Distinguishing between MSSM and NMSSM via combined LHC/ILC analyses

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

'Gedankenexperiment': NMSSM↔MSSM distinction

Start assumptions:

- LHC is running
- LC_{500} is running at the same time

One believes that:

– probably the Higgs sector divides the models because of Higgs singlet
Higgs: $S_{1,2,3}$, $P_{1,2}$, $H^{\pm}_{1,2}$ determined by $\tan\beta$, λ, x, κ, A_λ, A_κ

– gaugino/higgsino sector leaves also unique hints because of the 'singlin

 ∗ Chargino sector $\tilde{\chi}^{\pm}_{1,2}$ determined by M_2, $\mu_{eff} = \lambda x$, $\tan\beta$

 ∗ Neutralino sector $\tilde{\chi}^{0}_{1,2,3,4,5}$ determined by M_1, M_2, λ, κ, 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?

What has been done so far?

NMSSM:

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

NMSSM↔MSSM:

- Strategies for the separation of both models: — GMP et al.'99 ($\tilde{\chi}^0_1, \tilde{\chi}^0_2$: polarisation effec

Choi'et al 02 ($\tilde{\chi}^0_i$, $i = 1, \ldots, 4$: application of sumrules

What will be done today?

- light Higgs sector, $\tilde{\chi}^0_i$ and $\tilde{\chi}^\pm_1$ sector similar in both models

$\rightarrow$ how to get experimental hints which model is fulfilled in nature?

$\rightarrow$ strategy for combined analyses at LHC↔LC_{500} motivating $LC_{650}^{\mathcal{L}=1/3}$!

GMP, Hesselbach,Franke,Fraas'0

Take NMSSM scenario:

	M_1	M_2	$\tan\beta$	λ	x	(μ_{eff})	κ
NMSSM	360	147	10	0.5	915	(457.5)	0.2

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

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

$\Rightarrow$ S_1 ~SM, S_2, P_1 ~singlet-like ($S_1 \rightarrow P_1 P_1$ not open), S_3,P_2 >1 TeV

allowed for large ranges of A_λ, A_κ, checked/scanned with NMHDECAY!

'Usual' gaugino/higgsino parameter determination

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

- use only production of $\tilde{\chi}^0_1$, $\tilde{\chi}^0_2$, $\tilde{\chi}^+_1$

$\rightarrow$ determine the fundamental parameters M_1, M_2, μ, $\tan\beta = v_2/v_1$

Choi, Kalinowski, GMP, Zerwas'01,

$\rightarrow$ prediction for $\tilde{\chi}^0_3$, $\tilde{\chi}^0_4$, $\tilde{\chi}^\pm_2$

Procedure:

- Chargino mixing matrix depends on M_2, μ, $\tan\beta$
  diagonalised via two mixing angles $\cos 2\Phi_L$, $\cos 2\Phi_R$ *Choi et al '99,*
  $\rightarrow$ observables: masses and cross sections (depend also on $m_{\tilde{\nu}}$!)

- Neutralino mixing matrix depends on M_2, μ, $\tan\beta$ and M_1
  $\rightarrow$ 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)!

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

$\rightarrow$ 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 $P_{e^-} = \pm 80\%$, $P_{e^+} = \mp 60\%$

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

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

δ_{stat}	up to	$\sim 3\%$
$\delta_{P(e^\pm)}$	$\ll$	1% (σ_L) and $< 2\%$ (σ_R) , where $\Delta P(e^\pm)/P(e^\pm) = 0.5\%$
$\delta_{m_{\tilde{\chi}_1^\pm}}$	up to	$\sim 3\%$
$\delta_{m_{\tilde{\nu}}}$	$\ll$	1%

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

- $e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_2$: $\sigma_{L,R}(\tilde{\chi}^0_i\tilde{\chi}^0_j) = f(\cos 2\Phi_L, \cos 2\Phi_R, m_{\tilde{\chi}^\pm_1}, m_{\tilde{\chi}^0_1}, m_{\tilde{e}_{L,R}})$
  with polarised beams $P_{e^-} = \pm 80\%$, $P_{e^+} = \mp 60\%$

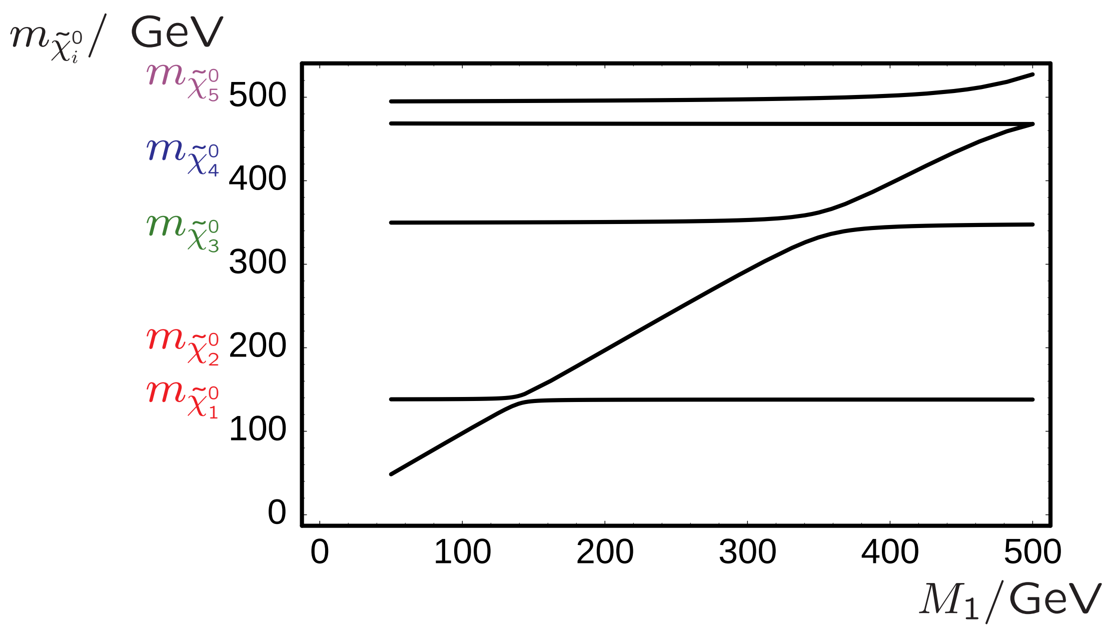
	$\sqrt{s} = 500$ GeV	
$\tilde{\chi}^0_1\tilde{\chi}^0_2$	$\sigma_L = 12 \pm 1$ fb	$\sigma_R = 0.2 \pm 0.1$ fb

- magnitude of errors
  dominant uncertainties: statistical error and error due to $m_{\tilde{\chi}^\pm_1}$
  $\Delta P(e^\pm)/P$ and $\Delta m_{\tilde{e}_{L,R}} < 1\%$, as before

Neutralino cross sections have low rates ...are they really needed?

In principle: only M_1 needed from neutralino sector

Often assumed: M_1 can be derived from $m_{\tilde{\chi}^0_1}$ ... That is not true!



- masses alone not sufficient, may be insensitive

$\Rightarrow$ cross sections needed for unique solution!

here: if $m_{\tilde{\chi}^0_1}$ used $\rightarrow M_1 < -300$ GeV negativ!

$\Rightarrow$ not consistent with cross sections!

Step I: analysis at LC@500 GeV

Results from this analytically based ’fit’-procedure:

ILC$_{500}$			
M_1	M_2	μ	$\tan\beta$
355 ± 15	154 ± 12	500 ± 100	$[1, 30]$

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

⇒ could happen, since only ‘gauginos’ are accessible

⇒ take e.g. scenario in the given ranges:
M_1=347 GeV
$M_2 = 145$ GeV
$\mu = 456$ GeV
$\tan\beta$=30

⇒ Would lead to same masses $\tilde{\chi}^0_{1,2}$, $\tilde{\chi}^\pm_1$ and ∼cross sections as before!

⇒ Is it therefore the right model?

How to find a possible inconsistency?

⇒ use predicted mass ranges o $\tilde{\chi}^0_{3,4}$, $\tilde{\chi}^\pm_2$ 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 $m_{\tilde{\chi}^0_1}$!)
LC input: $m_{\tilde{\chi}^0_1}$ and mass predictions extremely helpful Desch etal'04, Polesello'

- What could be done in this scenario?

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

→ ILC provides $m_{\tilde{\chi}^0_1}$, $m_{\tilde{\chi}^0_2}$ as input for LHC:
$\tilde{\chi}^0_3$ observable in cascades and perhaps – if lucky – also $\tilde{\chi}^0_5$.

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

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

Motivation for using a further ILC option

- use subsequently higher energy but low luminosity ILC option: $\text{ILC}_{650}^{\mathcal{L}=1/}$

$\rightarrow$ production cross sections [fb] for heavier $\tilde{\chi}_1^0\tilde{\chi}_i^0$ pairs and also $\tilde{\chi}_1^\pm\tilde{\chi}_2^\mp$:

$\sqrt{s}=650$ 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±1	6±0.4	<0.02
$P(e^-)=-90\%$, $P(e^+)=+60\%$	37±2	15±1	<0.07
$P(e^-)=+90\%$, $P(e^+)=-60\%$	0.6±0.1	2.2±0.3	<0.01

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

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

$\Rightarrow$ 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 measureable

$\Rightarrow$ With LHC+$\text{ILC}_{650}^{\mathcal{L}=1/3}$: 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 $\text{LHC+ILC}_{[1.\text{stage},500,650]}$ may be decisive!

- Here@ILC_{500} only: measured observables do not point to NMSSM!
  $\longrightarrow$ not obvious that the MSSM is the wrong model!

- Key points:
  ILC: analysis of non-coloured light particle sector
  $\longrightarrow$ precise mass of light particles
  $\longrightarrow$ and prediction of heavier states
  LHC: measurement of light+heavy gauginos
  $\Rightarrow$ 'Feeding back to ILC analysis'

- Important consistency tests of the new physics (NP) model already a
  $\sqrt{s} = 500$ GeV stage! $\Rightarrow$ outline for future search analysis strategies

- Results of $\text{LHC} \leftrightarrow \text{ILC}_{500}$ interplay motivates the use of the low luminosity option $\text{ILC}_{650}^{\mathcal{L}=1/3}$!

- Future: 'true' fits planned, however NMSSM simulation programs neede

App1:Typical features of the AMSB Susy breaking scenarios

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

$\rightarrow$ tricky scenario for LHC Allanach, 02082

if $\delta m_{(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)} < 200$ MeV no problem

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

and large background

assuming AMSB relations and specific cuts: resolvable Lester'

$\rightarrow$ simulation for the LC exist C. Hensel, Thesis, '

$\delta m_{(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)}$ measureable at per cent level

$\Rightarrow$ AMSB scenario may be perfectly suited for combined LHC/LC analyse

Mixing characteristics in the neutralino sector:

- inversion: lightest $\tilde{\chi}_1^0 \sim \tilde{W}$ determined mainly by M_2
  $\tilde{\chi}_2^0 \sim \tilde{B}$ determined mainly by M_1
- lightest chargino $\tilde{\chi}_1^\pm \sim \tilde{W}$ determined by M_2 (as 'usual')
  heavy chargino $\tilde{\chi}_2^\pm \sim \tilde{H}$ determined by μ ('as usual')

App2: Comparison of MSSM$\leftrightarrow$NMSSM scenario
Masses alone may be not sufficient!

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

both scenarios respect all exp. bounds!

GMP, Fraas, Franke, Hesselbach'05

$\Rightarrow$ 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

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

⇒ Only σ statistical error

1 σ stat. error on basis of $\mathcal{L}_{800,1000} = 500$ fb^{-1} and $\mathcal{L}_{3000} = 1000$ fb^{-1} ($\equiv 1\times10^{35}$cm^{-2}s^{-}