# LHC / LC Study Group Report

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IPPP Durham

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Worldwide Study of the Physics and Detectors for Future Linear $e^+e^-$ Colliders

www.ippp.dur.ac.uk/~georg/lhclc

# *1. Introduction*

*What does the LHC / LC Study Group do?*

- LHC / LC interplay: investigate how analyses at the LHC could profit from results obtained at a LC and vice versa

  $\Rightarrow$ mutual benefits for physics program at both machines

- Started in spring 2002 as a world-wide working group

- Collaborative effort of Hadron Collider and Linear Collider communities

# *Why now?*

Preparations for LHC physics currently move from first step:

Discovery Physics

to spectroscopy: determination of properties of physics beyond (and within) the SM

$\Rightarrow$ Design of experimental strategies

- Make LHC community aware of what kind of additional information might become available once the LC kicks in
- Transfer of knowledge, strategies for parameter determinations, etc. in both directions
- If LC gets in operation in time, LC results could influence detector, trigger, . . . choices at LHC upgrades

# *How do LHC / LC studies work?*

LHC / LC combined studies need collaboration of experimentalists from both LHC and LC and of theorists

It is difficult for experimentalists working at the LHC to find time to work on LC physics  and vice versa

$\Rightarrow$ many thanks to the experimentalists who are involved in this enterprise: your effort is very much appreciated!

Studies of LHC / LC interplay make it necessary to look at analyses from a different perspective than pure LHC or LC studies

$\Rightarrow$ it's fun!

# *How far are we?*

- We had six working group meetings so far (most at CERN)
- A lot of activity during Les Houches 2003 Workshop
- Draft of first working group report exists:

  $\approx$ 400 pages

  $\approx$ 40 individual contributions

  107 contributing authors

- Currently going through editorial process
- Editors: T. Barklow, E. Boos, A. De Roeck, D. Denegri, K. Desch, H. Haber, F. Gianotti, R. Godbole, J. Gunion, S. Heinemeyer, J. Hewett, K. Kawagoe, K. Mönig, M. Nojiri, F. Paige, G. Polesello, F. Richard, S. Riemann, H. Schellman, W.J. Stirling P. Zerwas, G. W.
- Requests for updates / modifications are being sent to authors; deadline for updates: Dec. 15
- Next meeting: early next year, CERN
  precise date will appear on
  `www.ippp.dur.ac.uk/~georg/lhclc`

# 2. Determination of SUSY parameters at LHC / LC

## *Reconstruction of sparticle masses at the LHC*

[*M. Chiorboli, B.K. Gjelsten, J. Hisano, K. Kawagoe, E. Lytken, U. Martyn, D. Miller, M. Nojiri, P. Osland, G. Polesello, A. Tricomi '03*]

Production of SUSY particles at LHC $\Rightarrow$ complicated final states,

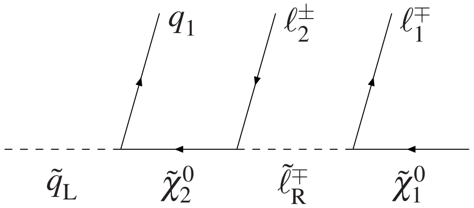
e.g.: $\tilde{g} \to \bar{q}\tilde{q} \to \bar{q}q\tilde{\chi}_2^0 \to \bar{q}q\tilde{\tau}\tau \to \bar{q}q\tau\tau\tilde{\chi}_1^0$

Production of uncolored particles via cascade decays often dominates over direct production

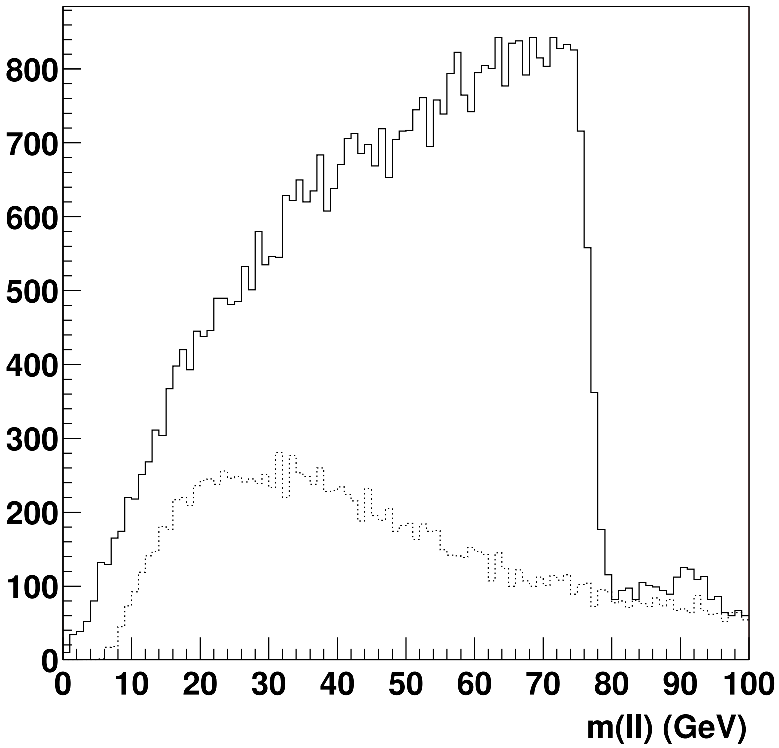
Many states are produced at once

# *Reconstruction of sparticle masses at the LHC*

Cascade decays: complicated decay chains for squarks and gluinos

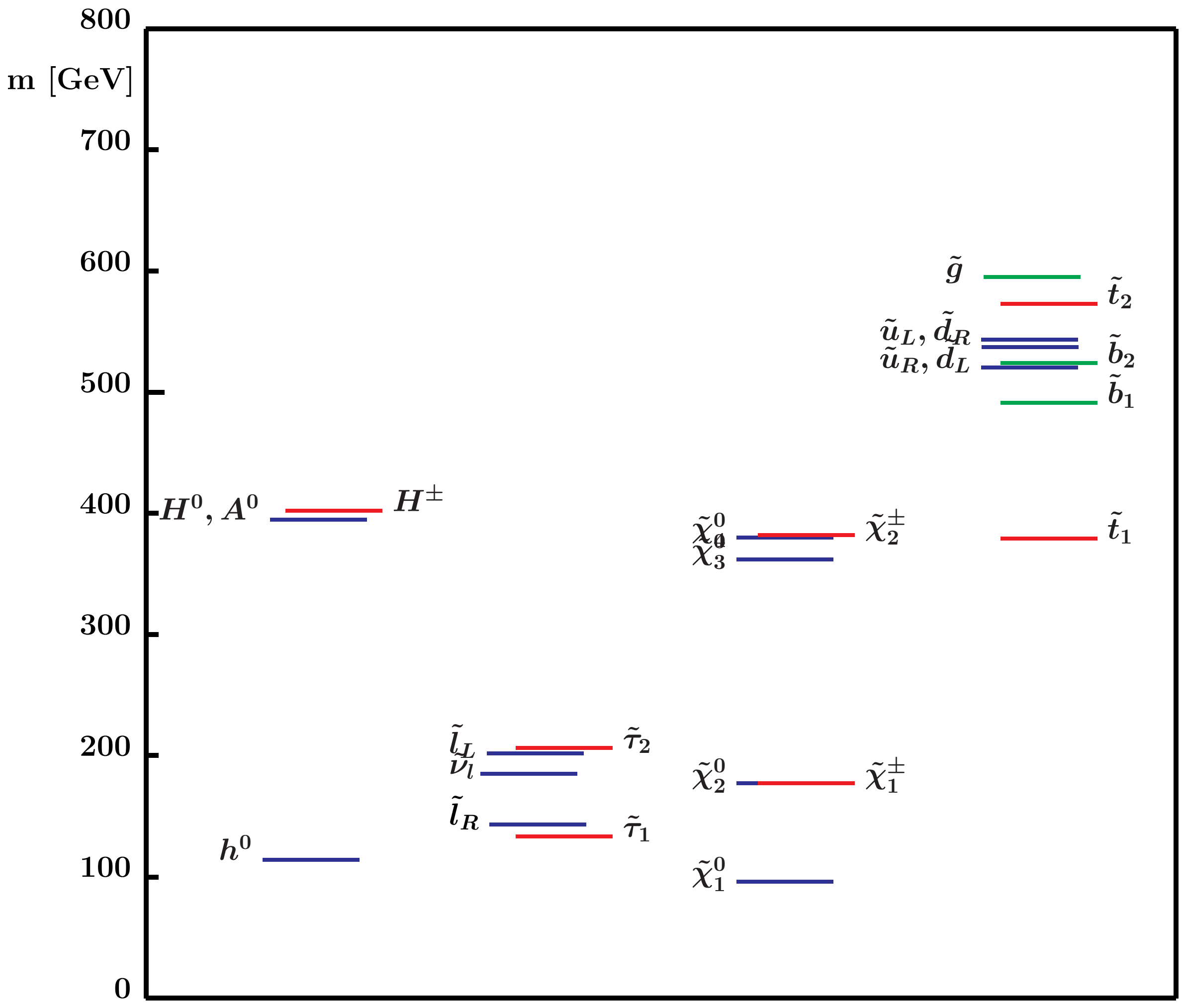



Main tool: dilepton "edge" from $\tilde{\chi}_2^0 \to \ell^+\ell^-\tilde{\chi}_1^0$



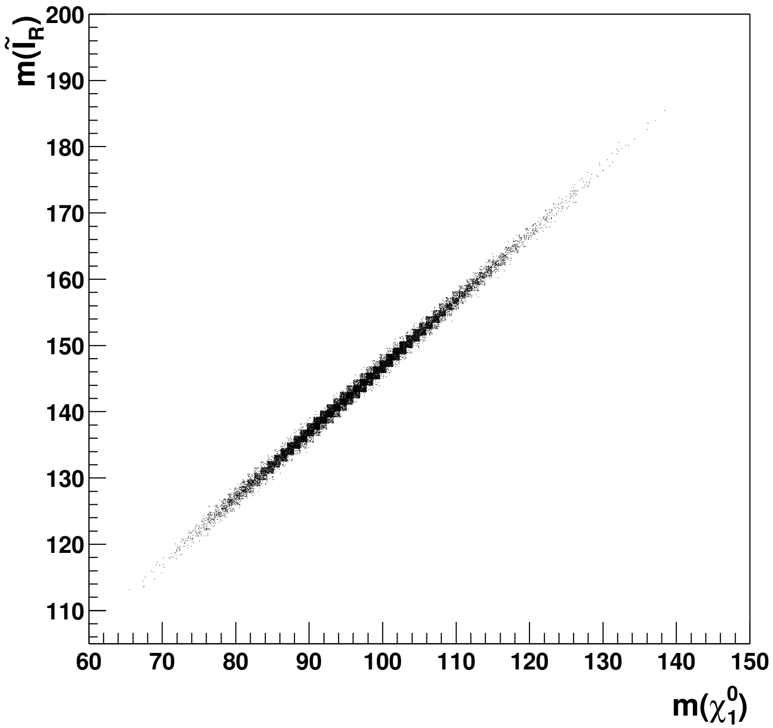

Examples worked out for SPS1a from ATLAS and CMS

# *Mass spectrum in SPS1a scenario*




$\Rightarrow$ Favourable scenario for both LHC and LC

## *Strong correlation between slepton mass and LSP mass, LSP mass can be constrained at LHC at the 10% level only:*



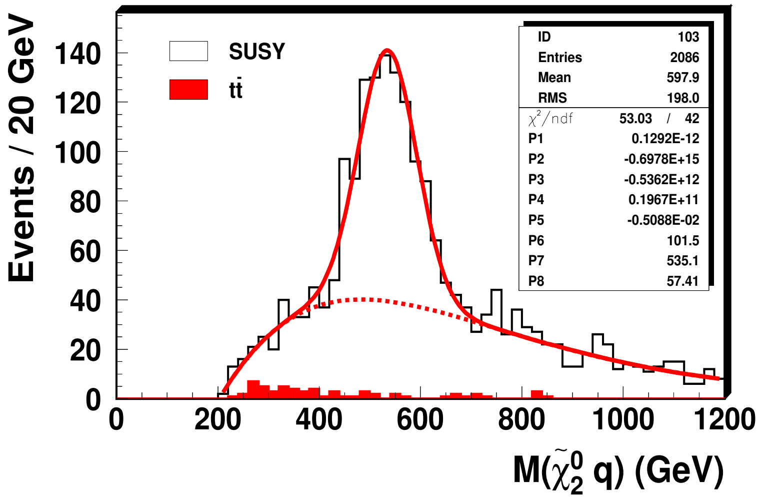

$\Rightarrow$ Take LSP mass as input from LC

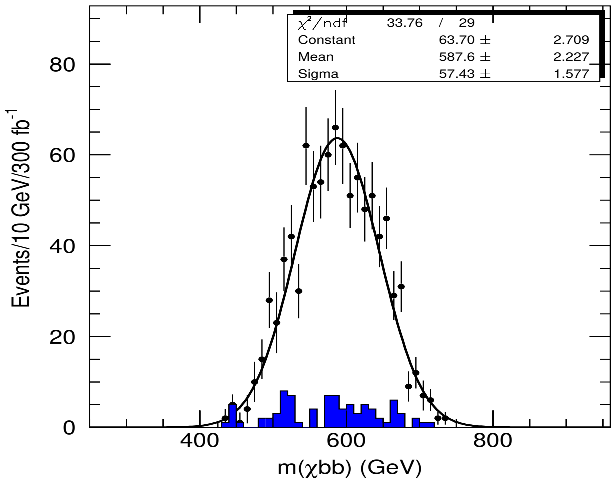
$$\vec{p}(\tilde{\chi}_2^0) = \left(1 - \frac{m(\tilde{\chi}_1^0)}{m(\ell\ell)}\right) \vec{p}_{\ell\ell}$$

$\Rightarrow$ Get sbottom/squark mass if LSP mass is known

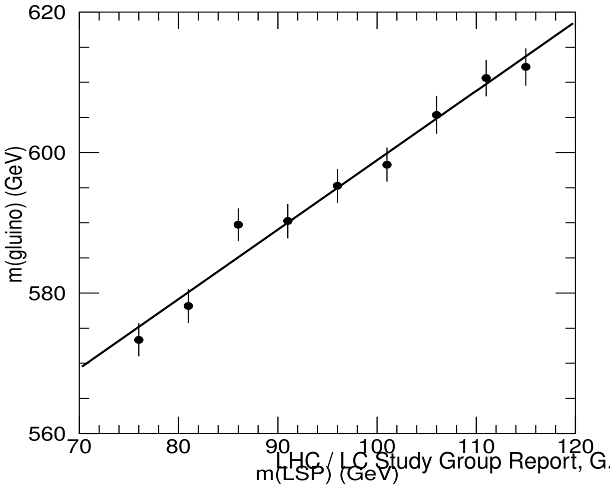
# *Squark and gluino reconstruction*

Squark peak (left) and gluino reconstruction from $(\chi_2^0 bb)$ invariant mass distribution (right):



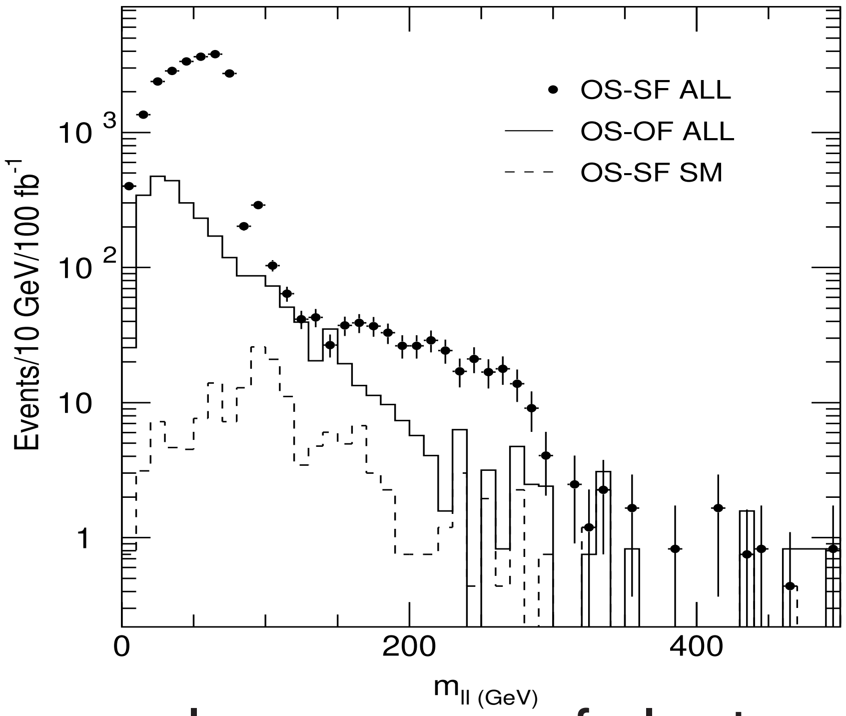




$m_{\tilde{g}}$ as function of the LSP mass:



# Determination of the mass of the heaviest neutralino at the LHC using LC input from the neutralino/chargino sector

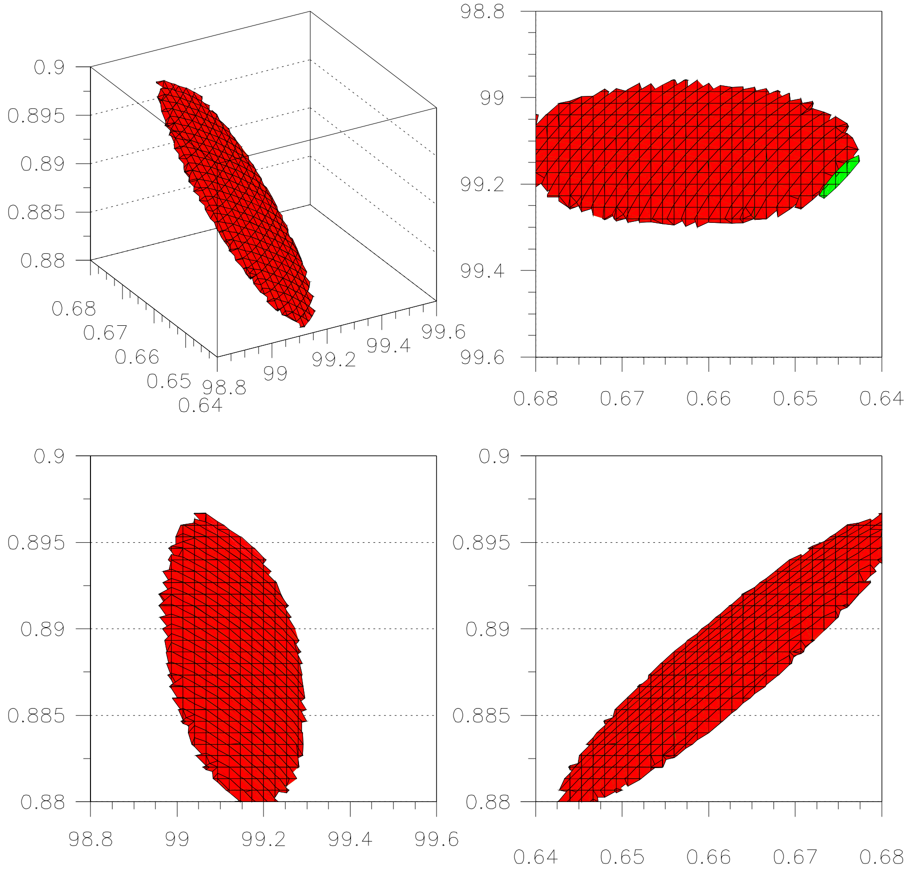
[K. Desch, J. Kalinowski, G. Moortgat-Pick, M. Nojiri, G. Polesello '03]



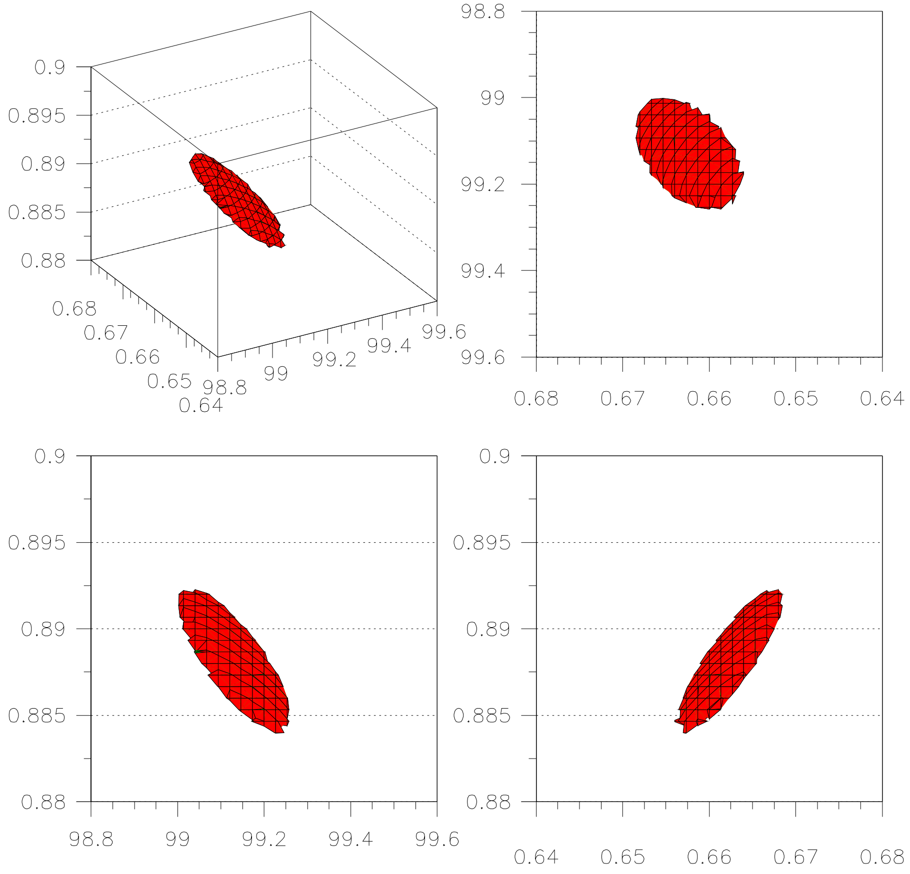

$\Rightarrow$ Need besides $m_{\mathrm{LSP}}$ also masses of sleptons, charginos from LC to correctly identify $\tilde{\chi}_4^0$; LC prediction: $m_{\tilde{\chi}_4^0} = 378.3 \pm 8.8$ GeV

# *Determination of neutralino parameter $M_1$ and chargino mixing angles $\cos\phi_L$, $\cos\phi_R$ ($\Delta\chi^2 = 6$ contours)*

## LC information alone




## LHC + LC information



## *Dedicated effort: detailed analysis for SPS1a on potential of LHC (300 fb$^{-1}$) alone and LHC $+$ LC*

| | LHC | LHC+LC |
|---|---|---|
| $\Delta m_{\tilde{\chi}_1^0}$ | 4.8 | 0.05 (input) |
| $\Delta m_{\tilde{l}_R}$ | 4.8 | 0.05 (input) |
| $\Delta m_{\tilde{\chi}_2^0}$ | 4.7 | 0.08 |
| $\Delta m_{\tilde{q}_L}$ | 8.7 | 4.9 |
| $\Delta m_{\tilde{q}_R}$ | 11.8 | 10.9 |
| $\Delta m_{\tilde{g}}$ | 8.0 | 6.4 |
| $\Delta m_{\tilde{b}_1}$ | 7.5 | 5.7 |
| $\Delta m_{\tilde{b}_2}$ | 7.9 | 6.2 |
| $\Delta m_{\tilde{l}_L}$ | 5.0 | 0.2 (input) |
| $\Delta m_{\tilde{\chi}_4^0}$ | 5.1 | 2.23 |

$\Rightarrow$ LC input improves accuracy significantly

# *Full reconstruction of stop/sbottom parameters using LHC / LC interplay*

[*J. Hisano, K. Kawagoe, M. Nojiri '03*]

- Take the set of electroweak SUSY parameters determined by the LC and LHC data
- Take ratios of branching ratios of $\tilde{\mathrm{b}}$ / $\tilde{\mathrm{t}}$ measured at the LHC
- Take $m_{\tilde{\mathrm{b}}_1}$, $m_{\tilde{\mathrm{b}}_2}$ from edge study (using LC input on LSP mass)

Measure:

– $tb$ invariant mass distribution

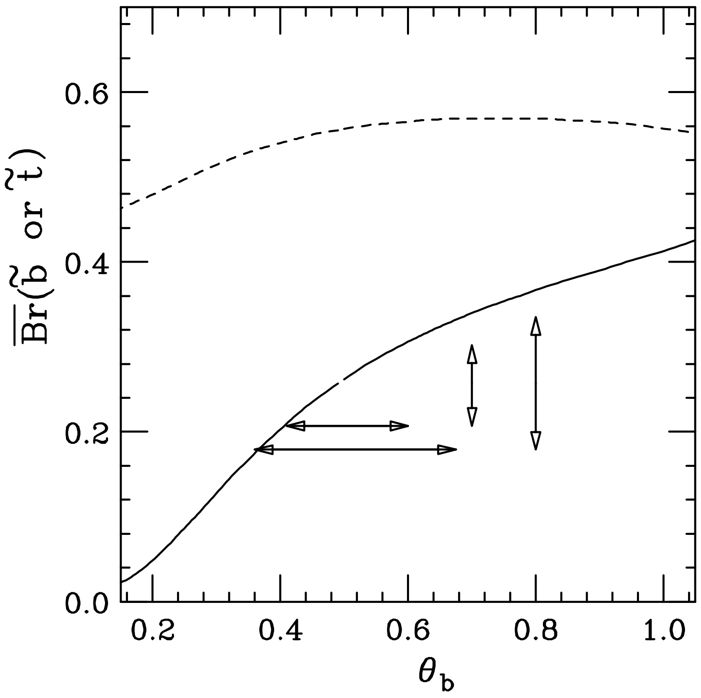
– rate of "edge-events" in $m_{\mathrm{tb}}$ distribution (chargino chain)

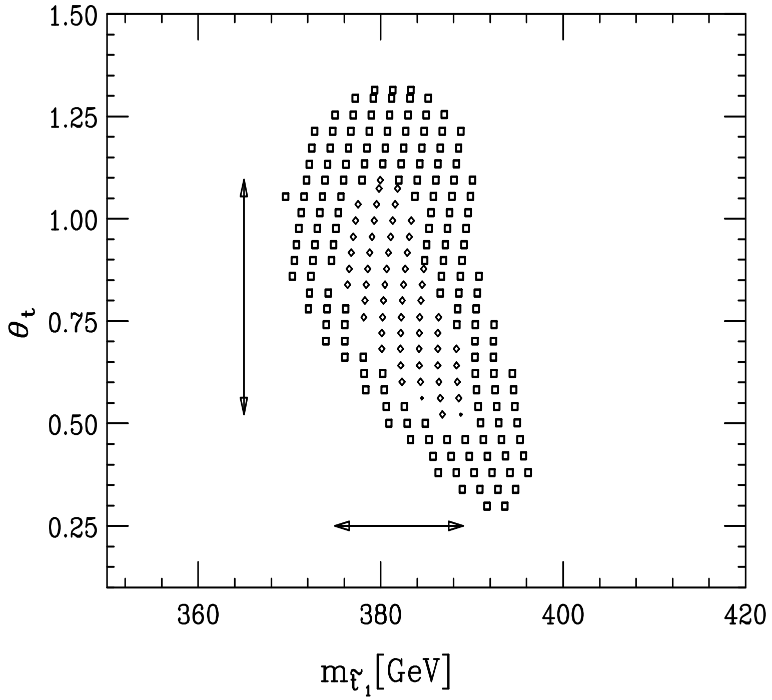
– rate of events in $\ell\ell b$ distribution ($\tilde{\chi}_2^0$ chain)

$\Rightarrow$ If chargino couplings $+$ BR's are known then observed rates are sensitive to sbottom/stop mixing parameters

## Determination of $\theta_{\tilde{\mathrm{b}}}$, $m_{\tilde{\mathrm{t}}_1}$, $\theta_{\tilde{\mathrm{t}}}$ in SPS1a

- Det. of $\theta_{\tilde{\mathrm{b}}}$ from $\mathrm{BR}(\tilde{g} \to b\tilde{b}_2 \to bb\tilde{\chi}_2^0)/\mathrm{BR}(\tilde{g} \to b\tilde{b}_1 \to bb\tilde{\chi}_2^0)$ (left)
- Det. of $m_{\tilde{\mathrm{t}}_1}$, $\theta_{\tilde{\mathrm{t}}}$ assuming also $\theta_{\tilde{\mathrm{b}}}$ is known (right)



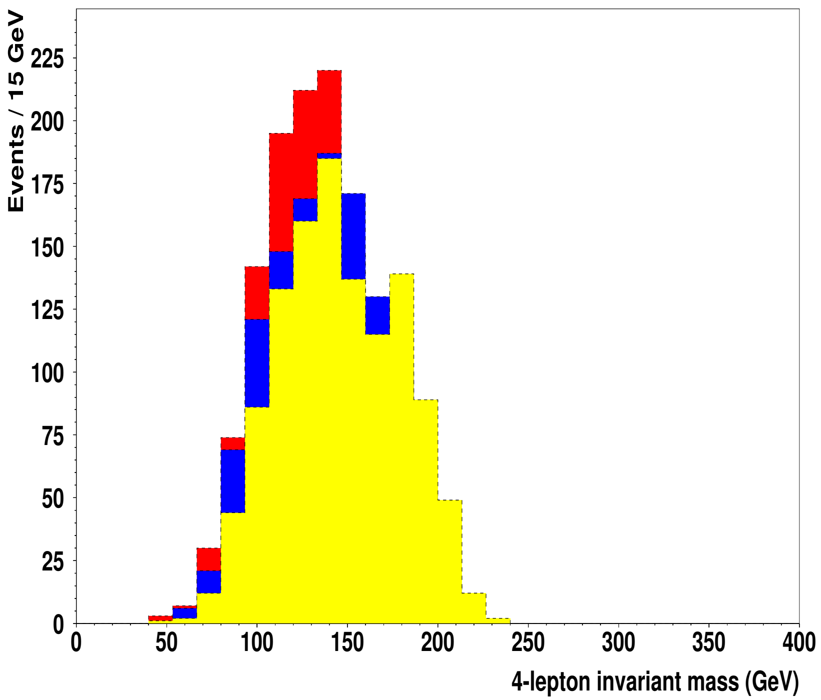



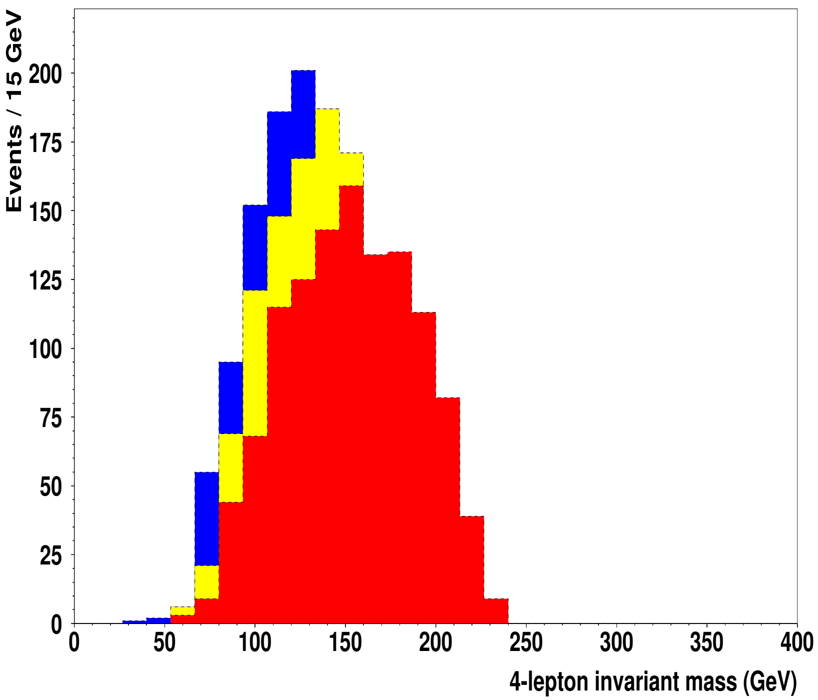

$\Rightarrow$ $\mathcal{O}(50\%)$ determination of mixing angles, $\Delta m_{\tilde{\mathrm{t}}_1}/m_{\tilde{\mathrm{t}}_1} < 5\%$

# Determination of $M_{\rm A}$ from heavy Higgs decays into SUSY particles at the LHC

[*F. Moortgat '03*]

$H, A \to \tilde{\chi}^0_2 \tilde{\chi}^0_2$: Four lepton invariant mass distribution for $M_{\rm A} = 350 \pm 20$ GeV (left) and $M_1 = 60 \pm 10$ GeV (right)



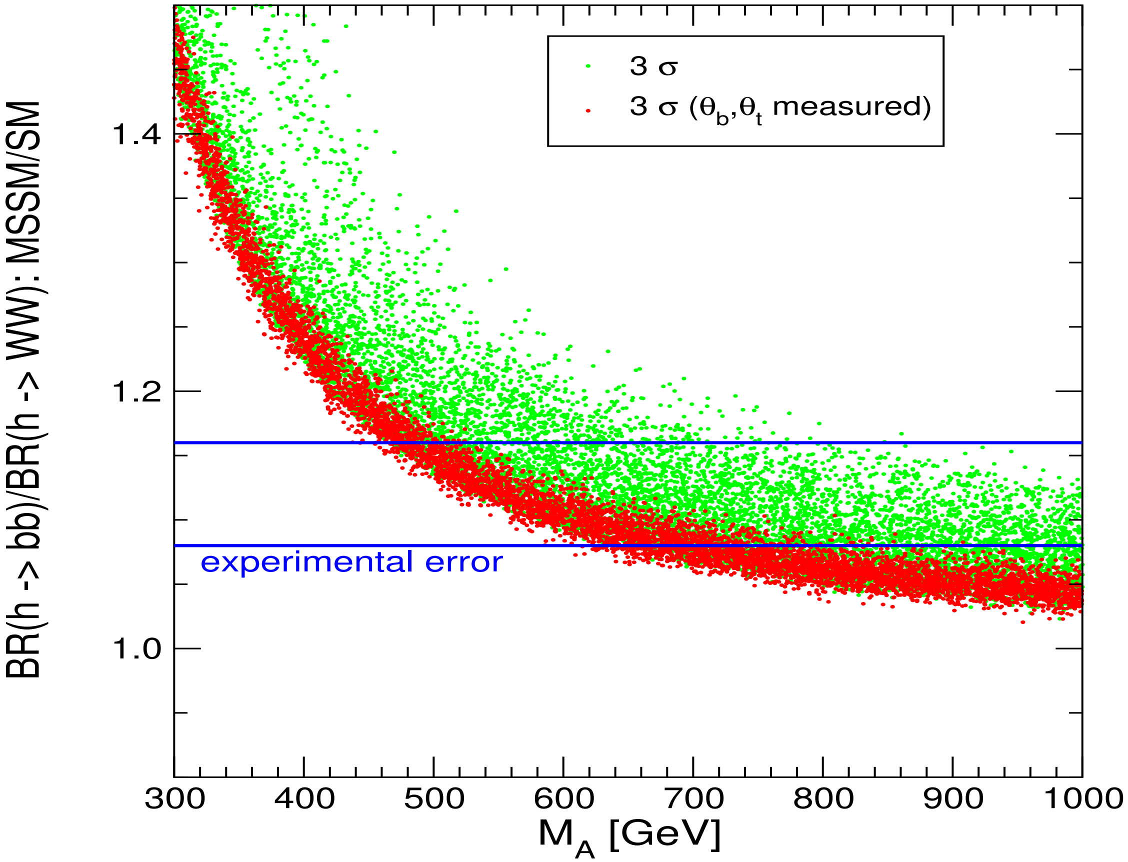

$\Rightarrow$ Precise knowledge of LSP mass from LC crucial for determination of $M_{\rm A}$

## *Indirect constraints on $M_{\rm A}$ from Higgs BR measurements at the LC using LHC / LC input*

[*K. Desch, E. Gross, S. Heinemeyer, G.W.*]

LC measurement of

$$\left[\mathrm{BR}(h \to b\bar{b})/\mathrm{BR}(h \to WW^*)\right]_{\rm MSSM} / \left[\mathrm{BR}(h \to b\bar{b})/\mathrm{BR}(h \to WW^*)\right]_{\rm SM}$$




Higgs BRs from LC measurements

Parameters of $\tilde{\rm t}$ / $\tilde{\rm b}$ sector from LHC / LC analysis

Comparison:

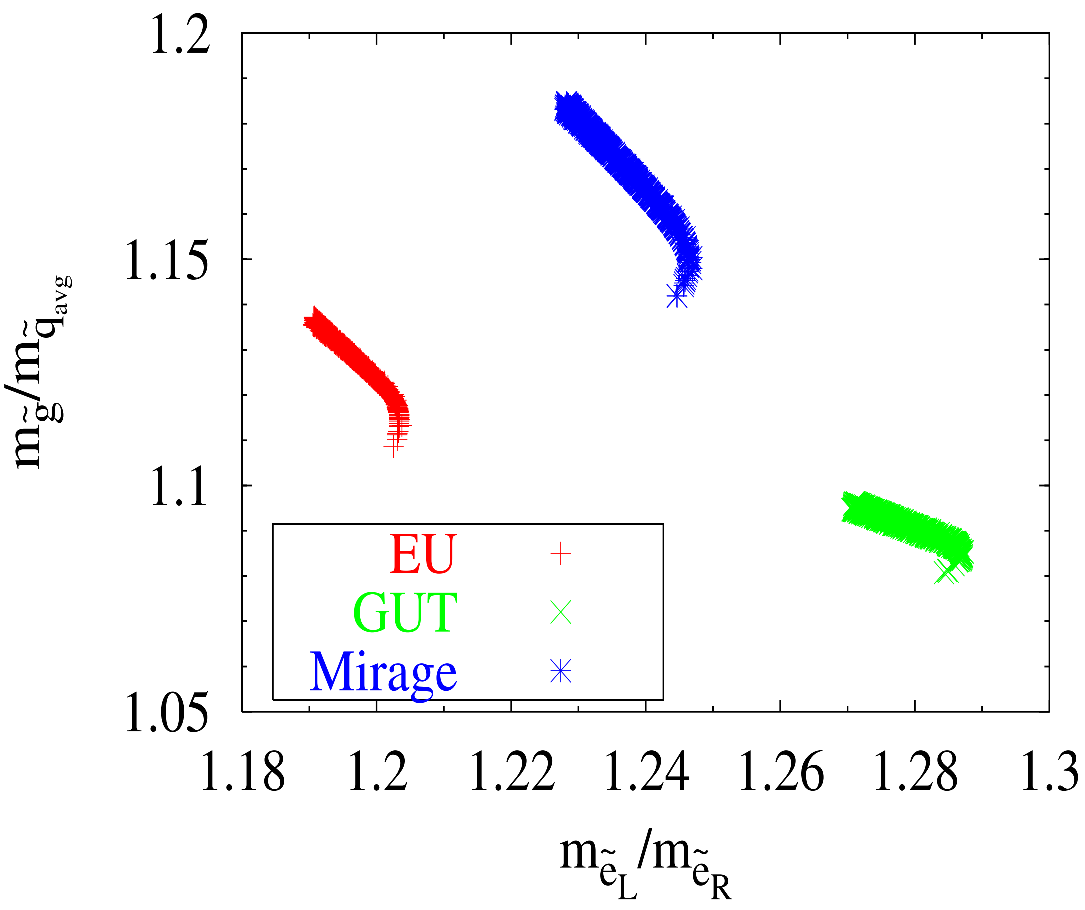
no experimental information on $\theta_{\tilde{\rm b}}$, $\theta_{\tilde{\rm t}}$

$\Delta\theta_{\tilde{\rm b}} = 20\%$, $\Delta\theta_{\tilde{\rm t}} = 10\%$

⇒ Knowledge of $\tilde{\rm t}$ / $\tilde{\rm b}$ sector parameters is crucial

# *Discrimination between different SUSY-breaking scenarios*

[*B. Allanach, D. Grellscheid, F. Quevedo '03*]




⇒ Need %-level accuracy to distinguish between different models

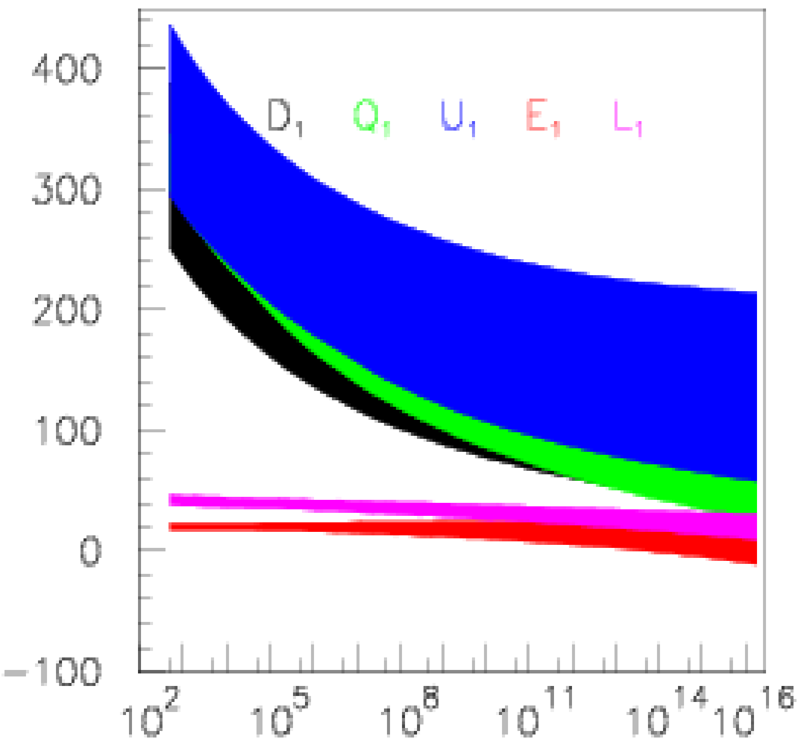
# *Extrapolation to physics at high scales*

[*G. Blair, U. Martyn, G. Polesello, W. Porod, P. Zerwas '03*]

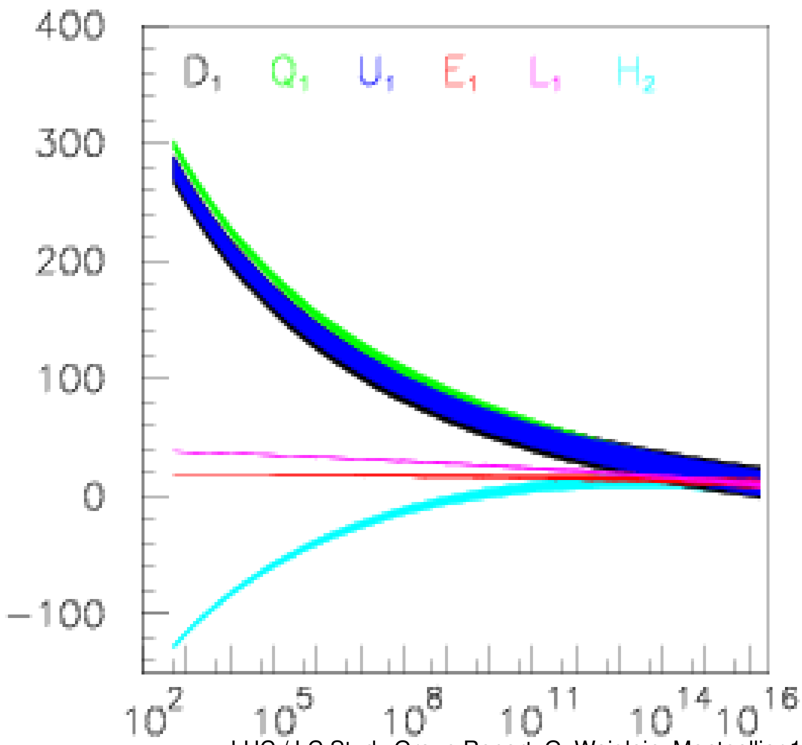
from combination of LHC and LC results, precise measurement of masses of SUSY particles, couplings

E.g.: evolution of first-gen. sfermion and Higgs mass parameters

LHC




LHC $\oplus$ LC



# *Some open issues*

- What is the theoretical uncertainty of Monte Carlo simulation of distributions, edges, etc.?

  Effects of initial / final state radiation?

- SPS1a is a rather favourable scenario both for LHC and LC

  What is the LHC / LC mutual benefit in a more difficult scenario?

# 3. Conclusions

- First LHC / LC working group document is on a good way:
  full draft will be circulated soon
- I have focussed on only one example here, there are many more interesting results that I couldn't cover in this talk:

  Higgs, electroweak and QCD precision physics, strong electroweak symmetry breaking, new gauge theories, extra dimensions, exotics, . . .
- Work does not stop here – we have just scratched the surface so far; certainly more ideas will come when we dig a bit deeper
- LHC / LC interplay is a very rich field – and a lot of fun