Distinguishing between MSSM and NMSSM via combined LHC/LC analyses

– ('work in progress') –

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- The question:
  → MSSM - NMSSM separation with light particles
  → numerical example (including some exp. errors)
  → assumption: no separation@LC_{500} possible
- The answer:
  → LHC/LC interplay
  → motivation for using LC_{650}
- Conclusions

'Gedankenexperiment' – The question:

Start assumptions:

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

One believes that:

– probably the Higgs sector divides the models

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

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 corresponding cross section are also 'similar?'
* 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, Ellis'89, Franke'95, Ellwanger et al.'95, 99', 00', Choi'04, Han'
- Neutralino sector phenomenology Franke'95, Hesselbach'00, '01, Choi'0

MSSM:

- Parameter determination in the general MSSM see all ECFA worksho
- Breaking scheme dependent methods at LHC Rurua'00 (mSUGRA), Allanach'02 (mAMS
- Combined analysis at LHC/LC Desch et al. '0

NMSSM↔MSSM:

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

→ how to get experimental hints which model is fulfilled in nature?

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

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, $\tan\beta$

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

∗ small 'singlino' cross sections

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

→ displaced vertices possible Hesselbach '

∗ Higgs sector: S_1 may be very light, escaped LEP Ellwanger '02, Choi et al. '

Our strategy and assumptions for today:

Assumptions:

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

– 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

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 an 'close'
   AMSB scenario (small $m_{\tilde{\chi}^\pm_1} - m_{\tilde{\chi}^0_1}$) C. Hen

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
   $\to$ feeding back the LHC results into LC analyses

5. If non resolvable contradictions occur:
   $\to$ motivation for using the low luminosity option LC_{650}

Our example: mass spectra in MSSM and NMSSM

- We use $M_1 \gg M_2$ – no GUT relation!

	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	–

- 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	383	138	344	366	410	–

$\Rightarrow$ masses are rather close

$\Rightarrow$ at $\sqrt{s} = 500$ GeV: only $\tilde{\chi}_1^0\tilde{\chi}_2^0$, $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ pairs can be produced

at $\sqrt{s} = 400$ GeV: only $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ accessible

$\Rightarrow$ polarised beams and both energies needed to resolve ambiguities and to improve statistics/errors

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	1441.3±3.8±70.2	1373.9±3.7±66.3
$P(e^-) = -90\%$, $P(e^+) = +60\%$	4381.0±6.6±213.4	4176.3±6.5±201.6
$P(e^-) = +90\%$, $P(e^+) = -60\%$	58.3 ± 0.8±2.8	55.3±0.7±2.7
$\sqrt{s} = 500$ GeV unpolarised beams	2770.4±5.3±57.9	2638.1±5.1±54.8
$P(e^-) = -90\%$, $P(e^+) = +60\%$	8421.9±9.2±175.9	8019±4.0±166.4
$P(e^-) = +90\%$, $P(e^+) = -60\%$	111.0±1.0±2.3	106.1±1.0±2.4

$\Rightarrow$ Errors that are taken into account:

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

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. '

$\Rightarrow$ cross sections rather similar within the experimental uncertainties

$\to$ no immediate MSSM$\leftrightarrow$NMSSM distinction expected (although different μ!)

$\Rightarrow$ But the chargino sector is not the crucial point...

Neutralino cross sections in MSSM and NMSSM

2. Step: Neutralino production at $\sqrt{s} = 500$ GeV

$\sqrt{s} = 500$ GeV	$\sigma^{NMSSM}(e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_2)$/fb	$\sigma^{MSSM}(e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_2)$/fb
unpolarised beams	5.4±0.3	5.2±0.3
$P(e^-) = -90\%$, $P(e^+) = +60\%$	16.5±0.5	15.8±0.5
$P(e^-) = +90\%$, $P(e^+) = -60\%$	0.23±0.1	0.23±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

$\tilde{\chi}^0_i$	$\tilde{B}^0$	$\tilde{W}^0$	$\tilde{H}^0_a$	$\tilde{H}^0_b$	$\tilde{S}$
$\tilde{\chi}^0_1$	0.05%	95%	1.2%	3.5%	0.5%
$\tilde{\chi}^0_2$	39%	2%	11%	4.8%	43%
$\tilde{\chi}^0_3$	56%	0.2%	1.4%	0.0%	42%
$\tilde{\chi}^0_4$	0.1%	0.7%	40%	59%	0.6%
$\tilde{\chi}^0_5$	4.4%	2.4%	46%	33%	14%

MSSM

$\tilde{\chi}^0_i$	$\tilde{B}^0$	$\tilde{W}^0$	$\tilde{H}^0_a$	$\tilde{H}^0_b$
$\tilde{\chi}^0_1$	0.08%	91%	2.6%	6.1%
$\tilde{\chi}^0_2$	51%	4.7%	27%	17%
$\tilde{\chi}^0_3$	0.1%	0.9%	38%	61%
$\tilde{\chi}^0_4$	48%	3.2%	33%	16%

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

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:

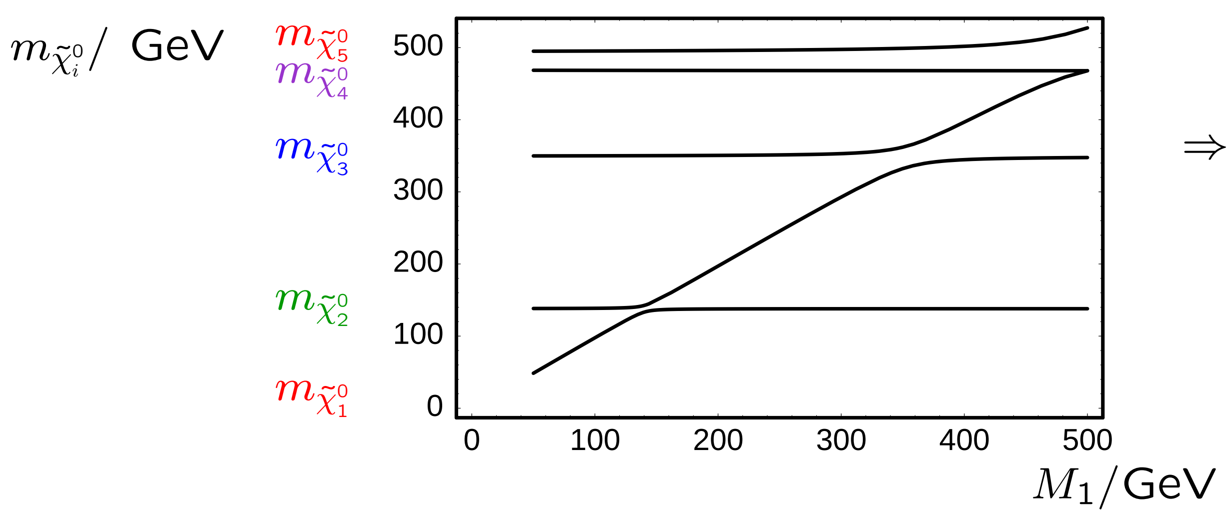
M_2/GeV=147.5±5.3	M_2^{th}=147 GeV
400 < μ/ GeV	μ_{eff} = 458 GeV
1 < tan β	tan β^{th} = 10

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

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

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

- if $m_{\tilde{\chi}_1^0}$ used ⇒ $M_1 < -300$ negativ! ⇒ not consistent with cross section!



⇒ be careful with $m_{\tilde{\chi}_1^0} \to M_1$!

GMP et al. '00

not always the right way!

Parameter determination, cont.

- if $m_{\tilde{\chi}^0_2}$ used:

M_1/GeV=360±21	M_1^{th}=360 GeV
M_2/GeV=148±5	M_2^{th}=147 GeV
μ/GeV=556±155	μ_{eff} = 458 GeV
$1 < \tan\beta$	$\tan\beta^{th} = 10$

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

$\Rightarrow$ 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 or ...?

Predictions, consistent with parameter tuples:

$$m_{\tilde{\chi}^0_3}/\text{GeV} = [410,730]$$
$$m_{\tilde{\chi}^0_4}/\text{GeV} = [420,800]$$
$$m_{\tilde{\chi}^\pm_2}/\text{GeV} = [420,750]$$

$\Rightarrow$ all heavier gauginos/higgsinos larger than 410 GeV!

- Could LHC measure the masses and confirm the model?

$\rightarrow$ heavy gauginos reconstructed in decay chains
e.g. via dilepton edges (strongly dependent on $m_{\tilde{\chi}^0_1}$!)
LC input: $m_{\tilde{\chi}^0_1}$ and mass predictions extremely helpful Desch etal'04, Polesello'

- What do we expect here?

$\Rightarrow$ 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

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

$\Rightarrow$ we assume that $\delta m^{\text{LHC}}_{\tilde{\chi}^0_3} \sim 2\%$: $m_{\tilde{\chi}^0_3} = 367 \pm 7$ GeV from LHC$\leftrightarrow$LC!

$\Rightarrow$ obvious contradiction with LC prediction ($m_{\tilde{\chi}^0_3} > 410$ GeV)!

Motivation for using a further LC option

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

$\rightarrow$ 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	$\sigma(e^+e^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_3^0)$	$\sigma(e^+e^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_4^0)$	$\sigma(e^+e^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_5^0)$
unpolarised	15.1±0.7	6.3±0.4	0.03±0.03
$P(e^-) = -90\%$, $P(e^+) = +60\%$	45.8±1.2	17.1±0.7	0.07±0.05
$P(e^-) = +90\%$, $P(e^+) = -60\%$	0.7±0.1	2.3±0.3	0.009±0.02

$\sqrt{s} = 650$ GeV	$\sigma(e^+e^- \rightarrow \tilde{\chi}_1^{\pm}\tilde{\chi}_2^{\mp})$
unpolarised	27.8±0.9
$P(e^-) = -90\%$, $P(e^+) = +60\%$	83.2±1.6
$P(e^-) = +90\%$, $P(e^+) = -60\%$	2.6±0.3

$\rightarrow$ 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+$\mathrm{LC}_{650}^{\mathcal{L}=1/3}$: strong evidence if deviations from MSSM!

application of more general fits will probably nail down the NMSSM

Further application: apply MSSM strategy on MSSM scenario

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

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

M_2/GeV=152.8±5.3	M_2^{th}=152 GeV
$340<\mu$ GeV<670	$\mu=360$ GeV
$1<\tan\beta<38$	$\tan\beta^{th}=8$

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

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

- if $m_{\tilde{\chi}^0_1}$ used:

M_1/GeV=363±13	M_1^{th}=375 GeV
M_2/GeV=153±2	M_2^{th}=152 GeV
μ/GeV=433±73	$\mu_{eff}=360$ GeV
$1<\tan\beta$	$\tan\beta^{th}=8$

- if $m_{\tilde{\chi}^0_2}$ used:

central value M_1/GeV=37

$\Rightarrow$ everything seems to be very promising!

MSSM scenario: which help could come from LHC?

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

- $\tilde{\chi}^0_3 \sim 99\% \tilde{H}$-like will not be accessible at the LHC
- However, $\tilde{\chi}^0_4 \sim 50\% \tilde{H}$ only, so, there are good chances.

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

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

→ we assume that the LHC can then measure/identify (as in SPS1a) Polesello'

a gaugino particle with

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

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

⇒ Play with both possibilities, determine the parameters, predict the masses and check it experimentally

Further motivation for $\mathrm{LC}_{650}^{\mathcal{L}=1/3}$ 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
   $m_{\tilde{\chi}_4^0}/\mathrm{GeV} = 440 \pm 10$ and $m_{\tilde{\chi}_2^\pm}/\mathrm{GeV} = 427 \pm 9$
   $m^{th}_{\tilde{\chi}_4^0}/\mathrm{GeV} = 410$ and $m^{th}_{\tilde{\chi}_2^\pm}/\mathrm{GeV} = 383$

2. Assuming measured particle is $\hat{m}_{\tilde{\chi}_i^0} = m_{\tilde{\chi}_4^0}$:
   $\Rightarrow$ this assumption leads to the predictions
   $m_{\tilde{\chi}_3^0}/\mathrm{GeV} = 367 \pm 15$ and $m_{\tilde{\chi}_2^\pm}/\mathrm{GeV} = 384 \pm 16$
   $m^{th}_{\tilde{\chi}_3^0}/\mathrm{GeV} = 366$ and $m^{th}_{\tilde{\chi}_2^\pm}/\mathrm{GeV} = 383$

$\longrightarrow$ in both cases sufficient motivation to use $\mathrm{LC}_{650}^{\mathcal{L}=1/3}$
$\longrightarrow$ immediate model verfication/falsification

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

Conclusions:
Crucial Synergy of LHC/LC in Susy Searches

- Example for new physics searches/determination where simultaneous running of $\mathrm{LHC+LC}_{[1.\mathrm{stage},500,650]}$ may be decisive!

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

  - Key points:
    LC: analysis of non-coloured light particle sector
    $\rightarrow$ prediction (!) of heavier states ('Telling the LHC, where to look!')
    LHC: prediction leads to increase of statistical sensitivity!
    test of a fixed hypotheses
    $\Rightarrow$ 'Feeding back to LC analysis'

  - Important consistency tests of the new physics (NP) model at an ear stage! $\Rightarrow$ outline for future search analysis strategies

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

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: Mass Measurement at the LHC: cascade decays

Search for heavy neutralinos at the LHC:

main decay chains for heavy $\tilde{\chi}^0_i$ + background $\longrightarrow$ very tricky analysis!

G. Polesello '04

- $\tilde{\chi}^0_i(q) \to \tilde{\ell}^{\pm}_R(\ell^{\mp}) \to \tilde{\chi}^0_1 \ell^{\pm}$
- $\tilde{\chi}^0_i(q) \to \tilde{\ell}^{\pm}_L(\ell^{\mp}) \to \tilde{\chi}^0_1 \ell^{\pm}$ or $\tilde{\chi}^0_2 \ell^{\pm}$
- $\tilde{\chi}^{\pm}_2(q') \to \tilde{\nu}_\ell(\ell^{\pm}) \to \tilde{\chi}^{\pm}_1 \ell^{\mp}$

$\Rightarrow$ heavy $m_{\tilde{\chi}^0_i}$ edge challenging!

in e.g. scenario SPS1a in combination with invariant masses:

$\Rightarrow$ OS-SF signal derivable

with $\delta(m_{\tilde{\chi}^0_4}) \pm 5.1$ GeV