The LHC / ILC Connection

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Les Houches 05/2005

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

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

Introduction

- Physics case is well established both for LHC and ILC, based on what each machine can do individually

- LHC: $\gtrsim 2007$, expected to run for about 15 years

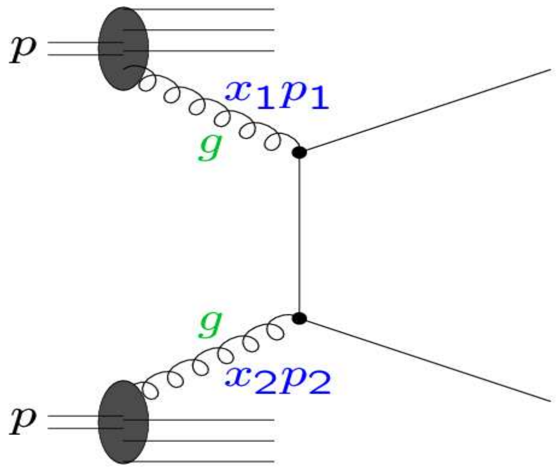
  ILC: $\gtrsim 2015$?

Expeditious realisation of the ILC $\Rightarrow$ period of concurrent running

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

Physics at the LHC and ILC in a nutshell

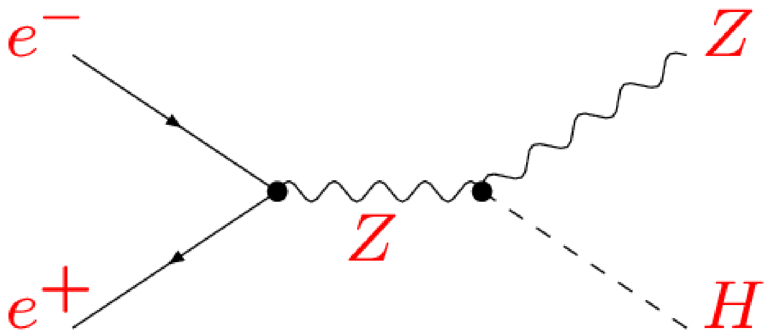
LHC: pp scattering at 14 TeV



Scattering process of proton constituents with energy up to several TeV,
strongly interacting

$\Rightarrow$ huge QCD backgrounds,
low signal–to–background ratios

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"*

We are prepared to explore Higgs physics, SUSY, extra dimensions, mini black holes, . . .

These are "known unknowns", but one also needs to be prepared for the unexpected

LHC: interaction rate of 10^9 events$/s$

$\Rightarrow$ can trigger on only 1 event in 10^7

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:

SM at quantum level, top quark, prediction of Higgs mass

HERA observation of high Q^2 events $\Rightarrow$ dedicated leptoquark searches at the Tevatron, results fed back to HERA analyses

Belle discovery of X(3872) $\Rightarrow$ dedicated search at CDF & D0

$\Rightarrow$ independent confirmation

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

ILC: direct production $\oplus$ high sensitivity to effects of new physics via precision measurements (cf.: WMAP vs. COBE)

ILC will have a lot to add to whatever the LHC will find out

$\Rightarrow$ Need this information as soon as possible to identify the nature of new physics

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

What is the gain of having ILC and LHC run concurrently – how do we find out?

Exploring physics gain from LHC / ILC interplay requires:

- Detailed information on how well LHC and ILC can measure wide variety of observables in different scenarios
- Close collaboration of experts from LHC and ILC as well as from theorists and experimentalists

$\Rightarrow$ LHC / ILC Study Group

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

World-wide working group, started in spring 2002

Collaborative effort of Hadron Collider and Linear Collider experimental communities and theorists

First report has recently 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

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Exploratory study

122 authors from
75 institutions,
472 pages

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

How far are we?

In order to assess the physics gain of LHC / ILC concurrent running need to know from both colliders for different scenarios of new physics:

(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?

⇒ 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

  $\Rightarrow$ LHC / ILC interplay is a very rich field

  $\Rightarrow$ great potential for important physics gain

  $\Rightarrow$ 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)

  $\Rightarrow$ 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)

  $+$ ongoing ILC studies

  $\Rightarrow$ Many new results, ideal input for LHC $\otimes$ ILC studies

- There is a strong demand from our colleagues (within and outside our field), funding agencies, . . . to justify why we want to start constructing the ILC so soon after the start-up of the LHC

  $\Rightarrow$ A strong case for concurrent running will help

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

Examples 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.

Examples from the U.S.

EPP Decadal Survey:

U.S. National Academy of Science reviews each field of physics every ten years
(last survey of Particle Physics was completed in 1998)

EPP 2010 charge:

- Identify, articulate, and prioritize the scientific questions and opportunities that define elementary particle physics
- Recommend a 15-year implementation plan with realistic, ordered priorities to realize these opportunities

$\Rightarrow$ emphasis on ranking science priorities

Some of the EPP questions on the ILC:

- What are the physics arguments for operating a Linear Collider during the same time frame as the LHC?
- How would the combination of the LHC and a Linear Collider answer questions that could not be addressed by either machine alone?
- What physics would a Linear Collider address that would be impossible to probe at the LHC?

$\Rightarrow$ The LHC / ILC Study Group was approached by the EPP, asked to provide a response to these questions

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

$\longrightarrow$ *See talk by A. Ali and discussion session on Monday*

LHC / ILC Study Group meetings since the completion of the first report

- LHC / ILC Complementarity Meeting

  CERN, November 15, 2004

  five presentations + discussion on scenarios where ILC could influence LHC triggers

- Workshop on LHC / ILC Synergies

  SLAC, March 23, 2005

  ten presentations + lively discussions

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

LHC: no absolute measurement of total production cross section (no recoil method like LEP, ILC: $e^+e^- \to ZH$, $Z \to e^+e^-, \mu^+\mu^-$)

Measurement of $\sigma \times \mathrm{BR}$: narrow-width approximation

$$\Rightarrow \quad \sigma(H) \times \mathrm{BR}(H \to a + b) = \frac{\sigma(H)^{\mathrm{SM}}}{\Gamma^{\mathrm{SM}}_{\mathrm{prod}}} \cdot \frac{\Gamma_{\mathrm{prod}}\Gamma_{\mathrm{decay}}}{\Gamma_{\mathrm{tot}}}$$

Observation of different channels (or upper bound from non-observation) provides information on combinations of $\Gamma_g, \Gamma_W, \Gamma_Z, \Gamma_\gamma, \Gamma_\tau, \Gamma_b, Y_t^2$

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

$\Rightarrow$ Determination of ratios of partial widths

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

LHC alone: strategy

Consider general multi-Higgs-doublet models (with or without additional Higgs singlets), includes e.g. MSSM

$\Rightarrow$ HVV couplings bounded by SM values: $\Gamma_V \leq \Gamma_V^{\rm SM}$ $(V = W, Z)$

$\Rightarrow$ Upper bound on Γ_V

Observation of Higgs production

$\Rightarrow$ Lower bound on production couplings, lower bound on total Higgs width, $\Gamma_{\rm tot}$

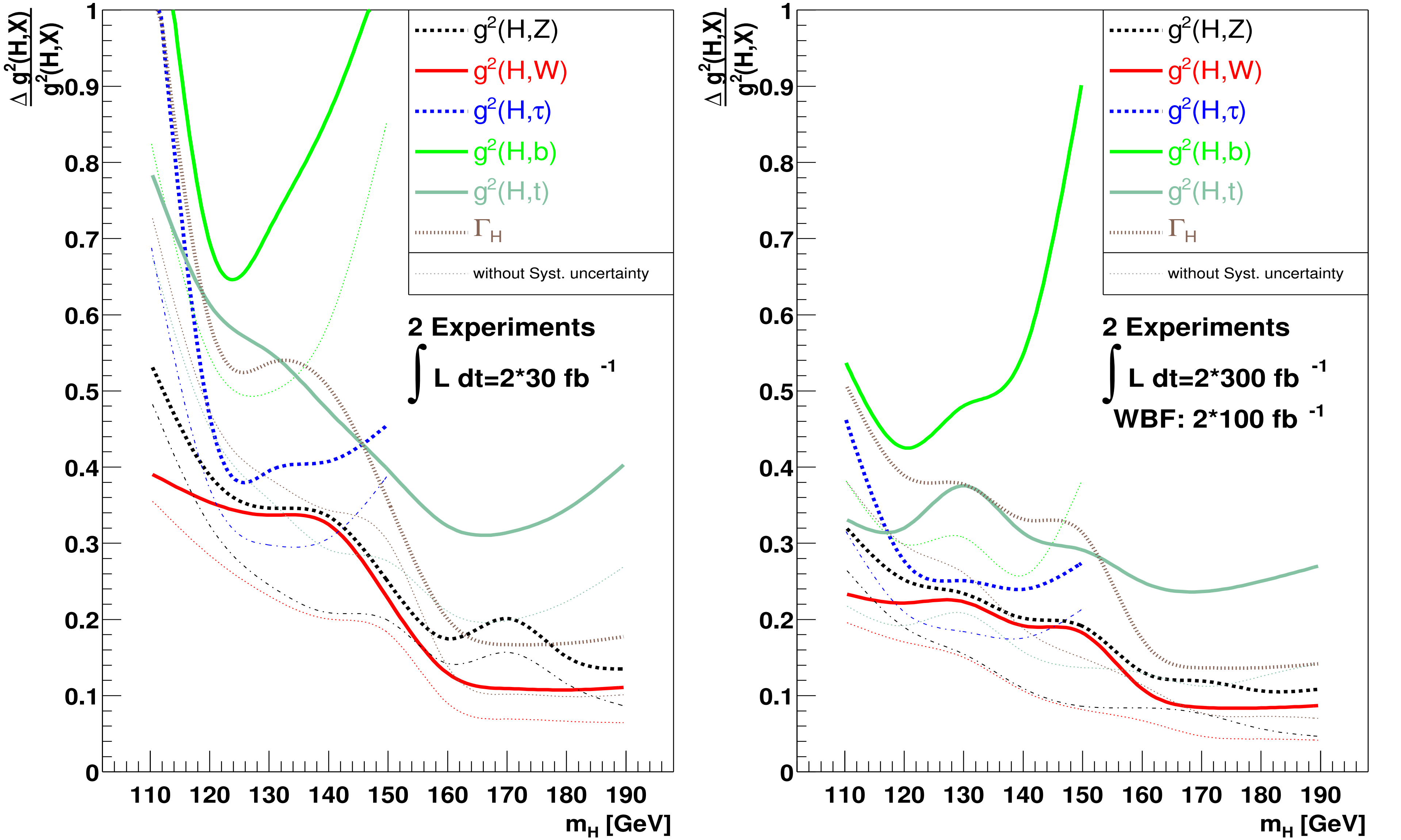
Observation of $H \to VV$ in WBF

$\Rightarrow$ Determines $\Gamma_V^2/\Gamma_{\rm tot}$ $\Rightarrow$ Upper bound on $\Gamma_{\rm tot}$

$\Rightarrow$ Absolute determination of $\Gamma_{\rm tot}$ and remaining Higgs couplings

Results for the couplings and the total Higgs width at the LHC with theory assumption

[*M. Dührssen, S. Heinemeyer, H. Logan, D. Rainwater, G. W., D. Zeppenfeld '04*]



Use ILC input instead of theory assumption: top Yukawa coupling at LHC $\oplus$ ILC

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

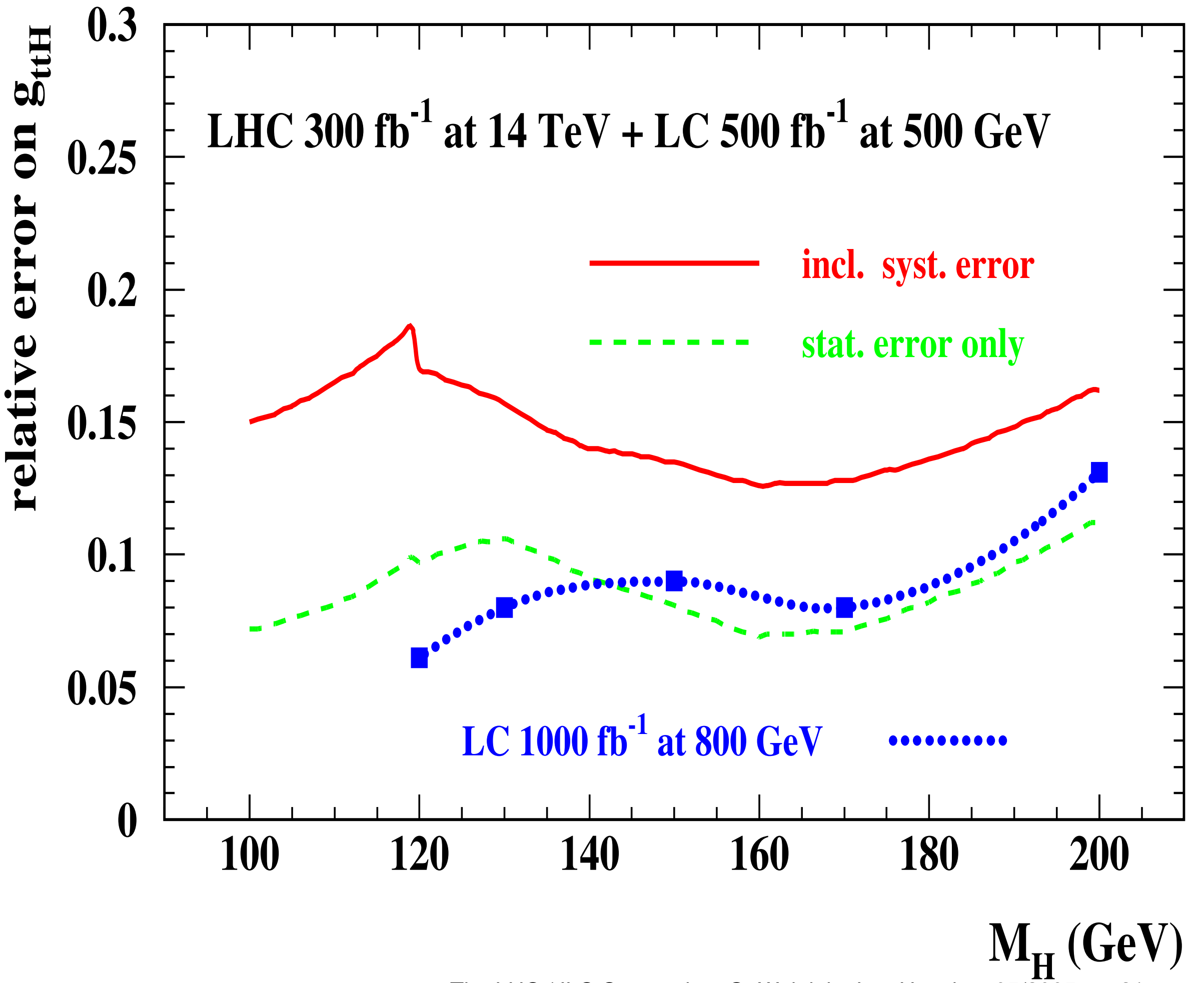
Precision measurement requires ILC with 800–1000 GeV

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 $\oplus$ ILC

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

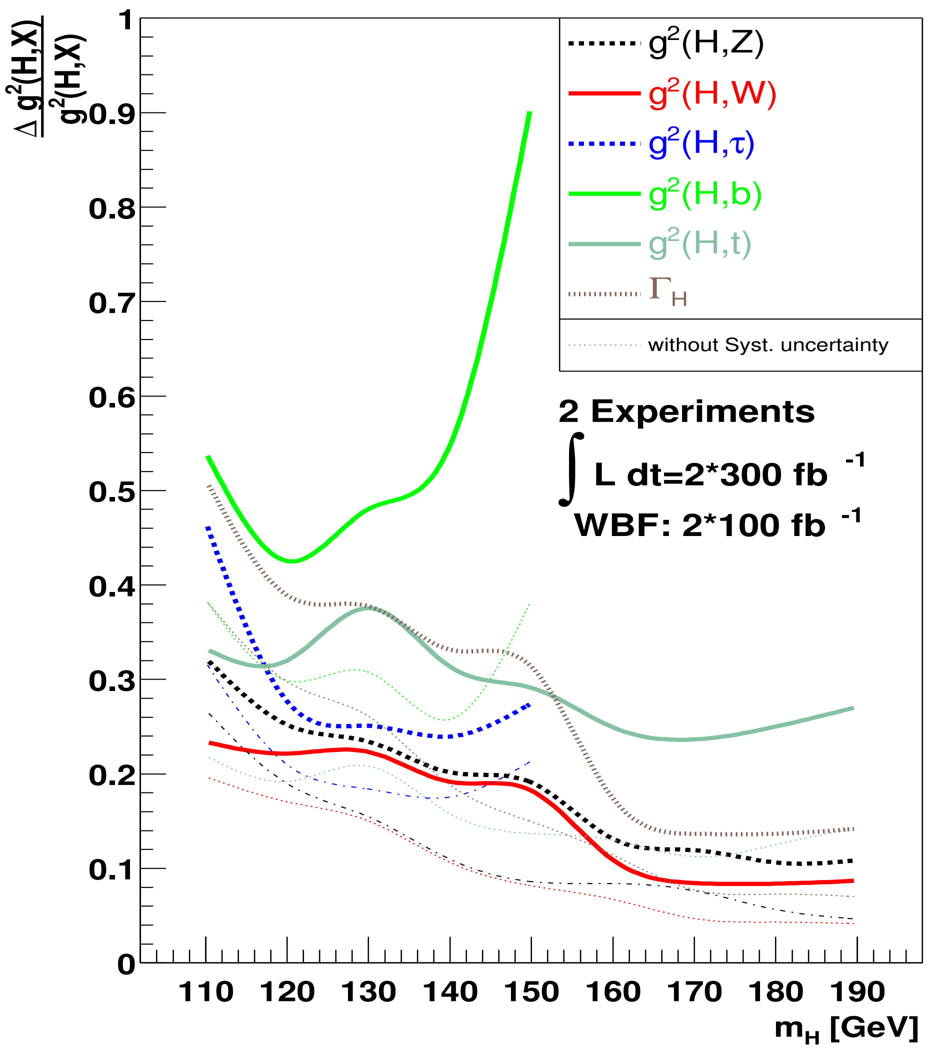
[*K. Desch, M. Dührssen, S. Heinemeyer, H. Logan, D. Rainwater, G. W., D. Zeppenfeld '05*]

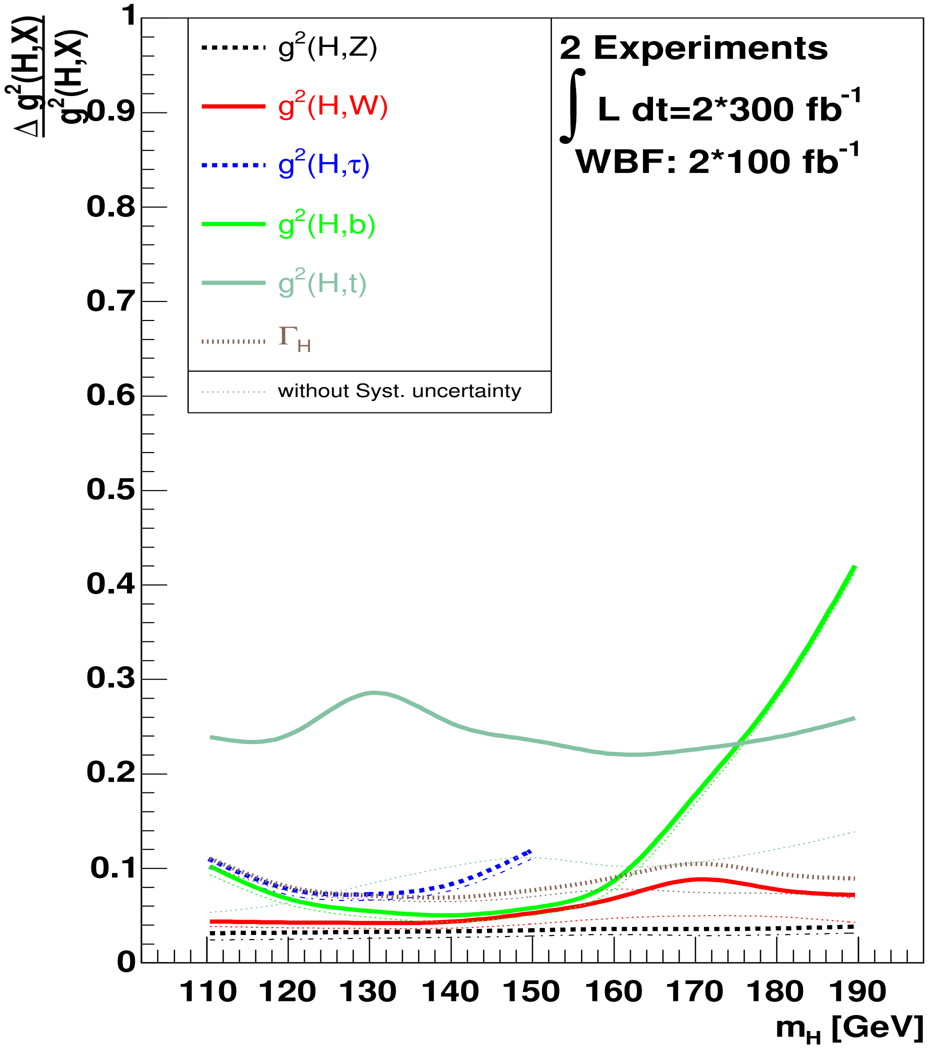
Combined fit for all LHC channels with ILC input:

M_H, $\sigma(e^+e^- \to HZ)$, $\mathrm{BR}(H \to b\bar{b}, \tau^+\tau^-, gg, WW^*)$,
$\sigma(e^+e^- \to \nu\bar{\nu}H) \times \mathrm{BR}(H \to b\bar{b})$

Results are still preliminary

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





$\Rightarrow$ higher accuracy on $g_{\mathrm{Ht\bar{t}}}$ (and also $g_{\mathrm{H\gamma\gamma}}$) than for LHC alone (+ theory) and ILC$_{500}$ alone: $\Delta g_{\mathrm{Ht\bar{t}}}/g_{\mathrm{Ht\bar{t}}} \approx 11$–$14\%$

Coupling determination from $H \to VV$ for heavy Higgses in 2HDM: LHC $\oplus$ ILC $\oplus$ photon collider

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

- Analysis of $H \to WW, ZZ$ for $200 \text{ GeV} \lesssim M_\text{H} \lesssim 350 \text{ GeV}$
- 2HDM(II) considered without and with (weak) $\mathcal{CP}$ violation
- Measurements at LHC, ILC, PC are sensitive to different combinations of Higgs-boson couplings

  $\Rightarrow$ complementarity
- Only combined analysis of LHC, ILC, PC measurements allows to determine $\mathcal{CP}$-violating H–A mixing angle ϕ_HA

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

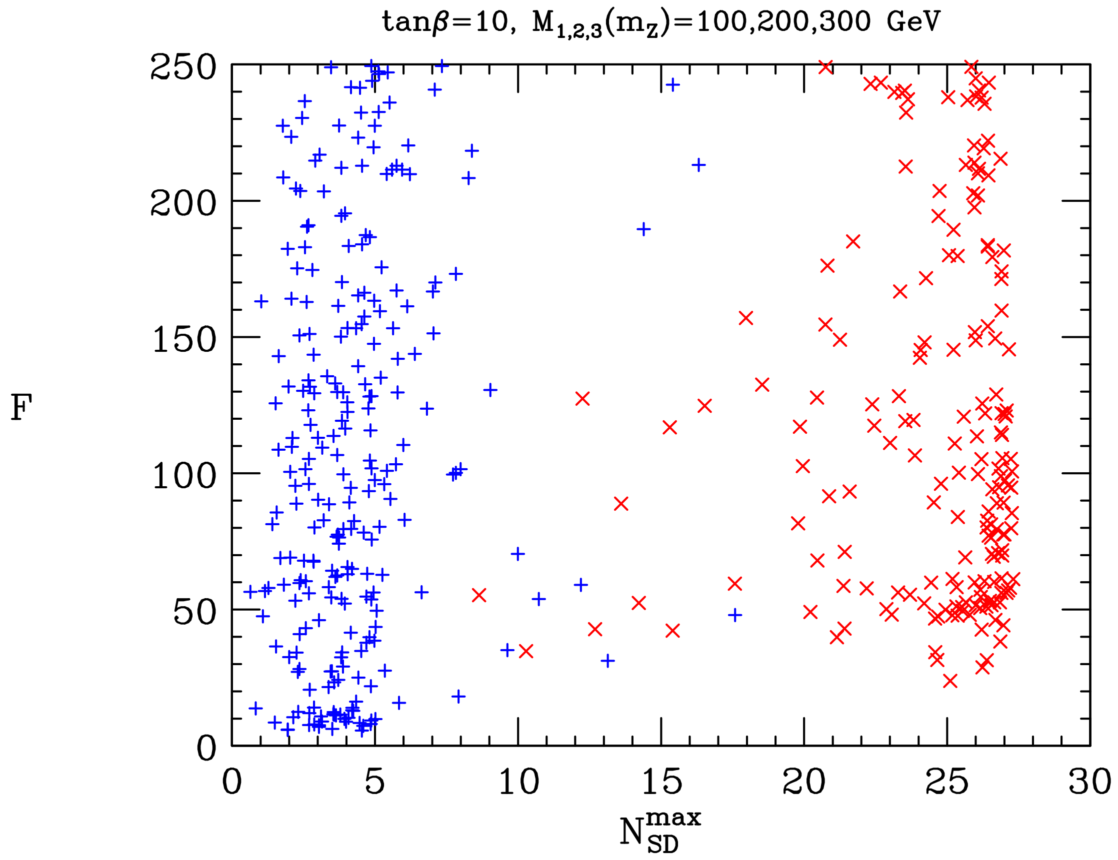
Structure of the Higgs sector can be very involved, difficult to disentangle

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

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!*



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

SUSY at LHC and ILC

LHC: good prospects for strongly interacting new particles

long decay chains $\Rightarrow$ complicated final states,

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

Many states are produced at once, difficult to disentangle

$\Rightarrow$ It quacks like SUSY!

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

Main background for SUSY is SUSY itself!

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 . . .

- 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, . . . ?

Even when we are sure that it is actually SUSY, we will still want to know:

- 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?

SUSY at the ILC: clean signatures, small backgrounds

$\Rightarrow$ 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

⇒ Increase of LHC statistical sensitivity!

⇒ crucial for extracting statistically marginal signal at LHC

⇒ Optimised searches at the LHC:

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

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*]

$\Rightarrow$ Identification of $(\chi_1^0, \chi_2^0, \chi_1^\pm)$ in LHC decay chains

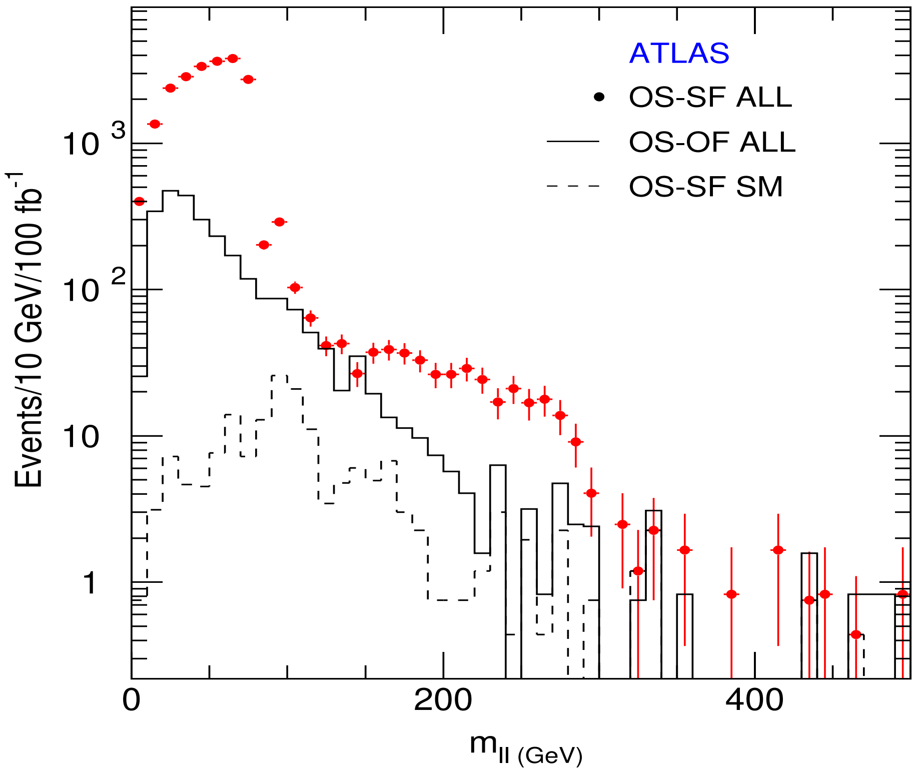
$\Rightarrow$ Determination of all parameters in neutralino/chargino sector

$\Rightarrow$ Prediction of masses, decay prop. of all neutralinos, charginos

$\Rightarrow$ 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

$\Rightarrow$ 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



$\Rightarrow$ Determination of $m(\tilde{\chi}_4^0)$ at LHC with high precision

$\Rightarrow$ Crucial test of the model

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

$\Rightarrow$ 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

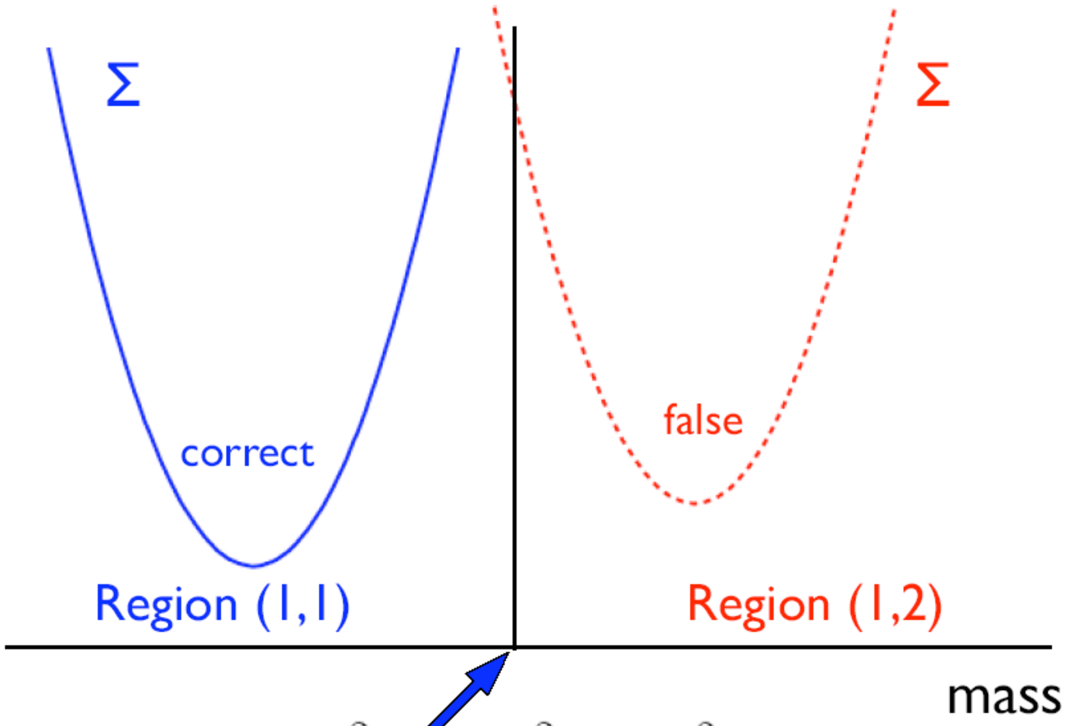
$\Rightarrow$ yields correct minimum

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

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

Problem due to compositeness of formulas:

If masses are close to border of 'region', may find a similar-quality or better minimum in 'other' region



$$m^2_{\tilde{l}_R} = (m^2_{\tilde{\chi}^0_1} + m^2_{\tilde{\chi}^0_2})/2$$

ILC input on LSP mass

$\Rightarrow$ correct minimum can be identified, ambiguities resolved

Distinguishing between MSSM and NMSSM

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

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

Parameter determination as in MSSM $\Rightarrow$ no contradiction

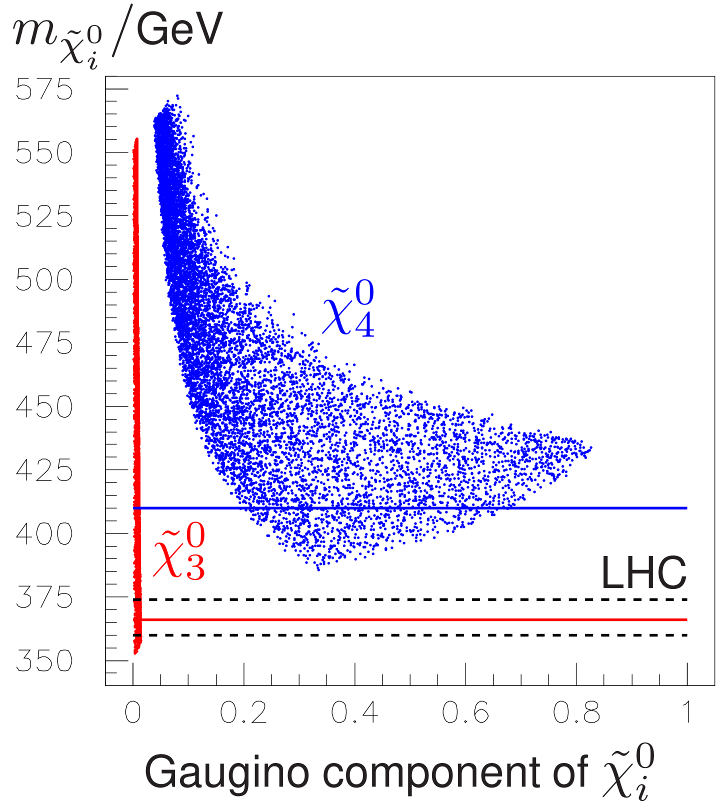
ILC input $\Rightarrow$ prediction of $m_{\tilde{\chi}^0_3}$ and mixing character

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

$\Rightarrow$ Evidence for NMSSM

Mixing character of $\tilde{\chi}^0_3$: MSSM vs. NMSSM

	NMSSM	MSSM
$m_{\tilde{\chi}^0_1}$	138 GeV	138 GeV
$m_{\tilde{\chi}^0_2}$	337 GeV	344 GeV
$m_{\tilde{\chi}^0_3}$	367 GeV	366 GeV
$m_{\tilde{\chi}^0_4}$	468 GeV	410 GeV
$m_{\tilde{\chi}^0_5}$	499 GeV	–
$m_{\tilde{\chi}^\pm_1}$	139 GeV	139 GeV
$m_{\tilde{\chi}^\pm_2}$	474 GeV	383 GeV

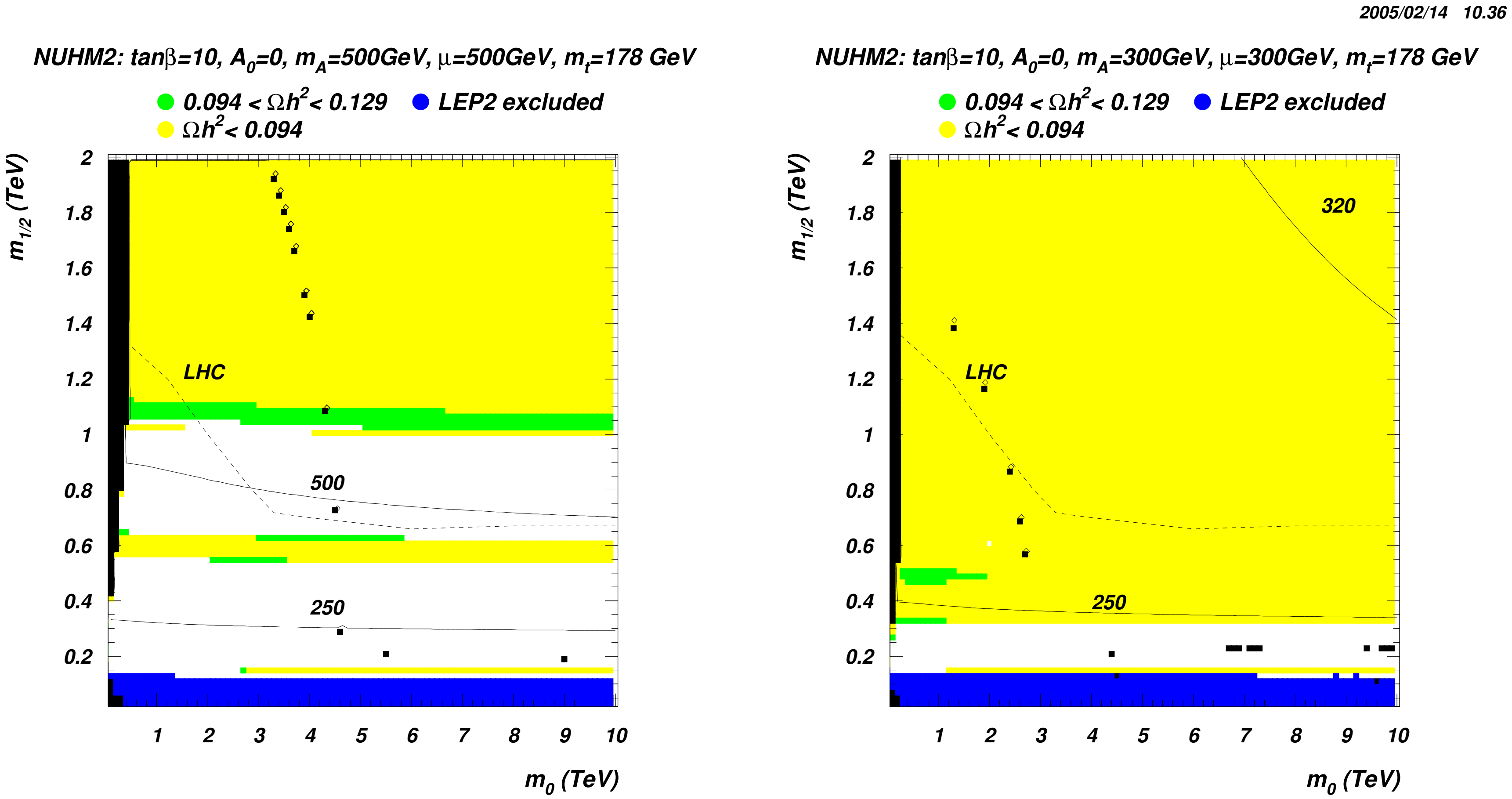


$\Rightarrow$ ILC prediction of mixing character yields distiction of NMSSM from MSSM

Investigation of different scenarios

Gravity-mediated SUSY with non-universal Higgs masses

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



⇒ ILC reach can exceed LHC reach

Determination of SUSY parameters: global fit

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

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

NEW!

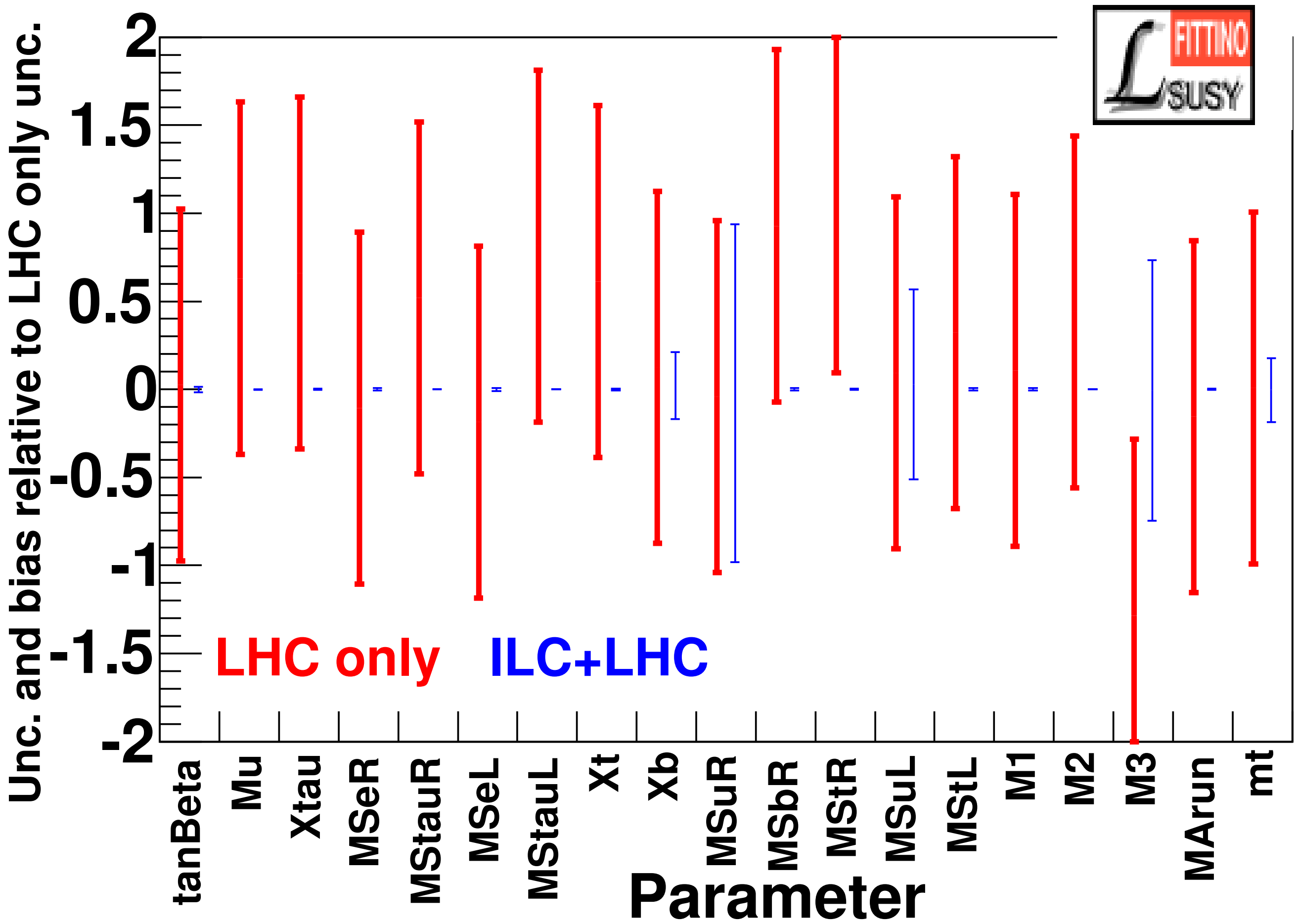
LHC input:

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 ⊕ ILC



⇒ precise determination of SUSY parameters only possible with LHC ⊕ ILC

How precisely do we need to know the SUSY parameters?

Dark matter relic density: measurement vs. prediction

Aim:

match the precision of the relic density measurement with the prediction based on collider data

$\Rightarrow$ sensitive test of SUSY dark matter hypothesis

Relic density measurement:

current (WMAP): $\approx 10\%$

future (Planck): $\approx 2\%$

Prediction of the dark matter density

LHC analysis for SPS 1a point: [*G. Polesello, D. Tovey '04*] [*P. Janot '04*]

- LHC input for SPS 1a point
- Theoretical assumption: mSUGRA is correct SUSY-breaking mechanism

$\Rightarrow$ Prediction of relic density with $\approx 3\%$ accuracy for full LHC-design integrated luminosity

Significantly better accuracy with ILC input (same th. assumption)

Much worse prospects at the LHC for less favourable parameter points [*P. Janot '04*]

Prediction of the dark matter density

Ultimately cannot assume SUSY-breaking scenario, have to test it

Even if SUSY-breaking scenario is assumed to be known:

RGE running from high scale introduces dependence on SM input parameters and uncertainties from unknown higher orders

$\Rightarrow$ need precise measurement of m_t

extreme case: mSUGRA focus point scenario
$\longrightarrow$ need m_t with accuracy of $\mathcal{O}(20\ \mathrm{MeV})$
$\longrightarrow$ tough to achieve even at the ILC, hopeless at LHC

ILC accuracy on m_t also needed in mSUGRA Higgs funnel region in order to match Planck precision

[*B. Allanach, G. Belanger, F. Boudjema, A. Pukhov '04*]

Prediction of the dark matter density

$\Rightarrow$ Precision measurements at ILC crucial for precise and model-independent prediction of relic density

Example: mSUGRA coannihilation region

Precise determination of masses of LSP and lightest slepton at ILC for general MSSM (no mSUGRA assumption)
[*P. Bambade, M. Berggren, F. Richard, Z. Zhang '04*]

Planck accuracy $\Leftrightarrow$ NLSP–LSP mass difference needed with precision of 0.2 GeV

Need also precise knowledge of cross section: neutralino mixing matrix, stau sector, masses of heavy Higgs bosons
[*B. Allanach, G. Belanger, F. Boudjema, A. Pukhov '04*]

SUSY parameter determination: example of a possible future study

Once the masses of the particles in the decay cascade are determined at LHC $\oplus$ ILC, can one do more?

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

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

Measurement of the top mass at the LHC

[*A. Mitov '05*]

NEW!

- Measurement of m_{t} at the LHC: analysis of invariant mass of decay products
- Main systematic uncertainty: b-fragmentation
- ILC with GigaZ option: reduction of b-fragmentation uncertainty by factor 2–3

Upcoming LHC / ILC activities

- This workshop!

- Snowmass Workshop: August 14–27, 2005

  Working group (within the four physics groups):
  "LHC / ILC Connections"

  Coordinators: *J. Conway, M. Nojiri, D. Rainwater, G. W., D. Zerwas*

  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

- First LHC / ILC Study Group report is an important step towards where we want to get

  But we cannot afford to slow down now

- There are many opportunities for interesting work on LHC / ILC interplay at this workshop!