Distinguishing between MSSM and NMSSM via combined LHC and ILC analyses

Gudrid Moortgat-Pick (CERN)

in collaboration with

S. Hesselbach, F. Franke, H. Fraas

CERN, 15/11/2004

- Introduction: the MSSM and the NMSSM
  - $\longrightarrow$ Gedankenexperiment
  - $\longrightarrow$ Gaugino/higgsino sector in both models
- Example NMSSM
  - $\longrightarrow$ Discrimination between the MSSM via LHC/ILC interplay
- Example MSSM
  - $\longrightarrow$ Association of masses via LHC/ILC interplay
- Motivation for the use of the $\mathrm{LC}_{650}^{\mathcal{L}=1/3}$ option via LHC/ILC interplay
- Summary

Introduction

NMSSM (='MSSM'+ one Higgs singlet):

$*$ Higgs singlet S needs also a Susy partner $\tilde{S}$

$\rightarrow$ now 5 neutralinos, mixtures of $\tilde{B}^0$, $\tilde{W}^0$, $\tilde{H}_1^0$, $\tilde{H}_2^0$ and $\tilde{S}$

$*$ Higgs singlet coupling to gauge bosons strongly suppressed

What has been done so far?

- Higgs sector — Drees'89, Ellis'89, Franke'95, Ellwanger et al.'95, 99, 00, 04, Choi'04, Han'04
- Neutralino sector phenomenology — Franke'95, Hesselbach'00, '01, Choi'04
- Strategies for model separation — GMP et al.'99 ($\tilde{\chi}_1^0, \tilde{\chi}_2^0$: polarisation effects)

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

'Typical' NMSSM features: one $\tilde{\chi}_k^0 \sim \tilde{S}$

$*$ small 'singlino' cross sections

$*$ small NLSP width if LSP=$\tilde{\chi}_1^0 \approx \tilde{S}$

$\rightarrow$ displaced vertices possible — Hesselbach '00

$*$ Higgs sector: S_1 may be very light, escaped LEP — Ellwanger '02, Choi et al. '04

'Gedankenexperiment'

One believes that:

– probably the Higgs sector divides the models

– gaugino/higgsino sector leaves also unique hints for the model

But could it happen 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 corresponding cross section are also 'similar?'

* the standard parameter strategies do not fail for the light spectrum?

How to proceed in that case?

Particle sectors in both models

MSSM:

* Higgs sector $h,\ H,\ A,\ H^{\pm}$ determined by $\tan\beta$ and m_A
* Chargino sector $\tilde{\chi}^{\pm}_{1,2}$ determined by M_2, μ, $\tan\beta$
* Neutralino sector $\tilde{\chi}^{0}_{1,2,3,4}$ determined by M_1, M_2, μ, $\tan\beta$

NMSSM (='MSSM'+ one 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
* 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, $\tan\beta$

$\Rightarrow$ 'typical' NMSSM features: one $\tilde{\chi}^0_k \sim \tilde{S}$

* small 'singlino' cross sections
* small NLSP width if LSP=$\tilde{\chi}^0_1 \approx \tilde{S}$
  $\rightarrow$ displaced vertices possible — Hesselbach '00
* Higgs sector: S_1 may be very light, escaped LEP — Ellwanger '02, Choi et al. '04

Susy parameter determination in combined LHC/ILC analyses

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

- analyse and divide the model in separate blocks
- use only production of expected light ew particles $\tilde{\chi}^0_1$, $\tilde{\chi}^0_2$, $\tilde{\chi}^+_1$

$\rightarrow$ determine the fundamental parameters:
'U(1)'$=M_1$, 'SU(2)'$=M_2$, 'higgsino'$=\mu$, 'Higgs vevs'$=\tan\beta = v_2/v_1$

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

$\rightarrow$ 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,'00*
  $\rightarrow$ observables: masses and cross sections

- Neutralino mixing matrix depends on M_2, μ, $\tan\beta$ and M_1
  $\rightarrow$ observables: masses and cross sections

- determination of these parameters including
  simulated errors for the scenario SPS1a ($\tan\beta = 10$)!
  $\rightarrow$ combination of analytical step-by-step and fit procedure

Our strategy and assumptions for today:

Assumptions:

– we only measure the light Susy masses, e.g. $m_{\tilde{\chi}^0_{1,2}}$, $m_{\tilde{\chi}^\pm_1}$, $m_{\tilde{e}_{L,R}}$=(240,220) GeV, $m_{\tilde{\nu}}$=226 GeV

– we only measure $\sigma_{L,R}(e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_2, \tilde{\chi}^+_1\tilde{\chi}^-_1)$ at $\sqrt{s} = 400$, 500 GeV ($\to$ 650 GeV)

– polarised beams with $P_{e^-} = \pm 90\%$, $P_{e^+} = \pm 60\%$ are available

Strategy:

1. We choose two scenarios, MSSM and NMSSM, with
   $\to$ similar masses
   $\to$ similar cross sections – although rather large $\tilde{S}$ admixture

2. take into account 'realistic' 'experimental' uncertainties
   $\to$ $\delta m \sim 1\%$, motivated by simulation for a 'similar'
   AMSB scenario (small $m_{\tilde{\chi}^\pm_1} - m_{\tilde{\chi}^0_1}$) C. Hensel

3. apply the 'usual' MSSM parameter strategy for BOTH scenarios
   $\to$ i.e. using 1. light charginos and 2. light neutralinos
   $\to$ derive the fundamental MSSM parameters
   $\to$ predict the heavier MSSM states

4. Verification/falsification of the predictions with analyses at the LHC

5. Feed-back from LHC
   $\to$ motivation for using the low luminosity option $LC_{650}^{\mathcal{L}=1/3}$ of the ILC_{500}
   (immediately possible at 500$\to$ 650 GeV, no add. costs!)

Comparison of MSSM↔NMSSM scenario

	M_1	M_2	$\tan\beta$	μ ($\mu_{eff} = \lambda x$)	κ
NMSSM	360	147	10	457.5	0.2
MSSM	375	152	8	360	–

→ points do respect all exp. bounds

GMP, Fraas, Franke, Hesselbach'04

Assumptions:

– we only measure the light Susy masses, e.g. $m_{\tilde{\chi}^0_{1,2}}$, $m_{\tilde{\chi}^\pm_1}$, $m_{\tilde{e}_{L,R}}$, $m_{\tilde{\nu}}$

– we only measure $\sigma_{L,R}(e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_2, \tilde{\chi}^+_1\tilde{\chi}^-_1)$ at $\sqrt{s} = 400$, 500 GeV ($\to$ 650 GeV)

– polarised beams with $P_{e^-} = \pm 90\%$, $P_{e^+} = \pm 60\%$ are available

- derived mass spectra:

	$\tilde{\chi}^\pm_1$	$\tilde{\chi}^\pm_2$	$\tilde{\chi}^0_1$	$\tilde{\chi}^0_2$	$\tilde{\chi}^0_3$	$\tilde{\chi}^0_4$	$\tilde{\chi}^0_5$
NMSSM	139	474	138	337	367	468	499
MSSM	139	383	138	344	366	410	–

⇒ masses are rather close

⇒ at $\sqrt{s} = 500$ GeV: only $\tilde{\chi}^0_1\tilde{\chi}^0_2$, $\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1$ pairs can be produced

at $\sqrt{s} = 400$ GeV: only $\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1$ accessible

Chargino cross sections in MSSM and NMSSM

1. Step: Chargino production at $\sqrt{s} = 400$ and 500 GeV

$\sqrt{s} = 400$ GeV	$\sigma^{NMSSM}(e^+e^- \to \tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp})$/fb	$\sigma^{MSSM}(e^+e^- \to \tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp})$/fb
unpolarised beams	323.9±1.8±8.3	314.8±1.8±7.9
$P(e^-) = -90\%$, $P(e^+) = +60\%$	984.0±3.1±25.2	956.5±3.1±24.0
$P(e^-) = +90\%$, $P(e^+) = -60\%$	13.6 ± 0.4±0.4	13.0±0.4±0.4
$\sqrt{s} = 500$ GeV unpolarised beams	287.5±1.7±4.2	276.4±1.7±3.9
$P(e^-) = -90\%$, $P(e^+) = +60\%$	873.9±3.0±12.5	839.7±2.9±11.9
$P(e^-) = +90\%$, $P(e^+) = -60\%$	11.7±0.3±0.2	11.6±0.3±0.2

⇒ Errors that are taken into account:

first number: 1 σ stat. error on $\mathcal{L} = 100$ fb^{-1} (per polarisation configuration)

second number: error due to $\delta m_{\tilde{\chi}_1^{\pm}} \approx 1\%$

δP and $\delta m_{\tilde{\nu}}$, $\delta m_{\tilde{e}_L}$ neglible

Desch et al. '04

⇒ cross sections rather similar within the experimental uncertainties

→ no immediate MSSM↔NMSSM distinction expected (although different μ!)

⇒ But the chargino sector is not the crucial point...

Neutralino cross sections in MSSM and NMSSM

Neutralino production at $\sqrt{s} = 500$ GeV

$\sqrt{s} = 500$ GeV	$\sigma^{NMSSM}(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0)$/fb	$\sigma^{MSSM}(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0)$/fb
unpolarised beams	4.0±0.4	3.9±0.4
$P(e^-) = -90\%$, $P(e^+) = +60\%$	12.1±1.0	11.7±1.0
$P(e^-) = +90\%$, $P(e^+) = -60\%$	0.2±0.1	0.2±0.1

⇒ Errors that are taken into account:

1 σ stat. error on $\mathcal{L} = 100$ fb^{-1}, all others neglible

⇒ neutralino cross sections very similar!

What are the mixing characters?

NMSSM

$\tilde{\chi}_i^0$	$\tilde{B}^0$	$\tilde{W}^0$	$\tilde{H}_a^0$	$\tilde{H}_b^0$	$\tilde{S}$
$\tilde{\chi}_1^0$	0.1%	94.7%	1.2%	3.5%	0.5%
$\tilde{\chi}_2^0$	39.0%	2.0%	11.3%	4.8%	42.9%
$\tilde{\chi}_3^0$	56.4%	0.2%	1.4%	0.0%	42.0%
$\tilde{\chi}_4^0$	0.1%	0.7%	39.7%	58.9%	0.6%
$\tilde{\chi}_5^0$	4.4%	2.4%	46.4%	32.8%	14.0%

MSSM

$\tilde{\chi}_i^0$	$\tilde{B}^0$	$\tilde{W}^0$	$\tilde{H}_a^0$	$\tilde{H}_b^0$
$\tilde{\chi}_1^0$	0.1%	91.2%	2.6%	6.1%
$\tilde{\chi}_2^0$	51.3%	4.7%	26.7%	17.3%
$\tilde{\chi}_3^0$	0.1%	1.0%	38.3%	60.6%
$\tilde{\chi}_4^0$	48.4%	3.2%	32.5%	15.9%

⇒ pretty large $\tilde{S}$ component in $\tilde{\chi}_2^0$

Parameter determination within assumed uncertainties

Start with NMSSM scenario and apply MSSM strategy:

a) Chargino sector: observables $m_{\tilde{\chi}_1^\pm}$, $\sigma(\tilde{\chi}_1^+\tilde{\chi}_1^-)|_{400,500}$ leads to:

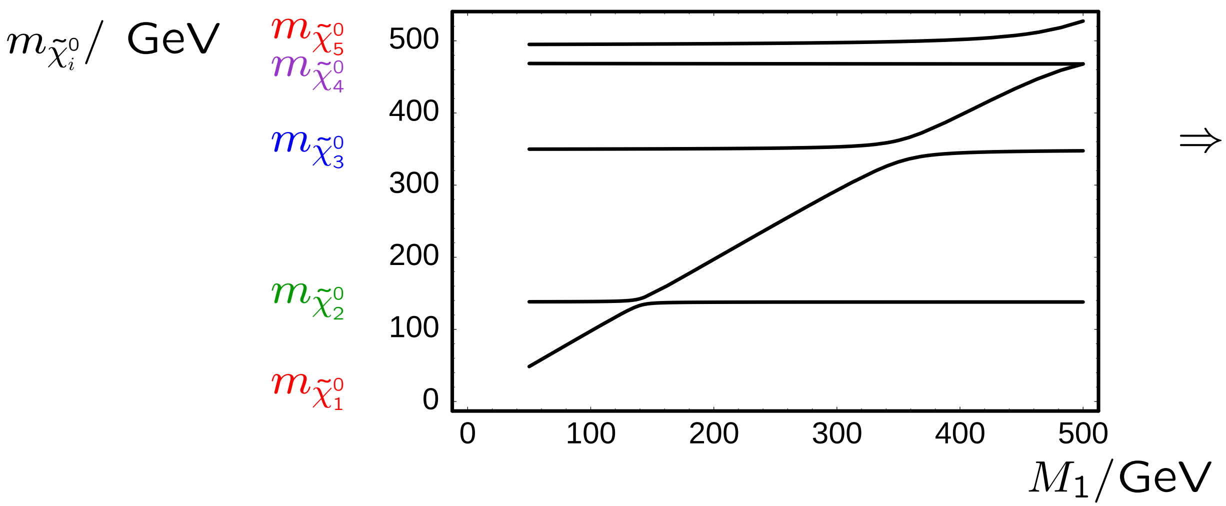
M_2/GeV=147.7±5.3	M_2^{th}=147 GeV
$370 < \mu/$ GeV	$\mu_{eff} = 458$ GeV
$1 < \tan\beta$	$\tan\beta^{th} = 10$

$\rightarrow$ rather good M_2, but μ, $\tan\beta$ very weak (expected since $\rightarrow \tilde{\chi}_1^\pm \sim \tilde{W}$)

b) Neutralino sector: observables $\sigma(\tilde{\chi}_1^0\tilde{\chi}_2^0)|_{500}$ and $m_{\tilde{\chi}_1^0}$ and/or $m_{\tilde{\chi}_2^0} \Rightarrow M_1$:

$\rightarrow$ use one of $m_{\tilde{\chi}_i^0}$ to determine M_1

- if $m_{\tilde{\chi}_1^0}$ used $\Rightarrow M_1 < -330$ negativ! $\Rightarrow$ not consistent with cross section!



$\Rightarrow$ be careful with $m_{\tilde{\chi}_1^0} \rightarrow M_1$!

GMP et al. '00

$m_{\tilde{\chi}_1^0}$ not always suitable!

Parameter determination within assumed uncertainties

I) Chargino sector: observables $m_{\tilde{\chi}_1^{\pm}}$, $\sigma(\tilde{\chi}_1^{+}\tilde{\chi}_1^{-})|_{400,500}$

II) Neutralino sector: observables $\sigma(\tilde{\chi}_1^0\tilde{\chi}_2^0)|_{500}$ and $m_{\tilde{\chi}_{1,2}^0}$

With these observables one obtains:

M_1/GeV=355±20	M_1^{th}=360 GeV
M_2/GeV=148±5	M_2^{th}=147 GeV
μ/GeV=[480,900]	$\mu_{eff} = 458$ GeV
$1 < \tan\beta$	$\tan\beta^{th} = 10$

⇒ rather large uncertainty in M_1 and μ, $\tan\beta$ very weak,
but were we worry about it?

⇒ Would you claim, that the wrong model has been applied?

How to find a possible inconsistency?

$\Rightarrow$ predict heavier particles and let them find from LHC

Predictions, consistent with parameter tuples:

$$m_{\tilde{\chi}^0_3}/\text{GeV} > \quad 480$$
$$m_{\tilde{\chi}^0_4}/\text{GeV} > \quad 500$$
$$m_{\tilde{\chi}^\pm_2}/\text{GeV} > \quad 500$$

$\Rightarrow$ all heavier neutralinos/chargino larger than 480 GeV!

- Could LHC measure the masses and confirm the model?

$\rightarrow$ heavy gauginos may be reconstructed in decay chains:

$\Rightarrow$ Since $\tilde{\chi}^0_3 \sim 43\%(\tilde{H}, \tilde{S})$–like, but $\tilde{\chi}^0_4 \sim 99\%$ $(\tilde{H}, \tilde{S})$–like and even $\tilde{\chi}^0_5 \sim 93\%$ $(\tilde{H}, \tilde{S})$–like

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

$\Rightarrow$ we assume that $\delta m^{\text{LHC}}_{\tilde{\chi}^0_3} \sim 2\%$ (prelim.): $m_{\tilde{\chi}^0_3} = 367 \pm 7$ GeV

$\Rightarrow$ obvious contradiction with ILC prediction ($m_{\tilde{\chi}^0_3} > 480$ GeV)!

Motivation for using a further ILC option

- use subsequently higher energy but low luminosity ILC option: $\text{ILC}_{650}^{\mathcal{L}=1/3}$

$\rightarrow$ 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	$\sigma(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_3^0)$	$\sigma(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_4^0)$	$\sigma(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_5^0)$
unpolarised	12.2±0.6	5.5±0.4	0.02±0.02
$P(e^-) = -90\%,\ P(e^+) = +60\%$	36.9±1.1	14.8±0.7	0.07±0.04
$P(e^-) = +90\%,\ P(e^+) = -60\%$	0.6±0.1	2.2±0.3	0.01±0.02

$\sqrt{s} = 650$ GeV	$\sigma(e^+e^- \to \tilde{\chi}_1^\pm\tilde{\chi}_2^\mp)$
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!

GMP,Franke,Fraas,Hesselbach'04

application of more general fits will probably nail down the NMSSM

b) Further application: apply MSSM strategy on MSSM scenario

Again: $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ at $\sqrt{s} = 400$ and 500 GeV and $\tilde{\chi}_1^0\tilde{\chi}_2^0$ at $\sqrt{s} = 500$ GeV

I) Chargino sector: observables $m_{\tilde{\chi}_1^{\pm}}$, $\sigma(\tilde{\chi}_1^{+}\tilde{\chi}_1^{-})|_{400,500}$ leads to:

M_2/GeV=153.0±5.2	M_2^{th}=152 GeV
μ=[340,600]	$\mu = 360$ GeV
$\tan\beta > 1$	$\tan\beta^{th} = 8$

II) Neutralino sector: observables $\sigma(\tilde{\chi}_1^0\tilde{\chi}_2^0)|_{500}$ and $m_{\tilde{\chi}_1^0}$ and/or $m_{\tilde{\chi}_2^0} \Rightarrow M_1$:

M_1/GeV=370±20	M_1^{th}=375 GeV
M_2/GeV=151±4	M_2^{th}=152 GeV
μ/GeV=[340,580]	$\mu_{eff} = 360$ GeV
$1 < \tan\beta$	$\tan\beta^{th} = 8$

$\Rightarrow$ results seem to be rather promising!

MSSM scenario: which help could come from LHC?

We assume – analogous to the former study in SPS1a: Desch et al. '04

- $\tilde{\chi}^0_3 \sim 99\% \tilde{H}$-like will not be accessible at the LHC
- However, $\tilde{\chi}^0_4 \sim 48\% \tilde{H}$ only, so, there are good chances.

Same game as before with heavy gauginos – mass predictions from LC studies:

$$m_{\tilde{\chi}^0_3}/\text{GeV} = \quad [360,505]$$
$$m_{\tilde{\chi}^0_4}/\text{GeV} = \quad [405,540]$$
$$m_{\tilde{\chi}^\pm_2}/\text{GeV} = \quad [380,520]$$

$\rightarrow$ we assume that the LHC can measure/identify (as in SPS1a) Polesello'04

a gaugino particle with

$$\hat{m}_{\tilde{\chi}^0_i} = 410 \pm 8 \text{ GeV} \qquad \text{(again 2\% uncertainty assumed)}$$

('maybe even better!', confirmed by Giacomo last week)

How to know that it is $\tilde{\chi}^0_4$?

$\Rightarrow$ Play with both possibilities, determine the parameters, predict the masses and check it experimentally

Further motivation for $LC_{650}^{\mathcal{L}=1/3}$ in the MSSM example

1. Assuming measured particle is $\hat{m}_{\tilde{\chi}_i^0} = m_{\tilde{\chi}_3^0}$:
   $\Rightarrow$ this assumption leads to the predictions
   $m_{\tilde{\chi}_4^0}$/GeV$= 439 \pm 9$ and $m_{\tilde{\chi}_2^\pm}$/GeV$= 425 \pm 10$
   $m^{th}_{\tilde{\chi}_4^0}$/GeV$= 410$ and $m^{th}_{\tilde{\chi}_2^\pm}$/GeV$= 383$

2. Assuming measured particle is $\hat{m}_{\tilde{\chi}_i^0} = m_{\tilde{\chi}_4^0}$:
   $\Rightarrow$ this assumption leads to the predictions
   $m_{\tilde{\chi}_3^0}$/GeV$= 370 \pm 15$ and $m_{\tilde{\chi}_2^\pm}$/GeV$= 385 \pm 15$
   $m^{th}_{\tilde{\chi}_3^0}$/GeV$= 366$ and $m^{th}_{\tilde{\chi}_2^\pm}$/GeV$= 383$

$\rightarrow$ in both cases sufficient motivation to use $LC_{650}^{\mathcal{L}=1/3}$
$\rightarrow$ immediate model verfication/falsification

$\Rightarrow$ LHC$\leftrightarrow$LC interplay crucial for model determination and searches outline!

Summary: Promising 'hand-in-hand' LHC/ILC procedures!

- Susy (as an example for tricky new physics searches) greatly benefits from synergy of combined LHC and ILC_{500} analyses

- LHC/ILC_{500} combined analysis: precise ('loop level') Susy parameter determination without assuming a specific Susy breaking scheme!

- Today: Discrimination between MSSM↔NMSSM
  → no separation if only Higgs sector or only light gaugino/higgsino sector

- Gain in 'model-independence' via combined analisis:
  → Analysis of light states at LC leads to predictions of heavier masses
  → Measuring/identification of heavier masses at the LHC
  → Comparison leads to verification/falsification of the model
  → Motivation to use immediately low lumi option of $LC_{650}^{\mathcal{L}=1/3}$

- Combined LHC/ILC analysis:

→ better prepared for the 'unexpected'!

App: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, 0208214

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'99

$\rightarrow$ simulation for the LC exist — C. Hensel, Thesis, '02

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

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

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')