Distinguishing between MSSM and NMSSM via combined LHC/LC analyses

– ('work in progress') –

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Susy Session

'ECFA04'@Durham, September 2nd, 2004

- The question:
  $\longrightarrow$ MSSM - NMSSM separation with light particles
  $\longrightarrow$ numerical example (including some exp. errors)
  $\longrightarrow$ assumption: no separation@LC_{500} possible
- The answer:
  $\longrightarrow$ LHC/LC interplay
  $\longrightarrow$ 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'04
- Neutralino sector phenomenology Franke'95, Hesselbach'00, '01, Choi'04

MSSM:

- Parameter determination in the general MSSM see all ECFA workshops
- Breaking scheme dependent methods at LHC Rurua'00 (mSUGRA), Allanach'02 (mAMSB)
- Combined analysis at LHC/LC Desch et al. '04

NMSSM$\leftrightarrow$MSSM:

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

  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

$\rightarrow$ how to get experimental hints which model is fulfilled in nature?

$\rightarrow$ strategy for combined analyses at LHC$\leftrightarrow$LC$_{500}$ motivating 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, $\tan\beta$

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

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

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
   $\longrightarrow$ similar masses
   $\longrightarrow$ similar cross sections – although rather large $\tilde{S}$ admixture

2. take into account 'realistic' 'experimental' uncertainties
   $\longrightarrow$ $\delta m \sim 1\%$, motivated by simulation for an 'close'
   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
   $\longrightarrow$ i.e. using 1. light charginos and 2. light neutralinos
   $\longrightarrow$ derive the fundamental MSSM parameters
   $\longrightarrow$ predict the heavier MSSM states

4. Verification/falsification of the predictions with analyses at the LHC
   $\longrightarrow$ feeding back the LHC results into LC analyses

5. If non resolvable contradictions occur:
   $\longrightarrow$ 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:

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

$\Rightarrow$ masses are rather close

$\Rightarrow$ 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

$\Rightarrow$ 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. '04

$\Rightarrow$ 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:

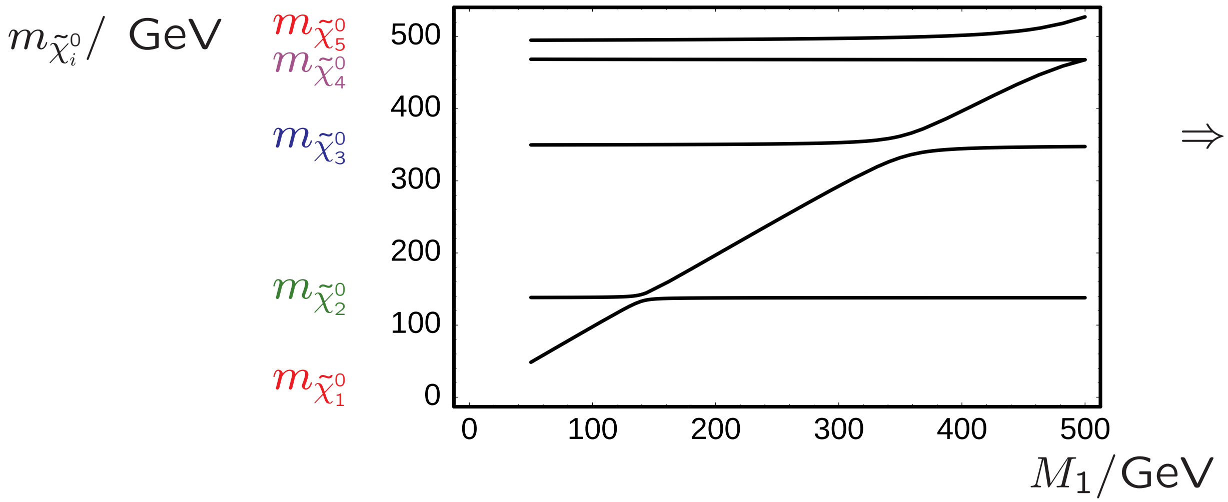
M_2/GeV=147.5±5.3	M_2^{th}=147 GeV
400 $< \mu/$ GeV	$\mu_{eff} = 458$ GeV
1 $< \tan\beta$	$\tan\beta^{th} = 10$

$\rightarrow$ 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 $\Rightarrow M_1 < -300$ negativ! $\Rightarrow$ not consistent with cross section!



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

GMP et al. '00

not always the right way!

Parameter determination, cont.

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

$$
\begin{array}{ll}
M_1/\text{GeV}{=}360{\pm}21 & M_1^{th}{=}360\ \text{GeV} \\
M_2/\text{GeV}{=}148{\pm}5 & M_2^{th}{=}147\ \text{GeV} \\
\mu/\text{GeV}{=}556{\pm}155 & \mu_{eff} = 458\ \text{GeV} \\
1 < \tan\beta & \tan\beta^{th} = 10
\end{array}
$$

$\Rightarrow$ 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:

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

$\Rightarrow$ 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'04

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

$\sqrt{s} = 650$ GeV	$\sigma(e^+e^- \to \tilde{\chi}_1^\pm\tilde{\chi}_2^\mp)$
unpolarised	27.8$\pm$0.9
$P(e^-) = -90\%$, $P(e^+) = +60\%$	83.2$\pm$1.6
$P(e^-) = +90\%$, $P(e^+) = -60\%$	2.6$\pm$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: $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ at $\sqrt{s} = 400$ and 500 GeV and $\tilde{\chi}_1^0\tilde{\chi}_2^0$ at $\sqrt{s} = 500$ GeV

a) Chargino sector: observables $m_{\tilde{\chi}_1^{\pm}}$, $\sigma(\tilde{\chi}_1^{+}\tilde{\chi}_1^{-})|_{400,500}$ 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 $\sigma(\tilde{\chi}_1^0\tilde{\chi}_2^0)|_{500}$ and $m_{\tilde{\chi}_1^0}$ and/or $m_{\tilde{\chi}_2^0} \Rightarrow M_1$:

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

- if $m_{\tilde{\chi}_1^0}$ 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 $m_{\tilde{\chi}_2^0}$ used:

central value M_1/GeV=370

$\Rightarrow$ 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. '04

- $\tilde{\chi}^0_3 \sim 99\%\tilde{H}$-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:

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

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

a gaugino particle with

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

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 $\mathrm{LC}_{650}^{\mathcal{L}=1/3}$ 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 $m^{th}_{\tilde{\chi}_2^\pm}/\mathrm{GeV} = 383$

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

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

Conclusions:
Crucial Synergy of LHC/LC in Susy Searches

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

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

  - Key points:
    LC: analysis of non-coloured light particle sector
    $\longrightarrow$ 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 early stage! $\Rightarrow$ outline for future search analysis strategies

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

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, 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')

App2: Mass Measurement at the LHC: cascade decays

Search for heavy neutralinos at the LHC:

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

G. Polesello '04

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

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

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

$\Rightarrow$ OS-SF signal derivable

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