Beyond the Standard Model

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BSM physics at the LC: different aspects

Phenomena of new physics discovered at the LHC will be probed at the LC with high precision and in a different experimental environment:

Identification of the nature of new physics
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Direct discovery of new phenomena beyond the scope of the LHC


**BSM physics at the LC: different aspects**

- Phenomena of new physics discovered at the LHC will be probed at the LC with high precision and in a different experimental environment:
  - Identification of the nature of new physics
- Direct discovery of new phenomena beyond the scope of the LHC
- Sensitivity to effects of new physics via high-precision measurements at the LC:
  - Electroweak precision observables, top physics, gauge sector, high-precision measurements in the Higgs and / or new-physics sector
Electroweak symmetry breaking

Discrimination between different kinds of underlying physics via precision measurements of Higgs couplings

⇒ Measurement of Higgs couplings with LC precision allows distinction between different models

LC potential for detecting invisible Higgs decays and decays that are undetectable at the LHC, total Higgs width

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Higgs couplings, triple gauge-boson couplings, high-precision measurements

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GigaZ: high precision measurement of electroweak mixing angle can reveal impact of new physics even in a “worst case” scenario where no new particles are observed at the LHC and the first phase of a LC
GigaZ: sensitivity to the scale of SUSY in a scenario where no SUSY particles are observed at the LHC

[S. Heinemeyer, W. Hollik, A.M. Weber, G. W. ’07]

⇒ GigaZ measurement provides sensitivity to SUSY scale, extends the direct search reach of LC500
**Fundamental or composite Higgs?**

Renewed interest in composite Higgs models, mostly from extra dimensions

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Relation extra dimensions $\Leftrightarrow$ new strong forces?
Correspondence (AdS/CFT):
Warped gravity model $\Leftrightarrow$ Technicolour-like theory in 4D
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Signatures at LHC: new resonances, $W'$, $Z'$, $t'$, KK excitations

Under pressure from electroweak precision tests
Strongly-Interacting Light Higgs: deviation of \( \sigma \times BR \) from the case of a SM Higgs

Sensitivity at LHC: 20–40%, LC: 1%

\( \Rightarrow \) LC500 can test scales up to \( \sim 30 \) TeV

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Strong electroweak symmetry breaking

Composite Higgs scenario is an example where in spite of a light Higgs-like state the gauge-boson sector is strongly interacting at high energies

⇒ Need precision measurement of Higgs couplings
+ test of gauge-boson sector

High-energy behaviour of gauge-boson sector can be probed at LC via $V_L V_L \rightarrow V_L V_L$, $V_L V_L \rightarrow H H$, $e^+ e^- \rightarrow VVV$, $e^+ e^- \rightarrow VV$, $e^+ e^- \rightarrow f \bar{f}$, ... processes

Sensitivity to heavy resonances
Electroweak symmetry breaking: LC discovery potential

- Discovery of non-SM like Higgs bosons:
  - Heavy SUSY Higgses, charged Higgs bosons
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- ... 

- Mixing of Higgs with radion, singlet scalar, ...

- ...
New physics: dark matter

LC: model-independent reconstruction of weakly interacting massive particle (WIMP) ⇔ dark matter candidate

Use WIMP production process where a photon is emitted in the initial state:

\[
\begin{align*}
e^+ & \rightarrow \gamma \rightarrow e^- \chi \bar{\chi} \\
e^- & \rightarrow \text{Reconstruct WIMP signal from the recoil mass distribution:}
\end{align*}
\]

\[
M_{\text{recoil}}^2 = s - 2\sqrt{s}E_{\gamma}
\]
Extra dimensions: production of KK gravitons

The signature with a photon + missing energy can also be a sign of extra dimensions via KK graviton production:

\[ e^+ e^- \rightarrow G_{KK} \gamma \]

Energy dependence of the cross section provides information about the number of extra dimensions.
New physics: pair production

LHC is sensitive mainly to the production of coloured states of new physics

Example: SUSY searches at the LHC

- Bounds on $\tilde{g}$ and $\tilde{q}$ of first two generations: $\mathcal{O}(\text{TeV})$
- Reduced sensitivity to compressed spectra
- Limited sensitivity to 3rd generation squarks
- Main sensitivity to colour-neutral particles from cascade decays of coloured particles
- Hardly any direct constraints on colour neutral SUSY particles up to now

LC has high sensitivity to production of colour–neutral states of new physics $\Rightarrow$ Complementarity of LHC and LC
LHC / LC complementarity

The results of LHC and LC will be highly complementary

**LHC:** large search reach for new heavy states, in particular strongly interacting new particles

**LC:** direct production, in particular colour-neutral new particles
  ⊕ high sensitivity to effects of new physics via precision measurements

LHC / LC interplay

⇒ enhanced physics gain
⇒ comprehensive picture of TeV scale physics
Linear Collider Physics

Key features:

- Precisely known centre-of-mass energy of hard process
- Tunable centre-of-mass energy
- Polarised beams: *longitudinal* and *transverse* ⇒ observables that are sensitive to new physics, enhancement of signal over background
- Clean, fully reconstructable events (also for hadronic final states), final state polarisation can be determined
- Moderate backgrounds ⇒ no trigger ⇒ unbiased physics
  
  . . .
Production of SUSY particles at the LC

Tunable energy ⇒ can run directly at threshold

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

\[ \frac{\Delta m_{\tilde{\mu}_R}}{m_{\tilde{\mu}_R}} < 1 \times 10^{-3} \]

⇒ test of $J = 0$ hypothesis

Furthermore: determination of quantum numbers, test of SUSY relations, information on SUSY breaking patterns, ...
Mass measurement from lepton energy spectra

$\sqrt{s} = 400 \text{ GeV} \quad \mathcal{L} = 200 \text{ fb}^{-1}$

$\mu^+ \mu^- E_{\text{miss}}$

$W^+ W^-$

$\chi^0 \chi^0$

$\mu_R \mu_R$

⇒ Mass determination at the per mille level
Determination of the nature of new physics

Example: SUSY

- Distinction of SUSY from other kinds of new physics, particle spins and quantum numbers, verification of SUSY predictions for couplings, mass relations, etc.

Example: determination of the chargino mixing angles \( \cos 2\phi_{L,R} \) from LC measurements with polarised beams and at different energies.

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**Determination of the nature of new physics**

Nature of the LSP, properties of dark matter candidate, prediction of relic density using LC input, …

- Minimal vs. non-minimal models, determination of the fundamental parameters, exploration of new sources of CP violation, probing the mechanism of SUSY breaking

- Reconstruction of the high-scale structure of the theory: test of unification, etc.
**New physics: resonances**

$Z', W', \ldots$: single particle produced in s channel

Example: LC determination of the leptonic $Z'$ couplings for a case where the mass of the $Z'$ is outside of the reach of LHC and LC. Comparison of the resolution for different models

$⇒$ High sensitivity for discriminating between different models
Sensitivity to contact interactions

LC500 with polarised beams:

\[ e^+ e^- \rightarrow \text{hadrons} \]

\[ e^+ e^- \rightarrow \mu^+ \mu^- \]

\[
\begin{array}{ccc}
\text{ee} & \Delta P/P=0.5\% & \Delta P/P=1.0\%\\
\text{ee} & \Delta \text{sys}=0.1\% & \Delta \text{sys}=0.5\% \\
\text{ee} & \Delta \text{sys}=0.5\% & \\
\text{LHC:} & L=100 \text{ fb}^{-1} & L=10 \text{ fb}^{-1} \\
\Delta \epsilon & \Delta \epsilon=4\% & \Delta \epsilon=15\% \\
\end{array}
\]

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\]

⇒ Sensitivity beyond LHC reach, up to scales of \( \mathcal{O}(100 \text{ TeV}) \)

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What is missing, what should be improved?

We are looking forward to your input!