

# Distinguishing between MSSM and NMSSM via combined LHC/ILC analyses

*Gudrid Moortgat-Pick (CERN)*

*S. Hesselbach, F. Franke, H. Fraas*

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- The question: distinction of MSSM $\leftrightarrow$ NMSSM always obvious?
  - MSSM parameter determination
  - numerical example (including some exp. errors)
  - assumption: no separation@ILC<sub>500</sub> possible
- The answer:
  - LHC/ILC interplay
  - motivation for using ILC<sub>650</sub>
- Conclusions

## 'Gedankenexperiment': NMSSM ↔ MSSM distinction

### Assumptions:

- LHC is running
- LC<sub>500</sub> is running at the same time

### One believes that:

- probably the Higgs sector divides the models because of Higgs singlet  
Higgs:  $S_{1,2,3}$ ,  $P_{1,2}$ ,  $H_{1,2}^\pm$  determined by  $\tan\beta$ ,  $\lambda$ ,  $x$ ,  $\kappa$ ,  $A_\lambda$ ,  $A_\kappa$
- gaugino/higgsino sector leaves also unique hints because of the 'singlino'
  - \* Chargino sector  $\tilde{\chi}_{1,2}^\pm$  determined by  $M_2$ ,  $\mu_{eff} = \lambda x$ ,  $\tan\beta$
  - \* Neutralino sector  $\tilde{\chi}_{1,2,3,4,5}^0$  determined by  $M_1$ ,  $M_2$ ,  $\lambda$ ,  $\kappa$ ,  $x$ ,  $\tan\beta$

### But could it happen, e.g. not assuming SUGRA conditions, that:

- \* the Higgs sectors are experimentally not distinguishable?
- \* the light neutralino and charginos have same mass spectra in MSSM and NMSSM although rather large singlino admixture?
- \* the cross section, BR's also do not point to the right model?
- \* the standard parameter strategies do not fail for the light spectrum?

How to proceed in that case?

## Chosen scenario in the NMSSM

### NMSSM:

- **Higgs** phenomenology Drees'89, Ellwanger'95, 99', 00', '04, Choi'04, Han'04, Gunion'04 et al
- **Neutralino** sector phenomenology Franke'95, Hesselbach'00, '01, Choi'04 et al.

Take NMSSM scenario:

	$M_1$	$M_2$	$\tan \beta$	$\lambda$	$x$	$(\mu_{eff})$	$\kappa$
<b>NMSSM</b>	360	147	10	0.5	915	(457.5)	0.2

⇒  $\tilde{\chi}_2^0, \tilde{\chi}_3^0$  strongly singlino-like ( $\tilde{S} > 40\%$ )

⇒  $S_1 \sim \text{SM}, S_2, P_1 \sim \text{singlet-like}$  ( $S_1 \rightarrow P_1 P_1$  not open),  $S_3, P_2 > 1 \text{ TeV}$

allowed for large ranges of  $A_\lambda, A_\kappa$ , checked/scanned with NMHDECAY!

⇒  $M_1 > M_2$  usual in AMSB scenarios; here: general MSSM used

**AMSB feature:** **small** mass difference  $\delta m_{(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)}$  between  $\tilde{\chi}_1^0$  and  $\tilde{\chi}_1^\pm$ :

→ tricky scenario for LHC

Allanach, 0208214

if  $200\text{MeV} < \delta m_{(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)} < 2 \text{ GeV}$ : tricky due to softly emitted particles, large background

assuming AMSB relations and specific cuts: resolvable

Lester'99

→ simulation for the LC exist:  $\delta m_{(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)}$  measurable at %-level

C. Hensel, Thesis, '02

⇒ AMSB scenario may be perfectly suited for combined LHC/LC analyses!

## 'Usual' gaugino/higgsino parameter determination

LC analysis at first stage with energy up to  $\sqrt{s} = 500$  GeV:

- use only production of  $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_1^+$
- determine the fundamental parameters  $M_1, M_2, \mu, \tan \beta = v_2/v_1$

*Choi, Kalinowski, GMP, Zerwas'01,'02*

- **prediction** for  $\tilde{\chi}_3^0, \tilde{\chi}_4^0, \tilde{\chi}_2^\pm$

### Procedure:

- **Chargino mixing matrix** depends on  $M_2, \mu, \tan \beta$   
diagonalised via two mixing angles  $\cos 2\Phi_L, \cos 2\Phi_R$   
→ observables: masses and cross sections (depend also on  $m_{\tilde{\nu}}$ )
- **Neutralino mixing matrix** depends on  $M_2, \mu, \tan \beta$  and  $M_1$   
→ observables: masses and cross sections (depend also on  $m_{\tilde{e}_L}, m_{\tilde{e}_R}$ )
- determination of these parameters including  
**estimated errors** (no simulation so far)!

*Choi et al '99,'00*

## Step I: analysis at LC@500 GeV

- taking into account **only light particles**

	$\tilde{\chi}_1^\pm$	$\tilde{\chi}_2^\pm$	$\tilde{\chi}_1^0$	$\tilde{\chi}_2^0$	$\tilde{\chi}_3^0$	$\tilde{\chi}_4^0$	$\tilde{e}_R$	$\tilde{e}_L$	$\tilde{\nu}_e$
mass	139	474	138	337	367	468	220	240	226

→ accessible at 500 GeV only  $\tilde{\chi}_1^\pm, \tilde{\chi}_{1,2}^0, \tilde{e}_{L,R}, \tilde{\nu}$

(Assumed mass uncertainties  $\sim 1\%$ )

- $e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^-$ :  $\sigma_{L,R}(\tilde{\chi}_1^+ \tilde{\chi}_1^-) = f(\cos 2\Phi_L, \cos 2\Phi_R, m_{\tilde{\chi}_1^\pm}, m_{\tilde{\nu}_e})$   
with polarised beams  $P_{e^-} = \pm 80\%$ ,  $P_{e^+} = \mp 60\%$

$\sqrt{s} = 400 \text{ GeV}$		$\sqrt{s} = 500 \text{ GeV}$	
$\sigma_L = 984 \pm 51 \text{ fb}$	$\sigma_R = 14 \pm 1 \text{ fb}$	$\sigma_L = 874 \pm 25 \text{ fb}$	$\sigma_R = 12 \pm 1 \text{ fb}$

⇒ **magnitude of errors** ( $\int \mathcal{L} = 100 \text{ fb}^{-1}$  for each configuration):

$$\begin{aligned} \delta_{stat} & \text{ up to } \sim 3\% \\ \delta_{m_{\tilde{\chi}_1^\pm}} & \text{ up to } \sim 3\% \quad \delta_{P(e^\pm)} \text{ and } \delta_{m_{\tilde{\nu}}} < 1\% \end{aligned}$$

⇒  $M_2, \mu$  and  $\tan \beta$  could be derived

## Step I: analysis at LC@500 GeV for SPS1a, cont.

- $M_1$  from neutralino sector ... masses sufficient?

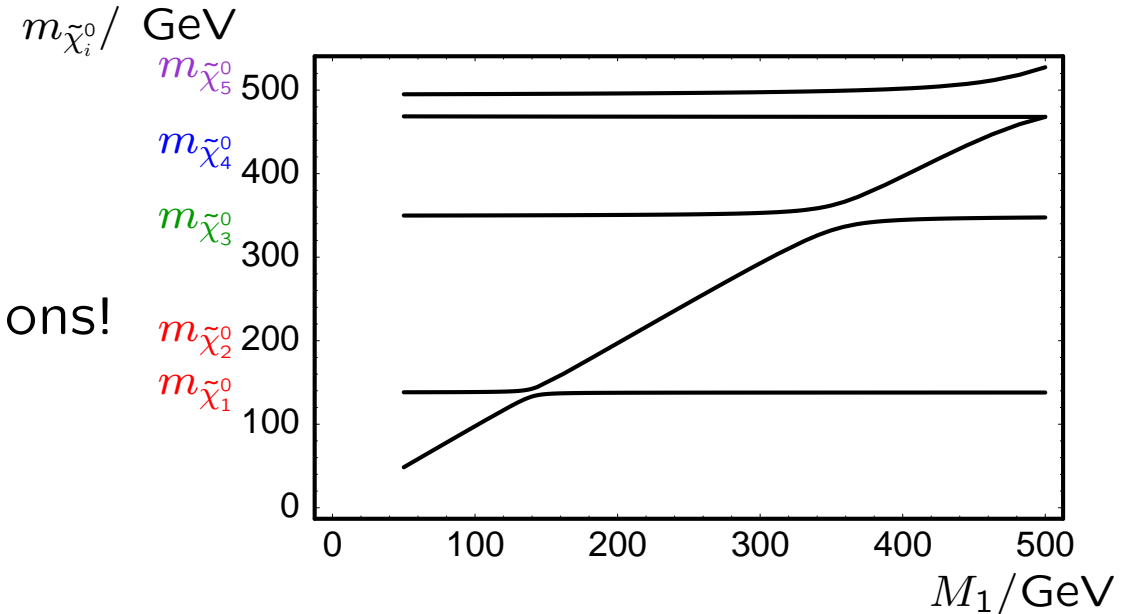
- no, may be insensitive

here: if  $m_{\tilde{\chi}_1^0}$  used

→  $M_1 < -300$  GeV negativ!

⇒ not consistent with cross sections!

⇒ cross sections needed



- $e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_2^0$ :  $\sigma_{L,R}(\tilde{\chi}_i^0 \tilde{\chi}_j^0) = f(\cos 2\Phi_L, \cos 2\Phi_R, m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0}, m_{\tilde{e}_{L,R}})$   
with polarised beams  $P_{e^-} = \pm 80\%$ ,  $P_{e^+} = \mp 60\%$

	$\sqrt{s} = 500$ GeV	
$\tilde{\chi}_1^0 \tilde{\chi}_2^0$	$\sigma_L = 12 \pm 1$ fb	$\sigma_R = 0.2 \pm 0.1$ fb

- magnitude of errors

→ dominant uncertainties: statistical error and error due to  $m_{\tilde{\chi}_1^\pm}$   
 $\Delta P(e^\pm)/P$  and  $\Delta m_{\tilde{e}_{L,R}} < 1\%$ , as before

## Step I: analysis at LC@500 GeV

Results from this analytically based 'fit'-procedure:

ILC <sub>500</sub>			
$M_1$	$M_2$	$\mu$	$\tan \beta$
$355 \pm 15$	$154 \pm 12$	$500 \pm 100$	[1, 30]

⇒ large uncertainty in  $M_1$   
and  $\mu$ , also  $\tan \beta$   
very weak...

⇒ could happen, since only  
'gauginos' are accessible

⇒ take e.g. scenario in the given ranges:

$$M_1 = 347 \text{ GeV}$$

$$M_2 = 145 \text{ GeV}$$

$$\mu = 456 \text{ GeV}$$

$$\tan \beta = 30$$

⇒ Would lead to same masses  $\tilde{\chi}_{1,2}^0$ ,  $\tilde{\chi}_1^\pm$   
and  $\sim$ cross sections as before!

(within the assumed uncertainties)

⇒ Is it therefore the right model?



## How to find a possible inconsistency?

⇒ use predicted mass ranges of  $\tilde{\chi}_{3,4}^0, \tilde{\chi}_2^\pm$  and let them find from LHC or ...?

⇒ all heavier gauginos/higgsinos larger than 390 GeV!

• Could LHC measure the masses and confirm/falsify the model?

→ heavy gauginos reconstructed in decay chains

e.g. via **dilepton edges** (strong dependent on  $m_{\tilde{\chi}_1^0}$ !)

**LC input:**  $m_{\tilde{\chi}_1^0}$  and mass predictions extremely helpful [Desch etal'04](#), [Polesello'04](#)

• What could be done in this scenario?

⇒ Since  $\tilde{\chi}_3^0 \sim 43\%$  ( $\tilde{H}, \tilde{S}$ )–like, but  $\tilde{\chi}_4^0 > 98\%$  ( $\tilde{H}, \tilde{S}$ )–like and even  $\tilde{\chi}_5^0 > 93\%$  ( $\tilde{H}, \tilde{S}$ )–like

→ ILC provides  $m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0}$  as input for LHC:

$\tilde{\chi}_3^0$  observable in cascades and perhaps – if lucky – also  $\tilde{\chi}_5^0$ .

⇒ we **assume** that  $\delta m_{\tilde{\chi}_3^0}^{\text{LHC}} \sim 2\%$ :  $m_{\tilde{\chi}_3^0} = 367 \pm 7$  GeV from LHC↔ILC!

⇒ **obvious contradiction with ILC prediction** ( $m_{\tilde{\chi}_3^0} > 390$  GeV)!



## Motivation for using a further ILC option

- use subsequently higher energy but **low luminosity ILC option: ILC<sub>650</sub><sup>ℒ=1/3</sup>**
- production cross sections [fb] for heavier  $\tilde{\chi}_1^0 \tilde{\chi}_i^0$  pairs and also  $\tilde{\chi}_1^\pm \tilde{\chi}_2^\mp$ :

$\sqrt{s} = 650 \text{ GeV}$	$\sigma(e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_3^0)$	$\sigma(e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_4^0)$	$\sigma(e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_5^0)$
unpolarised	$12 \pm 1$	$6 \pm 0.4$	$< 0.02$
$P(e^-) = -90\%, P(e^+) = +60\%$	$37 \pm 2$	$15 \pm 1$	$< 0.07$
$P(e^-) = +90\%, P(e^+) = -60\%$	$0.6 \pm 0.1$	$2.2 \pm 0.3$	$< 0.01$

$\sqrt{s} = 650 \text{ GeV}$	$\sigma(e^+e^- \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^\mp)$
unpolarised	$2.4 \pm 0.3$
$P(e^-) = -90\%, P(e^+) = +60\%$	$5.8 \pm 0.4$
$P(e^-) = +90\%, P(e^+) = -60\%$	$1.6 \pm 0.2$

→ only statistical error given based on  $\mathcal{L}/3 = 100/3 \text{ fb}^{-1}$  for each configuration.

⇒ at least  $\tilde{\chi}_3^0, \tilde{\chi}_4^0$  and  $\tilde{\chi}_2^\pm$  accessible!

expected: masses (e.g.  $m_{\tilde{\chi}_3^0}$ !) and rates **precisely** measurable

⇒ **With LHC+ILC<sub>650</sub><sup>ℒ=1/3</sup>**: strong evidence if **deviations from MSSM!**

application of more general fits will probably **nail down** the NMSSM

## Conclusions: Synergy of LHC/ILC in Susy Searches

- Example for new physics searches/determination where **simultaneous** running of **LHC+ILC**<sub>[1.stage,500,650]</sub> may be decisive!
- Here@**ILC**<sub>500</sub> only: measured observables **do not point to NMSSM!**  
→ **not obvious** that the MSSM is the **wrong model!**
- **Key points:**
  - ILC:** analysis of non-coloured light particle sector
    - precise mass of light particles
    - and **prediction** of heavier states
  - LHC:** measurement of light+heavy gauginos
    - ⇒ 'Feeding back to ILC analysis'
- Important consistency tests of the new physics (NP) model **already at**  **$\sqrt{s} = 500$  GeV stage!** ⇒ outline for future search analysis strategies
- Results of **LHC↔ILC**<sub>500</sub> **interplay motivates** the use of the **low luminosity option ILC**<sub>650</sub> <sup>$\mathcal{L}=1/3$</sup> !
- Future: 'true' fits planned, however **NMSSM simulation programs needed!**

## App2: Comparison of MSSM ↔ NMSSM scenario

Masses alone may be not sufficient!

	$M_1$	$M_2$	$\tan \beta$	$\mu$ ( $\mu_{eff} = \lambda x$ )	$\kappa$
NMSSM	360	147	10	457.5	0.2
MSSM	347	145	30	456	–

both scenarios respect all exp. bounds!

GMP, Fraas, Franke, Hesselbach'05

⇒ derived mass spectra:

	$\tilde{\chi}_1^\pm$	$\tilde{\chi}_2^\pm$	$\tilde{\chi}_1^0$	$\tilde{\chi}_2^0$	$\tilde{\chi}_3^0$	$\tilde{\chi}_4^0$	$\tilde{\chi}_5^0$
NMSSM	139	474	138	337	367	468	499
MSSM	139	472	139	340	462	475	–

## App3: Neutralino cross sections at higher energies

$\sigma(e^+e^- \rightarrow \tilde{\chi}_i^0 \tilde{\chi}_j^0)/\text{fb}$ , unpolarised	$\sqrt{s} = 800 \text{ GeV}$	$\sqrt{s} = 1000 \text{ GeV}$	$\sqrt{s} = 3000 \text{ GeV}$
$\tilde{\chi}_1^0 \tilde{\chi}_2^0/\text{fb}$	$27.6 \pm 0.2$	$23.6 \pm 0.2$	$4.0 \pm 0.06$
$\tilde{\chi}_1^0 \tilde{\chi}_3^0/\text{fb}$	$14.9 \pm 0.2$	$13.1 \pm 0.2$	$2.2 \pm 0.05$
$\tilde{\chi}_1^0 \tilde{\chi}_4^0/\text{fb}$	$6.1 \pm 0.1$	$4.4 \pm 0.1$	$0.5 \pm 0.02$
$\tilde{\chi}_1^0 \tilde{\chi}_5^0/\text{fb}$	$0.4 \pm 0.03$	$0.5 \pm 0.03$	$0.1 \pm 0.01$
$\tilde{\chi}_2^0 \tilde{\chi}_2^0/\text{fb}$	$7.2 \pm 0.1$	$10.6 \pm 0.1$	$2.4 \pm 0.05$
$\tilde{\chi}_2^0 \tilde{\chi}_3^0/\text{fb}$	$13.2 \pm 0.2$	$24.0 \pm 0.2$	$5.5 \pm 0.07$
$\tilde{\chi}_2^0 \tilde{\chi}_4^0/\text{fb}$	–	$5.7 \pm 0.1$	$0.8 \pm 0.03$
$\tilde{\chi}_2^0 \tilde{\chi}_5^0/\text{fb}$	–	$1.2 \pm 0.05$	$0.4 \pm 0.02$
$\tilde{\chi}_3^0 \tilde{\chi}_3^0/\text{fb}$	$6.1 \pm 0.1$	$15.9 \pm 0.2$	$4.0 \pm 0.06$
$\tilde{\chi}_3^0 \tilde{\chi}_4^0/\text{fb}$	–	$0.7 \pm 0.04$	$0.1 \pm 0.01$
$\tilde{\chi}_3^0 \tilde{\chi}_5^0/\text{fb}$	–	$1.5 \pm 0.05$	$0.7 \pm 0.03$
$\tilde{\chi}_4^0 \tilde{\chi}_4^0/\text{fb}$	–	0.0	0.0
$\tilde{\chi}_4^0 \tilde{\chi}_5^0/\text{fb}$	–	$13.7 \pm 0.2$	$4.1 \pm 0.06$
$\tilde{\chi}_5^0 \tilde{\chi}_5^0/\text{fb}$	–	0.0	0.0

⇒ Only  $\sigma$  statistical error

1  $\sigma$  stat. error on basis of  $\mathcal{L}_{800,1000} = 500 \text{ fb}^{-1}$  and  $\mathcal{L}_{3000} = 1000 \text{ fb}^{-1}$  ( $\equiv 1 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$ )