Role of the ILC in the LHC era

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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: $\hat{s} = x_1 x_2 s$

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**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, . . .
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LHC and ILC have different capabilities, probe different aspects

⇒ 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: \( e^+ e^- \rightarrow ZH, \ Z \rightarrow e^+ e^-, \mu^+ \mu^- \)
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\[ \Rightarrow \text{Verification of Higgs mechanism in model-independent way} \]

\[ \text{distinction between different possible manifestations: extended Higgs sector, invisible decays, Higgs–radion mix., . . .} \]
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
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⇒ combination of LHC results with ILC data on cross-section rise essential for disentangling new states
Electroweak precision physics

ILC: precision measurement of

- $m_t$, $\sin^2 \theta_{\text{eff}}$: factor $\gtrsim 10$ improvement compared to LHC
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With LHC precision on $m_t$:

$\Rightarrow \delta m_t^{\text{exp}}$ will be dominant source of uncertainty in electroweak precision physics
Large coupling of Higgs to top quark

One-loop correction $\sim G_\mu m_t^4$

$\Rightarrow M_H$ depends sensitively on $m_t$ in all models where $M_H$ can be predicted
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SUSY as an example: $\Delta m_t \approx \pm 4 \text{ GeV} \Rightarrow \Delta m_h \approx \pm 4 \text{ GeV}$
**Precision Higgs physics**

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\[
H \stackrel{t}{\longrightarrow} H
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SUSY as an example: \( \Delta m_t \approx \pm 4 \) GeV \( \Rightarrow \Delta m_h \approx \pm 4 \) 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 $e^+ e^- \rightarrow f \bar{f}$, $\sin^2 \theta_{\text{eff}}$, $M_W$ 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:
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- 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?
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- 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.: $\tilde{g} \rightarrow \bar{q}q \rightarrow \bar{q}q\tilde{\chi}_2^0 \rightarrow \bar{q}q\tilde{\tau} \rightarrow \bar{q}q\tau\tilde{\chi}_1^0$

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good prospects for uncoloured particles
precision measurement of LSP mass (factor 100 improvement)
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’)

\[ m_0 = 100 \text{ GeV}, \quad m_{1/2} = 250 \text{ GeV}, \quad A_0 = -100 \text{ GeV}, \quad \tan \beta = 10, \quad \mu > 0 \]
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Most observables depend on variety of SUSY parameters
\[ \Rightarrow \text{Need global fit to large set of observables} \]

[R. Lafaye, T. Plehn, D. Zerwas ’04] [P. Bechtle, K. Desch, P. Wienemann ’04]
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⇒ 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:

\[ \text{LHC: interaction rate of } 10^9 \text{ events can trigger on only } 1 \times 10^7 \text{ events} \]

\[ \text{ILC: untriggered operation can detect signals of unexpected new physics (direct production + large indirect reach) that manifests itself in events that are not selected by the LHC trigger strategies} \]

LHC and ILC information will be needed in order to determine the nature of new physics.
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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

⇒ Need this information as soon as possible to identify the nature of new physics

If the two colliders run at the same time

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

⇒ Improved experimental strategies, dedicated searches
LEP + SLC + Tevatron led to many success stories:
SM at quantum level, top quark, prediction of Higgs mass
Interplay between lepton and hadron colliders: some examples from the past

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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 ⊕ ILC

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

Precision measurement requires ILC with 800–1000 GeV

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LHC measures ($\sigma \times BR$)

$\Rightarrow$ 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]

![Graph showing relative error on g with respect to MH (GeV)](image-url)
Determination of $M_A$ from heavy Higgs decays into SUSY particles at the LHC

[F. Moortgat ’04]

$H, A \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0$: Four lepton invariant mass distribution for $M_A = 393 \pm 20$ 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

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

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]

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LHC: large sensitivity to production of Kaluza-Klein excitations
Parameter regions where Higgs significance is below $5\sigma$ at the LHC with 30 fb$^{-1}$ (left), regions where the precise measurements of the $h\bar{b}b$ 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]

⇒ Determination of all parameters in neutralino/chargino sector

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⇒ With this information the heaviest neutralino can be identified at the LHC using a dilepton “edge”
Search for the heaviest neutralino at LHC following the prediction from ILC

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

Role of the ILC in the LHC era, G. Weiglein, Taipei 11/2004 – p.23
LHC / ILC synergy

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- Improved selection criteria, modified triggers
- Call for higher luminosity
- ...
Exploring physics gain from LHC / ILC interplay requires:

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

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.
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Editors:


Working group members who have contributed to this report:


3. Conclusions

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LHC / ILC synergy extends physics potential of both machines; ILC results ⇒ new questions to the LHC ⇒ 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.