Beyond the Standard Model

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BSM physics at the LC: different aspects

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

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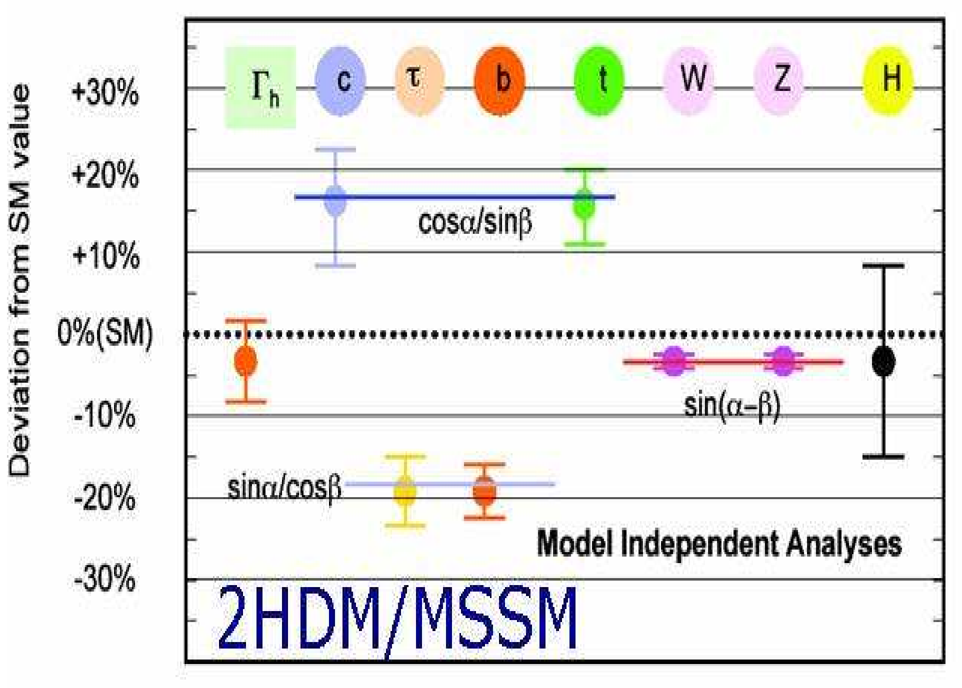
- Direct discovery of new phenomena beyond the scope of the LHC

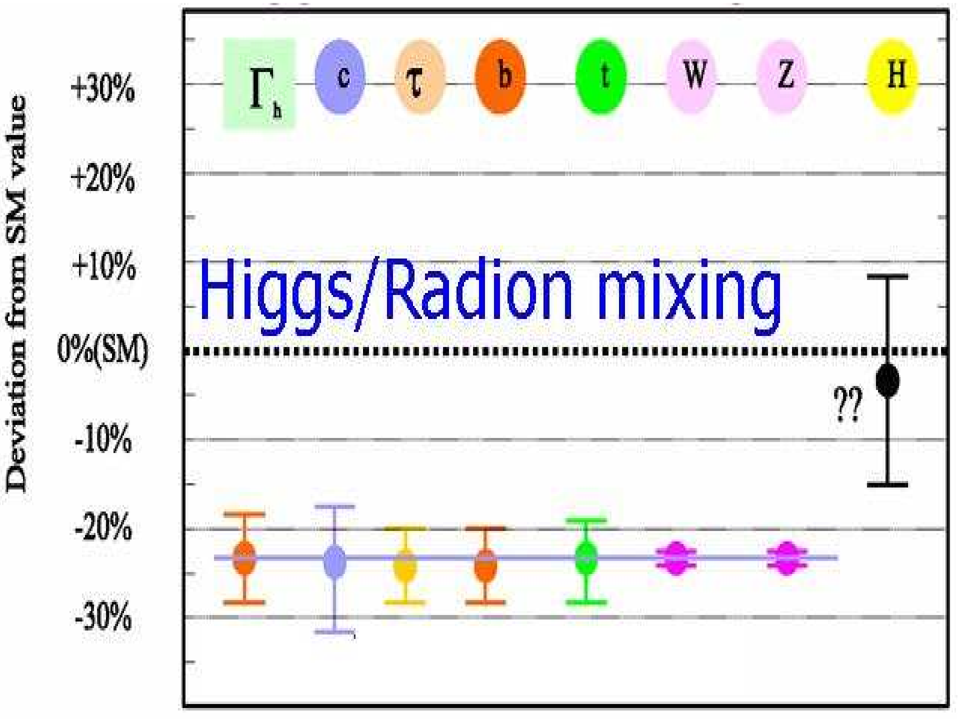
- Sensitivity to effects of new physics via high-precision measurements at the LC:

  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

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

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polarisation asymmetries, energy dependence, . . .

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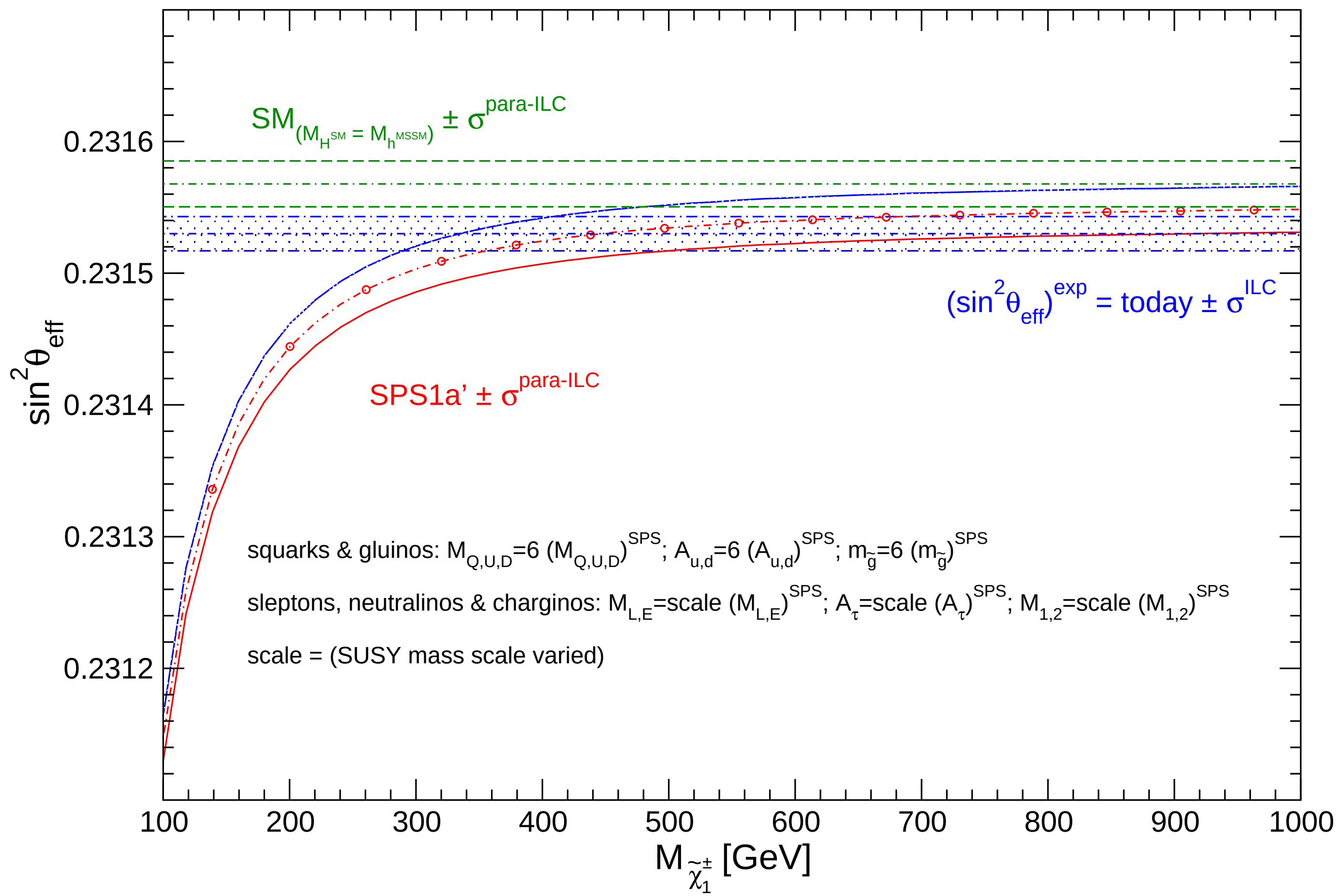
GigaZ: high precison measurement of electroweak mixing angle can reveal impact of new physics even in a “worst case” scenario where no new particles are observed at the LHC and the first phase of a LC

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?

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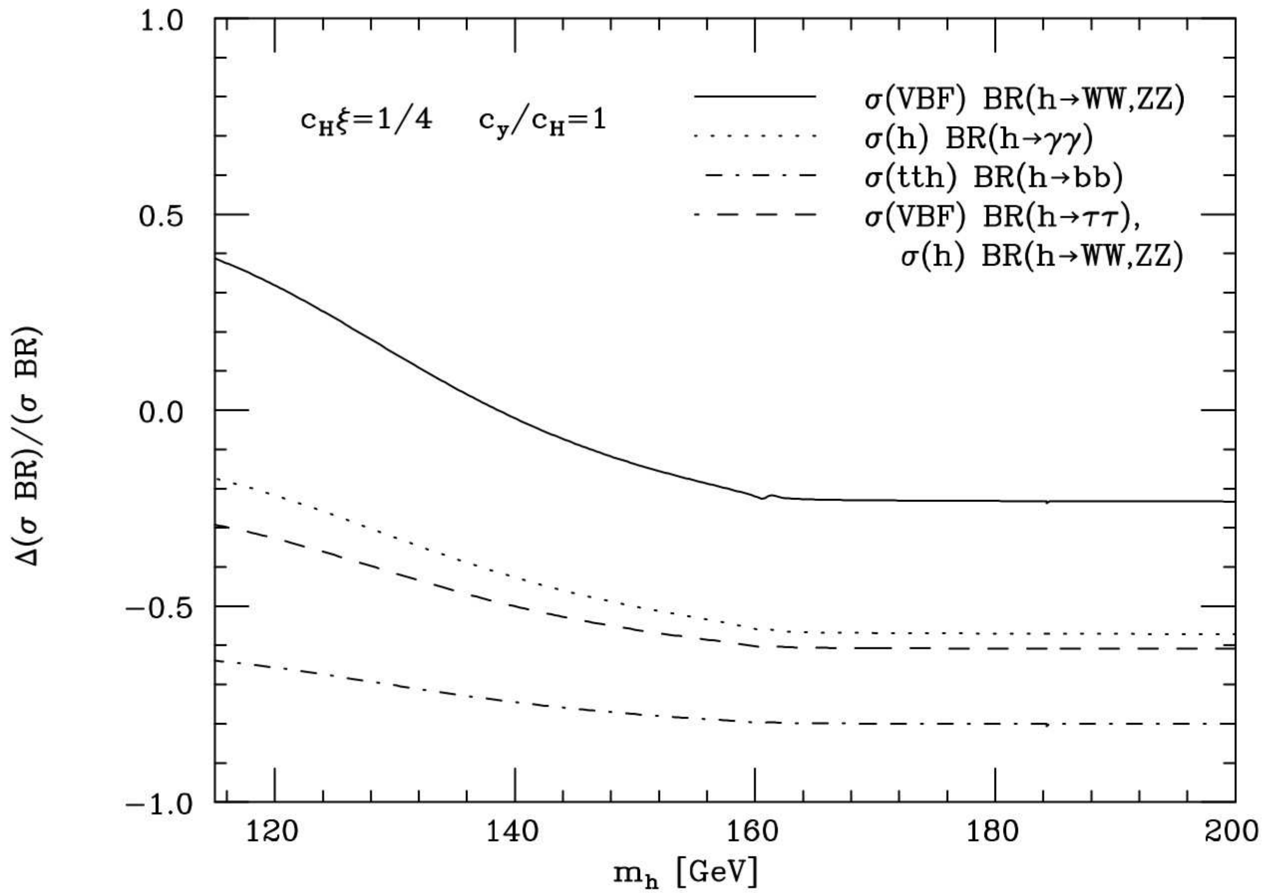
Signatures at LHC: new resonances, W', Z', t', KK excitations

Under pressure from electroweak precision tests

Strongly-Interacting Light Higgs: deviation of $\sigma \times \mathrm{BR}$ from the case of a SM Higgs



Sensitivity at LHC: 20–40%, LC: 1%

$\Rightarrow$ LC500 can test scales up to $\sim 30\ \mathrm{TeV}$

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

$\Rightarrow$ Need precision measurement of Higgs couplings
$+$ test of gauge-boson sector

High-energy behaviour of gauge-boson sector can be probed at LC via $V_L V_L \to V_L V_L$, $V_L V_L \to HH$, $e^+e^- \to VVV$, $e^+e^- \to VV$, $e^+e^- \to f\bar{f}$, . . . 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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    Example: the excess observed in the LHC Higgs searches at about $125\ \mathrm{GeV}$ would be compatible with the second-lightest Higgs of the MSSM or extensions of it

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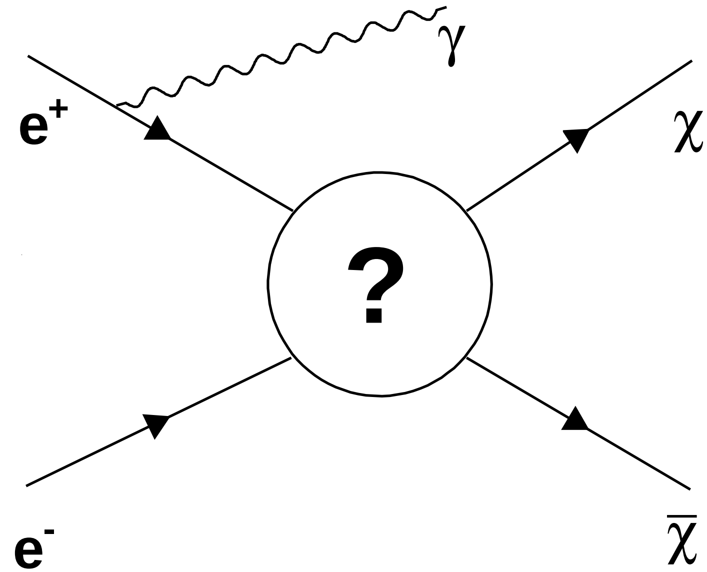
- Mixing of Higgs with radion, singlet scalar, ...
- ...

New physics: dark matter

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

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



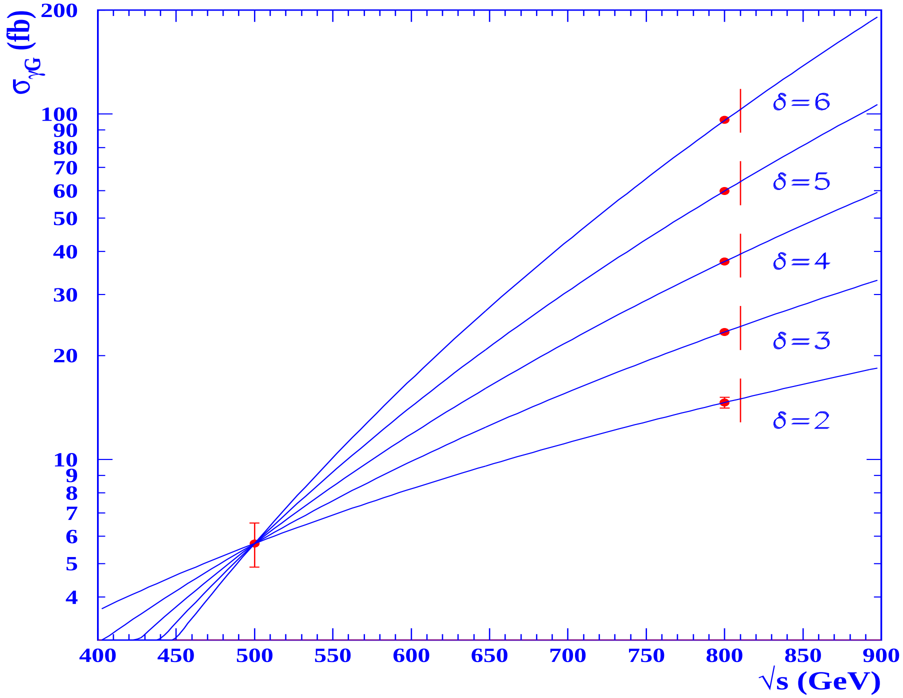
$\Rightarrow$ Reconstruct WIMP signal from the recoil mass distribution:
$M^2_{\mathrm{recoil}} = s - 2\sqrt{s}E_\gamma$

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:

$e^+e^- \to G_{\mathrm{KK}}\gamma$

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
$\oplus$ high sensitivity to effects of new physics via precision measurements

LHC / LC interplay

$\Rightarrow$ enhanced physics gain

$\Rightarrow$ comprehensive picture of TeV scale physics

Linear Collider Physics

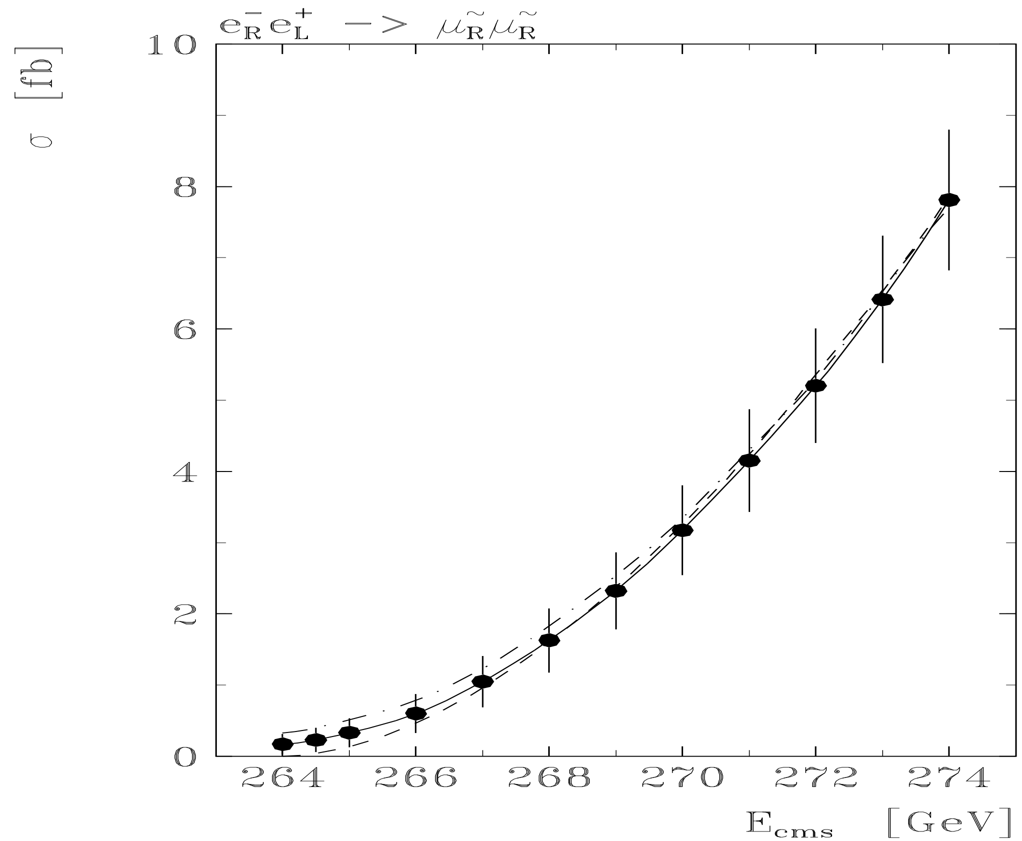
Key features:

- Precisely known centre-of-mass energy of hard process
- Tunable centre-of-mass energy
- Polarised beams: longitudinal and transverse
  $\Rightarrow$ 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 $\Rightarrow$ no trigger $\Rightarrow$ unbiased physics
- ...

Production of SUSY particles at the LC

Tunable energy $\Rightarrow$ can run directly at threshold

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

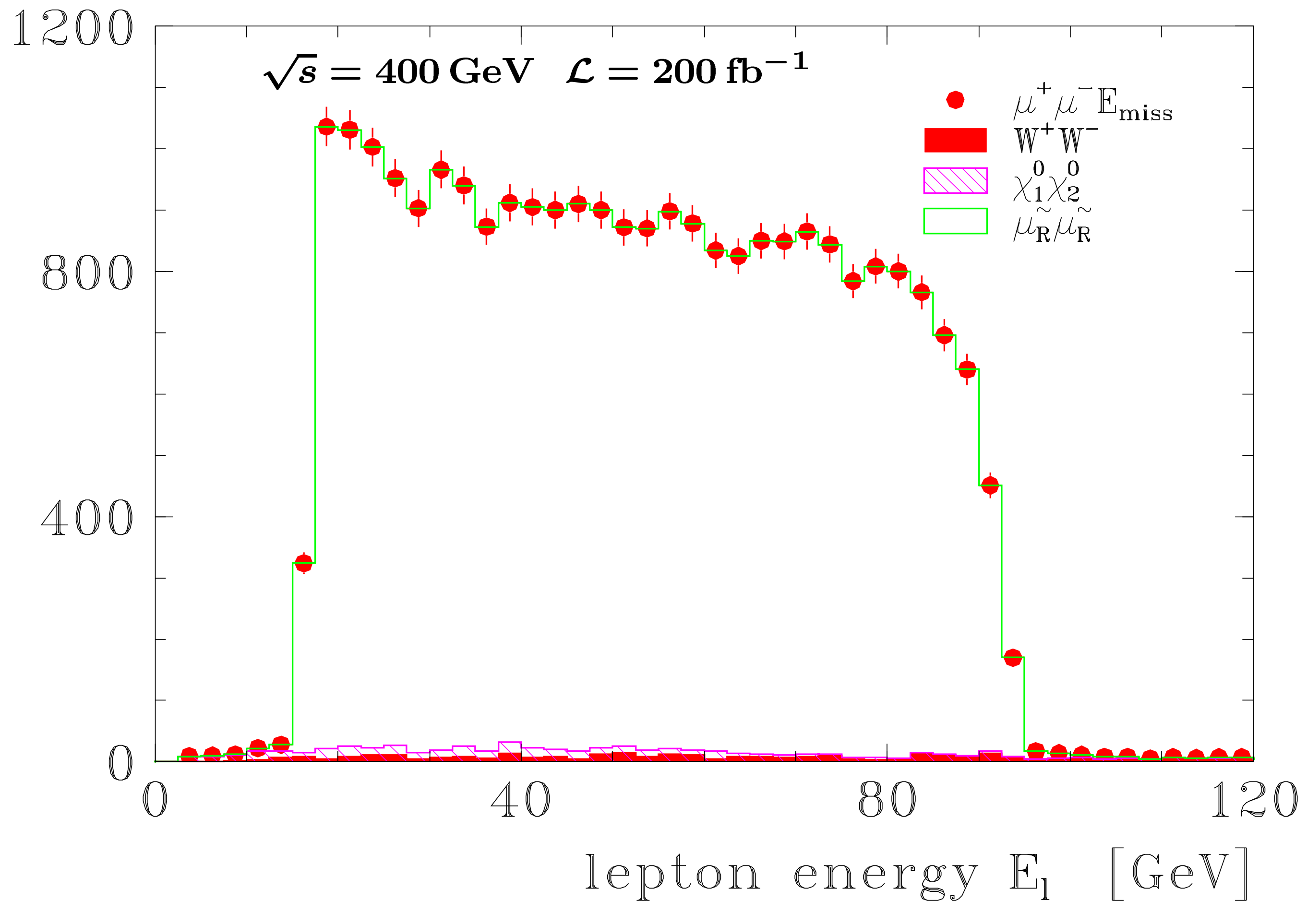


$$\Rightarrow \quad \frac{\Delta m_{\tilde{\mu}_R}}{m_{\tilde{\mu}_R}} < 1 \times 10^{-3}$$

$\Rightarrow$ 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



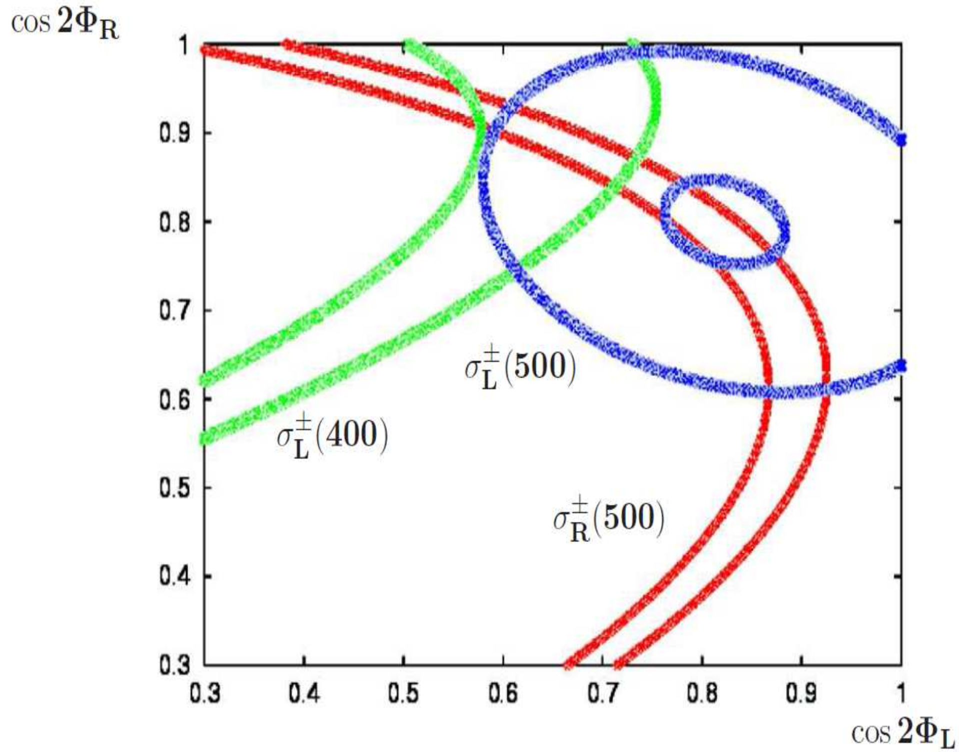
⇒ Mass determination at the per mille level

Determination of the nature of new physics

Example: SUSY

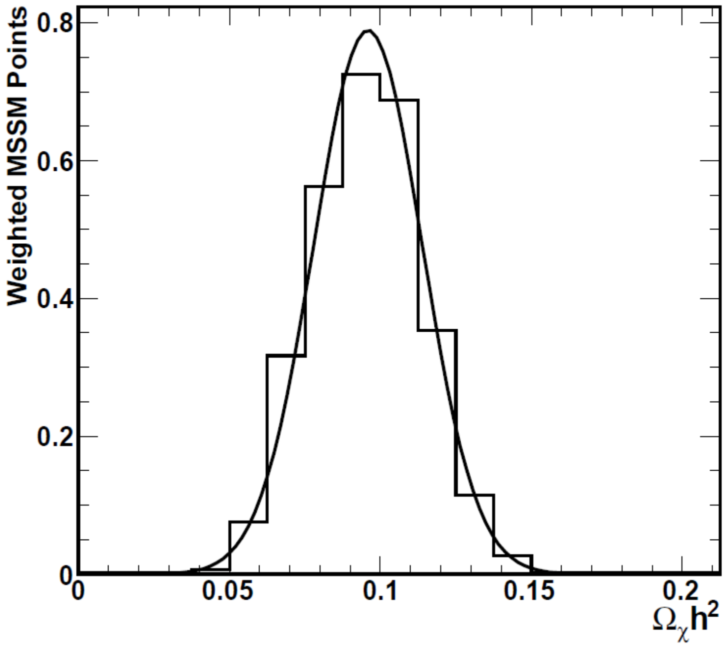
- Distinction of SUSY from other kinds of new physics, particle spins and quantum numbers, verification of SUSY predictions for couplings, mass relations, etc.

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



Determination of the nature of new physics

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



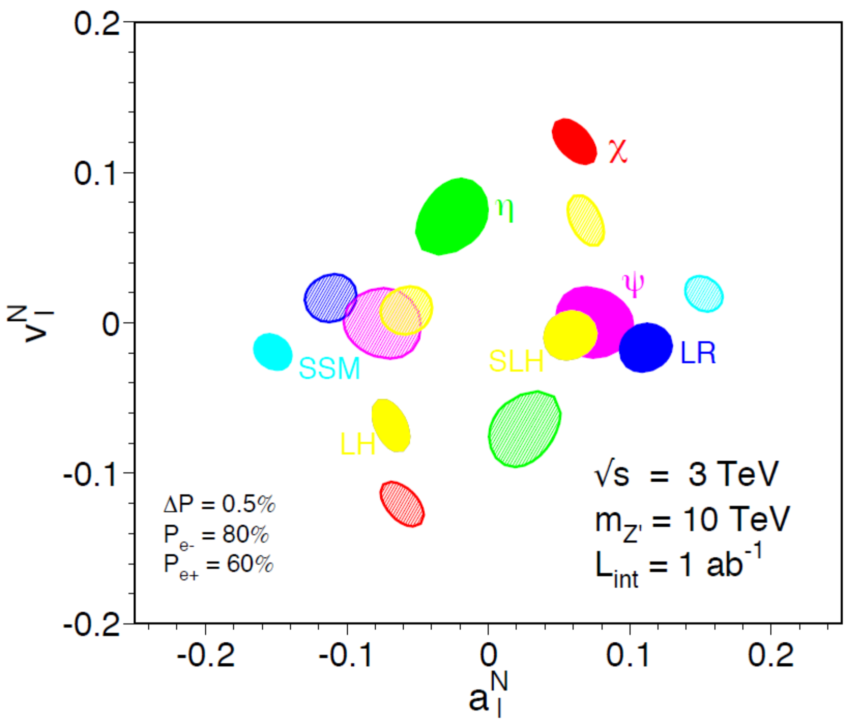
- Minimal vs. non-minimal models, determination of the fundamental parameters, exploration of new sources of $\mathcal{CP}$ violation, probing the mechanism of SUSY breaking

- 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

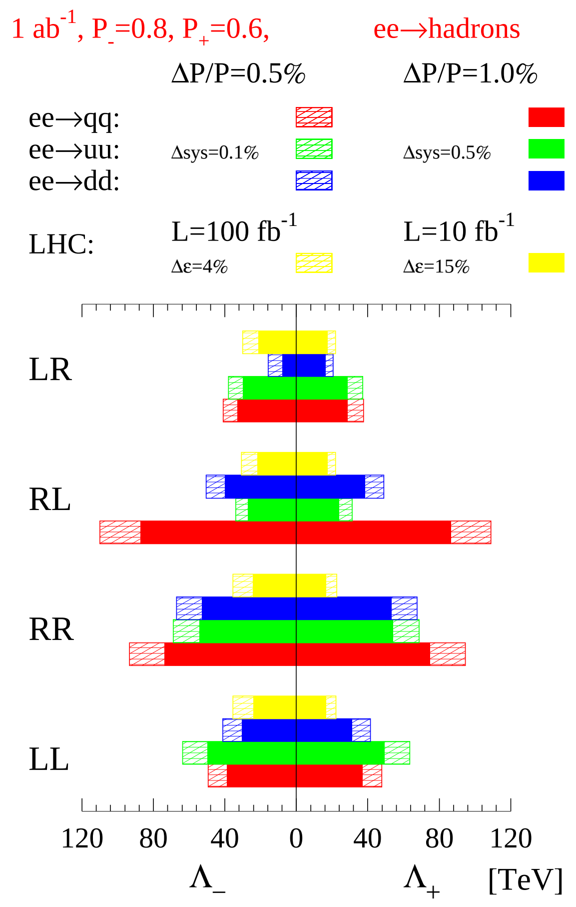


⇒ High sensitivity for discriminating between different models

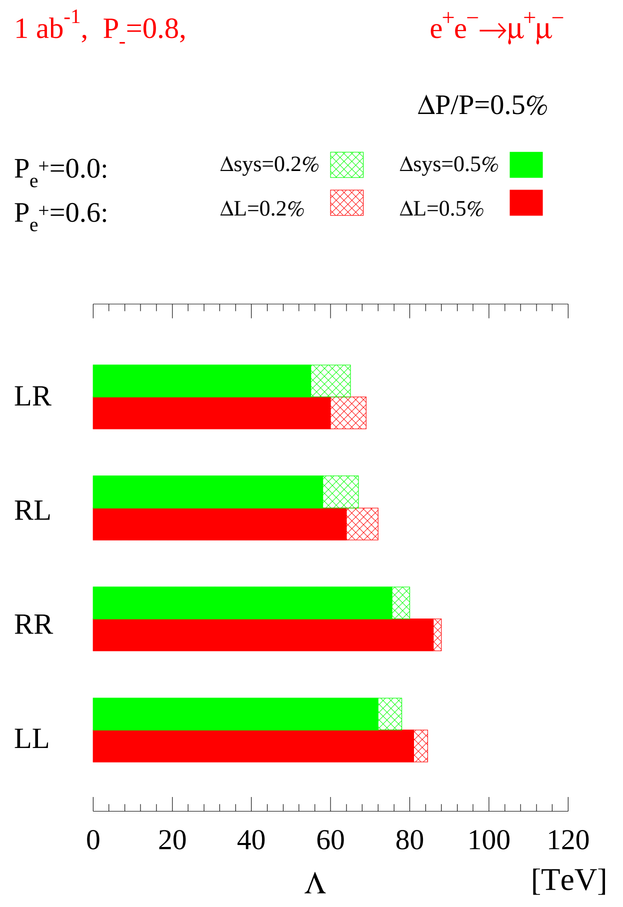
Sensitivity to contact interactions

LC500 with polarised beams:

$e^+e^- \to$ hadrons



$e^+e^- \to \mu^+\mu^-$



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

What is missing, what should be improved?

We are looking forward to your input!