# Distinguishing between MSSM and NMSSM by combined LHC and ILC analyses

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based on

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# Introduction

- NMSSM: MSSM + singlet/singlino

  In superpotential: $\mu \hat{H}_1 \hat{H}_2 \rightarrow \lambda \hat{H}_1 \hat{H}_2 \hat{S} + \frac{\kappa}{3} \hat{S}^3 \Rightarrow \mu \rightarrow \lambda x,\ x \equiv \langle S \rangle$

- Extended neutralino and Higgs sectors
- Distinguishing NMSSM $\leftrightarrow$ MSSM
  - Higgs sector: light singlet scalar or pseudoscalar Higgs
  - Neutralino sector: singlino LSP $\rightarrow$ displaced vertices

    [Ellwanger, Hugonie, '97, '98; Hesselbach, Franke, Fraas, '00; Franke, Hesselbach, '01]
- Here we assume
  - Higgs sector allows no distinguishing

    only MSSM-like lightest Higgs accessible
  - Masses and cross sections of neutralinos/charginos consistent with MSSM

# Higgs sector

- 3 scalar and 2 pseudoscalar Higgs bosons
- Light singlet dominated Higgs $\longrightarrow$ hint for NMSSM
  - Light scalar Higgs in LHC/ILC analyses [Miller, Moretti '04]
  - $S_2 \to S_1 S_1$ ($S_1 \to P_1 P_1$) for light scalars (pseudoscalars)

    [Ellwanger, Gunion, Hugonie, Moretti '03]
    [Gunion, Szleper, '04]
    [Ellwanger, Gunion, Hugonie, '05]
- However, in large parameter region:

  $S_1$ MSSM-like, singlet dominated Higgs heavy

  e.g. $m_{S_1}$ = 124 GeV, $m_{S_2}$ = 311 GeV, $m_{P_1}$ = 335 GeV

  for $A_\lambda$ = 4 TeV, $A_\kappa$ = 300 GeV in our scenario

# Scenario

- NMSSM scenario

  $M_1$ = 360 GeV, $M_2$ = 147 GeV, tan $\beta$ = 10,

  $x$ = 915 GeV, $\lambda$ = 0.5, $\kappa$ = 0.2

- Neutralino masses and mixing

| | $m_{\tilde{\chi}_i^0}$/GeV | mixing character in % {gaugino, higgsino, singlino} |
|---|---|---|
| $\tilde{\chi}_1^0$ | 138 | {94.7, 4.7, 0.5} |
| $\tilde{\chi}_2^0$ | 337 | {41.1, 16.1, 42.9} |
| $\tilde{\chi}_3^0$ | 367 | {56.6, 1.4, 42.0} |
| $\tilde{\chi}_4^0$ | 468 | {0.8, 98.6, 0.6} |
| $\tilde{\chi}_5^0$ | 499 | {6.8, 79.2, 14.0} |

| | $m_{\tilde{\chi}_i^\pm}$/GeV |
|---|---|
| $\tilde{\chi}_1^\pm$ | 139 |
| $\tilde{\chi}_2^\pm$ | 474 |

# Cross sections and errors

- Cross sections at ILC
- Error estimation:
  - Statistical error for $\int \mathcal{L} = 100\ \text{fb}^{-1}$
  - Polarization uncertainty $\Delta\mathcal{P}_{e^\pm}/\mathcal{P}_{e^\pm} = 0.5\%$
  - Mass uncertainties:
    1.5%: $\tilde{\chi}^0_{2,3}$, $\tilde{e}_{L,R}$, $\tilde{\nu}$
    2%: $\tilde{\chi}^0_1$, $\tilde{\chi}^\pm_1$

| $\sigma(e^+e^- \to \tilde{\chi}^\pm_1\tilde{\chi}^\mp_1)$/fb at $\sqrt{s}$ = 400 GeV | |
|---|---|
| Unpolarized beams | $323.9 \pm 33.5$ |
| $(\mathcal{P}_{e^-}, \mathcal{P}_{e^+}) = (-90\%, +60\%)$ | $984.0 \pm 101.6$ |
| $(\mathcal{P}_{e^-}, \mathcal{P}_{e^+}) = (+90\%, -60\%)$ | $13.6 \pm 1.6$ |

| $\sigma(e^+e^- \to \tilde{\chi}^\pm_1\tilde{\chi}^\mp_1)$/fb at $\sqrt{s}$ = 500 GeV | |
|---|---|
| Unpolarized beams | $287.5 \pm 16.5$ |
| $(\mathcal{P}_{e^-}, \mathcal{P}_{e^+}) = (-90\%, +60\%)$ | $873.9 \pm 50.1$ |
| $(\mathcal{P}_{e^-}, \mathcal{P}_{e^+}) = (+90\%, -60\%)$ | $11.7 \pm 1.2$ |

| $\sigma(e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_2)$/fb at $\sqrt{s}$ = 500 GeV | |
|---|---|
| Unpolarized beams | $4.0 \pm 1.2$ |
| $(\mathcal{P}_{e^-}, \mathcal{P}_{e^+}) = (-90\%, +60\%)$ | $12.1 \pm 3.8$ |
| $(\mathcal{P}_{e^-}, \mathcal{P}_{e^+}) = (+90\%, -60\%)$ | $0.2 \pm 0.1$ |

# Strategy

- Take “measured” masses and cross sections with errors
- Determine MSSM parameters with strategy of

  [Choi, Djouadi, Dreiner, Kalinowski, Zerwas, ’98]
  [Choi, Djouadi, Guchait, Kalinowski, Song, Zerwas, ’00]
  [Choi, Kalinowski, Moortgat-Pick, Zerwas, ’01, ’02]

- $m_{\tilde{\chi}_1^\pm}$, $\sigma(e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-)$ at $\sqrt{s}$ = 400 and 500 GeV
  $\Rightarrow$ chargino mixing matrix elements $U_{11}$, $V_{11}$
- $U_{11}$, $V_{11}$, $m_{\tilde{\chi}_1^\pm}$, $m_{\tilde{\chi}_1^0}$, $m_{\tilde{\chi}_2^0}$ and $\sigma(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0)$
  $\Rightarrow$ constraints for $M_1$, $M_2$, $\mu$, tan $\beta$
- Calculate masses and mixings of heavier neutralinos and charginos and compare with LHC analyses

  [Desch, Kalinowski, Moortgat-Pick, Nojiri, Polesello, ’03]
  [Allanach et al., Les Houches 2003]
  [Moortgat-Pick, ’04]

# Parameter determination at ILC

2 steps:

(I) Chargino sector

Input: $m_{\tilde{\chi}_1^\pm}$, $\sigma(e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-)$ at $\sqrt{s}$ = 400 and 500 GeV

$\Rightarrow$ $U_{11}^2 = [0.84, 1.0]$, $V_{11}^2 = [0.83, 1.0]$

(II) Add neutralino sector

Input: $U_{11}$, $V_{11}$, $m_{\tilde{\chi}_1^\pm}$, $m_{\tilde{\chi}_1^0}$, $m_{\tilde{\chi}_2^0}$ and $\sigma(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0)$

$\Rightarrow$

$M_1 = (377 \pm 42)$ GeV

$M_2 = (150 \pm 20)$ GeV

$\mu = (450 \pm 100)$ GeV

$\tan\beta = [1, 30]$

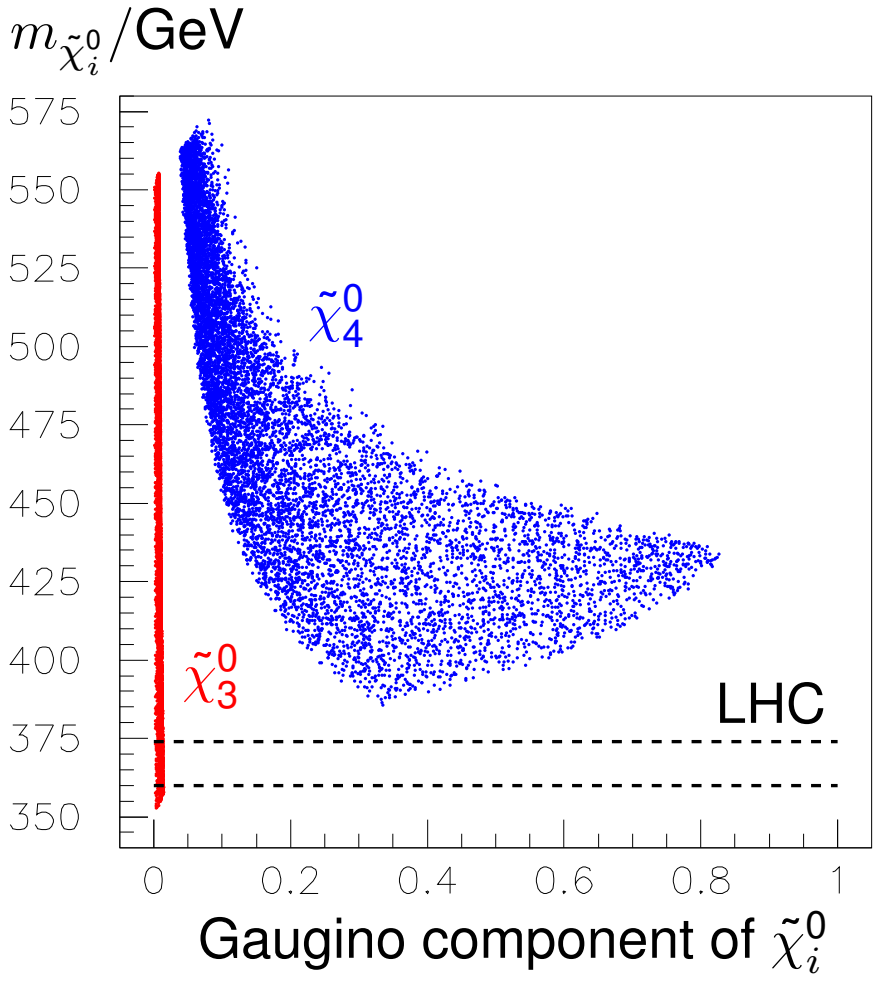
# Parameter determination at ILC

- "Measured" masses cross sections compatible with MSSM
- Predictions for masses and mixings of heavier particles:

$m_{\tilde{\chi}_3^0}$ = [352, 555] GeV

$m_{\tilde{\chi}_4^0}$ = [386, 573] GeV

$m_{\tilde{\chi}_2^\pm}$ = [450, 600] GeV



# SUSY searches at LHC

- Cascade decays of quarks and gluinos

  $\rightarrow$ Masses of heavy gauginos accessible in invariant mass distributions

- In our NMSSM scenario: $\tilde{\chi}_3^0$ has large gaugino component

  For simulations in mAMSB-like scenarios
  see e.g. [Barr, Lester, Parker, Allanach, Richardson, JHEP 0303, 045]

  $\rightarrow BR(\tilde{\chi}_3^0 \rightarrow \tilde{\ell}_{L,R}^{\pm} \ell^{\mp}) \sim 45\%$

  $\Rightarrow$ expected to see edges for $\tilde{\chi}_3^0 \rightarrow \tilde{\ell}_{L,R}^{\pm} \ell^{\mp}$

- With input from ILC measurements: $m_{\tilde{\chi}_1^0}$, $m_{\tilde{\chi}_2^0}$, $m_{\tilde{\ell}}$, $m_{\tilde{\nu}}$

  $\rightarrow$ Precision of 2% for $m_{\tilde{\chi}_3^0}$ may be possible: $m_{\tilde{\chi}_3^0} = (367 \pm 7)$ GeV

  $\rightarrow$ Mass value compatible with predictions in MSSM,
  however, not with predictions for gaugino component

- Interpretation of measured gaugino as $\tilde{\chi}_4^0$:
  incompatible with cross section measurements at ILC

# The ILC$_{650}^{\mathcal{L}=1/3}$ option

- Inconsistency of LHC and ILC analyses may motivate low-luminosity but higher-energy option ILC$_{650}^{\mathcal{L}=1/3}$
- ILC$_{650}^{\mathcal{L}=1/3}$: $\sqrt{s}$ = 650 GeV for $\mathcal{L}/3$ without hardware changes
- $\tilde{\chi}_3^0$, $\tilde{\chi}_4^0$, $\tilde{\chi}_2^\pm$ accessible via
  $\sigma(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_3^0)$, $\sigma(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_4^0)$, $\sigma(e^+e^- \to \tilde{\chi}_1^\pm\tilde{\chi}_2^\mp)$
- Precisely measured masses $m_{\tilde{\chi}_1^0}$, $m_{\tilde{\chi}_2^0}$, $m_{\tilde{\chi}_3^0}$, $m_{\tilde{\chi}_4^0}$, $m_{\tilde{\chi}_1^\pm}$, $m_{\tilde{\chi}_2^\pm}$ and cross sections

  $\longrightarrow$ observables for fit of NMSSM parameters

  $M_1$, $M_2$, tan $\beta$, $\lambda$, $\mu_{\text{eff}} = \lambda x$, $\kappa x$

# Conclusion

- NMSSM scenario that cannot be distinguished from MSSM at ILC with $\sqrt{s}$ = 500 GeV
- Masses and cross sections of accessible neutralinos/charginos compatible with MSSM
- Combined LHC+ILC analyses: show inconsistency with MSSM
- $\text{ILC}_{650}^{\mathcal{L}=1/3}$ could lead to clear identification of NMSSM