Determination of NMSSM parameters by combined LHC/ILC analyses

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based on

G. Moortgat-Pick, S. Hesselbach, F. Franke, H. Fraas, JHEP **06** (2005) 048 [hep-ph/0502036]

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Outline

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- Model discrimination in neutralino and Higgs sector
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- Outlook: Implementation of NMSSM in Fittino
- Conclusion

Introduction

- Revealing of underlying supersymmetric model:
  Essential goal of LHC and ILC
  $\leftrightarrow$ combined LHC-ILC analysis might be crucial
- Next-to-minimal Supersymmetric Standard Model (NMSSM):
  Extension of MSSM by singlet/singlino superfield $\hat{S}$
- In superpotential: μ-term replaced by trilinear terms

$$\mu \hat{H}_1 \hat{H}_2 \rightarrow \lambda \hat{H}_1 \hat{H}_2 \hat{S} + \frac{\kappa}{3} \hat{S}^3$$

$\Rightarrow$ $\mu \rightarrow \mu_{\text{eff}} = \lambda x$ with $x \equiv \langle S \rangle$

- Possible solution of μ problem, less fine-tuning
- Extended neutralino and Higgs sectors:
  5 neutralinos $\tilde{\chi}_i^0$, 3 scalars S_i, 2 pseudoscalars P_i

Introduction

- Distinguishing NMSSM $\leftrightarrow$ MSSM possible via
  - Neutralino sector:

    Additional neutralinos with singlino admixture accessible

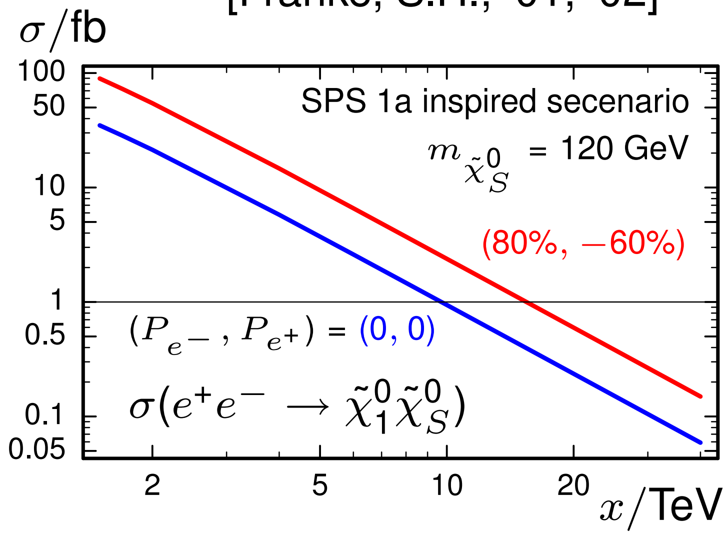
    Different polarization behavior
  - Higgs sector:

    Light singlet-dominated scalars or pseudoscalars
- Here we analyze scenario where
  - Higgs sector allows no distinction at LHC or ILC because only MSSM-like lightest scalar S_1 accessible
  - Masses, cross sections and BRs of neutralinos/charginos at LHC or ILC_{500} ($\sqrt{s}$ = 500 GeV) consistent with MSSM

Neutralino sector

- 5 neutralinos $\tilde{\chi}_i^0$ (additional singlino state)
  [e.g. Franke, Fraas, '95; Choi, Miller, Zerwas, '04]

- Hints for NMSSM:
  - Singlino-dominated LSP [Ellwanger, Hugonie, '97, '98; S.H., Franke, Fraas, '00]
    $\longrightarrow$ displaced vertices possible for $x = \langle S \rangle \gg m_W$
  - Direct production of singlino-dominated $\tilde{\chi}_i^0$: [Franke, S.H., '01, '02]
    $\longrightarrow$ detectable at ILC up to $x = \mathcal{O}(10\text{ TeV})$
    $\leftrightarrow$ singlino purity $\approx$ 99%
    $\longrightarrow$ similar in E_6 inspired SUSY models with additional U(1) factors
    [S.H., Franke, Fraas, '01]



  - Different polarization behavior [Moortgat-Pick, S.H., Franke, Fraas, '99]
    [S.H., Franke, Fraas, '00]

Higgs sector

- 5 neutral Higgs bosons: 3 scalars S_i, 2 pseudoscalars P_i

  [e.g. Franke, Fraas, '95; Miller, Nevzorov, Zerwas, '03]

- Light singlet dominated S_1, P_1 $\longrightarrow$ hint for NMSSM
  - Higgs decays: $S_2 \to S_1 S_1$ $(S_1 \to P_1 P_1)$
    for singlet dominated S_1 (P_1) [Ellwanger, Gunion, Hugonie, Moretti '03, '04]
    [Gunion, Szleper, '04]
    [Ellwanger, Gunion, Hugonie, '05]
  - Singlet dominated S_1 in LHC/ILC analyses [Miller, Moretti '04]
  - Sfermion decays: $\tilde{f}_2 \to \tilde{f}_1 + S_1, P_1$ [Kraml, Porod '05]

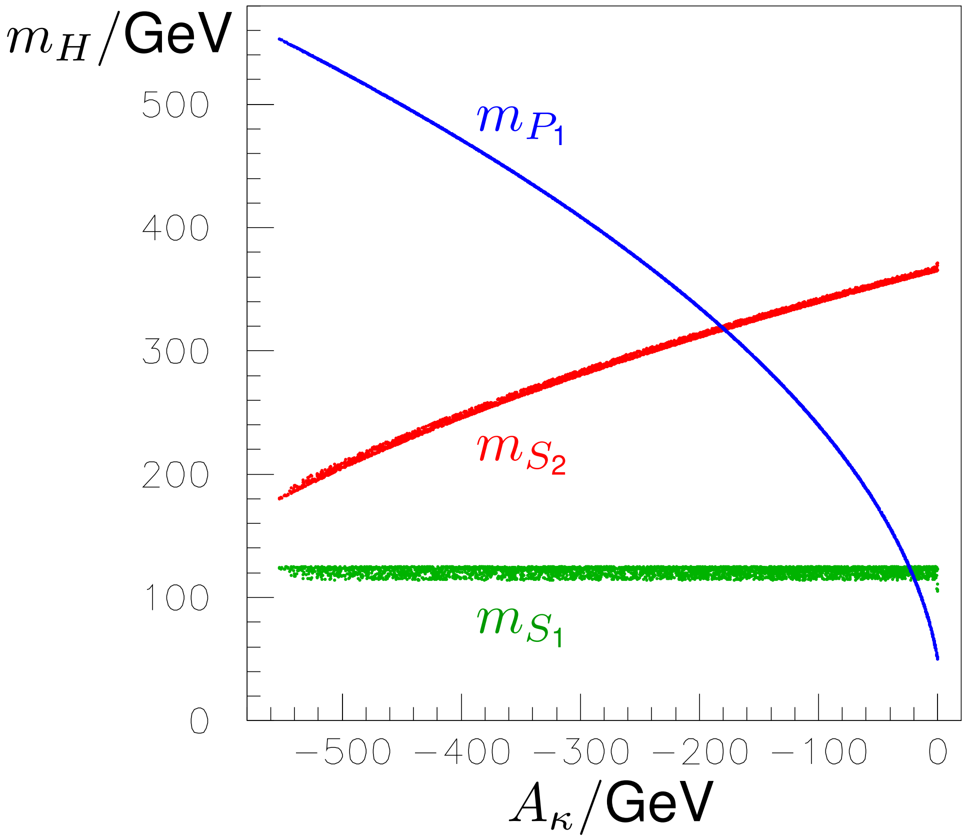
- However, additional trilinear soft scalar mass parameters A_λ and A_κ

  $\longrightarrow$ singlet dominated Higgs bosons may also be heavy

  $\longrightarrow$ our study in the following

Higgs sector

- In our scenario ($\tan\beta$ = 10, x = 915 GeV, λ = 0.5, κ = 0.2):
  Scan with NMHDECAY over A_λ and A_κ [Ellwanger, Gunion, Hugonie, '04]
  $\longrightarrow$ theoretical and experimental constraints satisfied for
  2740 GeV $< A_\lambda <$ 5465 GeV and $-$553 GeV $< A_\kappa <$ 0 GeV



- For $-$440 GeV $\lesssim A_\kappa \lesssim -$90 GeV:
  S_1 MSSM-like,
  singlet dominated S_2, P_1 heavy
  e.g. m_{S_1} = 124 GeV,
  m_{S_2} = 311 GeV, m_{P_1} = 335 GeV
  for A_λ = 4 TeV, A_κ = $-$200 GeV

NMSSM Scenario

- NMSSM scenario

  M_1 = 360 GeV, M_2 = 147 GeV, tan β = 10, x = 915 GeV, λ = 0.5, κ = 0.2

  $m_{\tilde{e}_L}$ = 240 GeV, $m_{\tilde{e}_R}$ = 220 GeV, $m_{\tilde{\nu}_e}$ = 226 GeV

- Neutralino/chargino 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

$\rightarrow$ small $\Delta(m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0})$

$\rightarrow$ similar to AMSB

Cross sections and errors

- Cross sections at ILC_{500} (only $\tilde{\chi}^0_{1,2}$, $\tilde{\chi}^{\pm}_1$ accessible)
- Error estimation:
  - Statistical error for $\int\mathcal{L}$ = 100 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 ± 33.5
$(\mathcal{P}_{e^-}, \mathcal{P}_{e^+})$ = (−90%, +60%)	984.0 ± 101.6
$(\mathcal{P}_{e^-}, \mathcal{P}_{e^+})$ = (+90%, −60%)	13.6 ± 1.6

$\sigma(e^+e^- \to \tilde{\chi}^{\pm}_1\tilde{\chi}^{\mp}_1)$/fb at $\sqrt{s}$ = 500 GeV	
Unpolarized beams	287.5 ± 16.5
$(\mathcal{P}_{e^-}, \mathcal{P}_{e^+})$ = (−90%, +60%)	873.9 ± 50.1
$(\mathcal{P}_{e^-}, \mathcal{P}_{e^+})$ = (+90%, −60%)	11.7 ± 1.2

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

Strategy

- Take "measured" masses and cross sections at ILC within uncertainties

- Determine MSSM parameters with strategy for ILC

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

- 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) Analysis of chargino sector

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

⇒ chargino mixing matrix elements $U_{11}^2 = [0.84, 1.0]$, $V_{11}^2 = [0.83, 1.0]$

(II) Add information from neutralino sector: $m_{\tilde{\chi}_1^0}$, $m_{\tilde{\chi}_2^0}$ and $\sigma(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0)$

⇒ constraints for MSSM parameters:

$M_1 = (377 \pm 42)$ GeV

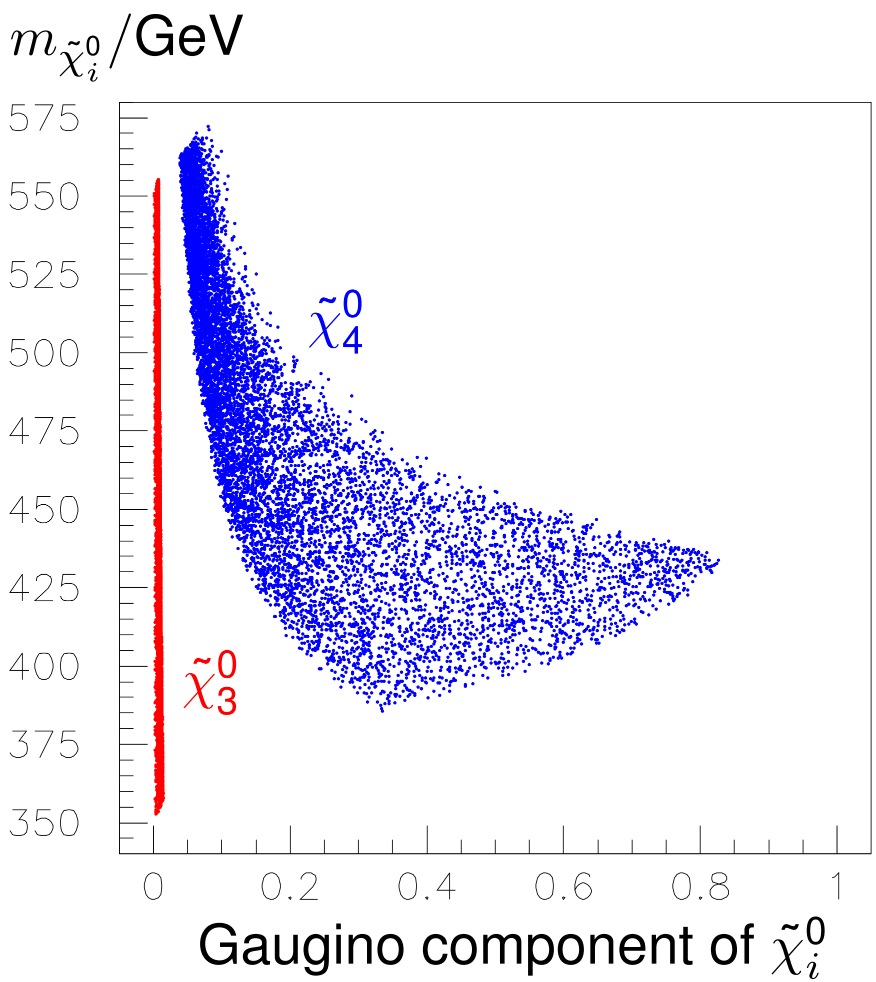
$M_2 = (150 \pm 20)$ GeV

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

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

Parameter determination at ILC

- "Measured" masses and cross sections compatible with MSSM
- Predictions for masses and mixings of heavier particles:
  - $\tilde{\chi}_3^0$: $m_{\tilde{\chi}_3^0}$ = [352, 555] GeV, strong higgsino character
  - $\tilde{\chi}_4^0$: $m_{\tilde{\chi}_4^0}$ = [386, 573] GeV larger gaugino admixture
  - $\tilde{\chi}_2^\pm$: $m_{\tilde{\chi}_2^\pm}$ = [450, 600] GeV



SUSY searches at LHC

- Cascade decays of squarks and gluinos

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

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

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

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

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

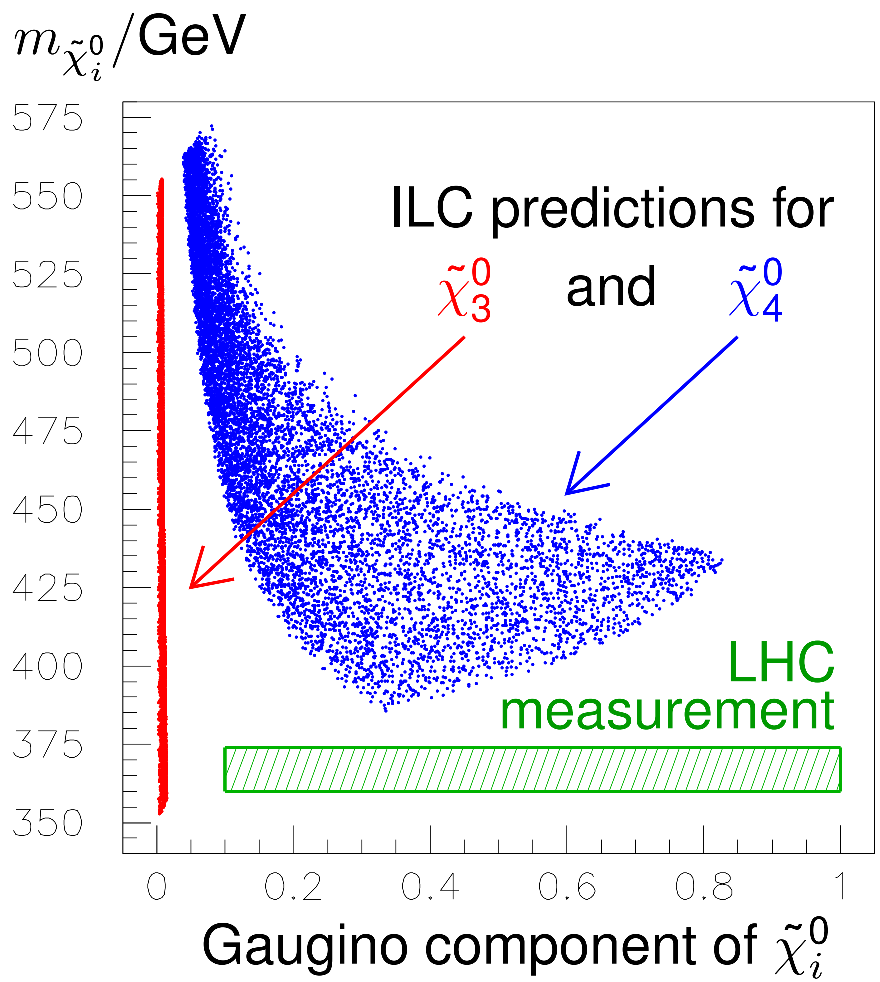
SUSY searches at LHC

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

  $\longrightarrow$ Precision of 2% for $m_{\tilde{\chi}_3^0}$ may be possible:

  $$m_{\tilde{\chi}_i^0} = (367 \pm 7)\ \text{GeV}$$

  $\longrightarrow$ Compatible with mass predictions in MSSM, however, not with predictions for small gaugino component!



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

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

- Inconsistency of LHC and ILC analyses may motivate low-luminosity but higher-energy option $\mathrm{ILC}_{650}^{\mathcal{L}=1/3}$
  $\rightarrow \sqrt{s}$ = 650 GeV at a third of the luminosity without hardware changes

- $\tilde{\chi}_3^0$, $\tilde{\chi}_4^0$, $\tilde{\chi}_2^\pm$ accessible

	σ/fb at $\sqrt{s}$ = 650 GeV		
	$e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_3^0$	$e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_4^0$	$e^+e^- \to \tilde{\chi}_1^\pm\tilde{\chi}_2^\mp$
Unpolarized beams	12.2 ± 0.6	5.5 ± 0.4	2.4 ± 0.3
$(\mathcal{P}_{e^-}, \mathcal{P}_{e^+})$ = (−90%, +60%)	36.9 ± 1.1	14.8 ± 0.7	5.8 ± 0.4
$(\mathcal{P}_{e^-}, \mathcal{P}_{e^+})$ = (+90%, −60%)	0.6 ± 0.1	2.2 ± 0.3	1.6 ± 0.2

- Masses $m_{\tilde{\chi}_1^0}$, $m_{\tilde{\chi}_2^0}$, $m_{\tilde{\chi}_3^0}$, $m_{\tilde{\chi}_4^0}$, $m_{\tilde{\chi}_1^\pm}$, $m_{\tilde{\chi}_2^\pm}$ precisely measurable

Outlook: Fit of NMSSM parameters

Goal: determination of NMSSM parameters

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

- Implementation of NMSSM in Fittino [Bechtle, Desch, Wienemann]
  [Bechtle, Desch, S.H., Moortgat-Pick, Porod, Wienemann]
  - NMSSM particle spectrum from SPheno [Porod]
  - Higgs spectrum from NMHDECAY [Ellwanger, Gunion, Hugonie]
- Input: precisely measured masses and cross sections at LHC and ILC

$\longrightarrow$ Determination of NMSSM parameters

Conclusion

- NMSSM scenario that cannot be distinguished from MSSM at LHC or ILC with $\sqrt{s}$ = 500 GeV
  $\longrightarrow$ example for $M_2 < M_1$
- Masses and cross sections of accessible neutralinos/charginos compatible with MSSM: no contradiction in "usual" analysis
- Combined LHC+ILC analyses: show inconsistency with MSSM
- Motivates immediate use of $\text{ILC}_{650}^{\mathcal{L}=1/3}$
  $\longrightarrow$ clear identification of NMSSM
- Outlook: Fit of NMSSM parameters

Neutralino cross sections at higher energies

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

$\rightarrow$ 1 σ statistical error on basis of $\mathcal{L}_{800,1000}$ = 500 fb^{-1} and $\mathcal{L}_{3000}$ = 1000 fb^{-1}