THE INTERNATIONAL LINEAR COLLIDER — PHYSICS CASE* **

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The physics case of the International Linear Collider is presented following the recently published ILC — Reference Design Report.

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1. Introduction

A long history of linear collider activity was summarised recently by G.A. Loew during the LCWS2006 workshop at Bangalore, India. The first workshop on linear collider technology was organised in 1988, on physics three years later. The last LCWS meeting was held at DESY, in the late spring 2007. This year is very special for the International Linear Collider (ILC) community since the estimation of the cost has been announced and the ILC Reference Design Report (called also Detector Concept Report) [1], the first comprehensive report on physics and the detectors at ILC, was issued in August 2007.

The ILC project was defined in 2004, after recommendation of the cold technology was formulated. Earlier various projects were discussed: Next Linear Collider (NLC) in USA, Global Linear Collider (GLC; also Japan Linear Collider — JLC) in Japan and TESLA in Europe. Requirements of ILC experiments are as follows: the e^+e^- energy 200–500 GeV . There should be high luminosity: 500–1000 fb^{-1}. Higher that 80% e^- polarisation (mandatory) and higher than 50% e^+ polarisation. The upgrade to 1 TeV in

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the second stage is planned. Energy and luminosity similar as in the e^+e^- collisions is foreseen for the Photon Linear Collider ($\gamma\gamma$, $e\gamma$). This option can be realized by using the Compton backscattering of the electron beam on a laser light to produce beams of high energy photons. As a possible option the GigaZ is considered, running at the Z peak with a higher luminosity.

The basic questions addressed at ILC are: Is there the Higgs particle at the Tera scale or some new physics which stabilises the electroweak scale. What is the dark matter? How are fundamental forces unified?

There is a hope about a discovery of a Higgs boson at LHC, or maybe even earlier at the Tevatron. Then, the next questions arise: is this really Higgs particle? Is the Higgs boson the SM one? If not, are there new phenomena besides the Higgs boson? A possible discovery of a new gauge boson at the LHC will open a discussion on the properties of new force, and further unification and cosmology. Discovery of SUSY particles at LHC are also expected and the related questions arise on SUSY breaking pattern, GUT and SUSY dark matter candidates. The precision measurements at ILC should be able at least partly to answer all these questions.

2. Higgs physics

The existing particle physics theory, the "Theory of Matter" according to Wilczek [2], is based on quantum field theory, gauge symmetry, spontaneous symmetry breaking, asymptotic freedom and the assignments of the lightest quarks and leptons. A name "Standard Models" can be used to describe models in which, for generating in a spontaneous way masses of fundamental particles, SU(2) doublets (called also Higgs doublets) are introduced. In the SM one scalar doublet is introduced, so SM $\equiv$ 1HDM. Models with two such doublets are denoted as 2HDM; the most important representative of such model is the Minimal Supersymmetric Standard Model (MSSM). Non-Standard Models are based on more radical assumptions on mass generation and not only (see *e.g.* [3]).

2.1. Present limits and limits expected from LHC

The physical Higgs particles in the simplest Standard Models are: $h_{\rm SM}$ in SM while in 2HDM — h, H (CP-odd), A(CP-even) ($h_{1,2,3}$ if CP is violating) and $H^{\pm}$, and similarly in MSSM. The direct search at LEP led to the following constraint for mass of the Higgs boson in SM: $M_{h_{\rm SM}} > 114$ GeV (at 95% CL). The newest exclusion for the SM-Higgs boson obtained at the Tevatron is presented in Fig. 1 (Left). This limit is close to the SM prediction for mass around 160 GeV. In Fig. 1 (Right) an expectation of discovery and 95% CL exclusions for the SM-Higgs boson at the LHC is presented.

A good (combined) sensitivity for a light SM-Higgs boson can be reached already with 10 fb^{-1} (5σ for mass above 120 GeV) [6]. Results for the MSSM, the newest from Tevatron and expected at the LHC, are shown in Fig. 2. Exclusions for the A mass as a function of $\tan\beta$ were obtained by the CDF Coll. (Fig. 2 (Left)) and the D0 Coll. They do not exclude region of $\tan\beta$ 10–60 and $M_A \sim$ 90–200 GeV. At the LHC the whole MSSM parameter space (M_A *versus* $\tan\beta$) can be covered by at least one Higgs boson, for 10 times higher luminosity than for the SM-Higgs boson search. However, even for $\int Ldt = 300\ \mathrm{fb}^{-1}$ there is a large region (starting at $M_A \simeq 200$, $\tan\beta$ around 6) in which only one Higgs boson, moreover the SM-like h, can be seen (the "LHC wedge"), as presented in Fig. 2 (Right). At ILC this region up to $M_A \sim$ half of the e^+e^- energy can be tested, see Fig. 3 (Left).

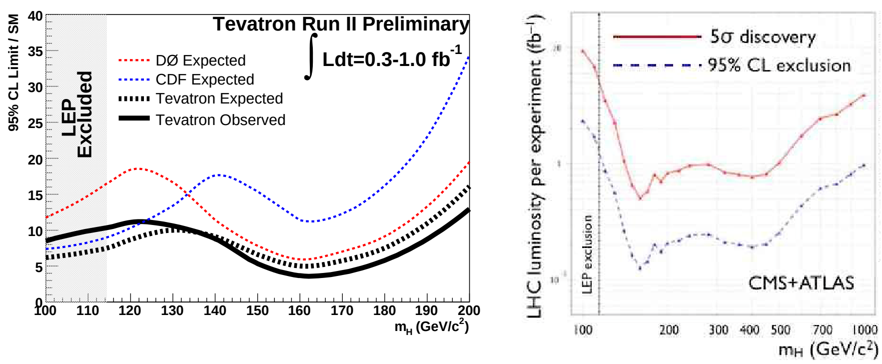


Fig. 1. Left: Limits on the SM-Higgs boson from the Tevatron [4]. Right: The discovery and 95% CL exclusion limits for the SM-Higgs boson at the LHC [5].

The indirect information about the SM and MSSM Higgs sectors are coming from the radiative corrections to SM observables, which are sensitive to the mass of the Higgs bosons. At the Tevatron the new precise measurement of the W mass by CDF Coll. leads to a new world average (2007): $M_W = 80398 \pm 25$ MeV [7]. The newest value of the mass of top quark from precise measurements at the Tevatron is 170.9 $\pm$1.8 GeV [8]. These new values of masses for W and top quark can be compared to the results of theoretical calculations including radiative corrections [9], see Fig. 3 (Right). The new data marginally agree with the SM prediction while for MSSM the agreement looks better. The ellipses corresponding to the expected accuracy of the mass measurements for the top quark and the W boson at the LHC and ILC (in the GigaZ option) are also shown.

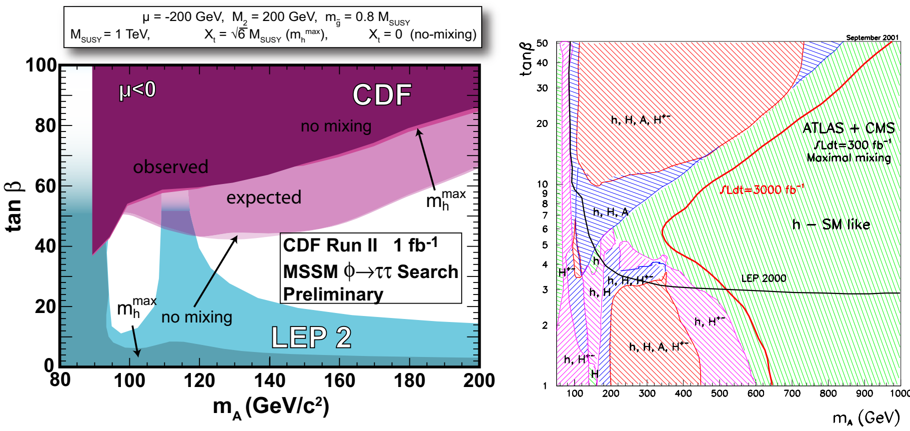


Fig. 2. Left: CDF constraints for M_A *versus* $\tan\beta$ in MSSM [4]. Right: The "LHC wedge" for two luminosity cases, from [6].

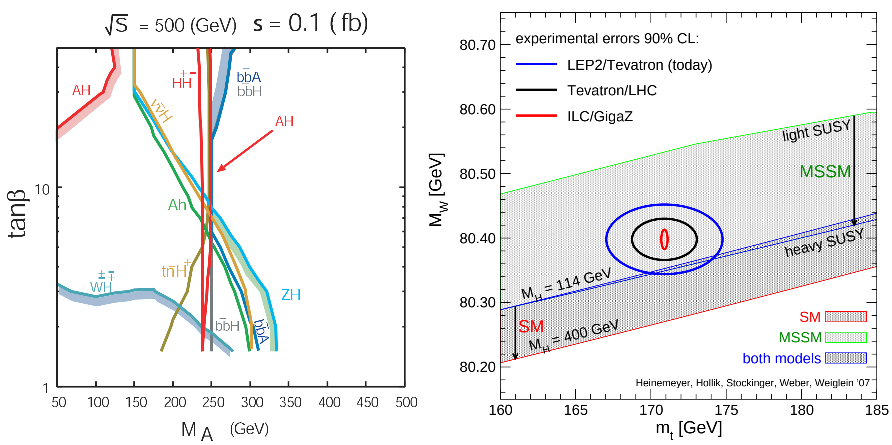


Fig. 3. Left: Covering the LHC wedge by ILC at energy 500 GeV [1]. Right: The newest data for mass of the W boson and top quark in comparison with the precise calculation in the SM and MSSM (updated from [9]).

2.2. Higgs Physics at ILC

The cross sections for the SM-Higgs boson production at ILC is presented in Fig. 4. A model independent determination of the Higgs mass from the recoil mass distribution in $e^+e^- \to \mu^+\mu^- X$ can be performed with an accuracy 70–40 MeV (from ACFA report) [1], see Fig. 5.

Study of the threshold behaviour of the cross section for the $e^+e^- \to$ "h"Z rules out some J^P-states, see Fig. 6 (Left). Also angular correlations in Z/h distributions can support $J^P = 0^+$ hypothesis for h. The J^{PC}

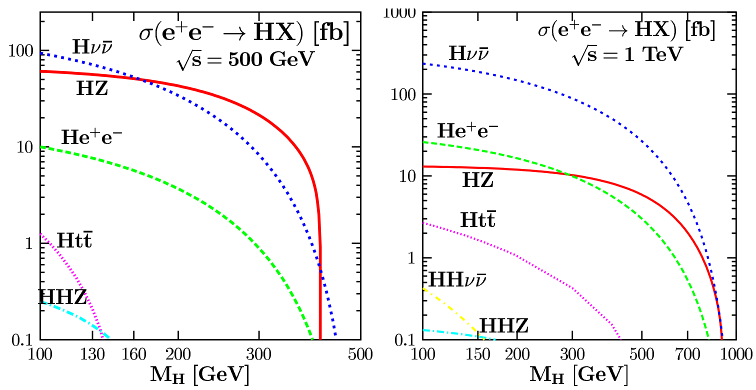


Fig. 4. The cross sections for the SM-Higgs boson production at ILC with energy 500 GeV and 1 TeV [1].

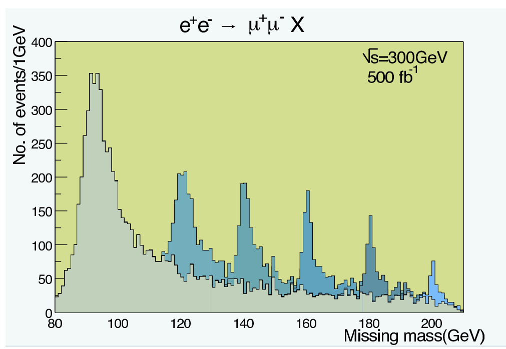


Fig. 5. Recoil mass reconstruction in $e^+e^- \to ZX$, $Z \to \mu^+\mu^-$. From [1].

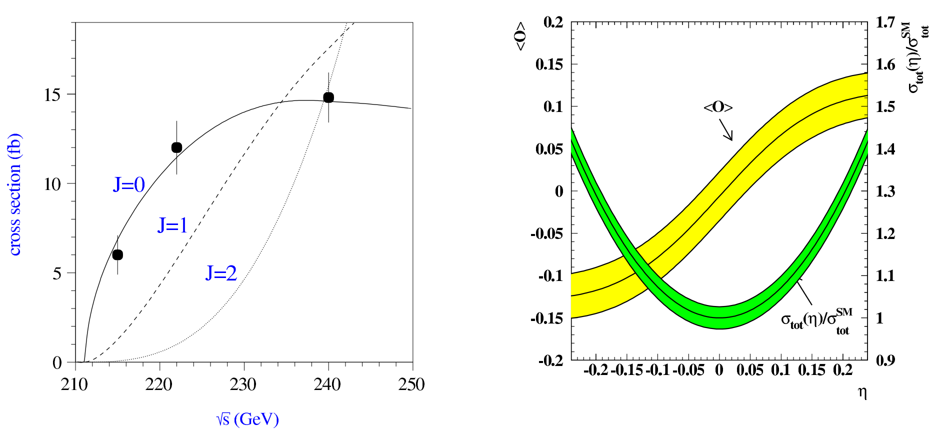
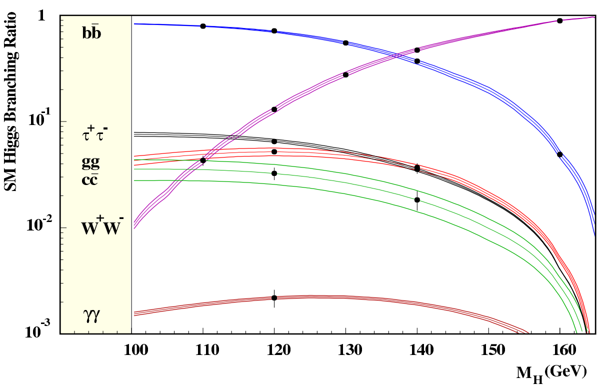


Fig. 6. Left: The discrimination of various J states from the threshold behaviour. Right: The determination of the CP mixing parameter η. From [1].

quantum numbers can be tested in $hZ \to 4f$ or in $h \to WW/ZZ$ with $ZZ \to 4f$. CP mixing, parametrised by the η parameter, can also be established (Fig. 6 (Right)).

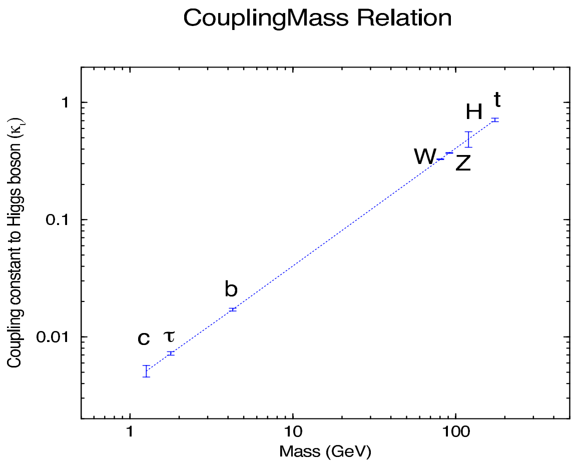
Measurements of Higgs-boson production and decays will allow to determine precisely the branching fractions for the SM-Higgs boson (mass 120 GeV), as presented in Fig. 7. In Fig. 8 the linear dependence of the Higgs boson coupling to the various SM particles as a function of their masses is presented, together with a table of accuracy of the couplings to heavy fermions (c, b, t, τ) and gauge bosons W/Z, of the selfcoupling and total width determination. In Fig. 9 the relative accuracy of the htt coupling determination for SM-Higgs boson mass range 120–200 GeV, based on four different channels, and a combined relative accuracy is shown.



Decay mode	Relative precision (%)
$b\bar{b}$	1.0–2.4
$c\bar{c}$	8.1–12.3
$\tau^+\tau^-$	4.6–7.1
gg	4.8–10
WW	3.6–5.3
$\gamma\gamma$	23–35

Fig. 7. Left: Accuracy of the branching ratios measurements for SM-Higgs boson with masses 100–160 GeV, at ILC with energy 350 GeV, luminosity 500 fb^{-1}. Right: A relative accuracy for the BR measurements for the SM-Higgs boson with mass 120 GeV at ILC with luminosity 500 fb^{-1}. From [1].

The $\gamma\gamma$ decay width can be measured with the highest precision in the PLC$_{\gamma\gamma}$ option, since here the Higgs boson can be produced as an s-channel resonance. The 2.1% precision can obtained for the cross section measurement for $\gamma\gamma \to h \to b\bar{b}$ in SM, for mass of h equal 120 GeV for one year of running [10, 11] (Fig. 10 (Left)). It drops to 7% for mass 160 GeV. After using the BR for the $b\bar{b}$ decay from the measurement at e^+e^- ILC, the $\Gamma_{\gamma\gamma}$ can be measured with 3% accuracy. This loop induced h decay is sensitive to new heavy charged particles, getting masses from the Higgs mechanism. The heavy MSSM Higgs boson search can also be performed at PLC$_{\gamma\gamma}$ with a high accuracy (Fig. 10 (Right)) [12] — 11% for mass of A and H equal 300 GeV (heavy A and H are degenerate if h is SM-like). For mass 200 GeV accuracy is 21% while for 350 GeV it is equal to 15%. So, covering a LHC wedge beyond the region accessible at the e^+e^- collision,



coupling	error
λ_{HHH}	$\pm$ 0.22
g_{HWW}	$\pm$ 0.012
g_{HZZ}	$\pm$ 0.012
g_{Htt}	$\pm$ 0.030
g_{Hbb}	$\pm$ 0.022
g_{Hcc}	$\pm$ 0.037
$g_{H\tau\tau}$	$\pm$ 0.033
Γ_H	$\pm$ 0.061

Fig. 8. Accuracy of the couplings to heavy fermions (c, b, t, τ), gauge bosons W/Z, selfcoupling and of the total width determination for SM-Higgs boson with mass 120 GeV and 500 fb^{-1}, energy 300 GeV except for hhh (500 GeV) and tth (700 GeV) and with a higher luminosity. From [1].

compare Fig. 3 (Left), is possible. This is due to fact that PLC allows for a singly production of neutral Higgs particles, in contrast to the e^+e^- collision, where they are produced in HA pairs. Results for PLC were obtained using the high energy part of the $\gamma\gamma$ spectra, at the e^+e^- energy optimised for the given Higgs boson mass.

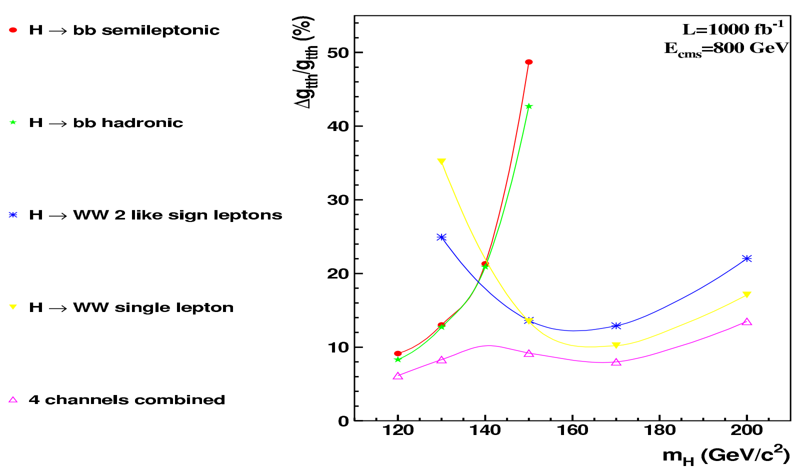


Fig. 9. The relative accuracy of the htt coupling for SM-Higgs boson mass range 120–200 GeV for 4 channels and a combined relative accuracy [1].

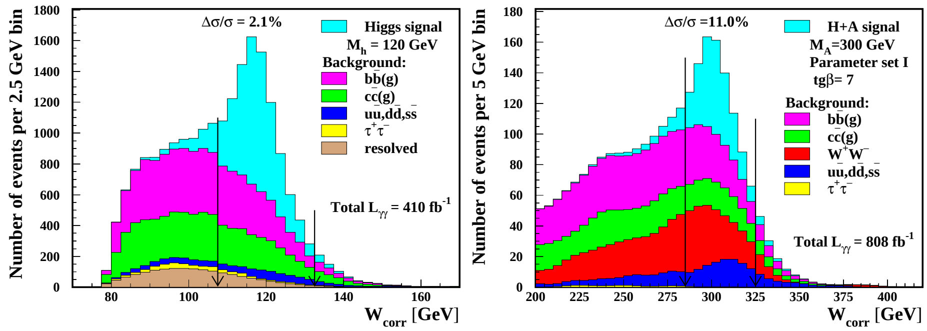


Fig. 10. Left: The cross section for $\gamma\gamma \to h \to b\bar{b}$ in SM, for mass of h equal 120 GeV [10]. Right: The cross section for $\gamma\gamma \to H, A \to b\bar{b}$ in MSSM, for mass of H, A equal 300 GeV and $\tan\beta = 7$ [12].

3. Couplings of the gauge bosons

Anomalous couplings among gauge bosons can be described by two terms, $\sim \kappa_V W^-_\mu W^+_\nu V_{\mu\nu} + (\lambda_V/M_W^2)\, W^-_{\lambda\mu} W^+_{\mu\nu} V_{\nu\lambda}$, where $V_{\nu\lambda} = \partial_\nu W_\lambda - \partial_\lambda W_\nu$ (for CP conserving case). The accuracy of determination the corresponding coefficients at various machines are given in Fig. 11. It is clear that the coefficient κ_γ can be measured best at ILC.

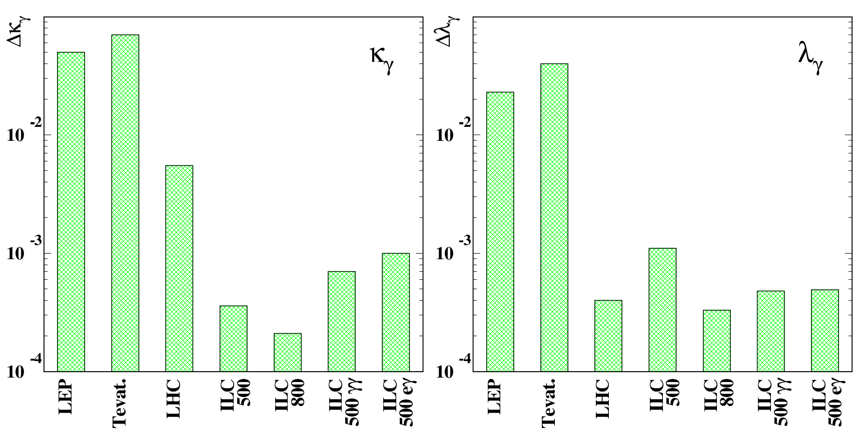


Fig. 11. Accuracy of the κ_γ (Left) and λ_γ (Right) at: LEP, Tevatron, LHC, ILC and PLC ($\gamma\gamma$ and $e\gamma$) at e^+e^- energy 500 GeV, and ILC at 800 GeV [1].

4. Top quark physics

At the ILC the high precision of the top quark mass measurement, between 100 and 200 MeV, can be achieved by studying the threshold behaviour, known at NNLL QCD accuracy, see Fig. 12 (Top) [1]. In comparison, at the Tevatron the corresponding precision is 2 GeV and at the LHC — 1 GeV. As it was mentioned already, precise value of $m_{\rm top}$ plays an important role in the electroweak precision analysis. Top quark anomalous interactions: the top Yukawa coupling and anomalous coupling to gauge bosons can also be tested see Fig. 12 (Bottom). Here model with 4$^{\rm th}$ generation and the TopFlavor, Little Higgs with T-parity models are compared.

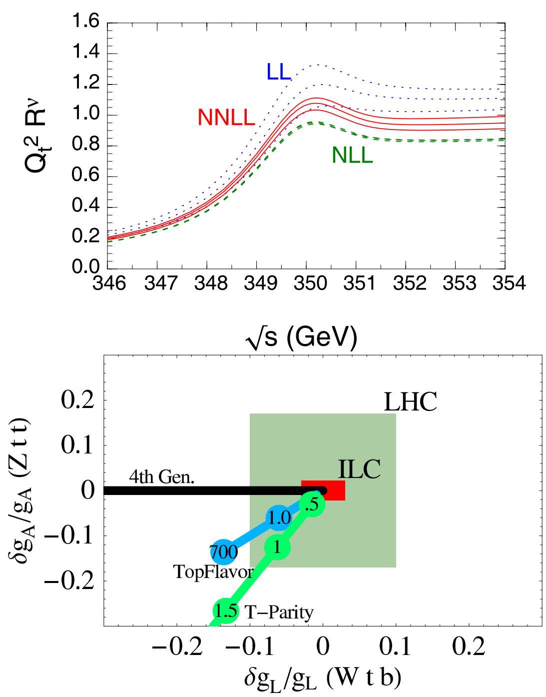


Fig. 12. Top: The cross section for $e^+e^- \to t\bar{t}$. Bottom: Prediction of various models for the axial Ztt and left-handed Wtb couplings, at the LHC and ILC. From [1].

5. SUSY particles

Precision measurements of properties of SUSY particle at the ILC, like mass and mixing of chargino, neutralino, slepton and squark are feasible. Slepton mass can be measured in threshold scan or in the continuum. Above the threshold is can be obtained from endpoint energies of leptons coming from sleptons decays. These methods allow to measure masses with accuracy $\sim$ 50–100 MeV, see Fig. 13 [1].

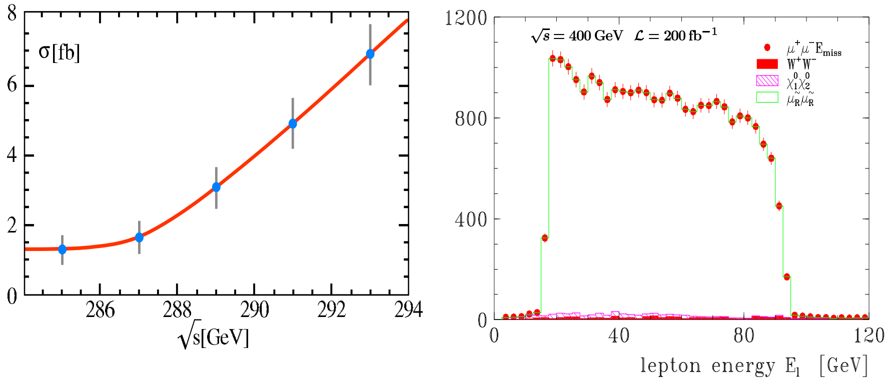


Fig. 13. Left: Slepton mass measurement in SPA1 point. Right: Lepton energy spectra from sleptons. From [1].

Determination of SUSY breaking and GUT scenarios at ILC were studied. Extrapolation of gaugino and scalar mass parameters to the GUT scale with inputs from combined analysis of LHC and ILC are presented in Fig. 14.

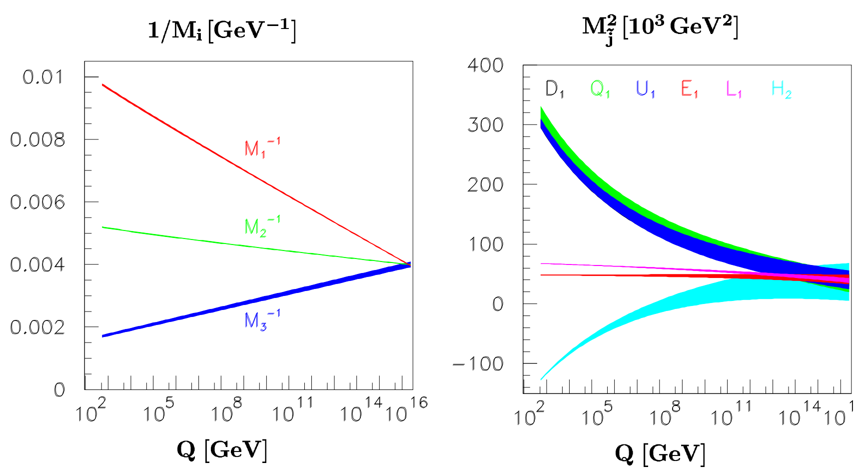


Fig. 14. Gaugino and scalar mass parameters extrapolated to the GUT scale [1].

6. Alternative scenarios

Alternative scenarios explaining the stability of the weak scale involve new strong dynamics or change of space-time, and new signals at the TeV scale are: Large extra dimensions, Warped extra dimensions, Universal extra dimensions, Little Higgs models *etc.* Figure 15 (Top) shows how the number of extra dimension can be determined at ILC, by comparing the cross section for single photon and missing energy, due to KK graviton emission, at two energies 500 and 800 GeV.

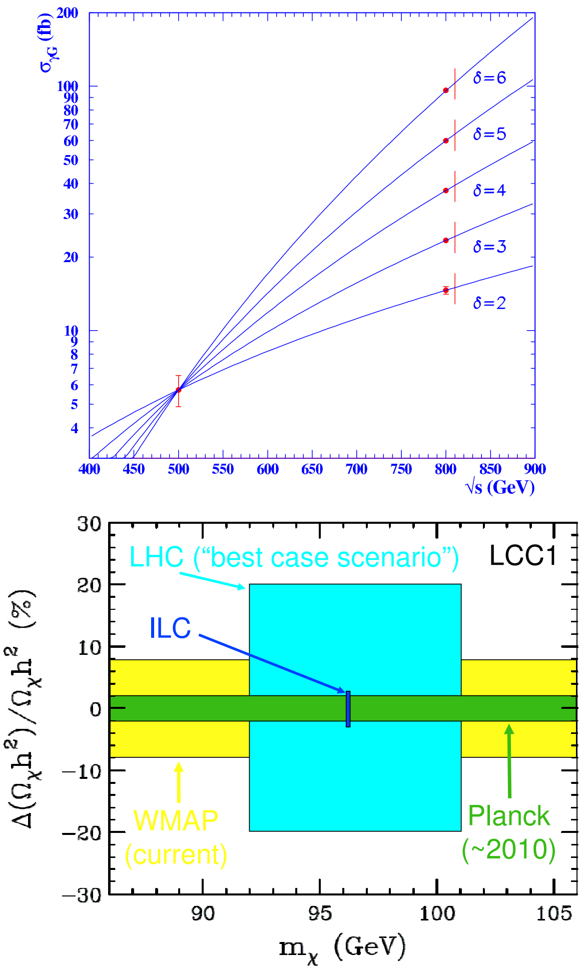


Fig. 15. Top: Determination of the number of extra dimension at ILC with energy 500 and 800 GeV in. Bottom: SUSY dark matter determination. From [1].

7. Connection to cosmology

Dark matter candidates appear in SUSY, in Universal Extra Dimension model, in Little Higgs model with T-parity, *etc.* ILC can distinguish different scenarios and determine dark matter particle's properties to match the observed dark matter density in the Universe, what illustrates Fig. 15 (Bottom). The DM density in the Universe is determined by the WMAP satellite, and will be in the future probed with a higher precision by the Planck one. The LHC and ILC may provide constraints on mass and density of DM particle (here neutralino χ in cMSSM SPS1a scenario).

8. A need for PLC

In PLC option, both energy and polarisation of the photon beams vary. One can use the high energy $\gamma\gamma$ peak ranging from 0.6 to 0.8 of e^+e^- energy. The physics potential is very reach. Resonance production of $C = +$ states (*e.g.* Higgs boson) allows to make very precise determination of its properties. Both $\gamma\gamma$ and $e\gamma$ have higher mass reach than the corresponding e^+e^- collider. High polarisation of the beams (both circular and linear) allows to treat $\mathrm{PLC}_{\gamma\gamma}$ as a CP filter. Direct production of charged scalars scalars, fermions and vectors occurs with high cross section, not decreasing with energy. Pair production of neutral particles (*e.g.* light-on-light) proceed via loops. Study of hadronic interaction of the photon is possible, both in $\gamma\gamma$ and $e\gamma$ colliders.

PLC is especially useful for study the Higgs sector. In Fig. 16 there is a comparison of determination of the relative couplings to gauge bosons and top quark as well as a CP mixing parameter (angle Φ_{HA}) in the CP violating 2HDM at LHC, ILC and $\mathrm{PLC}_{\gamma\gamma}$ [13].

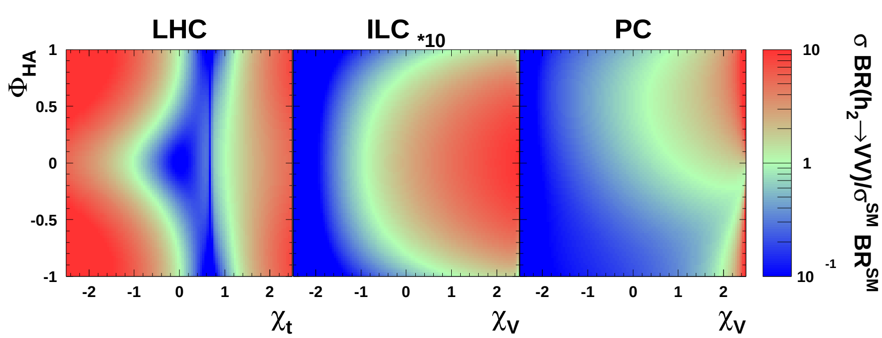


Fig. 16. A determination of the relative couplings to $V = W/Z$ and t-quark as well as a CP mixing angle Φ_{HA} in the CP violating 2HDM at LHC, ILC and $\mathrm{PLC}_{\gamma\gamma}$ [13].

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