Distinction of tricky scenarios in MSSM/NMSSM in the light of LHC results

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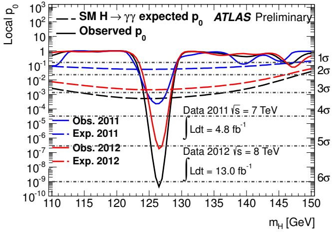
DESY

Outline

- LHC and SUSY
- Strategy to distinguish between NMSSM and MSSM scenarios.
- Example of analysis: light singlino scenario.
- Heavy singlino scenarios.
- Conclusions and outlook.

LHC News

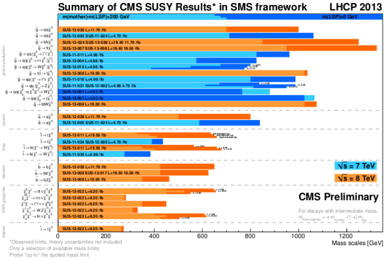
2012 gave us many of results from LHC, in particular:



- SM-like Higgs discovery at 125 GeV at ATLAS and CMS.

BUT

- No direct observation of BSM particles



- Technicolor, Composite H models, Little Higgs [Reuter et al '13] . . . under pressure

  as well as

- SUSY constrained minimal models, i.e. CMSSM; simplified models etc..

SUSY possible scenarios?

SUSY is still in good shape. Much parameter space to explore.

It is the case if we do not apply as strict higher energy constraints as in mSUGRA.

For example, addressing the Higgs sector,

- Heavy CP-even Higgs at 125 GeV option in the MSSM [Bechtle et al].
- No lose theorems for the next-to-minimal SM (NMSSM) [Ellwanger et al.] . . . .
- Natural SUSY [Papucci et al '11].
- . . .

The singlet

In the MSSM we have the so called "μ-problem"

$$W_h = \mu \, \hat{H}_u \cdot \hat{H}_d$$

why μ should be at the SUSY-breaking scale?

($\mathbb{Z}_3$-)NMSSM offers an explanation:

$$W_h = \lambda \, \hat{S} \, \hat{H}_u \cdot \hat{H}_d + \frac{\kappa}{3} \hat{S}^3$$

A gauge singlet superfield is added such that $\mu_{\text{eff}} = \lambda \langle S \rangle = \lambda \, x$.

How to distinguish between NMSSM and MSSM scenarios?

MSSM vs NMSSM?

MSSM		$(\mathbb{Z}_3\text{-})$NMSSM
$h,\ H,\ A,\ H^\pm$: $\tan\beta, m_A$		$S_{1,2,3},\ P_{1,2},\ H^\pm$: $\tan\beta,\ \lambda,\ x,\ \kappa,\ A_\lambda,\ A_\kappa$
	$+$ Singlet $=$	
$\tilde{\chi}_1^\pm,\ \tilde{\chi}_2^\pm$: $M_2,\ \mu,\ \tan\beta$		$\tilde{\chi}_1^\pm,\ \tilde{\chi}_2^\pm$: $M_2,\ \lambda\cdot x,\ \tan\beta$
$\tilde{\chi}^0_{1,2,3,4}$: $M_1,\ M_2,\ \mu,\ \tan\beta$		$\tilde{\chi}^0_{1,2,3,4,5}$: $M_1,\ M_2,\ \lambda,\ x,\ \kappa, \tan\beta$

Often one looks only at the Higgs scalar sector.

What if:

- Higgs spectra are not distinguishable at the LHC and/or not reacheable at the LC?
- Very similar chargino/neutralino spectra? $\Rightarrow$ **focus**
- Close $\sigma(e^+e^- \to \tilde{\chi}^0_i\tilde{\chi}^0_j)$, $\sigma(e^+e^- \to \tilde{\chi}^+_i\tilde{\chi}^-_j)$? $\Rightarrow$ **on this**

These conditions are possible for unconstrained scenarios [hep-ph/0502036].

Classes of scenarios

Looking at the NMSSM **chargino/neutralino** sector, we can distinguish two classes:

- High $\tilde{S}$ admixture in $\tilde{\chi}_1^0$ or $\tilde{\chi}_2^0$ [hep-ph/0502036].

  Easier to distinguish from MSSM looking at higgsino/gaugino features of neutralino from decay channels.

- $\tilde{S}$, mainly in the heavier states $\tilde{\chi}_3^0, \tilde{\chi}_4^0, \tilde{\chi}_5^0$:
  - $\mu < M1, M2$
  - $\mu > M1, M2$

  Trickier scenario to be distinguished with MSSM, due to similar admixture in the lighter neutralinos and MSSM-like signatures.

Strategy

We assume:

- We measure at LHC/LC only the light SUSY masses: $m_{\tilde{\chi}^0_{1,2}}$, $m_{\tilde{\chi}^\pm_1}$ ($m_{\tilde{\nu}}$, $m_{\tilde{e}_{R,L}}$).
- Experimental uncertainties: $\delta m_{\tilde{\chi}^\pm_1}$, $\delta m_{\tilde{\chi}^0_1}$, $\delta m_{\tilde{\chi}^0_2} \sim 0.1\%$.
- At the LC:
  - We exploit polarized beams: $P_{e^-} \in [-0.9, +0.9]$, $P_{e^+} \in [-0.6, +0.6]$.
  - We measure $\sigma(e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_2)$ and $\sigma(e^+e^- \to \tilde{\chi}^+_1\tilde{\chi}^-_1)$ at $\sqrt{s} = 350$ (top threshold), 500 GeV.

The strategy is to:

- χ^2-fit of the measured values to the MSSM parameters M_1, M_2, μ, $\tan\beta$. [Desch et al '03]
- Derive heavier MSSM neutralinos, as $m_{\tilde{\chi}^0_3}$.
- Cross-check at LHC/LC of predicted $m_{\tilde{\chi}^0_3}$ and study its properties.

Example: Light singlino scenario

For $M_1 > M_2$, contempled also in AMSB, one can get (also [hep-ph/0502036]):

	M_1 [GeV]	M_2 [GeV]	$\mu, \mu_{eff} = \lambda \cdot x$ [GeV]	$\tan\beta$	κ	λ
MSSM	411	115.7	358.5	8		
NMSSM	365	111	484	9.5	0.16	0.06

Leading to $m_h = 125$ GeV and, and the tree-level masses [GeV]:

	$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\chi}_2^0}$	$m_{\tilde{\chi}_3^0}$	$m_{\tilde{\chi}_4^0}$	$m_{\tilde{\chi}_5^0}$	$m_{\tilde{\chi}_1^\pm}$	$m_{\tilde{\chi}_2^\pm}$
MSSM	105.0	354.8	364.6	431.5		105.2	379.2
NMSSM	104.9	354.8	364.7	489.7	504	105.1	498.5

We also take $m_{\tilde{e}_L} = 303.5$, $m_{\tilde{e}_R} = 303$, $m_{\tilde{\nu}_e} = 293.3$ GeV.

MSSM	$\tilde{B}$	$\tilde{W}$	$\tilde{H}_a$	$\tilde{H}_b$
$\tilde{\chi}_1^0$	0.0%	93.0%	1.7%	5.4%
$\tilde{\chi}_2^0$	25.4%	4.9%	43.2%	26.6%
$\tilde{\chi}_3^0$	0.1%	1.1%	38.3%	60.5%
$\tilde{\chi}_4^0$	74.5%	1.1%	16.9%	7.5%

NMSSM	$\tilde{B}$	$\tilde{W}$	$\tilde{H}_a$	$\tilde{H}_b$	$\tilde{S}$
$\tilde{\chi}_1^0$	0.0%	96.6%	0.6%	2.8%	0.0%
$\tilde{\chi}_2^0$	63.6%	0.4%	3.6%	2.7%	29.8%
$\tilde{\chi}_3^0$	31.0%	0.0%	0.0%	0.3%	68.8%
$\tilde{\chi}_4^0$	0.1%	0.7%	39.8%	59.3%	0.1%
$\tilde{\chi}_5^0$	5.4%	2.3%	56.1%	34.9%	1.3%

Example: Light singlino scenario - production cross-sections at LO

$\sigma(e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-)$ [fb]

$\sqrt{s}$ =350 GeV	MSSM	NMSSM
P=(0,0)	848.26±1.46	876.66±1.49
P=(-0.9,0.6)	2496.66±4.19	2578.73±4.31
P=(0.9,-0.6)	39.64±0.75	42.48±0.77

$\sqrt{s}$ =500 GeV	MSSM	NMSSM
P=(0,0)	396.64±0.92	412.10±0.94
P=(-0.9,0.6)	1167.64±2.16	1213.41±2.22
P=(0.9,-0.6)	18.33±0.38	18.77±0.39

$\sigma(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0)$ [fb]

$\sqrt{s}$ =500 GeV	MSSM	NMSSM
P=(0,0)	7.04±0.15	6.38±0.14
P=(-0.9,0.6)	20.68±0.32	18.80±0.30
P=(0.9,-0.6)	.38±0.03	.29±0.02

- The statistic error is given by 1 σ at $\int \mathcal{L} = 500$ fb^{-1}.
- $\delta m_{\tilde{\nu}_e}$, $\delta m_{\tilde{e}_L} = 0.1\%$, $\delta m_{\tilde{\chi}_1^\pm}$, $\delta m_{\tilde{\chi}_1^0}$, $\delta m_{\tilde{\chi}_2^0}$ at 0.1%.
- Relative error on the polarizations: $\Delta P/P = 0.5\%$.

Data fit to MSSM and model distinction

χ^2-fit with NMSSM $m_{\tilde{\chi}_1^0}$, $m_{\tilde{\chi}_2^0}$, $m_{\tilde{\chi}_1^\pm}$, $\sigma_{L,R}(e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-)$ and $\sigma_{L,R}(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0)$ to MSSM parameters:

M_1 [GeV]	M_2 [GeV]	μ [GeV]	$\tan\beta$
362.7 $\pm$0.4	108.3$\pm$0.1	519.6$\pm$8.7	unconstrained: [1, 60]

Fit result excludes that the “data” are consistent with the MSSM (χ^2/d.o.f. $= 220.8/11$).

Moreover, observing the NMSSM $m_{\tilde{\chi}_3^0} = 364.7 \pm 1.8$ GeV. Away from fit $m_{\tilde{\chi}_3^0} \in [520, 532]$ GeV !!

$\tilde{\chi}_3^0$	$\tilde{B}$	$\tilde{W}$	$\tilde{H}_a$	$\tilde{H}_b$	$\tilde{S}$
NMSSM	31.0%	0.0%	0.0%	0.3%	68.8%
MSSM fit	0.1%	0.6%	38.0%	61.3%	

One can also look at gaugino properties through precision observables.

In the case of heavy singlino scenarios, it can be particularly difficult to distinguish between NMSSM and MSSM.

Two classes considered:

- Case 1, $M_1, M_2 > \mu$: higgsino-like lightest neutralinos-chargino
- Case 2, $M_1, M_2 < \mu$: gaugino-like lightest neutralinos-chargino

Heavy singlino, case 1: $\mu < M_1 < M_2$

	M_1 [GeV]	M_2 [GeV]	$\mu, \mu_{eff} = \lambda \cdot x$ [GeV]	$\tan\beta$	A_λ	A_{kappa}
MSSM/NMSSM	450	1000	120	27	3000	-30

neutralino/chargino tree-level spectra very close to MSSM, in [GeV]:

	λ	κ	$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\chi}_2^0}$	$m_{\tilde{\chi}_3^0}$	$m_{\tilde{\chi}_4^0}$	$m_{\tilde{\chi}_5^0}$	$m_{\tilde{\chi}_1^\pm}$	$m_{\tilde{\chi}_2^\pm}$
MSSM			113.30	124.24	454.35	1006.6		118.74	1006.6
NMSSM 1	0.05	0.4	113.28	124.26	454.35	1006.6	1920	118.74	1006.6
NMSSM 2	0.1	0.09	111.95	124.68	217.80	454.35	1007	118.74	1006.6
NMSSM 3	0.1	0.08	111.55	124.72	194.23	454.35	1007	118.74	1006.6

MSSM: $\tilde{\chi}_1^0, \tilde{\chi}_2^0 \sim \frac{1}{2}(\tilde{H}_a + \tilde{H}_b)$, $\tilde{\chi}_3^0 \sim \tilde{B}$, $\tilde{\chi}_4^0 \sim \tilde{W}_3$

NMSSM 1: $\tilde{\chi}_1^0, \tilde{\chi}_2^0 \sim \frac{1}{2}(\tilde{H}_a + \tilde{H}_b)$, $\tilde{\chi}_3^0 \sim \tilde{B}$, $\tilde{\chi}_4^0 \sim \tilde{W}_3$, $\tilde{\chi}_5^0 \sim \tilde{S}$

NMSSM 2: $\tilde{\chi}_1^0, \tilde{\chi}_2^0 \sim \frac{1}{2}(\tilde{H}_a + \tilde{H}_b)$, $\tilde{\chi}_3^0 \sim \tilde{S}$, $\tilde{\chi}_4^0 \sim \tilde{B}$, $\tilde{\chi}_5^0 \sim \tilde{W}_3$

NMSSM 3: $\tilde{\chi}_1^0, \tilde{\chi}_2^0 \sim \frac{1}{2}(\tilde{H}_a + \tilde{H}_b)$, $\tilde{\chi}_3^0 \sim \tilde{S}$, $\tilde{\chi}_4^0 \sim \tilde{B}$, $\tilde{\chi}_5^0 \sim \tilde{W}_3$

Heavy singlino, case 1: $\mu < M_1 < M_2$

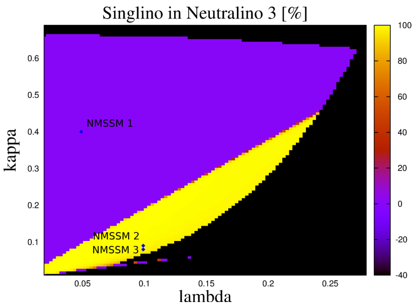
Scanning the $\lambda - \kappa$ plane with:

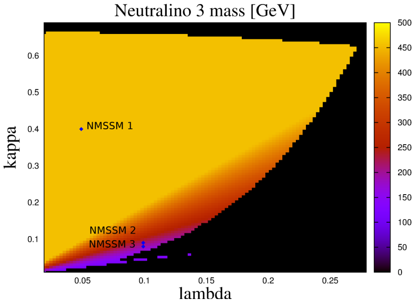
- `NMSSMTools-4.1.2` and `micrOMEGAs-3.0` for pheno and DM constraints.

- `HiggsBounds-4.0.0` and `HiggsSignals-1.0.0` to check the Higgs sector.

Black areas correspond to excluded points.

Disclaimer: Scans not yet updated to the recent LUX results [1310.8214]





Heavy singlino, case 1: $\mu < M_1 < M_2$, $\sigma(e^+e^- \to \tilde{\chi}_1^0 \tilde{\chi}_2^0)$

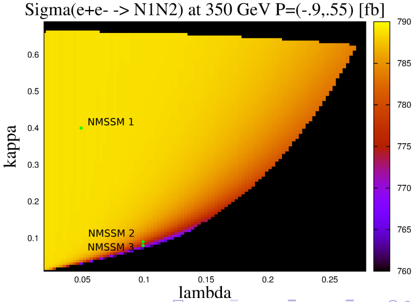
$\sqrt{s}$ =350 GeV, in fb	MSSM	NMSSM 1	NMSSM 2	NMSSM 3	$\delta\sigma$
P=(0,0)	438.37	438.37	433.03	429.59	0.94
P=(-0.9,0.55)	788.75	788.74	779.14	772.94	1.50
P=(0.9,-0.55)	521.99	521.98	515.62	511.52	1.11
$\sqrt{s}$ =500 GeV, in fb	MSSM	NMSSM 1	NMSSM 2	NMSSM 3	$\delta\sigma$
P=(0,0)	217.05	217.05	214.15	212.34	0.65
P=(-0.9,0.55)	389.81	389.80	384.59	381.34	0.96
P=(0.9,-0.55)	259.19	259.19	255.71	253.55	0.75
$\tilde{\chi}_3^0$	$\tilde{B}$		$\tilde{S}$		

The χ^2-fit tells that, for 7 d.o.f

NMSSM 1 data: χ^2=0.01 < 14.07
consistent with MSSM.

NMSSM 2 data: χ^2=11.44 < 14.07
consistent with MSSM.

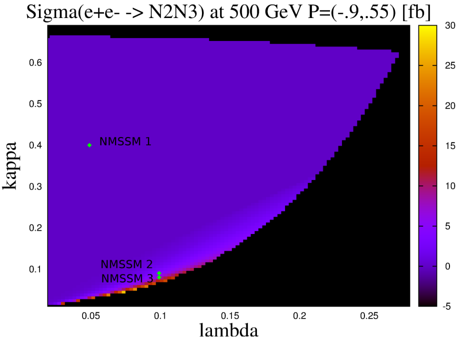
NMSSM 3 data: χ^2=32.18 > 14.07
not consistent with MSSM at 95% CL.

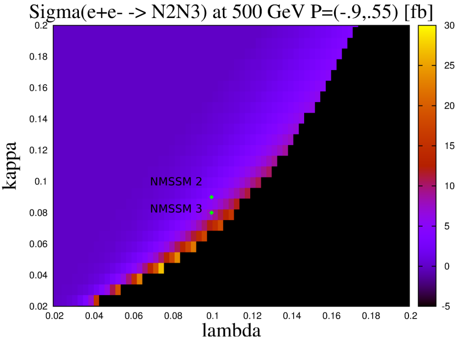


Heavy singlino, case 1: $\mu < M_1 < M_2$, $\sigma(e^+e^- \to \tilde{\chi}_2^0\tilde{\chi}_3^0)$

$\sqrt{s}$ =500 GeV	MSSM	NMSSM 1	NMSSM 2	NMSSM 3
P=(0,0)	kinematically not allowed		2.36±0.1	4.13±0.12
P=(-0.9,0.55)			4.23±0.16	7.42±0.19
P=(0.9,-0.55)			2.82±0.11	4.94±0.14
$\tilde{\chi}_3^0$	$\tilde{B}$		$\tilde{S}$	

Distinction possible also detecting/not detecting $\tilde{\chi}_3^0$ at 500 GeV ($\delta m_{\tilde{\chi}_3^0} \sim 0.5\%$).





Heavy singlino, case 2: $M_2 < M_1 < \mu$

	M_1 [GeV]	M_2 [GeV]	$\mu, \mu_{eff} = \lambda \cdot x$ [GeV]	$\tan\beta$	A_λ	A_{kappa}
MSSM/NMSSM	240	105	455	9.2	3700	-120

neutralino/chargino tree-level spectra very close to MSSM, in [GeV]:

	λ	κ	$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\chi}_2^0}$	$m_{\tilde{\chi}_3^0}$	$m_{\tilde{\chi}_4^0}$	$m_{\tilde{\chi}_5^0}$	$m_{\tilde{\chi}_1^\pm}$	$m_{\tilde{\chi}_2^\pm}$
MSSM			98.49	236.30	460.58	470.78		98.62	470.37
NMSSM 1	0.08	0.2	98.49	236.31	460.62	470.74	2275.08	98.62	470.37
NMSSM 2	0.5	0.2	97.6	235.56	349.37	465.85	492.31	98.62	470.37

MSSM:

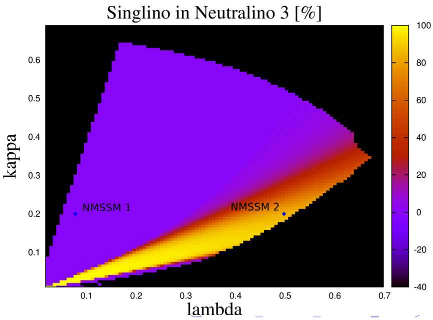
$\tilde{\chi}_1^0 \sim \tilde{W}_3, \quad \tilde{\chi}_2^0 \sim \tilde{B}, \quad \tilde{\chi}_3^0, \tilde{\chi}_4^0 \sim \frac{1}{2}(\tilde{H}_a + \tilde{H}_b),$

NMSSM 1:

$\tilde{\chi}_1^0 \sim \tilde{W}_3, \quad \tilde{\chi}_2^0 \sim \tilde{B}, \quad \tilde{\chi}_3^0, \tilde{\chi}_4^0 \sim \frac{1}{2}(\tilde{H}_a + \tilde{H}_b), \quad \tilde{\chi}_5^0 \sim \tilde{S}$

NMSSM 2:

$\tilde{\chi}_1^0 \sim \tilde{W}_3, \quad \tilde{\chi}_2^0 \sim \tilde{B}, \quad \tilde{\chi}_3^0 \sim \tilde{S}, \quad \tilde{\chi}_4^0, \tilde{\chi}_5^0 \sim \frac{1}{2}(\tilde{H}_a + \tilde{H}_b)$



Heavy singlino, case 2: $M_2 < M_1 < \mu$, $\sigma(e^+e^- \to \tilde{\chi}_1^0 \tilde{\chi}_2^0)$

$\sqrt{s}$ =350 GeV, in fb	MSSM	NMSSM 1	NMSSM 2	$\delta\sigma$
P=(0,0)	1.40	1.40	1.65	0.06
P=(-0.9,0.55)	4.14	4.14	4.85	0.14
$\sqrt{s}$ =500 GeV, in fb	MSSM	NMSSM 1	NMSSM 2	$\delta\sigma$
P=(0,0)	23.28	23.28	23.86	0.22
P=(-0.9,0.55)	68.514	68.52	70.20	0.39
P=(0.9,-0.55)	1.09	1.09	1.14	0.05
$\tilde{\chi}_3^0$	$\frac{1}{2}(\tilde{H}_a + \tilde{H}_b)$		$\tilde{S}$	

The χ^2-fit allows to distinguish MSSM, at 95% confidence level, only with NMSSM 2.

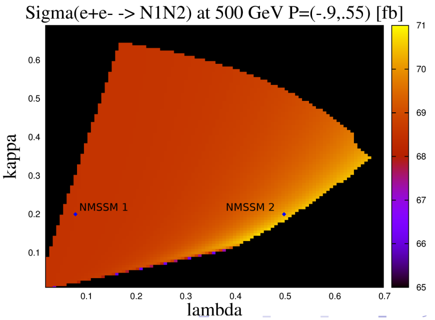
Indeed, for 6 d.o.f.,

NMSSM 1 data: χ^2=0.84< 12.6

consistent with MSSM.

NMSSM 2 data: χ^2=37.77> 12.6

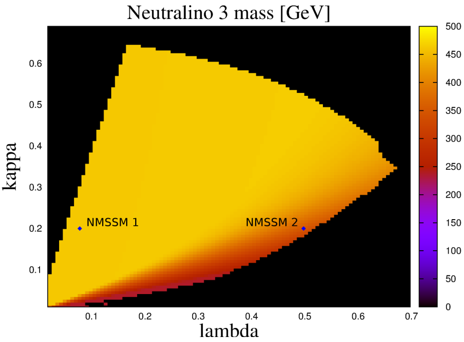
not consistent with MSSM.

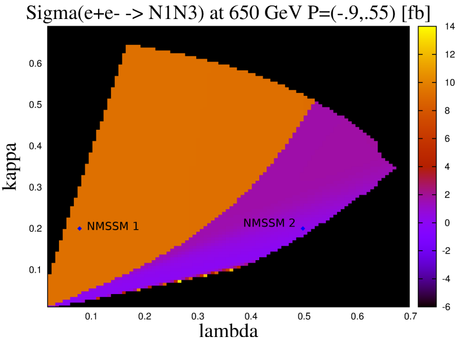


Heavy singlino, case 2: $M_2 < M_1 < \mu$, $\sigma(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_3^0)$

$\sqrt{s}$ =**650 GeV**, in fb	MSSM	NMSSM 1	NMSSM 2
P=(0,0)	3.74±0.58	3.74±0.58	.16
P=(-0.9,0.55)	9.19±1.35	9.19±1.35	.46
P=(0.9,-0.55)	1.99±0.38	1.99±0.38	.03
$\tilde{\chi}_3^0$	$\frac{1}{2}(\tilde{H}_a + \tilde{H}_b)$		$\tilde{S}$

Distinction possible also detecting/not detecting $\tilde{\chi}_3^0$ at 650 GeV ($\delta m_{\tilde{\chi}_3^0} \sim 0.5\%$).





Conclusions and outlook

- LHC data have severely put under pressure constrained SUSY models, not SUSY in general. NMSSM is a fashionable option.
- MSSM and NMSSM scenarios can lead to similar lower spectra and production cross section.
- Exploit the power of polarized beam at the LC. Look at the neutralino/chargino sector. Measure $\sigma_{L,R}(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0)$ and $\sigma_{L,R}(e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-)$.
- Fit to the MSSM parameters and search for heavier resonances; interplay LHC/LC.
- Strategy effective for light-singlino scenarios. Trickier with heavy-singlino scenarios, for certain areas in the $\lambda - \kappa$ plane need more information.

To do:

- Extend analysis to other observables as asymmetries, spin-dependent observables, tau polarization [0908.0876], stop sector.
- Include quantum level precision.
- Include more Higgs sector observables in the analysis, i.e. couplings to fermions etc..

Thank you for your attention!

Backup: Higgs sector in the light singlino scenario

	MSSM	NMSSM
m_{S_1}	124.60	124.60
m_{S_2}	4470	335.2
m_{S_3}		4471
m_{P_1}	4470	250.8
m_{P_2}		4471
$m_{H^\pm}$	4472	4472

- In the NMSSM, S_2 and P_2 are singlet-like at 99.99%.

Backup: effective theory approach

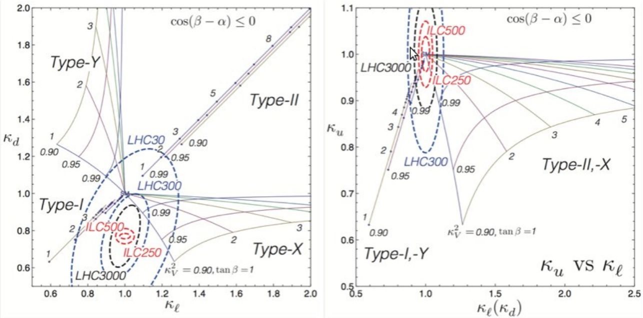


Figure 1.17. The deviation in $\kappa_f = \xi_h^f$ in the 2HDM with Type I, II, X and Y Yukawa interactions are plotted as a function of $\tan\beta = v_2/v_1$ and $\kappa_V = \sin(\beta-\alpha)$ with $\cos(\beta-\alpha) \leq 0$. For the illustration purpose only, we slightly shift lines along with $\kappa_x = \kappa_y$. The points and the dashed curves denote changes of $\tan\beta$ by one steps. The scaling factor for the Higgs-gauge-gauge coupling constants is taken to be $\kappa_V^2 = 0.99, 0.95$ and 0.90. For $\kappa_V = 1$, all the scaling factors with SM particles become unity. The current LHC constraints, expected LHC and ILC sensitivities on (left) κ_d and κ_ℓ and (right) κ_u and κ_ℓ are added.

Snowmass ILC Higgs White Paper (arXiv: 1310.0763)

Similar analysis, relative to LHC in [hep-ph/1212.5240].