Synergy Between the LHC and LC.

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IISc

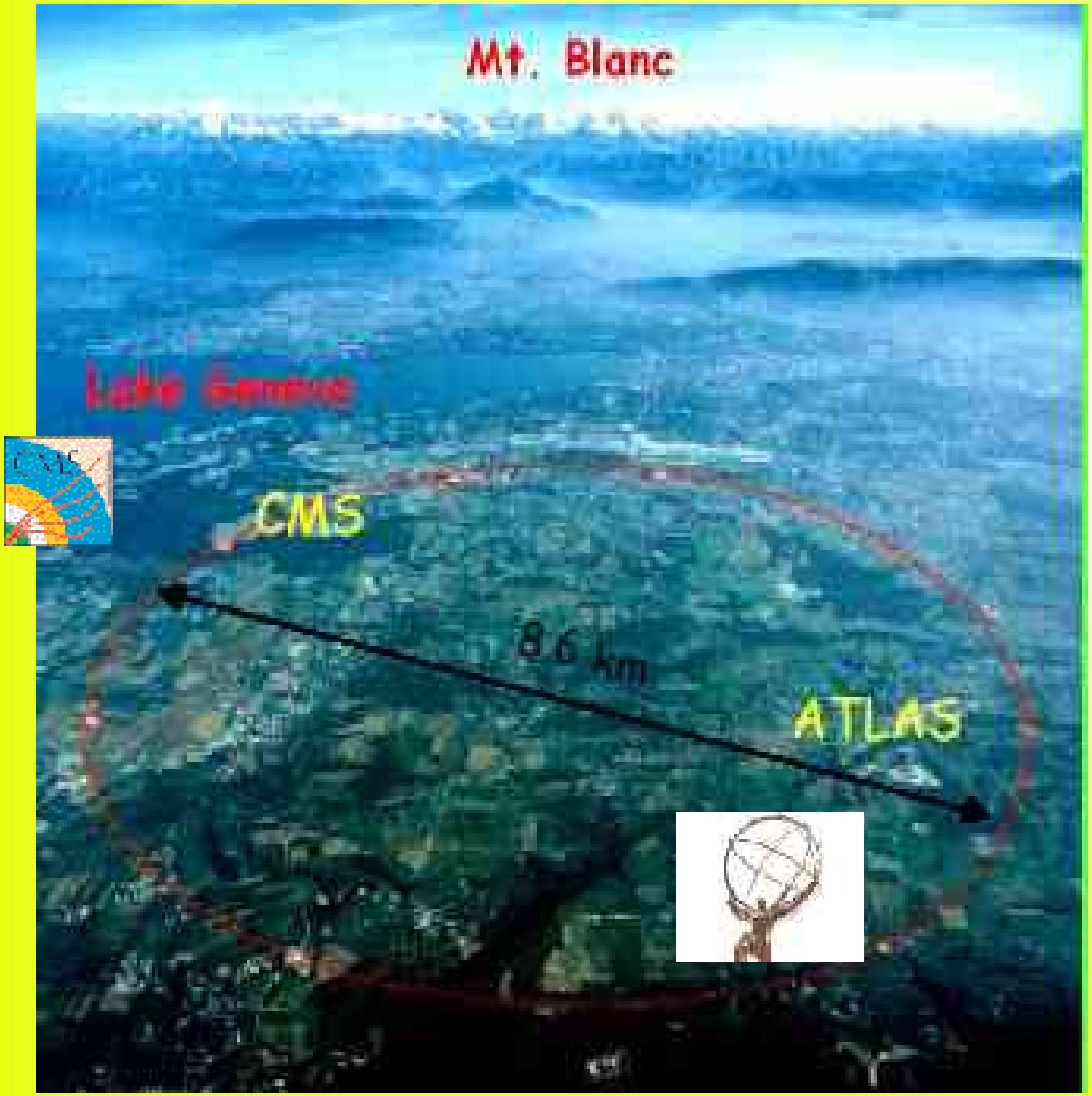
International Conference on Linear Colliders: LCWS04

April 19-23, 2004.

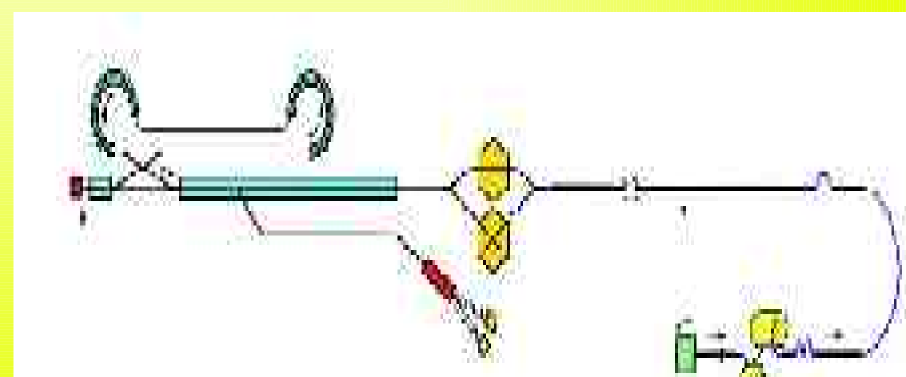
Plan of the talk

- The LHC-LC interplay : general comments.
- The LHC-LC study group.
- The LHC-LC study group document.
- A few examples of the LC-LHC synergy taken from the document.

LHC/LC interplay



Worldwide Study of the Physics and Detectors for Future Linear e e Colliders



LHC/LC Interplay

- ✗ Historically there has been always interplay and feedback between hadronic and leptonic colliders. What is the special need for discussing the LHC/LC synergy?

- ✗ The reason is the current state of play in HEP and the high stakes in physics studies at the next generation colliders ; both on the physics front and the economic front.

- ✗ As a community it is very IMPORTANT for us to assess the desired energy, luminosity and ***the timing*** of the LC vis-a-vis the physics goals we hope to reach at the LHC.

High Energy Frontier in HEP

LHC : Preparations full steam ahead.
Hopefully start in 2007

LC : (?) European, American and Asian Study Groups

Worldwide Study

- *No Sanction, No Budget so far apart from R&D. Likely startup: middle of next decade?*
- **HEP Community world wide convinced of the need for LC**

However not much interaction between the LHC and LC experimental communities. In 2002 a LHC/LC study group was formed first in Europe and then soon it took a worldwide character.

LHC/LC STUDY GROUP

LHC/LC Study Group Activities

- Initiative started in ECFA/DESY framework
- Working Group contains 116 members from among Theorists, CMS, ATLAS, Members of *all* the LC study Groups + Tevatron contact persons.
- Working Group Coordinators:
  Georg Weiglein, R.G.
- Web Page :
  www.ippp.dur.ac.uk/~georg/lhclc
- Mailing List :
  LHC-LC@listserv.fnal.gov
- **A series of meetings held over two years.**

Editors : G. Weiglein, T. Barklow, E. Boos, A. de Roeck, K. Desch, F. Gianotti, R.M. Godbole, J. F. Gunion, H.E. Haber, S. Heinemeyer, J.L. Hewett, K. Kawagoe, K. Moenig, M.M. Nojiri, G. Polesello, F. Richard, S. Riemann, W.J. Stirling.

Aims of the LHC/LC Study Group

- Collaborative Effort of the Hadron Collider (LHC) and the Linear Collider (LC) Community.

  Physics case for both the machines well established, each with its own virtues.

- Aim of the LHC/LC group NOT to compare which collider can do better, but rather

  How the two can complement each other?

- Study how information obtained at both machines can be put **together** to explore, more ***conclusively and effectively*** the basic questions of HEP. GET MORE VALUE FOR MONEY.

  Combined studies might give pointers to new bench marks for measurements at LHC. Might affect analysis if **not** the triggering, the luminosity/detector upgrades, provide yet more focus to the LHC studies.

Aims of the LHC/LC Study Group

- Aim : identify issues where the cross-talk between two colliders can increase the utility of *BOTH*.

Possibilities of cross talk analysed assuming that the LHC will run for about 20 years and LC will kick off after LHC has been running for a few years.

Generic situation: Tevatron and LHC will see some new physics but the nature of new physics will not be clear. Analyse possibilities of cross talk in this situation.

LHC/LC Study Group Recognition

Group Recognised by the International Linear Collider Steering Committee: ILCSC

Cornell

Newman Laboratory
Cornell University
Ithaca, NY 14853

Floyd R. Newman Laboratory for Elementary Particle Physics

Georg Weiglein <georg.weiglein@durham.ac.uk>,
Frank Paige <paige@bnl.gov>,
Rohini Godbole <rohini.godbole@cern.ch>

Dear Georg, Rohini and Frank,

On behalf of the International Linear Collider Steering Committee I am happy to tell you that the Committee was very pleased to hear about the successful launch of your group. Your studies of the interdependence of the LHC and Linear Collider programmes and the benefits to be obtained from simultaneous operation of the two facilities will form an important input to the case which we must make for the Linear Collider. We look forward to your reports on the detailed physics analyses and we expect to quote them extensively. The ILCSC voted unanimously to support of your group's activities (in spirit of course - we have no funds to offer).

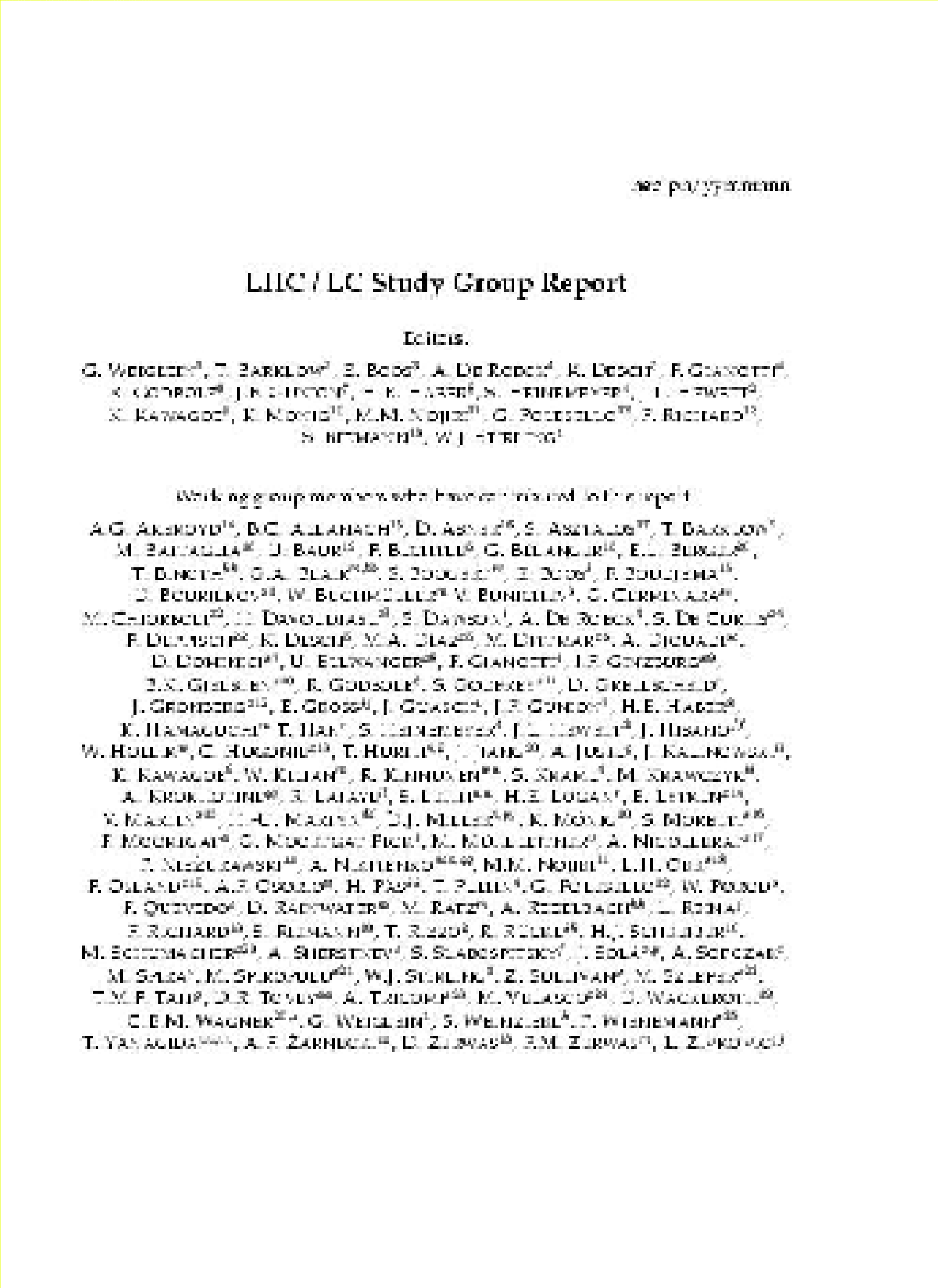
Sincerely,

Maury Tigner

Chair, ILCSC

cc DIM

LHC/LC Study Group Document


LHC / LC Study Group Report

Contains work discussed at about 7 meetings.

~470 pages, 116 authors,
~ 50 contributions.

Draft available on the web page.
8 April, 2004, close to the Final Draft.

At present contains a large number of comparisons between the two machines. A large number of examples of complementarity and/or cross-talk are identified and studied.

Points for further studies identified.

LHC/LC Study Group Document

1) Higgs Physics and Electroweak Symmetry Breaking

   A deRoeck, H.E. Haber, R.G., J. Gunion, G. Weiglein (*)

2) Strong Electroweak Symmetry breaking

   T. Barklow, K. Moenig

3) Supersymmetric Models

   K. Desch K. Kawagoe, M.M. Njoiri, G. Polesello

4) Electroweak and QCD precision physics

   E. Boos, A deRoeck, S. Heinemeyer, W.J. Stirling.

5) New Gauge Theories

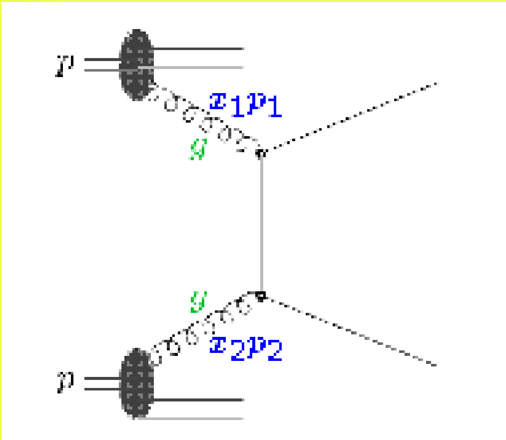
   S. Riemann

6) Models with Extra Dimensions

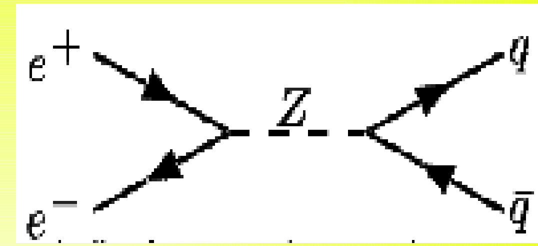
   J. L. Hewett

(*) = main chapter editors/organizers

LHC/LC



Different characteristics of the two machines
Different virtues.



LHC pp collisions Öat ?s = 14 TeV

⇒ Strong point: larger mass reach for direct discoveries

- Kinematics: can use conservation of p_t
- Composite nature of colliding protons
- ⇒ underlying events and ⇒ √s of the hard interaction not fixed.
- Strongly interacting particles
- ⇒Large QCD backgrounds.
- Big ADVANTAGE: Under Construction

e+e- collisions at √s = 0.5-1.0 TeV

Strong point: high precision physics

- Kinematics: momentum conservation used to analyse the decays,…
- Well defined initial state, beam polarization, √s ......
- Backgrounds smaller than LHC
- Options: $\gamma\gamma$, eγ , e^-e^- colliders open up more avenues.
- We still are not sure of IF, WHEN and WHERE Construction will happen.

LHC/LC

LHC will have higher reach in energy and hence can create perhaps the new particles expected in the extensions of SM directly

LC can make precision measurements and can be sensitive to the indirect effects of the same particles even if masses are much higher than the energy of the LC. Thus information from a lower energy LC can still feedback into studies at the LHC.
This is the simplest form of synergy between different colliders.

- We have seen the example in the mass of the top quark as estimated from the precision EW measurements and as measured directly from the Tevatron data. Now we see similar interplay for the prediction of (SM) Higgs mass, being sharpened by knowledge of the top mass from Tevatron.

LHC/LC

Precision measurements from the LC can therefore sometimes tell LHC where to focus the effort.

Precision measurements at the LHC are difficult if not impossible, possible only after a few years. These studies can benefit due to the feedback from the LC.

- Of course the ability of LC not restricted to precision measurement alone but also for discoveries which at times will be difficult or impossible at the LHC.

Qualitative statements are obvious. Quantitative studies necessary. These are present in the document.

LHC/LC

Many scenarios for cross talk possible:

1) LC data help clear up the underlying structure of new physics of which Tevatron and LHC give some glimpse. **LHC + LC**

2) **Combined interpretation of LHC/LC data**

In particular to reduce **possible model dependencies**

LHC $\oplus$ LC $>$ LHC + LC

3) Combined Analysis of LHC/LC data : if the machines have some overlap in time, LC results could influence the second phase of LHC.

LC results can provide input to the upgrade options for the LHC machines and detectors.

LHC $\otimes$ LC $>$ LHC $\oplus$ LC

Choice of topics to discuss Synergy

I will take examples in the document from

1) EW symmetry breaking
Establishing and Understanding the Higgs Mechanism

2) Supersymmetry

3) Supersymmetric Higgs

4) EW symmetry breaking : Alternates to Higgs Mechanism

i) Dynamical Symmetry breaking,
ii) Extra Dimensions and Radions......

LHC/LC: EW Symmetry Breaking, Higgs

All of us sure,

LHC will be able to observe the SM Higgs and afford measurements of its various properties such as width, relative couplings to some accuracy (about 15-20 %) by the end of the high luminosity run, ***if the Higgs exists.***

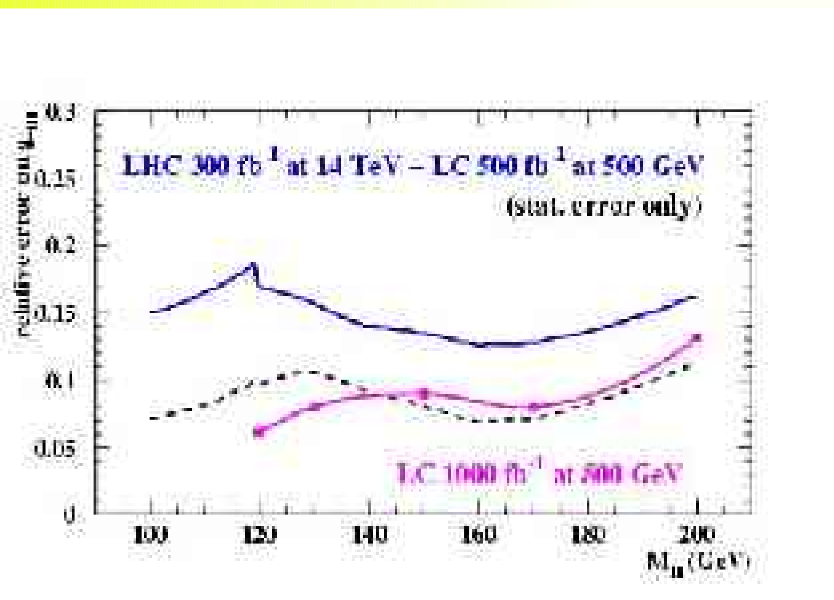
LC can of course profile a Higgs most accurately even in the low energy, moderate luminosity option, except for $\bar{t}\,t$ H coupling ***and*** the reconstruction of the Higgs potential.

Question: can cross talk between LHC/LC improve this situation?

EW symmetry breaking

1) H $\bar{t}\, t$ Yukawa Coupling: S. Dawson, A. Juste, L. Reina, K. Desch, M. Schumacher, D.Rainwater.

A measurement quite essential to be able to confirm the Higgs Mechanism as the origin of fermion masses. All Higgs couplings other than this one can be measured accurately at an low energy (< 500 GeV) LC. LHC can produce higgs in association with $\bar{t}\, t$ and can measure rates.Information on Yukawa coupling from the LHC alone is ***model dependent*.**



At an LC precision measurement of t tH coupling requires $\sqrt{s} \approx$ 800 – 1000 GeV. LHC measures σ X B.R. into difft. Channels Use LC info. on other B.R. of the Higgs.Get information on ttH coupling in a ***model independent*** way, using ***BOTH the LC and LHC.***

EW symmetry breaking

2) Higgs Self Coupling Measurements: U. Bauer, T. Plehn, D. Rainwater.

Measurements important to confirm the spontaneous symmetry breaking mechanism.

For M_H < 140 GeV LHC can offer no meaningful extraction of the self coupling λ. But a 500 GeV LC, with 1 ab $^{-1}$ luminosity will allow determination up to 23% using ZHH production. Increasing energy of LC worsens the accuracy.

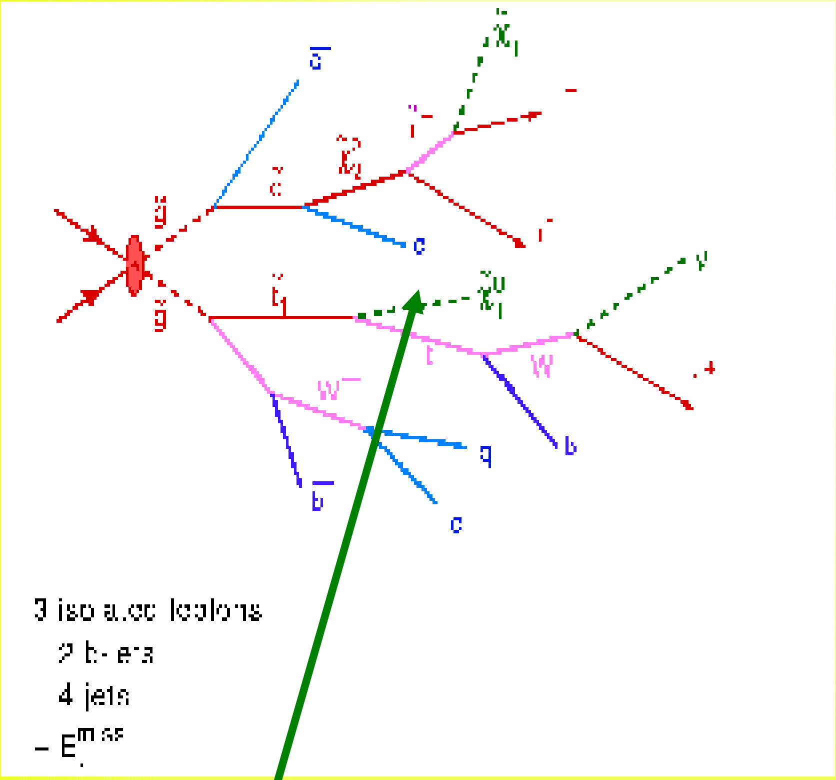
For $M_H \geq$ 140 GeV, LHC offers a better chance. With luminosity upgrade at the LHC it will offer a chance of reconstructing the Higgs potential

This will need precision input on top Yukawa coupling, HWW coupling and the total Higgs boson decay width.. thus will need information from a low energy LC.

Authors conclude more studies on issues of systematic uncertainties etc. need to be addressed and studied still.

Supersymmetry

Symmetry between fermions and bosons: stabilizes the EW symmetry breaking scale against radiative corrections.



Lightest SUSY particle stable: LSP the dark matter candidate

Supersymmetry is broken

We don't see the superpartners

In unconstrained MSSM: 105 new parameters! :masses, mixing angles…

Normally in LHC studies:

Reduce # of parameters by working in a particular SUSY breaking model.

a) Minimal SUSY Gravity(MSUGRA)

b) Gauge mediated SUSY breaking

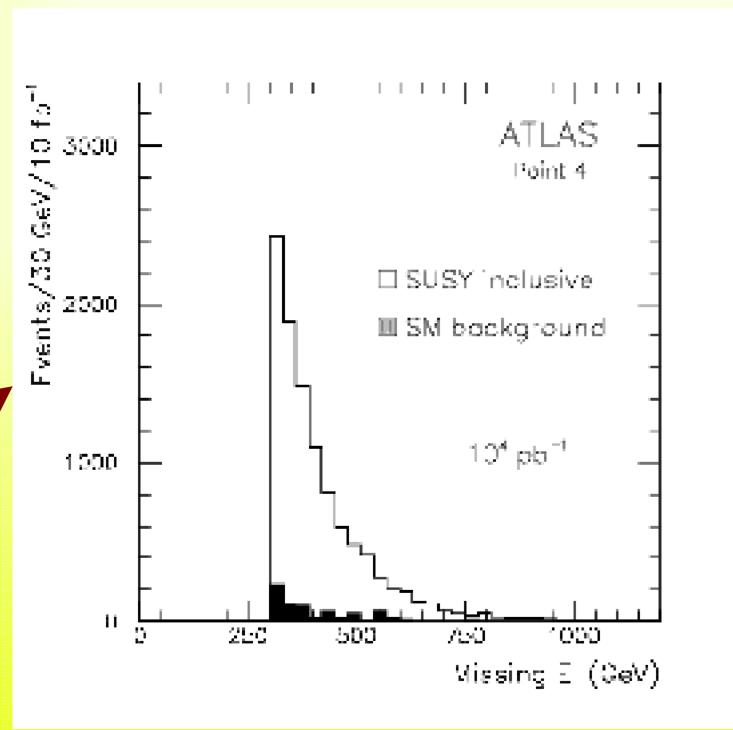
c) Anomaly mediated SUSY breaking

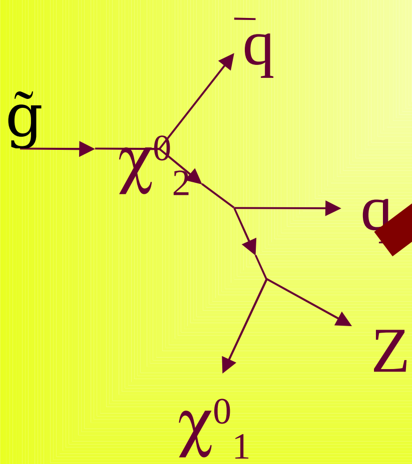
d) Gravitino mediated SUSY breaking… etc.

Why time is ripe now?

Studies at LHC moving from 'discovery' mode to 'spectroscopy' mode

e.g. Jets + missing E_T due to gluino pair production.





Now Studies focus on sparticle mass measurements, SUSY parameter determination,

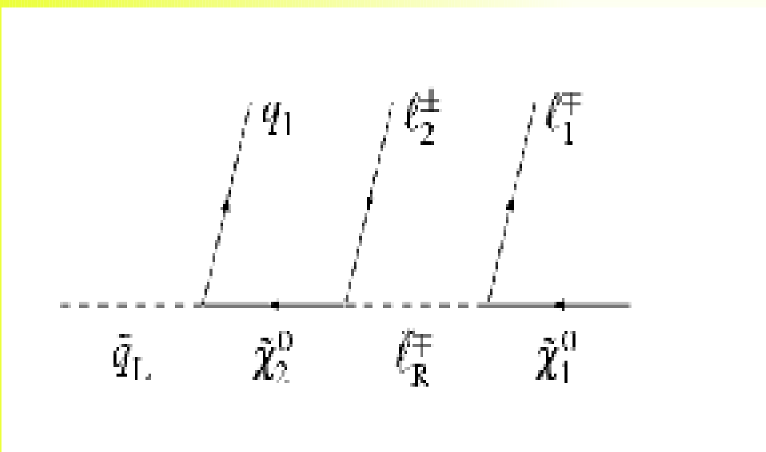
Model dependent

Model independent

Examples

Sparticle Mass determination at LHC: How will LC improve it?
[B. Gjelsten, J. Hisano, E. Lytken, K. Kawagoe ,D. Miller, U. Martyn, P. Osland, G. Polesello, M. Nojiri,, M. Chiorboli and A. Tricomi]

Sparticle mass dtermination at LHC by using 'edges' from e.g. $\chi_2 \rightarrow \chi_1\, l^+ l^-$



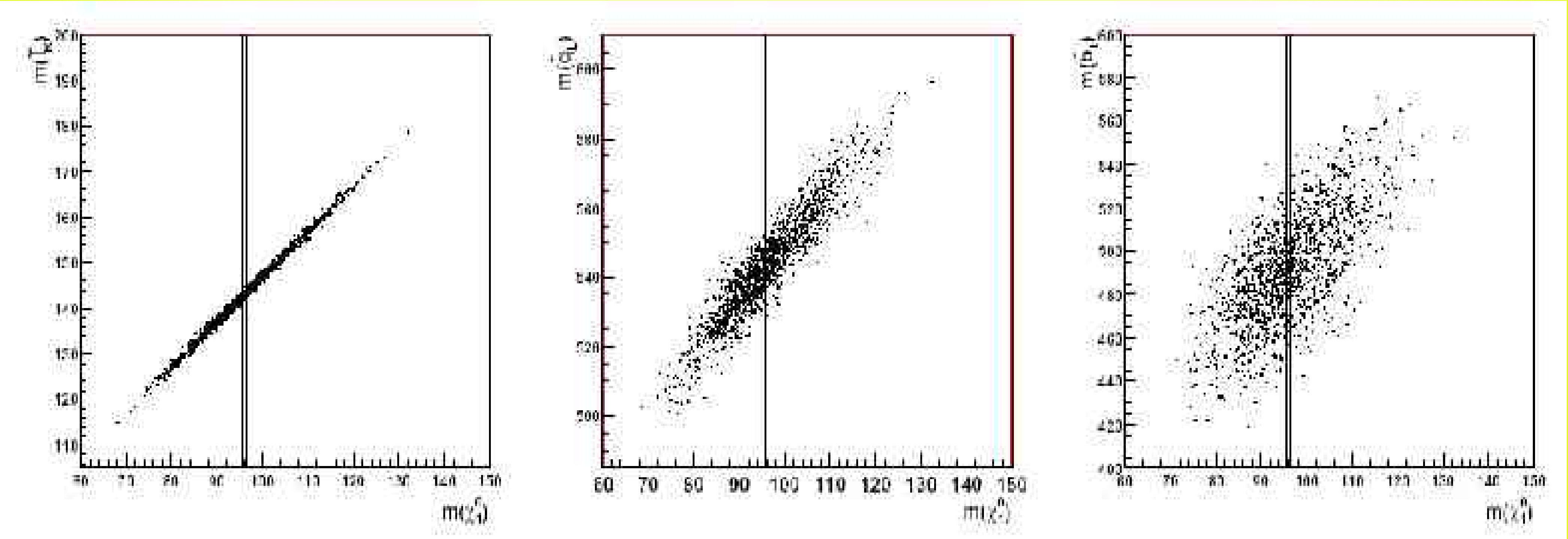
LSP is 'lost' and hence particle mass reconstruction has to be done using 'edges'

Problem: Strong correlation between the sparticle mass and the LSP mass.

The Bottle Neck

Uncertainty in the knowledge of the LSP mass thus affects the accuracy with which sparticle masses can be determined.

Thus, e.g., $\Delta m_{\text{gluino}} \sim \Delta m_{\text{LSP}}$ (Relation affected by jet scale uncertainty)



Examples worked out for a particular point SPS1a from ATLAS and CMS. For this point both LC and LHC have reach for a large number of the lighter sparticles.

What can LC do?

Using LHC luminosity

$\mathscr{L}$ = 300 fb $^{-1}$

ΔM in GeV

	LHC	LHC+LC (0.2%)	LHC+LC (1.0%)
$\Delta m_{\tilde{\chi}^0_1}$	4.8	0.19	1.0
$\Delta m_{\tilde{\ell}_R}$	4.8	0.34	1.0
$\Delta m_{\tilde{\chi}^0_2}$	4.7	0.24	1.0
$\Delta m_{\tilde{q}_L}$	8.7	4.9	5.1
$\Delta m_{\tilde{b}_1}$	13.2	10.5	10.6

	LHC	LHC+LC (0.2%)	LHC+LC (1.0%)
$\Delta m_{\tilde{g}}$	8.0	6.4	6.5
$\Delta m_{\tilde{q}_R}$	11.8	10.9	10.9
$\Delta m_{\tilde{b}_1}$	7.5	5.7	5.7
$\Delta m_{\tilde{b}_2}$	7.9	6.3	10.6
$\Delta m_{\tilde{\ell}_L}$	5.0	1.6	1.9
$\Delta m_{\tilde{\chi}^0_4}$	5.1	2.25	2.4

Significant improvement in the accuracy of mass measurement of sparticles if the LC accuracy is better than 1%.

What can LC do?(update)

	LHC	LHC+LC
$\Delta m_{\tilde\chi^0_1}$	4.8	0.05 (input)
$\Delta m_{\tilde l_R}$	4.8	0.05 (input)
$\Delta m_{\tilde\chi^0_2}$	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)
$\Delta m_{\tilde\chi^0_4}$	5.1	2.23

Use of LC information increases the accuracy substantially.

The accuracy of LHC + LC analysis limited by LHC jets measurement. Hence improvements are possible

At higher tanβ situation much worse for LHC.

Detailed analysis of point SPS1a

Masses of heavier neutralinos, charginos and SUSY parameter determination

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

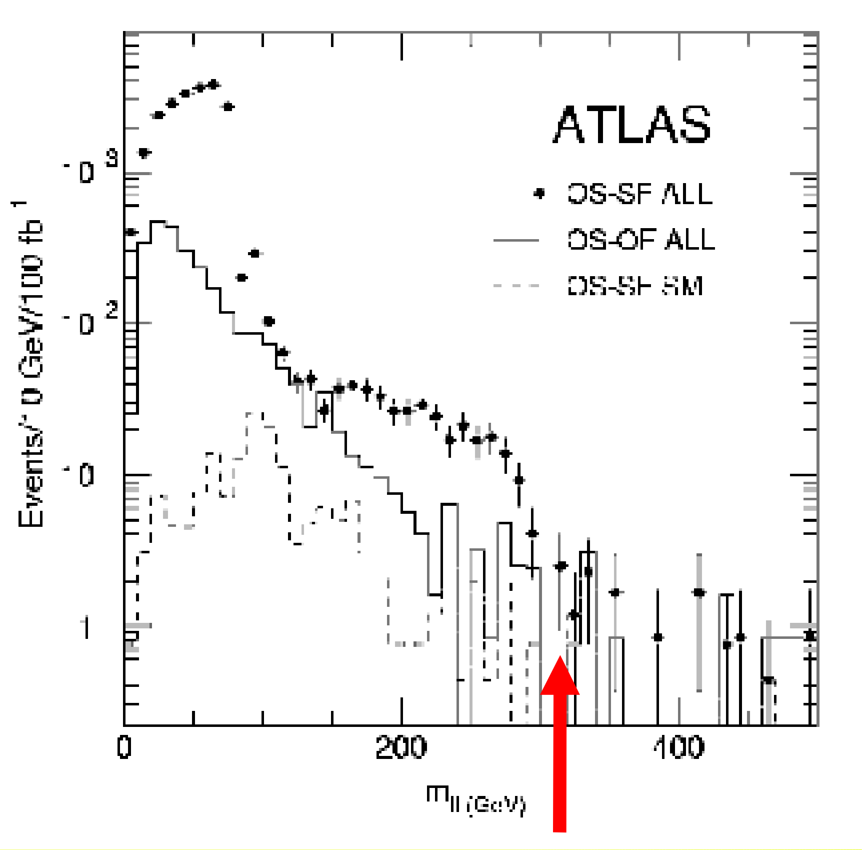
Feedback from LC into LHC studies and ***vice versa.***

Heavier neutralinos/charginos : may be produced only at the LHC. Use LC input on lighter neutralino, chargino masses and slepton masses to correctly identify the χ_4^0 . Use the accurate parameter determination from LC for that. BUT only LHC will be able to see it. SO LC TELLS LHC WHERE TO LOOK.

Further feeding this value of m(χ^0_4) can increase the accuracy of parameter determination at LC. LHC INFO FEEDS BACK INTO LC STUDIES.

Masses of heavier neutralinos, charginos

Predicting sparticle masses from LC data.
LC can measure χ_1^0, χ_2^0 and χ_1^+ precisely
$\Rightarrow$ Measurements of masses, cross sections, the mixing angles (using polarized beams)
Determine the SUSY parameters
M_1, M_2 (U(2) and SU(2) gaugino masses)
μ (higgsino mass parameter) and tanβ



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

Predicts: m(χ_4^0)=378.3 ± 8.8 GeV

With a tailored analysis mass of $\geq \chi_4^0$ can be measured. With(out) using information from LC to 2.5 (5) GeV.

Bit more on this synergy

LC prediction for m(χ_4^0) increases the stastistical significance of the LHC. Testing only one mass hypothesis rather than many hypotheses.

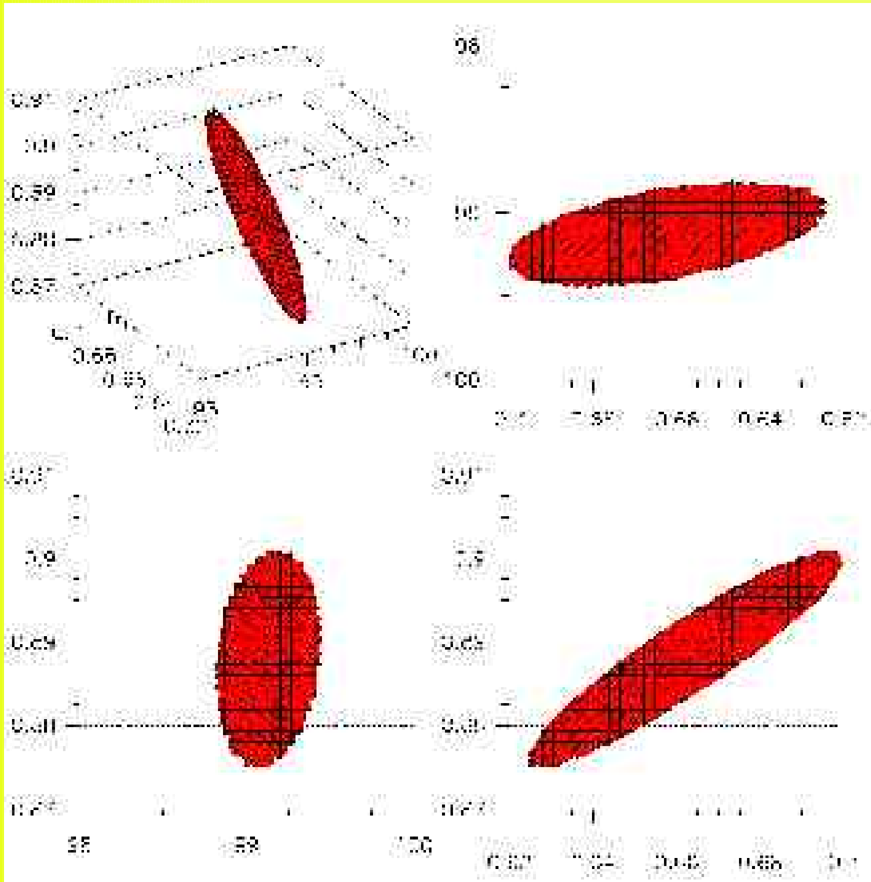
A mismatch between LC prediction and LHC measurement can imply (N)MSSM or something entirely different. So will be important any way.

Prototype of LHC/LC synergy:
for example a signal with small statistical significance seen at the LHC after LC predicts it, calls for higher luminosity, improved cuts/triggers in the upgrade etc.
Overlap in LHC/LC running important for such cases.

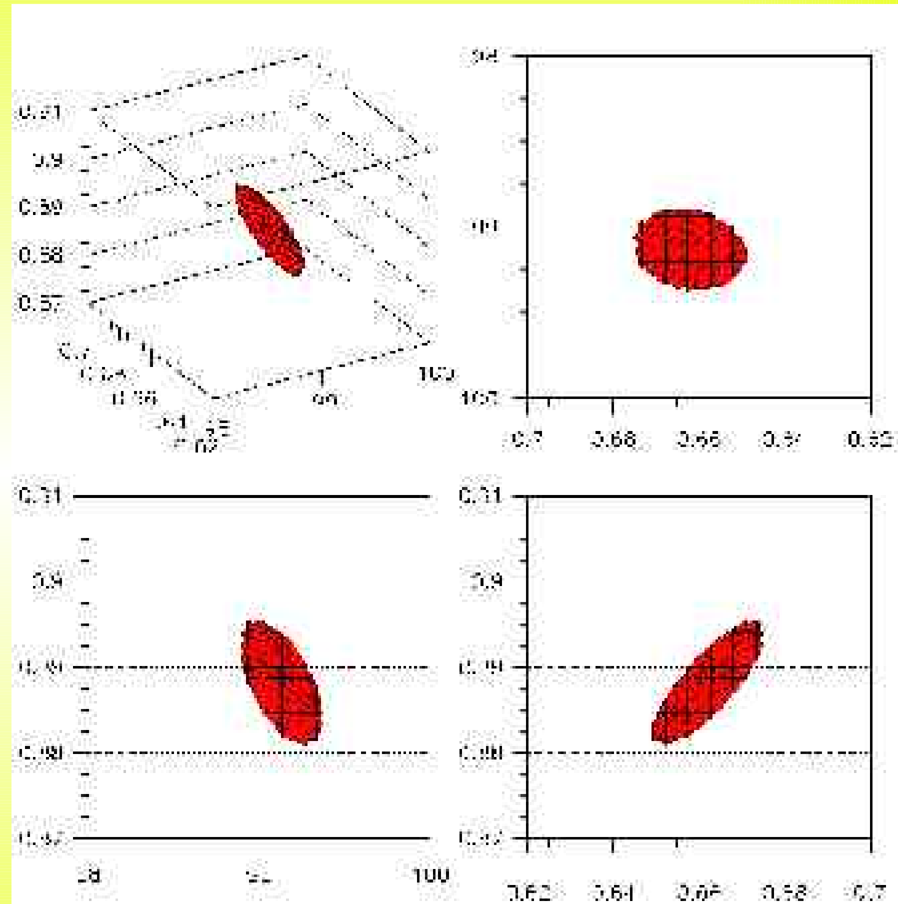
See talk by G. Mootgart-Pick on the subject.

Feed this back into LC analysis

Determine M_1 , mixing angles $\cos \Phi_L$, $\cos \Phi_R$. Plotted contours of $\Delta \chi^2 = 6$.



LC alone



LC + LHC

Significant improvement in precision with LC + LHC

Susy Parameters			
M_1	M_2	μ	$\tan\beta$
99.1 ± 0.3	192.7 ± 0.6	$\mu = 353.2 \pm 2.5$	$[8.6; 12.0]$

Use of LC/LHC to determine SUSY parameters with a global fit.

Note :

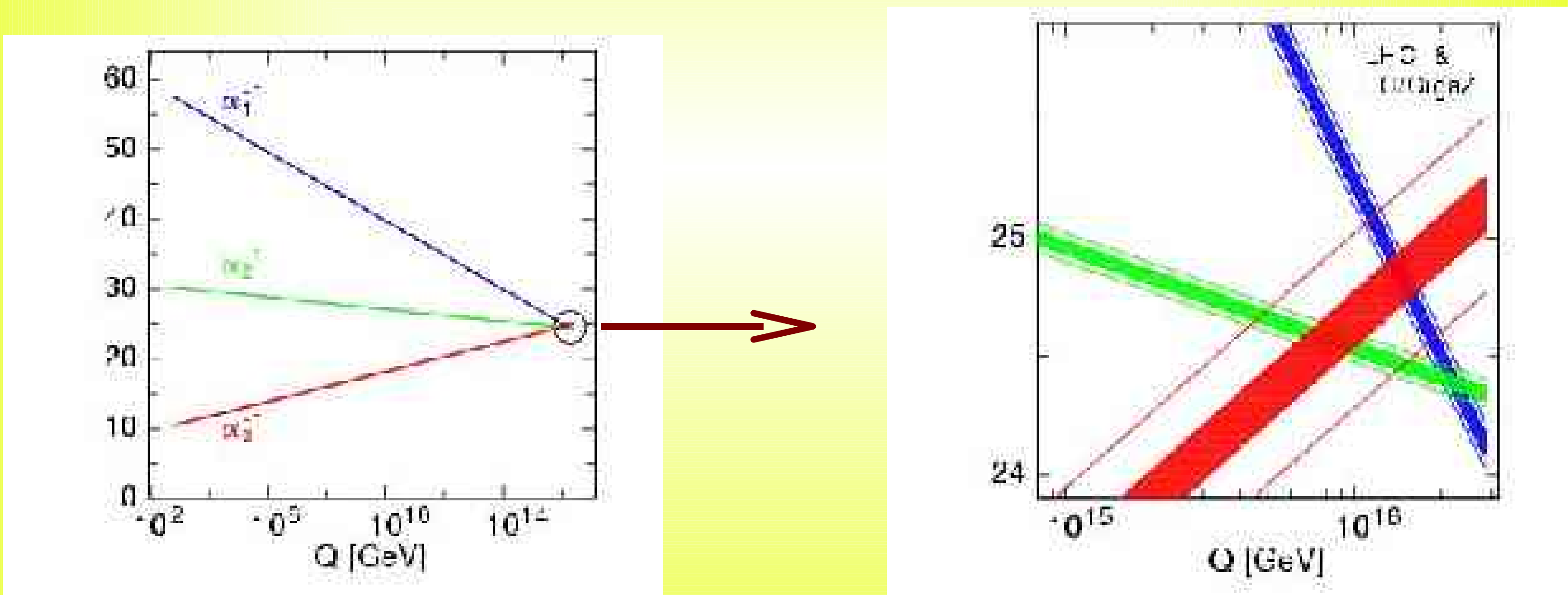
SPS 1a point used as that is the point for which complete LC and LHC simulation is available.

No convergence in Global fits of the MSSM parameters unless the LC + LHC analysis included.

See talk by Wienemann in parallel session.

Use of LC/LHC to determine pattern of SUSY breaking

From a combination of LHC and LC results, precise measurements of masses of SUSY particles, couplings: Evolution of gaugino mass parameters [B. Allanach, G. Blair , S.Kraml, , U. Martyn W. Porod,, G. Polesello, P. Zerwas] for SPS 1a point.



Broad error bands for LHC sparticle measurements alone.
Narrower with LHC + LC measurements (including Giga Z)

LHC/LC: EW Symmetry Breaking, SUSY Higgs

For the light higgs $\Delta m_h^{exp} \simeq 200$ MeV at the LHC,

for m_t expected accuracy at the LHC = 1-2 GeV.

To match this high experimental precision on m_h, with equally accurate theoretical prediction in MSSM, one needs Δm_t ? 0.1 GeV, possible only from the LC.

If LHC sees only one neutral Higgs and all the other SUSY Higgs states are not accessible even to LHC, the sector can be probed only via the precision measurements of Higgs Branching Ratios at the LC.

Probing and testing the consistency of the MSSM by probing the Higgs sector through indirect measurements, can improve in accuracy due to the information on the strongly interacting sparticle sector from the LHC and LC precision measurements can in turn give clues towards the SUSY phenomenology at the LHC.

EW symmetry breaking:MSSM

Higgs Physics:

1) [K. Desch, E. Gross, S. Heinemeyer, G. Weiglein, L. Zivkovic.]

Assume:

LHC can see A.

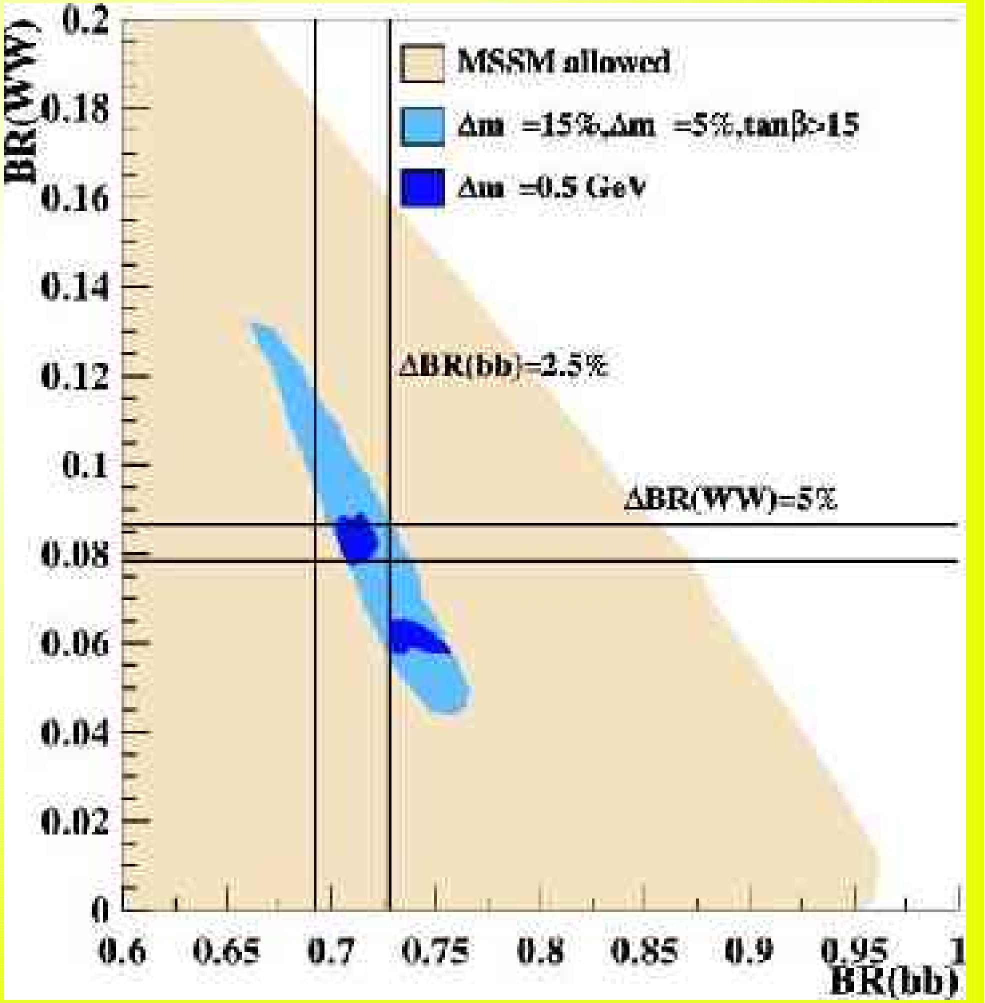
1)LHC information on M_A and $\tan\beta$

2) ⊕ (LHC ⊗ LC) information on stop and bottom masses.

3) LHC/LC measurement of m_H

Comparison of MSSM prediction for the given point on assumed inputs with LC measurements tests the model sensitively.

Indirect determination of trilinear coupling A_t is also discussed.



EW symmetry breaking

F. Boudjema, G. Belanger and R.G.

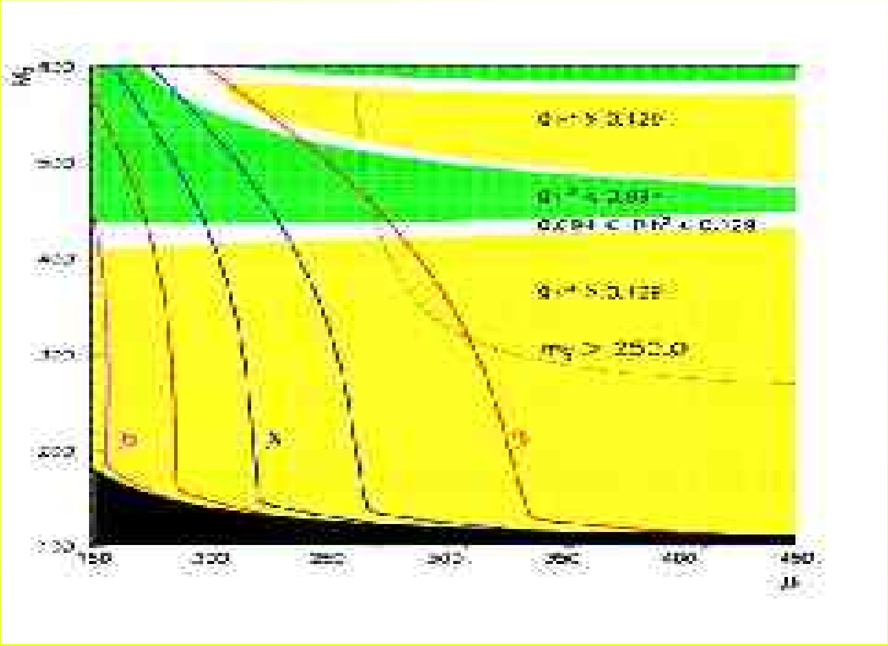
Invisible Higgs:

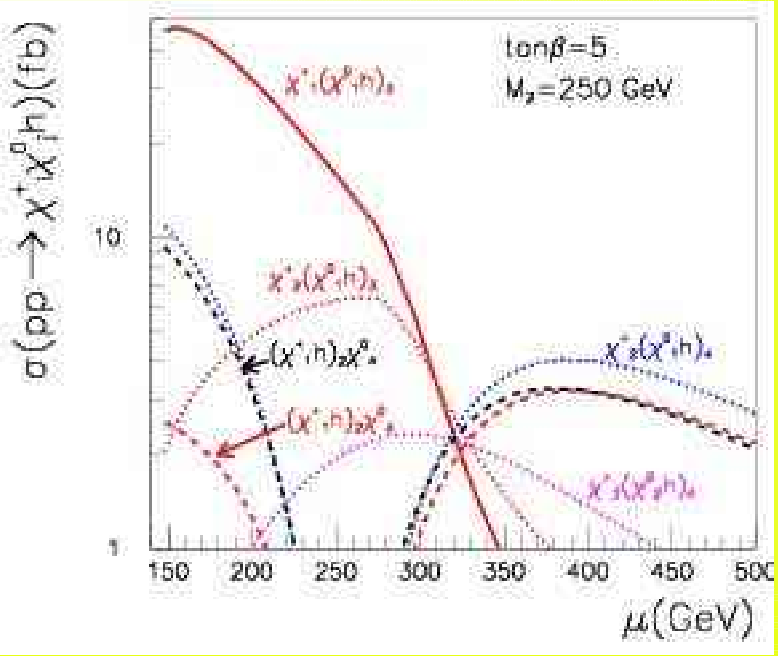
1) SUSY can make Higgs 'Invisible': for nonuniversal gaugino masses due to decays into neutralinos.

2) Cosmology constraints disfavour a big part of the region but still regions with large invisible b.r. Possible.

3) Direct detection of such a Higgs at LHC difficult.

4)If invisibility due to SUSY decays, production of h in χ^0_i decays

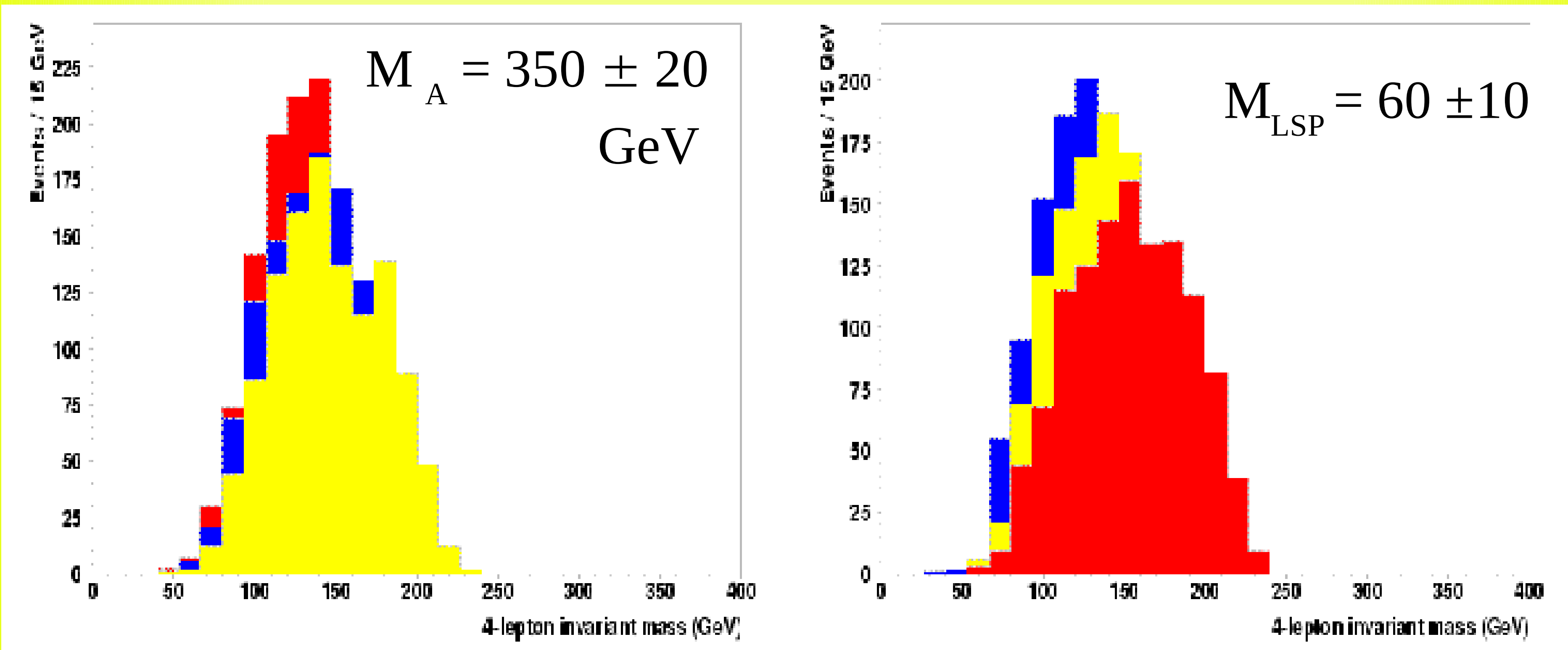




EW symmetry breaking: determination of M_A

[Mootgart Philip]

$$H, A \to \tilde{\chi}_2^0 \tilde{\chi}_2^0$$



Get Sensitivity from 4 lepton invariant mass.

LHC: Sensitivity dominated by uncertainty of the LSP mass measurement :**(LHC ⊗ LC)** Sensitive to M_A if mass of LSP known to better than 1%

More things in words:

1) Hisano, Kawagowe and Nojiri: Strategy using LHC + LC to determine the parameters of the third genration of squarks; the mixing angles for stop sector and sbottom sector.

2) In turn this information very significant for the precision prediction of m_h as well as predictions of the branching ratios of the light Higgs. K. Desch, G. Weiglein ... show how this knowledge from LHC + LC, improves the significance of testing the consistency of the MSSM from accurate measurements of the B.R. Of h into WW and bbar.

Strong EW Symmetry breaking

[T. Barklow, S. Boogert, G. Cerminara, A. Krokhotine, W. Kilian,K. Moenig, A.F. Osorio,]

If no light Higgs boson exists ⇒ The EW symmetry breaking dynamics has to be probed in W/Z scattering processes

LHC and LC sensitive to different/complementary channels

To make full use of the LHC data detailed information from LC and angular distributions etc. CRUCIAL. So a case of **(LHC ⊗ LC).**

Resonances at high energy not only directly accessible at the LHC, a combination with sub TeV data from LC on cross-sections essential for disentangling the new states.

Contact interactions, new gauge theories..etc.

[D. Bourikov, S. Godfrey, J. Hewett, F. Richard, S. Riemann, T Rizzo]

New Theoretical impetus due to Little Higgs Models etc.

Distinction between Z' and (say) KK excitations

Scenario:

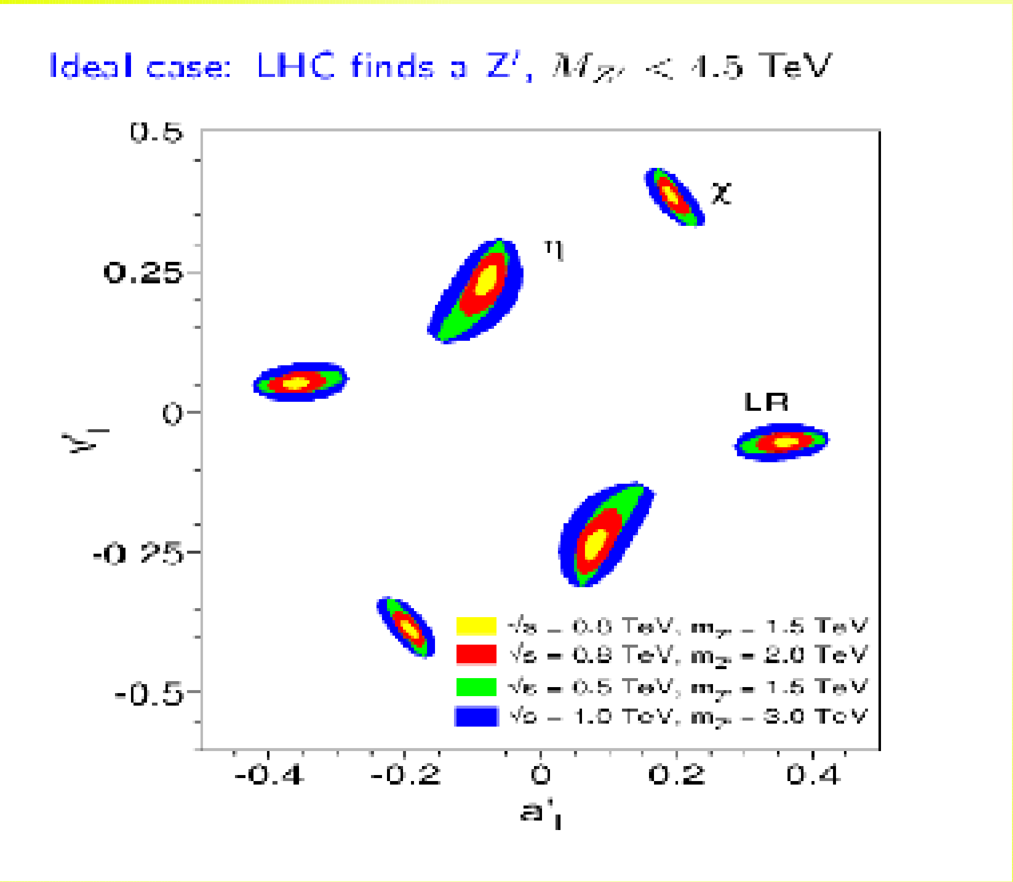
LHC sees new DY resonance, measures mass

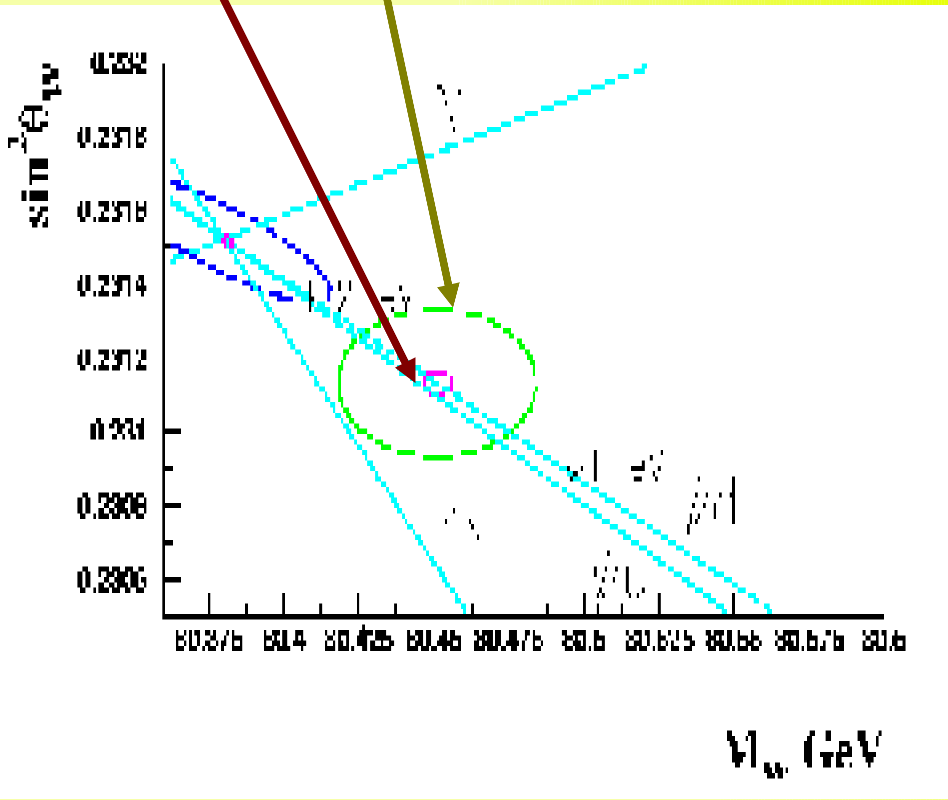
LC uses LHC pointer, measures couplings and then use precision measurements at a GigaZ to distinguish between different models by EW Precision measurements.

Contact interactions, new gauge theories..etc.

Measurement of Z' coupling

GigaZ vs Current accuracy





More

- Lots more on
  - Electroweak physics
  - QCD
  - Top physics
  - ADD extra dimensions
  - CP studies in the Higgs sector
  - Higgs potential
  - NMSSM studies
  - Little Higgs studies
  - ‘Invisible’ Higgs
  - Contact interactions
  - Radion-Higgs separation
  - etc… etc.

Conclusions

- Topics covered here just a small survey. Many more examples in the document
- This document can be used by the community to discuss the issue further.
- LHC/LC study group has only scratched the surface so far.
- But various good examples of the synergy established ***quantitatively***
- Certainly more ideas waiting to be thought about and studied.
- Hard to believe, after these studies, that after LC turn on no new questions will be asked of the LHC.

Please do join the effort of LHC + LC studies.

Positive outcome is good synergy between LHC and LC enthusiasts

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