Synergy effects of LHC and ILC

Learning from experience

In the past it was often beneficial for particle physics
to have several experimental tools available simultaneously
to assess closely related questions.

Latest example:

LEP+SLC+Tevatron led to many success stories

- EW standard model at quantum level
- top quark
- QCD
- prediction of (SM) Higgs mass

If we want to formulate a scientific roadmap for particle physics,
we must look at the physics potential of future facilities in a coherent
fashion. (not only accelerator-based, see cosmic connection; but
we should look at the accelerator-based projects in the first place)

Synergy effects of LHC and ILC

The scientific questions to be studied in the LHC/ILC group:

0. Compare the physics reach of the machines
   (this is a preparatory exercise of the real thing, but very helpful still)

1. What will we learn if information from the machines are interpreted simultaneously??

$$\mathrm{LHC} \oplus I\mathrm{LC}$$

2. Will we learn more (or cover more of the "physics space") if LHC and ILC operation will overlap in time?

$$\mathrm{LHC} \otimes I\mathrm{LC}$$

LHC/ILC study group

These questions have started to be investigated in the

LHC/ILC study group

formed in Spring 2002
acknowledged by ICFA
Coordinator: G. Weiglein

Collaborative effort of LHC+LC exp. communities and theory/pheno

First report published (hep-ph/0410364) – 122 authors 75 institutions 472pp.

More information at **http://www.ippp.dur.ac.uk/~georg/lhclc**

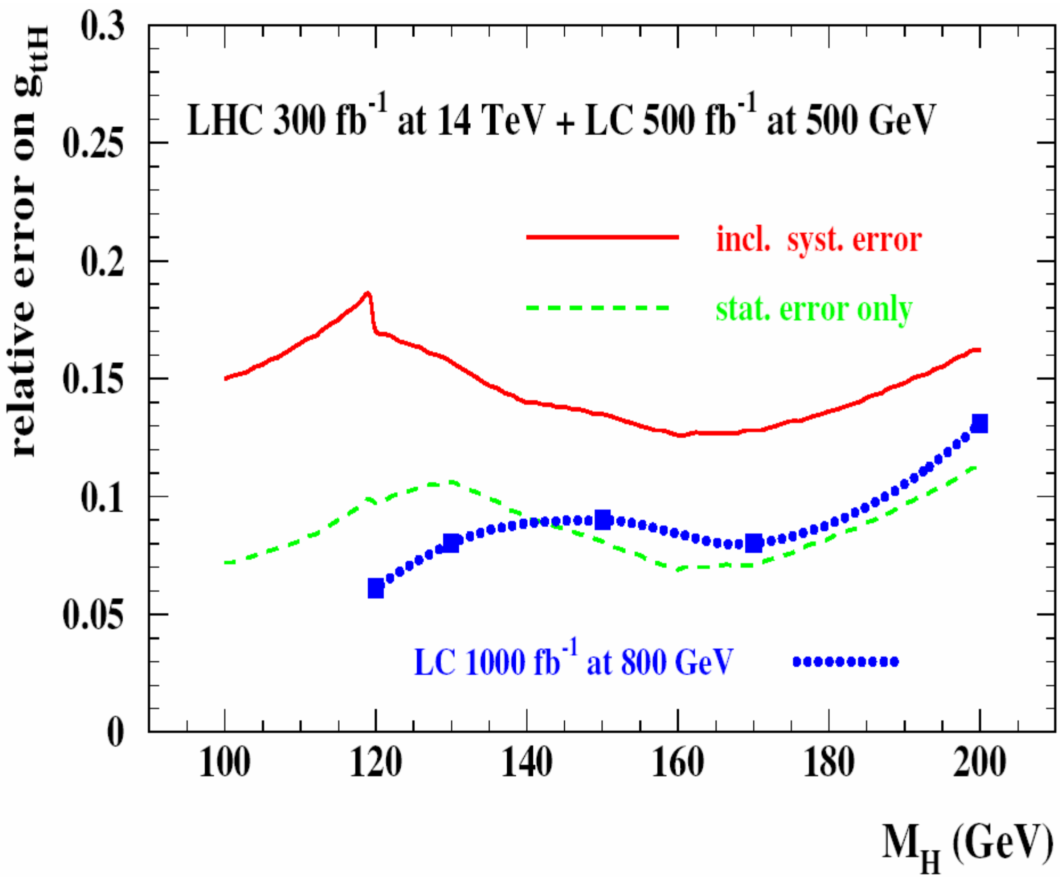
Studies so far (naturally) were focused on what the individual machines >can< do alone.
Going further needs new way of thinking in the communities (interesting!). "can I make it with a little help from my friends ??"

LHC/ILC study group

The report covers examples of the synergy for the whole list of physics topics

- Higgs Physics
- Strong EWSB
- SUSY
- EW Precision Tests
- New Gauge Bosons
- Extra Dimensions

LHC is sensitive to top Yukawa coupling of light Higgs through tth production. LC BR measurement (h→bb and h→WW) turns the rate measurement into an absolute coupling measurement
(LC can only do it at high energy (> 800 GeV))



SUSY Higgs: predicting m_A

Light Higgs branching ratios are sensitive to the mass of the heavy Higgses in the MSSM.
However, they are also strongly influenced by 3rd generation fermions (m_{top}!) and 3rd generation sfermions (sbottom, stop) → LHC

sensitive observable:

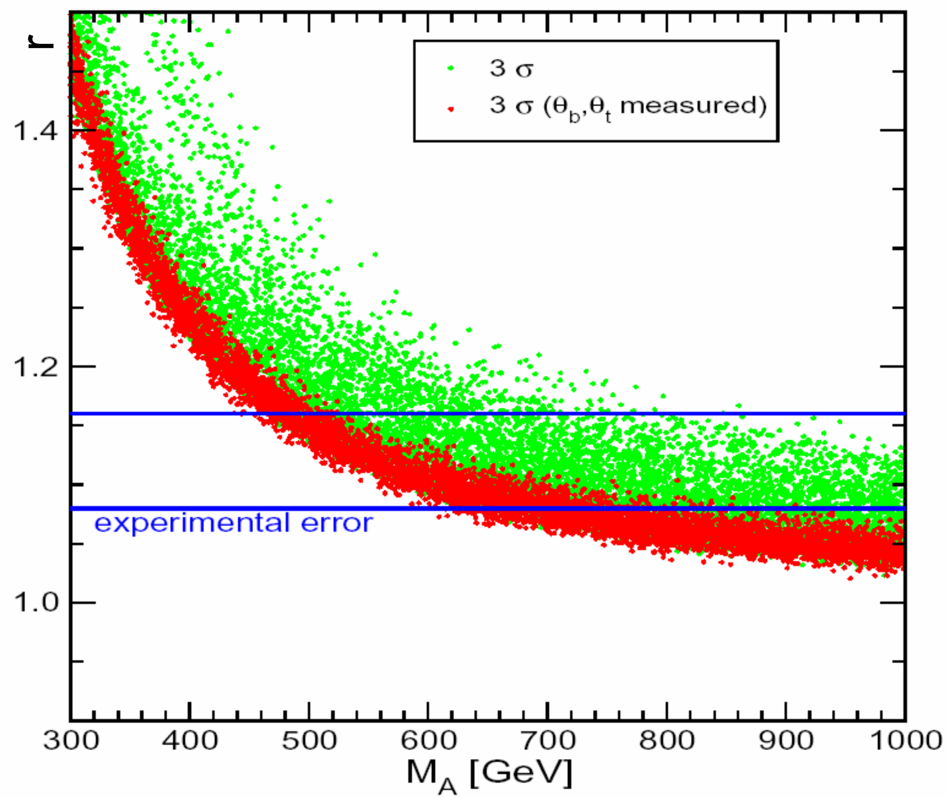
$$r \equiv \frac{\left[\mathrm{BR}(h \to b\bar{b})/\mathrm{BR}(h \to WW^*)\right]_{\mathrm{MSSM}}}{\left[\mathrm{BR}(h \to b\bar{b})/\mathrm{BR}(h \to WW^*)\right]_{\mathrm{SM}}}$$

need to know precise m_h,m_{top} from ILC

and sbottom/stop masses and mixing angles from LHC

green: all SUSY points with LC constraints

red: θ_b θ_t known to 20%/10% from LHC



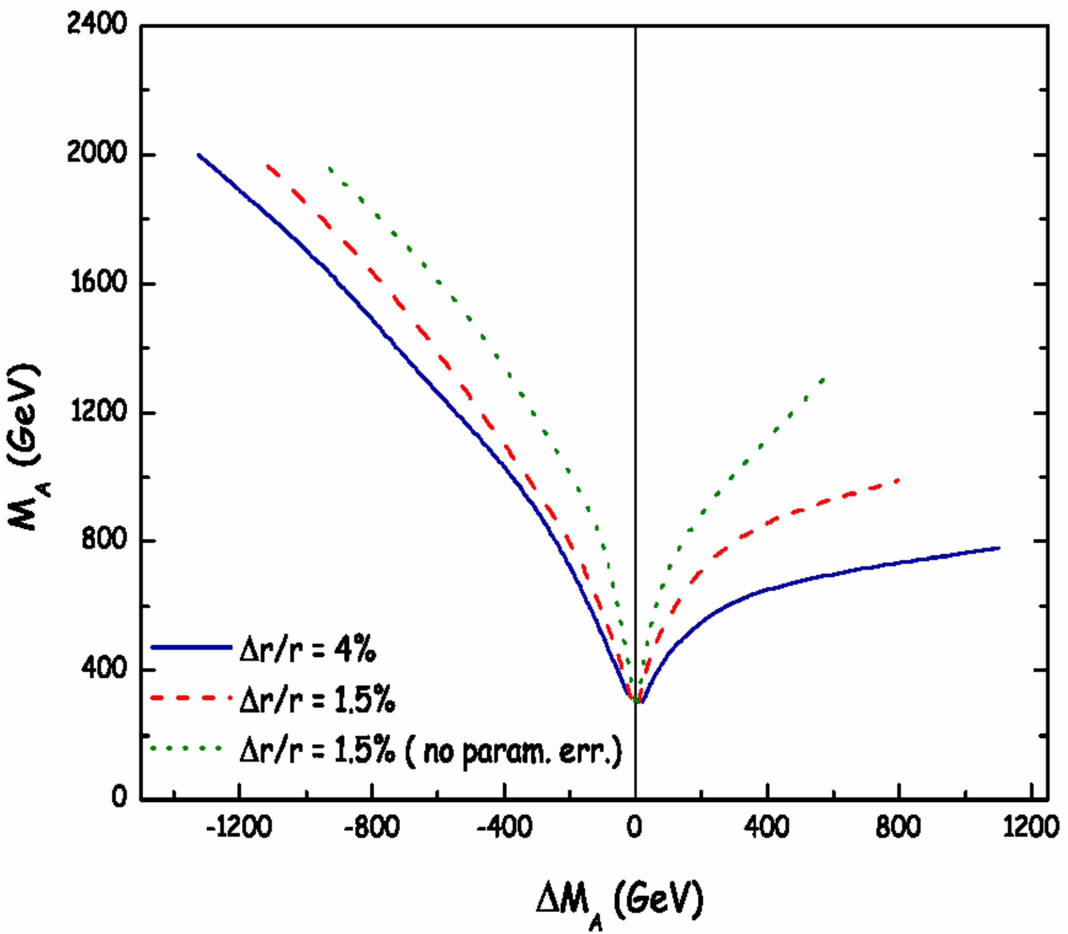
SUSY Higgs: predicting m_A

Indirect prediction of heavy Higgs mass m_A from r measurement:

<u>Result:</u>

$\Delta m_A/m_A$ = 20% (30%)
for
m_A = 600 (800) GeV

could still be improved
by using more BR's

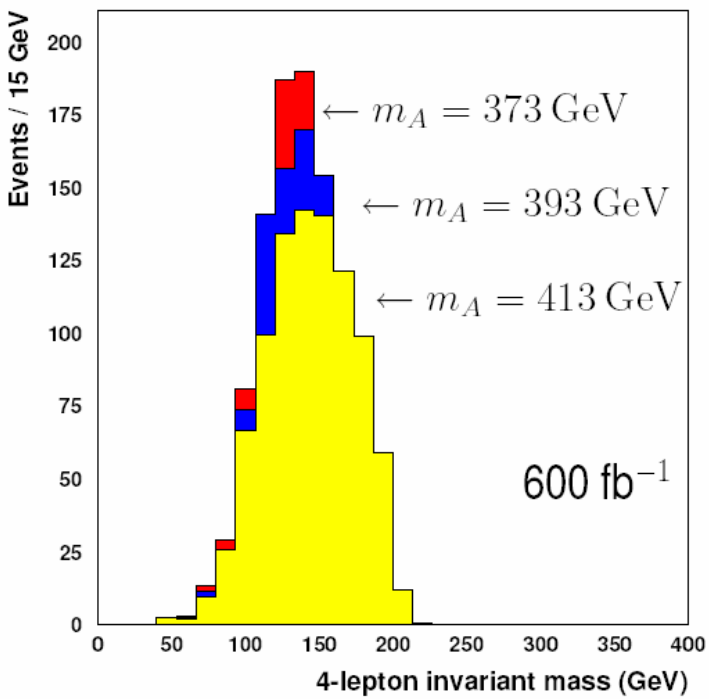


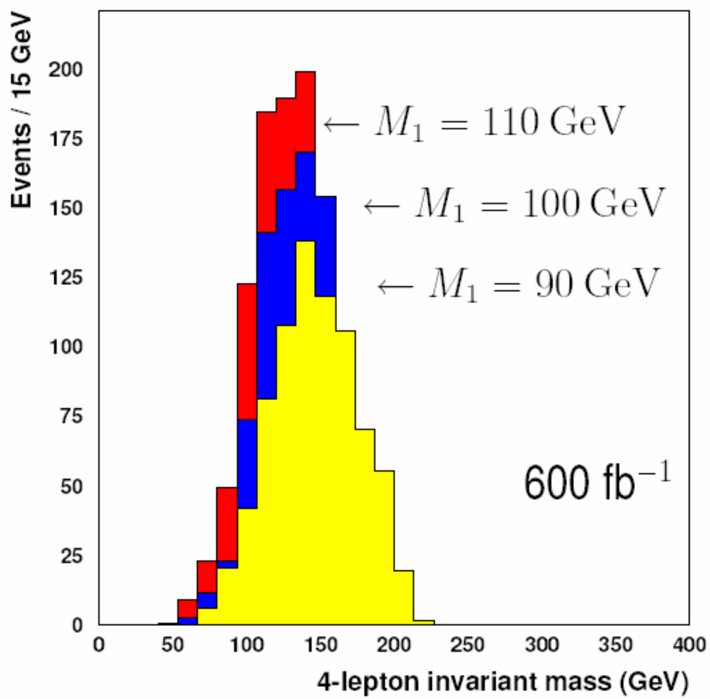
SUSY Higgs: ILC helping in LHC reconstruction

Mass measurement of heavy SUSY Higgs at LHC depends on LSP mass
Hard to get precisely from LHC (see later). Use input from ILC:

$$H / A \to \chi_2^0 \chi_2^0 \to 4\ell + 2\chi_1^0$$

possible LHC discovery channel for H/A if SUSY decays are open (intermediate tanβ range)

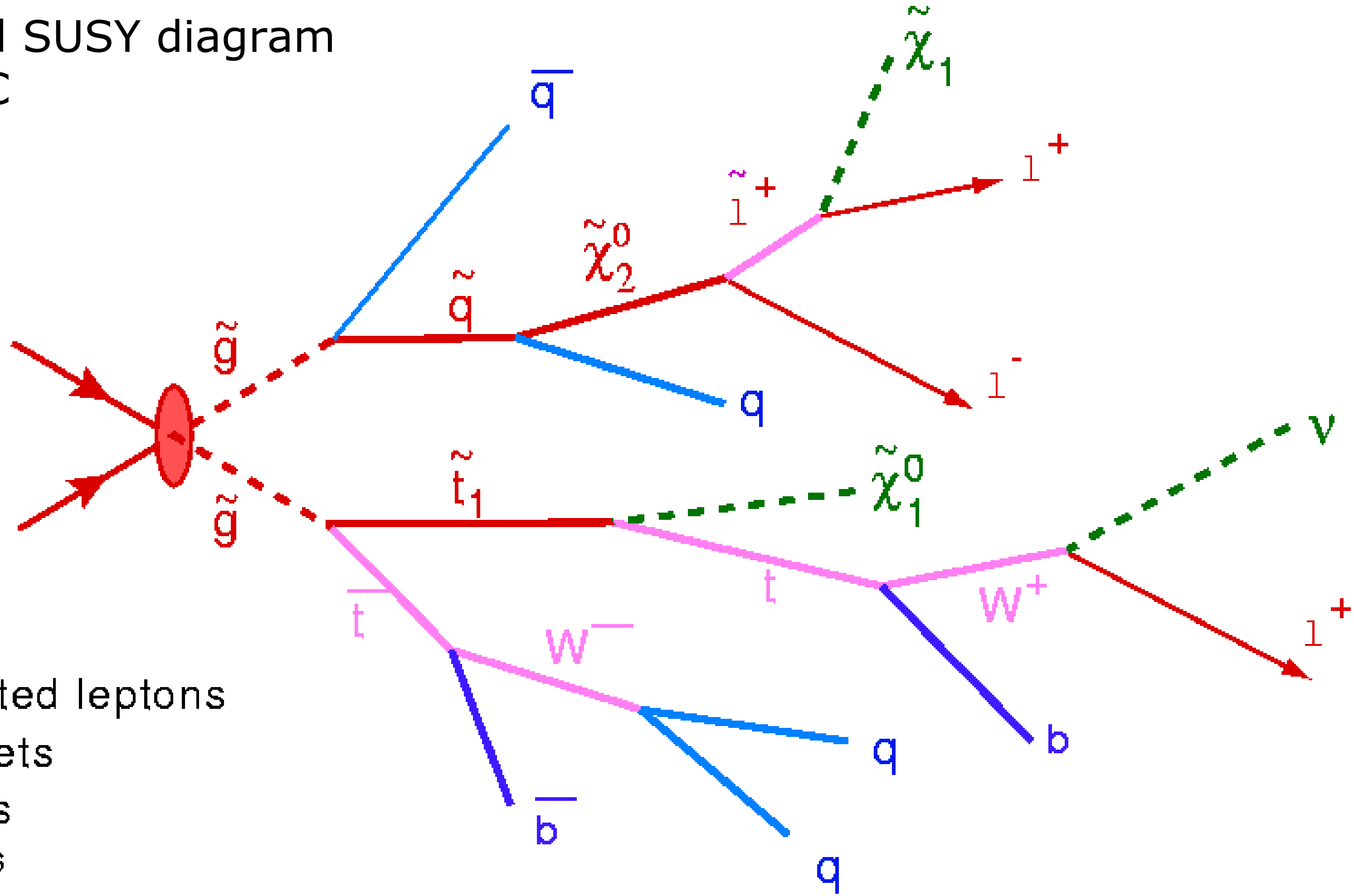




Dependence of 4-lepton mass on m_A is as large as on m_χ

SUSY: ILC helping in LHC reconstruction

typical SUSY diagram
at LHC



3 isolated leptons
+ 2 b-jets
+ 4 jets
+ E_t^{miss}

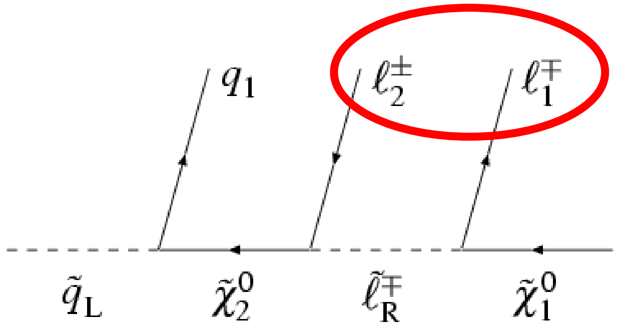
Due to escaping LSP and unknown initial state momentum
full mass reconstruction cannot be performed event-by-event at LHC

'standard' trick:
kinematic endpoints

Example: $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell\ell$

calculate diplepton mass

endpoint at: $M_{\ell\ell}^{max} = M_{\tilde{\chi}_2^0} - M_{\tilde{\chi}_1^0}$



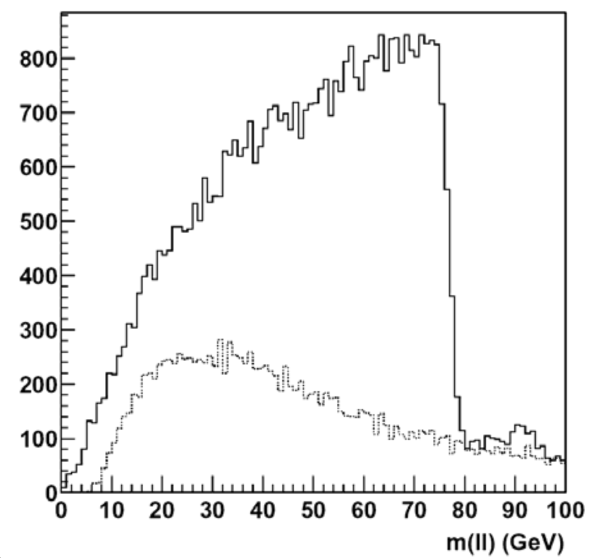
But for cascade decay

$\tilde{\chi}_2^0 \to \tilde{\ell}\ell \to \tilde{\chi}_1^0 \ell\ell$

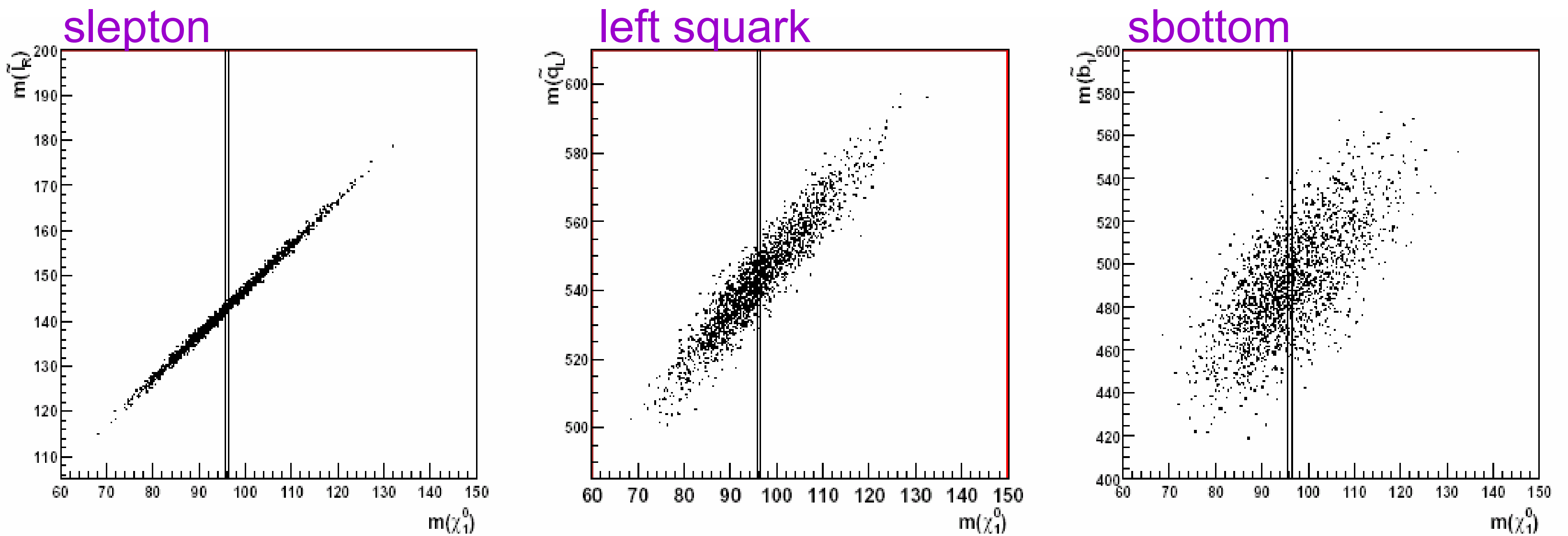
endpoint at:

$$M_{\ell\ell}^{max} = \frac{1}{M_{\tilde{\ell}}}\sqrt{(M_{\tilde{\chi}_2^0}^2 - M_{\tilde{\ell}}^2)(M_{\tilde{\ell}}^2 - M_{\tilde{\chi}_1^0}^2)}$$

→ need to know $M_{\tilde{\chi}_1^0}, M_{\tilde{l}}$



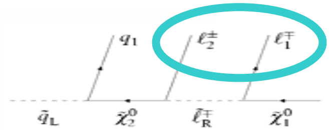
Results in huge correlation between superpartner masses and LSP mass



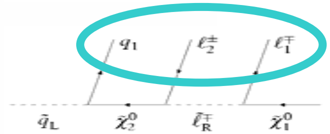
but LHC alone can do better:

joint fit of various kinematic ‘edges’ yields an over-constrained system:

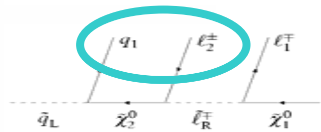
$$\left(m_{ll}^2\right)^{\text{edge}} = \frac{\left(m_{\tilde\chi_2^0}^2 - m_{\tilde l_R}^2\right)\left(m_{\tilde l_R}^2 - m_{\tilde\chi_1^0}^2\right)}{m_{\tilde l_R}^2}$$



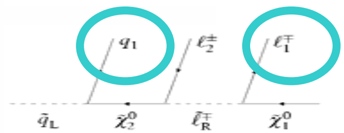
$$\left(m_{qll}^2\right)^{\text{edge}} = \frac{\left(m_{\tilde q_L}^2 - m_{\tilde\chi_2^0}^2\right)\left(m_{\tilde\chi_2^0}^2 - m_{\tilde\chi_1^0}^2\right)}{m_{\tilde\chi_2^0}^2}$$



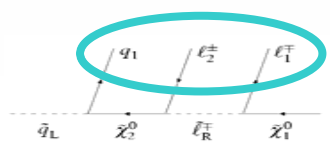
$$\left(m_{ql}^2\right)^{\text{edge}}_{\text{min}} = \frac{\left(m_{\tilde q_L}^2 - m_{\tilde\chi_2^0}^2\right)\left(m_{\tilde\chi_2^0}^2 - m_{\tilde l_R}^2\right)}{m_{\tilde\chi_2^0}^2}$$



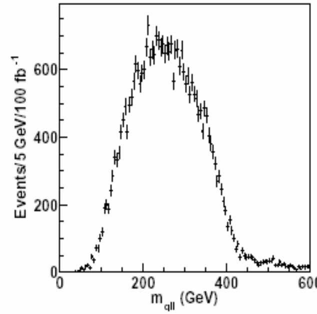
$$\left(m_{ql}^2\right)^{\text{edge}}_{\text{max}} = \frac{\left(m_{\tilde q_L}^2 - m_{\tilde\chi_2^0}^2\right)\left(m_{\tilde l_R}^2 - m_{\tilde\chi_1^0}^2\right)}{m_{\tilde l_R}^2}$$

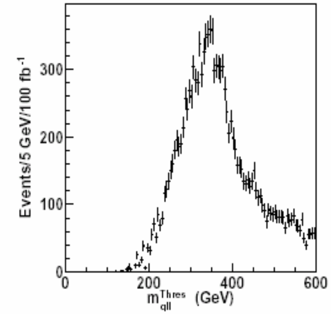


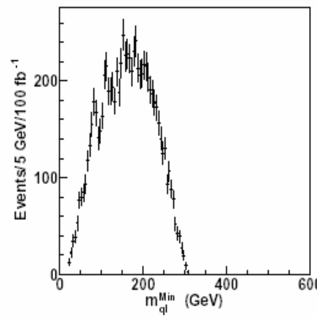
$$\left(m_{qll}^2\right)^{\text{thres}} = \left[\left(m_{\tilde q_L}^2 + m_{\tilde\chi_2^0}^2\right)\left(m_{\tilde\chi_2^0}^2 - m_{\tilde l_R}^2\right)\left(m_{\tilde l_R}^2 - m_{\tilde\chi_1^0}^2\right)\right.$$
$$-\left(m_{\tilde q_L}^2 - m_{\tilde\chi_2^0}^2\right)\sqrt{\left(m_{\tilde\chi_2^0}^2 + m_{\tilde l_R}^2\right)^2\left(m_{\tilde l_R}^2 + m_{\tilde\chi_1^0}^2\right)^2 - 16 m_{\tilde\chi_2^0}^2 m_{\tilde l_R}^4 m}$$
$$\left. + 2 m_{\tilde l_R}^2\left(m_{\tilde q_L}^2 - m_{\tilde\chi_2^0}^2\right)\left(m_{\tilde\chi_2^0}^2 - m_{\tilde\chi_1^0}^2\right)\right] / \left(4 m_{\tilde l_R}^2 m_{\tilde\chi_2^0}^2\right)$$

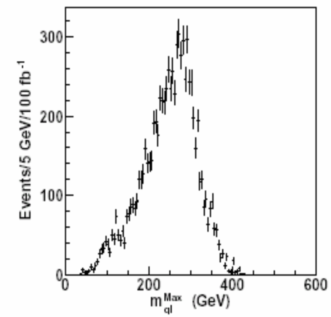


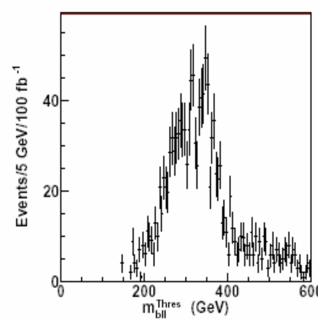
for events with large m_{ll}











SUSY: turning silver into gold

	LHC	LHC+LC
$\Delta m_{\tilde{\chi}_1^0}$	4.8	0.05 (LC input)
$\Delta m_{\tilde{\chi}_2^0}$	4.7	0.08
$\Delta m_{\tilde{\chi}_4^0}$	5.1	2.23
$\Delta m_{\tilde{l}_R}$	4.8	0.05 (LC input)
$\Delta m_{\tilde{\ell}_L}$	5.0	0.2 (LC input)
Δm_{τ_1}	5-8	0.3 (LC input)
$\Delta m_{\tilde{q}_L}$	8.7	4.9
$\Delta m_{\tilde{q}_R}$	7-12	5-11
$\Delta m_{\tilde{b}_1}$	7.5	5.7
$\Delta m_{\tilde{b}_2}$	7.9	6.2
$\Delta m_{\tilde{g}}$	8.0	6.5

huge improvement on sparticle masses which can only be seen by LHC better reconstructed with LHC input

Note: mass errors on squarks, gluino are dominated by had. energy scale systematics at LHC.

Any improvement on this will turn into improvement of squark/gluino mass

Prediction of masses

At the ILC, the complete tree-level parameters of the chargino/neutralino system of the MSSM (M_1,M_2,μ,$\tan\beta$) can be extracted from mass + (polarized) cross section measurements of the lightest (χ^0_1, χ^0_2, $\chi^\pm_1$) states.

SUSY Parameters			
M_1	M_2	μ	$\tan\beta$
99.1 ± 0.3	192.7 ± 1.0	$\mu = 352.8 \pm 9.3$	$[7.4; 15.1]$

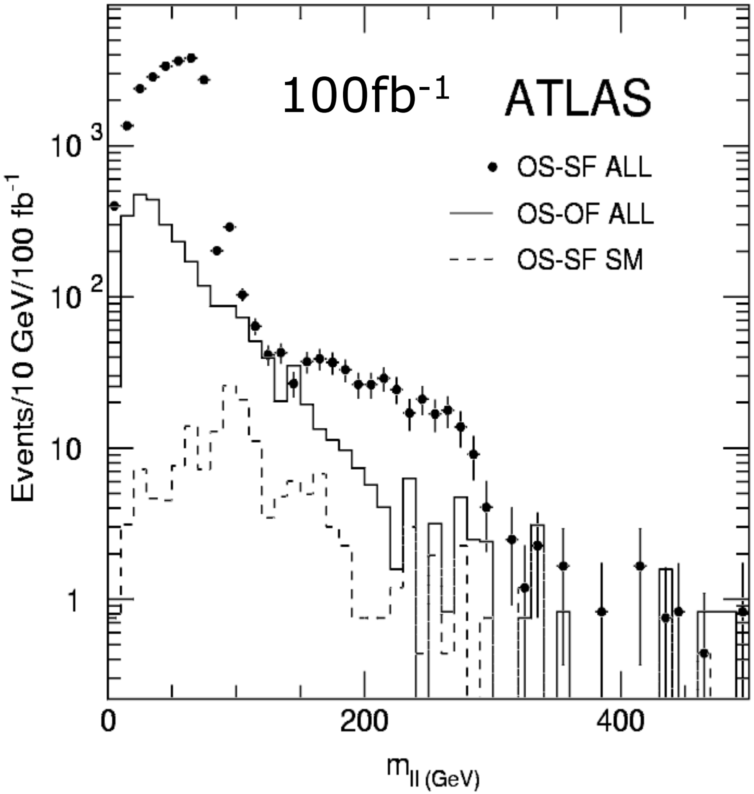
for 100/100 fb^{-1} LR/RL
at 400 and 500 GeV
Polarisation 80/60 (e^-/e^+)

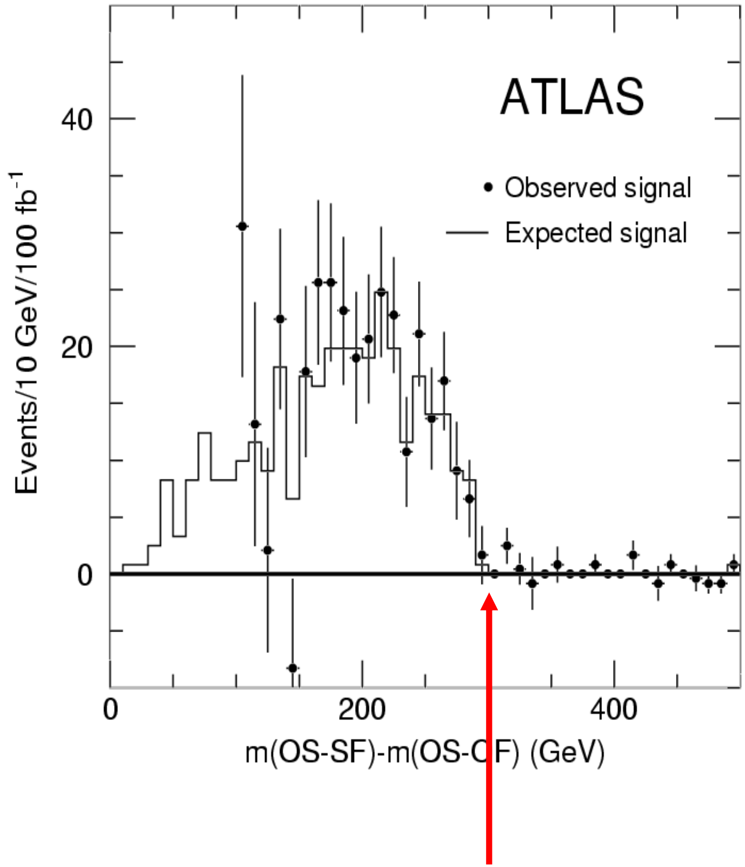
With these parameters measured all chargino and neutralino masses can be predicted, e.g.:

$$m(\chi^0_4) = 378.3 \pm 8.8 \text{ GeV}$$

χ^0_4 occurs occasionally also in squark decays leading to another dilepton edge at the LHC:

Prediction of masses



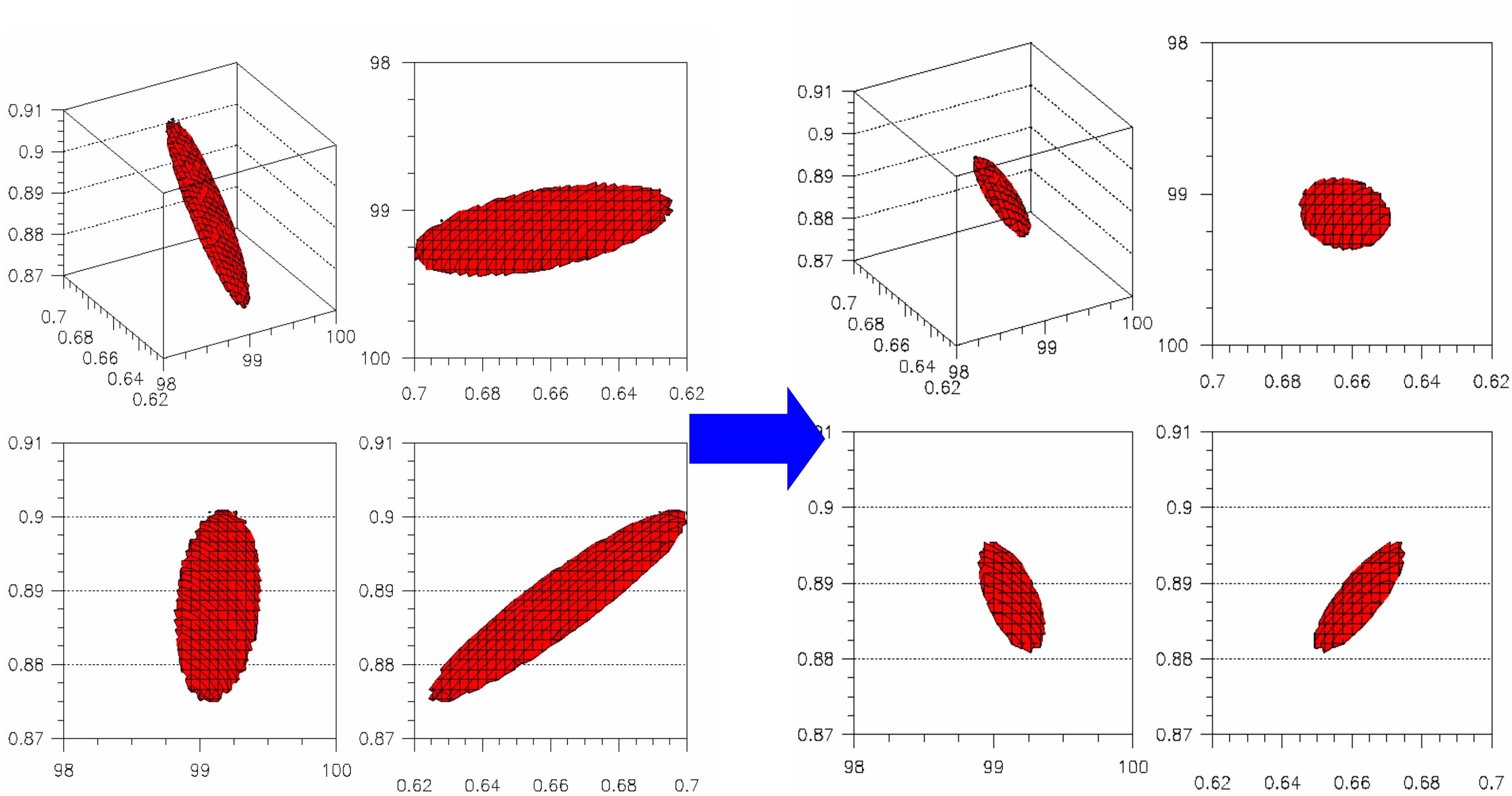


LC prediction turns edge search into a single hypothesis test
→ increased stat. sensitivity

LC can predict position of this edge

9. LHC/LC — Prediction of masses

feeding this mass back into parameter determintation helps a lot:



Reconstruction of the fundamental theory

Ultimate goal: reconstruction of the details of the SUSY model
- test GUT unification
- learn about SUSY breaking

Specific models (mSuGra, GMSB, AMSB etc) have few parameters that can be fitted to the observations

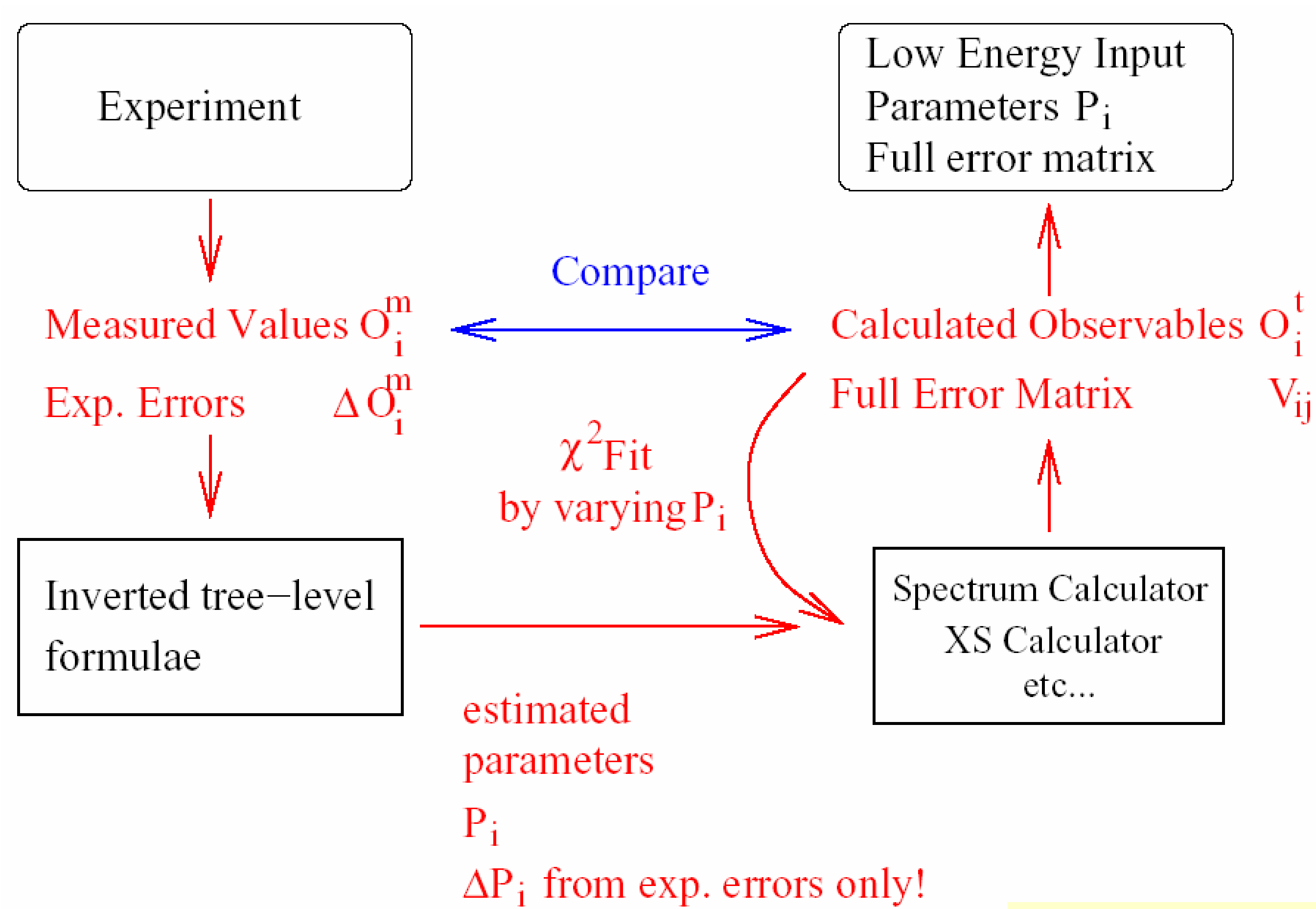
Much more ambitious:

Try to extract the high-scale structure from the low-energy parameters of the general MSSM Lagrangian

Two steps:

1. Extract the Lagrangian parameters of MSSM from LHC+LC data
2. Extrapolate these parameters to high scales using RGEs to look for characteristic unification patterns

Extraction of the Low-Energy SUSY Parameters



radiative corrections important
→ interdependence of all SUSY sectors

use ‘simplified’ MSSM
with 19 parameters
non-trivial task

Extraction of the Low-Energy SUSY Parameters

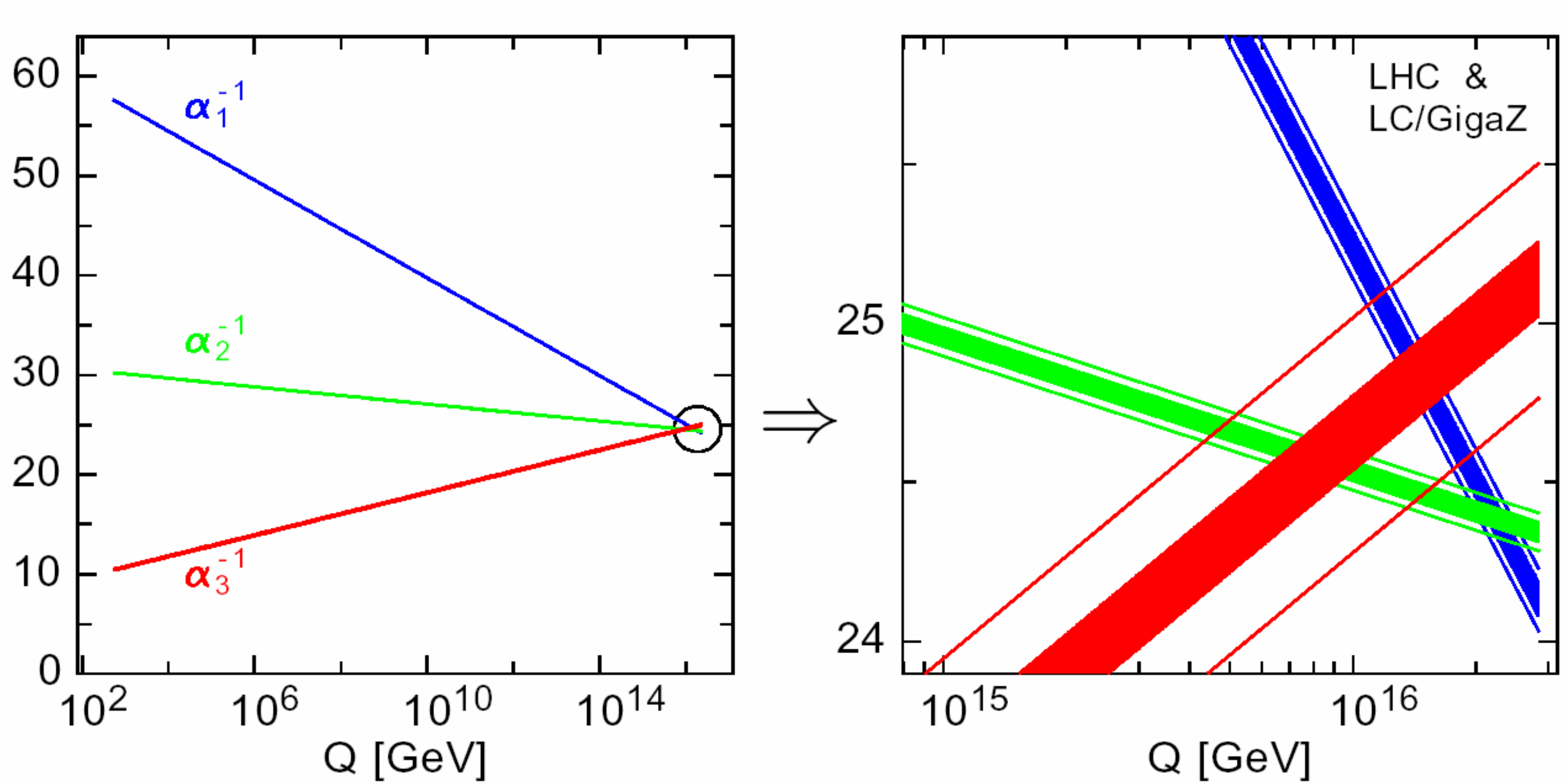
example fit result from `Fittino`:

Using 82 simulated measurements from LHC and LC

Parameter	SPS1a$_{\mathrm{mod}}$ value	Tree-level	Final fi t result
$\tan\beta$	10.0	9.97	10.0 ± 0.33
μ	358.64 GeV	354.4 GeV	358.6 ± 1.14 GeV
X_τ	-3837.23 GeV	-3533.0 GeV	-3837.2 ± 131.0 GeV
$M_{\tilde{e}_R}$	135.76 GeV	150.2 GeV	135.76 ± 0.39 GeV
$M_{\tilde{\tau}_R}$	133.33 GeV	141.0 GeV	133.33 ± 0.75 GeV
$M_{\tilde{e}_L}$	195.21 GeV	202.7 GeV	195.21 ± 0.18 GeV
$M_{\tilde{\tau}_L}$	194.39 GeV	206.6 GeV	194.4 ± 1.18 GeV
X_{top}	-506.388 GeV	-43.5 GeV	-506.4 ± 29.5 GeV
X_{bottom}	-4441.0 GeV	-3533.0 GeV	-4441.1 ± 1765 GeV
$M_{\tilde{d}_R}$	528.14 GeV	567.3 GeV	528.2 ± 17.6 GeV
$M_{\tilde{b}_R}$	524.718 GeV	566.0 GeV	524.7 ± 7.67 GeV
$M_{\tilde{u}_R}$	530.253 GeV	566.9 GeV	530.2 ± 19.1 GeV
$M_{\tilde{t}_R}$	424.382 GeV	373.7 GeV	424.4 ± 8.54 GeV
$M_{\tilde{u}_L}$	548.705 GeV	581.3 GeV	548.7 ± 5.16 GeV
$M_{\tilde{t}_L}$	499.972 GeV	575.4 GeV	500.0 ± 8.06 GeV
M_1	101.809 GeV	99.07 GeV	101.81 ± 0.06 GeV
M_2	191.7556 GeV	195.08 GeV	191.76 ± 0.10 GeV
M_3	588.797 GeV	630.5 GeV	588.8 ± 7.88 GeV
m_{A}	399.767 GeV	399.8 GeV	399.8 ± 0.71 GeV
m_{top}	174.3 GeV	174.3 GeV	174.3 ± 0.3 GeV

Neither LHC nor LC data alone yield a converging fit!
(even in favorable SPS1a scenario)
Information from both machines needed!

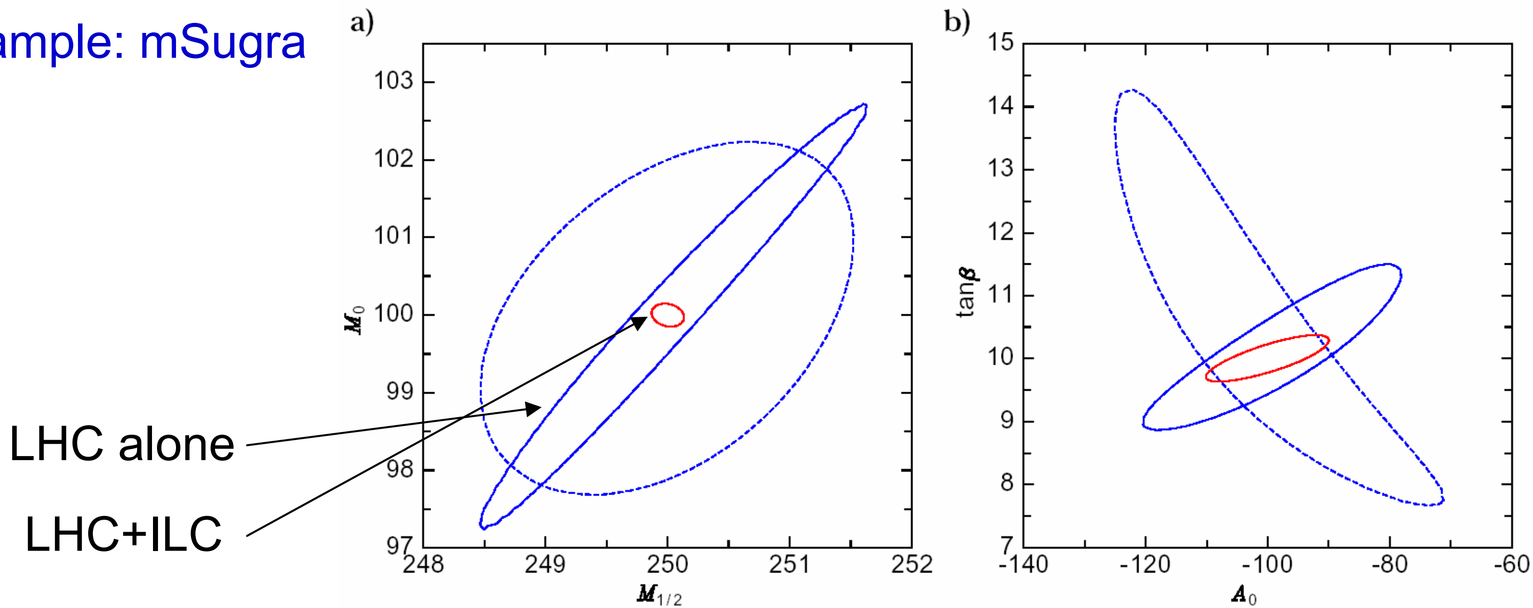
1. Precision test of the unification of gauge couplings:



→ sensitivity to threshold effects at the GUT scale

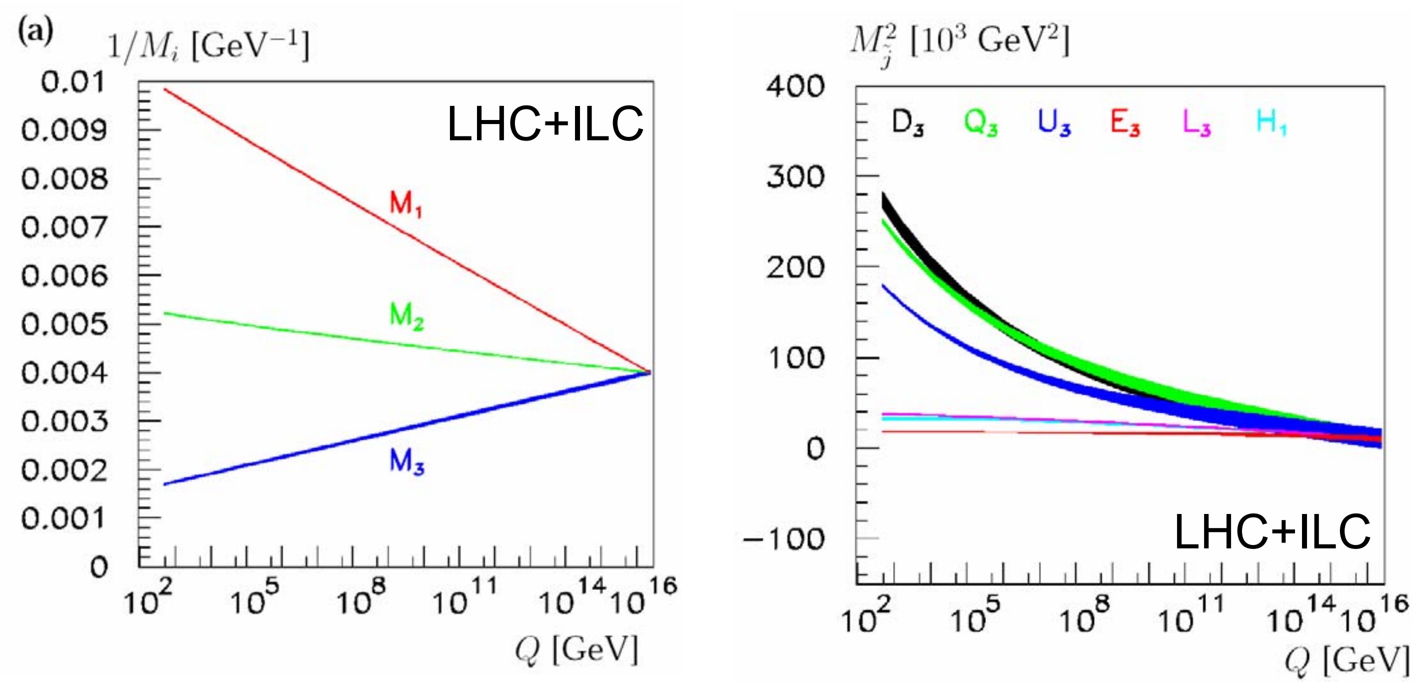
2. Fits to constrained models

Example: mSugra



	"LHC"	"LC"	"LHC+LC"
$M_{1/2}$	250.0 ± 2.1	250.0 ± 0.4	250.0 ± 0.2
M_0	100.0 ± 2.8	100.0 ± 0.2	100.0 ± 0.2
A_0	-100.0 ± 34	-100.0 ± 27	-100.0 ± 14
$\tan\beta$	10.0 ± 1.8	10.0 ± 0.6	10.0 ± 0.4

3. Model-independent bottom-up approach: Combined information on Low-Energy SUSY parameters as input to RGE evolution



Look for unification patterns in SUSY parameters without a-priori assumption of a SUSY breaking mechanism.

Summary

- LHC and ILC are looking at the same physics from different viewpoints
- Joint analyses and joint interpretation of data will be an enormous benefit – this benefit is maximed if both machines run concurrently
- First LHC/LC has only scratched the surface so far – more possibilities through direct influence on running of the machines (trigger, upgrades) to be worked out
- The synergy has already started: LHC-SUSY analyses pushed forward in the coarse of the workshop…

Final remarks

<u>We live in exciting times:</u>

- High energy physics will not be finished with LHC+ILC
  Active R&D for the multi-TeV regime is vital and necessary now
  CLIC is a promising way to get there

- ILC technology at hands – if we all work (and talk) together
  this dream can turn into reality

- LHC startup soon – highest priority: let's make this a success

Many thanks to CERN and in particular to Albert de Roeck
(and to all who helped me in preparing of these lectures…)