The LHC/ILC Connection

Sven Heinemeyer, IFCA (CSIC – UCSA)

Vancouver, 07/2006

1. The LHC and the ILC
2. Past
3. Present
4. Future
5. Conclusions

1. The LHC and the ILC

The (un)official LHC timeline:

2007: Pilot run, first collisions
2008: 0.1 fb^{-1} – $\mathcal{O}$(few) fb^{-1} $\Rightarrow$ first physics results?
2009 – 2011: 10 fb^{-1} per year $\Rightarrow$ physics results with "low" luminosity
2012 – ?: 100 fb^{-1} per year $\Rightarrow$ physics results with "high" luminosity
2015 + X: upgrade to SLHC?

The (un)official ILC timeline:

2005: Baseline design (accomplished!)
2006: Reference design (report)
2009: Technical design (report)
2009: decision about site (and money!) $\Rightarrow$ **THE CRUCIAL POINT**
2010: start digging the tunnel, . . .
2015: first collisions, first physics?

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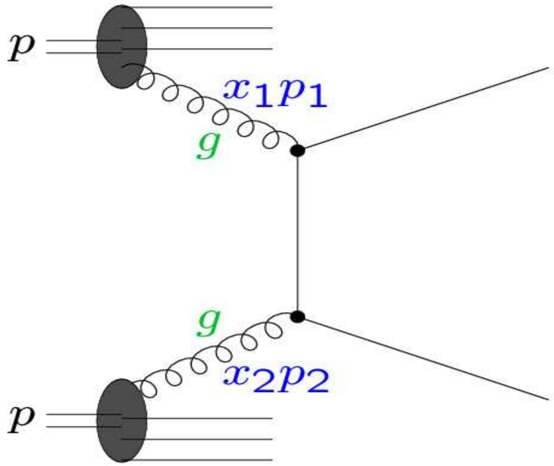
2015: first collisions, first physics? $\Rightarrow$ **2015** is the crucial date here

$\Rightarrow$ concurrent running possible

Physics at the LHC and the ILC in a nutshell:

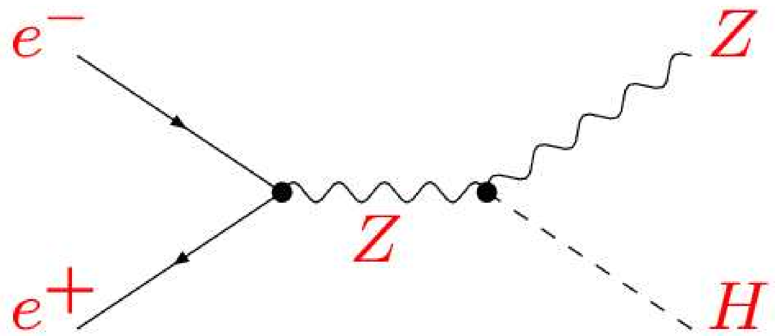
LHC: pp scattering at 14 TeV



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 ≈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

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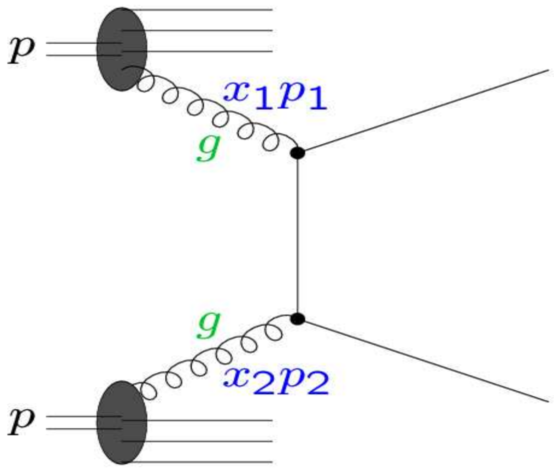

interaction rate of 10^9 events/s

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

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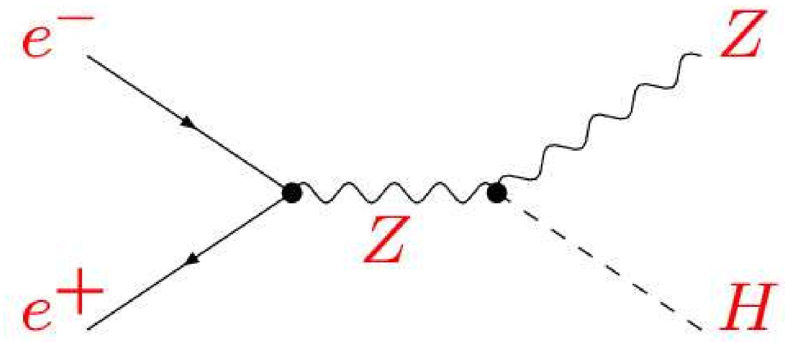

untriggered operation

$\Rightarrow$ 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

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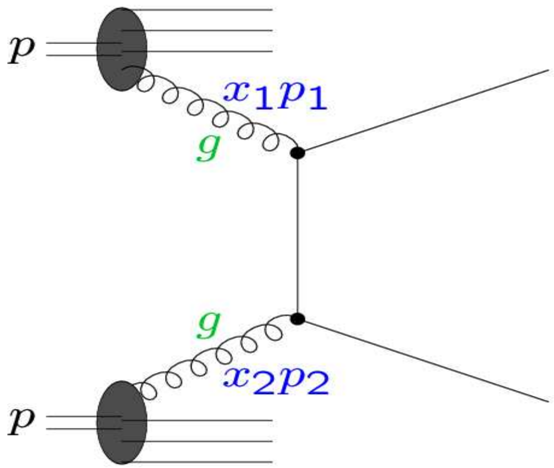

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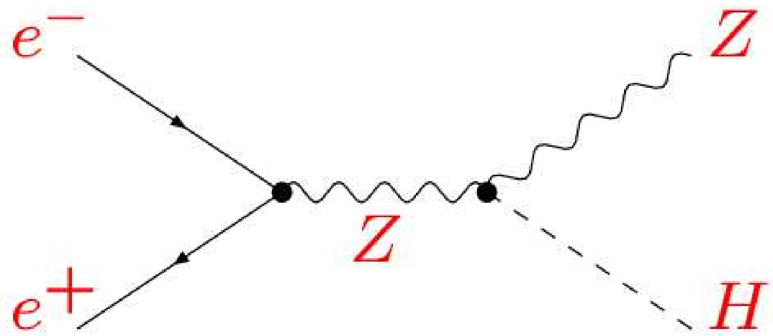

untriggered operation

⇒ Concurrency is an issue

ls of unexpected

(direct production + large indirect reach) that manifests itself in events that are not selected by the LHC trigger strategies

Reality: ILC will start in 2015 earliest

World of High Energy Physics in the year 2015:

Both LHC detectors will have accumulated $\sim 300\ \text{fb}^{-1}$

Initial LHC physics goals are accomplished:

– state compatible with a Higgs found
  (except in especially designed tricky scenarios)
  corresponding couplings measured to 10–30%
– SUSY-like signatures observed (if realized at the EW scale)
– Extra dimensions or . . . -like signatures observed

LHC may await luminosity upgrade

LHC will focus on

– Improvement in “Higgs-like” couplings (is it a Higgs?)
– Improvement of accuracy of new parameters (masses, . . .)
– Extension of high mass discovery region
– Extension of sensitivity to rare processes

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- There is a world wide consensus about the ILC
  (ACFA, ECFA, ICFA, XCFA, . . .)
  only some people tend to forget . . .
- The EPP2010:
  strongly recommended the ILC
- The European Strategy Group:
  "What are (early) LHC results?" ⇒ could be a "moving target"
  ⇒ decisions could be "politics driven", not physics driven

Equally important: the physics itself

Reality: ILC will start in 2015 earliest

Q: Does the ILC decision have to wait for physics results of the LHC?

A: NO! The ILC physics case and it has been made **many**^{2} times

The ILC will add precision The ILC can make discoveries	} Complementarity

This has been shown for basically all (thinkable) physics aspects:

– Top/QCD
– electroweak precision observables
– Higgs (SM and beyond)
– Strong electroweak symmetry breaking
– Supersymmetry (SUSY)
– Extra dimensions, KK towers
– ...

⇒ the ILC adds "model independence"!

Reality: ILC will start in 2015 earliest

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A': But there is more:

Reality: ILC will start in 2015 earliest

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A: NO! The ILC physics case and it has been made **many**^{2} times

The ILC will add precision
The ILC can make discoveries
} Complementarity

A': But there is more:

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

$\Rightarrow$ Enable improved strategies,
dedicated searches
} Synergy / Concurrency

ILC physics case does not rely on Synergy/Concurrency, but it helps!

What is the physics gain of LHC / ILC synergy?
What is the added value of concurrent running?

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/lhcilc`

World-wide working group, started in spring 2002

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

2. Past

⇒ LHC / ILC Study Group

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

World-wide working group, started in spring 2002

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

First report has been completed: **hep-ph/0410364**:
122 authors from 75 institutions, 472 pages,
appeared as G. Weiglein et al., *Phys. Rept.* 426 (2006) 47
(still waiting for the party :-)

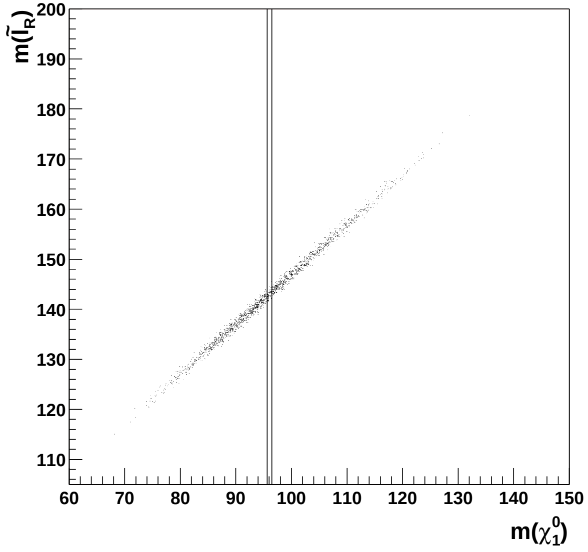
Just a few most prominent examples:

– SUSY mass determination
– BSM Higgs sector: indirect bounds
– . . .

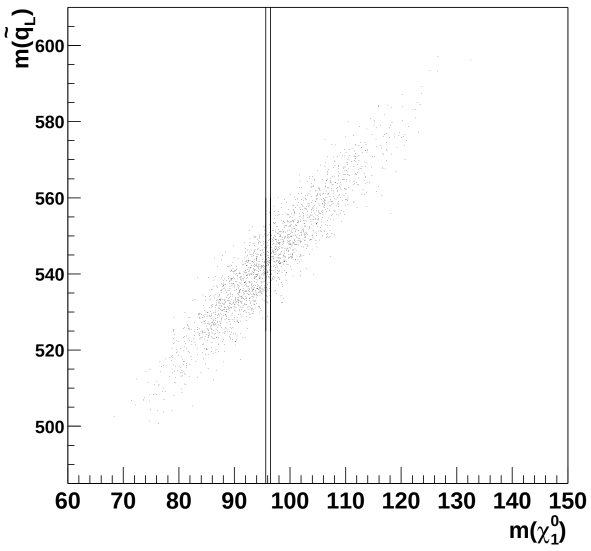
Example I: SUSY mass determination

[*hep-ph/0410364*]

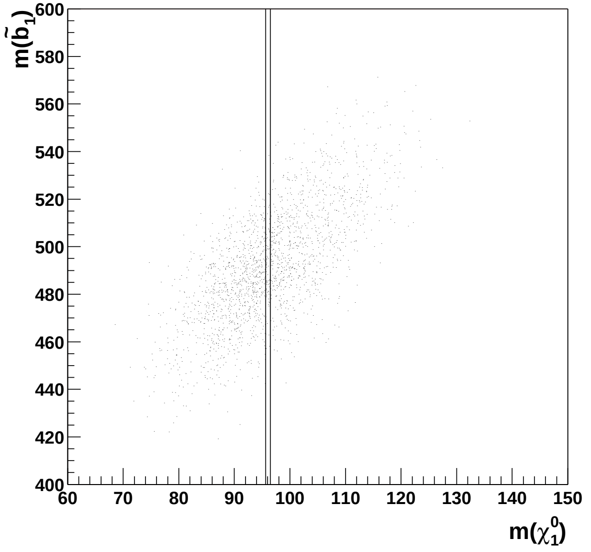
mass of $\tilde{l}_R$



mass of $\tilde{q}_L$



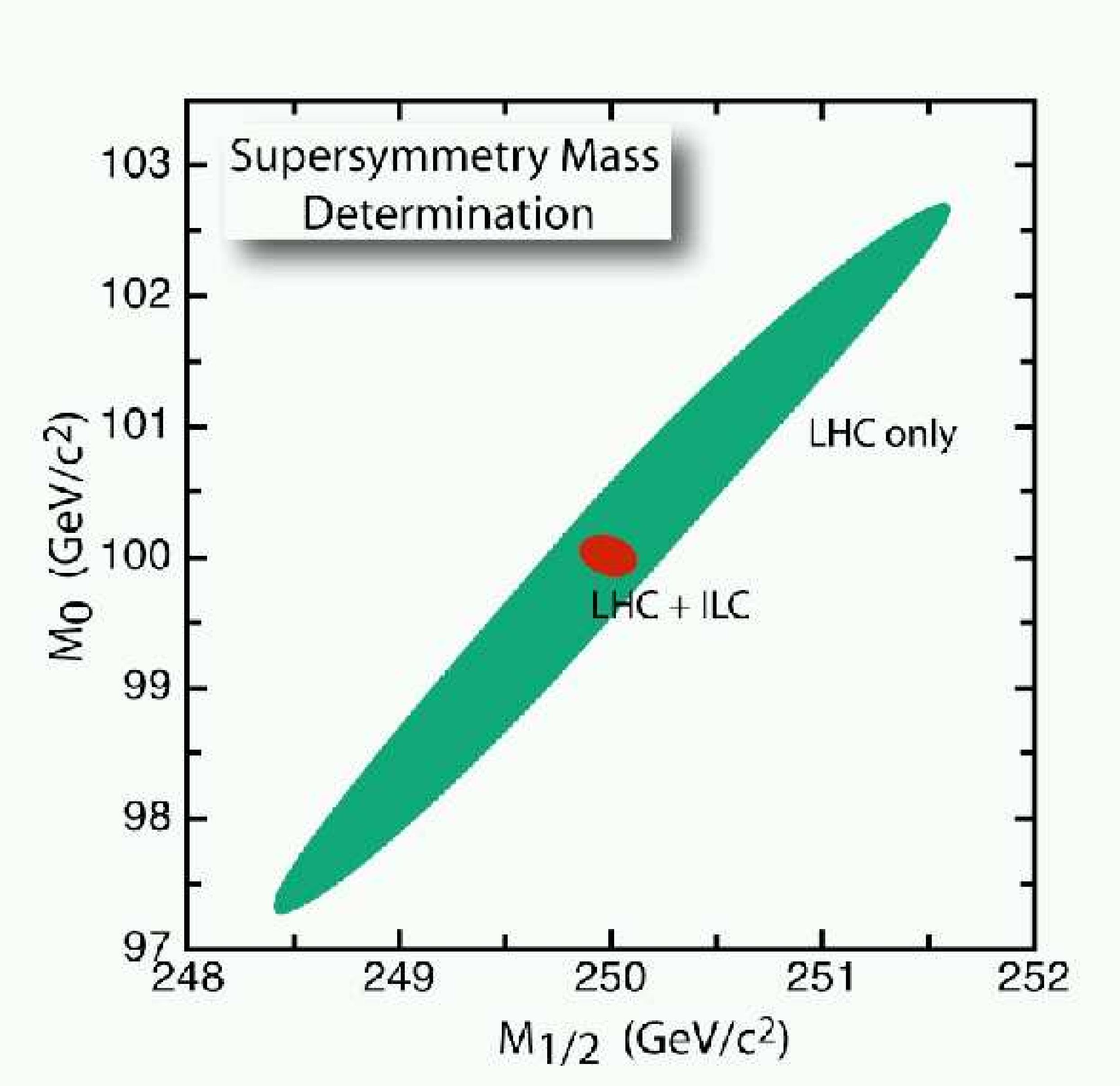
mass of $\tilde{b}_1$



$\Rightarrow$ drastic improvement from ILC LSP measurements

Example II: fit to SUSY-GUT parameters

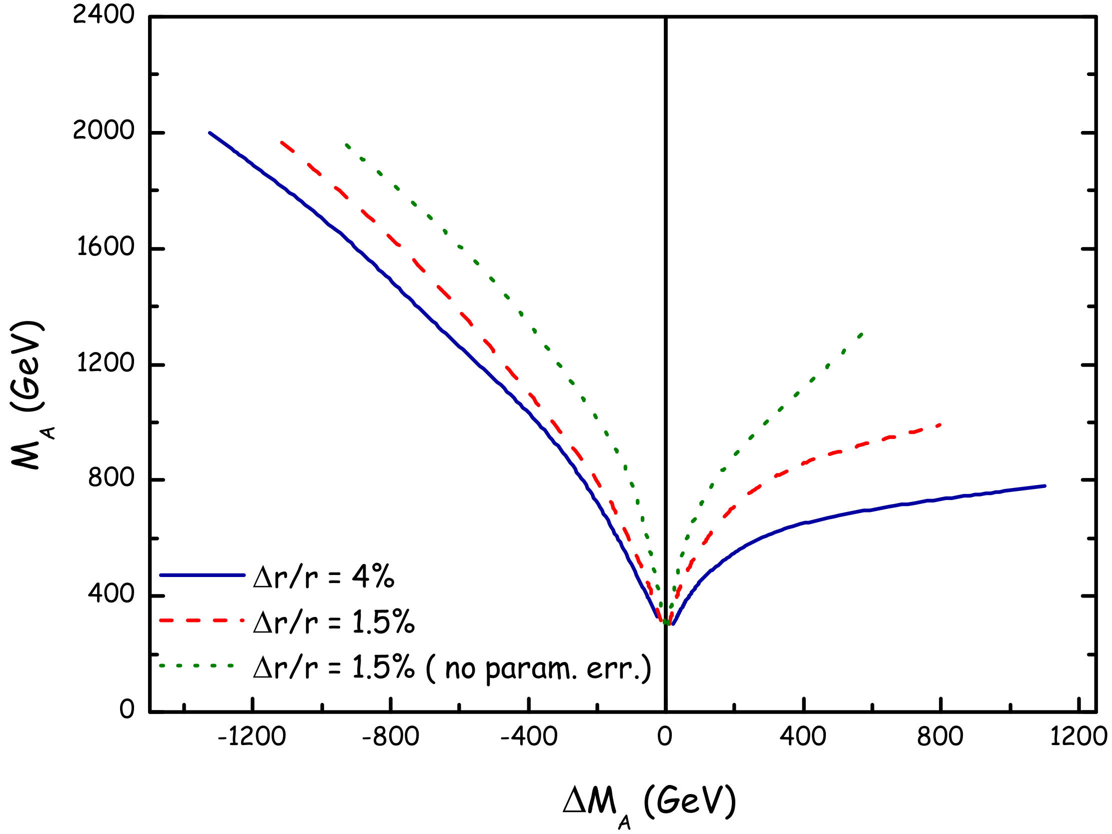
[*hep-ph/0410364*]



⇒ drastic improvement from combined LHC/ILC analysis

Example III: indirect determination of heavy MSSM Higgs boson masses

[*hep-ph/0410364*]



input: mass measurements from LHC, ILC

light Higgs BR measurements from ILC

⇒ indirect determination only possible in combined LHC/ILC analysis

3. Present

⇒ LHC / ILC Study Group

www.ippp.dur.ac.uk/∼georg/lhcilc

Activities continue(d) after the report!

Recent meetings:
– dedicated working group at Snowmass ’05
– LHC/ILC working group meeting @ CERN, 12/05

⇒ try to coordinate on-going activities

⇒ some recent (2005–2006) results

(partially presented at LHC/ILC Study group meetings, partially at other ILC meetings (e.g. here))

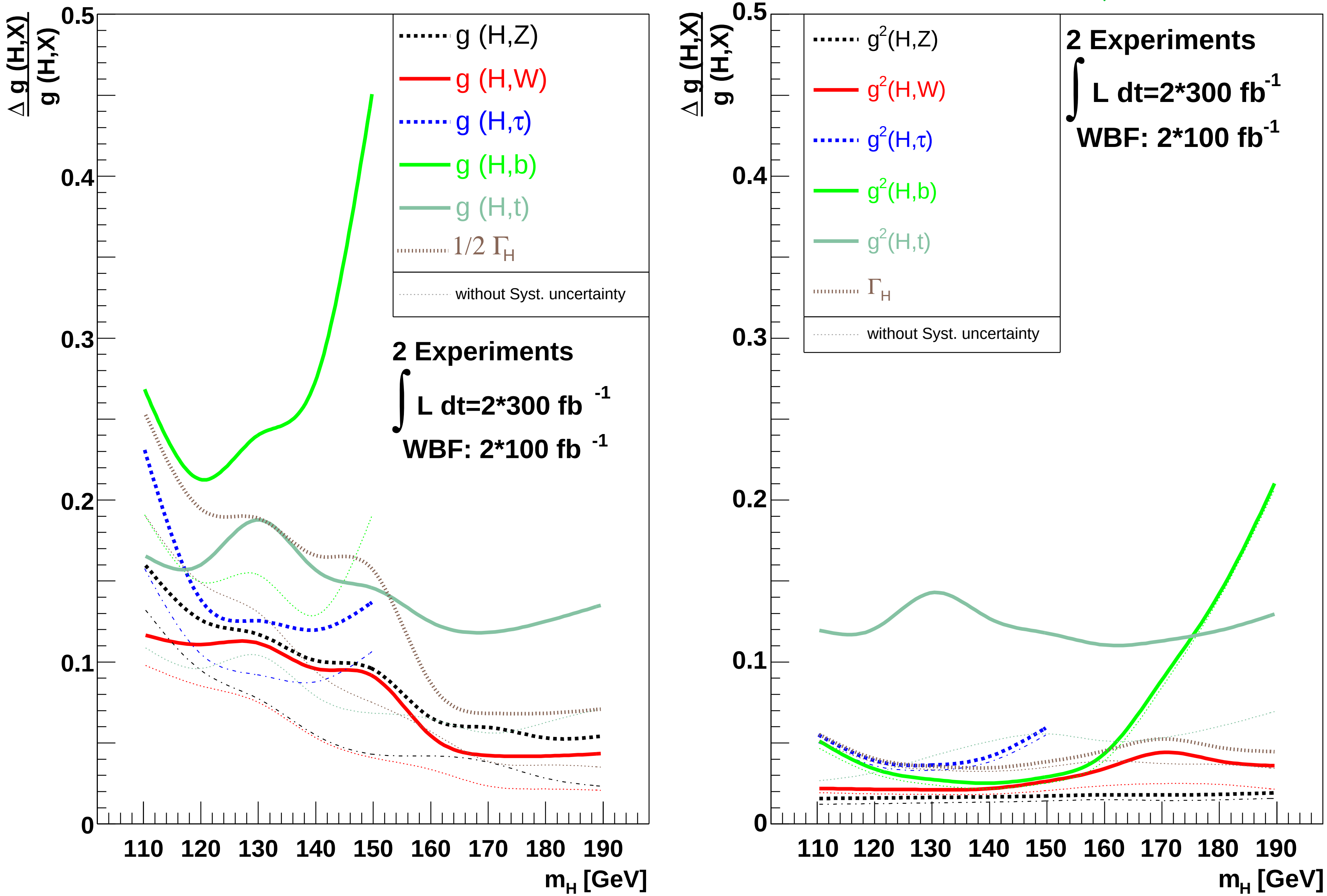
⇒ results for SM Higgs, SUSY, Z'

Example I: SM Higgs: determination of $g_{Ht\bar{t}}$:

NEW

[*M. Dührssen et al. '05*]

LHC alone (model dep.) LHC $\oplus$ ILC @ $\sqrt{s} = 500$ GeV



Example I: SM Higgs: determination of $H\gamma\gamma$ coupling: NEW

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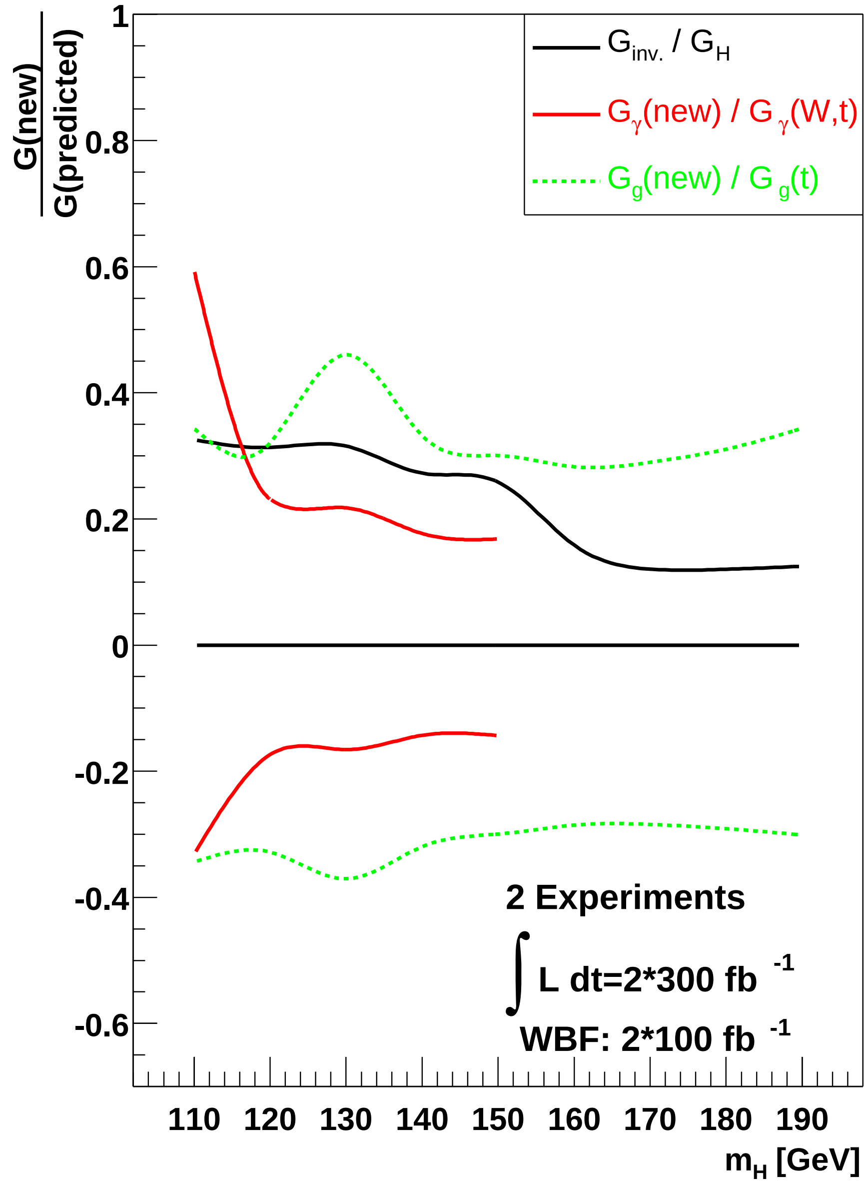
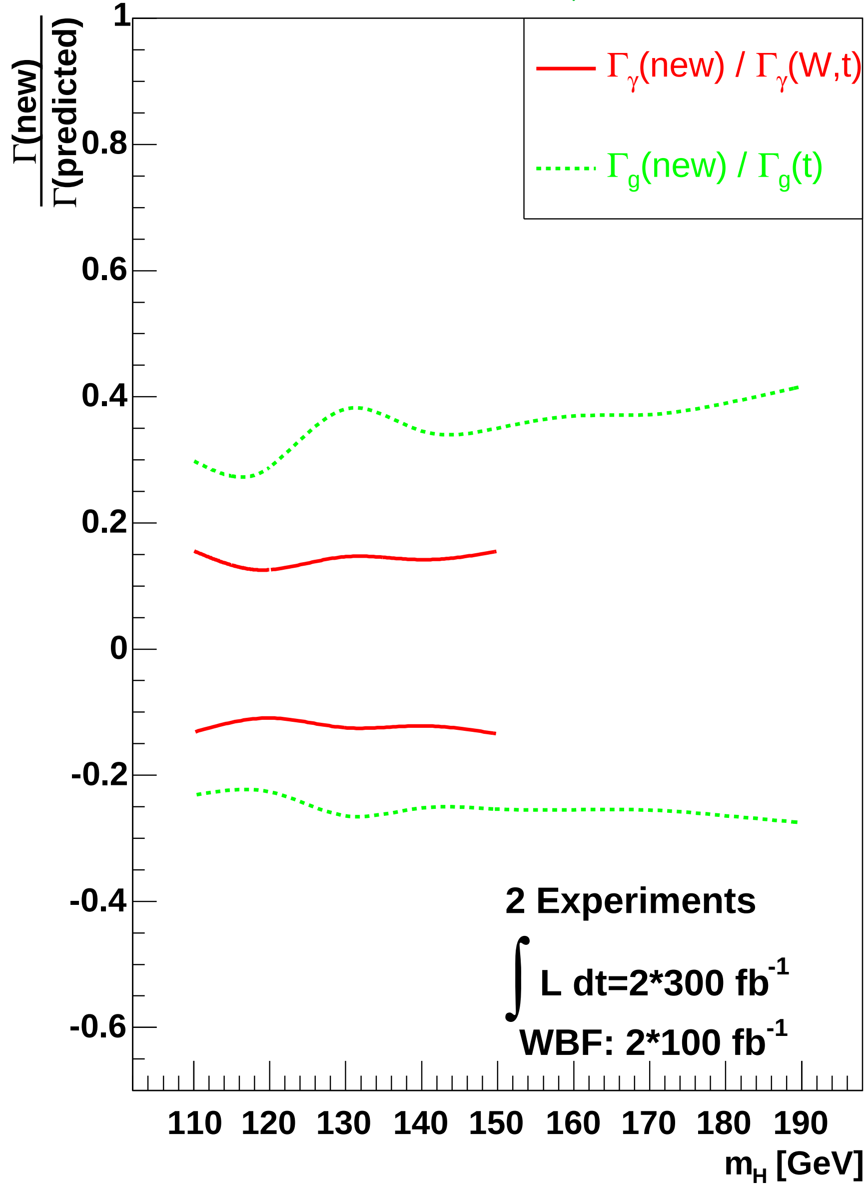


LHC $\oplus$ ILC @ $\sqrt{s} = 500$ GeV



Example: SUSY

In order to establish SUSY experimentally:

Need to demonstrate that:

- every particle has superpartner
- their spins differ by 1/2
- their gauge quantum numbers are the same $\rightarrow$ example II
- their couplings are identical
- mass relations hold $\rightarrow$ example III

finally: determine SUSY Lagrangian parameters $\rightarrow$ example IV

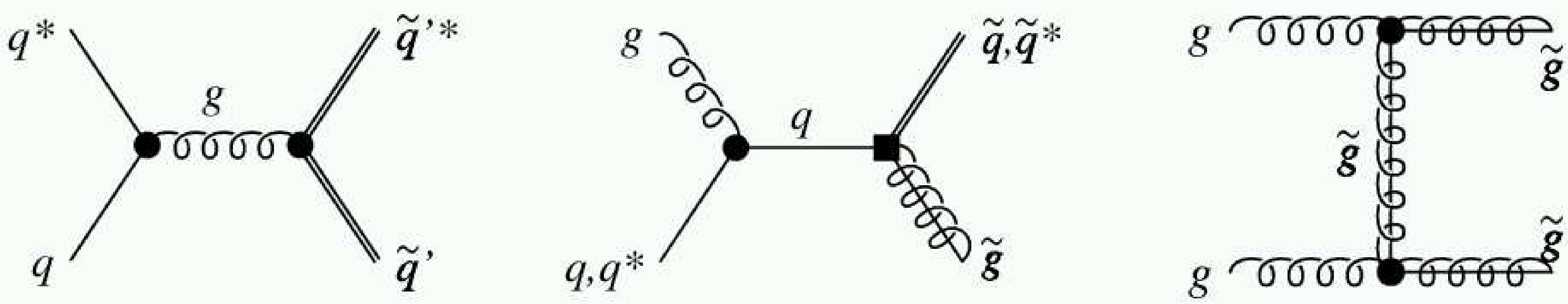
$\Rightarrow$ We need both: hadron colliders (Tev./LHC) and high luminosity ILC

Example II: determination of SUSY QCD coupling:

NEW

[*A. Freitas, P. Skands '06*]

Measure squark/gluino production at the LHC



$\rightarrow$ measurement of decay chains

Measure accurately corresponding branching ratios that appear in the LHC decay chains at the ILC

$\Rightarrow$ Determination of absolute SUSY QCD production cross sections at the LHC $\sim \tilde{g}_s^4$ to $\sim 20\%$

$\Rightarrow$ $\tilde{g}_s$ measurement to $\sim 5\%$

Example III: SUSY: parameter determination in a "heavy" scenario: **NEW**

[*K. Desch, J. Kalinowski, G. Moortgat-Pick, K. Rolbiecki, J. Stirling '06*]

→ see talk by G. Moortgat-Pick in LHC/ILC session

heavy CMSSM: $m_{1/2} = 144$ GeV, $m_0 = 2$ TeV, $A_0 = 0$, $\tan\beta = 20$, $\mu > 0$
⇒ squark and slepton masses $\mathcal{O}(2$ TeV$)$

LHC: measurement of squark masses, $\delta m \approx 50$ GeV

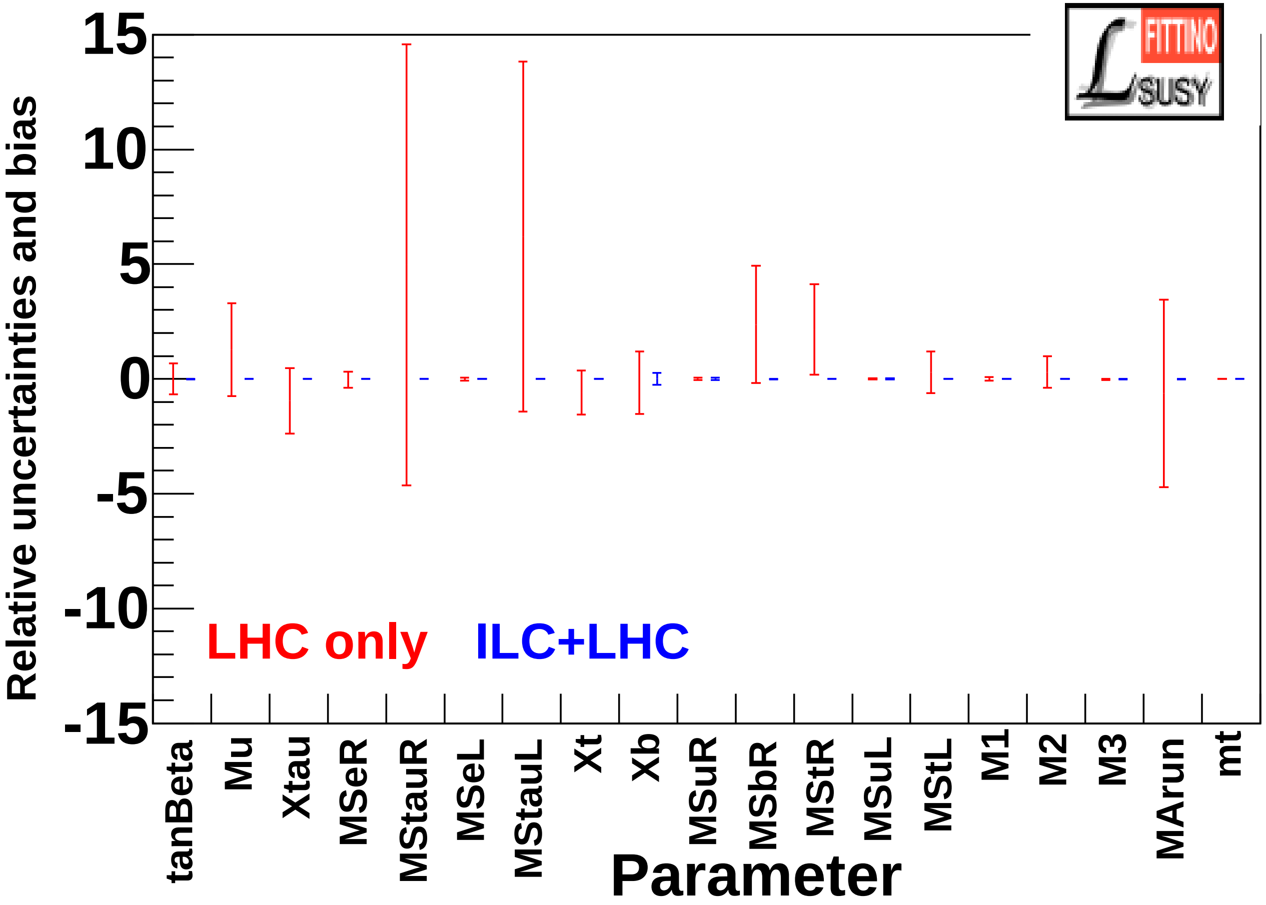
ILC: measurement of $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^- \to \dots$ incl. spin correlations,
$A_{\rm FB}$ for hadronic and leptonic decays

step 1: determination of M_1, M_2, μ, $m_{\tilde{\nu}}$
step 2: using leptonic $A_{\rm FB}$: determination of $\tan\beta$ and $m_{\tilde{\nu}}$ better
step 3: using in addition hadronic $A_{\rm FB}$ $\oplus$ squark masses from LHC
⇒ independent determination of $m_{\tilde{l}}$, $m_{\tilde{\nu}}$
⇒ test of $SU(2)$ relation in $\tilde{l}$ sector

Example IV: SUSY: global fit for SUSY Lagrange parameters: NEW

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

Compare LHC and LHC $\oplus$ ILC :



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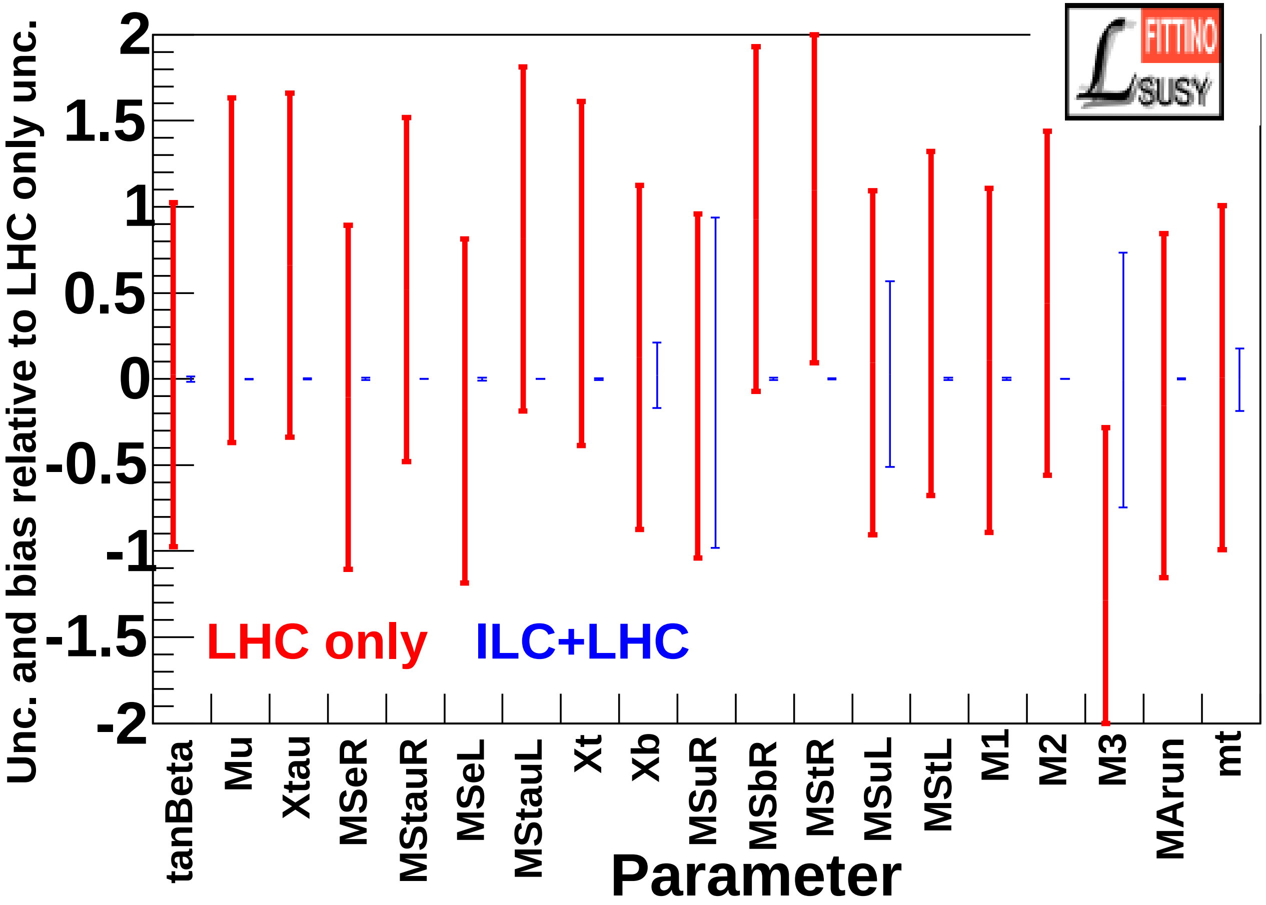

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Example V: models with Z': parameter determination:

NEW

[*S. Godfrey, A. Tomkins '05*]

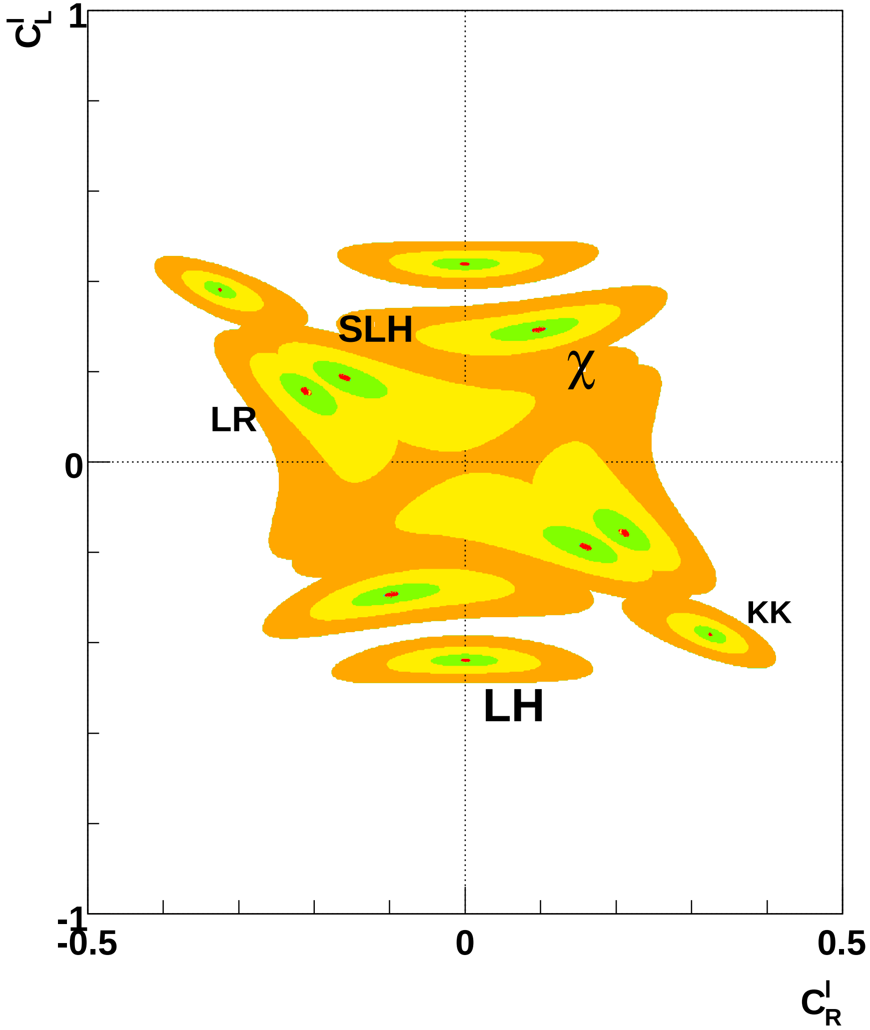
$\rightarrow$ see talk by S. Godfrey in LHC/ILC session

LHC: discovers single heavy resonance

ILC: measurement of indirect effects
($\sqrt{s} = 500$ GeV, $\mathcal{L}_{\text{int}} = 1$ ab^{-1})

new: extended analysis to higher masses
$M_{Z'} = 1, 2, 3, 4,$ TeV

$\Rightarrow$ various models can be distinguished
up to $M_{Z'} \gtrsim 2-3$ TeV



4. Future

$\Rightarrow$ LHC / ILC Study Group

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

Activities are continuing!

Next meetings:

– workshop at Fermilab 10/06

– . . .

Good sign:

VLCW06: ILC workshop with LHC/ILC working group

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Where should we go? How should we develop?

A) same direction, but better

B) new direction(s)

4. A) Future: same direction, but better

How far are we?

- Many possibilities of LHC / ILC synergy have been investigated

  ⇒ 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

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

  + ongoing ILC studies

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

⇒ Concurrency is an issue

The case of concurrent running:

Counter arguments:

– “Global fits etc. can be done without concurrent running, you just need the data.”
– “You can always re-analyze the data.”

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My answer:

– Ask the people who try to re-analyze Tevatron Run I data . . .
– There are nice examples that profit from the joint analysis of concurrent data
– We want to disentangle the new physics as soon as possible

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⇒ What LHC physics do we lose by not having the ILC at the same time?

⇒ More concurrency examples are nice but not crucial

SUSY example for concurrent running:

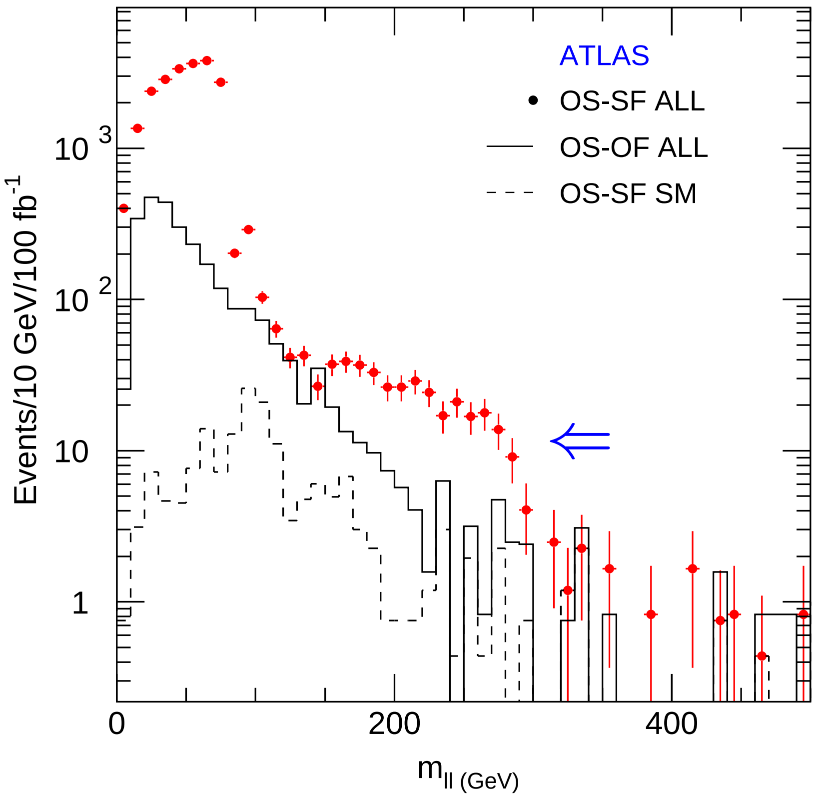
[K. Desch, J. Kalinowski, G. Moortgat-Pick, M. Nojiri, G. Polesello '04]

$\rightarrow$ Measurement of $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_1^\pm$ at the ILC

$\Rightarrow$ determination of all parameters in the chargino/neutralino sector

$\Rightarrow$ prediction of neutralino masses that are too heavy for the ILC

$\Rightarrow$ tell the LHC where to look $\Rightarrow$ "one-bin" search, high statistical power



The $\tilde{\chi}_4^0$ can be identified at the LHC via this dilepton "edge"

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

$\Rightarrow$ Crucial test of the model

$\Rightarrow$ Information can be fed back into ILC analysis

4. B) Future: new directions

Decision for the ILC will take place roughly at the same time we have data from the LHC . . .

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> What could be the impact of results from early data at the LHC on the ILC?

A scientifically well-founded investigation of this issue requires expertise on the experimental aspects at both the LHC and the ILC and on the possible theoretical interpretations of signals of new physics.

$\Rightarrow$ investigate various possible scenarios of early LHC data
("early LHC data" = up to 10 fb^{-1})

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⇒ Workshop at Fermilab on the LHC/ILC interplay: October 2006

Coordinators: M. Carena, M. Demarteau, H. Weerts, G. Weiglein, . . .

New questions/the charge:

1. Could there be cases that would change the consensus about the physics case for an ILC with an energy of about 500 GeV?

2. What could be the impact of early LHC results on the choice of the ultimate ILC energy range and the ILC upgrade path? Could there be issues that would need to be implemented into the ILC design from the start?

3. What are the prospects for LHC / ILC interplay based on early LHC data?

$\Rightarrow$ investigate various possible scenarios of early LHC data
("early LHC data" = up to 10 fb^{-1})

$\Rightarrow$ Workshop at Fermilab on the LHC/ILC interplay: October 2006

Coordinators: M. Carena, M. Demarteau, H. Weerts, G. Weiglein, ...

Working groups:

– discovery of a state compatible with a Higgs

– no evidence for a Higgs boson

– detection of states beyond the SM
(→ missing energy signals, leptonic resonances,
multi-gauge-boson signals, . . .)

→ distinguish between assumed experimental signatures (e.g. kinematic edges) and their possible interpretations within certain models

→ possible theoretical uncertainties should be carefully investigated

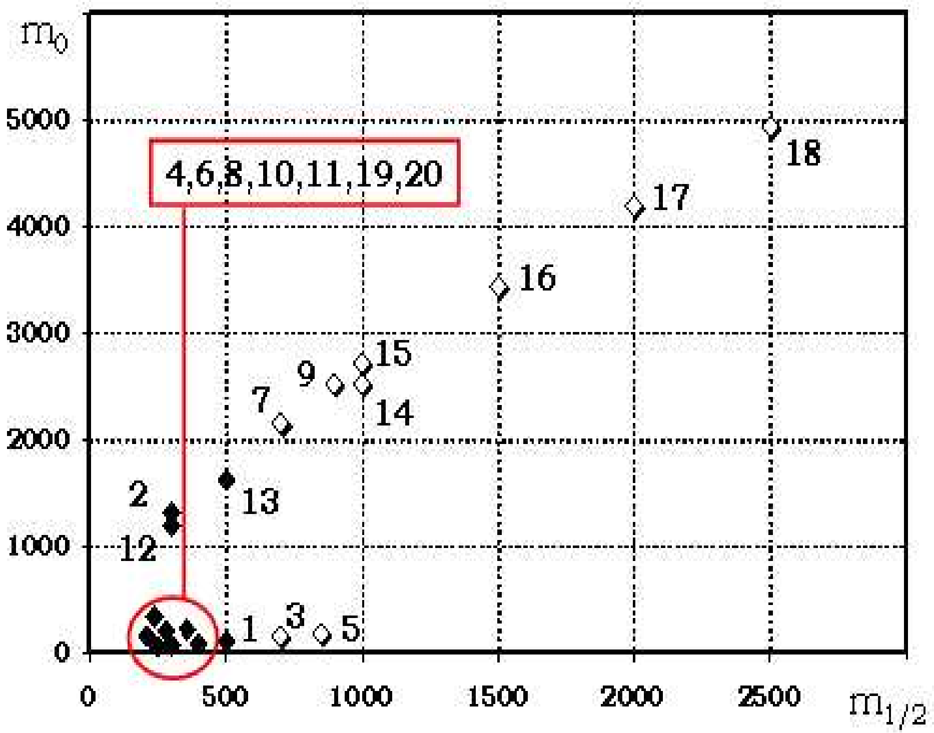
$\Rightarrow$ 3 physics examples for early LHC data

Example I: SUSY discovery potential of CMS/ILC implications

[A. Drozdetskiy, S.H., G. Weiglein et al. '06]

SUSY discovery potential of CMS in the same sign di-muon channel

Framework: CMSSM, used only for data generation, not for exp. analysis



10 fb^{-1} can test the CMSSM up to $m_{1/2} \lesssim 650$ GeV

$\Rightarrow$ ILC reach in CMSSM

open questions:

Evidence for CMSSM?

ILC implications beyond CMSSM?

$\Rightarrow$ model indep. interpretation?

Example II:

The LHC finds only a state compatible with a SM-like Higgs

and nothing else

Q: Do we still need the ILC?

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A: Of course!

Example II:

The LHC finds only a state compatible with a SM-like Higgs
and nothing else

Q: Do we still need the ILC?

A: Of course! Or better: even more!
In fact: one of the best ILC cases (just hard to sell to the politicians)

The ILC provides:

– precise Higgs coupling measurements

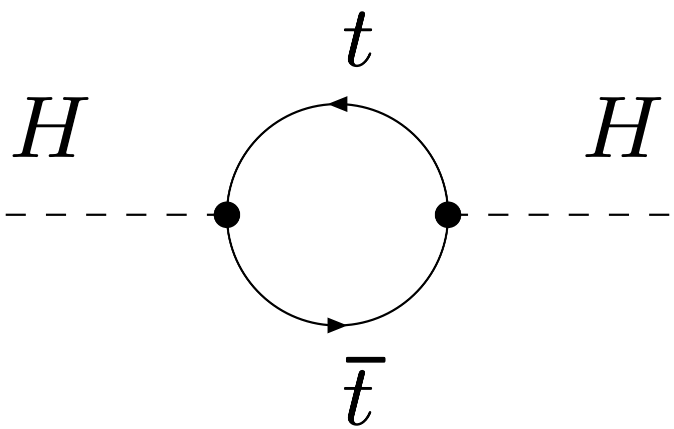
– precision observable measurements with the GigaZ option

⇒ Only the ILC can find deviations from the SM predictions via the various precision measurements

⇒ Only the ILC can point towards extensions of the SM

Example III: LHC data points towards certain extensions of the SM:

Nearly any model: large coupling of the Higgs to the top quark:



$\Rightarrow$ one-loop corrections $\Delta M_H^2 \sim G_\mu m_t^4$

$\Rightarrow$ M_H depends sensitively on m_t in all models where M_H can be predicted (SM: M_H is free parameter)

$\Rightarrow$ What can the LHC do with 10 fb^{-1}?

SUSY as an example: $\Delta m_t \approx \pm 2$ GeV $\Rightarrow$ $\Delta M_h \approx \pm 2$ GeV

$\Rightarrow$ Precision Higgs physics needs precision top physics

$\Rightarrow$ LHC precision of M_h requires ILC precision of m_t, 500 GeV sufficient

5. Conclusions

[*Thanks go to K. Desch, G. Weiglein*]

- LHC/ILC interplay is a very important, rich and active field

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

  Concurrency is an issue!

- First report (hep-ph/0410364) is an important step
  We cannot afford to slow down!

- There are new (2005–2006) results, e.g.: SM Higgs, SUSY, Z'

- Future: same direction, but better

  ATLAS and CMS are preparing for data taking + ongoing ILC studies
  ⇒ ideal input for studying the LHC/ILC interplay
  ⇒ There is a good case for concurrent running (more examples . . . ?)

- Future: new direction

  investigate various possible scenarios of early LHC data

  ⇒ implications for the ILC (design, options, physics)?

  ⇒ dedicated workshop at Fermilab 10/06