# Combined Susy analyses at LHC/LC: Mass predictions $\leftrightarrow$ Parameter determination


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in collaboration with

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Susy Session

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- Motivation
- Strategy
  - $\longrightarrow$ LC analysis: prediction of heavy particles
  - $\longrightarrow$ LHC analysis: measurement and feed-back to LC
- Application: numerical example SPS1a
  - $\longrightarrow$ including realistic simulated errors for the observables
- Conclusions

# Synergy of LHC/LC in Susy Searches

- This talk: a 'prototype' example for new physics searches (Susy as an example), where simultaneous running of LHC+$LC_{[1.stage,500]}$ is very important!

  - Key points:
    LC: analysis of non-coloured light particle sector
    $\rightarrow$ prediction (!) of heavier states
    $\Rightarrow$ 'Telling the LHC, where to look!'

    LHC: prediction leads to increase of statistical sensitivity!
    test of a fixed hypotheses instead of many mass hypotheses
    ($\rightarrow$ 'look elsewhere effect')
    LC prediction might be crucial for statistically marginal signals!
    e.g. leads to measurement and identification(!) of heavier states
    $\Rightarrow$ 'Feeding back to LC analysis'

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

# Susy searches in combined LHC/LC analyses

Case study: take Susy scenario SPS1a (mSUGRA like)

(But without imposing any GUT or breaking scheme assumptions!)

- quite favourable point for LHC and LC
- ATLAS and CMS studies exist

  $\rightarrow$ LHC: dominant $\tilde{g}$,$\tilde{q}$ production; other states from cascade decays
- However, mass reconstruction difficult at LHC: decay chains,

  e.g. $\tilde{q}_L \rightarrow q\tilde{\chi}^0_2 \rightarrow \ell^{\pm}_2 \tilde{\ell}^{\mp}_R \rightarrow \ell^{\mp}_1 \tilde{\chi}^0_1$, to some extent also heavy gauginos
- most promising: dilepton edges,

  however strong dependence on lightest Susy particle (here: $m_{\tilde{\chi}^0_1}$)

  $\Rightarrow$ input from LC analysis important

- joint fit of various kinematic 'edges' yields an overconstrained system

$\rightarrow$ but assumptions about particle identities

$\Rightarrow$ consistency tests from LC analysis very desirable...

# Application example for LHC/LC hand-in-hand analysis

LC analysis at first stage with energy up to $\sqrt{s} = 500$ GeV:

- use only production of $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{\chi}_1^+$

→ determine the fundamental parameters $M_1$, $M_2$, $\mu$, $\tan\beta = v_2/v_1$

*Choi, Kalinowski, GMP, Zerwas'01,'02*

→ prediction for $\tilde{\chi}_3^0$, $\tilde{\chi}_4^0$, $\tilde{\chi}_2^\pm$

Procedure:

- Chargino mixing matrix depends on $M_2$, $\mu$, $\tan\beta$
  diagonalised via two mixing angles $\cos 2\Phi_L$, $\cos 2\Phi_R$ *Choi et al '99,'00*
  → observables: masses and cross sections (depend also on $m_{\tilde{\nu}}$!)

- Neutralino mixing matrix depends on $M_2$, $\mu$, $\tan\beta$ and $M_1$
  → observables: masses and cross sections (depend also on $m_{\tilde{e}_L}$, $m_{\tilde{e}_R}$)

- determination of these parameters including
  simulated errors for the scenario SPS1a ($\tan\beta = 10$)!
  → combination of analytical step-by-step and fit procedure

# Step I: analysis at LC@500 GeV for SPS1a

- taking into account only light particles

$\rightarrow$ simulation of determination of light masses (U. Martyn, M. Ball):

| | $\tilde{\chi}_1^\pm$ | $\tilde{\chi}_2^\pm$ | $\tilde{\chi}_1^0$ | $\tilde{\chi}_2^0$ | $\tilde{\chi}_3^0$ | $\tilde{\chi}_4^0$ | $\tilde{e}_R$ | $\tilde{e}_L$ | $\tilde{\nu}_e$ |
|---|---|---|---|---|---|---|---|---|---|
| mass | 176.03 | 378.50 | 96.17 | 176.59 | 358.81 | 377.87 | 143.0 | 202.1 | 186.0 |
| error | 0.55 | | 0.05 | 1.2 | | | 0.05 | 0.2 | 0.7 |

- $e^+e^- \rightarrow \tilde{\chi}_1^+\tilde{\chi}_1^-$: $\sigma_{L,R}(\tilde{\chi}_1^+\tilde{\chi}_1^-) = f(\cos 2\Phi_L, \cos 2\Phi_R, m_{\tilde{\chi}_1^\pm}, m_{\tilde{\nu}_e})$

  with polarised beams $P_{e^-} = \pm 80\%$, $P_{e^+} = \mp 60\%$

| $\sqrt{s} = 400$ GeV | $\sqrt{s} = 500$ GeV |
|---|---|
| $\sigma_L = 215$ fb $\quad \sigma_R = 6$ fb | $\sigma_L = 504$ fb $\quad \sigma_R = 15$ fb |

$\Rightarrow$ magnitude of errors ($\int \mathcal{L} = 100$ fb$^{-1}$ for each configuration):

| | | |
|---|---|---|
| $\delta_{stat}$ | up to | $\sim 4\%$ |
| $\delta_{P(e^\pm)}$ | $\ll$ | $1\%$ $(\sigma_L)$ and $< 2\%$ $(\sigma_R)$ , where $\Delta P(e^\pm)/P(e^\pm) = 0.5\%$ |
| $\delta_{m_{\tilde{\chi}_1^\pm}}$ | up to | $\sim 3\%$ |
| $\delta_{m_{\tilde{\nu}}}$ | $\ll$ | $1\%$ |

# Step I: analysis at LC@500 GeV for SPS1a, cont.

- $e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_2,\ \tilde{\chi}^0_2\tilde{\chi}^0_2$: $\sigma_{L,R}(\tilde{\chi}^0_i\tilde{\chi}^0_j) = f(\cos 2\Phi_L, \cos 2\Phi_R, m_{\tilde{\chi}^\pm_1}, m_{\tilde{\chi}^0_1}, m_{\tilde{e}_{L,R}})$
  with polarised beams $P_{e^-} = \pm 80\%$, $P_{e^+} = \mp 60\%$

| | $\sqrt{s} = 400$ GeV | | $\sqrt{s} = 500$ GeV | |
|---|---|---|---|---|
| $\tilde{\chi}^0_1\tilde{\chi}^0_2$ | $\sigma_L = 148$ fb | $\sigma_R = 20$ fb | $\sigma_L = 168$ fb | $\sigma_R = 21$ fb |
| $\tilde{\chi}^0_2\tilde{\chi}^0_2$ | $\sigma_L = 86$ fb | $\sigma_R = 2$ fb | $\sigma_L = 217$ fb | $\sigma_R = 6$ fb |

$\Rightarrow$ magnitude of errors ($\int \mathcal{L} = 100$ fb$^{-1}$ for each configuration):

| | | |
|---|---|---|
| $\delta_{stat}$ | up to | $\sim 2\%$ $(\sigma_L)$ and $\sim 8 - 16\%$ $(\sigma_R)$ |
| $\delta_{P(e^\pm)}$ | up to | $\ll 1\%$ $(\sigma_L)$ and $< 2\%$ $(\sigma_R)$ , where $\Delta P(e^\pm)/P(e^\pm) = 0.5\%$ |
| $\delta_{m_{\tilde{\chi}^\pm_1}}$ | up to | $\sim 2\%$ |
| $\delta_{m_{\tilde{e}_L}}$ | up to | 0.2% |
| $\delta_{m_{\tilde{e}_R}}$ | up to | 0.1% |

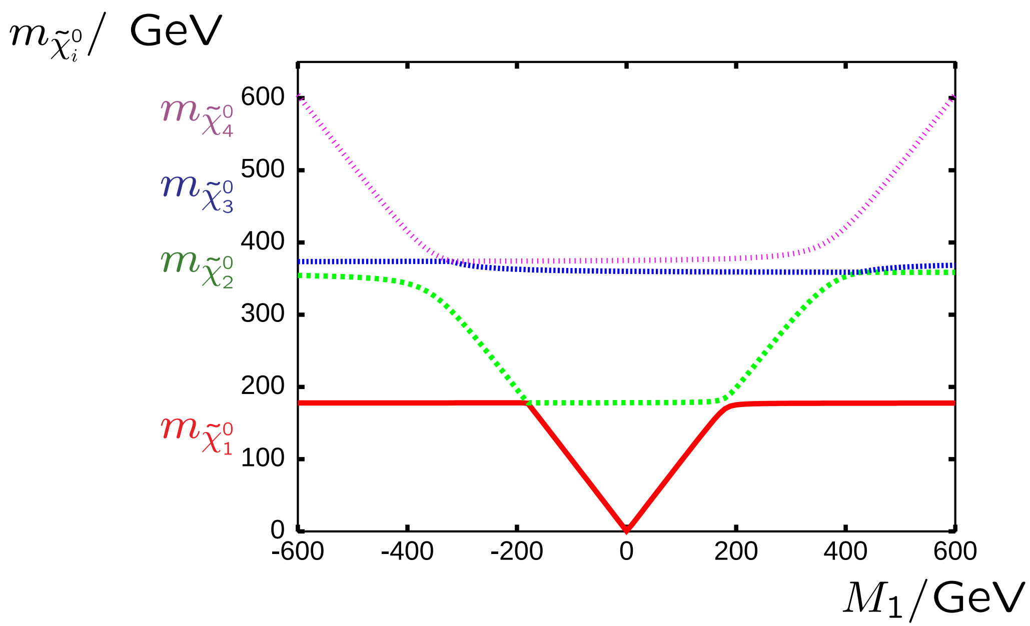
- light particle production: statistical error and error due to $m_{\tilde{\chi}^\pm_1}$ dominating

# One side remark: are neutralino cross section needed?

In principle: only $M_1$ needed from neutralino sector

Often assumed: $M_1$ can be derived from $m_{\tilde{\chi}^0_1}\ldots$ That is not true!

GMP, Bartl, Fraas, Majerotto '00




- other possibility: characteristic equation for $m^2_{\tilde{\chi}^0_i}$: quadratic in $M_1$

$\longrightarrow$ theoretically only two masses needed, in principle,...

$\Rightarrow$ cross sections needed for unique solution!

# Step I: analysis at LC@500 GeV for SPS1a, cont.

Results from the 3-parameter fit of this analytically based procedure:

| SPS1a scenario (all masses in GeV) | | | | | | | |
|---|---|---|---|---|---|---|---|
| | $M_1$ | $M_2$ | $\mu$ | $\tan\beta$ | $m_{\tilde{\chi}^\pm_2}$ | $m_{\tilde{\chi}^0_3}$ | $m_{\tilde{\chi}^0_4}$ |
| theo | 99.1 | 192.7 | 352.4 | 10 | 378.5 | 358.8 | 377.9 |
| $LC_{500}$ | Susy parameters | | | | Resulting Predictions | | |
| | $99.1 \pm 0.2$ | $192.7 \pm 0.6$ | $352.8 \pm 8.9$ | $10.3 \pm 1.5$ | $378.8 \pm 7.8$ | $359.2 \pm 8.6$ | $378.2 \pm 8.1$ |

⇒ Results confirmed by P. Bechtle&P. Wienemann and K. Desch: global fit with program 'Fittino'!

⇒ quite accurate predictions for the LHC analysis!

What's going on at the LHC?

# Mass Measurement at the LHC: cascade decays

Search for heavy neutralinos at the LHC:

main decay chains for $\tilde{\chi}_4^0$ + background $\rightarrow$ very tricky analysis!

- $\tilde{\chi}_4^0(q) \rightarrow \tilde{\ell}_R^{\pm}(\ell^{\mp}) \rightarrow \tilde{\chi}_1^0 \ell^{\pm}$
- $\tilde{\chi}_4^0(q) \rightarrow \tilde{\ell}_L^{\pm}(\ell^{\mp}) \rightarrow \tilde{\chi}_1^0 \ell^{\pm}$ or $\tilde{\chi}_2^0 \ell^{\pm}$
- $\tilde{\chi}_2^{\pm}(q') \rightarrow \tilde{\nu}_\ell(\ell^{\pm}) \rightarrow \tilde{\chi}_1^{\pm} \ell^{\mp}$

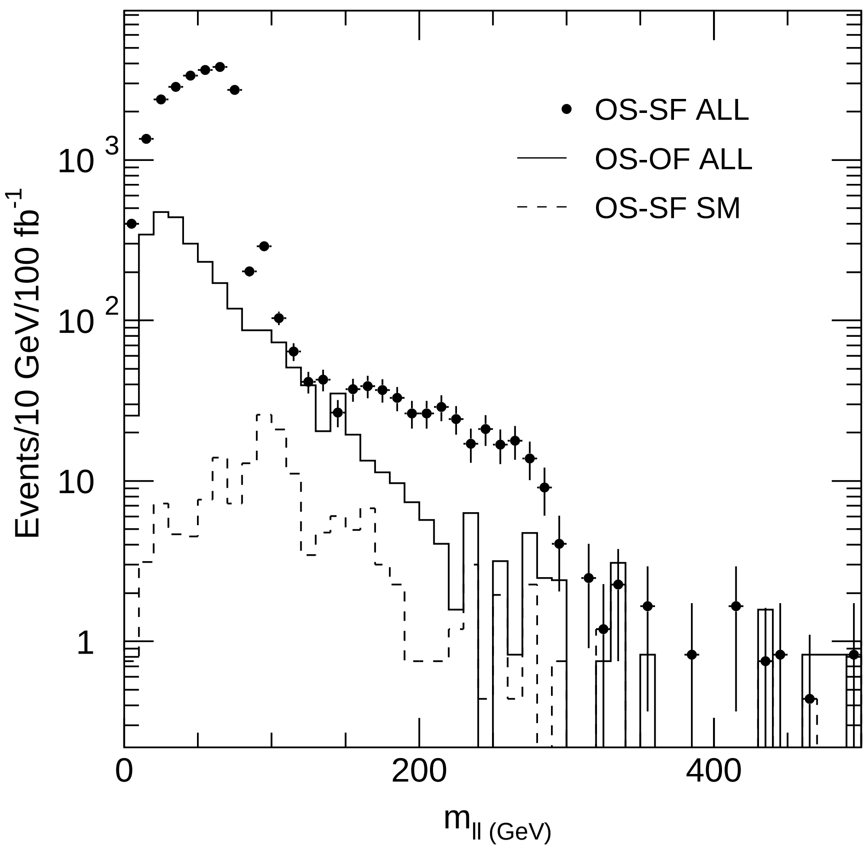
$\Rightarrow$ $m_{\tilde{\chi}_4^0}$ edge challenging!

in combination with invariant masses:

$\Rightarrow$ OS-SF signal derivable

with $\delta(m) \pm 5.1$ GeV

G. Polesello '04



# Step 2 – combined analysis with LHC/LC(500)

LC output: 'Telling the LHC, where to look!'
Prediction of the heavier $m_{\tilde{\chi}^0_4} = 378.2 \pm 8.1$ GeV

feed in LHC analysis:

a) using precisely measured light particles $m_{\tilde{\chi}^0_1}$, $m_{\tilde{\chi}^\pm_1}$, $m_{\tilde{e}_{L,R}}$, $m_{\tilde{\nu}}$

b) increase of statistical sensitivity due to LC prediction ('look elsewhere effect')
$\rightarrow$ might be crucial for such stat. marginally signals!

leads to LHC output:

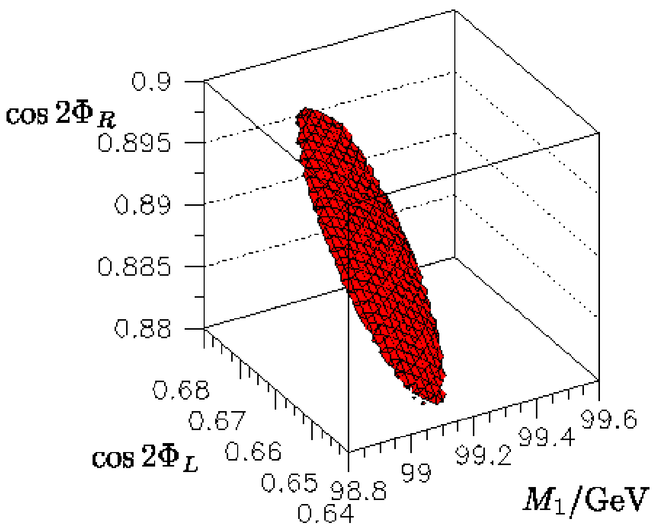
a) precise measurement of $m_{\tilde{\chi}^0_2}$:
$\Rightarrow \delta(m_{\tilde{\chi}^0_2}) = 0.08$ GeV!

b) '$\tilde{\chi}^0_4$' story:
now clear identification of $\tilde{\chi}^0_4$ edge followed by a precise measurements
$\Rightarrow m_{\tilde{\chi}^0_4} = 377.87 \pm 2.23$ GeV

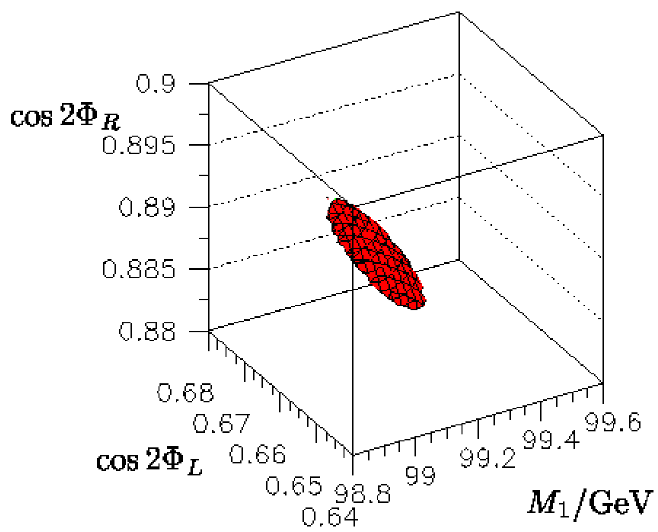
$\Rightarrow$ important model check with LC prediction!
$\Rightarrow$ feeding back precise mass measurements to LC analysis

# Step 2 – combined analysis withLHC/LC(500),cont.

$LC_{500}$ only




LHC+$LC_{500}$ combined




| | $M_1$ | $M_2$ | $\mu$ | $\tan\beta$ |
|---|---|---|---|---|
| theo | 99.1 | 192.7 | 352.4 | 10 |
| $LC_{500}$ | $99.1 \pm 0.2$ | $192.7 \pm 0.6$ | $352.8 \pm 8.9$ | $10.3 \pm 1.5$ |
| LHC+$LC_{500}$ | $99.1 \pm 0.1$ | $192.7 \pm 0.3$ | $352.4 \pm 2.1$ | $10.2 \pm 0.6$ |

$\Rightarrow$ precise results, without assuming a specific breaking scheme!

## Conclusions: Promising 'hand-in-hand' LHC/LC procedures!

- Susy (as an example for tricky new physics searches) greatly benefits from synergy of combined LHC and LC analyses

- LHC: edges of heavier non-coloured states quite tricky
  suppose, there is statistically marginal signal right at the LC prediction

⇒ optimised search at the LHC

⇒ clear identification and precise measurement possible or possible LHC upgrades: call for more luminosity (?), ...

- LHC/LC combined analysis: precise ('loop level') Susy parameter determination without assuming a specific Susy breaking scheme!

- LC prediction is prototype example for LHC/LC synergy effects

→ Outlook: study of 'more difficult' scenarios for both machines

- further examples: LHC/LC study group report ($\geq$ 400 pages!)

→ LHC/LC webpage: http://www.ippp.dur.ac.uk/~georg/lhclc

# Motivation: Why LHC/LC studies?

- LHC and LC physics is complementary in many respects

$\Rightarrow$ Mutual benefits for physics program of both machines expected:
  a) What is the benefit if both machines are interpreted simultaneously?
  b) What do we learn more, if both machines have overlapping running time? ('cover more physics space'?)

- LHC: start $\geq$ 2007, expected to run for O(20) years

- LC: $\geq$ 2015(?), starting with $\sqrt{s} = 500$ GeV$\rightarrow\sim 1$ GeV

- LHC/LC study group: world–wide working group, started in 2002

$\rightarrow$ collaborative effort of Hadron collider and Linear collider communities

## Supersymmetry (very short)

- one of the best motivated extensions of the Standard Model (SM)

- Susy transformations:

$$\begin{array}{lcl} [e,\mu,\tau]_{L,R} & \leftrightarrow & [\tilde{e},\tilde{\mu},\tilde{\tau}]_{L,R} \\ [\gamma, Z^0, W^{\pm}, g] & \leftrightarrow & [\tilde{\gamma},\tilde{Z},\tilde{W},\tilde{g}] \\ [H_1, H_2] & \leftrightarrow & [\tilde{H}_1,\tilde{H}_2] \end{array}$$

- since $m_p \neq m_{\tilde{p}} \Rightarrow$ Susy is broken

→ leads to a large amount of new free parameters
(MSSM $\sim$ 105 parameters!)

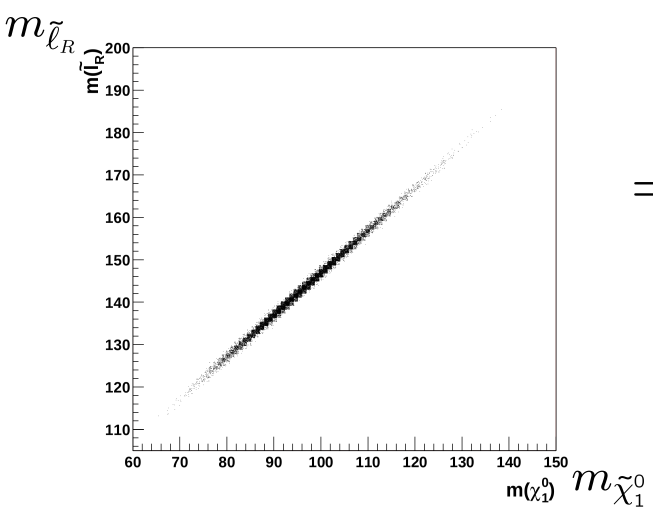
→ assumptions about Susy breaking mechanism leads to
GUT assumptions and parameter reduction:
m(inimal)SUGRA: 5, mGMSB: 5, mAMSB: 4 parameters

- particular demanding searches for new physics

→ tasks for experiments: detection as well as
determination 'without' model assumptions!

# LHC analysis with LC input: mass of $\tilde{\chi}_1^0$

Reconstruction of the states in decay chain requires precise knowledge of LSP $\tilde{\chi}_1^0$ mass:




$\Rightarrow$ Precision measurement of $m_{LSP}$ leads to significant improvement in determination of $\tilde{\ell}$, $\tilde{q}$ and $\tilde{g}$ masses at the LHC

- joint fit of various kinematic 'edges' yields an overconstrained system

$\rightarrow$ but assumptions about particle identities

$\Rightarrow$ consistency tests from LC analysis very desirable...

## Some more details: Errors in $\sigma_{L,R}(\tilde{\chi}^0_i\tilde{\chi}^0_j)$, cont.

Remark: simulation for unpolarised beams (M. Ball@K. Desch)

- efficiency 25%

→ 'scaling' the stat. error for the polarised case with

  - the same efficiency
  - $\delta\sigma/\sigma = \sqrt{S+B}/S$

- uncertainty in background processes: adding $\delta\sigma_{bg}$
  (respectively to their relative contribution)

What's about $\tilde{\chi}^0_2\tilde{\chi}^0_2$ production?

- no simulation exists so far
- 'multiple' $\tau$'s in the final state
- but quite 'background save'

⇒ estimate efficiency of 15%