Search for lighter top-squark and non-Standard Higgses within NMSSM

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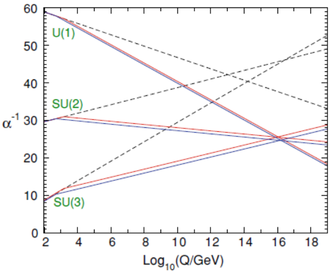
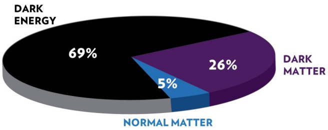
Supersymmetry

Supersymmetric extensions of the Standard Model (SM) are motivated by

- establishing a symmetry between bosons and fermions,
- an automatic unification of the running gauge couplings at a Grand Unified (GUT) energy scale, and
- the possibility of explaining the dark matter relic density in terms of a stable neutral particle





Minimal Supersymmetric Standard Model

MSSM is considered minimal, as it involves the minimum number of new particle states and new interactions consistent with phenomenology

sparticle	Spin	R_P	Gauge Eigenstates	Mass Eigenstates
Higgsinos	0	+1	H_u^0 H_d^0 H_u^+ H_d^-	h^0 H^0 A^0 $H^\pm$
squarks	0	-1	$\tilde{u}_L$ $\tilde{u}_R$ $\tilde{d}_L$ $\tilde{d}_R$ $\tilde{s}_L$ $\tilde{s}_R$ $\tilde{c}_L$ $\tilde{c}_R$ $\tilde{t}_L$ $\tilde{t}_R$ $\tilde{b}_L$ $\tilde{b}_R$	$\tilde{u}_L$ $\tilde{u}_R$ $\tilde{d}_L$ $\tilde{d}_R$ $\tilde{s}_L$ $\tilde{s}_R$ $\tilde{c}_L$ $\tilde{c}_R$ $\tilde{t}_1$ $\tilde{t}_2$ $\tilde{b}_1$ $\tilde{b}_2$
sleptons	0	-1	$\tilde{e}_L$ $\tilde{e}_R$ $\tilde{\nu}_e$ $\tilde{\mu}_L$ $\tilde{\mu}_R$ $\tilde{\nu}_\mu$ $\tilde{\tau}_L$ $\tilde{\tau}_R$ $\tilde{\nu}_\tau$	$\tilde{e}_L$ $\tilde{e}_R$ $\tilde{\nu}_e$ $\tilde{\mu}_L$ $\tilde{\mu}_R$ $\tilde{\nu}_\mu$ $\tilde{\tau}_1$ $\tilde{\tau}_2$ $\tilde{\nu}_\tau$
neutralinos	1/2	-1	$\tilde{B}^0$ $\tilde{W}^0$ $\tilde{H}_u^0$ $\tilde{H}_d^0$	$\tilde{\chi}_1^0$ $\tilde{\chi}_2^0$ $\tilde{\chi}_3^0$ $\tilde{\chi}_4^0$
charginos	1/2	-1	$\tilde{W}^\pm$ $\tilde{H}_u^+$ $\tilde{H}_d^-$	$\tilde{\chi}_1^\pm$ $\tilde{\chi}_2^\pm$
gluinos	1/2	-1	$\tilde{g}$	$\tilde{g}$
gravitino	3/2	-1	$\tilde{G}$	$\tilde{G}$

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Next-to-Minimal Supersymmetric Standard Model

MSSM + additional singlet chiral superfield S = NMSSM

sparticle	Spin	R_P	Gauge Eigenstates	Mass Eigenstates
Higgsinos	0	+1	H_u^0 H_d^0 H_u^+ H_d^- S^0	h_1^0 h_2^0 h_3^0 H^0 A_1^0 A_2^0 $H^\pm$
squarks	0	-1	$\tilde{u}_L$ $\tilde{u}_R$ $\tilde{d}_L$ $\tilde{d}_R$ $\tilde{s}_L$ $\tilde{s}_R$ $\tilde{c}_L$ $\tilde{c}_R$ $\tilde{t}_L$ $\tilde{t}_R$ $\tilde{b}_L$ $\tilde{b}_R$	$\tilde{u}_L$ $\tilde{u}_R$ $\tilde{d}_L$ $\tilde{d}_R$ $\tilde{s}_L$ $\tilde{s}_R$ $\tilde{c}_L$ $\tilde{c}_R$ $\tilde{t}_1$ $\tilde{t}_2$ $\tilde{b}_1$ $\tilde{b}_2$
sleptons	0	-1	$\tilde{e}_L$ $\tilde{e}_R$ $\tilde{\nu}_e$ $\tilde{\mu}_L$ $\tilde{\mu}_R$ $\tilde{\nu}_\mu$ $\tilde{\tau}_L$ $\tilde{\tau}_R$ $\tilde{\nu}_\tau$	$\tilde{e}_L$ $\tilde{e}_R$ $\tilde{\nu}_e$ $\tilde{\mu}_L$ $\tilde{\mu}_R$ $\tilde{\nu}_\mu$ $\tilde{\tau}_1$ $\tilde{\tau}_2$ $\tilde{\nu}_\tau$
neutralinos	1/2	-1	$\tilde{B}^0$ $\tilde{W}^0$ $\tilde{H}_u^0$ $\tilde{H}_d^0$ $\tilde{S}^0$	$\tilde{\chi}_1^0$ $\tilde{\chi}_2^0$ $\tilde{\chi}_3^0$ $\tilde{\chi}_4^0$ $\tilde{\chi}_5^0$
charginos	1/2	-1	$\tilde{W}^\pm$ $\tilde{H}_u^+$ $\tilde{H}_d^-$	$\tilde{\chi}_1^\pm$ $\tilde{\chi}_2^\pm$
gluinos	1/2	-1	$\tilde{g}$	$\tilde{g}$
gravitino	3/2	-1	$\tilde{G}$	$\tilde{G}$

Next-to-Minimal Supersymmetric Standard Model

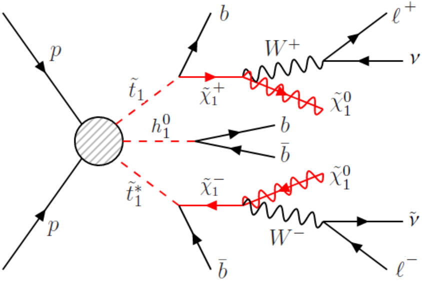
MSSM + additional singlet chiral superfield S = NMSSM

sparticle	Spin	R_P	Gauge Eigenstates	Mass Eigenstates
Higgsinos	0	+1	$H_u^0 \quad H_d^0 \quad H_u^+ \quad H_d^- \quad S^0$	$h_1^0 \quad h_2^0 \quad h_3^0 \quad H^0 \quad A_1^0 \quad A_2^0 \quad H^\pm$
squarks	0	-1	$\tilde{u}_L \quad \tilde{u}_R \quad \tilde{d}_L \quad \tilde{d}_R$ $\tilde{s}_L \quad \tilde{s}_R \quad \tilde{c}_L \quad \tilde{c}_R$ $\tilde{t}_L \quad \tilde{t}_R \quad \tilde{b}_L \quad \tilde{b}_R$	$\tilde{u}_L \quad \tilde{u}_R \quad \tilde{d}_L \quad \tilde{d}_R$ $\tilde{s}_L \quad \tilde{s}_R \quad \tilde{c}_L \quad \tilde{c}_R$ $\tilde{t}_1 \quad \tilde{t}_2 \quad \tilde{b}_1 \quad \tilde{b}_2$
sleptons	0	-1	$\tilde{e}_L \quad \tilde{e}_R \quad \tilde{\nu}_e$ $\tilde{\mu}_L \quad \tilde{\mu}_R \quad \tilde{\nu}_\mu$ $\tilde{\tau}_L \quad \tilde{\tau}_R \quad \tilde{\nu}_\tau$	$\tilde{e}_L \quad \tilde{e}_R \quad \tilde{\nu}_e$ $\tilde{\mu}_L \quad \tilde{\mu}_R \quad \tilde{\nu}_\mu$ $\tilde{\tau}_1 \quad \tilde{\tau}_2 \quad \tilde{\nu}_\tau$
neutralinos	1/2	-1	$\tilde{B}^0 \quad \tilde{W}^0 \quad \tilde{H}_u^0 \quad \tilde{H}_d^0 \quad \tilde{S}^0$	$\tilde{\chi}_1^0 \quad \tilde{\chi}_2^0 \quad \tilde{\chi}_3^0 \quad \tilde{\chi}_4^0 \quad \tilde{\chi}_5^0$
charginos	1/2	-1	$\tilde{W}^\pm \quad \tilde{H}_u^+ \quad \tilde{H}_d^-$	$\tilde{\chi}_1^\pm \quad \tilde{\chi}_2^\pm$
gluinos	1/2	-1	$\tilde{g}$	$\tilde{g}$
gravitino	3/2	-1	$\tilde{G}$	$\tilde{G}$

NMSSM Signal

We used the package NMSSMTools 5.0.1 to obtain the sparticle spectrum and decay branching ratios. We randomly scanned approximately 1M points.

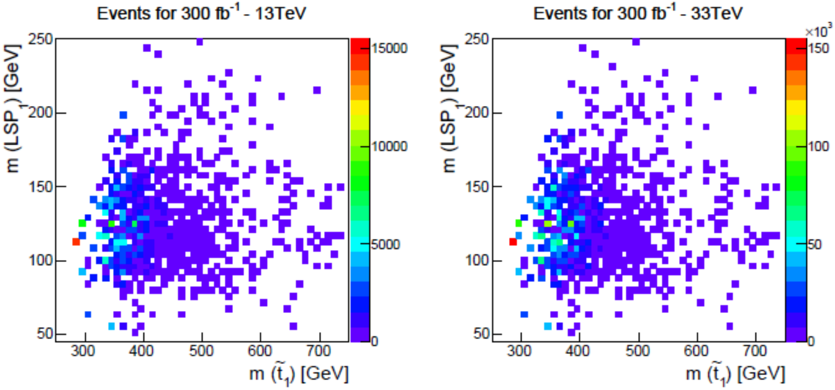
$$pp \to \tilde{t}\tilde{t}^* h_1$$
$$\tilde{t} \to b\tilde{\chi}_1^{\pm}, (\tilde{\chi}_1^{\pm} \to W^{\pm}\tilde{\chi}_1^0)$$
$$h_1 \to b\bar{b}$$



$$pp \to b\bar{b}b\bar{b}\ell\ell\nu\nu\tilde{\chi}_1^0\tilde{\chi}_1^0$$

4 b-jets + 2 leptons + E_T^{miss}

Number of signal events



Benchmark points for signal simulation

Benchmark Points Masses [GeV]					Events for 300 fb^{-1}	
$\tilde{t}_1$	h_1^0	h_2^0	$\tilde{\chi}_1^{\pm}$	$\tilde{\chi}_1^0$	13 TeV	33TeV
283.8	70.33	125.2	221.3	112.3	14547	150911
293.9	62.43	122.1	209.8	124.7	8344	86816
346.8	64.89	124.6	222.9	137.5	3575	41875

Backgrounds

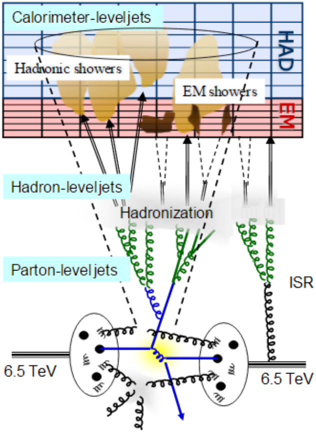
Table: SM Backgrounds and cross sections for center of mass energy of 13 and 33 TeV.

Background	Sub-processes	$\sigma(13\text{TeV})[pb]$	$\sigma(33\text{TeV})[pb]$
$t\bar{t}$+l.f.	$t\bar{t}+jj,\ (j=guds)$	10.02	63.62
$t\bar{t}$+h.f.	$t\bar{t}+cj,\ (j=gudsc)$	7.072	68.07
	$t\bar{t}+bj,\ (j=gudscb)$	6.154	55.70
$t\bar{t}+V$	$t\bar{t}+W^{\pm}$	0.3504	1.582
	$t\bar{t}+Z$	0.5884	5.185
	$t\bar{t}+\gamma$	2.071	14.57
$t\bar{t}+H$		0.4001	3.347
Wt		55.66	364.8
Z+jets	$Z+bbj,\ (Z\to\nu\bar{\nu})$	13.87	64.65

Monte Carlo Event Generation

We generate signal and background samples using:

- **Delphes** to simulate the efficiencies and algoriths of a detector [5].
- **Pythia6** to generate the parton shower and for hadronization [6].
- **MadGraph5** to calculate the parton level matrix elements [7].



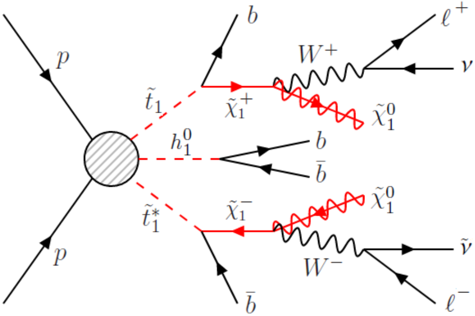
Reconstruction at detector

Jets: anti-kT algorithm with

- p_T(jets) = 15 GeV
- ΔR = 0.4

Leptons:

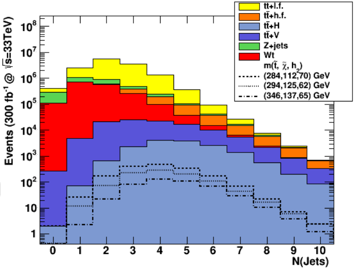
- ΔR = 0.3 for electrons
- ΔR = 0.4 for muons

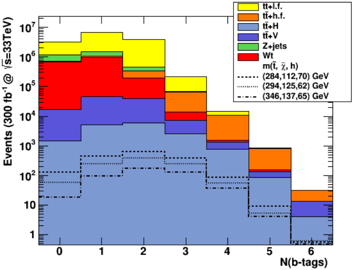


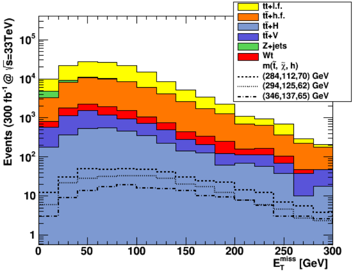
Event selection criteria

Baseline Cuts	
Leptons ($\ell = e, \mu$)	$N(\ell)$=2 $p_T(\ell) > 15$, $\lvert\eta(\ell)\rvert < 2.4$
Jets	$p_T(j) > 20$, $\lvert\eta(j)\rvert < 5$ $N(j) \geq$4 N(b-tags) $\geq$3
Missing transverse energy	$E_T^{miss} > 60$ GeV
Additional cuts	
Mass reconstruction	$40 < m_h^{bb} < 125$ GeV
$R_{\ell\ell} = E_T^{miss}/p_T(\ell_1) + p_T(\ell_2)$	> 0.4
$R_{\ell j} = E_T^{miss}/E_T^{miss} + p_T(\ell_1) + p_T(\ell_2) + \sum_{i=1,\dots,4} p_T(j_i)$	> 0.1
$R_1 = E_T^{miss}/E_T^{miss} + p_T(\ell_1) + p_T(\ell_2) + p_T(j_1) + p_T(j_2)$	> 0.14
Specific cuts	
M_{T2}^{112}	> 130 GeV
M_{T2}^{125}	> 150 GeV
M_{T2}^{137}	> 160 GeV

Distributions for N(Jets), N(b-tags) & E_T^{miss}





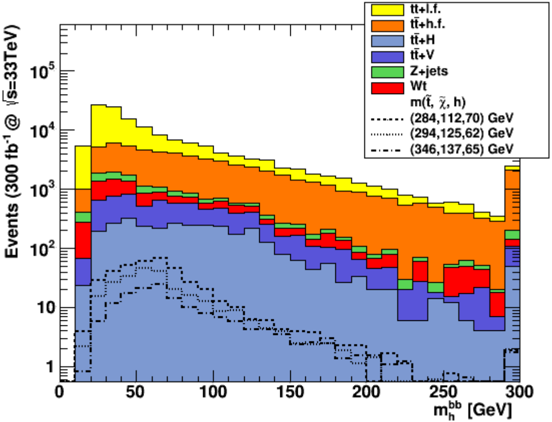


Distribution for reconstructed mass m_h^{bb}

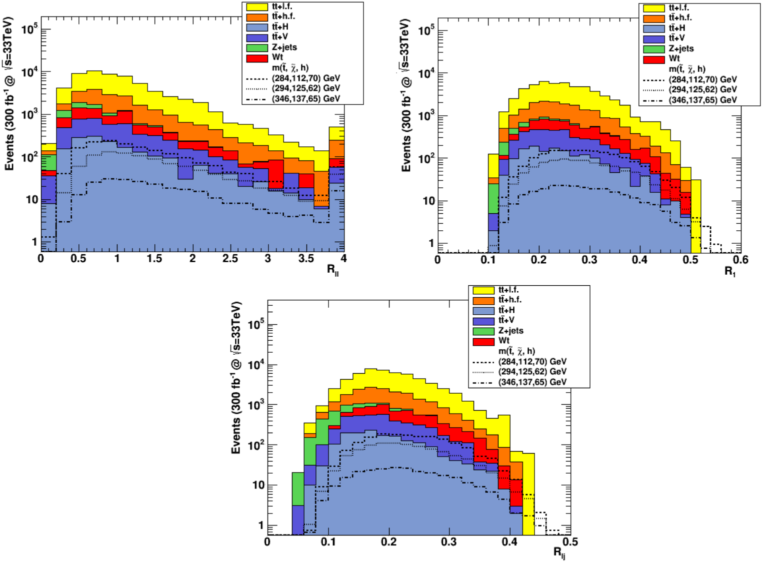
$$40 < m_h^{bb} < 125\,\text{GeV}$$

We select the two closest b-jets, minimizing the angular separation

$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$

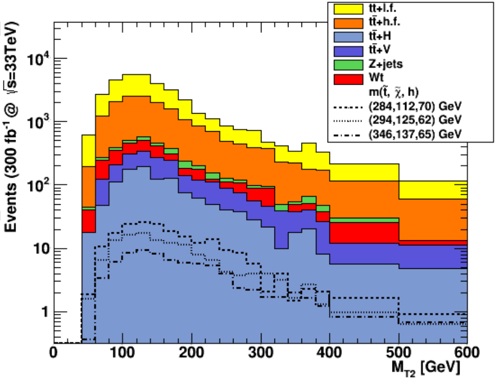


Ratio Distributions

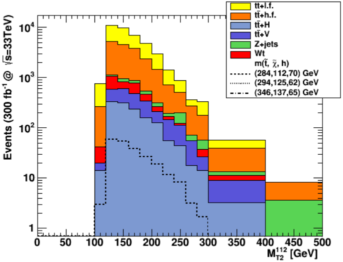


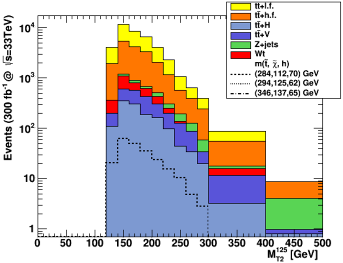
Distribution for M_{T2}

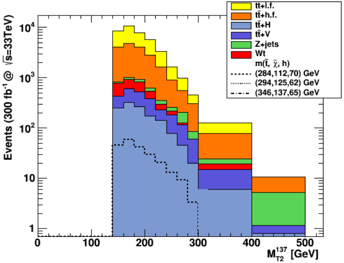
$$M_{T2}(m_{\tilde{\chi}}) = \min_{\mathbf{p}_T^{\tilde{\chi}(1)}+\mathbf{p}_T^{\tilde{\chi}(2)}=\mathbf{p}_T^{miss}} \left\{ \max \left[M_T^{(1)}(\mathbf{p}_T^{\tilde{\chi}(1)}), M_T^{(2)}(\mathbf{p}_T^{\tilde{\chi}(2)}) \right] \right\}$$



Distribution for $M_{T2}^{m(LSP)}$





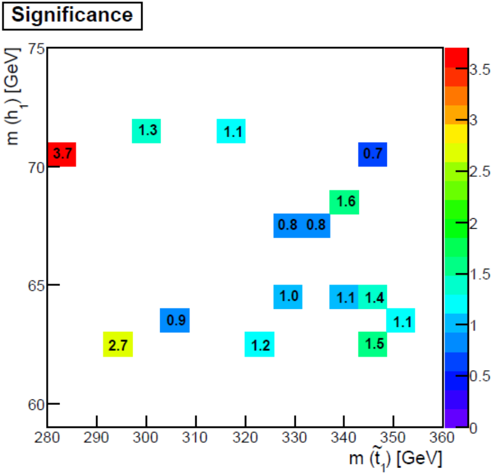


Event Flow for 33 TeV

	Total Back	$m(t_1, \chi_1^0, h_1^0)$ [GeV]		
		(284,112,70)	(294,125,62)	(346,137,65)
Total Events	3.23×10^7	150080	87170	41874
$N(\ell) = 2$	2.59×10^7	3007	1768	866
$N(j) \geq 4$	2.11×10^6	1084	670	353
N(b-tags) ≥ 3	1.57×10^5	406	261	156
$E_T^{miss} > 60$ GeV	87266	315	205	130
$40 < m_h^{bb} < 125$	39832	229	150	91
$R_{\ell\ell} > 0.40$	36819	222	149	90
$R_{\ell j} > 0.12$	35778	221	147	88
$R_1 > 0.14$	34539	220	145	87
$S/\sqrt{S+B}$		1.18(3.73)	0.78(2.47)	0.47(1.48)
$M_{T2}^{112} > 130$ GeV	29154	189	-	-
$M_{T2}^{125} > 150$ GeV	27338	-	107	-
$M_{T2}^{137} > 160$ GeV	23124	-	-	59
$S/\sqrt{S+B}$		1.11(3.49)	0.65(2.05)	0.39(1.23)

Significance for 3000 fb^{-1} @ 33 TeV

$m(\tilde{t}_1, \tilde{\chi}_1^0, h_1^0)$ [GeV]	$S/\sqrt{S+B}$
(284, 112, 70)	3.73
(294, 125, 62)	2.47
(346, 137, 65)	1.48



Conclusions

- We have studied the optimal branching decays for the production of $pp \to \tilde{t}\tilde{t}^* h_1$.
- We have made a study of three NMSSM signal benchmark points for the dileptonic final states

$$pp \to \tilde{t}\tilde{t}^* h_1, (\tilde{t} \to b\tilde{\chi}_1^{\pm}, (\tilde{\chi}_1^{\pm} \to W^{\pm}\tilde{\chi}_1^0)), h_1 \to b\bar{b}$$

  for a luminosity of 300 fb^{-1} and for center of mass energies of 13 and 33 TeV.
- We have optimized the basic selection criteria values and other variables in order to maximize the significance of signal respect to backgrounds.
- Our best BP has $m(\tilde{t}_1, \tilde{\chi}_1^0, h_1^0) = (284, 112, 70)$ [GeV], and corresponds to the compressed mass region.
- For this BP we have estimated a significance of 3.7 for a luminosity of 3000 fb^{-1} @33TeV.
- This processes is still out of reach of the current LHC energy and luminosity.

Thanks for
your attention

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Jorge F. Fraga. Tesis de Grado M.Sc. Universidad de los Andes (2017)

Backup

Next-to-Minimal Supersymmetric Standard Model

The Higgs superpotential W_{Higgs} reads

$$W_{\text{Higgs}} = (\mu + \lambda\widehat{S})\,\widehat{H}_u \cdot \widehat{H}_d + \xi_F\widehat{S} + \frac{1}{2}\mu'\widehat{S}^2 + \frac{\kappa}{3}\widehat{S}^3$$

$$\begin{aligned}-\mathcal{L}_{\text{soft}} = & m_{H_u}^2|H_u|^2 + m_{H_d}^2|H_d|^2 + m_S^2|S|^2 + m_Q^2|Q^2| + m_U^2|U_R^2| \\ & + m_D^2|D_R^2| + m_L^2|L^2| + m_E^2|E_R^2| \\ & + (h_uA_u\;Q \cdot H_u\;U_R^c - h_dA_d\;Q \cdot H_d\;D_R^c - h_eA_e\;L \cdot H_d\;E_R^c \\ & + \lambda A_\lambda\,H_u \cdot H_d\;S + \frac{1}{3}\kappa A_\kappa\,S^3 + m_3^2\,H_u \cdot H_d + \frac{1}{2}m_S'^2\,S^2 + \xi_S\,S + \text{h.c.})\;,\end{aligned}$$

Minimum and maximum values of varied NMSSM parameters

parameters fixed:
M_3 = 1900.0 GeV;
$m_{\tilde{\ell}}$ = 300.0 GeV
A_τ=A_e=A_μ = 1500.0 GeV.

$$m_{\tilde{q}_R} = m_{\tilde{q}_L}$$

Parameters	Min	Max
λ	0.001	0.7
κ	0.001	0.7
A_λ	100.0	2500.0
A_κ	-2500.0	100.0
$\tan\beta$	1.5	60.0
μ_{eff}	100.0	500.0
M_1	50.0	400.0
M_2	50.0	500.0
m_{q_L}	300.0	1500.0
A_t=A_b	-4000.0	1000.0
M_A	100.0	500.0
M_P	100.0	3000.0