Distinction between MSSM and NMSSM from the neutralino/chargino sector

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Particles, Strings, and the Early Universe
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DESY

μ-problem and NMSSM

MSSM

1 spartner $\forall$ SM particle, 2 Higgs Doublets.

$$W_{h,\,\text{MSSM}} = \mu\,\hat{H}_u \cdot \hat{H}_d$$

$\longrightarrow$ "μ-problem": why μ should be at the SUSY-breaking scale?

NMSSM

MSSM + gauge singlet superfield $\hat{S} = (S, \tilde{S})$.

$$W_{h,\,(\mathbb{Z}_3\text{-})\text{NMSSM}} = \lambda\,\hat{S}\,\hat{H}_u \cdot \hat{H}_d + \frac{\kappa}{3}\hat{S}^3$$

$$\longrightarrow \mu_{\text{eff}} = \lambda\langle S\rangle = \lambda\,x.$$

How to distinguish between NMSSM and MSSM scenarios?

MSSM vs NMSSM?

MSSM	$(\mathbb{Z}_3\text{-})$NMSSM
$h,\ H,\ A,\ H^{\pm}$: $\tan\beta, m_A$	$h_{1,2,3},\ a_{1,2},\ H^{\pm}$: $\tan\beta,\ \lambda,\ x,\ \kappa,\ A_\lambda,\ A_\kappa$
$\tilde{\chi}_1^{\pm},\ \tilde{\chi}_2^{\pm}$: $M_2,\ \mu,\ \tan\beta$	$\tilde{\chi}_1^{\pm},\ \tilde{\chi}_2^{\pm}$: $M_2,\ \lambda\cdot x,\ \tan\beta$
$\tilde{\chi}^0_{1,2,3,4}$: $M_1,\ M_2,\ \mu,\ \tan\beta$	$\tilde{\chi}^0_{1,2,3,4,5}$: $M_1,\ M_2,\ \lambda,\ x,\ \kappa, \tan\beta$

To pinpoint the underlying model, one would usually look only at the Higgs scalar sector.
[Cao et al., 1202.5821], [Benbrik et al., 1207.1096], [Beskidt et al., 1308.1333]

What if, given a MSSM and NMSSM scenarios:

- Higgs spectra are not distinguishable at the LHC and/or not reachable at the LC?
- Similar chargino/neutralino spectra and $\sigma(e^+e^- \to \tilde{\chi}^0_i\tilde{\chi}^0_j)$, $\sigma(e^+e^- \to \tilde{\chi}^+_i\tilde{\chi}^-_j)$?

These conditions are possible for unconstrained scenarios [hep-ph/0502036].

Strategy: chargino/neutralino sectors for model distinction

We assume:

- We measure at LHC/LC only the light SUSY masses: $m_{\tilde{\chi}^0_{1,2}}$, $m_{\tilde{\chi}^\pm_1}$, $(m_{\tilde{\chi}^0_3})$.
- At the LC:
  - We exploit polarized beams: $(P_{e^-}, P_{e^+}) = (\mp 0.9, \pm 0.55)$.
  - We measure $\sigma(e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_2)$ and $\sigma(e^+e^- \to \tilde{\chi}^+_1\tilde{\chi}^-_1)$ at $\sqrt{s} = 350$ and 500 GeV.

The strategy is to:

- χ^2-fit with `Minuit` the measured values to the MSSM parameters M_1, M_2, $\mu, \tan\beta$.
  [Desch et al '03]
- Check the compatibility of the fitted (tree-level)-parameters with the MSSM.
  A non compatible result may suggest the NMSSM.
- Further information from Higgs sector? (resonances, couplings etc.).

Classes of scenarios

Looking at the NMSSM **chargino/neutralino** sector, we can distinguish the classes:

- **Light singlino (LS) scenarios**

  high $\tilde{S}$ admixture in the light states $\tilde{\chi}_1^0$ or $\tilde{\chi}_2^0$.

- **Light higgsino (LH) scenarios**

  higgsino-like $\tilde{\chi}_1^0$, with $\mu_{\text{eff}} < M_1, M_2$ and high $\tilde{S}$ admixture mainly in $\tilde{\chi}_3^0, \tilde{\chi}_4^0, \tilde{\chi}_5^0$.

- **Light gaugino (LG) scenarios**

  gaugino-like $\tilde{\chi}_1^0$, with $\mu_{\text{eff}} > M_1, M_2$ and high $\tilde{S}$ admixture mainly in $\tilde{\chi}_3^0, \tilde{\chi}_4^0, \tilde{\chi}_5^0$.

LS: Easier distinction looking at higgsino/gaugino features of neutralinos;
LH,LG : trickier distinction, similar admixture between the models in the lighter states.

Light singlino scenario (LS)

For $M_1 > M_2$, contempled also in AMSB, one can get (also [hep-ph/0502036]):

	M_1 [GeV]	M_2 [GeV]	$\mu, \mu_{eff} = \lambda \cdot x$ [GeV]	$\tan\beta$	κ	λ
MSSM	406	115.8	354	8		
NMSSM	365	111	484	9.5	0.16	0.0585

Leading to $m_h = 125$ GeV and, and the tree-level masses [GeV]:

	$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\chi}_2^0}$	$m_{\tilde{\chi}_3^0}$	$m_{\tilde{\chi}_4^0}$	$m_{\tilde{\chi}_5^0}$	$m_{\tilde{\chi}_1^\pm}$	$m_{\tilde{\chi}_2^\pm}$
MSSM	104.8	350.4	360.1	426.7		105.1	375
NMSSM	104.9	350.1	360.5	489.7	504.1	105.1	498.5

We also take $m_{\tilde{e}_L}$ =303.5 GeV.

MSSM
$\tilde{\chi}_1^0 \sim 93\%\ \tilde{W}$
$\tilde{\chi}_2^0 \sim 26\%\ \tilde{B} + 69\%\ \tilde{H}_{u,\,d}$
$\tilde{\chi}_3^0 \sim \tilde{H}_{u,\,d}$

NMSSM
$\tilde{\chi}_1^0 \sim 97\%\ \tilde{W}$
$\tilde{\chi}_2^0 \sim 22\%\ \tilde{B} + 73\%\ \tilde{S}$
$\tilde{\chi}_3^0 \sim 72\%\ \tilde{B} + 25\%\ \tilde{S}$

Light singlino scenario (LS) - fit

$\sigma_{\rm LO}(e^+e^- \to \tilde\chi_1^+\tilde\chi_1^-)$ [fb]

$\sqrt{s}$ =350 GeV	MSSM	NMSSM
P=(-0.9,0.6)	2491.0	2575.3
P=(0.9,-0.6)	39.5	42.4

$\sqrt{s}$ =500 GeV	MSSM	NMSSM
P=(-0.9,0.6)	1165.4	1213.0
P=(0.9,-0.6)	18.3	18.8

$\sigma_{\rm LO}(e^+e^- \to \tilde\chi_1^0\tilde\chi_2^0)$ [fb]

$\sqrt{s}$ =500 GeV	MSSM	NMSSM
P=(-0.9,0.6)	24.1	8.6

$\sigma_{\rm LO}(e^+e^- \to \tilde\chi_1^0\tilde\chi_3^0)$ [fb]

$\sqrt{s}$ =500 GeV	MSSM	NMSSM
P=(-0.9,0.6)	25.1	15.0

- We assume $\delta m/m = 0.5\%$; $\delta\sigma/\sigma = 1\%$.

χ^2-fit with NMSSM $m_{\tilde\chi^0_{1,2,3}}$, $m_{\tilde\chi^\pm_1}$, $\sigma_{L,R}(e^+e^- \to \tilde\chi_1^+\tilde\chi_1^-,\ \tilde\chi_1^0\tilde\chi_2^0,\ \tilde\chi_1^0\tilde\chi_3^0)$ to MSSM parameters:

$$M_1 = 430.0 \pm 1.6 \text{ GeV}, \quad M_2 = 111.8 \pm 0.8 \text{ GeV},$$
$$\mu_{\rm eff} = 370.4 \pm 0.7 \text{ GeV}, \quad m_{\nu_e} = 310.6 \pm 2.8 \text{ GeV}$$
$$\tan\beta \text{ unconstrained}$$

Fit result excludes that the "data" are consistent with the MSSM (χ^2/d.o.f. $= 62.6/5$).

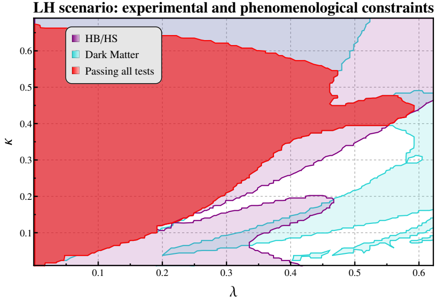
Light higgsino scenario (LH): $\mu < M_1 < M_2$

	M_1 [GeV]	M_2 [GeV]	$\mu, \mu_{eff} = \lambda \cdot x$ [GeV]	$\tan\beta$	A_λ	A_{kappa}
MSSM/NMSSM	450	1600	120	27	3000	-30

NMSSM, scanning the $\lambda - \kappa$ plane with:

- `NMSSMTools-4.2.1` and `micrOMEGAs-3.0` for pheno and DM constraints.
  [Ellwanger et Al. '05], [Das et Al '11], [Belanger et Al. '05]

- `HiggsBounds-4.0.0` and `HiggsSignals-1.0.0` to check the Higgs sector.
  [Bechtle et Al. '05, '13]

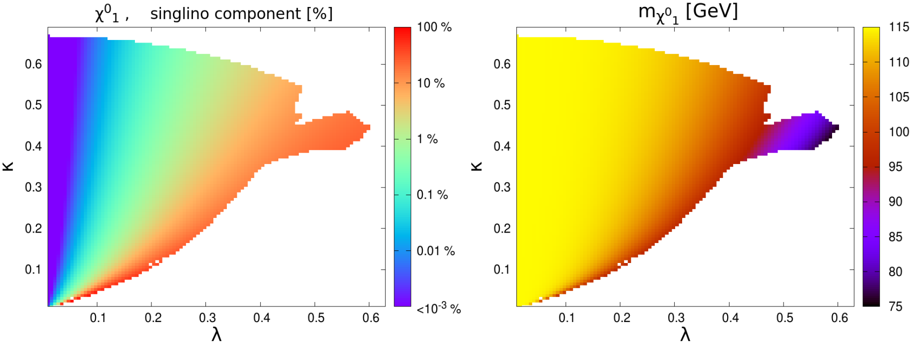


Light higgsino scenario (LH) - neutralino masses

MSSM neutralino/chargino tree-level spectrum in [GeV]:

$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\chi}_2^0}$	$m_{\tilde{\chi}_3^0}$	$m_{\tilde{\chi}_4^0}$	$m_{\tilde{\chi}_1^\pm}$	$m_{\tilde{\chi}_2^\pm}$
114.8	123.3	454.4	1604.1	119.4	1604.1

NMSSM:

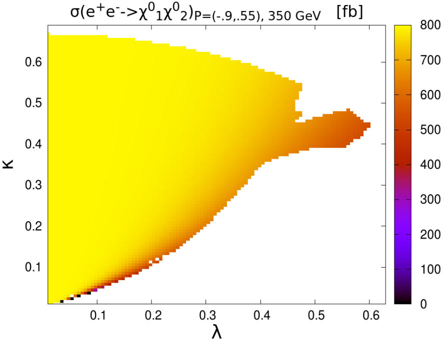


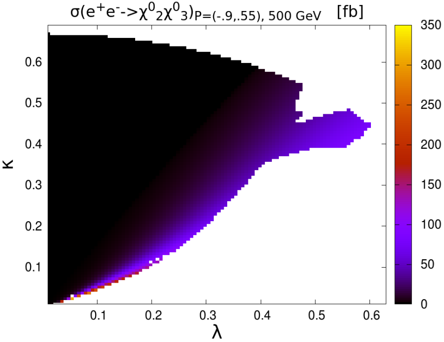
Light higgsino scenario (LH): cross sections

MSSM neutralino production cross sections ($e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_3^0$, $\tilde{\chi}_2^0\tilde{\chi}_3^0$ not open) in [fb]:

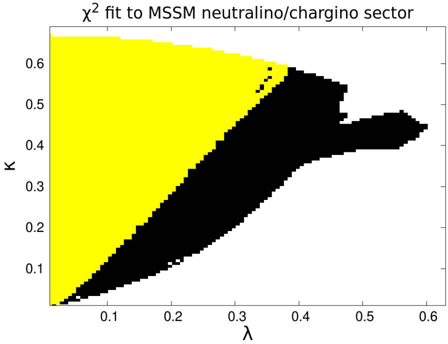
$\sigma(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0)$	$\sqrt{s} = 350$ GeV	$\sqrt{s} = 500$ GeV
$P = (-0.9, 0.55)$	791.7 fb	391.4 fb
$P = (0.9, -0.55)$	526.7 fb	261.7 fb

NMSSM:



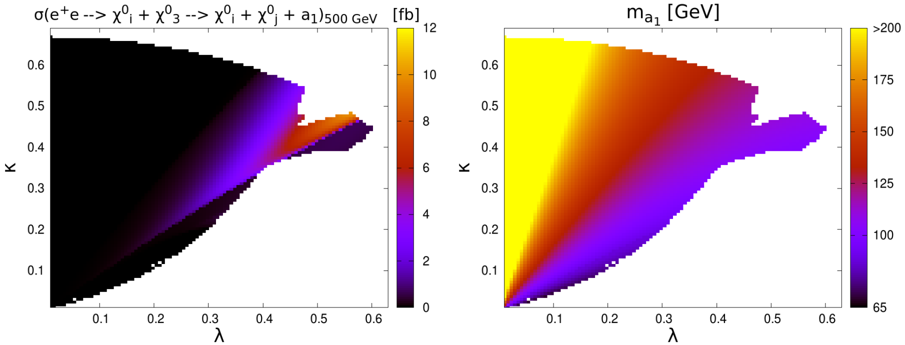


Light higgsino scenario (LH) - fit



χ^2-fit assuming the measurement of the NMSSM $m_{\tilde{\chi}^0_{1,2,3}}$, $m_{\tilde{\chi}^\pm_1}$, with $\delta m/m = 0.5\%$ and $\sigma_{L,R}(e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_2)$, $\sigma_{L,R}(e^+e^- \to \tilde{\chi}^0_2\tilde{\chi}^0_3)$, $\sigma_{L,R}(e^+e^- \to \tilde{\chi}^+_1\tilde{\chi}^-_1)$ with $\delta\sigma/\sigma = 1\%$.

In black the regions with not compatible with the **MSSM**.



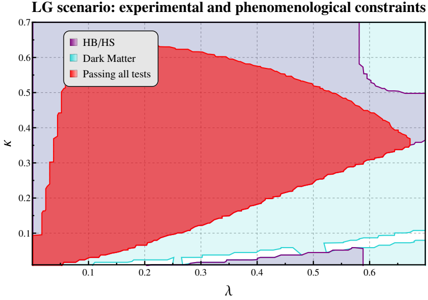
In parts of the allowed parameter space, the inclusive $\sigma(e^+e^- \to \tilde{\chi}_i^0\tilde{\chi}_3^0 \to \tilde{\chi}_i^0\tilde{\chi}_j^0 a_1) \sim \mathcal{O}(10\,\mathrm{fb})$ at 500 GeV, therefore detecting $a_1 \sim$ singlet is possible, confirming the NMSSM.

Light gaugino scenario (LG): $M_2 < M_1 < \mu$

	M_1 [GeV]	M_2 [GeV]	$\mu, \mu_{eff} = \lambda \cdot x$ [GeV]	$\tan\beta$	A_λ	A_{kappa}
MSSM/NMSSM	240	105	505	9.2	3700	-50

NMSSM, scanning the $\lambda - \kappa$ plane with:

- NMSSMTools-4.2.1 and micrOMEGAs-3.0 for pheno and DM constraints.
  [Ellwanger et Al. '05], [Das et Al '11], [Belanger et Al. '05]
- HiggsBounds-4.0.0 and HiggsSignals-1.0.0 to check the Higgs sector.
  [Bechtle et Al. '05, '13]

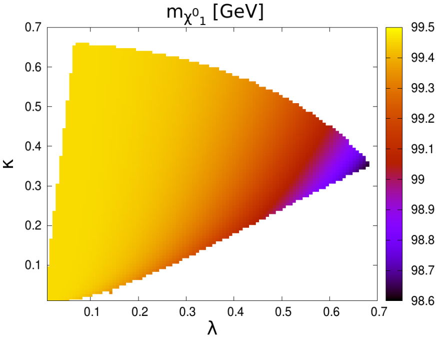


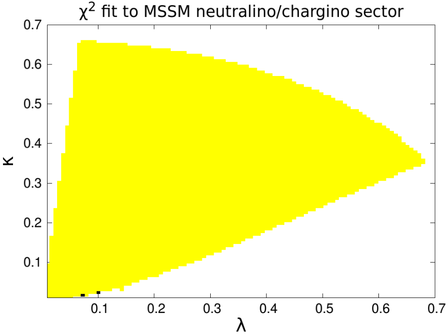
Light gaugino scenario (LG) - fit

MSSM neutralino/chargino tree-level spectrum in [GeV]:

$m_{\tilde{\chi}^0_1}$	$m_{\tilde{\chi}^0_2}$	$m_{\tilde{\chi}^0_3}$	$m_{\tilde{\chi}^0_4}$	$m_{\tilde{\chi}^\pm_1}$	$m_{\tilde{\chi}^\pm_2}$
99.46	237.03	510.13	518.65	99.55	518.71

NMSSM:





Assuming $\delta m/m = 0.5\%$ and $\delta\sigma/\sigma = 1\%$, the χ^2-fit is not sufficient to distinguish from **MSSM**.

Less info from the Higgs sector: SM-like Higgs couplings are similar to the MSSM case and a siglet a_1 is not visible at 500 GeV.

Conclusions and outlook

- SUSY most studied models, MSSM and NMSSM, can lead to similar Higgs and chargino/neutralino lower spectra and production cross section. Distinction tools required.

- Looking at the **neutralino/chargino sector**, with polarized beams at the LC, distinction is possible.
  - Measure $m_{\tilde{\chi}^0_{1,2}}$, $\sigma_{L,R}(e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_2)$ and $\sigma_{L,R}(e^+e^- \to \tilde{\chi}^+_1\tilde{\chi}^-_1)$.
  - Reconstruct MSSM M_1, M_2, μ, $\tan\beta$ and fit.

- Additional info may be given by heavier neutralino states and Higgs singlet resonances.

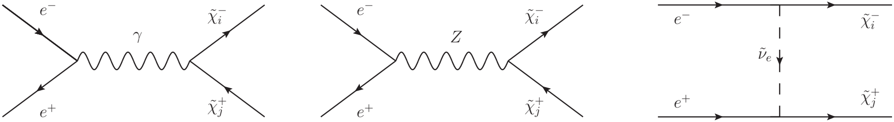
- Strategy effective depending on the class of scenario considered:
  - Light singlino scenarios ✓
  - Light higgsino scenarios ✓
  - Light gaugino scenarios ✗

To do:

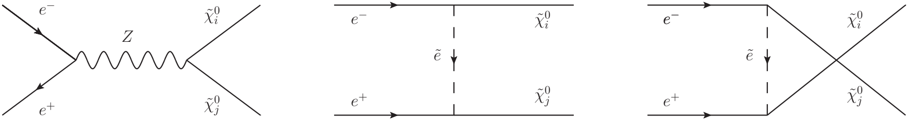
- Include more Higgs sector observables in the analysis, i.e. couplings to fermions, singlet production etc..
- Extend analysis to other observables as asymmetries, spin-dependent observables, tau polarization, stop sector.

Thank you for your attention!

Backup: chargino and neutralino pair production



Chargino tree-level production channels at e^+e^- colliders.



Neutralino tree-level production channels at e^+e^- colliders.

Backup: LS parameters and Higgs masses

$\mathbf{M_1}$	$\mathbf{M_2}$	$\mathbf{M_3}$	$\tan\beta$	$\mu_{\rm eff} = \lambda s$	$\mathbf{A_\lambda}$	$\mathbf{A_\kappa}$
365 GeV	111 GeV	2000 GeV	9.5	484 GeV	4200 GeV	−200 GeV

$\mathbf{M_{Q_{1,2}}, M_{u_{1,2}}, M_{d_{1,2}}}$	$\mathbf{M_{Q_3}}$	$\mathbf{M_{u_3}}$	$\mathbf{M_{d_3}}$	$\mathbf{M_l, M_e}$	$\mathbf{A_{u_3}}$	$\mathbf{A_{d_3}, A_{e_3}}$
2000 GeV	1500 GeV	1000 GeV	800 GeV	300 GeV	2750 GeV	2000 GeV

LS scenario: $\tan\beta$, $\mu_{\rm eff}$ and soft parameters, while $(\lambda, \kappa) = (0.0585, 0.16)$.

	m_{h_1} [GeV]	m_{h_2} [GeV]	m_{h_3} [GeV]	m_{a_1} [GeV]	m_{a_2} [GeV]	$m_{H^\pm}$ [GeV]
NMSSM	124.9	303.0	4467.3	324.0	4467.3	4468.1

Higgs spectrum calculated at the 1-loop level with full 2-loops contributions from bottom/top Yukawa couplings with `NMSSMTools`; h_2, $a_1 \sim 100\%$ singlets.

[GeV]	$m_{\tilde\chi_1^0}$	$m_{\tilde\chi_2^0}$	$m_{\tilde\chi_3^0}$	$m_{\tilde\chi_4^0}$	$m_{\tilde\chi_5^0}$	$m_{\tilde\chi_1^\pm}$	$m_{\tilde\chi_2^\pm}$
MSSM	104.8	350.4	360.1	426.7		105.1	375
NMSSM	104.9	350.1	360.5	489.7	504.1	105.1	498.5
MSSM_{fit}	106.0	368.0	378.0	445.9		106.1	389.1

Backup: LH parameters

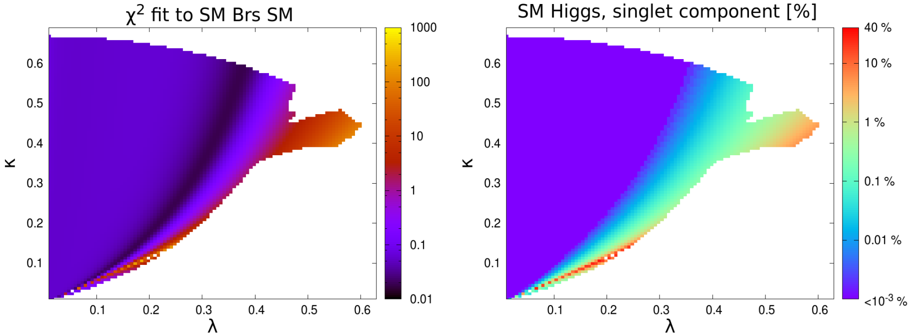
M_1	M_2	M_3	$\tan\beta$	$\mu_{\rm eff} = \lambda s$	A_λ	A_κ
450 GeV	1600 GeV	2000 GeV	27	120 GeV	3000 GeV	-30 GeV

$M_{Q_{1,2}}$, $M_{u_{1,2}}$, $M_{d_{1,2}}$	M_{Q_3}, M_{u_3}, M_{d_3}	M_l, M_e	A_{u_3}	A_{d_3}, A_{e_3}
2000 GeV	1500 GeV	300 GeV	3300 GeV	200 GeV

LH scenario: $\tan\beta$, $\mu_{\rm eff}$ and soft parameters.

Backup: LH - naïve fit to SM Higgs

A naïve fit to SM Higgs may suggest different behaviour of the SM-like Higgs between the MSSM and NMSSM.



(a) (b)

(a) 7-d.o.f. χ^2-fit to the SM of the reduced couplings to $g, \gamma, W, Z, b, c, \tau$; (b) Singlet component in the SM-like Higgs, in %.

In the LH case, the only regions not compatible to the SM correspond to a higher singlet component in the SM-like Higgs, confirm the neutralino/chargino sector fit result.

Backup: LG parameters

M_1	M_2	M_3	tanβ	$\mu_{\rm eff} = \lambda s$	A_λ	A_κ
240 GeV	105 GeV	2000 GeV	9.2	505 GeV	3700 GeV	-40 GeV

$M_{Q_{1,2}}$, $M_{u_{1,2}}$, $M_{d_{1,2}}$	M_{Q_3}	M_{u_3}, M_{d_3}	$M_{l_{1,2}}$, $M_{e_{1,2}}$	M_{l_3}, M_{e_3}
2000 GeV	1800 GeV	1500 GeV	300 GeV	500 GeV

A_{u_3}	A_{d_3}	A_{e_3}
3700 GeV	2500 GeV	1500 GeV

LG scenario: tanβ, $\mu_{\rm eff}$ and soft parameters.

Backup: LG cross sections

In the LG scenario the neutralino production cross sections are very close in all the allowed region in the $(\lambda,\ \kappa)$-plane to the values of the corresponding MSSM scenario,

MSSM, $\sigma(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0)$	$\sqrt{s} = 350$ GeV	$\sqrt{s} = 500$ GeV
$P = (-0.9, 0.55)$	7.3 fb	113.4 fb
$P = (0.9, -0.55)$	0.1 fb	1.8 fb

For example, taking $(\lambda, \kappa) = (0.2, 0.35)$,

NMSSM, $\sigma(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0)$	$\sqrt{s} = 350$ GeV	$\sqrt{s} = 500$ GeV
$P = (-0.9, 0.55)$	7.3 fb	113.5 fb
$P = (0.9, -0.55)$	0.1 fb	1.8 fb