The LHC and the ILC

Georg Weiglein

IPPP Durham

Stanford 03/2005

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

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

Introduction

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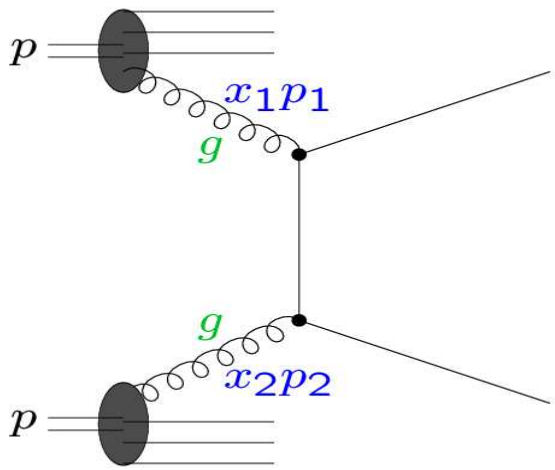
What is the added value of having both machines run in parallel?

Physics at the LHC and ILC in a nutshell

LHC: pp scattering at 14 TeV



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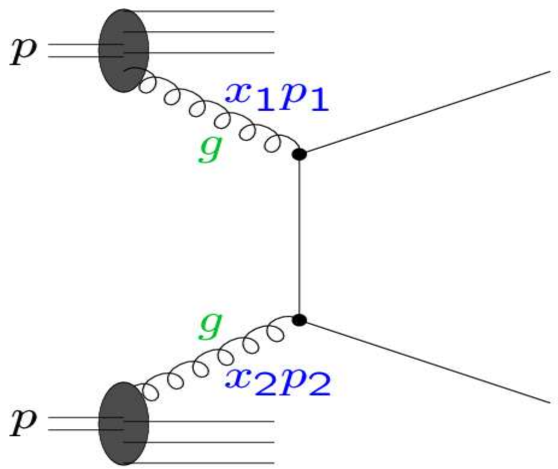

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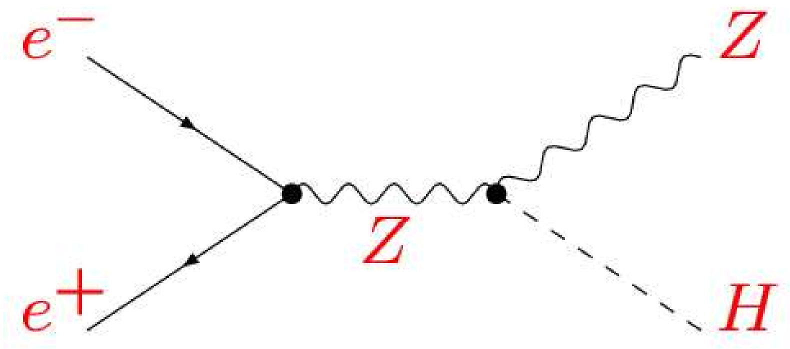
ILC: e^+e^- scattering at $\approx$0.5–1 TeV



Clean exp. environment:
well-defined initial state,
tunable energy,
beam polarization, GigaZ,
$\gamma\gamma$, $e\gamma$, e^-e^- options, . . .

$\Rightarrow$ rel. small backgrounds
high-precision physics

What will physics at the TeV scale be like?

"Known unknowns" vs. "unknown unknowns"

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ILC: untriggered operation

$\Rightarrow$ can find signals of unexpected new physics (direct production $+$ large indirect reach) that manifests itself in events that are not selected by the LHC trigger strategies

Interplay between lepton and hadron colliders: some examples from the past

LEP + SLC + Tevatron led to many success stories:

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LHC and ILC will explore a new energy domain

$\Rightarrow$ expect ground-breaking discoveries

$\Rightarrow$ large potential for synergy

LHC / ILC interplay

LHC: good prospects for producing new heavy states

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Concurrent running: LHC $\otimes$ ILC

$\Rightarrow$ Information obtained at the ILC can be used to improve analyses at the LHC and vice versa

$\Rightarrow$ Enable improved strategies, dedicated searches

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⇒ LHC / ILC Study Group

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

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First report has just been completed: hep-ph/0410364

First LHC / ILC Study Group report: hep-ph/0410364

hep-ph/0410364

Physics Interplay of the LHC and the ILC

The LHC / LC Study Group

Editors:

G. Weiglein[1], T. Barklow[2], E. Boos[3], A. De Roeck[4], K. Desch[5], F. Gianotti[4], R. Godbole[6], J.F. Gunion[7], H.E. Haber[8], S. Heinemeyer[4], J.L. Hewett[2], K. Kawagoe[9], K. Mönig[10], M.M. Nojiri[11], G. Polesello[12,4], F. Richard[13], S. Riemann[10], W.J. Stirling[1]

Working group members who have contributed to this report:

A.G. Akeroyd[14], B.C. Allanach[15], D. Asner[16], S. Asztalos[17], H. Baer[18], T. Barklow[2], M. Battaglia[19], U. Baur[20], P. Bechtle[5], G. Bélanger[21], A. Belyaev[18], E.L. Berger[22], T. Binoth[23], G.A. Blair[24], S. Boogert[25], E. Boos[3], F. Boudjema[21], D. Bourilkov[26], W. Buchmüller[27] V. Bunichev[3], G. Cerminara[28], M. Chiorboli[29], H. Davoudiasl[30], S. Dawson[31], A. De Roeck[4], S. De Curtis[32], F. Deppisch[23], K. Desch[5], M.A. Díaz[33], M. Dittmar[34], A. Djouadi[35], D. Dominici[32], U. Ellwanger[36], J.L. Feng[37], F. Gianotti[4], I.F. Ginzburg[38], A. Giolo-Nicollerat[34], B.K. Gjelsten[39], R. Godbole[6], S. Godfrey[40], D. Grellscheid[41], J. Gronberg[17], E. Gross[42], J. Guasch[43], J.F. Gunion[7], H.E. Haber[8], K. Hamaguchi[27] T. Han[44], S. Heinemeyer[4], J.L. Hewett[2], J. Hisano[45], W. Hollik[46], C. Hugonie[47], T. Hurth[4,2], J. Jiang[22], A. Juste[48], J. Kalinowski[49], K. Kawagoe[9], W. Kilian[27], R. Kinnunen[50], S. Kraml[4,51], M. Krawczyk[49], A. Krokhotine[52], T. Krupovnickas[18], R. Lafaye[53], S. Lehti[50], H.E. Logan[44], E. Lytken[54], V. Martin[55], H.-U. Martyn[56], D.J. Miller[55,57], K. Mönig[10], S. Moretti[58], F. Moortgat[4], G. Moortgat-Pick[1,4], M. Mühlleitner[43], P. Nieżurawski[59], A. Nikitenko[60,52], M.M. Nojiri[11], L.H. Orr[61], P. Osland[62], A.F. Osorio[63], H. Päs[23], T. Plehn[4], G. Polesello[12,4], W. Porod[64,47], A. Pukhov[3], F. Quevedo[15], D. Rainwater[61], M. Ratz[27], A. Redelbach[23], L. Reina[18], F. Richard[13], S. Riemann[10], T. Rizzo[2], R. Rückl[23], H.J. Schreiber[10], M. Schumacher[41], A. Sherstnev[3], S. Slabospitsky[65], J. Solà[66,67], A. Sopczak[68], M. Spira[43], M. Spiropulu[4], W.J. Stirling[1], Z. Sullivan[48], M. Szleper[69], T.M.P. Tait[48], X. Tata[70], D.R. Tovey[71], A. Tricomi[29], M. Velasco[69], D. Wackeroth[20], C.E.M. Wagner[22,72], G. Weiglein[1], S. Weinzierl[73], P. Wienemann[27], T. Yanagida[74,75], A.F. Żarnecki[59], D. Zerwas[13], P.M. Zerwas[27], L. Živković[42]

Exploratory study

122 authors from
75 institutions,
472 pages

Has been submitted
to *Physics Reports*,
CERN Yellow Report

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(1) can a signal be detected?

(2) which properties can be measured; how precisely?

(3) how well are we able to tell what it is?

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⇒ Summary given in the report

Main focus of LHC studies so far was on (1), less results available on (2) and (3)

How far are we?

- Many possibilities of LHC / ILC synergy have been highlighted

  ⇒ LHC / ILC interplay is a very rich field

  ⇒ great potential for important physics gain

  ⇒ Needs to be worked out and confirmed in detailed case studies, experimental simulations

- Many of the analyses so far were mainly LHC analyses where at the very end some ILC input was injected (or the other way round)

  ⇒ Aim should be LHC / ILC analyses that make use of the interplay from the start

How far are we?

- ATLAS and CMS are actively preparing for the start of data taking: CMS writes physics TDR, many new studies in ATLAS (full simulations, new scenarios)

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$\Rightarrow$ We cannot afford to slow down in our efforts for exploring LHC / ILC interplay

Example from the U.S.

Presentation from M. Turner (NSF) to HEPAP, Sep. 23, 2004:

Complementarity

Inevitably, the question will arise of why we need a second, *less* powerful accelerator to explore the energy frontier. To educate us and to clarify this issue more generally, we would like HEPAP to form a subpanel to address complementarity, paying particular attention to the following aspects of LC/LHC complementarity:

- In the context of physics discoveries (e.g., low-energy supersymmetry) made at the Tevatron or early at the LHC, what is the role of a subTeV Collider?
- In the context of physics discoveries made an LC, what is the role of the LHC
- In the context of "known physics" (e.g., electroweak physics), what are the synergies and complementaries of these two machines?

You should assume that the LC and LHC (with possible upgrades) will have a significant period of overlapping operation.

We are looking for a short document (20 pages), accessible to knowledgeable non-experts (e.g., members of the EPP2010 Study, OSTP Staff and ourselves). We ask that the report be completed by April 2005.

Finally, to further educate us as well as giving us an opportunity to refine and discuss the charge with you in more detail, we suggest a half-day session at the next HEPAP meeting devoted to Complementarity.

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⇒ Initiative has to come from the ILC community

⇒ from you!

The idea to explore interplay between different machines has found wider interest:

New initiative at CERN:

Study the synergy and complementarity of the LHC and flavour factories

[*M. Mangano et al.*]

Main goal will be to develop a document similar to the LHC / ILC report

Want to use existing LHC / ILC studies as guiding framework

In this talk:

- Some examples of LHC / ILC synergy
- Main emphasis on new results (after completion of first report), possible topics of future studies

Example: Higgs coupling determination at LHC

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Large uncertainty on $H \to b\bar{b}$, ...

$\Rightarrow$ Determination of ratios of partial widths

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$\Rightarrow$ Determination of ratios of partial widths

$\Rightarrow$ Additional theoretical assumptions needed for absolute determination of partial widths at the LHC

Use ILC input instead: measurement of the top Yukawa coupling at LHC $\oplus$ ILC

Only crude measurement of tth coupl. at 500 GeV ILC (light Higgs)

Precision measurement requires ILC with 800–1000 GeV

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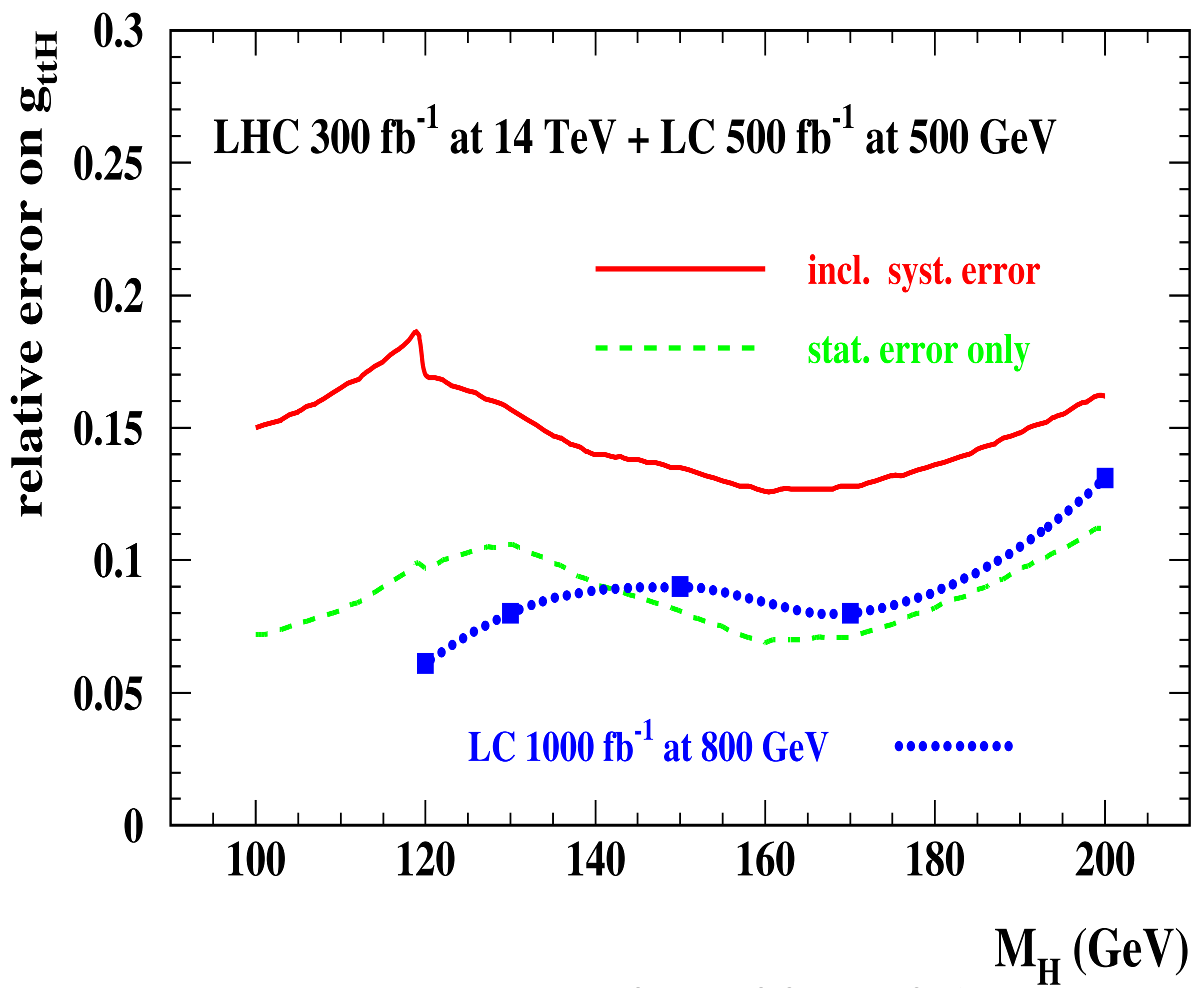
LHC measures $(\sigma \times \mathrm{BR})$

$\Rightarrow$ Yukawa coupling can be extracted if precise measurement of Higgs BR's from ILC are used

LHC $\oplus$ ILC (500 GeV):

[*K. Desch, M. Schumacher '04*]



Higgs coupling determination at LHC and ILC

Fit of Higgs couplings with input from LHC and ILC *NEW!*

[*M. Dührssen, S. Heinemeyer, H. Logan, D. Rainwater, G. W., D. Zeppenfeld '05*]

$\longrightarrow$ *See talk by S. Heinemeyer at LHC / ILC meeting next Wednesday*

Higgs coupling determination from combined input of LHC, ILC and photon collider *NEW!*

[*P. Nieżurawski, M. Krawczyk, A. Żarnecki '04*]

$\longrightarrow$ *See talk by A. Żarnecki at LHC / ILC meeting next Wednesday*

$\mathcal{CP}$-violation and non-standard Higgs physics

Structure of the Higgs sector can be very involved, dificult to disentangle

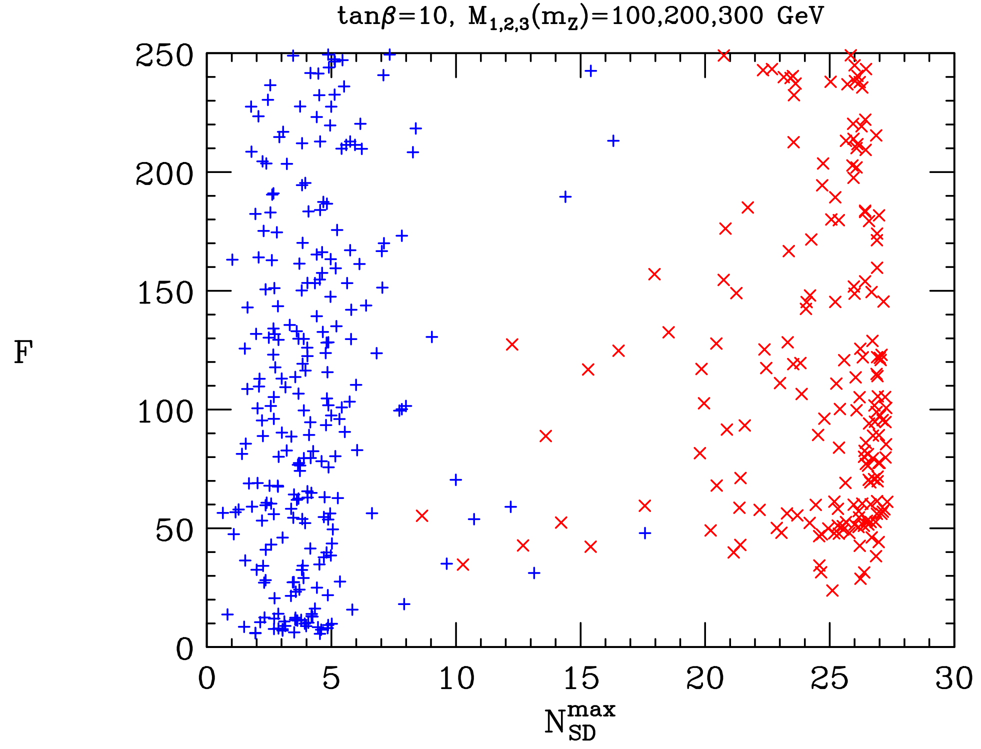
Examples: MSSM with $\mathcal{CP}$-violation, non-minimal SUSY models, Higgs–radion mixing, . . .

$\Rightarrow$ LHC / ILC interplay can be crucial to identify the structure of the Higgs sector

$\longrightarrow$ *See CPNSH meeting next Thursday* $+$ *Friday*

NMSSM: fine-tuning and observability at the LHC

NMSSM: light Higgs with dominant decay $h \to aa$ possible (blue points) [*R. Dermisek, J. Gunion '05*] *NEW!*



⇒ Points with lowest fine-tuning are most difficult to observe at the LHC ⇒ crucial to have ILC input

⟶ *See talks by R. Dermisek at LCWS05, J. Gunion at LHC / ILC meeting*

Example: SUSY at LHC and ILC

LHC: good prospects for strongly interacting new particles

long decay chains $\Rightarrow$ complicated final states,

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

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But ist it really SUSY? Which particles are actually produced?

Main background for SUSY is SUSY itself!

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SUSY phenomenology investigated in detail for SPS 1a benchmark point: “best case scenario”

more results needed for less favourable points (in progress at ATLAS & CMS)

It quacks like SUSY, but . . .

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- does every SM particle really have a superpartner?
- do their spins differ by $1/2$?
- are their gauge quantum numbers the same?
- are their couplings identical?
- do the SUSY predictions for mass relations hold, . . . ?

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- is the lightest SUSY particle really the neutralino, or the stau or the sneutrino, or the gravitino or . . . ?
- is it the MSSM, or the NMSSM, or the mNSSM, or the N^2MSSM, or . . . ?
- what are the experimental values of the 105 (or more) SUSY parameters?
- does SUSY give the right amount of dark matter?
- what is the mechanism of SUSY breaking?

We will ask similar questions for other kinds of new physics

When and how will we find out?

- How much will we learn from the LHC alone?
- How much more will we know once we have ILC data?
- What is the added value of having the LHC and the ILC run concurrently?

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SUSY at the ILC: clean signatures, small backgrounds

⇒ precise determination of masses, spin, couplings, mixing angles, complex phases . . . ,

good prospects for weakly interacting SUSY particles

precision measurement of mass of lightest SUSY particle (factor 100 improvement)

Some results from the first report:

- Precise determination of the properties of the SUSY particles accessible at the ILC
  $\Rightarrow$ identify whether or not these particles appear in the decay cascades at the LHC

- Precision measurement of the LSP mass at the ILC as input for LHC analyses
  $\Rightarrow$ significantly improves precision of mass determination of heavier SUSY particles at the LHC

- From part of the SUSY spectrum accessible at the ILC
  $\Rightarrow$ can predict the properties of heavier particles
  $\Rightarrow$ tell the LHC where to look

"Telling the LHC where to look"

ILC prediction transforms search for edge in di-lepton mass spectrum into single hypothesis test

$\Rightarrow$ Increase of LHC statistical sensitivity!

$\Rightarrow$ crucial for extracting statistically marginal signal at LHC

$\Rightarrow$ Optimised searches at the LHC:

Improved selection criteria, modified triggers, different running strategy, . . .

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Compare the situation at LEP, where we had a statistically marginal excess of Higgs-like events

Suppose a collider running concurrently with LEP had predicted a Higgs boson with $M_{\mathrm{H}} = 115 \pm 1\ \mathrm{GeV}$

this would have certainly affected the running strategy of LEP

Example of LHC / ILC interplay from first report

SUSY case study where the lightest neutralino and chargino states $(\chi_1^0, \chi_2^0, \chi_1^\pm)$ are precisely measured at the ILC

[*K. Desch, J. Kalinowski, G. Moortgat-Pick, M. Nojiri, G. Polesello '04*]

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$\Rightarrow$ Prediction of masses of particles that are too heavy to be produced at the ILC but are produced with low statistics at the LHC, e.g. heaviest neutralino: $m_{\tilde{\chi}_4^0} = 378.3 \pm 8.8$ GeV

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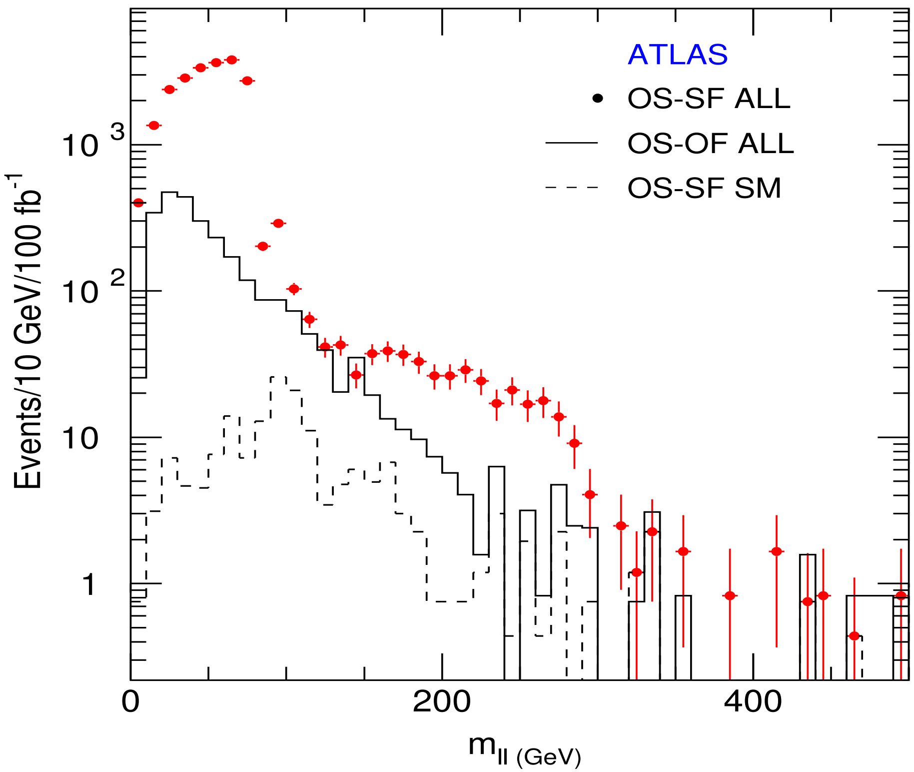
⇒ With this information the heaviest neutralino can be identified at the LHC using a dilepton "edge"

Search for the heaviest neutralino at LHC following the prediction from ILC



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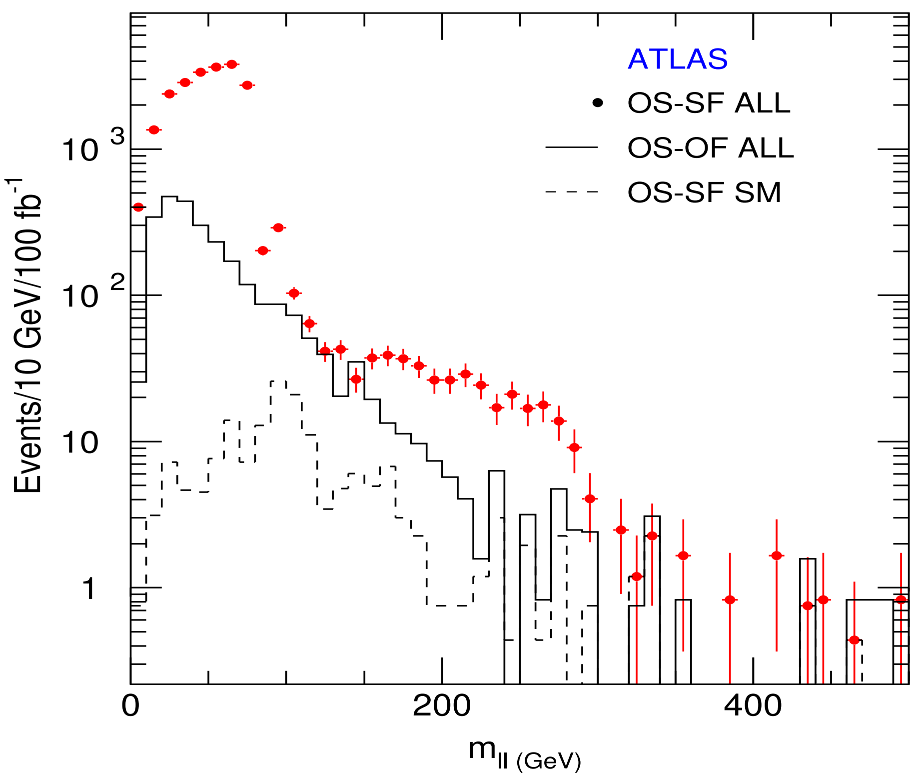

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Feeding information on $m(\tilde{\chi}^0_4)$ back into ILC analysis

⇒ Improved accuracy of parameter determination at ILC

New results, possible topics of future studies

Determination of the gluino mass: using ILC input to resolve ambiguities at the LHC *NEW!*

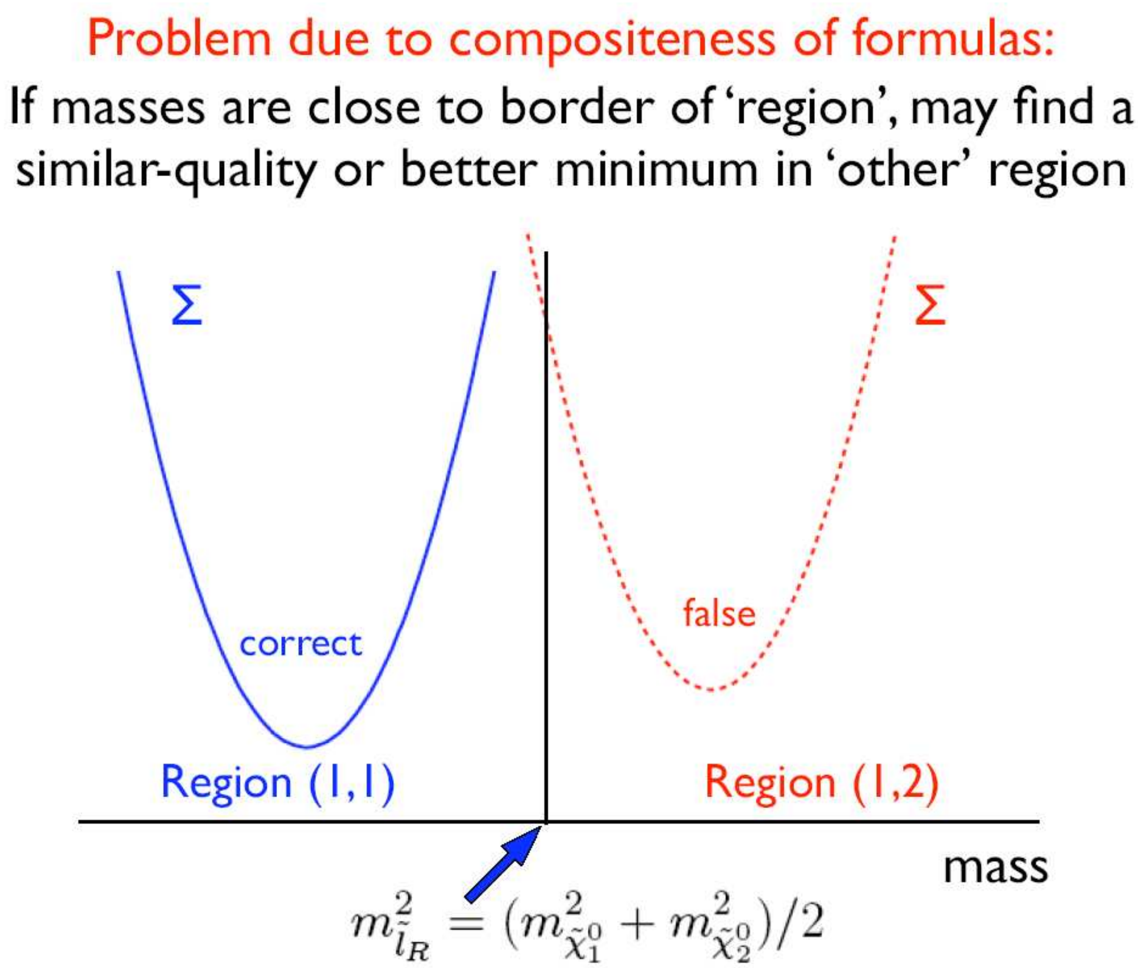
[*B. Gjelsten, D. Miller, P. Osland '05*]

Mass determination from cascade decays: invert endpoint formulas, fit masses

$\Rightarrow$ yields correct minimum

$+$ false minima (can be off by 10–20 GeV)

Determination of the gluino mass: using ILC input to resolve ambiguities at the LHC



ILC input on LSP mass ⇒ correct minimum can be identified, ambiguities resolved

⟶ *See talk by P. Osland at LCWS05*

Distinguishing between MSSM and NMSSM

Case study of scenario where Higgs sector and light neutralino / chargino spectra and cross sections are indistinguishable in the two models

[*G. Moortgat-Pick, S. Hesselbach, F. Franke, H. Fraas '05*] *NEW!*

Parameter determination as in MSSM $\Rightarrow$ no contradiction

ILC input $\Rightarrow$ prediction of $m_{\tilde{\chi}^0_3}$

$\Rightarrow$ Detection of $\tilde{\chi}^0_3$ at LHC yields contradiction with MSSM prediction

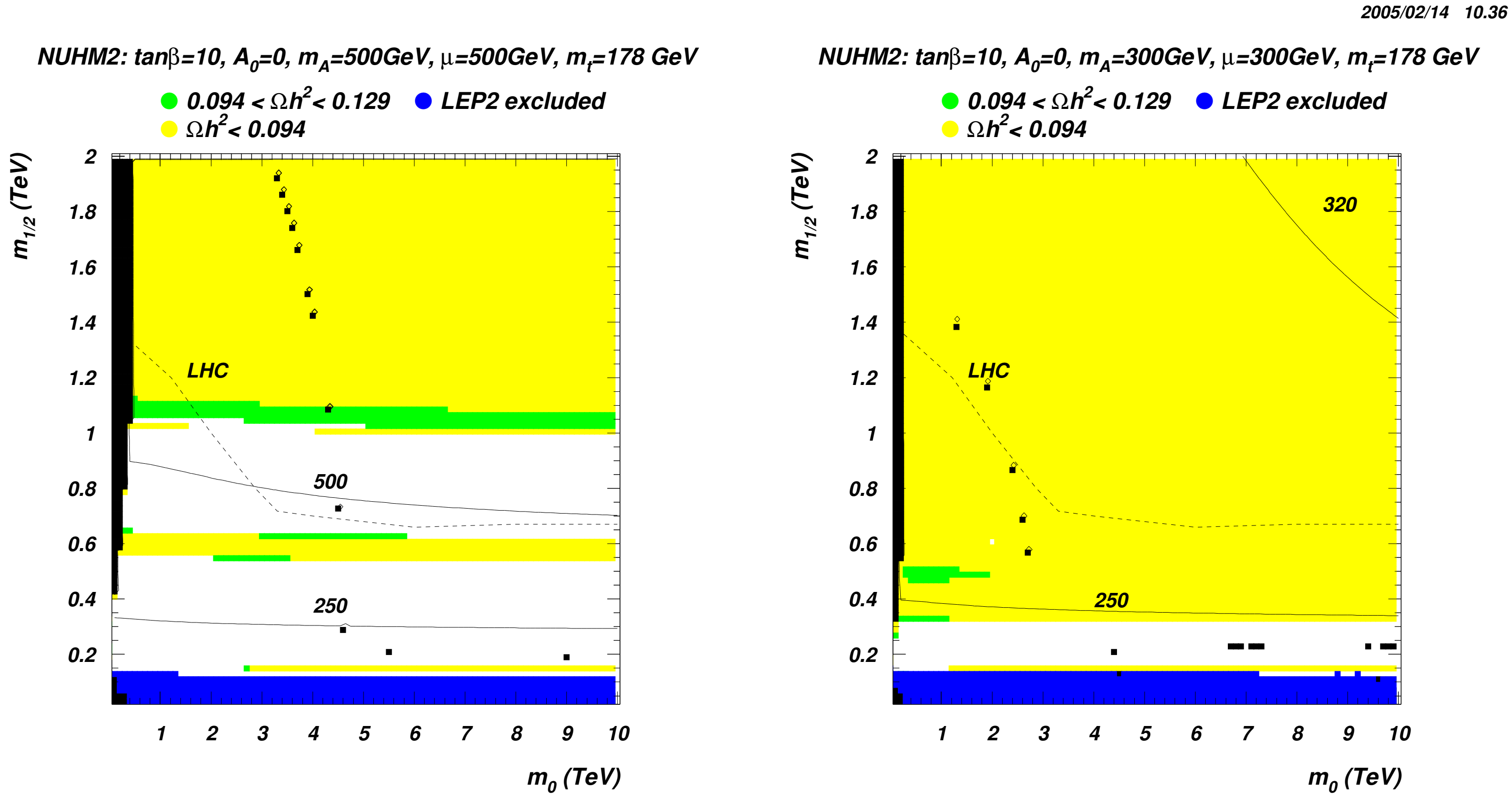
$\Rightarrow$ Evidence for NMSSM

$\longrightarrow$ *See talks by G. Moortgat-Pick at LCWS05, LHC / ILC meeting*

Investigation of different scenarios

Gravity-mediated SUSY with non-universal Higgs masses

[*H. Baer, A. Belyaev, A. Mustafayev, S. Profumo, X. Tata '05*] NEW!



$\Rightarrow$ ILC reach can exceed LHC reach

$\longrightarrow$ *See talk by H. Baer at LHC / ILC meeting*

Determination of SUSY parameters: global fit

Use *Fittino* to compare the ability of LHC only and $\mathrm{LHC} \oplus \mathrm{ILC}$ for SPS1a' point

[*P. Bechtle, K. Desch, P. Wienemann '05*] *NEW!*

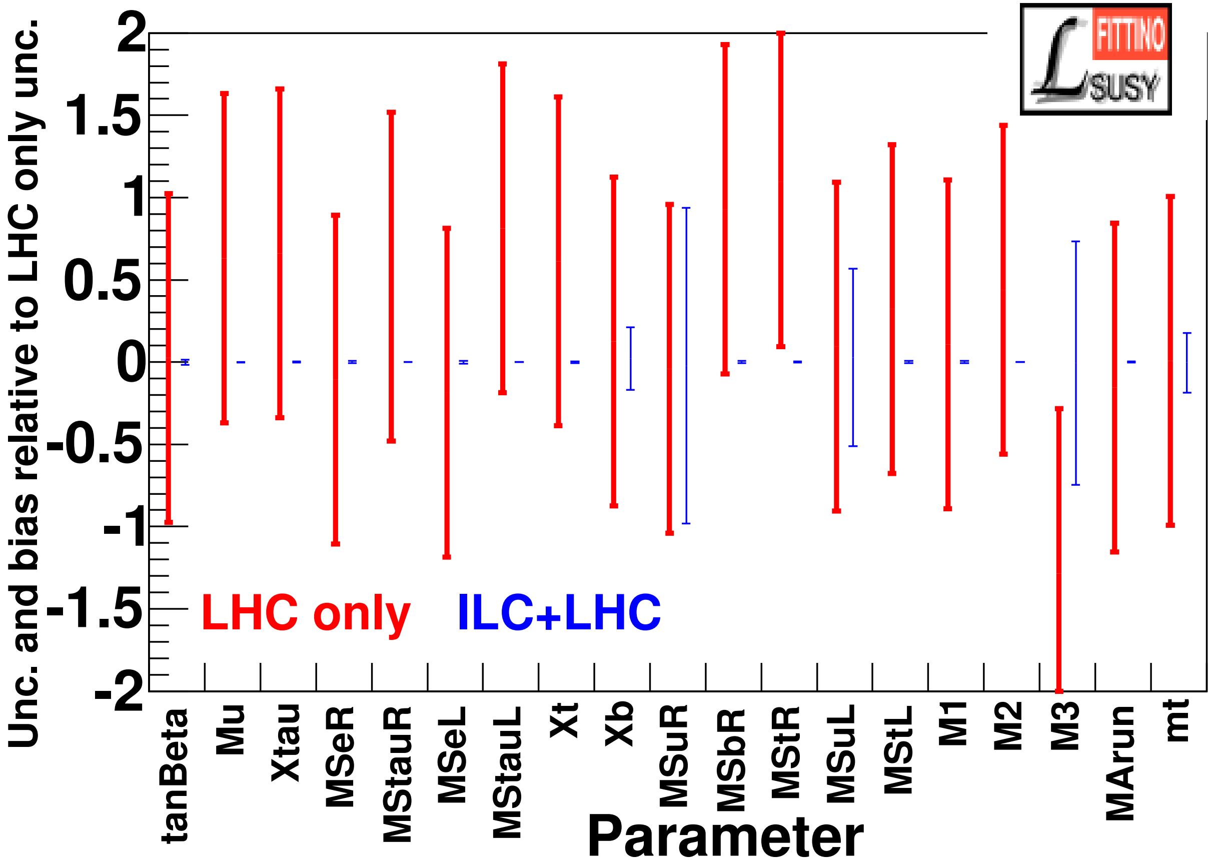
LHC input:

mass measurements and precision as in LHC / ILC report

$+$ assumption on $\tilde{t}_{1,2}$ mass measurement

$+$ ratios of Higgs branching ratios (see above)

Fittino: LHC only vs. LHC $\oplus$ ILC



$\Rightarrow$ precise determination of SUSY parameters only possible with LHC $\oplus$ ILC

$\longrightarrow$ *See talks by P. Bechtle at LCWS05, LHC / ILC meeting*

Example of a possible future study:

Once the masses of the particles in the decay cascade are determined, can one do more?

$\Rightarrow$ Insert more ILC results into LHC analysis:
couplings, decay properties, ...

$\Rightarrow$ Coupling determination of heavy particles at the LHC?

Upcoming LHC / ILC activities

- Workshop on LHC / ILC Synergies:
  SLAC, March 23, 2005

- Les Houches Workshop: Physics at TeV Colliders
  Meeting: May 2–20, 2005

- Snowmass Workshop: August 14–27, 2005
  Aspen Workshop: August 14 – September 10, 2005

Conclusions

- LHC / ILC interplay is a very rich field

  LHC / ILC synergy has the potential to greatly enhance the physics programme of both facilities

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  But we cannot afford to slow down now

- Please come and actively participate in the Workshop on LHC /ILC Synergies on Wednesday