The physics goals of the TESLA project

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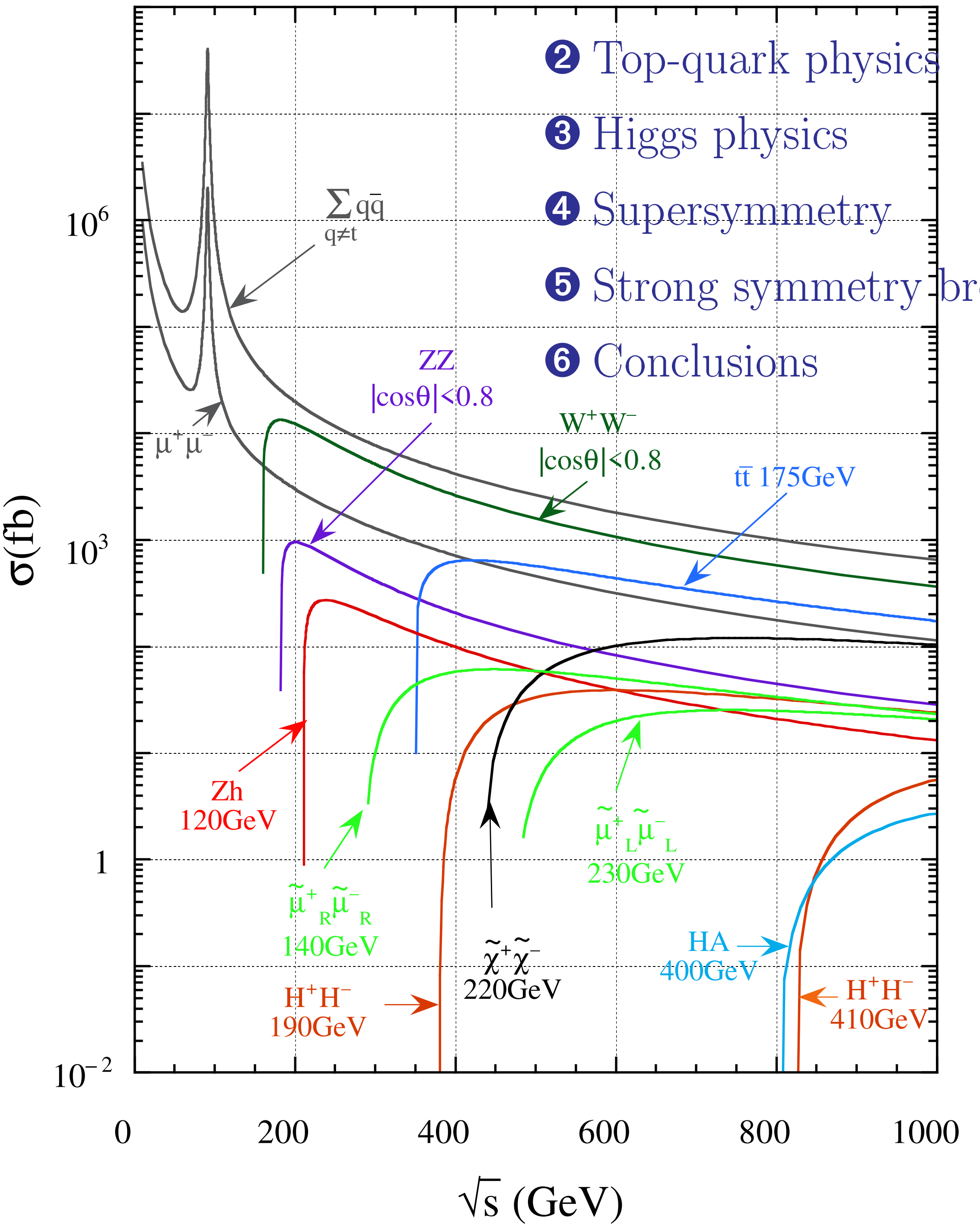


❶ Introduction

Most important question at the next generation high energy colliders:

How is the electroweak symmetry broken?

Possible scenarios

1. Masses are generated by a light Higgs
   (a) The SM is the final theory (very unlikely)
   (b) The world is supersymmetric
   (c) The gauge group is larger than $SU(3) \times SU(2) \times U(1)$
   (d) There are more than three space dimensions
2. The Higgs mechanism is mimicked by a new strong interaction

- In all cases it is likely that the LHC will see first signals of the mechanism at work
- However also in all cases one needs complementary information from a lepton collider to understand the underlying theory

Currently three designs for next generation e^+e^- linear colliders are (almost) ready:

- TESLA (Europe)
- NLC (USA)
- JLC (Asia (Japan))

All three designs:

- cover the energy range up to $\sim 1\,\mathrm{TeV}$
- could be ready ≥ 2010

This talk concentrates on TESLA:

- superconducting cavities
- energy range: 1st stage: $\sqrt{s} \leq 500\,\mathrm{GeV}$
  2nd stage: $\sqrt{s} \sim 1\,\mathrm{TeV}$

- Luminosity: $50(91\,\mathrm{GeV})-500(800\,\mathrm{GeV})\,\mathrm{fb}^{-1}/\mathrm{year}$
- electron polarisation $\sim 80\%$
- positron polarisation of $40-60\%$ possible
- TESLA can also be used as a $\gamma\gamma$-collider

Expected event rates with the TESLA luminosity:

- few$\cdot 10^4$ $e^+e^- \rightarrow HZ$/year
  at $\sqrt{s} \approx 350\,\mathrm{GeV}$ $(m_\mathrm{H} \approx 120\,\mathrm{GeV})$

- 10^5 $e^+e^- \rightarrow t\bar{t}$/year
  at $\sqrt{s} \approx 350\,\mathrm{GeV}$

- $5 \cdot 10^5$ $e^+e^- \rightarrow q\bar{q}$/year
  at $\sqrt{s} \approx 500\,\mathrm{GeV}$ (no rad. ret)

- 10^5 $e^+e^- \rightarrow \mu^+\mu^-$/year
  at $\sqrt{s} \approx 500\,\mathrm{GeV}$ (no rad. ret)

- 10^6 $e^+e^- \rightarrow W^+W^-$/year
  at $\sqrt{s} = 500 - 1000\,\mathrm{GeV}$

- 10^9 $e^+e^- \rightarrow Z$/year
  at $\sqrt{s} \approx 91\,\mathrm{GeV}$

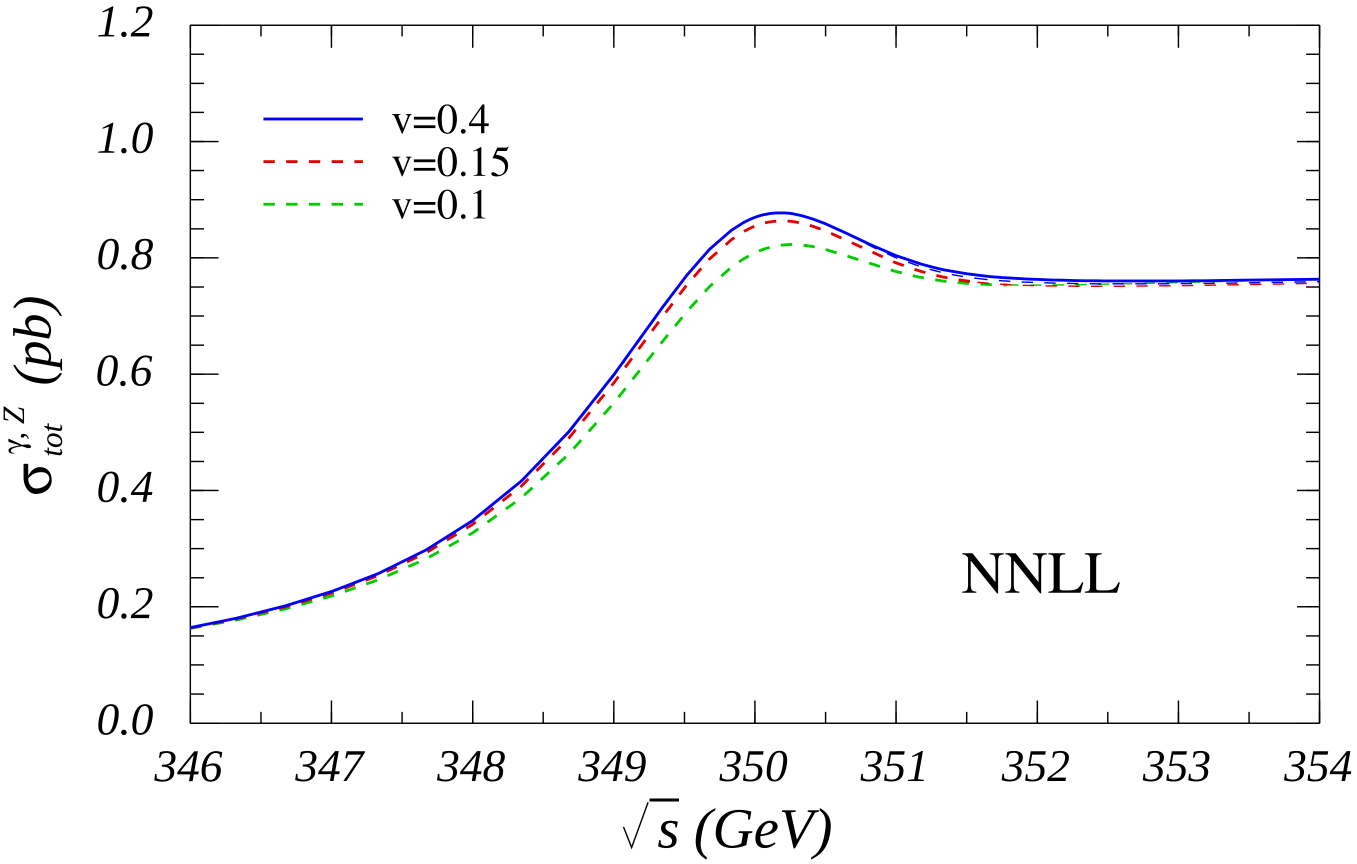
❷ Top quark physics

Why?

- $m_\mathrm{t} \sim v$ might not be a pure accident
- a future theory of flavour might call for precise measurements in the quark sector
- in precision tests of the SM m_t enters quadratically:
  - $\Delta m_\mathrm{W} / \Delta m_\mathrm{t} = 0.006$
    ultimately: $\Delta m_\mathrm{W} = 6\,\mathrm{MeV}$
  - $\Delta \sin^2\theta^\ell_\mathrm{eff} / \Delta m_\mathrm{t} = 0.00003/\,\mathrm{GeV}$
    ultimately: $\Delta \sin^2\theta^\ell_\mathrm{eff} = 0.00002$

  $\Rightarrow$ need $\Delta m_\mathrm{t} < 1\,\mathrm{GeV}$
- In SUSY models radiative corrections to light Higgs (h) mass: $\Delta m_h / \Delta m_\mathrm{t} \approx 1$
  $\Rightarrow$ aim for $\Delta m_\mathrm{t} \approx \Delta m_h \approx 50\,\mathrm{MeV}$

With the new mass definitions and the very recent NNLL calculations the peak position and the normalisation is under control now.



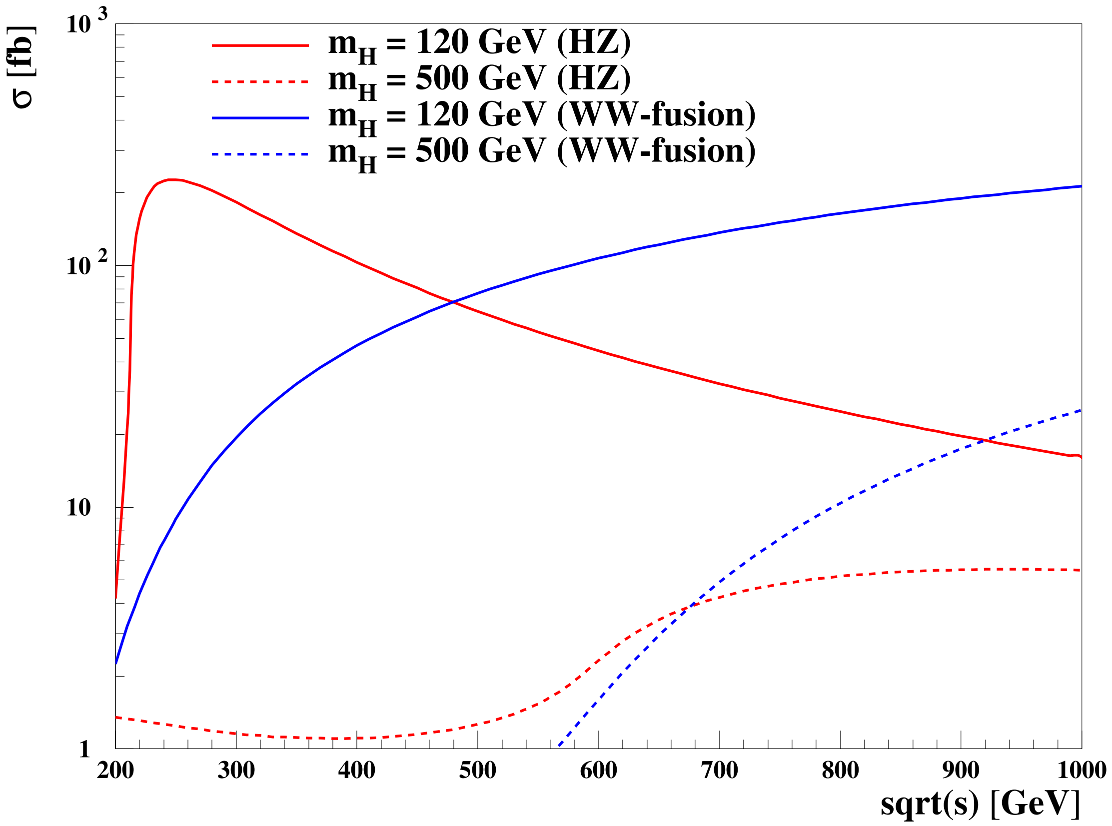
(v=top velocity parameter, should be > 0.15)

- $\Delta m_{\mathrm{t}}(\overline{\mathrm{MS}}) = \pm 50\,\mathrm{MeV}(\mathrm{exp}) \pm 100\,\mathrm{MeV}(\mathrm{theo})$ possible
- Γ_t might be measured to few % from shape and forward-backward asymmetry near threshold
- ttH Yukawa coupling might be measured to $\sim$ 30% from cross section normalisation

❸ Higgs Physics

- If a light Higgs exists it will almost certainly be discovered by the TEVATRON or the LHC
- A LC is needed to show that the discovered particle is really responsible for mass generation
- extended Higgs sectors like in the MSSM predict small deviations from the SM predictions that call for precision measurements

Cross section:



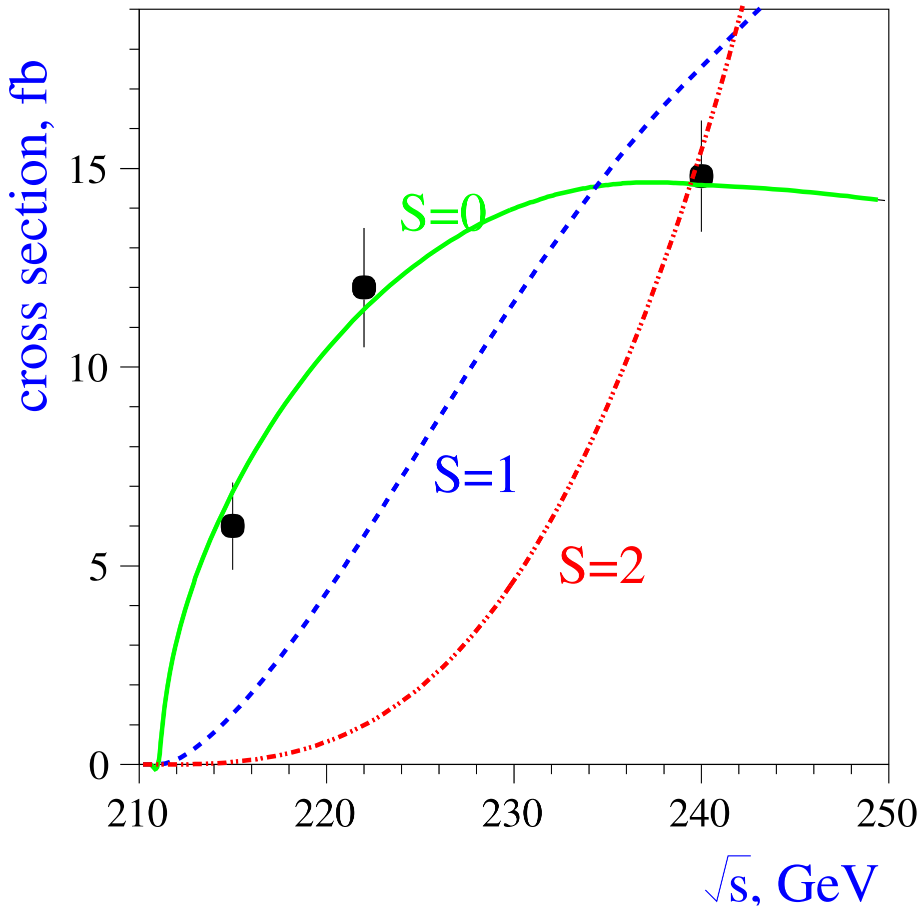
- Higgsstrahlung and W-fusion visible at TESLA
- $\sigma \sim 100(10)$ fb for $m_{\mathrm{H}} = 120(500)$ GeV

➧ few$\times 10^4(10^3)$ Higgses per year

Measurement of the H quantum numbers

After the H has been discovered it has to be proven that its quantum numbers are really 0^+

At the LC this can be done with a threshold scan of $e^+e^- \rightarrow ZH$:



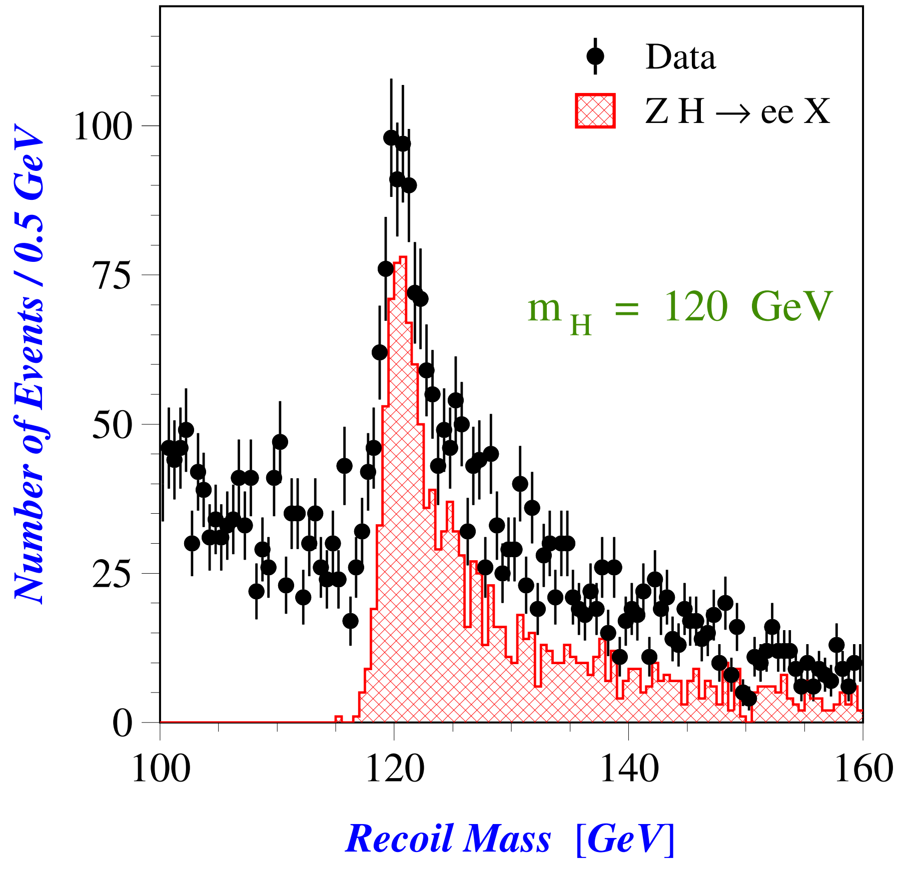
- Large sensitivity to the different states
- The few remaining ambiguities can be resolved from angular dependences and the observation of $H \rightarrow \gamma\gamma$
- Alternatively spin/parity can be measured in transverse/longitudinally polarised $\gamma\gamma$-collisions

Measurement of the $e^+e^- \to HZ$ cross section

Need a measurement of the total cross section $\sigma(e^+e^- \to HZ)$ independent of the H decay mode:

- $\sigma(e^+e^- \to HZ)$ measures $\Gamma(H \to ZZ)$
- absolute normalisation for H-branching ratio measurements

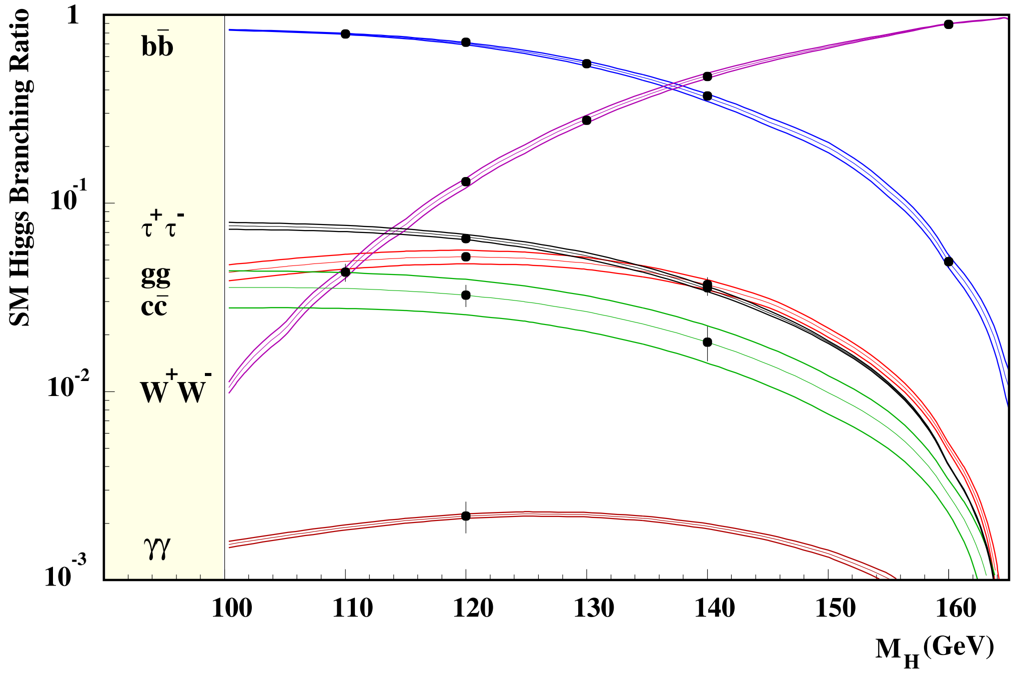
Can be done from $\ell\ell$ recoil mass in $e^+e^- \to ZH \to \ell\ell X$ events



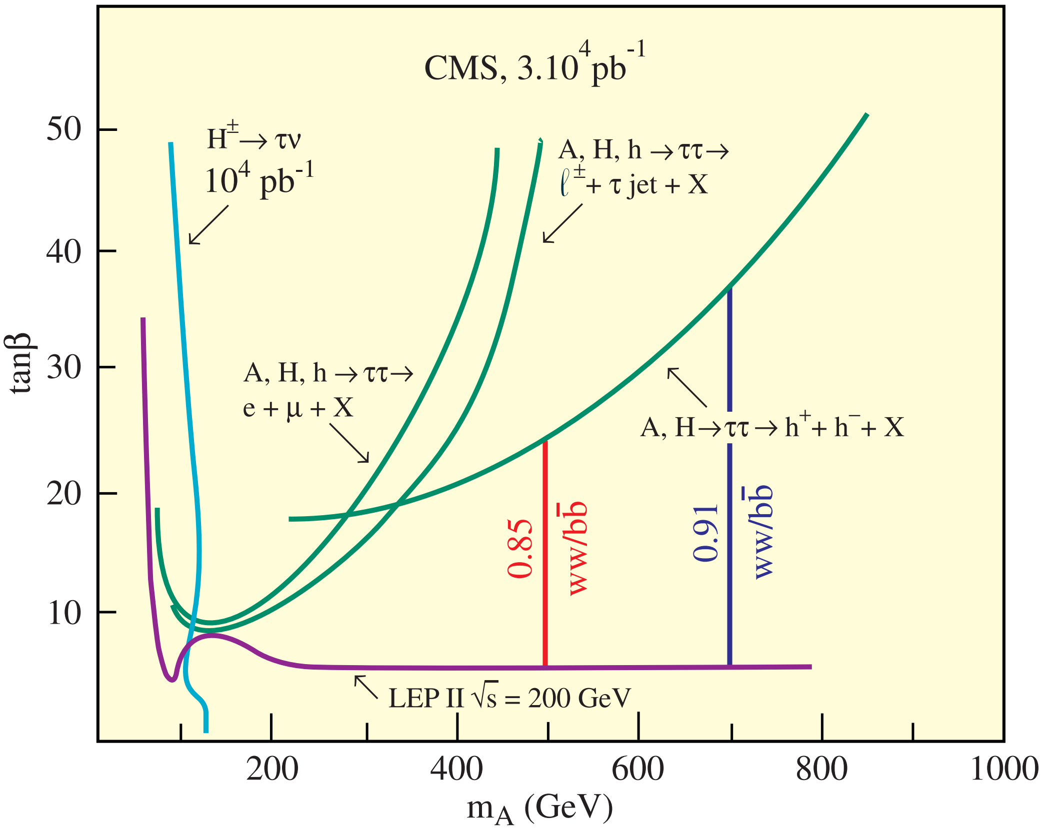
Expected precision: $\approx 2.5\%$

Measurement of the Higgs branching ratios

With the excellent b- and c-tagging capabilities all significant Higgs branching ratios can be measured

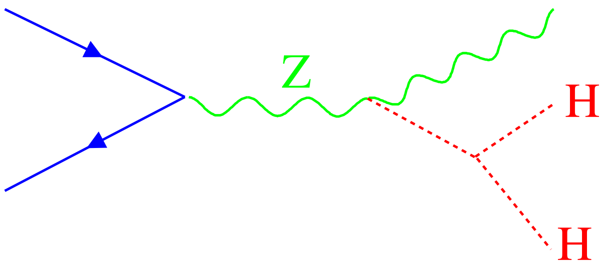


e.g. sensitive to m_A in MSSM



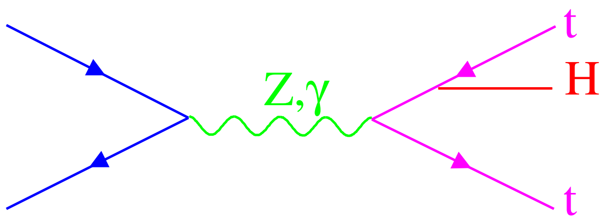
Other Higgs measurements

- Measurement of $\Gamma(H \to \gamma\gamma)$
  - $BR(H \to \gamma\gamma)$ can be measured with 10-15% accuracy if $m_{\mathrm{H}} < 120\,\mathrm{GeV}$
  - A photon collider might measure $\Gamma(H \to \gamma\gamma)$ to 3%
- Measurement of m_{H}
  with direct reconstruction techniques like for the W-mass at LEP $m_{\mathrm{H}} \approx 50\,\mathrm{MeV}$ is possible
- Measurement of the Higgs potential
  - SM Higgs potential $V(\Phi) = \lambda(\Phi^*\Phi - v^2/2)^2$, completely known once m_{H} is measured
  - trilinear Higgs coupling:
    $\lambda_{\mathrm{HHH}} = 3m_{\mathrm{H}}^2/m_{\mathrm{Z}}^2\lambda_0$, $\lambda_0 = m_{\mathrm{Z}}^2/v$
  - can be measured from $\mathrm{e}^+\mathrm{e}^- \to ZHH$

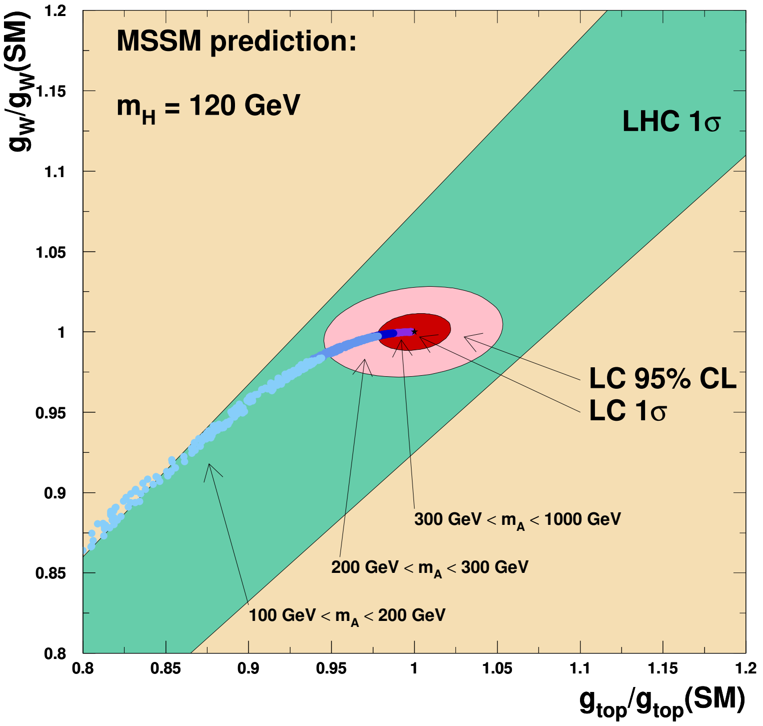


  - difficult analysis that requires high luminosity at $\sqrt{s} = 500\,\mathrm{GeV}$, excellent b-tagging and excellent energy flow ($\sigma(ZHH) \approx 0.5\,\mathrm{fb}$)
  - $\Delta\lambda/\lambda \sim 20\%$ within reach

- the total Higgs width
  - Already seen $BR(H \to WW) = \Gamma_{WW}/\Gamma_{\mathrm{tot}}$ known to $\sim 5\%$
  - can measure $\sigma(H \to WW) \propto \Gamma_{WW}$ to few %
  - ➟ Γ_{tot} can be measured to $\sim 5\%$
- the $\mathrm{Ht\bar{t}}$-Yukawa coupling
  - can be measured from $\mathrm{t\bar{t}H}$- events



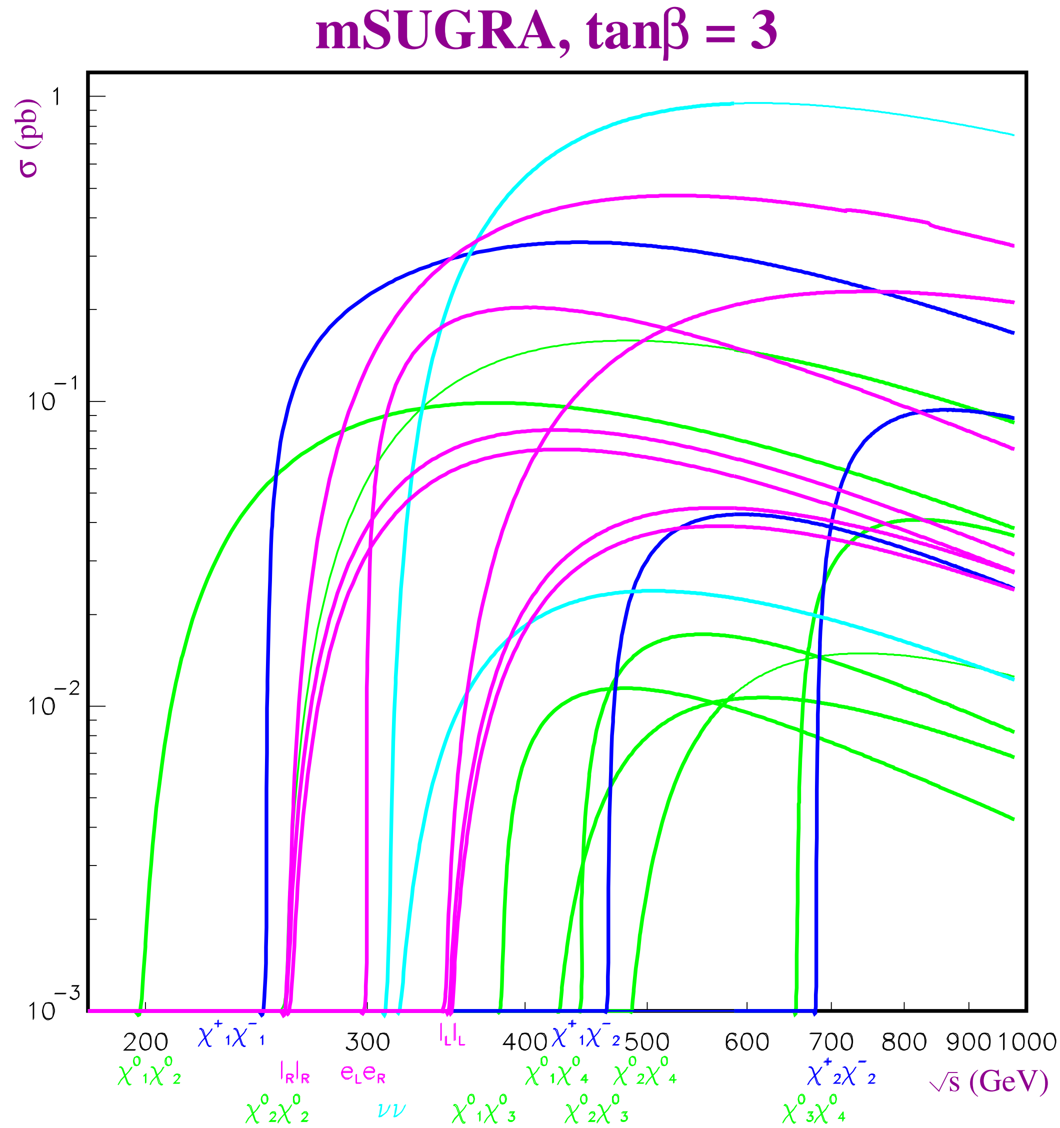
  - need $\sqrt{s} = 800\,\mathrm{GeV}$
  - again high requirements on b-tagging and background suppression ($\sigma(\mathrm{t\bar{t}}H) \approx 2.5\,\mathrm{fb}$)
  - 5% precision possible



❹ Supersymmetry

Possible accessible signals

(after some parameter optimisation)



- all channels have cross sections $\sim 10 - 1000\,\mathrm{fb}$
- all channels have visible decays of at least 50%

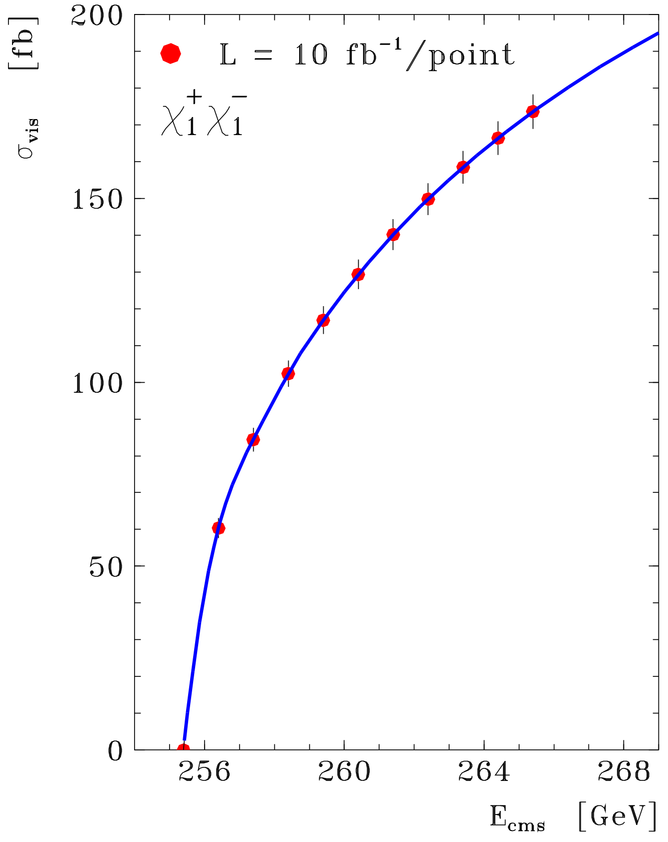
Mass measurements

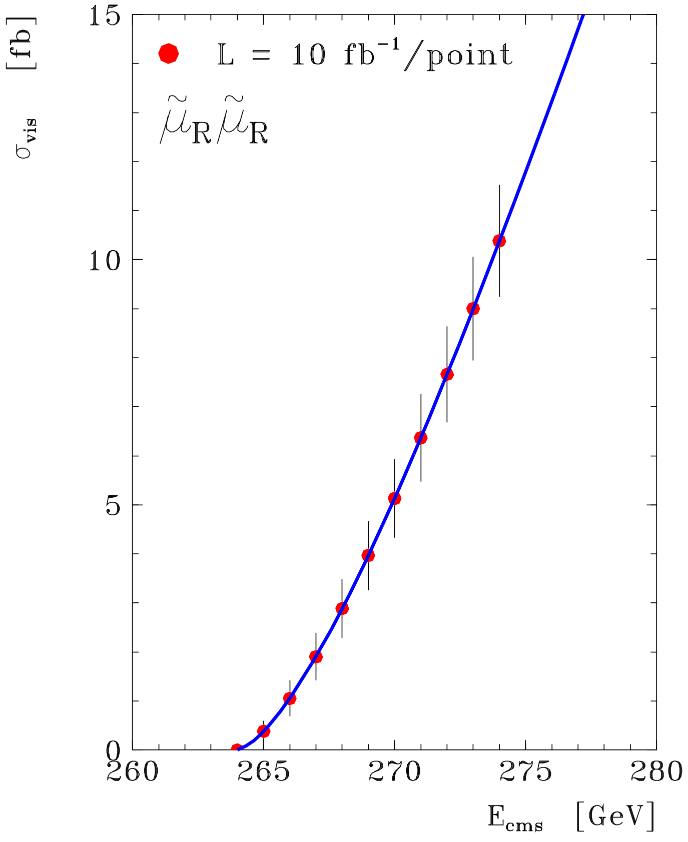
Two principle methods:

- threshold scan
- reconstruction

Threshold scan:

- gauginos: threshold suppression $\propto \beta$
  $\Rightarrow$ good precision ($< 0.05\%$)
- sfermions: threshold suppression $\propto \beta^3$
  $\Rightarrow$ precision slightly worse ($< 0.1\%$)
- $\tilde{e}, \tilde{\nu}_1$: mixture of β^3 from s-channel Z,γ- and β from t-channel χ-exchange $\rightarrow$ model dependent





Reconstruction:

Decay of scalar particle $\tilde{\ell} \to \ell\chi$:

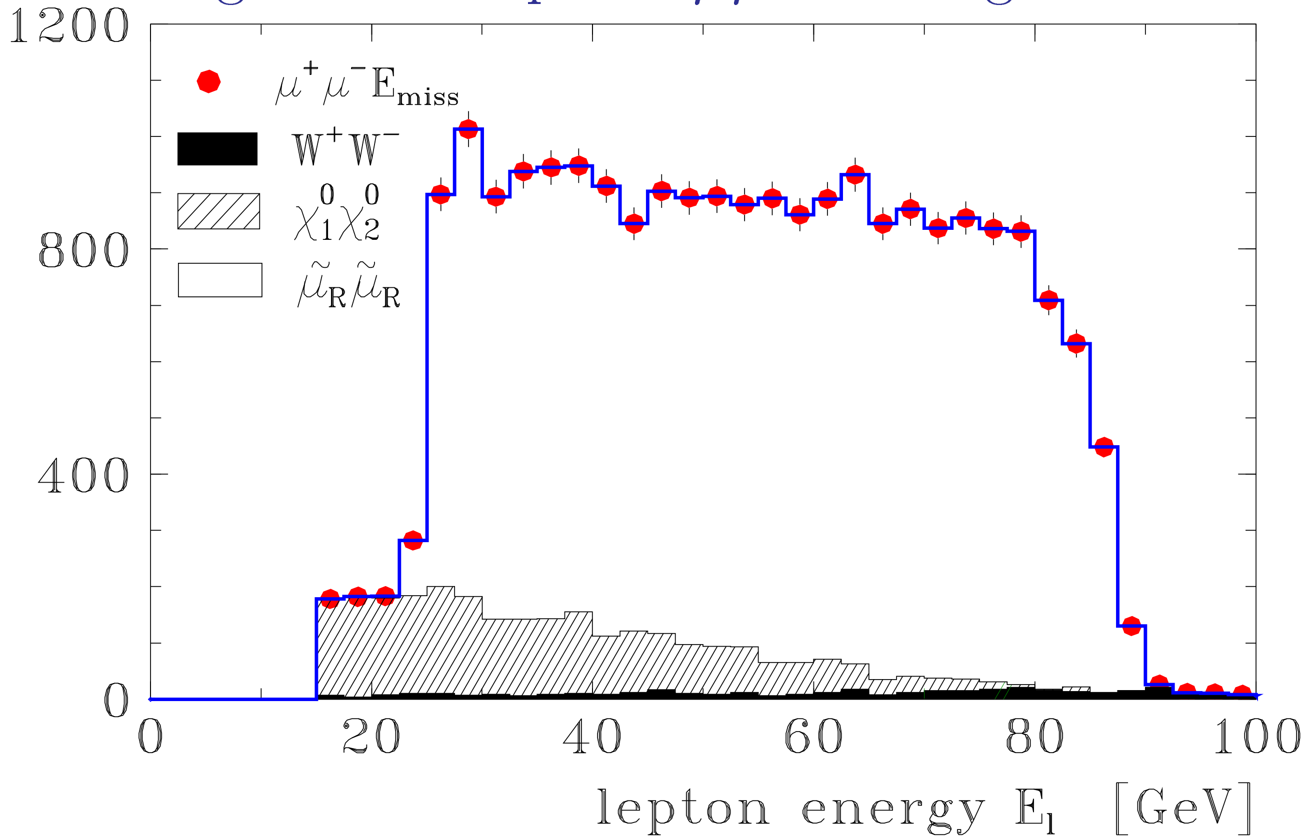
Flat energy distribution of ℓ between

$$\frac{E_\ell}{E_{\rm beam}} = \frac{1}{2}(1 \pm \beta)\left(1 - \frac{m_\chi^2}{m_{\tilde{\ell}}^2}\right)$$

$\Rightarrow$ m_χ and $m_{\tilde{\ell}}$ can be obtained in a model independent way

e.g. $\mathrm{e^+e^-} \to \tilde{\mu}_R^+\tilde{\mu}_R^- \to \mu^+\chi_1^0\mu^-\chi_1^0$:

low background sample in $\mu\mu$+missing mass



$\Rightarrow$ Can measure $m_{\chi_1^0}$ and $m_{\tilde{\mu}_R}$ to 0.3% with $\sqrt{s} = 320\,\mathrm{GeV}$, $\mathcal{L} = 160\,\mathrm{fb}^{-1}$

Analysis of charginos

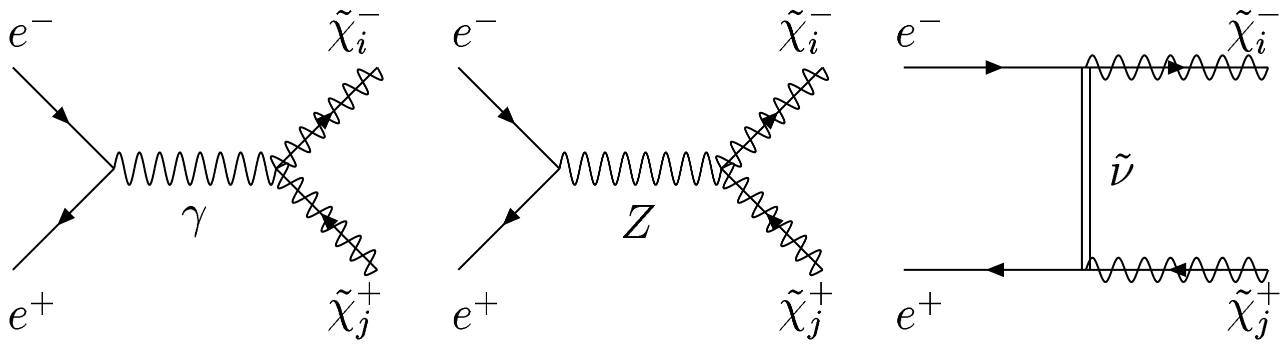
Chargino mass matrix is given by

$$\mathcal{M}_\chi = \begin{pmatrix} M_2 & \sqrt{2} m_W \cos\beta \\ \sqrt{2} m_W \sin\beta & \mu \end{pmatrix}$$

Matrix not symmetric $\Rightarrow$ need two mixing angles $\Phi_{L,R}$ for left- and right-handed states

Mixing angles and and chargino masses are (complicated) functions of M_2, μ and $\tan\beta$

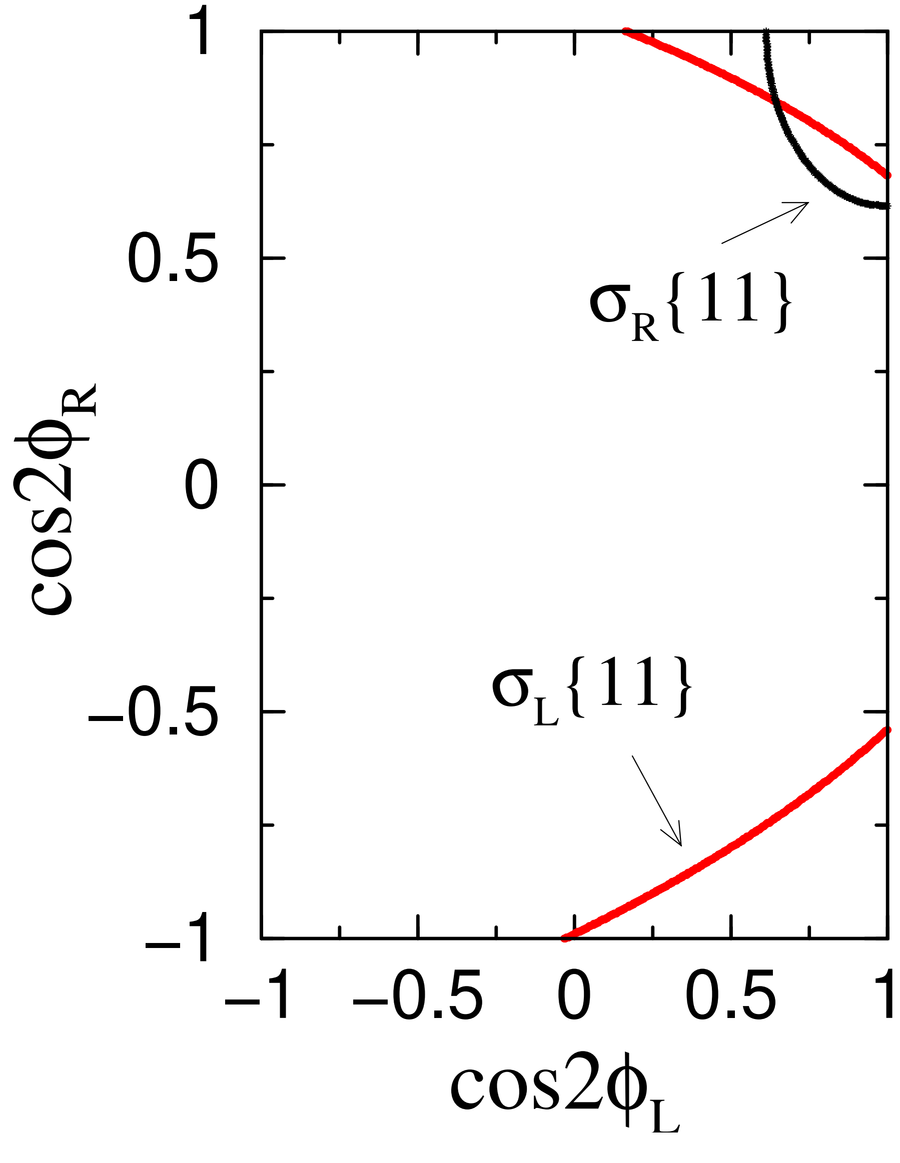
Chargino production via Z,γ s-channel and $\tilde{\nu}_e$ t-channel exchange



Need to know sneutrino mass to calculate cross section

Cross sections of $\mathcal{O}(100\,\mathrm{fb})$
$\Rightarrow$ expect several$\times 10^4$ events per channel

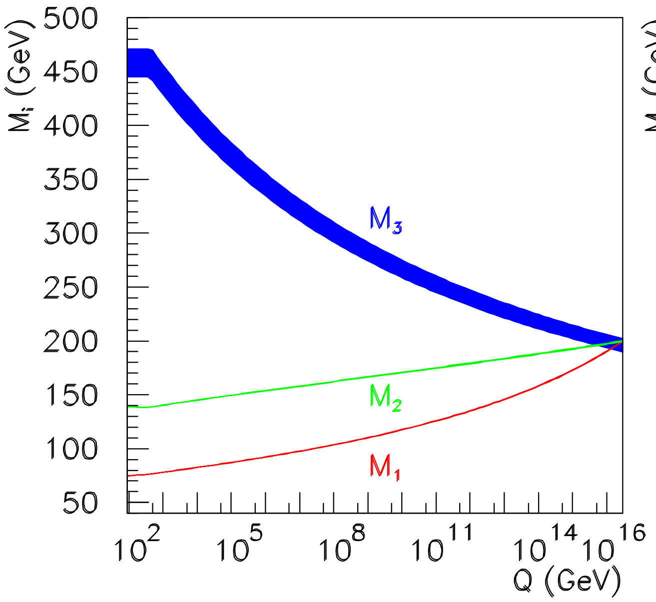
Even if only $\chi_1^+\chi_1^-$ channel is accessible (and $m_{\tilde{\nu}}$ known) can reconstruct mixing angles from polarised cross section

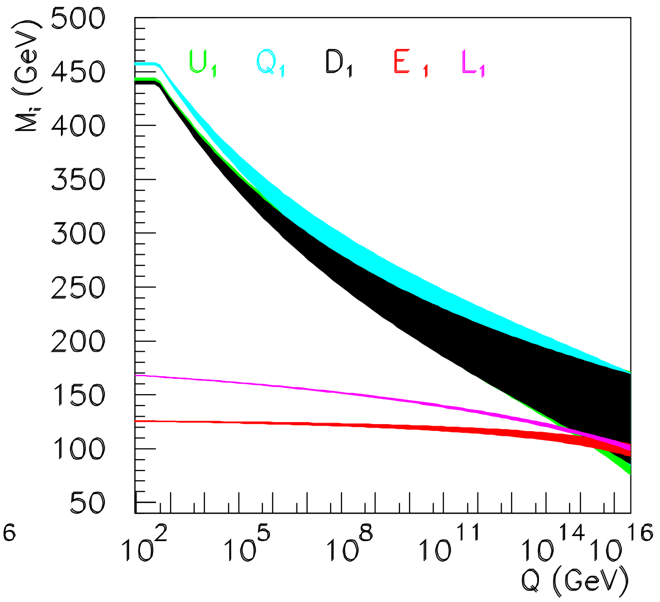


$\Rightarrow$ M_2, μ and $\tan\beta$ can be determined from $m_{\chi_1^\pm}$ and $\chi_1^+\chi_1^-$ polarised cross sections

Reconstruction of SUSY parameters

- measure masses and cross sections of SUSY particles and Higgses
- fit SUSY parameters at the weak scale
- extrapolate to GUT scale using RGEs
- bottom up approach that needs no model assumptions
- get model independent prediction at high scales





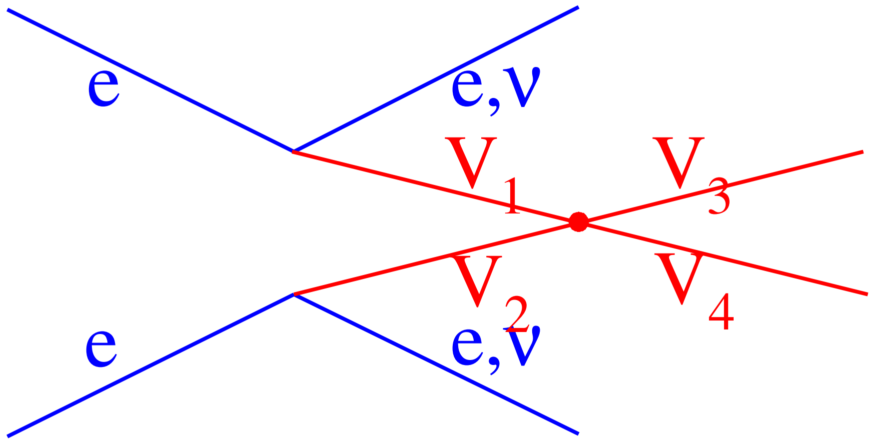
- can check unification at m_{GUT} experimentally

Comparison with LHC

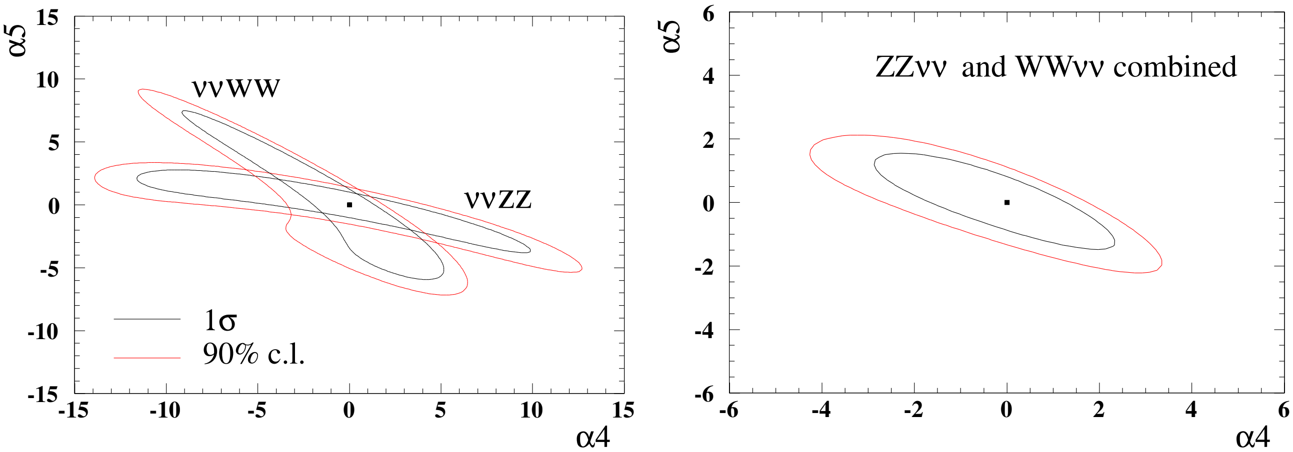
- LHC SUSY events normally start with gluino or squarks having masses up to 2 TeV
- other SUSY particles may be seen in cascade decays
- pretty accurate measurements of mass differences
- LHC squark and gluino masses profit enormously from LC $m_{\chi_1^0}$ measurement
- LC precision significantly better for sleptons and gauginos
  ➤ important for model independent extrapolations
- if SUGRA with mass unification is valid higher reach for LHC
- however for a free ratio $M_1/M_2/M_3$ both machines have regions difficult for the other
- to understand the mechanism of SUSY breaking (if SUSY exists) one needs the masses and polarised cross sections of all different kinds of SUSY particles
- probably this can only be done if both machines work together

❺ Strong electroweak symmetry breaking

- in models of strong electroweak symmetry breaking the longitudinal vector bosons are the Goldstone-bosons of the new interaction
- the longitudinal vector-bosons can thus been identified with the pions of QCD (LET)
- most intuitive channel: VV scattering (V=W,Z)

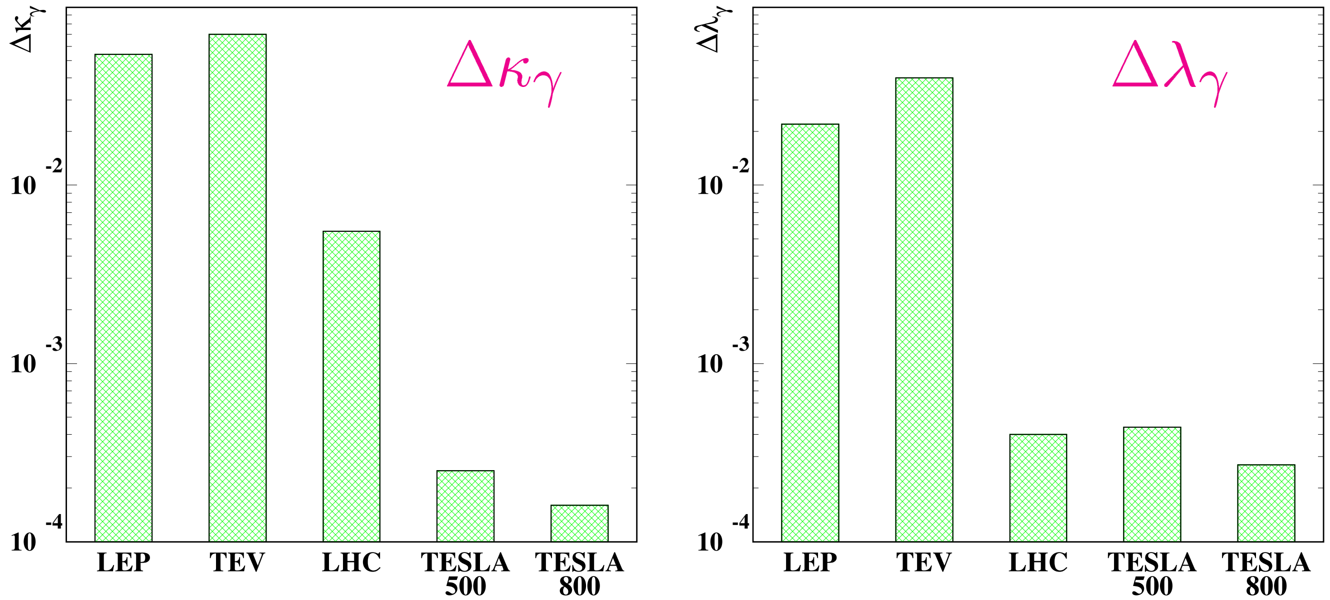


Precision estimate at $\sqrt{s} = 800\,\mathrm{GeV}$:

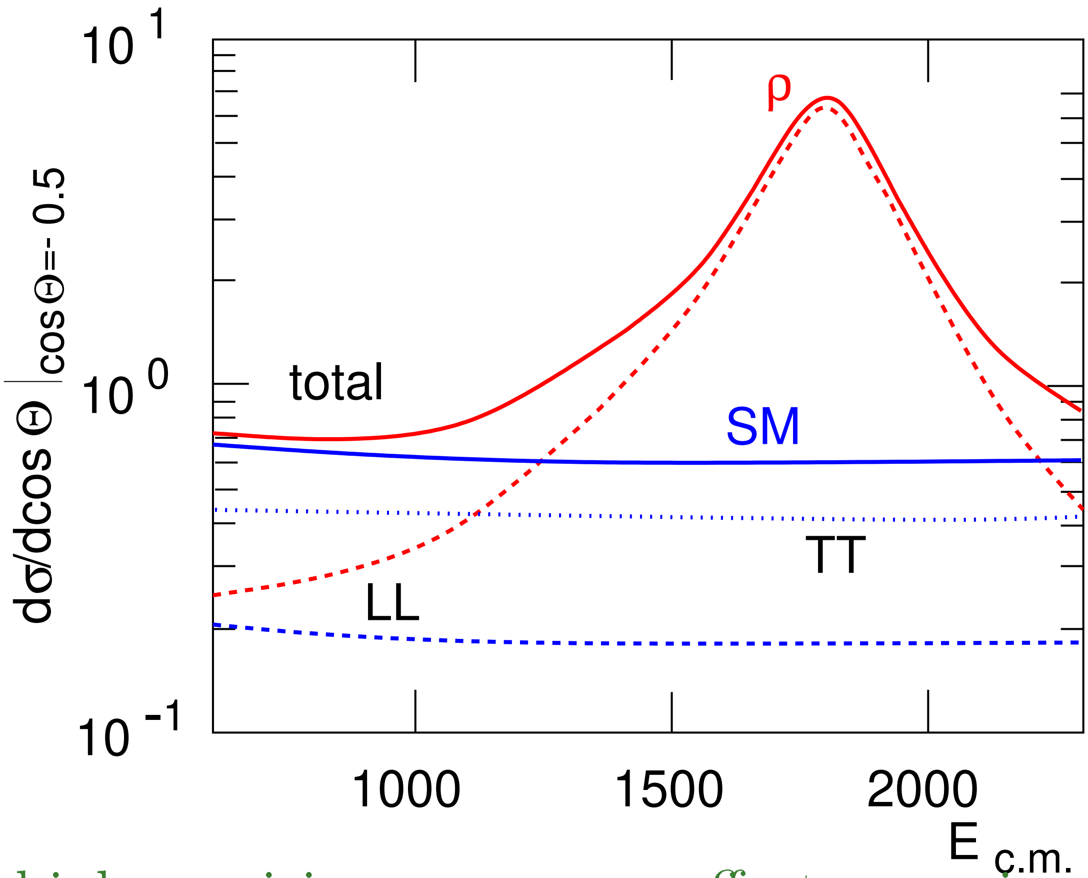


New physics scale of $\Lambda^* = 3 - 5\,\mathrm{TeV}$ can be reached

More sensitive: W-pair production



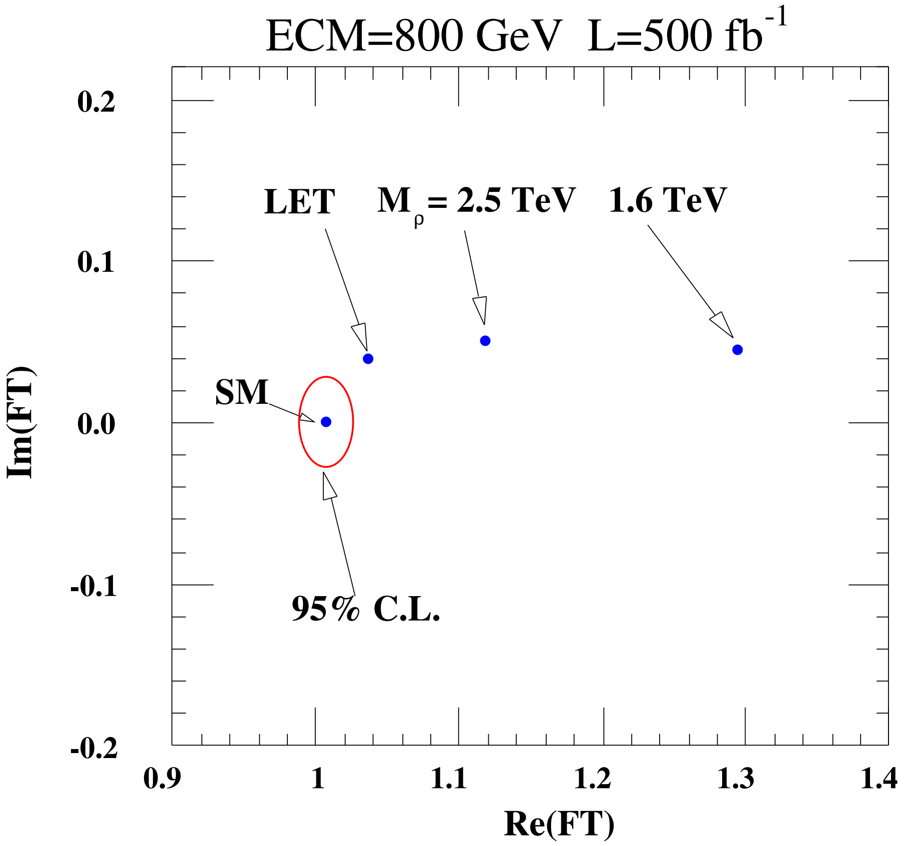
I=J=1 resonances should be seen the same ways as the ρ and the ω are seen in $e^+e^- \to \pi^+\pi^-$



with high precision resonance effects remain visible at lower energy

Analysis within technicolour models

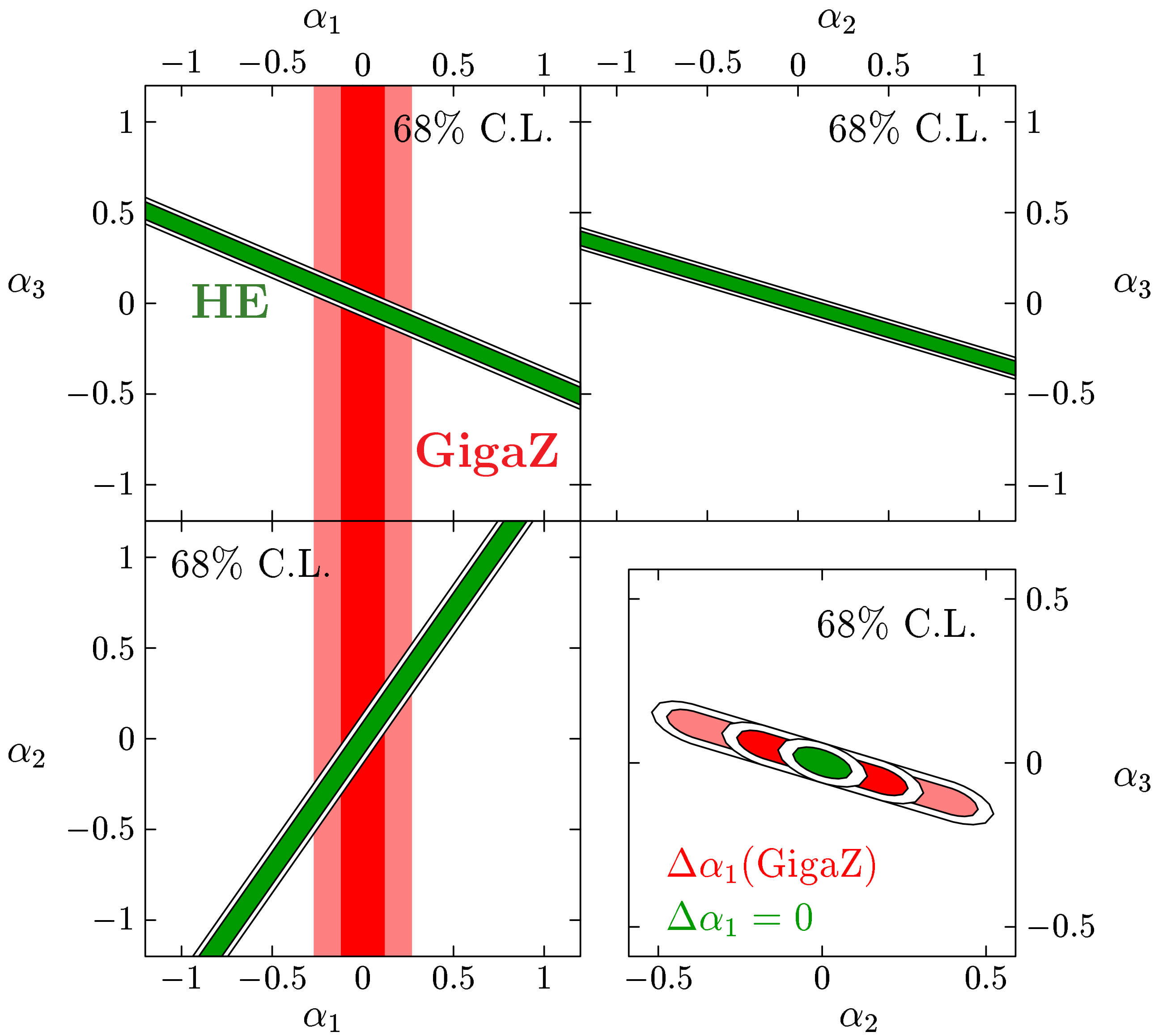
- Parameterise $e^+e^- \rightarrow WW$ with a form factor similar to $e^+e^- \rightarrow \pi^+\pi^-$
- can predict form factor as a function of m_ρ
- LET is limit for large m_ρ



- Linear Collider is sensitive to techni-ρ masses up to $\sim 2.5\,\text{TeV}$ and can distinguish LET from SM
- The LHC has a similar reach
- however the information is very complementary since the LHC measures the mass of a resonance and the LC measures the couplings

Model independent analysis

Rephrase anomalous couplings $(g_1^Z, \kappa_\gamma, \kappa_Z)$ in terms of coupling constants in an effective Lagrangian



Need precise $\sin^2\theta^l_{eff}$ (and m_W) from LC low energy running to solve remaining ambiguities

Limits correspond to $\Lambda^* = \mathcal{O}(10\,\mathrm{TeV}) \gg 3\,\mathrm{TeV}$

❻ Conclusions

- TESLA with its energy reach up to around 1 TeV has the potential to enlarge our knowledge on electroweak symmetry breaking significantly.

- If a light Higgs exist, especially in conjunction with Supersymmetry, a huge amount of information can be obtained from such a machine.

- If no light Higgs exists first hints towards a theory of strongly interacting symmetry breaking can be obtained.

- In all cases TESLA is complementary to the LHC and we finally need both of them to understand electroweak symmetry breaking.