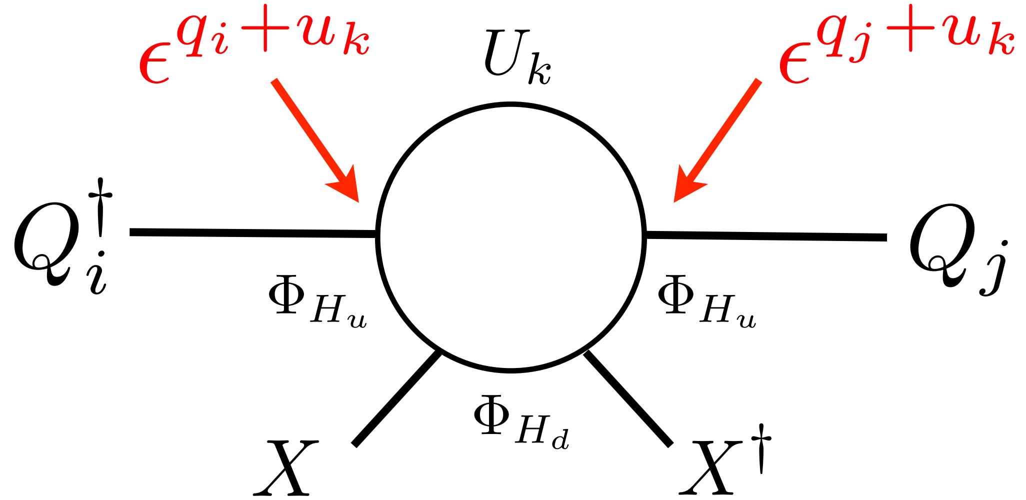
Calibbi, Paradisi, RZ, '13

Estimate couplings in terms of masses and mixings through FN charges

$$(y_U)_{ij} = \underbrace{x_{ij}}_{\mathcal{O}(1)} \epsilon^{q_i+u_j} \quad \longrightarrow \quad (\lambda_U)_{ij} = y_{ij}\epsilon^{q_i+u_j}$$

Loop origin gives CKM suppression of flavor violation

$$\left(\tilde{m}_Q^2\right)_{ij} \sim (\lambda_U)_{ik} (\lambda_U)^*_{jk} \sim \epsilon^{q_i+q_j+2u_3} \sim V_{i3}V^*_{j3}y_t^2$$



Comparison

Parametric flavor suppression of $\left(\tilde{m}_Q^2\right)_{ij}$

Flavored GM + U(1) $\sim \left(\lambda_U \lambda_U^\dagger\right)_{ij} \sim \epsilon^{q_i+q_j+2u_3} \sim V_{i3}V_{j3}^* y_t^2$

Gravity Mediation + U(1) $\sim \epsilon^{q_i-q_j} \sim V_{i3}/V_{j3}$

SUSY Partial Compositeness $\sim \epsilon^{q_i+q_j} \sim V_{i3}V_{j3}^*$

Minimal Flavor Violation $\sim \left(y_U y_U^\dagger\right)_{ij} + \left(y_D y_D^\dagger\right)_{ij} \sim V_{i3}V_{j3}^* y_t^2$

	MFV	PC	$U(1)$	$\text{FGM}_{U,D}+U(1)$	$\text{FGM}_U+U(1)$
$(\delta^u_{LL})_{ij}$	$V_{i3}V^*_{j3}y_b^2$	$(\epsilon^q_3)^2 V_{i3}V^*_{j3}$	$\frac{V_{i3}}{V_{j3}}\vert_{i\leq j}$	$V_{i3}V^*_{j3}y_t^2$	$V_{i3}V^*_{j3}y_t^2$
$(\delta^d_{LL})_{ij}$	$V^*_{3i}V_{3j}y_t^2$	$(\epsilon^q_3)^2 V_{i3}V^*_{j3}$	$\frac{V_{i3}}{V_{j3}}\vert_{i\leq j}$	$V^*_{3i}V_{3j}y_t^2$	$V^*_{3i}V_{3j}y_t^2$
$(\delta^u_{RR})_{ij}$	$y_i^U y_j^U V_{i3}V^*_{j3}y_b^2$	$\frac{y_i^U y_j^U}{V_{i3}V^*_{j3}}\frac{(\epsilon^u_3)^2}{y_t^2}$	$\frac{y_i^U V_{j3}}{y_j^U V_{i3}}\vert_{i\leq j}$	$\frac{y_i^U y_j^U}{V_{i3}V^*_{j3}}$	$\frac{y_i^U y_j^U}{V_{i3}V^*_{j3}}$
$(\delta^d_{RR})_{ij}$	$y_i^D y_j^D V^*_{3i}V_{3j}y_t^2$	$\frac{y_i^D y_j^D}{V_{i3}V^*_{j3}}\frac{(\epsilon^u_3)^2}{y_t^2}$	$\frac{y_i^D V_{j3}}{y_j^D V_{i3}}\vert_{i\leq j}$	$\frac{y_i^D y_j^D}{V_{i3}V^*_{j3}}$	$y_i^D y_j^D V^*_{3i}V_{3j}y_t^2$
$(\delta^u_{LR})_{ij}$	$y_j^U V_{i3}V^*_{j3}y_b^2$	$y_j^U\frac{V_{i3}}{V^*_{j3}}$	$y_j^U\frac{V_{i3}}{V^*_{j3}}$	$y_j^U V_{i3}V^*_{j3}y_t^2 + y_i^U\frac{y_i^U y_j^U}{V_{i3}V^*_{j3}}$ $y_j^U\frac{V_{i3}}{V^*_{j3}}y_t^6$	$y_j^U V_{i3}V^*_{j3}y_t^2 + y_i^U\frac{y_i^U y_j^U}{V_{i3}V^*_{j3}}$ $y_j^U\frac{V_{i3}}{V^*_{j3}}y_t^6$
$(\delta^d_{LR})_{ij}$	$y_j^D V^*_{3i}V_{3j}y_t^2$	$y_j^D\frac{V_{i3}}{V^*_{j3}}$	$y_j^D\frac{V_{i3}}{V^*_{j3}}$	$y_j^D V^*_{3i}V_{3j}y_t^2 + y_i^D\frac{y_i^D y_j^D}{V_{i3}V^*_{j3}}$ $y_j^D\frac{V^*_{3i}}{V_{3j}}y_t^4 y_b^2$	$y_j^D V^*_{3i}V_{3j}y_t^2$

Flavor violation similar to SUSY Partial Compositeness (dominantly in LR sector)

The Higgs mass in Gauge Mediation

How to increase Higgs mass?

- large radiative A_t

  ➡ heavy gluino & squarks

- large boundary A_t

  ➡ new couplings messenger - Q,U,H_u

  Part I

- new tree-level Δm_h^2

  ➡ D-terms, F-terms, mixing

  NMSSM

  Part II

Part II: 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 $\quad \Delta W = \lambda S H_u H_d + \frac{\kappa}{3} S^3$

mixing angles constrained by LEP and LHC

maximal contribution to Higgs mass for

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

Badziak, Olechowski, Pokorski '13

Embedding into GMSB

Can one realize this scenario in Gauge Mediation?

(besides predictivity motivated by μ-B_μ problem of GMSB)

MSSM + GM: $\mu \sim a\frac{\Lambda}{16\pi^2}$ $B_\mu \sim a\frac{\Lambda^2}{16\pi^2} \sim 16\pi^2\mu^2$

NMSSM + GM: $\mu \sim \langle S \rangle \sim m_{soft}$ $B_\mu \sim \langle F_S \rangle \sim m_{soft}^2 \sim \mu^2$

...not in minimal Gauge Mediation because singlet soft terms too small

Dine, Nelson '93

de Gouvea, Friedland, Murayama '13

The DGS Model

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

Delgado, Giudice, Slavich '07

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

$$A_\lambda \sim A_\kappa \sim \tilde{m}\,\xi^2 \qquad \tilde{m}_S^2 \sim \tilde{m}^2\,\xi^2\left(\xi^2 + \kappa^2 + g^2\right)$$

$\tilde{m} \equiv 1/(16\pi^2)\,F/M \approx m_{\tilde{g}}/2$

4 parameters: $\lambda,\ \tilde{m},\ \xi,\ M$

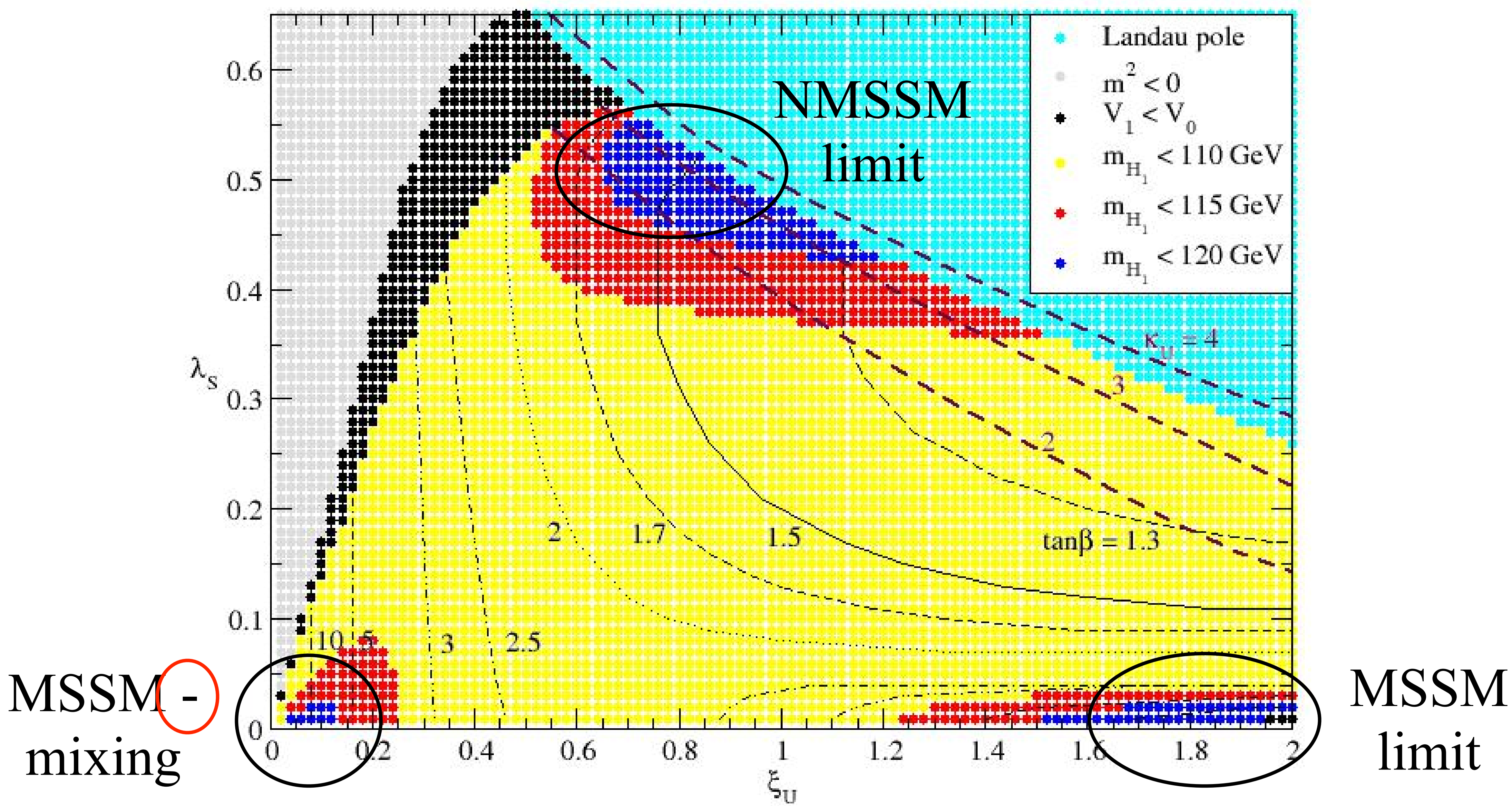
[correct EWSB fixes κ]

DGS Parameter Space

Only 3 regions with sizable Higgs mass

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

bounded by M_Z^2 (perturbativity up M_{GUT})

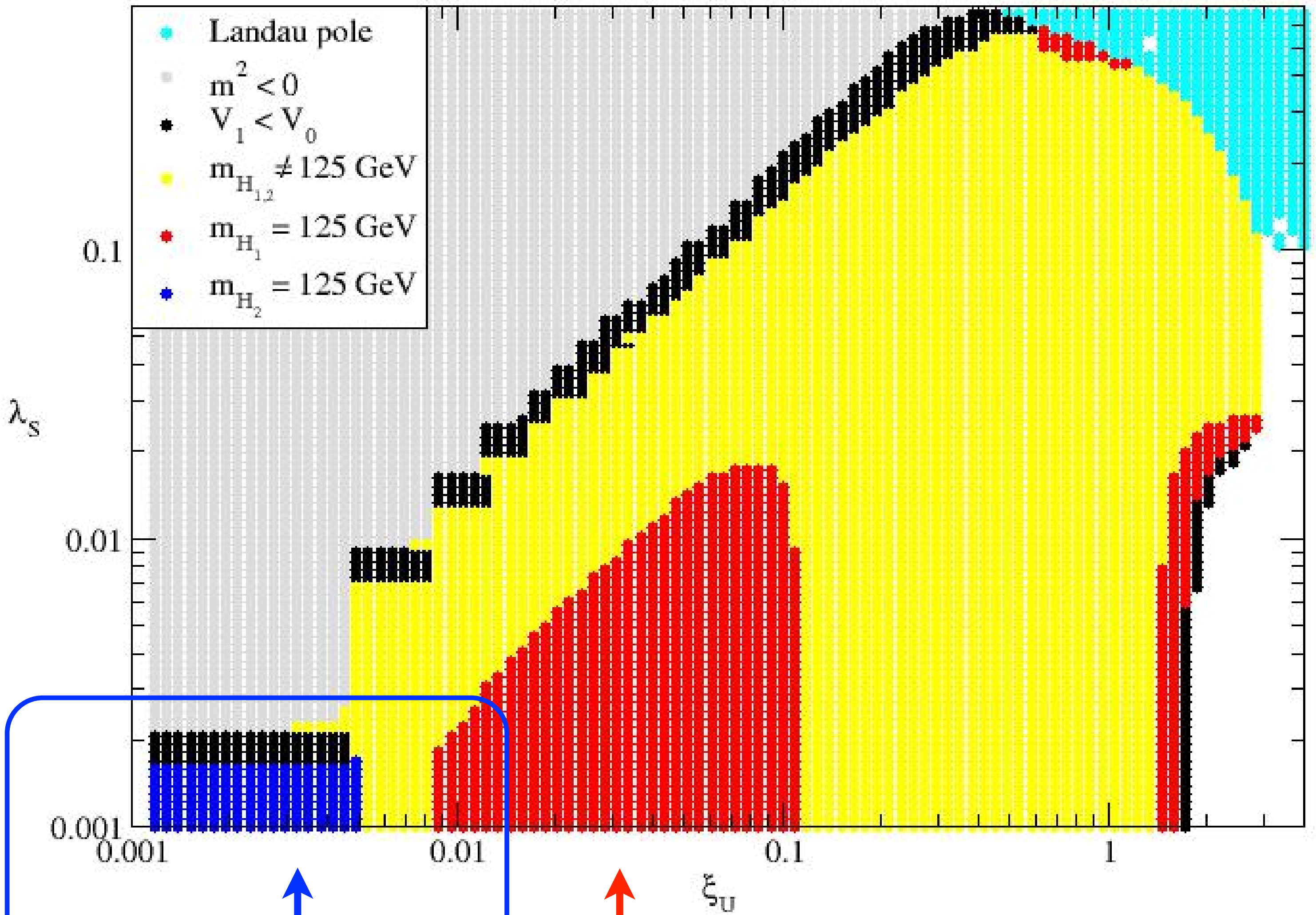


The Push-Up Region

"...even in these regions the lightest Higgs mass is not larger than the maximal value attainable in the usual GMSB."

Delgado, Giudice, Slavich '07

MSSM + mixing region exists but hard to find



$h_{\rm SM} \approx h_2$ $h_{\rm SM} \approx h_1$

Look for maximal singlet-Higgs mixing

Allanach, Badziak, Hugonie, RZ '15

Maximize tree-level Higgs contribution from mixing

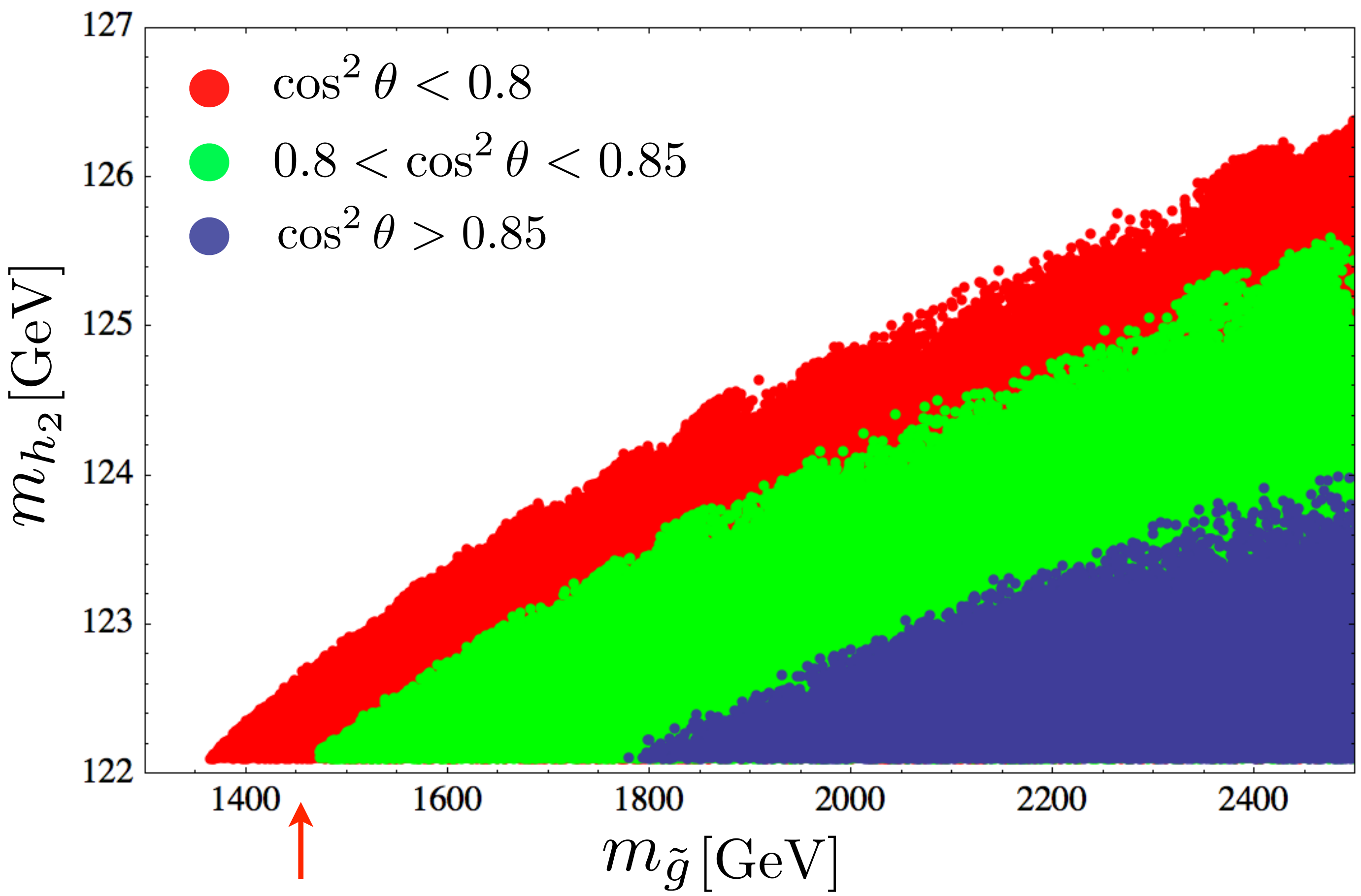
$m_{h_1} \approx 94\,\mathrm{GeV}$ $\cos\theta \approx 0.88$

$m_{h_2} \approx 125\,\mathrm{GeV}$

determines 3/4 parameters, only messenger scale free
(determines gravitino phenomenology)

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

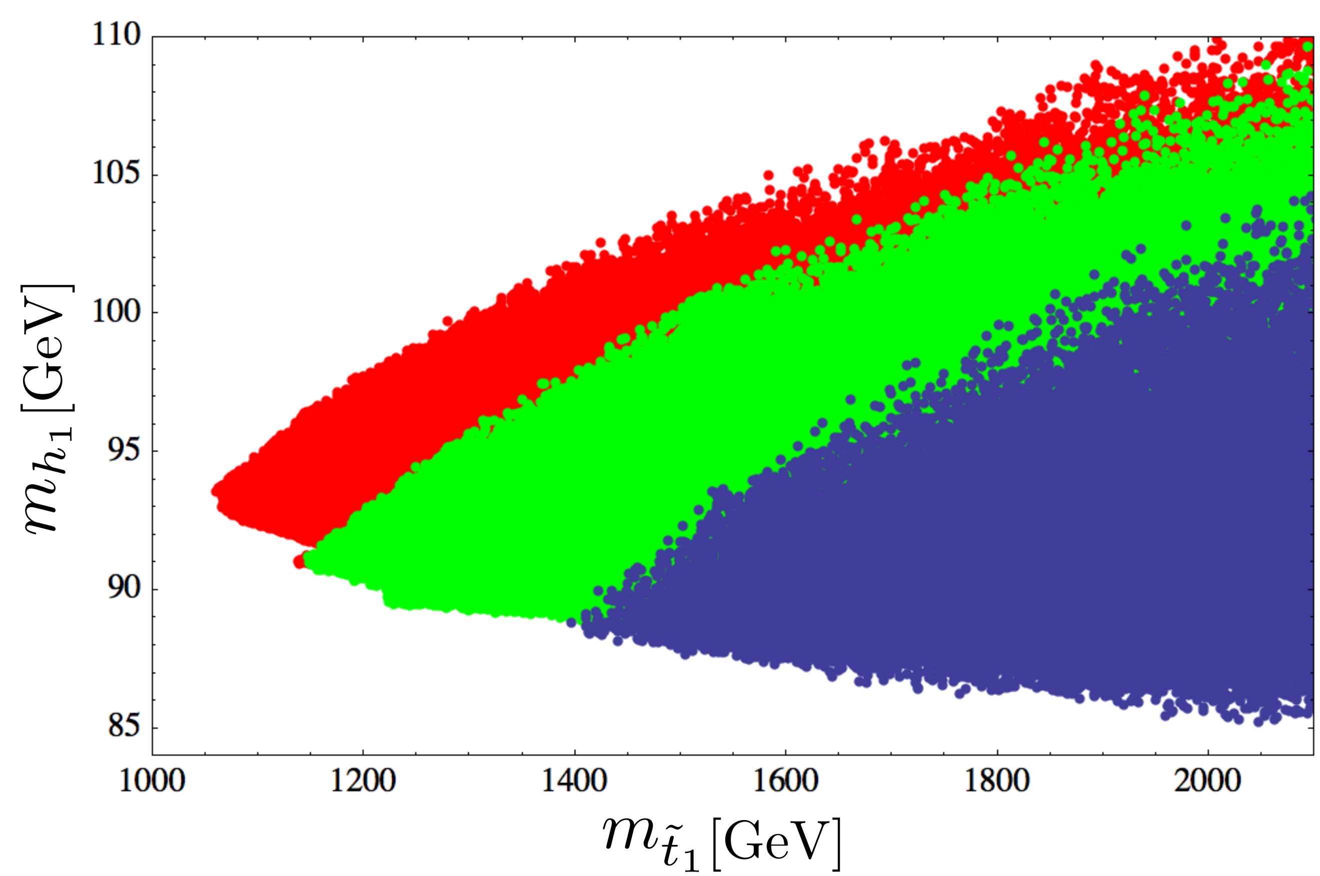
Higgs mass still drives lower bounds on sparticles, but can be close to direct exclusion bounds



Allows for 1.4 TeV Gluinos

← small Higgs-singlet mixing

↑ large Higgs-singlet mixing



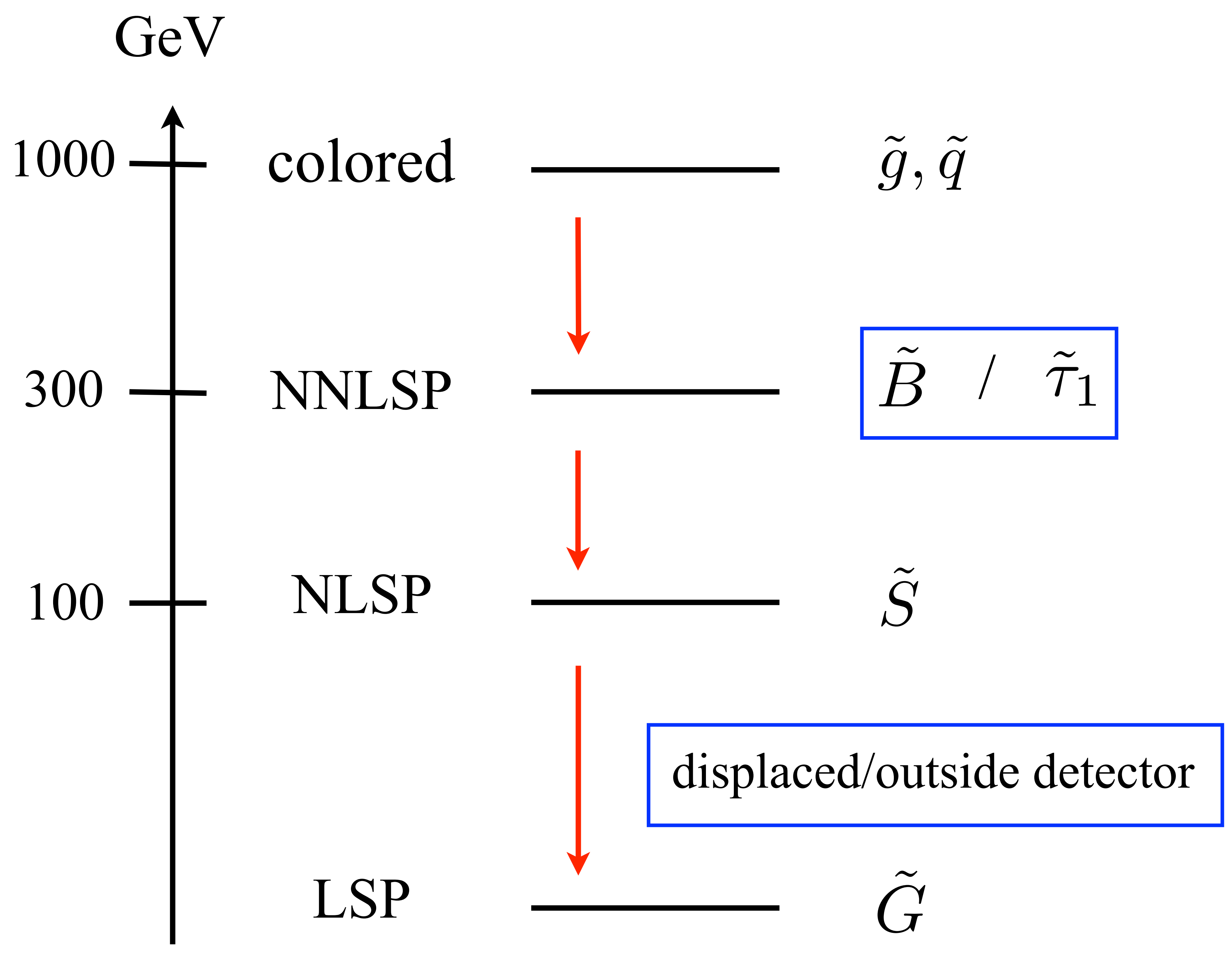
and 1.1 TeV stops

Benchmarks

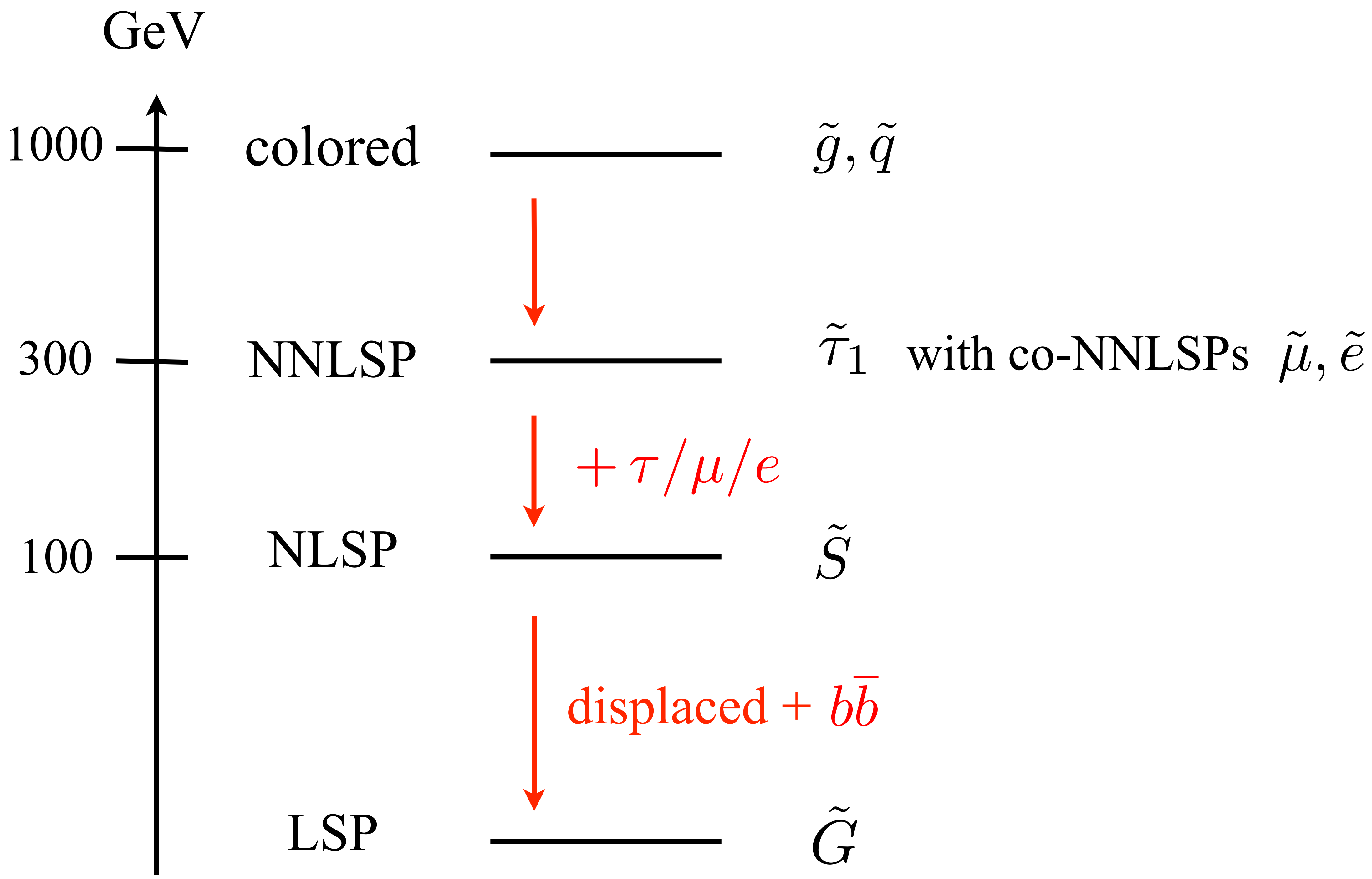
		P1	P2	P3	P4	P5
	$\tilde{m}$	$7.5 \cdot 10^2$	$8.7 \cdot 10^2$	$9.3 \cdot 10^2$	$5.9 \cdot 10^2$	$9.3 \cdot 10^2$
	M	$1.4 \cdot 10^6$	$2.8 \cdot 10^6$	$3.3 \cdot 10^7$	$8.3 \cdot 10^{14}$	$3.4 \cdot 10^{14}$
	λ	$1.0 \cdot 10^{-2}$	$9.3 \cdot 10^{-3}$	$6.7 \cdot 10^{-3}$	$9.2 \cdot 10^{-3}$	$6.9 \cdot 10^{-3}$
	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
$[m]$	$c\tau_{\tilde{N}_1}$	$6.4 \cdot 10^{-2}$	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
	$\sigma^{13\text{TeV}}_{\tilde{q}\tilde{g}}$	11.9	3.30	2.01	91.1	2.48
$[fb]$	$\sigma^{13\text{TeV}}_{\text{strong}}$	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

- reduced Higgs signal strengths $\mu \sim 0.75$
- light pseudoscalar ~ 25 GeV
- **singlino NLSP ~ 100 GeV**
  displaced decays/stable
- **stau/bino NNLSP ~ 300 GeV**
- singlino essentially decoupled
  SUSY decays through NNLSP

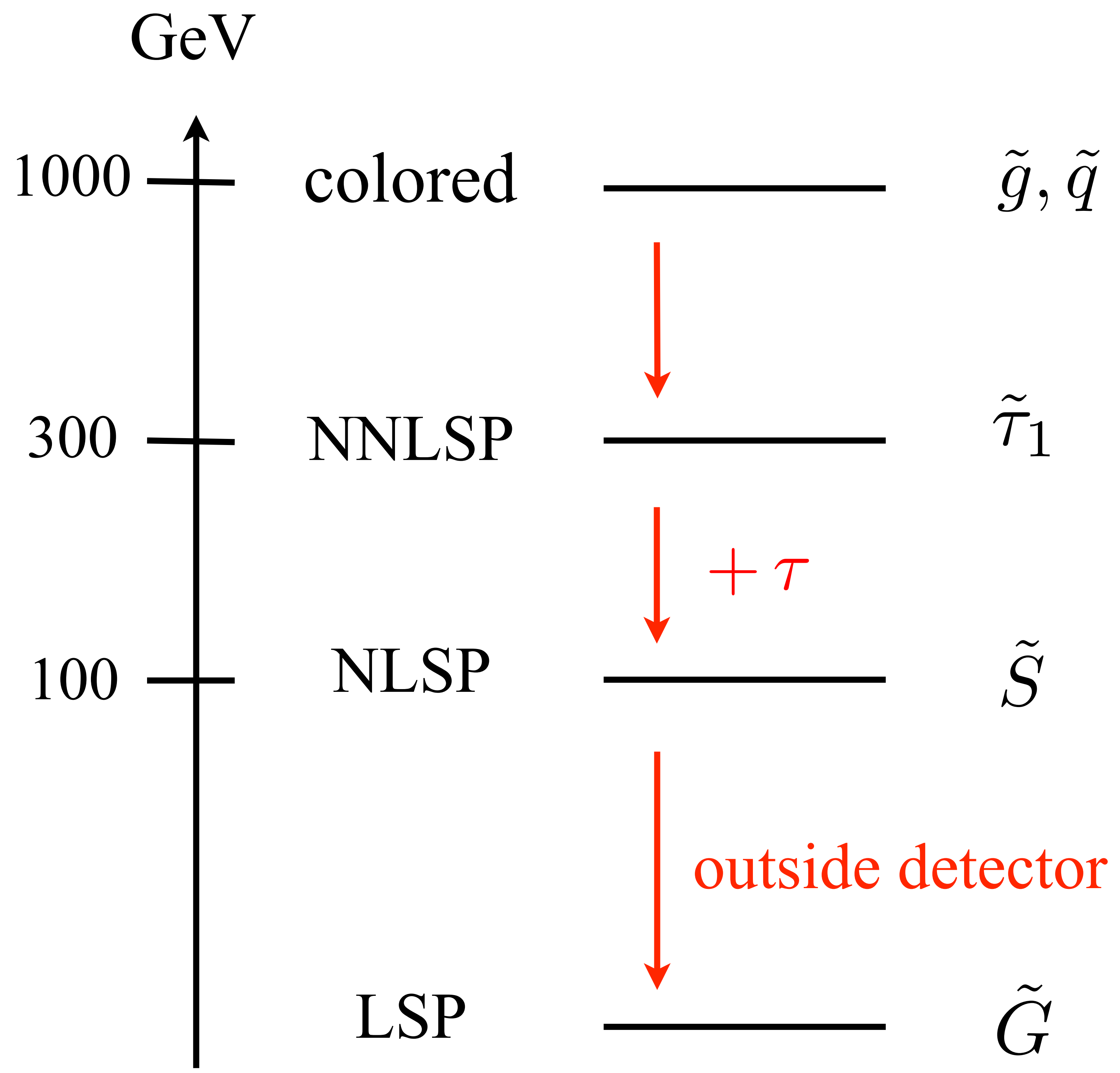
Signals depend on NNLSP nature and singlino decay length



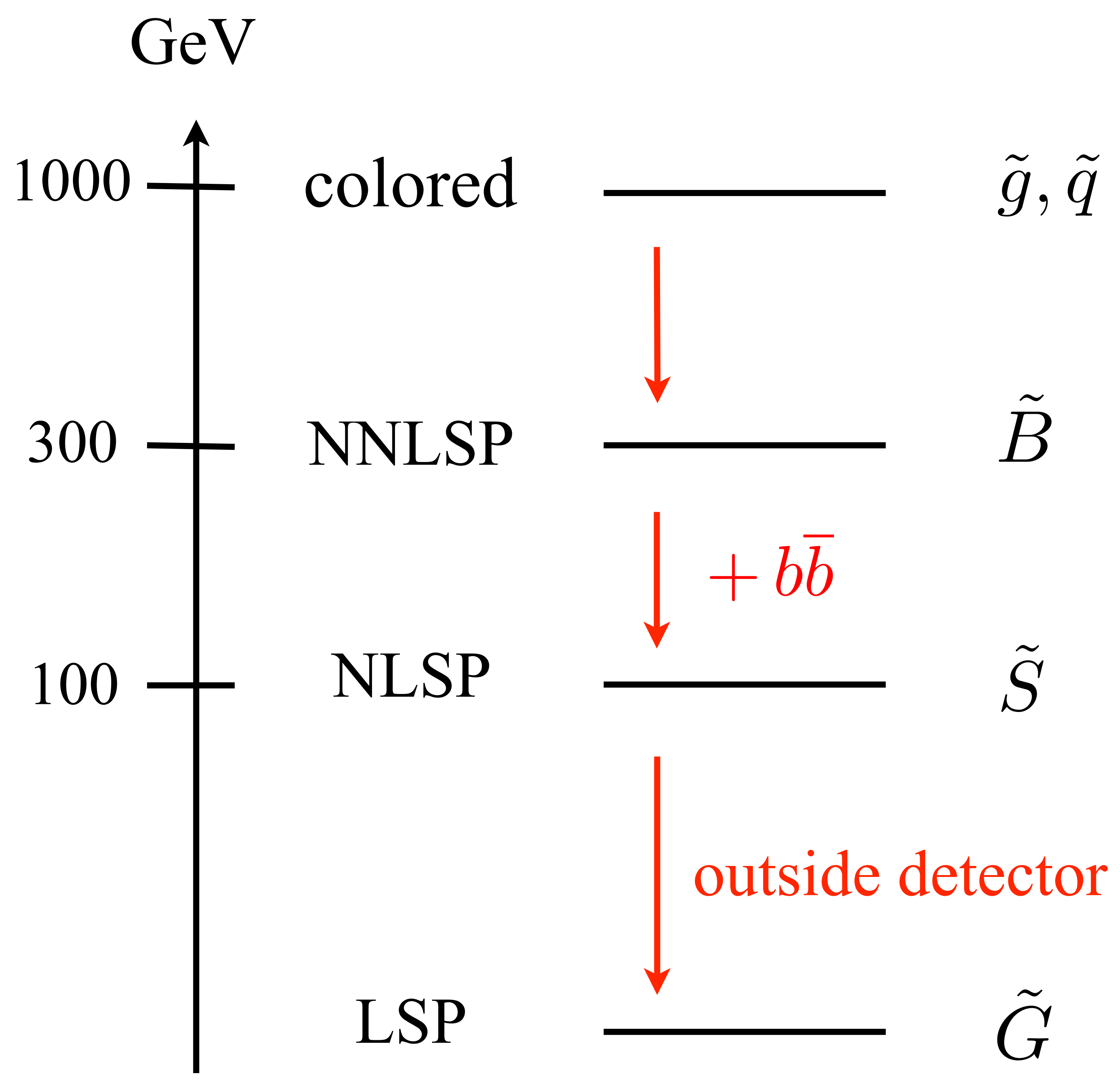
Low-M region: M < 10^7 GeV



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



Large-M region: $M > 10^9$ GeV



LHC Phenomenology

Allanach, Badziak, Cottin, Desai, Hugonie, RZ
in progress

	P1	P2	P3	P4	P5
NNLSP	stau	stau	stau	bino	bino
$m_{\tilde{g}}$	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
$\sigma^{13\text{TeV}}_{\text{strong}}[fb]$	25	7.3	4.6	190	6.0
$\sigma^{8\text{TeV}}_{\text{strong}}[fb]$	0.51	0.07	0.03	10.1	0.05
$c\tau_{\tilde{N}_1}[m]$	$6.4 \cdot 10^{-2}$	0.34	48	$\sim \infty$	$\sim \infty$
search	multi-ℓ + MET	multi-ℓ + MET	multi-ℓ + MET	jets + MET	jets + MET
$\sigma/\sigma^{\text{excl}}_{95\%}$	0.08	0.36	0.04	0.93	0.03

- All benchmarks allowed by run1
- Displaced singlino vertex dramatically reduces sensitivity
- Dedicated DV searches not effective due to 2nd DVs from b-jets

Summary

- A 125 GeV Higgs in Minimal Gauge Mediation requires colored 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 from displaced singlino decays into b-jets

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

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

Only 1 new parameter relevant for spectrum

Flavor constraints

Most constraints automatically satisfied for $\tilde{m} \sim 1\,\mathrm{TeV}$

$(\delta^D_{XX})_{12}$	9.2×10^{-2} [Re]	1.2×10^{-2} [Im]
$\langle\delta^D_{12}\rangle$	1.9×10^{-3} [Re]	2.6×10^{-4} [Im]
$(\delta^D_{LR})_{12}$	5.6×10^{-3} [Re]	4.0×10^{-5} [Im]
$(\delta^U_{XX})_{12}$	1.0×10^{-1} [Re]	6.0×10^{-2} [Im]
$\langle\delta^U_{12}\rangle$	6.2×10^{-3} [Re]	4.0×10^{-3} [Im]
$(\delta^U_{LR})_{12}$	1.6×10^{-2} [Re]	1.6×10^{-2} [Im]
$(\delta^D_{XX})_{13}$	2.8×10^{-1} [Re]	6.0×10^{-1} [Im]
$\langle\delta^D_{13}\rangle$	4.2×10^{-2} [Re]	1.8×10^{-2} [Im]
$(\delta^D_{LR})_{13}$	6.6×10^{-2} [Re]	1.5×10^{-1} [Im]
$(\delta^D_{LR})_{11}$	2.0×10^{-6}	
$(\delta^U_{LR})_{11}$	4.0×10^{-6}	
[illegible]	[illegible]	[illegible]

$D - \overline{D}$ mixing

$$(\delta^u_{RR})_{12} \sim (\lambda^*_U)_{31}(\lambda_U)_{32}$$

Neutron EDM

$$(\delta^u_{LR})_{11} \sim (\lambda_U)_{13}(\lambda_U)_{31}$$