Interplay between the LHC and the ILC

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IPPP Durham

MPI München 02/2006

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

www.ippp.dur.ac.uk/∼georg/lhclc

Some of the open questions in particle physics

What is the mechanism of electroweak symmetry breaking?

- SM, SUSY, . . . :

  Higgs mechanism, elementary scalar particle(s)

- Strong electroweak symmetry breaking (technicolour, . . .):

  new strong interaction, non-perturbative effects, resonances, . . .

- Higgsless models in extra dimensions: boundary conditions for SM gauge bosons and fermions on Planck and TeV branes in higher-dimensional space

$\Rightarrow$ New phenomena required at the TeV scale

Open questions, cont'd

Hierarchy problem: how can the Planck scale be so much larger than the weak scale?

Weak-scale physics is affected by high (cutoff-) scale Λ via quantum corrections

If $\Lambda \approx M_{\mathrm{Planck}} \Rightarrow$ would expect to drive up all physics to the Planck scale

Nature has found a way to prevent this; no explanation in SM
$\Rightarrow$ Expect new physics at the TeV scale

Supersymmetry: large corrections cancel out because of symmetry fermions $\Leftrightarrow$ bosons

Extra-dim. models: fundamental Planck scale is $\sim \mathrm{TeV}$ (large extra dim.), hierarchy of scales related to "warp factor" (RS)

Open questions, cont'd

Do the gauge interactions unify?

SM: no, SUSY: yes, Extra-dim. models: ??

What is dark matter?

SM: —, SUSY: lightest SUSY particle (LSP): neutralino, gravitino, axino, . . . ,
Extra-dim. models: lightest massive KK mode (LKP), . . .

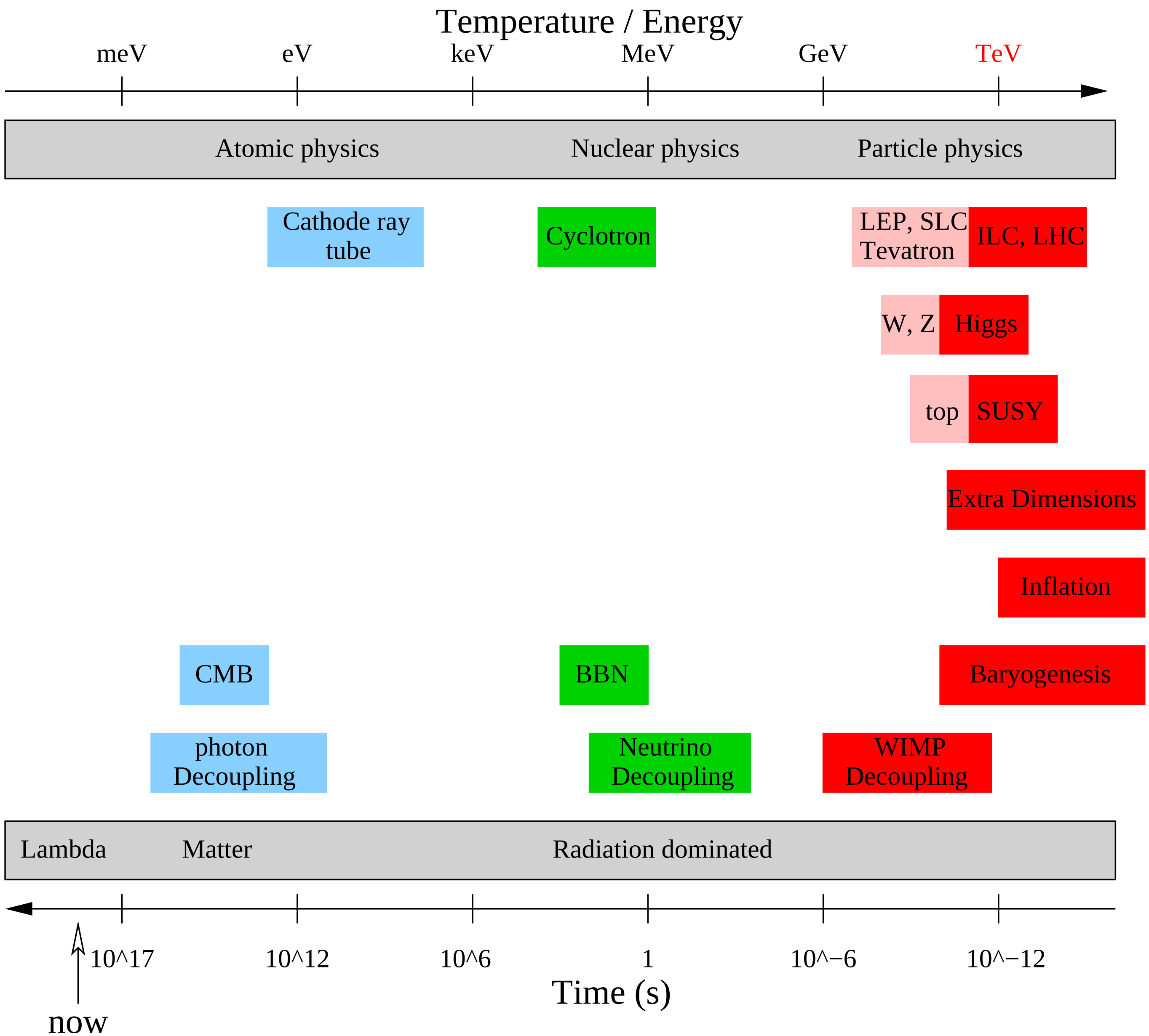
What is dark energy?

SM: ???, SUSY: ???, Extra-dim. models: ???

. . .

LHC and ILC will explore a new territory:

TeV scale ($1\ \mathrm{TeV} \Leftrightarrow 2 \times 10^{-19}\ \mathrm{m}$)

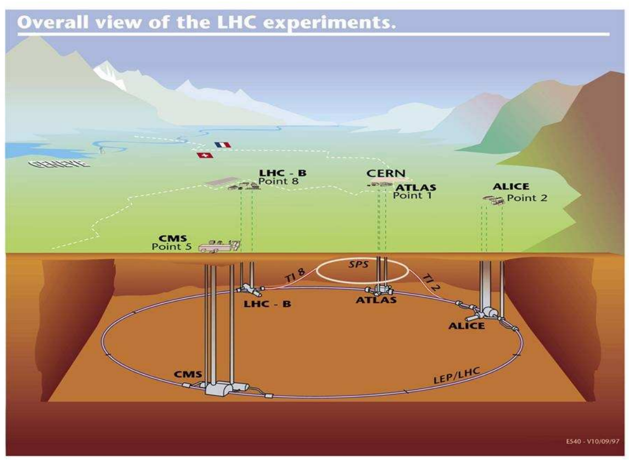


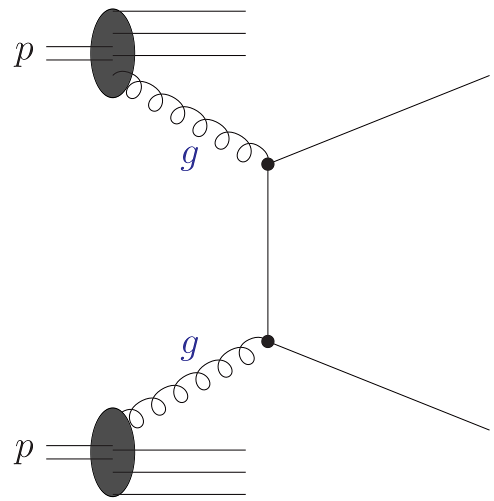
How can we probe the TeV scale? — LHC

The Large Hadron Collider (LHC)

under construction at CERN (Geneva), scheduled to take first data in 2007, expected to run for about 15–20 years

Proton–proton scattering at 14 TeV: composite objects of quarks and gluons, bound together by strong interaction





Complicated scattering process, difficult to interpret

10^9 scattering events$/s \Rightarrow$ only 1 event in 10^7 will be recorded

How can we probe the TeV scale? — ILC

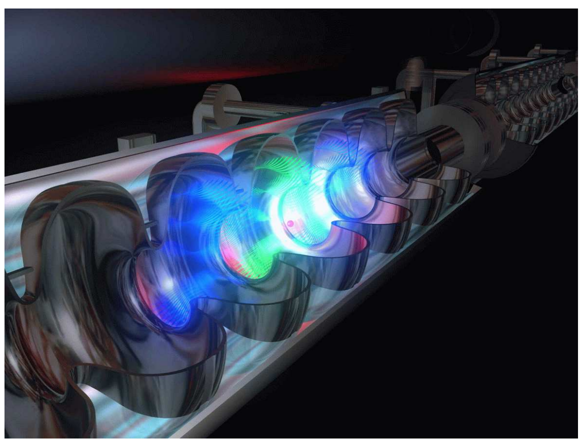
The International Linear Collider (ILC)

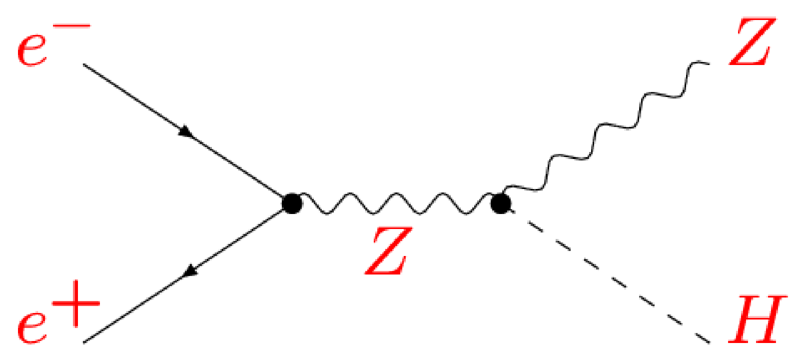
world-wide project, construction could start as early as ≈ 2009
first data in $\gtrsim 2015$?

Electron–positron scattering at ≈0.5–1 TeV:

fundamental particles, point-like, electroweak interaction

well-defined initial state, full collision energy usable, tunable



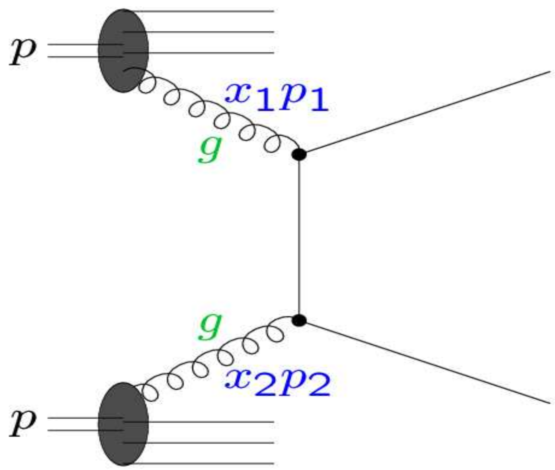


Results are easy to interpret, all events can be recorded

$\Rightarrow$ high-precision physics

Physics at the LHC and ILC in a nutshell

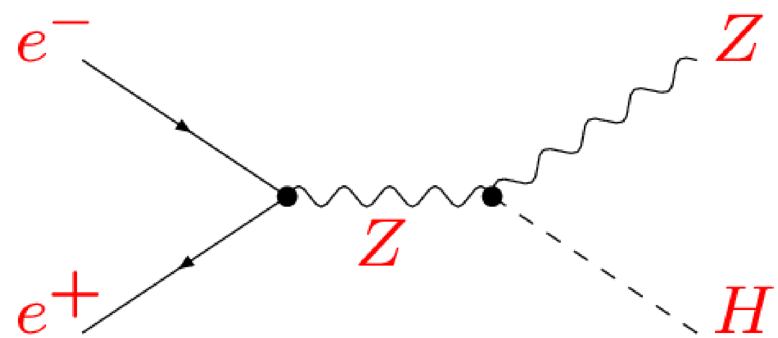
LHC: pp scattering at 14 TeV



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

LHC / ILC complementarity

The results of LHC and ILC will be highly complementary

LHC: good prospects for producing new heavy states
(in particular strongly interacting new particles)

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

LHC / ILC synergy during concurrent running

LHC: $\gtrsim 2007$, expected to run for about 15–20 years

ILC: $\gtrsim 2015$?

Expeditious realisation of the ILC

$\Rightarrow$ period of concurrent running

During 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

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

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

⇒ 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: hep-ph/0410364, to appear in *Physics Reports*

How far are we?

Main focus of the LHC studies so far was to investigate whether a signal can be detected

Less results available on expected precisions, measurable properties of new physics, etc.

For scenarios where detailed experimental simulations are available for both the LHC and the ILC

$\Rightarrow$ Quantitative results on physics gain from LHC / ILC interplay have been worked out

The issue of LHC / ILC synergy has found a lot of attention within and outside our field, of funding agencies, etc.

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.

HEPAP subpanel on LHC / ILC complementarities

- Official request from NSF (R. Staffin, M. Turner) to HEPAP on March 21, 2005:

  form subpanel, provide report by summer 2005

- Panel members:

  J. Lykken (Co-Chair), J. Siegrist (Co-Chair), J. Bagger, B. Barrish, N. Calder, A. De Roeck, J. Feng, F. Gilman, J. Hewett, J. Huth, J. Jackson, Y.-K. Kim, R. Kolb, K. Matchev, H. Murayama, R. Weiss

- Report to the Elementary Particle Physics (EPP) 2010 Committee from HEPAP (July 27, 2005):

  "Discovering the Quantum Universe"

  `www.science.doe.gov/hep/hepap.shtm`

EPP 2010 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

Response of the LHC / ILC Study Group to the EPP questions

Document prepared, writing team: J. Conway, J. Gunion, H. Haber, S. Heinemeyer, G. Moortgat-Pick, G. W.

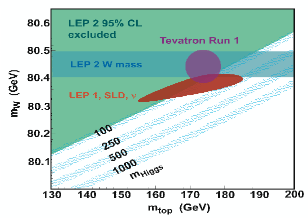
The EPP Questions

Response from the LHC/ILC Study Group

Ground-breaking discoveries are expected from the experiments under construction at the Large Hadron Collider (LHC) and those planned for the International Linear Collider (ILC). These high-energy particle accelerators will open up a new energy domain that will allow us to examine the very fabric of matter, energy, space and time. The experimental results should reveal how particles obtain the property of mass, whether the different forces that we experience in nature are in fact different manifestations of only one fundamental force, whether space and time are embedded into a wider framework of "supersymmetric" coordinates, and whether dark matter can be produced on Earth.

The LHC and ILC will probe this new TeV energy regime (roughly equivalent to 1000 proton masses) in very different ways, as a consequence of the distinct features of the two machines. Due to its high collision energy and luminosity, the LHC has a large mass reach for the discovery of new heavy particles. The striking advantages of the ILC are its clean experimental environment, polarized beams, and tunable collision energy. The ILC can thus perform precision measurements and detailed studies of directly accessible new particles, and also has exquisite sensitivity to quantum effects of unknown physics. Indeed, the fingerprints of very high-scale new physics (e.g. very high mass particles) will often only be manifest in small effects whose measurement requires the greatest possible precision.

The need for instruments that are optimized in different ways is typical in all branches of natural sciences, for example earth- and space-based telescopes in astronomy. In high-energy physics there has historically been a great synergy between hadron colliders, which can reach the highest energies, and lepton colliders, at which high-precision measurements are possible. As an example, the precise knowledge of the Z boson mass from LEP and precise measurement of its decay properties led to the prediction of a heavy top quark. Its mass was well beyond the energy reach of LEP but accessible to the Tevatron. Following the Tevatron's discovery of the top quark, its mass was determined. Subsequently the Tevatron and LEP measured the W boson mass with high precision. In combination, these measurements point tantalizingly toward a light Higgs boson.



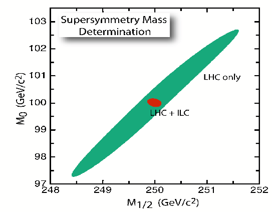
Precise measurements from concurrent running of LEP and the Tevatron experiments have brought us to the threshold of discovering the Higgs boson.

We expect an even greater synergy between the LHC and ILC. Discoveries made at the LHC will guide the operation of the ILC, and the precision ILC measurements can make it possible for the LHC to extract subtle signals for new physics and particles that may have escaped detection. Ultimately both machines will be needed to definitively connect TeV-scale measurements with the underlying theoretical structure.

In general, the LHC can most readily discover the heavy states of new physics that are "strongly coupled" (that is, produced via the strong interaction). These strongly coupled states typically decay via complicated cascades into new "weakly coupled" particles. The ILC is ideal for directly producing and detecting these weakly coupled particles. Precision ILC measurement of the properties of these particles are essential in understanding the strongly coupled ones and their decay patterns. Moreover, ILC measurements of quantum effects can be combined with direct LHC and ILC measurements to infer the existence and properties of additional heavy states at first missed by the LHC and too massive to be directly produced at the ILC. In many cases, these could then be directly discovered using modified LHC procedures.

How would the combination of the LHC and a Linear Collider answer questions that could not be addressed by either machine alone?

As an example, the existence and properties of heavy Higgs bosons and/or difficult-to-detect scalar Higgs-like particles associated with extra dimensions can be inferred from precision ILC Higgs measurements. A dedicated LHC search can then confirm their existence. In supersymmetry and extra-dimension theories, the LHC and the ILC will typically access different parts of the spectrum of new states.



Summary

Together the ILC and LHC can measure the unified supersymmetry masses much more precisely than either machine alone.

There will be a profound synergy between the physics results from the LHC and those from the ILC. The two machines complement and supplement one another in many ways, and concurrent operation will maximize the impact of both. Understanding the physics of the TeV scale will have an important impact on cosmology and other fields, as well as give timely guidance regarding future facilities. The sooner the ILC can be brought into operation, the sooner these benefits can be exploited. Optimal use of the capabilities of both machines will greatly improve our knowledge of the fundamental nature of matter, energy, space and time.

We urge the international high energy physics community and the governments of all the countries involved to strive to make the ILC a reality in the coming decade.

See the full report of the LHC/ILC Study Group at http://arxiv.org/abs/hep-ph/0410364

John Conway, Jack Gunion, Howard Haber, Sven Heinemeyer, Gudrid Moortgat-Pick, and Georg Weiglein

May 16, 2005

Released to the EPP members at the EPP meeting in May '05 at Fermilab, see `www.ippp.dur.ac.uk/~georg/lhcilc`

Some examples of recent results

In the following: some examples of LHC / ILC synergy

Focus on:

- Electroweak symmetry breaking
- Supersymmetry

Many more results on electroweak symmetry breaking, electroweak and QCD precision physics, SUSY, new gauge theories, extra dimensions, . . . in hep-ph/0410364

Electroweak symmetry breaking

ILC will determine electroweak symmetry breaking mechanism regardless of its nature

Higgs discovery possible independent of decay modes

"Golden" production channel: $e^+e^- \to ZH$, $Z \to e^+e^-, \mu^+\mu^-$

ILC is a "Higgs factory"

e.g.: $E_{\mathrm{CM}} = 800$ GeV, 1000 fb^{-1}, $M_{\mathrm{H}} = 120$ GeV:

$\Rightarrow$ ≈ 160000 Higgs events in "clean" experimental environment

$\Rightarrow$ Precise measurement of Higgs mass, couplings, determination of Higgs spin and quantum numbers, . . .

$\Rightarrow$ Verification of Higgs mechanism in model-independent way

distinction between different possible manifestations: extended Higgs sector, invisible decays, Higgs–radion mix., . . .

Higgs coupling determination at LHC $\oplus$ ILC

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

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

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 $H \to b\bar{b}$, . . .

$\Rightarrow$ LHC can directly determine only ratios of couplings

Higgs coupling determination at LHC $\oplus$ ILC

Need additional (mild) theory assumption to obtain absolute values of the couplings at the LHC:

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

Assume: HVV couplings bounded by SM values: $\Gamma_V \leq \Gamma_V^{\rm SM}$ ($V = W, Z$), valid in wide class of models: SM, MSSM, ...

$\Rightarrow$ Upper bound on Γ_V

Observation of Higgs production

$\Rightarrow$ Lower bound on production couplings and $\Gamma_{\rm tot}$

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 Higgs couplings

Use LHC / ILC interplay use ILC input instead of theory assumption: top Yukawa coupling

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

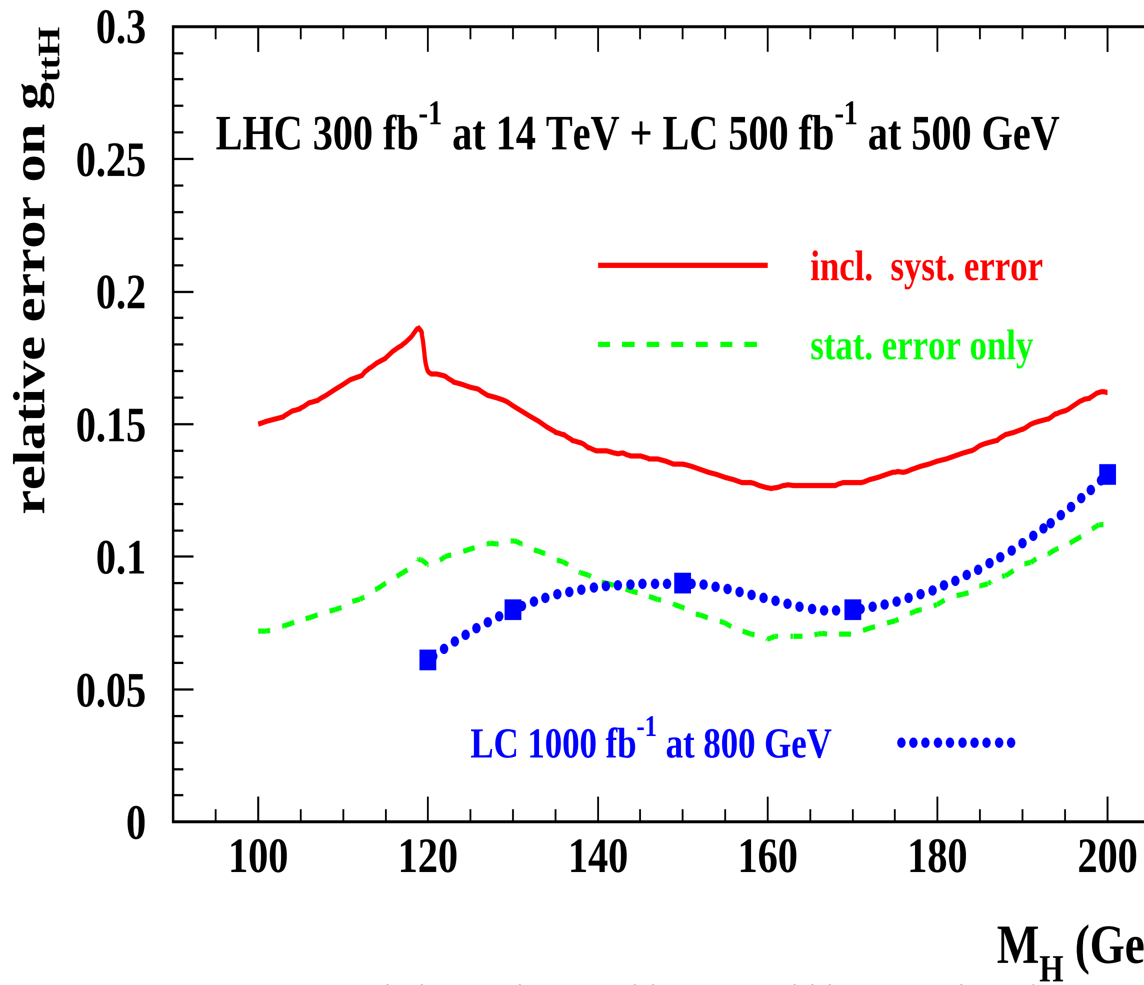
Precision measurement requires ILC with 800–1000 GeV

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*]



LHC / ILC interplay: fit of Higgs couplings

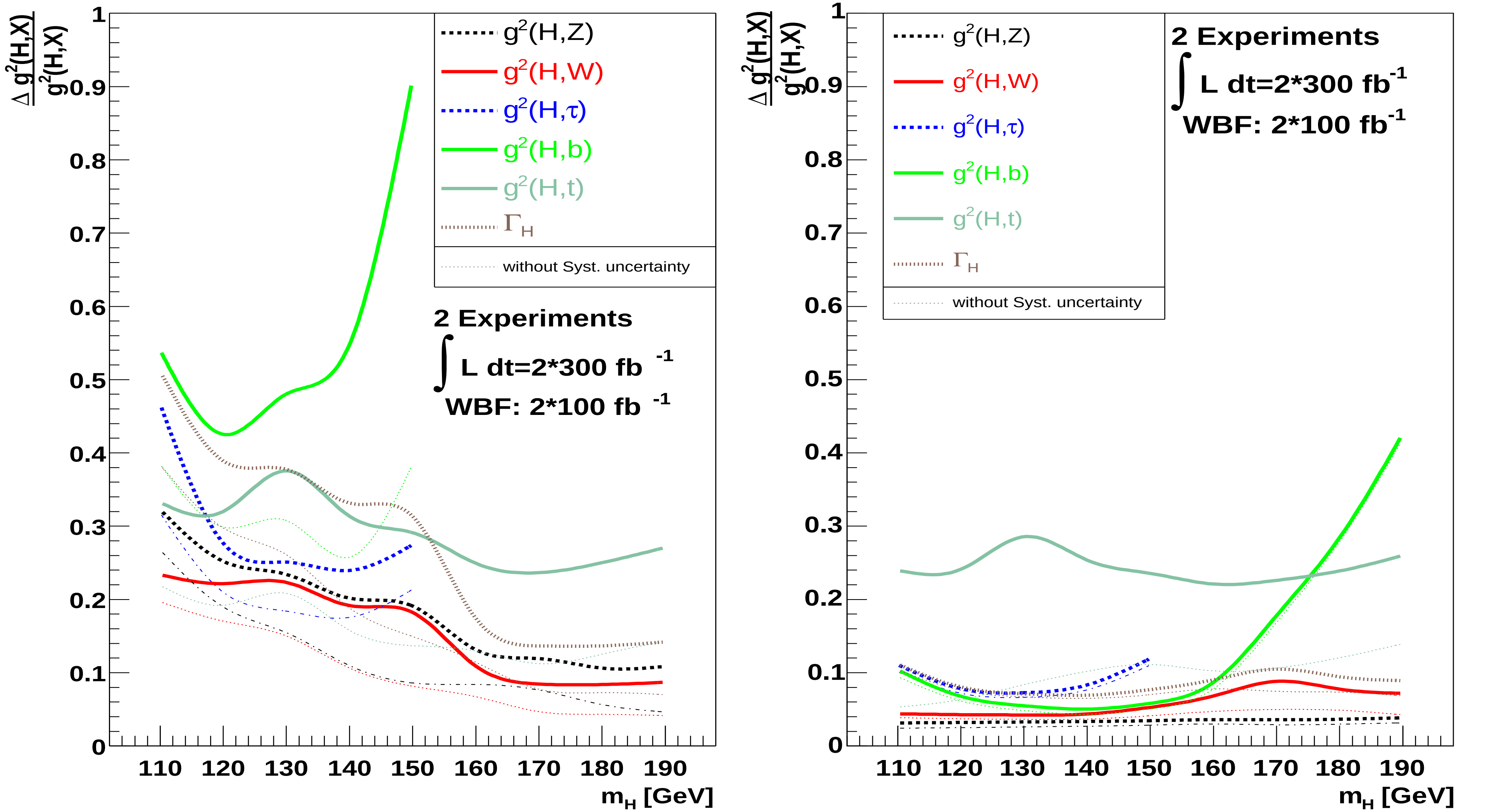
Fit of Higgs couplings with input from LHC and ILC

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

Combined fit for all LHC channels with ILC input:

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

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

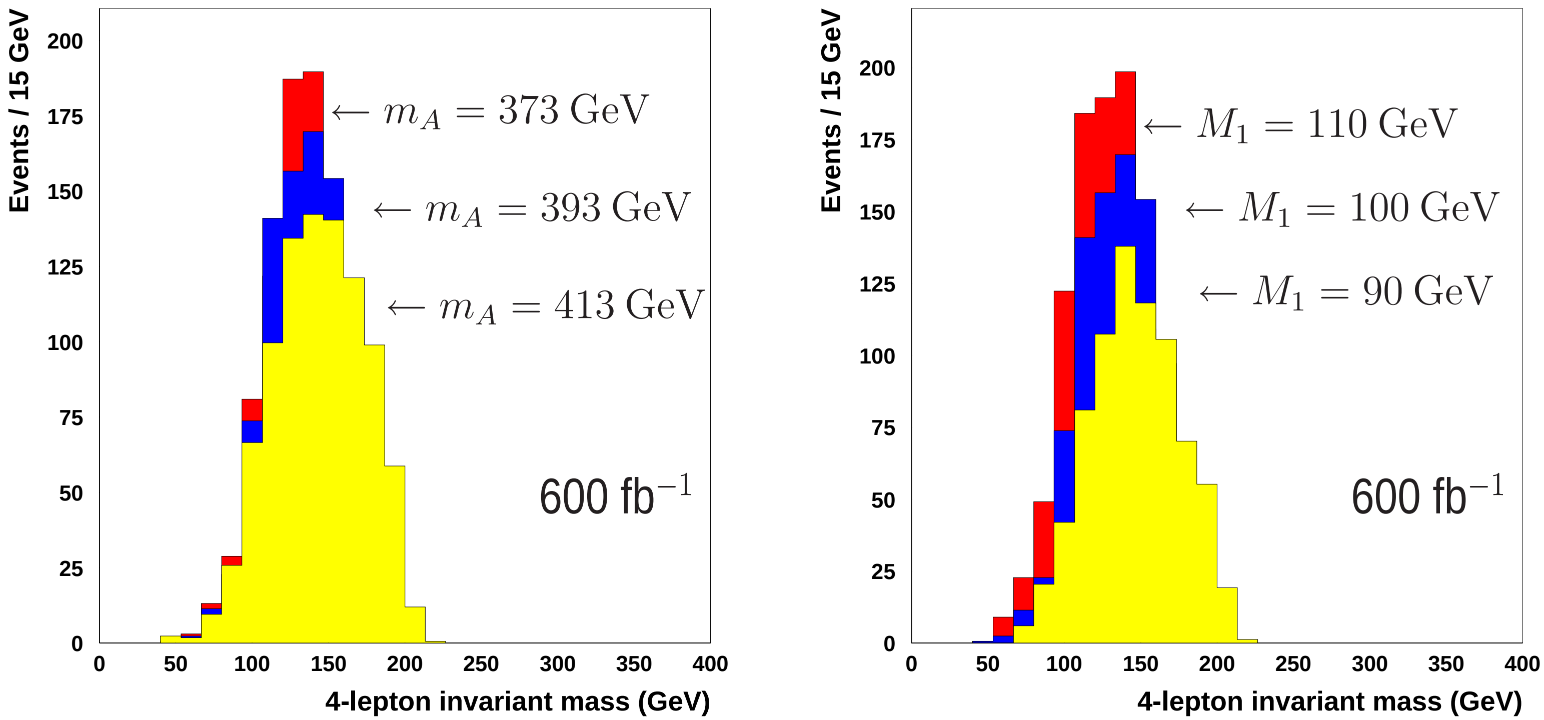


$\Rightarrow$ higher accuracy on $g_{Ht\bar{t}}$ (and also $g_{H\gamma\gamma}$) than for LHC alone (+ theory) and ILC$_{500}$ alone: $\Delta g_{Ht\bar{t}}/g_{Ht\bar{t}} \approx 11$–$14\%$

Determination of M_A from heavy Higgs decays into SUSY particles at the LHC

[*F. Moortgat '04*]

$H, A \to \tilde{\chi}_2^0 \tilde{\chi}_2^0$: Four lepton invariant mass distribution for $M_\mathrm{A} = 393 \pm 20$ GeV (left) and $M_1 = 100 \pm 10$ GeV (right)



$\Rightarrow$ Precise knowledge of LSP mass from ILC crucial for determination of M_A

Indirect constraints on M_A from Higgs BR measurements at the ILC using LHC / ILC input

Precision measurement of

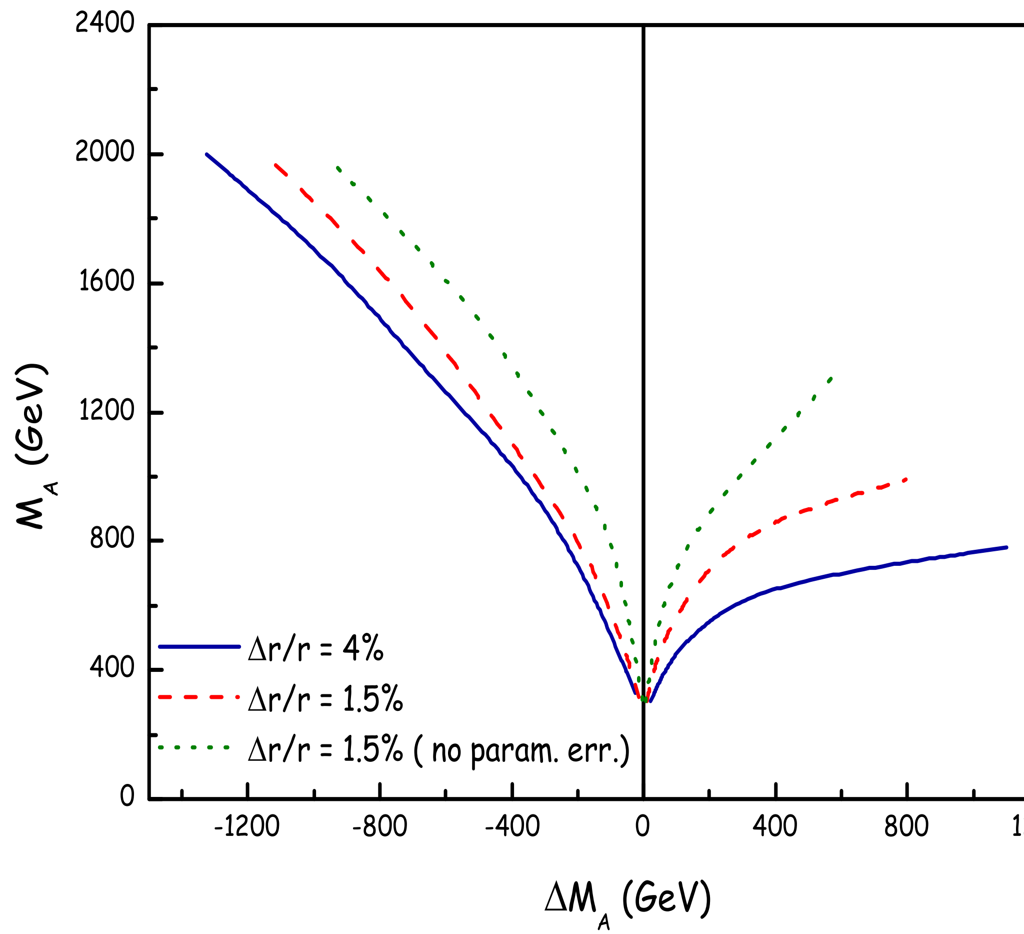
$$r \equiv \frac{[\mathrm{BR}(h \to b\bar{b})/\mathrm{BR}(h \to WW^*)]_\mathrm{MSSM}}{[\mathrm{BR}(h \to b\bar{b})/\mathrm{BR}(h \to WW^*)]_\mathrm{SM}}$$

at the ILC

and

LHC $\oplus$ ILC information on SUSY spectrum (SPS1a scenario)

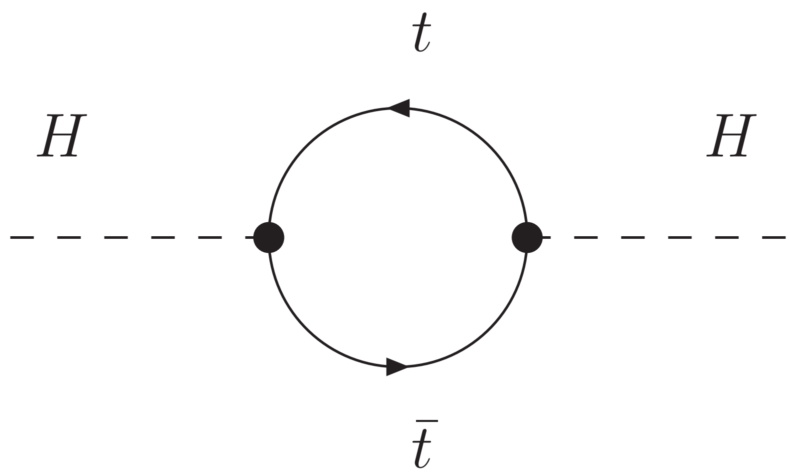
[*K. Desch, E. Gross, S. Heinemeyer, G. W., L. Zivkovic '04*]



$\Rightarrow$ Sensitive indirect bounds on M_A only with high-precision measurements, LHC $\oplus$ ILC information

Precision Higgs physics

Large coupling of Higgs to top quark



One-loop correction $\sim G_\mu m_\mathrm{t}^4$

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

SUSY as an example: $\Delta m_\mathrm{t} \approx \pm 3 \text{ GeV} \Rightarrow \Delta m_\mathrm{h} \approx \pm 3 \text{ GeV}$

$\Rightarrow$ Precision Higgs physics needs precision top physics

LHC: $\Delta m_\mathrm{h} \approx 0.2$ GeV, $\Delta m_\mathrm{t} \gtrsim 1$ GeV, ILC: $\Delta m_\mathrm{t} \lesssim 0.1$ GeV

Higgs–radion mixing

[*M. Battaglia, S. De Curtis, A. De Roeck, D. Dominici, J. Gunion '03*]

Models with 3-branes in extra dimensions predict radion ϕ, can mix with the Higgs

$\Rightarrow$ Higgs properties modified, can be difficult to detect at the LHC

LHC may observe radion instead

ILC guarantees Higgs observation over full parameter space

$\Rightarrow$ precision measurements at ILC crucial to disentangle the nature of the observed state

LHC: large sensitivity to production of Kaluza-Klein excitations

Electroweak symmetry breaking without Higgs

If no light Higgs boson exists

⇒ dynamics of electroweak symmetry breaking can be probed in quasi-elastic scattering processes of W and Z at high energies

LHC / ILC sensitive to different scattering channels, yield complementary information

LHC: direct sensitivity to resonances

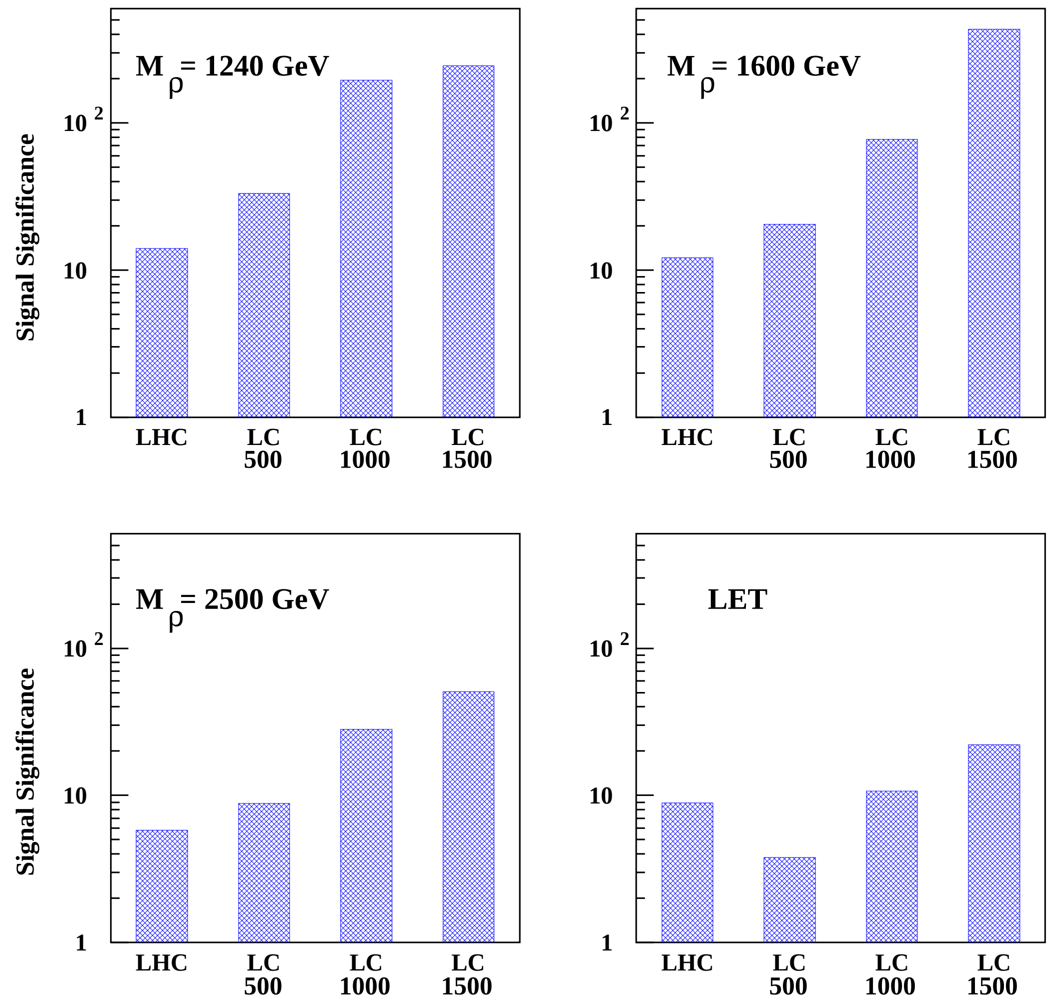
ILC: detailed measurements of cross sections and angular distributions

⇒ combination of LHC results with ILC data on cross-section rise essential for disentangling new states

Strong electroweak symmetry breaking

Sensitivity of LHC and ILC measurements to signals of strong electroweak symmetry breaking:
[*American LC WG ’01*]

Signal significance in σ for various masses M_ρ of vector resonance in $W_\mathrm{L}W_\mathrm{L}$ scattering:



$\Rightarrow$ Strong electroweak symmetry breaking scenarios can be probed in detail at LHC $\oplus$ ILC

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles:

$\left[u, d, c, s, t, b\right]_{L,R}$ $\left[e, \mu, \tau\right]_{L,R}$ $\left[\nu_{e,\mu,\tau}\right]_L$ Spin $\frac{1}{2}$

$\left[\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}, \tilde{t}, \tilde{b}\right]_{L,R}$ $\left[\tilde{e}, \tilde{\mu}, \tilde{\tau}\right]_{L,R}$ $\left[\tilde{\nu}_{e,\mu,\tau}\right]_L$ Spin 0

g $\underbrace{W^{\pm}, H^{\pm}}$ $\underbrace{\gamma, Z, H_1^0, H_2^0}$ Spin 1 / Spin 0

$\tilde{g}$ $\tilde{\chi}^{\pm}_{1,2}$ $\tilde{\chi}^{0}_{1,2,3,4}$ Spin $\frac{1}{2}$

Enlarged Higgs sector: two Higgs doublets, physical states: $h^0, H^0, A^0, H^{\pm}$

SUSY breaking

MSSM: no particular SUSY breaking mechanism assumed, parametrization of possible soft SUSY-breaking terms

$\Rightarrow$ relations between dimensionless couplings unchanged

$\Rightarrow$ no quadratic divergencies (hierarchy problem)

Most general case: 105 new parameters

Good phenomenological description for universal breaking terms

Specific models for soft-SUSY breaking:

“Hidden sector”:		Visible sector:
SUSY breaking	$\longrightarrow$	MSSM

“Gravity-mediated”: mSUGRA

“Gauge-mediated”: GMSB

“Anomaly-mediated”: AMSB

. . .

SUSY at LHC and ILC

LHC: good prospects for strongly interacting new particles

long decay chains $\Rightarrow$ complicated final states,

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

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

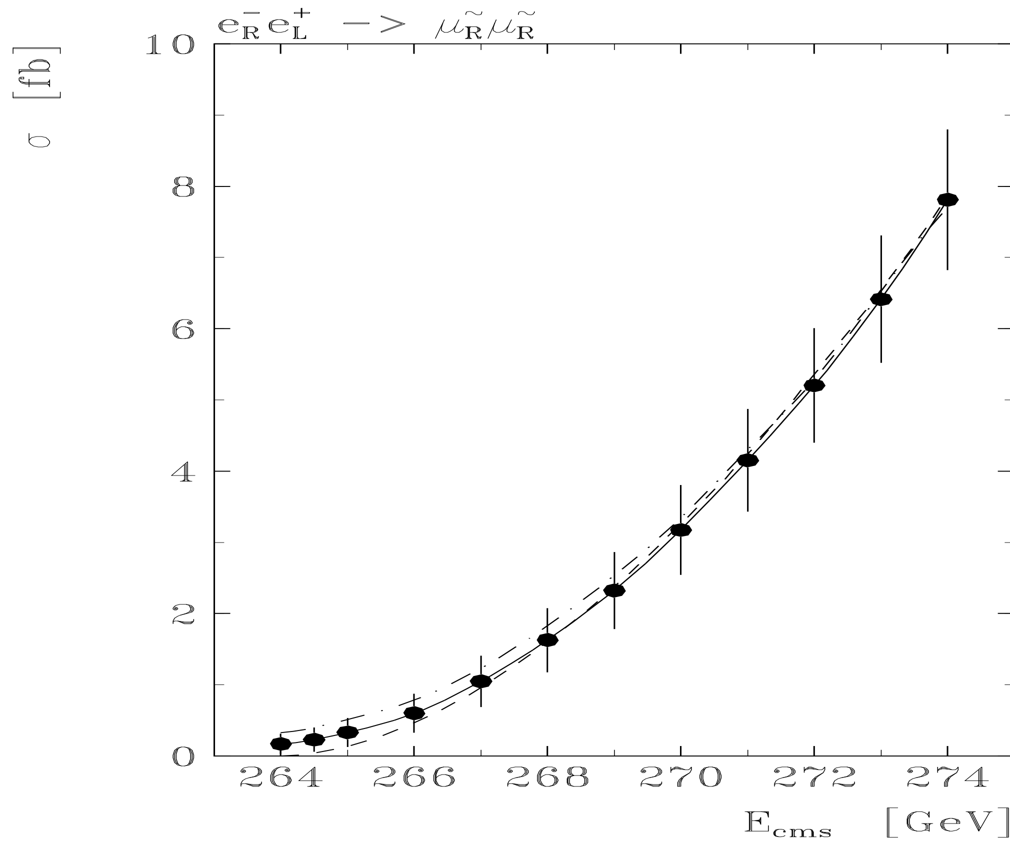
precision measurement of mass of lightest SUSY particle (factor 100 improvement)

Production of new particles at the ILC

Tunable energy $\Rightarrow$ can run directly at threshold

Example: Determination of mass and spin of SUSY particle $\tilde{\mu}_R$ from production at threshold:

[*TESLA TDR '01*]



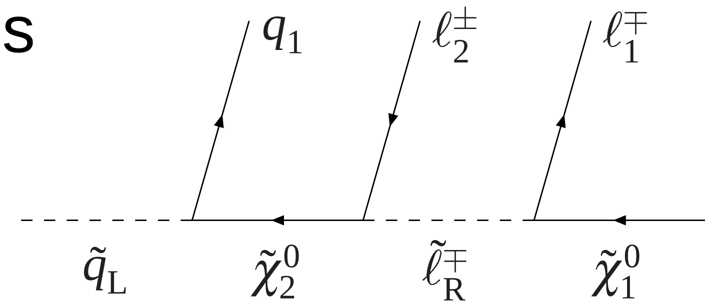
$$\Rightarrow \quad \frac{\Delta m_{\tilde{\mu}_R}}{m_{\tilde{\mu}_R}} < 1 \times 10^{-3}$$

$\Rightarrow$ test of $J = 0$ hypothesis

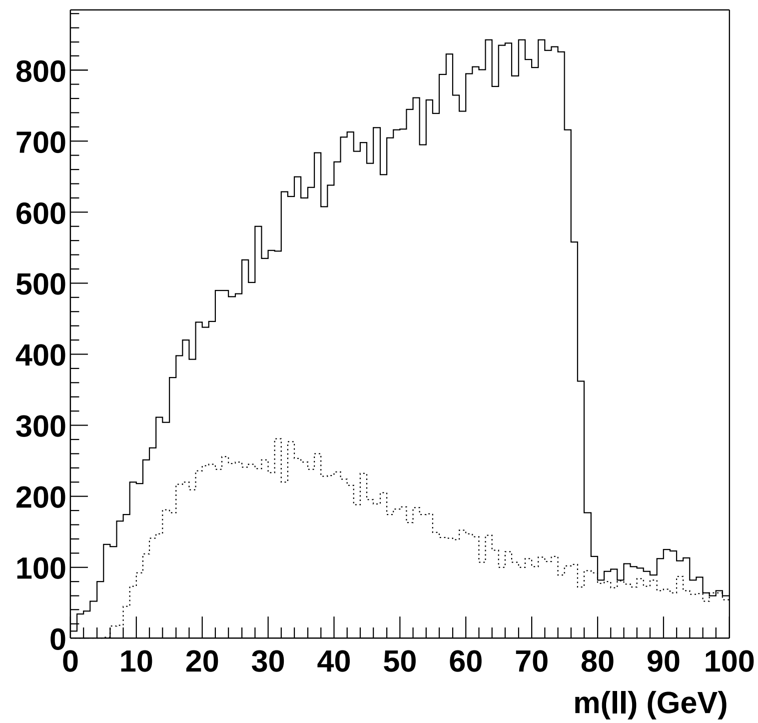
SUSY analyses at LHC / ILC

[*M. Chiorboli, B.K. Gjelsten, J. Hisano, K. Kawagoe, E. Lytken, U. Martyn, D. Miller, M. Nojiri, P. Osland, G. Polesello, A. Tricomi ’03*]

Cascade decays: complicated decay chains for squarks and gluinos

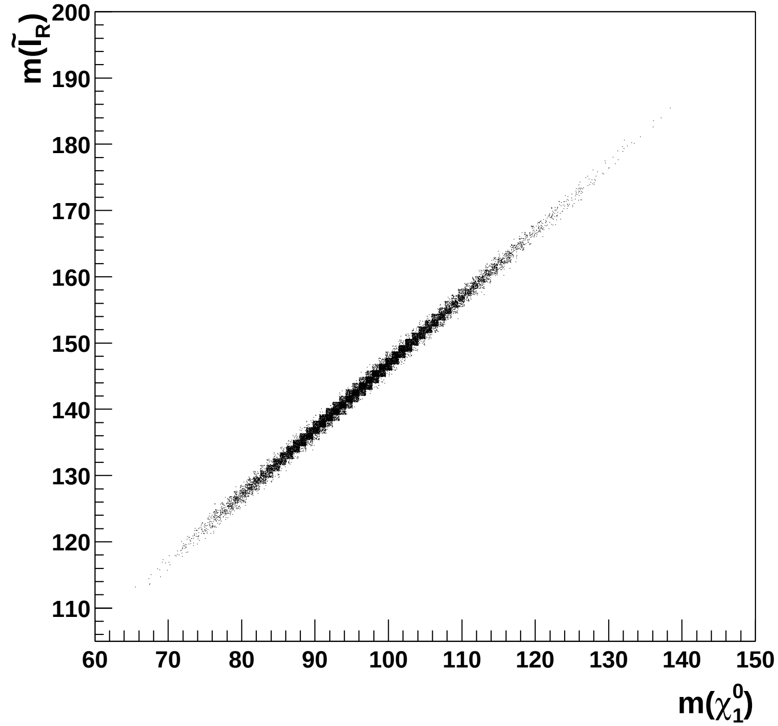


Main tool: dilepton “edge” from $\tilde{\chi}_2^0 \to \ell^+\ell^-\tilde{\chi}_1^0$



LHC analysis with ILC input: mass of lightest SUSY particle (LSP)

Reconstruction of the states in decay chain requires precise knowledge of LSP mass



$\Rightarrow$ Precision measurement of m_{LSP} at ILC leads to significant improvement in determination of slepton, squark and gluino masses at the LHC

Detailed analysis for SPS1a benchmark scenario: potential of LHC (300 fb^{-1}) alone and LHC $\oplus$ ILC

	LHC	LHC$\oplus$ILC
$\Delta m_{\tilde{\chi}_1^0}$	4.8	0.05 (input)
$\Delta m_{\tilde{l}_R}$	4.8	0.05 (input)
$\Delta m_{\tilde{\chi}_2^0}$	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)
$\Delta m_{\tilde{\chi}_4^0}$	5.1	2.23

LHC$\oplus$ILC accuracy limited by LHC jet energy scale resolution

SPS 1a benchmark scenario:

favourable scenario for both LHC and ILC

$\Rightarrow$ ILC input improves accuracy significantly

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

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

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

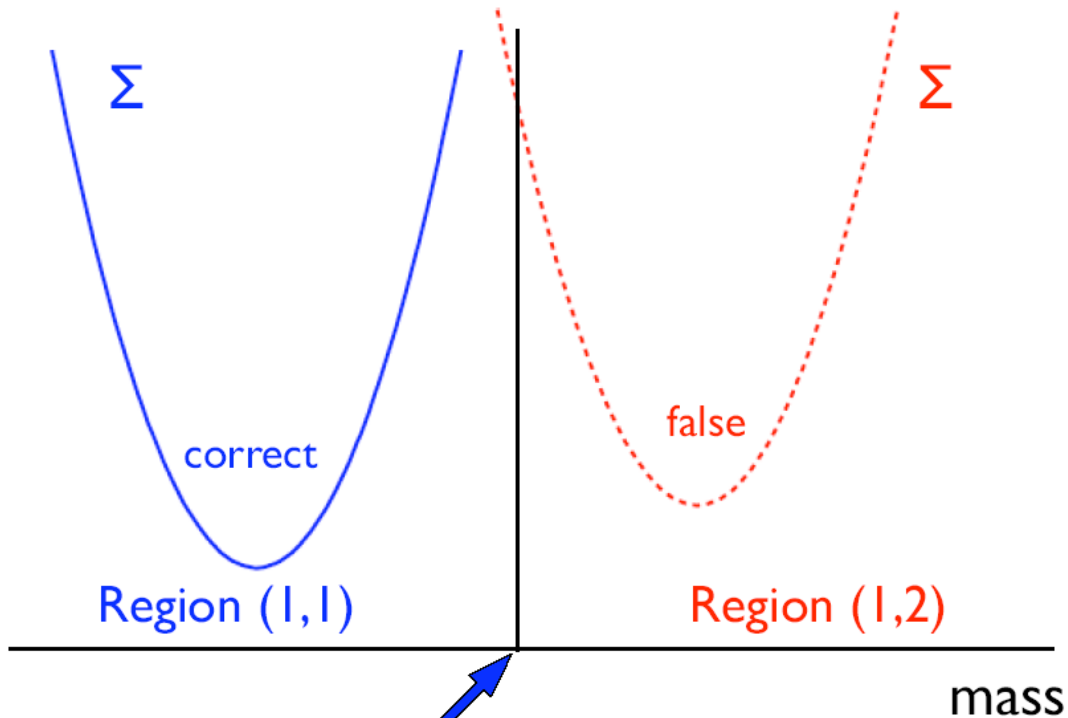
$\Rightarrow$ yields correct minimum

$+$ 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



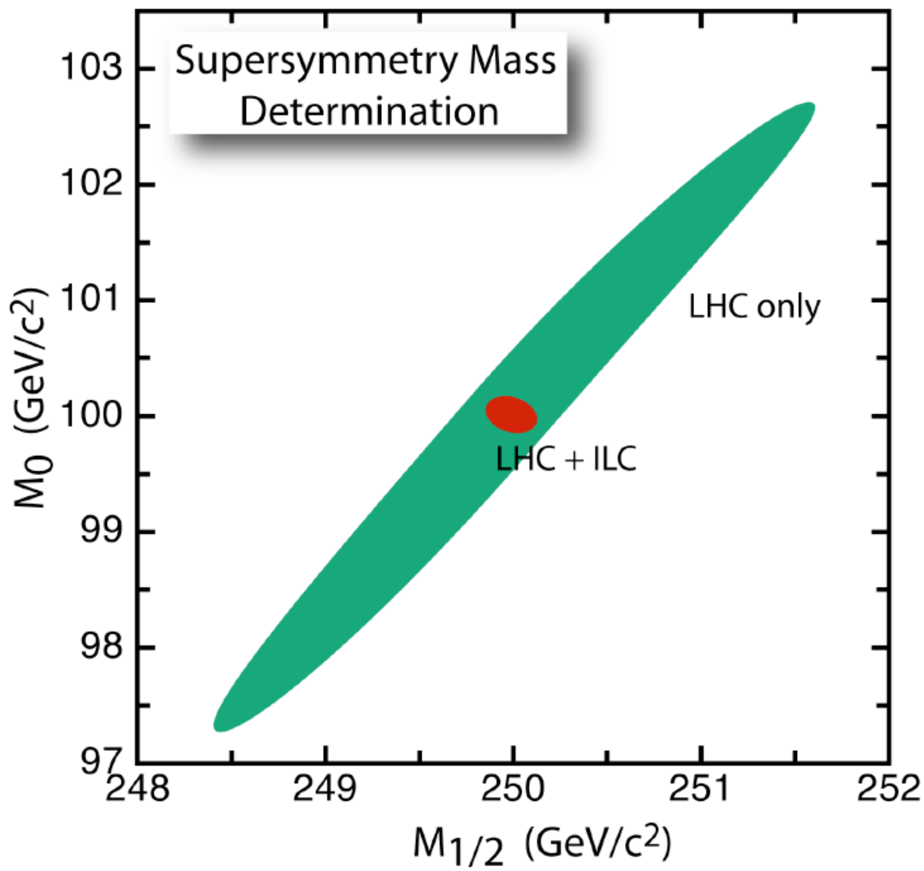
$$m^2_{\tilde{l}_R} = (m^2_{\tilde{\chi}^0_1} + m^2_{\tilde{\chi}^0_2})/2$$

ILC input on LSP mass

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

Determination of GUT-scale parameters m_0, $m_{1/2}$ in the mSUGRA scenario

LHC only vs. LHC $\oplus$ ILC



$\Rightarrow$ Combined information from LHC and ILC yields drastic improvement

LHC / ILC interplay in SUSY searches

- 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, . . .

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 $M_{\rm H} = 115 \pm 1$ GeV

this would have certainly affected the running strategy of LEP

Example of LHC / ILC interplay

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

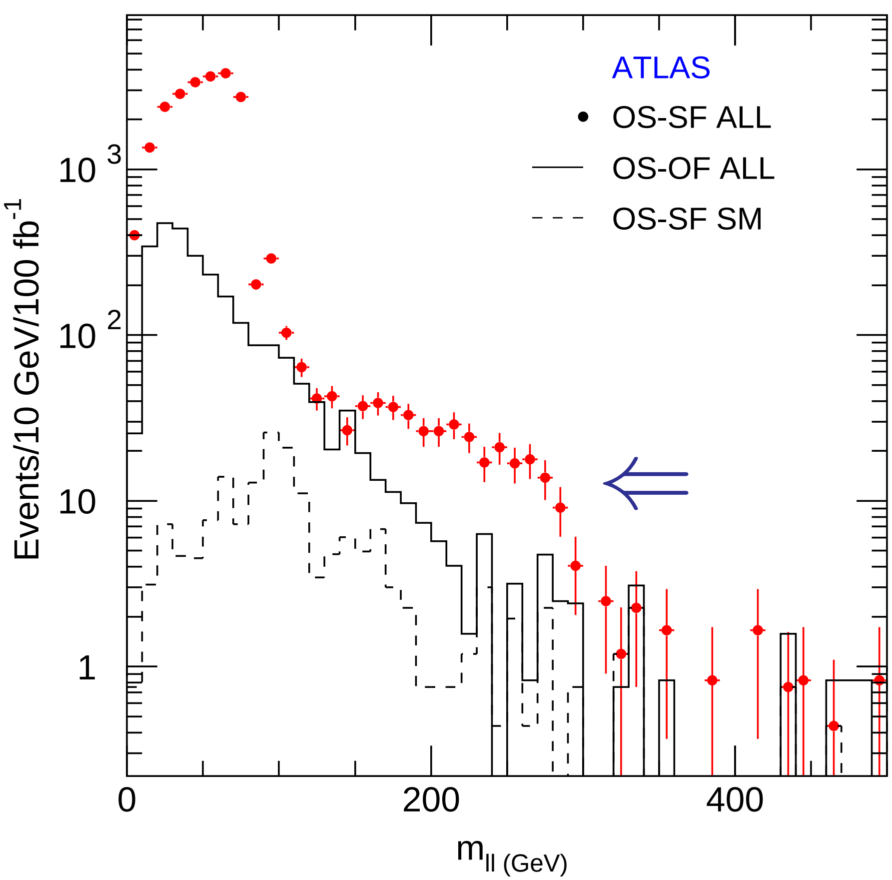
$\Rightarrow$ Determination of all parameters in neutralino/chargino sector

$\Rightarrow$ 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



The new particle can be identified at the LHC via this “edge”

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

$\Rightarrow$ Crucial test of the model

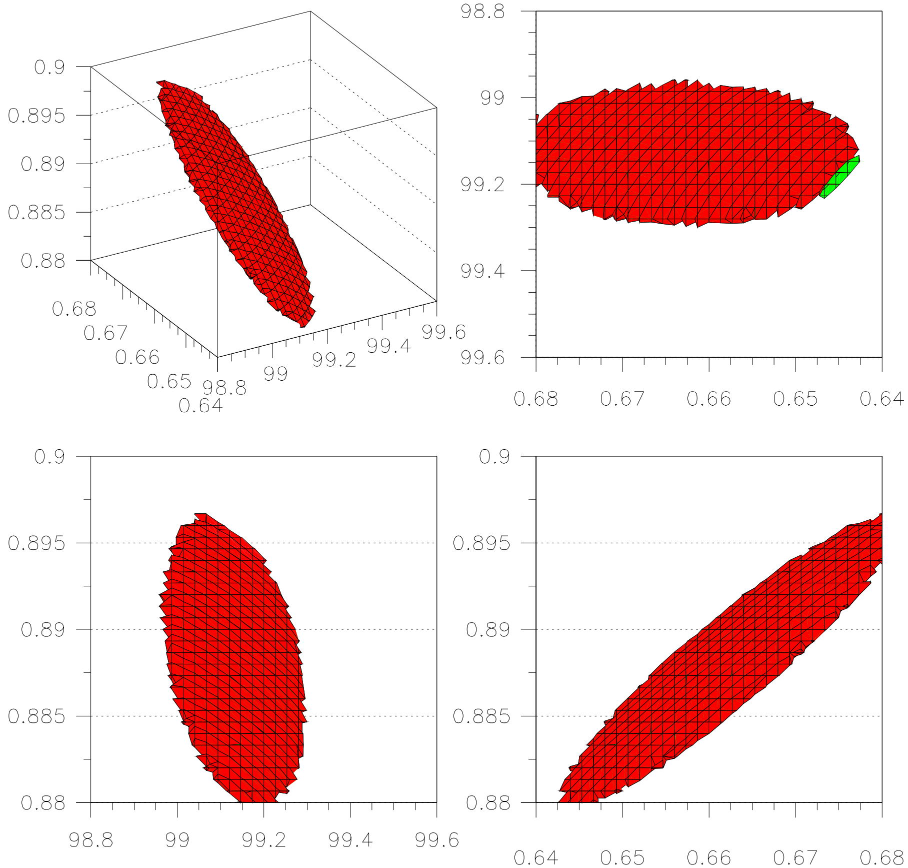
Feeding information on $m(\tilde{\chi}^0_4)$ back into ILC analysis

$\Rightarrow$ Improved accuracy of parameter determination at ILC

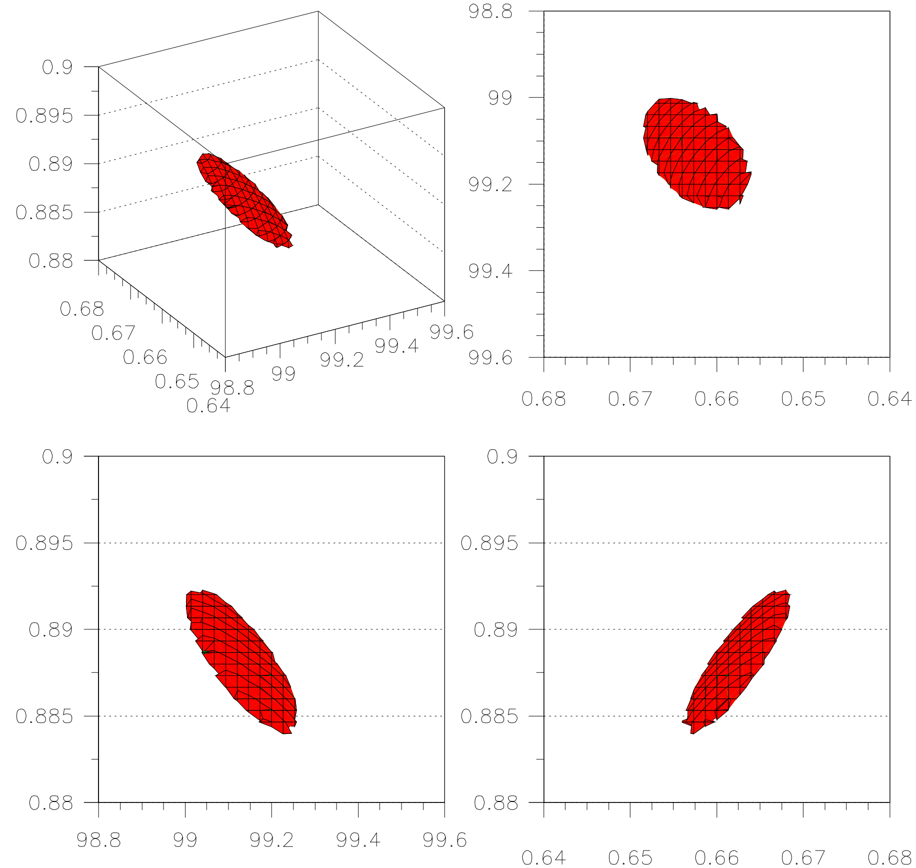
ILC analysis with LHC input

Determination of neutralino parameter M_1 and chargino mixing angles $\cos\phi_{\mathrm{L}}$, $\cos\phi_{\mathrm{R}}$:

ILC information alone



LHC $\oplus$ ILC information



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*]

Parameter determination as in MSSM $\Rightarrow$ no contradiction

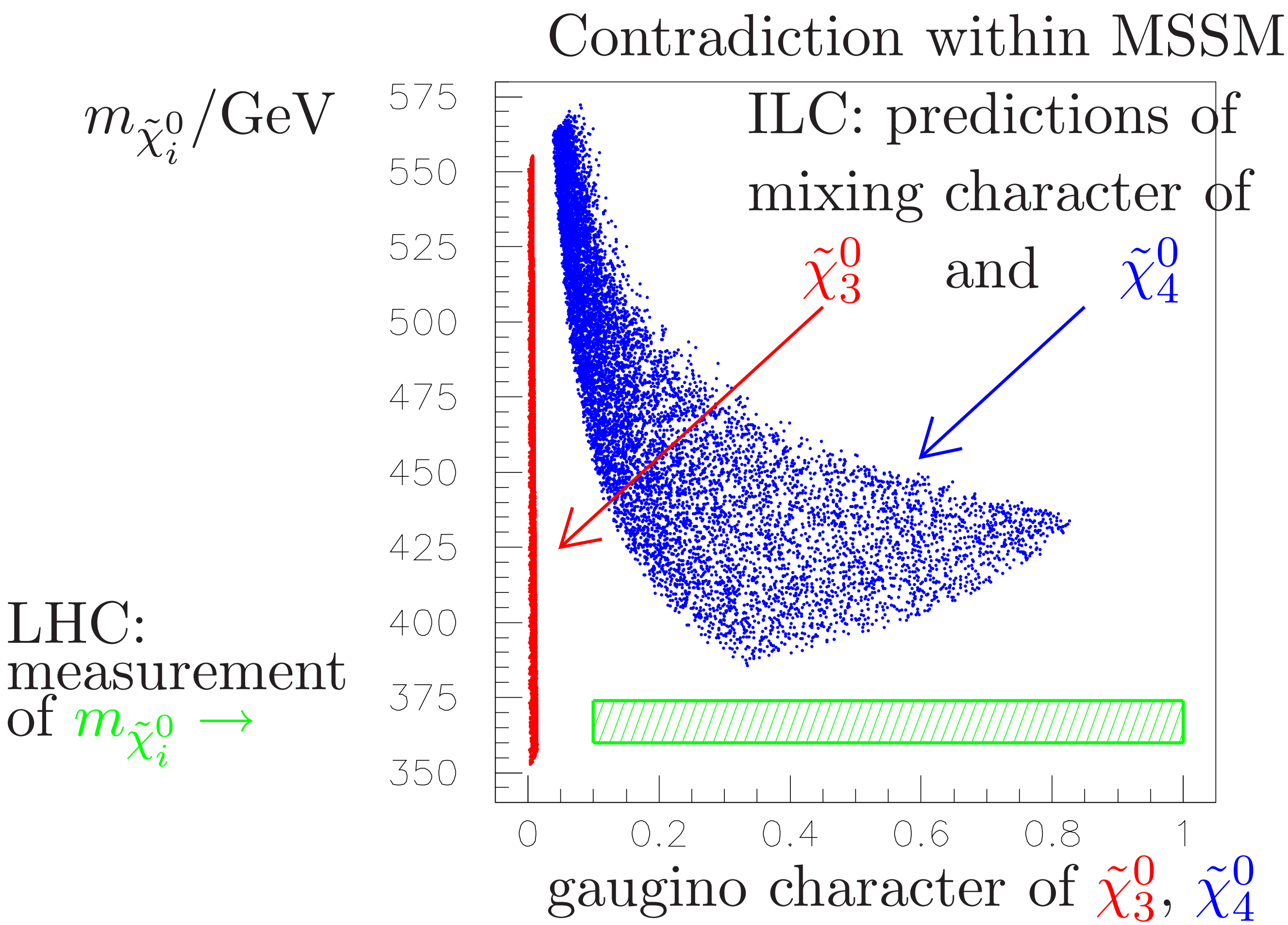
ILC input $\Rightarrow$ prediction of masses and mixing character of heavy neutralinos

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

$\Rightarrow$ Evidence for NMSSM

Mixing character of $\tilde{\chi}_3^0$, $\tilde{\chi}_4^0$: MSSM vs. NMSSM

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



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

SUSY parameter determination

Prospects for SUSY parameter determination at LHC and ILC investigated in detail for SPS 1a benchmark point:

"bulk" region of mSUGRA scenario ('best case scenario')

$m_0 = 100\,\mathrm{GeV},\; m_{1/2} = 250\,\mathrm{GeV},\; A_0 = -100\,\mathrm{GeV},\; \tan\beta = 10,\; \mu > 0$

Most observables depend on variety of SUSY parameters

$\Rightarrow$ Need global fit to large set of observables

[*R. Lafaye, T. Plehn, D. Zerwas '04*] [*P. Bechtle, K. Desch, P. Wienemann '04*]

$\Rightarrow$ Reliable determination of SUSY parameters only possible from combined LHC $\oplus$ ILC data

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*]

LHC input:

mass measurements and precisions as above

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

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

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

Parameter	"True" value	ILC Fit value	Uncertainty (ILC+LHC)	Uncertainty (LHC only)
$\tan\beta$	10.00	10.00	0.11	6.7
μ	400.4 GeV	400.4 GeV	1.2 GeV	811. GeV
X_τ	-4449. GeV	-4449. GeV	20.GeV	6368. GeV
$M_{\tilde{e}_R}$	115.60 GeV	115.60 GeV	0.27 GeV	39. GeV
$M_{\tilde{\tau}_R}$	109.89 GeV	109.89 GeV	0.41 GeV	1056. GeV
$M_{\tilde{e}_L}$	181.30 GeV	181.30 GeV	0.10 GeV	12.9 GeV
$M_{\tilde{\tau}_L}$	179.54 GeV	179.54 GeV	0.14 GeV	1369. GeV
X_t	-565.7 GeV	-565.7 GeV	3.1 GeV	548. GeV
X_b	-4935. GeV	-4935. GeV	1284. GeV	6703. GeV
$M_{\tilde{u}_R}$	503. GeV	503. GeV	24. GeV	25. GeV
$M_{\tilde{b}_R}$	497. GeV	497. GeV	8. GeV	1269. GeV
$M_{\tilde{t}_R}$	380.9 GeV	380.9 GeV	2.5 GeV	753. GeV
$M_{\tilde{u}_L}$	523. GeV	523. GeV	10. GeV	19. GeV
$M_{\tilde{t}_L}$	467.7 GeV	467.7 GeV	3.1 GeV	424. GeV
M_1	103.27 GeV	103.27 GeV	0.06 GeV	8.0 GeV
M_2	193.45 GeV	193.45 GeV	0.10 GeV	132. GeV
M_3	569. GeV	569. GeV	7. GeV	10.1 GeV
$m_{A run}$	312.0 GeV	311.9 GeV	4.6 GeV	1272. GeV
m_t	178.00 GeV	178.00 GeV	0.050 GeV	0.27 GeV

χ^2 for unsmeared observables: 5.3×10^{-5}

$\Rightarrow$ most of the Lagrangian parameters can hardly be constrained by LHC data alone

$\Rightarrow$ precise determination of SUSY parameters only possible with LHC $\oplus$ 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 (4 parameters and a sign)

$\Rightarrow$ 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
$\to$ need m_{t} with accuracy of $\mathcal{O}(20\ \mathrm{MeV})$
$\to$ 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*]

Conclusions

- LHC / ILC interplay is a very rich field

  ⇒ promising potential for important physics gain

- 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

  ⇒ Many new results, ideal input for studying LHC / ILC interplay

- LHC will start to take data very soon

  We are looking forward to finding out what the real data will tell us