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Physics overview: Introduction to international linear collider physics

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Abstract. Physics at the international linear collider (ILC) is described as an introductory talk at Linear Collider Workshop 2006 (LCWS06).

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1. Introduction

It has been a long time since the high energy physics community recognized the importance of the future e^+e^- linear collider with energy starting from the 500 GeV range. Physics studies of such a linear collider have been performed in international as well as regional frameworks, and there are many documents describing physics case of linear colliders [1–4]. In this talk, I will review physics potential of the International Linear Collider (ILC).

There has been much progress in understanding fundamental constituents of matter and forces acting among them throughout the last century. In fact, the development of elementary particle theory in the 20th century was a history of how we identified and understood four fundamental forces of Nature, namely gravity, electromagnetic, weak and strong interactions. In the early 1970s, so called standard model was proposed, in which three interactions except for gravity were described in a unified fashion in terms of gauge theory. Since then, a primary focus of high energy experiments has been to establish the basic principle of the standard model. Discovery of W and Z bosons at CERN in the early 1980s, increasing understanding of QCD as a fundamental theory of strong interaction and precise measurements of electroweak processes at LEP and SLC in the 1990s have led us to confidence that gauge symmetry is a guiding principle of the law of elementary particle physics.

Although the aspect of gauge invariance is well understood by recent experimental studies, there is another important ingredient in the standard model, which is the Higgs mechanism. Quarks, leptons and gauge bosons are introduced as massless fields in the standard model, and their masses are generated only through spontaneous breaking of the electroweak symmetry. Even though the concept of the spontaneous symmetry breaking in the particle physics is well established in the study of chiral symmetry of the strong interaction, we know little about how electroweak symmetry breaking occurs and what is the dynamics determining the scale of the weak interaction. This is a primary reason why we need to explore the TeV scale physics.

Finding the dynamics behind the electroweak symmetry breaking is likely to lead to physics beyond the standard model. There are many theoretical proposals for physics beyond the standard model, and each model offers different scenario for the electroweak symmetry breaking sector. In supersymmetric models the Higgs boson is accompanied by fermionic partners and the weak scale is related the supersymmetry (SUSY) breaking scale. In the little Higgs model, the Higgs boson is a composite particle arising from dynamics of new strong interaction at a more fundamental level. In the model of extra space-dimensions, the Higgs field may have some geometrical origin. Thus, the question of how the weak scale is generated could be related to physics scenario beyond the TeV scale, which may lead to unification of all forces, change our understanding of the fundamental constituents, or new concept on space and time.

Since the discovery of the cosmic microwave background of the Universe, cosmology has made a tight connection with physics laws at the microscopic world. The relationship becomes more and more important as we understand physics at smaller distance. It is likely that collider experiments play crucial roles in identifying dark matter in the Universe. Furthermore, cosmological problems such as baryogensis, inflation and dark energy require understanding physics scenario beyond the standard model.

In 2008, the LHC experiment will start its operation. This is a proton–proton collider with the center-of-mass energy of 14 TeV. The main purpose of the experiment is to discover the Higgs particle and explore physics at the TeV scale. Discovery reach of a new particle increases roughly by one order of magnitude in its mass compared to Tevatron and LEP II experiments, so that LHC is a crucial machine determining the future direction of particle physics.

The main purpose of the ILC experiment is to explore the Higgs physics and physics beyond the standard model, following the initial outcome of the LHC experiment. In this respect, once LHC finds something new, there will be more questions to be answered at ILC. LHC and ILC are two machines with different characters. Discovery reach for new particles is generally larger for LHC than ILC with 500 GeV center-of-mass energy, unless signals are suppressed in hadron collider or hidden by backgrounds. On the other hand, ILC has such advantages as initial state are elementary particles with well-defined kinematics, and the background level is less severe. The ILC's capability of beam polarization and energy scan will be important in many physics studies. ILC has several options like γ–γ, e–γ, and e^-–e^- collider modes, and the Z-pole operation. These options may become essential once new physics scenario is found out.

In the following, I will briefly review physics goals of the ILC experiment.

2. Higgs physics

Finding the dynamics of electroweak symmetry breaking and the mass generation mechanism of elementary particles is the most important issue of the current particle physics. We first have to discover the Higgs particle that is a physical excitation mode of the field responsible for the electroweak symmetry breaking. In order to show that the discovered particle is relevant for the Higgs mechanism, the coupling constants to quarks, leptons and gauge bosons have to be determined in good accuracy.

Although it is almost clear that the W and Z boson masses are generated from the spontaneous breaking of the electroweak symmetry, little is known about the Higgs sector. In the minimal standard model, only one Higgs doublet field is introduced, and consequently, we are able to make a precise prediction of the property of the Higgs boson in terms of a single parameter, the Higgs boson mass. We can even derive the upper bound of the Higgs boson mass from precise electroweak measurements together with the top quark mass, and the favored mass region is below 200 GeV [5].

The decay branching ratio and production processes of the Higgs boson crucially depend on the mass of the Higgs boson. The general property of the Higgs boson is that it couples more strongly to heavier elementary particles, because the role of the Higgs field is to generate mass terms for particles. This is quite different from the gauge interaction, where universality is a basic property.

Detailed study on the Higgs search at the LHC experiment shows that Higgs boson can be discovered independent of its mass region, as long as its production and decay properties are not much different from the standard model case [6,7]. If the mass is above two Z boson decay threshold, basic parameters of the particle like spin and width can be determined using the four lepton decay mode. On the other hand, there will be inconsistency between the indirect information on the Higgs boson mass and direct observation, if the candidate of the Higgs boson becomes much heavier than 200 GeV. In such case, an urgent question will be to find out some missing ingredients that can fill the gap. If the Higgs boson mass is lighter, an important issue will be to single out the correct model of the Higgs sector that is consistent with existence of the light Higgs boson. For example, in the minimal supersymmetric standard model (MSSM), the lightest Higgs boson mass is less than 140 GeV [8]. In such a situation, we need to determine whether or not the Higgs sector corresponds to that of the MSSM.

The goal of the Higgs physics at ILC is to determine basic properties of the Higgs particle and coupling constants related to the Higgs particle. The main production mechanism of the Higgs boson (H) at e^+e^- collider are ZH production from an s-channel virtual Z boson and $H\nu\bar{\nu}$ production from the WW fusion process. For example, the production cross-section of a 120 GeV Higgs boson through the ZH process is about 200 fb^{-1} for ILC with the center-of-mass energy of 300 GeV. This means that the number of produced Higgs bosons can be $\mathcal{O}(10^5)$ for integrated luminosity of 500 fb, which is a target number of the ILC machine. With this number, we will be able to determine the Higgs property very precisely.

The spin and parity of the Higgs boson will be determined without ambiguity at ILC using the threshold scan and the production angular distribution. These measurements are necessary to confirm that the discovered particle corresponds to the Higgs boson.

The main goal of the Higgs physics at ILC is, however, to determine the coupling constant of the Higgs boson with gauge bosons and quarks and leptons. These are directly related to mass generation mechanism of these elementary particles. In particular, ZZH and WWH coupling constants as well as $Hb\bar{b}$ coupling are determined up to a few % accuracy for the Higgs boson mass of 120 GeV, which is within a favored mass range by current global fit of the standard model parameters. The determination of ZZH and WWH coupling constants has fundamental meaning for the establishment of the Higgs mechanism because this three-point coupling can only arise after the Higgs field develops its vacuum expectation value. The magnitude of this coupling is related to the gauge boson mass. The three point coupling and the mass term are in fact originated from the same term in the original gauge invariant Lagrangian. The $Hb\bar{b}$ coupling is also important for the Higgs boson of this mass range because $H \to b\bar{b}$ is the main decay mode, and information obtained on this coupling at LHC is very limited. Indeed, LHC experiments can give useful information on some ratios of the coupling constants [9], but precise determination of absolute values of coupling constant is a major goal achievable at ILC. The precision of various coupling constants is shown in figure 1, which is taken from ref. [4]. The expected coupling determination relevant for mass-generation mechanism is plotted against a particle mass for each particle. For precise determination of the top Yukawa coupling, the energy of ILC has to be upgraded from 500 GeV. In this figure, the triple Higgs coupling constant is also included. This measurement is very important because it gives first access to the shape of the Higgs potential.

Precise measurements of Higgs coupling constants offer opportunity to search for new physics scenario. In many new physics models, extension of the Higgs sector is required, or new interaction related to the Higgs field is introduced. Thus, some Higgs coupling constants can deviate from the standard model prediction by enough amount that can be distinguished at the ILC experiment. Some of the examples are as follows:

- The ratio like $h \to WW$ and $h \to \tau\tau$ branching ratios for the lightest Higgs boson (h) in MSSM as a probe of the heavy Higgs boson mass [2,10–12].
- The ratio of $h \to bb$ and $h \to \tau\tau$ branching ratios as a probe to SUSY loop corrections to the Yukawa couplings for the large $\tan\beta$ case in MSSM [12–14].
- Radion-Higgs mixing effects on the Higgs coupling constants in models with extra space dimensions [15,16].
- Shift of the light Higgs boson branching ratios in the little Higgs model with T parity [17].
- Deviation of the Higgs triple coupling constant from the standard model prediction in models in which electroweak baryogenesis is possible such as two Higgs doublet model [18] or standard model with a low cutoff scale [19].

In this way, even if only one Higgs boson is found at the ILC experiment at the first stage, precision measurements may provide valuable information on physics at higher energy scale and point us to the next energy threshold. Just as we are now expecting a relatively low mass Higgs particle from the precise measurements

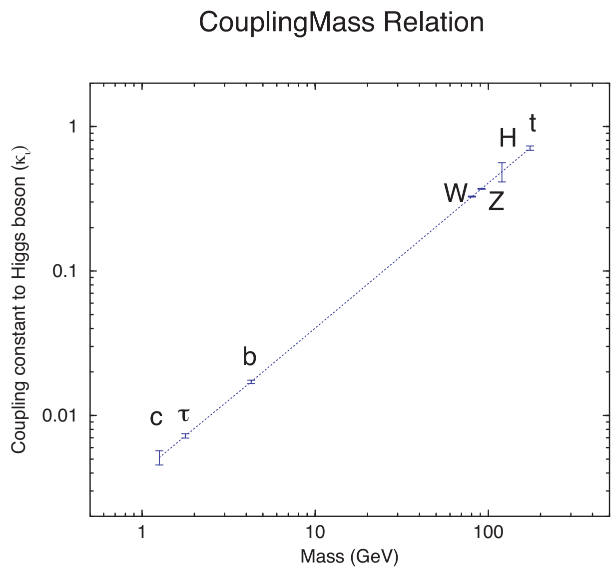

Figure 1. Precision of the coupling constant determination at ILC with $\mathcal{L} = 500$ fb^{-1}. The coupling constant κ_i is defined from the Higgs boson coupling to the "i" particle. $m_i = \kappa_i v$ holds in the standard model. The Higgs boson mass is taken to be 120 GeV. For the charm, tau, bottom, W and Z coupling measurements, $\sqrt{s} = 300$ GeV is assumed. $\sqrt{s} = 500$ GeV (700 GeV) is taken for the Higgs self-coupling ($t\bar{t}H$) coupling measurement (from ref. [4]).

on the gauge interaction, Higgs physics at ILC may determine scenario in higher energy scale.

3. Direct search for new physics

Although there are various reasons to expect physics beyond the standard model, solving the hierarchy problem has been a major theoretical motivation. Now the problem is how to explain the weak scale of $\mathcal{O}(100)$ GeV that is much smaller than the gravity scale of 10^{19} GeV in spite of the fact that this hierarchy seems to be easily destroyed by quantum corrections within the standard model. SUSY is a unique symmetry that can eliminate the quadratic divergence in the Higgs mass renormalization. The composite Higgs scenario is another way to solve the hierarchy problem, and little Higgs models proposed recently are classified in this category [20,21]. There are also attempts to change the gravity scale by considering extra spatial dimensions [22–24].

In all of these proposals, there should be some signals at the TeV scale. Search for such signals is one of main purposes of the LHC experiment. Expected signals depend on the correct new physics model and masses of new particles. In some cases, different models give similar signals at the LHC.

Once some new signals are found at the LHC, ILC experiments are necessary to figure out what is new physics. Spin, quantum numbers and coupling constants of new particles will be measured, and one may be able to find lower mass particles which have escaped detection at LHC. These measurements are important to select a correct new physics model and new physics principle underlying new phenomena. The ILC's ability of beam polarization, energy scan, and well-defined kinematics is a powerful tool for many new physics studies.

Among various new physics models, SUSY is the most promising candidate. This symmetry is realized as a part of generalization of Poincaré algebra, which is algebra formed by space–time symmetries of the relativistic world. In a sense, discovery of SUSY demands change of our understanding of space and time. Furthermore, SUSY plays a fundamental role in the formulation of SUSY theory.

Search limit of squarks and gluino are extended to above 2 TeV at the LHC experiment in ordinary scenarios of SUSY mass spectrum such as the minimal supergravity model [6,7]. Series of SUSY particles are produced by cascade decay processes.

The ILC experiment, on the other hand, produces SUSY particles in pair from lower mass particles. Information on spin and chiral structure is essential for SUSY because it is a symmetry between bosons and fermions. Electron–positron linear colliders are ideal machines, and beam polarization and threshold scan are very useful for this purpose.

By precise determination of masses, spin, quantum numbers and coupling constants of SUSY particles, we can determine various parts of SUSY Lagrangian. These measurements are essential to establish new symmetry and look for deeper structure of the theory. Examples are:

- Test of SUSY relation between electron–selectron–Bino and electron–gauge boson couplings for right-handed selectron productions [25]. The precession of this test may allow us to look for loop corrections to a tree level relation (super-oblique corrections) [26,27].
- Reconstruction of chargino and neutralino mass matrices. This is a SUSY analogy to the weak mixing angle measurement in the $SU(2) \times U(1)$ gauge boson sector. There is also a possibility to measure CP violation measurements in chargino and slepton sectors [28].
- Test of GUT relation between $SU(2)$ and $U(1)$ gaugino masses [29].
- Search for lepton flavor violation in slepton production and decays [30,31]. These measurements have potential impacts on the study of neutrino mass generation mechanism in SUSY models, along with lepton flavor violation searches in charged lepton rare decay processes.
- Determination of the left–right mixing for third generation squarks [32]. These are important parameters for the Higgs mass formula through one loop corrections.
- Tau polarization measurement which is useful to determine the composition of the lightest neutralino [25,33].

In order to understand whole structure of the SUSY model, combined analysis of LHC and ILC experiments is important. Inputs from lower mass spectrum at ILC can improve what can be extracted from LHC experiments. Squark and gluino

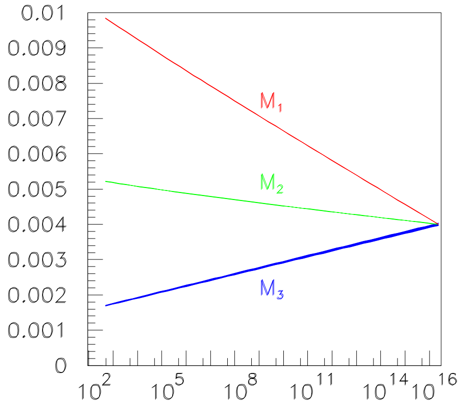

Figure 2. Evolution of three gaugino mass parameters in the SUSY GUT using inputs from LHC and ILC measurements (from ref. [34]).

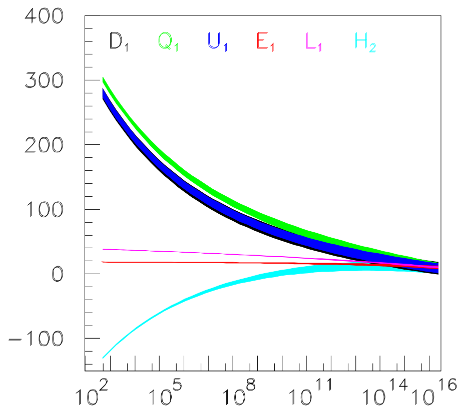

Figure 3. Evolution of scalar quark and lepton and Higgs mass parameters in a minimal supergravity point using inputs from expected results in LHC and ILC combined analysis (from ref. [34]).

masses from LHC and precise measurements on the neutralino, chargino and slepton sectors from ILC allow us to extrapolate SUSY breaking mass parameters toward the high energy scale. In this way we may be able to know the origin of SUSY breaking mechanism and test various unification scenarios. Figures 2 and 3 show how the unifications of gaugino and scalar mass parameters can be tested from combined analysis of LHC and ILC experiments [34].

4. Dark matter and collider physics

There have been significant improvements in our understanding of cosmological parameters. In particular, the recent measurement of cosmic microwave background by WMAP has shown that a large part of the energy content of the present Universe is not understood. Only 4% is made of baryon, and about one-fourth is dark matter and the rest is considered to be dark energy [35]. How to identify the nature of dark matter has become one of the most important questions in particle physics and cosmology.

Since there is no good candidate particle within the minimal standard model, solution of the dark matter problem most likely requires a new physics model. A new particle should have properties appropriate for dark matter. First of all, there should be some theoretical reason to guarantee the stability of the dark matter particle. This usually involves a new global or discrete symmetry. Furthermore, to explain the correct amount of relic density the mass of the dark matter particle is close to the weak scale in an ordinary thermal relic scenario, although different mass range is possible in other cases like the axion dark matter.

If the dark matter particle is in the mass range below 1 TeV, and produced by decays from colored particle, it is possible that some signal is obtained in the missing energy channel of the LHC experiment. Several models are proposed for such signals, for example, SUSY with R-parity, universal extra-dimension model with KK-parity [36,37], and little Higgs models with T-parity [38,39]. In these models, new parity symmetries are introduced by different phenomenological reasons, but a common feature is the existence of an appropriate dark matter candidate.

The ILC experiment is important to determine whether or not the candidate particle is actually the dark matter. Measurements of spin and quantum numbers of new particles at ILC can tell us which new physics model is a correct one. Then, we can determine coupling constants and mass spectrum relevant for calculation of thermal relic abundance of dark matter, and compare theoretical calculation with the dark matter quantity determined by cosmological observation. There have been much work on whether or not LHC and ILC measurements can match the precision obtained by WMAP and future Planck experiments for the case of typical SUSY dark matter [40,41]. It was shown that improvement expected at the ILC experiment is essential for quantitative test for the dark matter. If theoretical prediction agrees with the cosmological observation, we can conclude that the particle produced at collider experiments is indeed the dark matter and the thermal history of the Universe behind the calculation is correct. This will be a significant improvement of our understanding of cosmology.

The identification of the dark matter will also open a new area for astroparticle physics [41]. There are many experimental attempts to detect dark matter signals directly and indirectly. In indirect searches, cosmic ray particles that are supposed to be originated from annihilation of dark matter particles are detected using gamma ray, positron, anti-proton and neutrino. If the dark matter property is determined precisely at collider experiments, annihilation cross-sections in halos of galaxies as well as detection cross-sections for various detection methods are known. We then can obtain important information on how dark matter is distributed in our galaxy or in the Universe, since different methods are sensitive to the dark matter density in different regions. In this way, we may be able to improve our understanding of the Universe. Cosmic parameter determination, identification of dark matter particle at collider experiments, and direct and indirect searches for dark matter are all important in the new field, and ILC is expected to play an essential role.

5. Precision measurements of the standard model processes

Precision measurements in top quark, gauge boson and fermion pair production processes are guaranteed physics in the ILC experiment. On the one hand, precise determination of fundamental parameters like the top quark mass is important by themselves, but the other aspect is that these measurements provide new opportunities to search for new physics.

The threshold scan of the top quark production is unique for ILC. The precision of top mass measurement is about 100 MeV, which is an improvement by more than one order of magnitude from what is expected at LHC. The top quark width can be measured at a few % level.

In the standard model, the top Yukawa coupling constant is among the five dimensionless coupling constants determining the main dynamics of the theory along with the three gauge coupling constants and the Higgs self-coupling constant. Therefore, the top quark mass plays an important role in various phenomenological studies within and beyond the standard model. For example, the analysis on oblique parameters of gauge boson propagators would give a different picture for the new physics constraint with improved top quark mass and the observed Higgs boson mass. It is also known that theoretical prediction on the lightest CP-even Higgs boson mass crucially depends on the precision of top quark masses in MSSM due to large radiative corrections from top and stop loop diagrams. In addition, there is a possibility that new physics effects appear in the top width and anomalous coupling constant measurements. An interesting example is provided by the little Higgs model, where one of the essential ingredients is extension of the top quark sector.

Fermion pair production processes are important channels at ILC. These provide indirect ways to look for new particles beyond the kinematical reach for the collider. For instance, if the correct new physics model contains a new neutral gauge boson (Z'), the indirect search limit can extend to a few TeV range for 500 GeV ILC, which is comparable with direct Z' boson search limit at the LHC. If the LHC experiment finds the new gauge boson, the ILC experiment will become important to determine the coupling constants using angular distribution and initial beam polarization. One such analysis is shown in figure 4 from ref. [42]. We may be able to choose the correct model among possible candidates with an extra gauge boson by combined information on the mass and the coupling.

6. Conclusions

The LHC experiment which will be in operation soon is expected to open a new era of the high energy physics. A Higgs boson is likely to be discovered, and its mass alone provides very important information. New particles and new phenomena are also expected in various new physics scenarios.

The most urgent question of the current high energy physics is to establish the mass generation mechanism of quarks, leptons and gauge bosons, namely the Higgs physics. The discovery of a new particle is only the first step, and we have to check that the discovered particle indeed plays the role of the Higgs boson. This will be

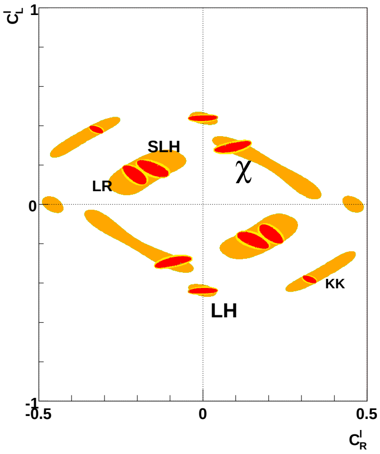

Figure 4. Resolving power (95% CL) for $M_{Z'} = 2$ TeV and $\sqrt{s} = 500$ GeV, $\mathcal{L}_{\rm int} = 1{\rm ab}^{-1}$ for leptonic couplings based on the leptonic observables $\sigma^{\mu}_{P_{e^-} P_{e^+}}$, $A^{\mu}_{\rm LR}$, and $A^{\mu}_{\rm FB}$. The largest region corresponds to the unpolarized case while the smallest region corresponds to electron and positron polarization of 80% and 60% respectively with the middle region corresponding to only electron polarization. The couplings correspond to various models with a Z' boson (E_6 χ, LR, LH, SLH and KK models) (from ref. [42]).

achieved by precise determinations of the Higgs couplings, and ILC will play an essential role for this purpose.

There are several approaches to explore physics beyond the standard model at ILC. The Higgs coupling measurements themselves are one way to find new physics effects. Direct studies of new particles and new phenomena give clear information on the new model, if new particles are kinematically accessible. Even if the collider energy is not enough to produce new particles directly at the first stage of the ILC experiment, indirect searches through processes involving only the standard model particles have great potential to provide useful information in selecting the correct model. ILC's features like clean experimental environment, availability of polarized beams, and energy scan are useful tools for precise measurements.

In this way, TeV scale physics explored at LHC and ILC is expected to help us to understand physics laws at the shortest distance and state of our Universe in the earliest time.

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