Role of the ILC in the LHC era

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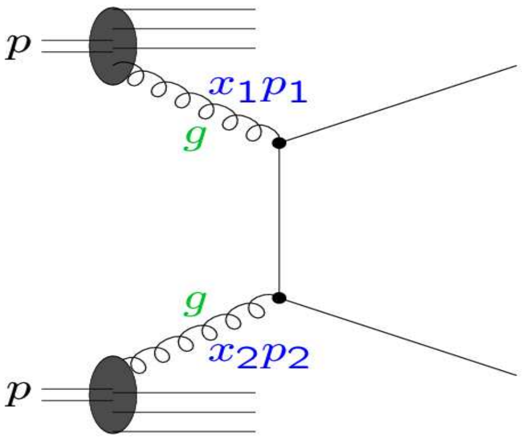
Worldwide Study of the Physics and Detectors for Future Linear e^+e^- Colliders

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

1. Why does one need the ILC in addition to the LHC?

LHC: pp scattering,
$\sqrt{s} = 14$ TeV, contains "hard" collision process

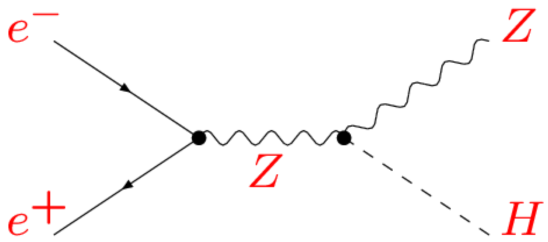


Available $(\text{energy})^2$ for partonic sub-process: $\hat{s} = x_1 x_2 s$

$\sqrt{\hat{s}}$ up to several TeV

huge QCD backgrounds, low signal–to–background ratios

ILC: e^+e^- scattering,
$\sqrt{s} = 0.5$–1 TeV,
clean exp. environment,
small backgrounds



well-defined initial state,
full momentum conservation usable,
beam polarisation, variable energy $\Rightarrow$ threshold scans
$\Rightarrow$ high-precision physics

Some of the issues addressed at LHC and ILC

- Electroweak symmetry breaking: SM-like Higgs sector, Higgs with non-standard properties, no Higgs, . . .
- Precision physics of the electroweak and strong interaction: top, electroweak precision tests, gauge couplings, extended gauge sector, . . .
- Hierarchy problem: Supersymmetry, extra spatial dimensions, Little Higgs scenarios, . . .
- Dark Matter: lightest supersymmetric particle, Kaluza-Klein excitations of the photon, . . .

LHC and ILC have different capabilities, probe different aspects

$\Rightarrow$ Experimental information from both LHC and ILC is crucial

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

Electroweak symmetry breaking without Higgs

If no light Higgs boson exists

$\Rightarrow$ 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

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

Electroweak precision physics

ILC: precision measurement of

– $m_{\rm t}$, $\sin^2\theta_{\rm eff}$: factor $\gtrsim 10$ improvement compared to LHC

– $M_{\rm W}$: factor 2–3 improvement

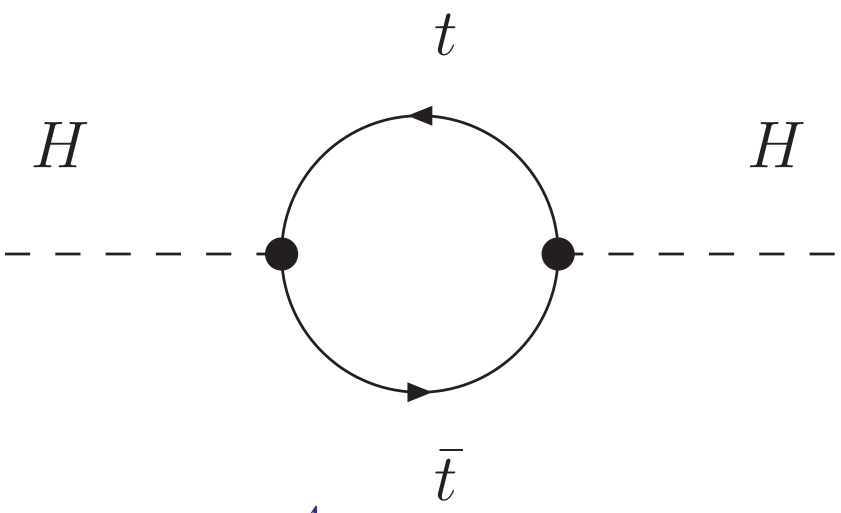
$\Rightarrow$ high sensitivity to effects of new physics
(cf.: WMAP vs. COBE)

With LHC precision on $m_{\rm t}$:

$\Rightarrow$ $\delta m_{\rm t}^{\rm exp}$ will be dominant source of uncertainty in electroweak precision physics

Precision Higgs physics

Large coupling of Higgs to top quark



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

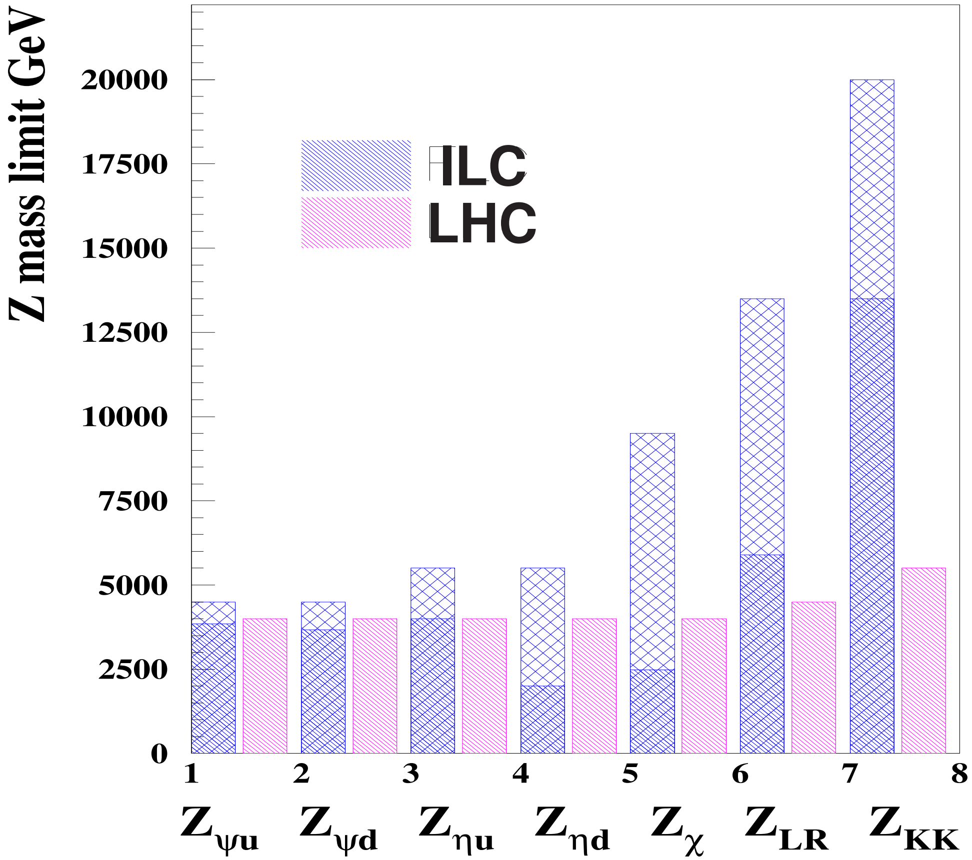
$\Rightarrow$ M_H depends sensitively on m_t in all models where M_H can be predicted

SUSY as an example: $\Delta m_\mathrm{t} \approx \pm 4$ GeV $\Rightarrow$ $\Delta m_\mathrm{h} \approx \pm 4$ GeV

$\Rightarrow$ ILC accuracy on m_t crucial for precision Higgs physics

Sensitivity to new heavy states

Example: various scenarios predicting a Z' [*F. Richard '03*]



$\Rightarrow$ ILC search reach via precision measurements of $e^+e^- \to f\bar{f}$, $\sin^2\theta_{\mathrm{eff}}$, M_{W} exceeds LHC discovery reach

Hierarchy problem

Expect new physics at the TeV scale to stabilise hierarchy between weak scale and Planck scale:

Weak scale supersymmetry (SUSY), extra spatial dimensions, Little Higgs models, ...

In order to establish, e.g., SUSY experimentally, need to demonstrate that:

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

Necessary experimental information

⇒ Precise measurements of masses, branching ratios, cross sections, angular distributions, . . . mandatory for

- establishing SUSY experimentally
- determining how SUSY is realised (particle content, . . .)
  MSSM, NMSSM, . . .
  MSSM: 105 low-energy parameters
- disentangling underlying mechanism of SUSY breaking
- verifying SUSY nature of Dark Matter?

SUSY at LHC and ILC

LHC: good prospects for production of coloured particles

long decay chains $\Rightarrow$ complicated final states,

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

Many states are produced at once, difficult to disentangle

$\Rightarrow$ Main background for SUSY is SUSY itself!

ILC: clean signatures, small backgrounds

$\Rightarrow$ precise determination of masses, spin, mixing angles, complex phases . . . ,

good prospects for uncoloured particles

precision measurement of LSP mass (factor 100 improvement)

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, global fit doesn't converge if LHC or ILC data are taken alone

$\Rightarrow$ ILC measurements crucial for extrapolation to physics at high scales, prediction of Dark Matter density

From “known unknowns” to “unknown unknowns”

Above examples 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

LHC $\oplus$ ILC information will be needed in order to determine the nature of new physics

2. What is the gain of having ILC and LHC run concurrently?

ILC has a lot to add to what the LHC will find out

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

If the two colliders run at the same time

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

$\Rightarrow$ Improved experimental 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

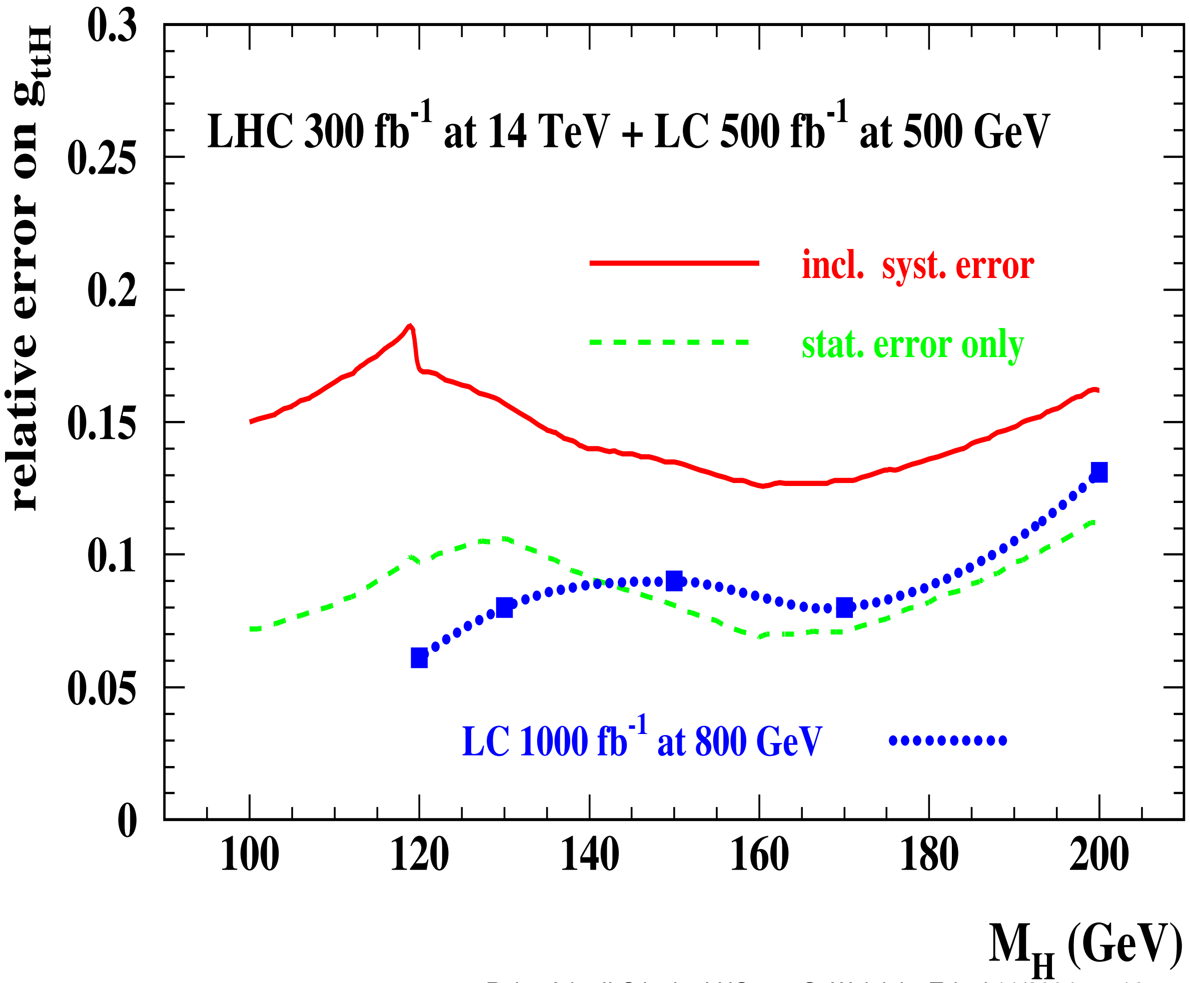
Higgs physics example: Measurement of the top Yukawa coupling at LHC $\oplus$ ILC

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

Precision measurement requires ILC with 800–1000 GeV

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

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



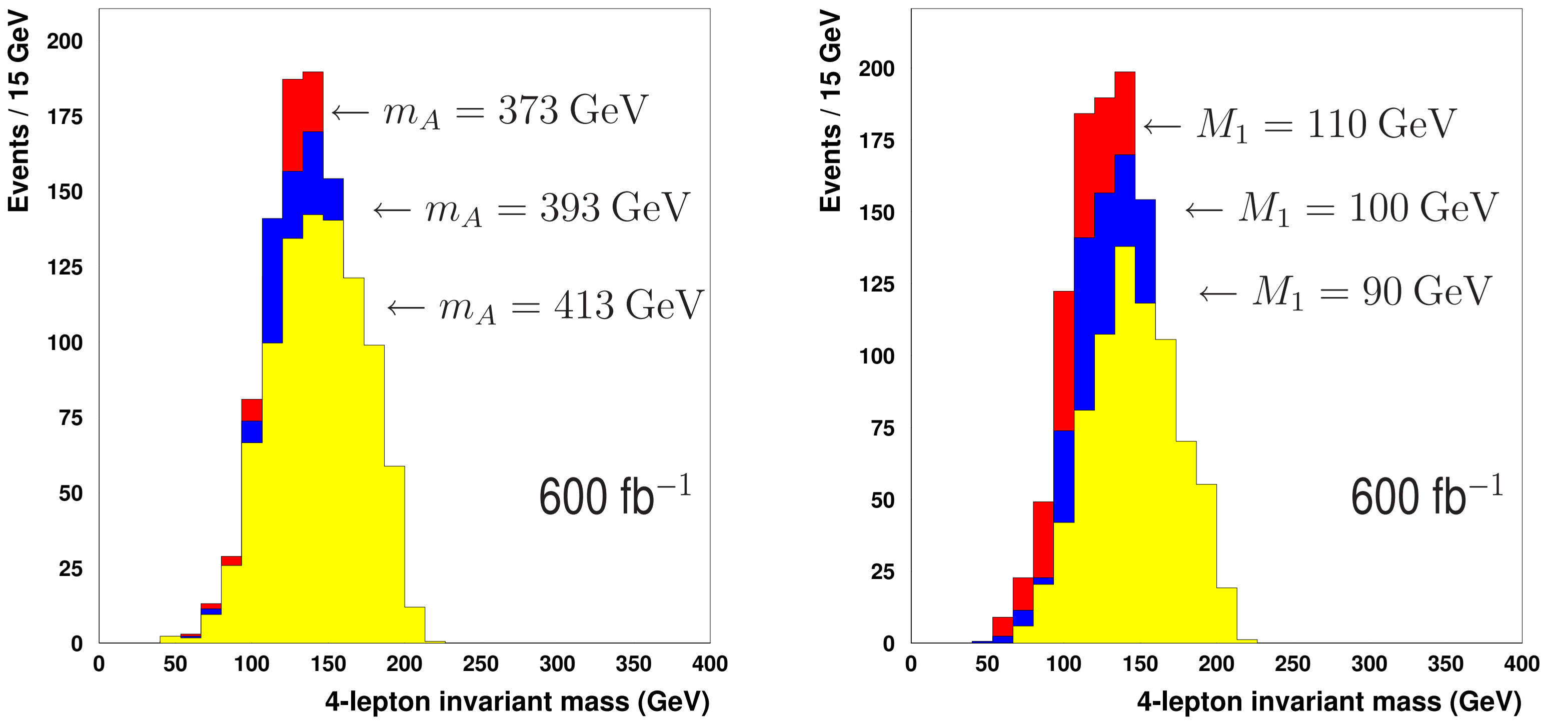
LHC $\oplus$ ILC (500 GeV):

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

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

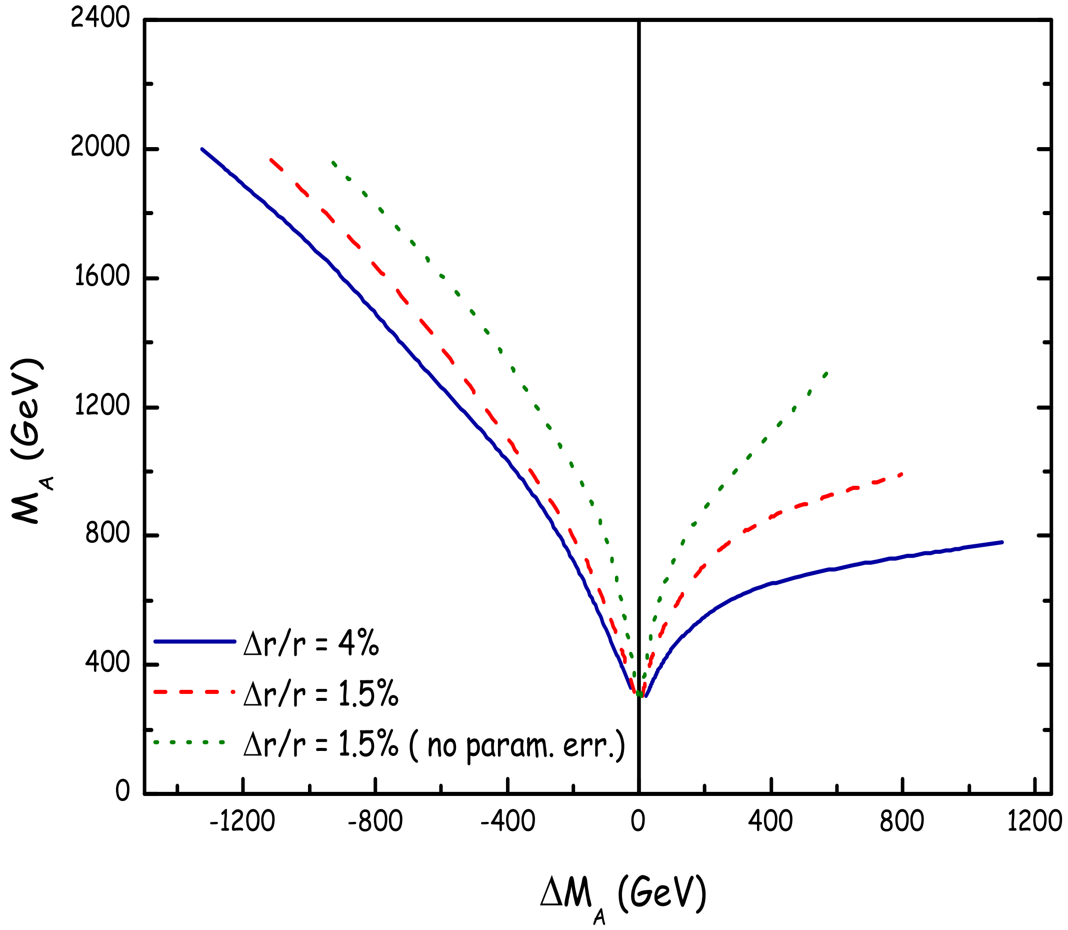
$$r \equiv \frac{[\mathrm{BR}(h \to b\bar{b})/\mathrm{BR}(h \to WW^*)]_{\mathrm{MSSM}}}{[\mathrm{BR}(h \to b\bar{b})/\mathrm{BR}(h \to WW^*)]_{\mathrm{SM}}}$$

at the ILC

and

LHC $+$ 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

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

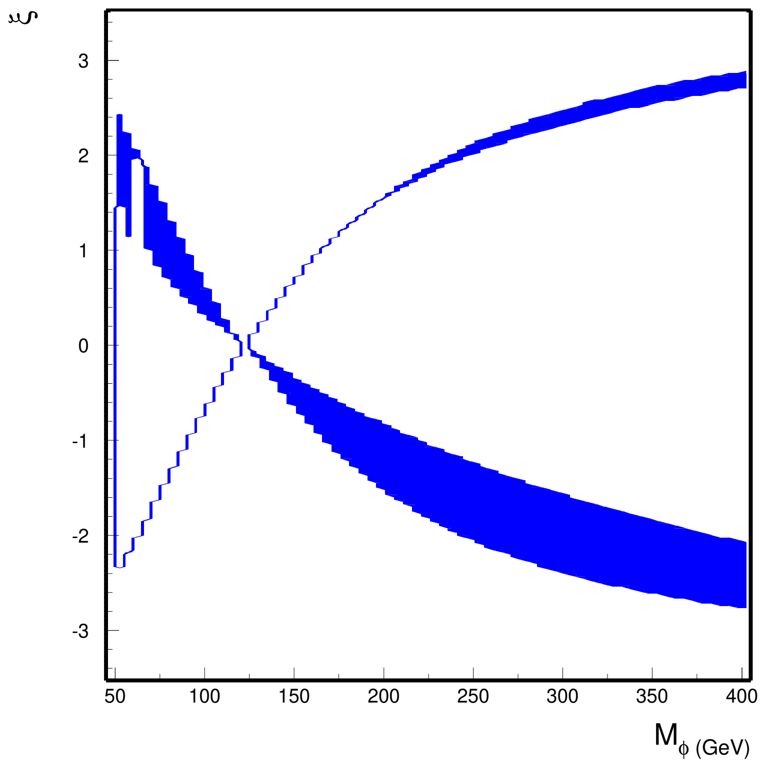
ILC guarantees Higgs observation over full parameter space

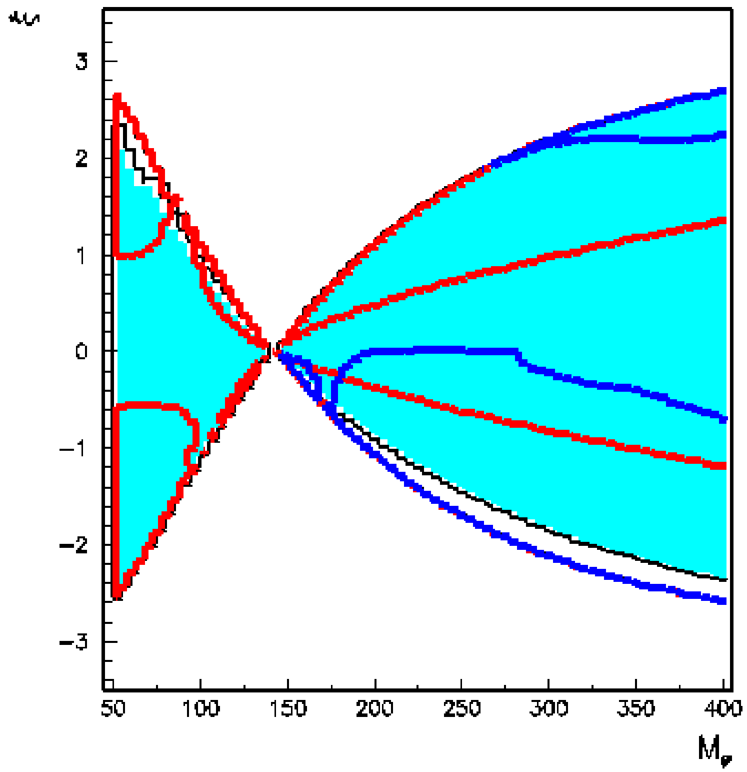
$\Rightarrow$ precision measurements at ILC crucial to disentangle the nature of the observed state

LHC: large sensitivity to production of Kaluza-Klein excitations

Higgs–radion mixing

Parameter regions where Higgs significance is below 5σ at the LHC with 30 fb^{-1} (left), regions where the precise measurements of the $hb\bar{b}$ and hWW couplings at the ILC provide $> 2.5\sigma$ evidence for the radion mixing effect (right):





SUSY example: "Telling the LHC where to look"

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

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

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

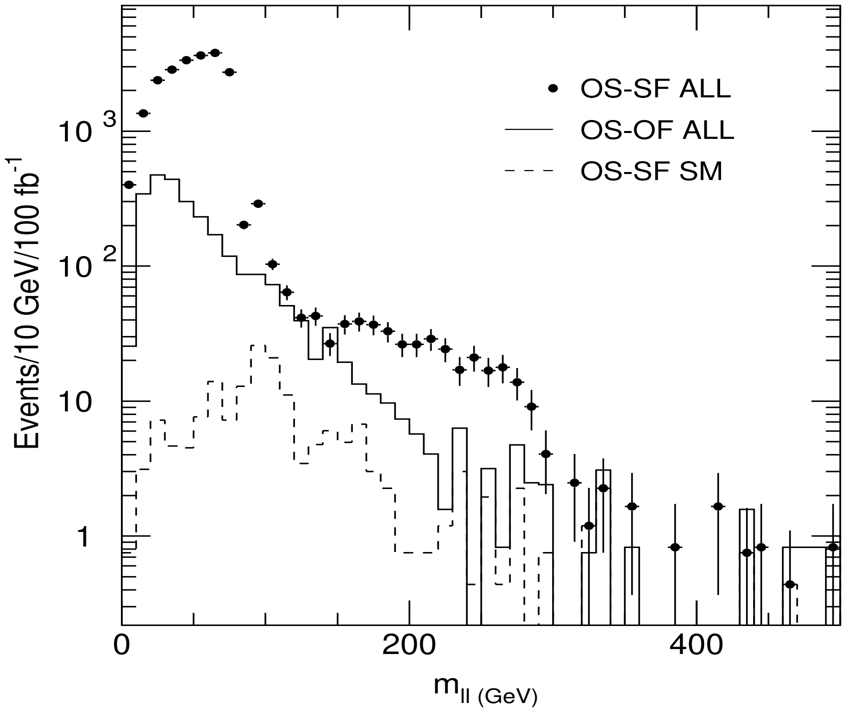
$\Rightarrow$ Prediction of masses, decay prop. of all neutralinos, charginos

$\Rightarrow$ Identification of particles produced in LHC decay chains

$\Rightarrow$ Prediction of particles which are produced with low statistics at the LHC, e.g. $m_{\tilde{\chi}_4^0} = 378.3 \pm 8.8$ 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



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

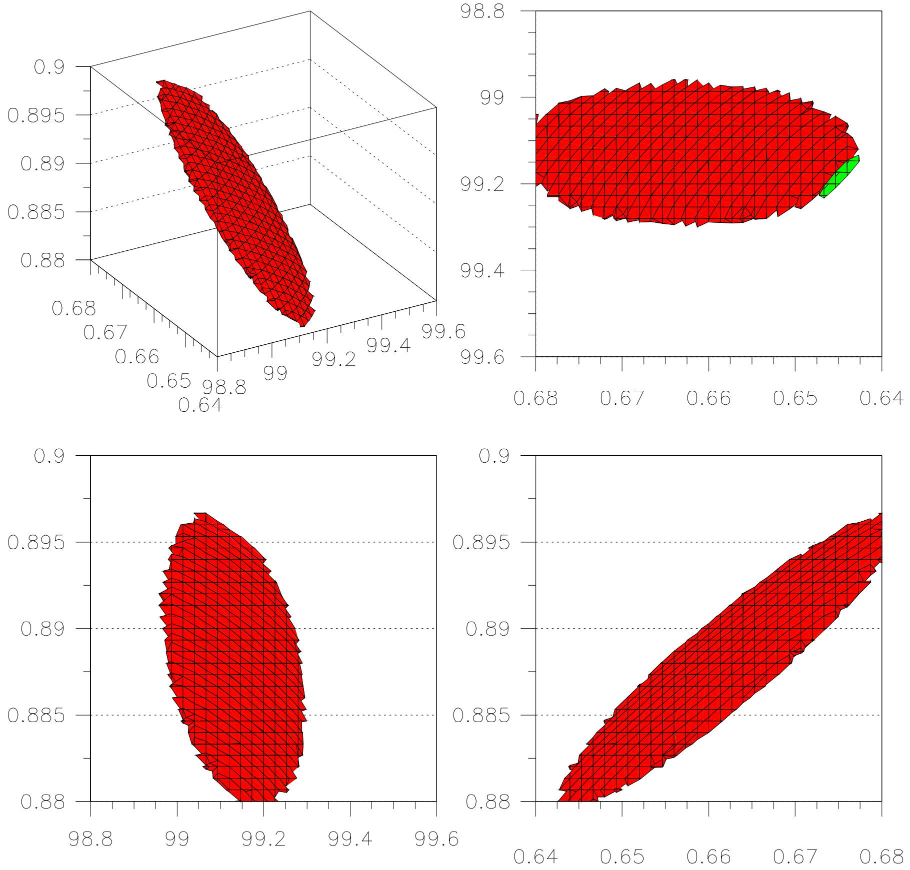
⇒ Feeding $m(\tilde{\chi}_4^0)$ back into ILC analysis provides additional information

⇒ Improved accuracy of parameter determination at ILC

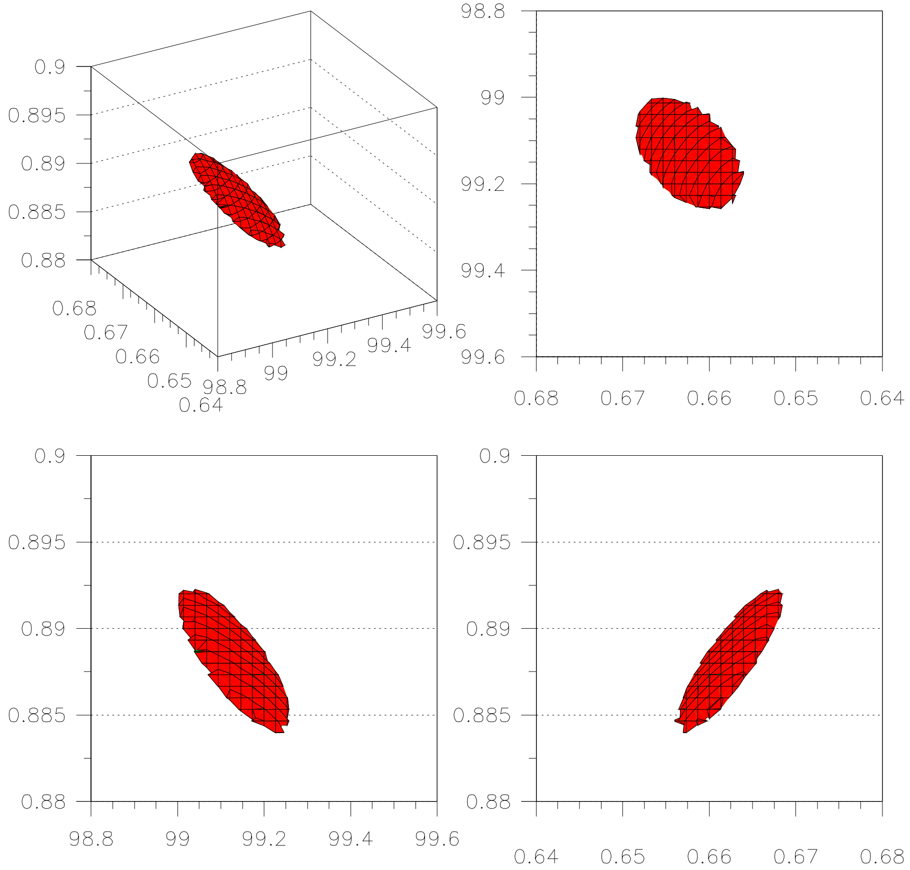
ILC analysis with LHC input

Determination of neutralino parameter M_1 and chargino mixing angles $\cos\phi_L$, $\cos\phi_R$:

ILC information alone



LHC + ILC information



LHC / ILC synergy

Search for heaviest neutralino at LHC is typical example for possible LHC / ILC synergy effects:

If statistically marginal signal appears at the LHC right where it was predicted from ILC information

$\Rightarrow$ ILC input can be crucial for optimised searches and possible upgrades at the LHC

- ILC prediction leads to increase of LHC statistical sensitivity!
- Improved selection criteria, modified triggers
- Call for higher luminosity
- ...

LHC / LC Study Group

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 / LC 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 just been completed: hep-ph/0410364
122 authors from 75 institutions, 472 pages

First LHC / LC 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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3. Conclusions

- Physics case for the ILC is well established, independently of what the LHC will find; need both the LHC and ILC in order to identify the nature of physics at the TeV scale
- LHC / ILC synergy extends physics potential of both machines; ILC results $\Rightarrow$ new questions to the LHC

  $\Rightarrow$ Improved experimental strategies, dedicated searches
- First LHC / LC Study Group report just released

  LHC / ILC interplay is a very rich field, we have only scratched the surface so far

  Need to build up framework for coherent LHC / ILC analyses to maximise physics benefit from both machines