# Addendum:
# Japan's Updated Strategy for Future Projects in Elementary Particle Physics

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A submission to the 2020 update of the European Strategy for Particle Physics

The following documents are included in this Addendum:

1. M. Ishino (chair), *et al.*, "*Final Report of the Committee on Future Projects in High Energy Physics*," September 2017.
`http://www.jahep.org/files/20170906-en.pdf`

2. S. Asai (chair), *et al.*, "*Report by the Committee on the Scientific Case of the ILC Operating at 250 GeV as a Higgs Factory*," July 2017.
`http://www.jahep.org/files/ILC250GeVReport-EN-FINAL.pdf`

3. Japan Association of High Energy Physicists (JAHEP), "*Scientific Significance of ILC and Proposal of its Early Realization in Light of the Outcomes of LHC Run 2*," August 2017.
`http://www.jahep.org/files/JAHEP-ILCstatement-170816-EN.pdf`

[1]Represented by High Energy Physics Committee: H. Aihara (chair), A. Ichikawa, O. Jinnouchi, S. Kanemura T. Mori, T. Nakaya, K. Sakashita, M. Tomoto, Y. Ushiroda, T. Yamanaka, and S. Yamashita,

# 1 Final Report of the Committee on Future Projects in High Energy Physics

# Final report of the committee on Future Projects in High Energy Physics

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06 September 2017

# Preface

In February 2012, the subcommittee on Future Projects in High Energy Physics made the recommendation that ”should a new particle such as a Higgs boson with a mass below approximately 1 TeV be confirmed at LHC, Japan should aim for an early realization of an $e^+e^-$ linear collider” and ”should the neutrino mixing angle $\theta_{13}$ be confirmed as large, Japan should aim to realize a large-scale neutrino detector allowing studies on CP symmetry through neutrino oscillations”. In the same year, there were two extremely important results in physics: the discovery of the Higgs boson and the establishment of three-generation neutrino mixing.

The charge of the committee on Future Projects in High Energy Physics is to update the 2012 report based on recent progress in the field and to examine the future plans of the Japanese physics community on a time scale longer than 10 years in the future. The most important task is to report on future large-scale projects while taking into account their competitive and cooperative relationships with other projects around the world. The committee investigated progress in physics since 2012 and discussed new future plans that Japan should realize and lead.

It is also important to continuously advance particle physics research on a variety of fronts, including for example, the Belle II experiment which will start physics running in the next fiscal year, and medium- to small-scale experiments at J-PARC and other facilities. Realization of future large-scale projects may depend on the results obtained from these smaller-scale projects. In addition, a coherent strategy for cosmological observations and underground particle physics experiments needs to be adopted since these fields are becoming more and more important. The committee has therefore surveyed and examined these issues.

The committee on Future Projects in High Energy Physics consists of members the High Energy Committee and relevant persons appointed thereby. This report has been prepared mainly by the latter group based on the discussion among all committee members.

# Contents

# Recommendation

In 2012, not only was a Higgs boson with a mass of 125 GeV discovered at the LHC, but three-generation neutrino mixing was also established. Taking full advantage of the opportunities provided by these discoveries the committee makes the following recommendations concerning large-scale projects, which comprise the core of future high energy physics research in Japan.

- With the discovery of the 125 GeV Higgs boson at the LHC, **construction of the International Linear Collider (ILC) with a collision energy of 250 GeV should start in Japan immediately** without delay so as to guide the pursuit of particle physics beyond the Standard Model through detailed research of the Higgs particle. In parallel, continuing studies of new physics should be pursued using the LHC and its upgrades.

- Three-generation neutrino mixing has been established and has provided a path to study CP symmetry in the lepton sector. Therefore, **Japan should promote the early realization of Hyper-Kamiokande as an international project** due to its superior proton decay sensitivity, and should continue to search for CP violation with the T2K experiment and upgrades of the J-PARC neutrino beam.

The High Energy Committee should pursue all available options to achieve the early realization of these key, large-scale projects.

It is important to complete construction of SuperKEKB and start physics studies as scheduled. Some of the medium- and small-scale projects currently under consideration have implicit potential to develop into important research fields in the future, as happened with neutrino physics. They should be promoted in parallel in order to pursue new physics from various directions. Flavor physics experiments, such as muon experiments at J-PARC, searches for dark matter and neutrinoless double beta decay, observations of CMB B-mode polarization and dark energy, are considered to be projects that have such potential.

Furthermore, accelerator R&D should be continued to dramatically increase particle collision energies in preparation for future experimental efforts that may indicate the existence of new particles and new phenomena at higher energy scale.

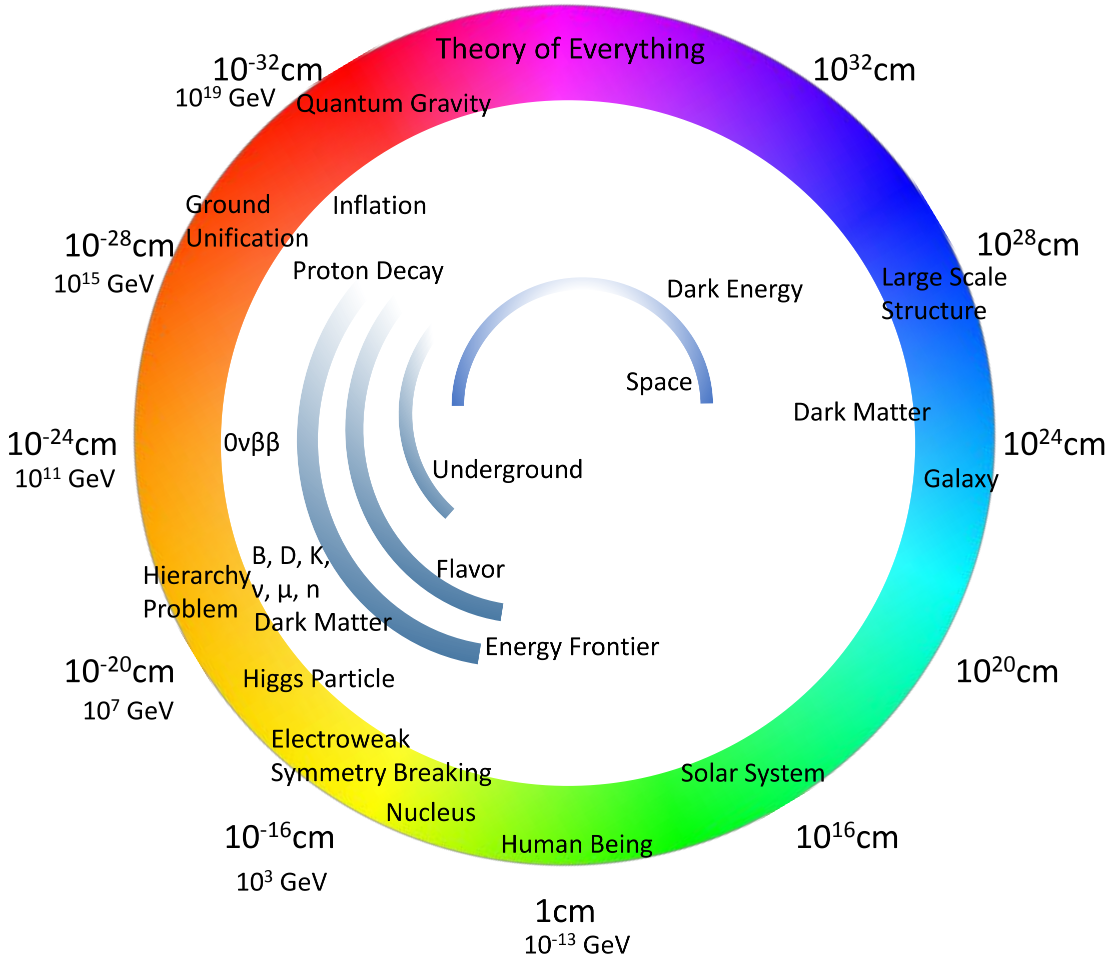


Figure 1: The figure shows the hierarchy of energy scales in the study of matter and physical processes as represented by an ouroboros (Sheldon Glashow, who received the Nobel Prize in Physics in 1979, introduced the idea to map the energy scales onto the ouroboros, and the idea is reused here). Going backward in time, the scale of the universe shrinks smaller and smaller until finally reaching the moment when the universe was born. The physics of both extremely large and extremely small scales are connected and an understanding of microscopic physics is therefore essential to understanding large scale physics. In other words, in order to understand the physics of the beginning of universe, we must also understand the microscopic world of elementary particles. It has long been a dream of physicists to construct "The Theory of Everything", and we are approaching this goal from many fronts including, energy-frontier experiments, flavor experiments, underground experiments and cosmological experiments.

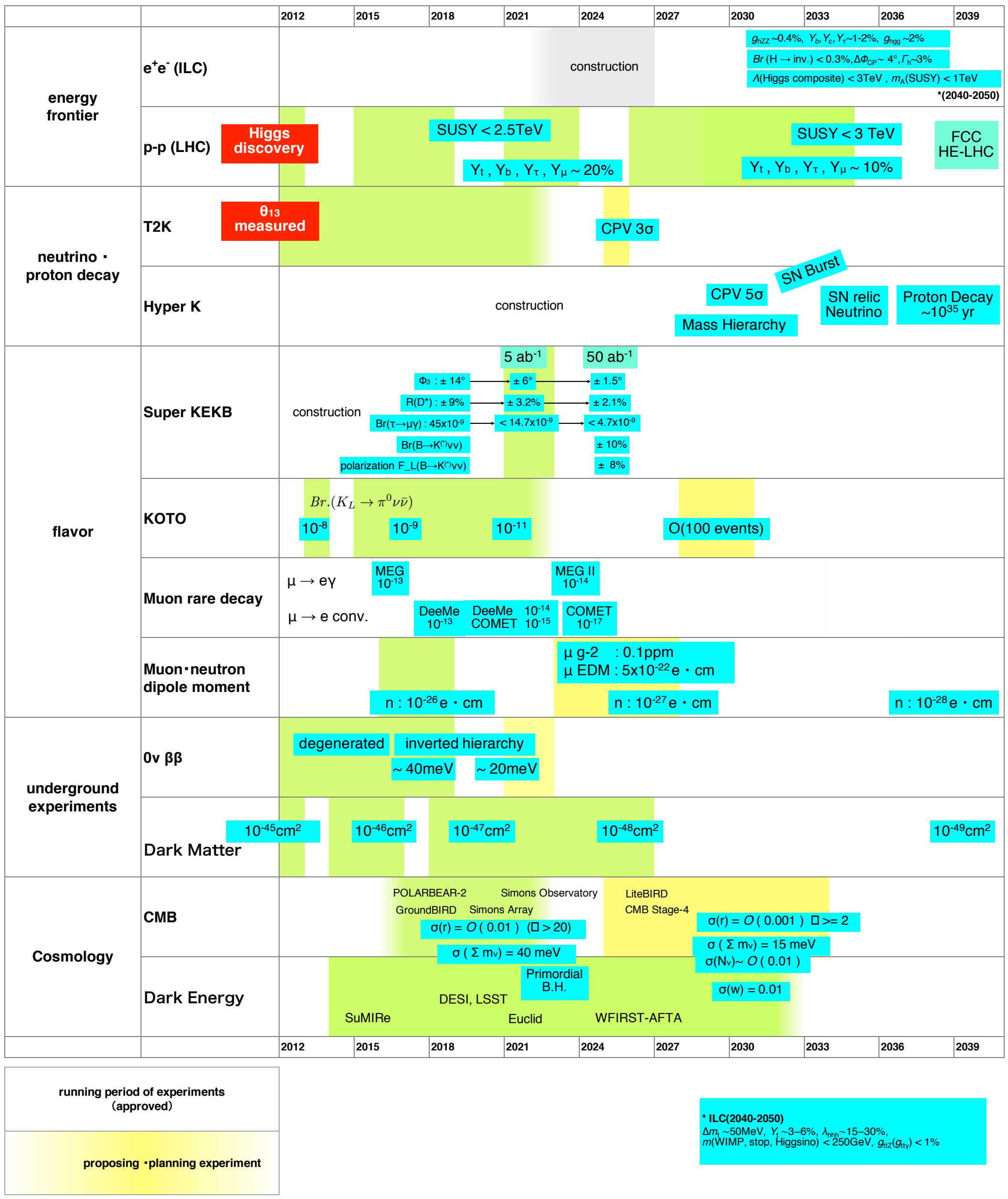


Figure 2: Summary of timelines of ongoing and future projects described in the report. Sensitivities numbers are shown at the times when the sensitivity is expected to be realized (2012 – 2040).

The goal ; Theory of Everything

Approaches from Particle Physics →

| | **Precision measurement of the higgs boson** | **hierarchy problem ・the origin of EW symmetry breaking** | **generation ・ the origin of CP violation** | **Grand Unification ・ origin of the interactions** | **neutrino precision measurement ・ origin of the neutrino masses** | **origin of asymmetry between matter and anti-matter** | **dark matter** | **inflation** | **origin of the accelerating universe** |
|---|---|---|---|---|---|---|---|---|---|
| **ILC・LHC** | Higgs Coupling ・ additional Higgs | SUSY・new particle search | Higgs CP | Gauge Coupling | | Higgs self coupling ・ extra scalar | direct production | | |
| **neutrino oscillation・proton decay** | | | neutrino CP violation | baryon number violation | neutrino mixing matrix | neutrino CP violation and PMNS matrix | indirect search | | |
| **B , D , K** | anomalies in branching ratios (charged higgs) | brancing ratio and anomalies of the angle distributions | CPV ・ new CP violation | | | new CP violation | light Dark Matter | | |
| **muon , tau** | | | LFV, $\mu$-EDM, g-2 | LFV | | $\mu$-EDM | g-2 ・ $\mu$-EDM | | |
| **neutron** | | lifetime | T-Violation | | | EDM ・ $n-\bar{n}$ oscillation | | | |
| **underground & $0\nu\beta\beta$** | | WIMP | | Majorana neutrino ( see-saw ) | Majorana neutrino | Lepton number violation (lepto genesis | Direct Search | | |
| **Cosmology** | | | | inflation | total mass ・ number of generations | | distribution of dark matter | primodial gravitational wave | equation of state |
| | **Precision measurement of the higgs boson** | **hierarchy problem ・the origin of EW symmetry breaking** | **generation ・ the origin of CP violation** | **Grand Unification ・ origin of the interactions** | **neutrino precision measurement ・ origin of the neutrino masses** | **origin of asymmetry between matter and anti-matter** | **dark matter** | **inflation** | **origin of the accelerating universe** |

← Approaches from Cosmology

Figure 3: List of future experiments that will probe "physics beyond the standard model". Projects described in this report are listed vertically and the horizontal axis lists major physics topics to be explored in order to achieve this goal. Each cell describes the target physics parameters for each of these studies.

# 1 Status and Prospects for Particle Physics

## 1.1 Current Status of Particle Physics

Particle physics has evolved to understand the elementary units of matter as well as the basic principles of the interactions between them. The standard model of elementary particles is based on the local gauge symmetry, $SU(3)_C \times SU(2)_L \times U(1)_Y$, and successfully describes all physics processes at energies up to the electroweak scale (approximately 100 GeV). Recently the discovery of the Higgs boson by the Large Hadron Collider (LHC) experiments revealed that spontaneous breaking of the electroweak symmetry is caused by the condensation of the Higgs field.

In spite of great success of the standard model, it is known to inadequately describe physics processes up to the Planck scale. Indeed the model's mass hierarchy problem, which requires unnaturally large radiative corrections to the Higgs mass, can be solved naturally if there are new particles just above the electroweak energy scale. A large number of new physics models, such as Super-Symmetric models or models with Extra-Dimensions, which include such particles have been proposed, and therefore direct searches for new particles using energy-frontier accelerators is highly important. Accordingly, further increases to the instantaneous luminosity of the LHC as well as the extremely clean environment of the International Linear Collider (ILC) will play a key role in extending the reach of searches for new particles.

It is also important to precisely measure the couplings between the Higgs boson and all the gauge bosons and the fermions as well as to further clarify the nature of the Higgs field. The precision of coupling constant measurements is improving as the integrated luminosity of LHC increases. It will improve sharply when the High-Luminosity LHC (HL-LHC) and ILC projects start operations. Differences in the measured coupling constants from the predictions for the standard model Higgs boson will tell us about physics beyond the standard model.

At the same time, research in the flavor violation and the CP asymmetry of quarks and leptons has been evolving to clarify the origin of matter in the universe and the origin of quark mixing. As Japan is operating two world class accelerators, KEKB and J-PARC, it leads the field of the flavor physics and is expected to play an even greater role in future. If new physics exists at TeV energy scales, it may effect the branching ratio of rare decay processes or induce new sources of CP violation. In particular, efforts to achieve higher precision measurements of various decay modes of $B, D, K, \tau, \mu$ have been performed. Recently several experimental results report deviations from the predictions of the standard model. It is therefore highly important to establish the validity of these anomalies and confirm their existence in other physical processes, since they may ultimately guide us to the origin of the mechanisms and shape of physics beyond the standard model. To achieve this goal, many efforts to improve the performance of both accelerators and detectors making this measurements are underway.

The discovery of neutrino oscillations indicates that neutrinos have tiny masses. This fact implies the existence of physics beyond the standard model. In addition, the pattern of flavor mixing in the neutrino sector is largely different from that in the quark sector. This may suggest that the origin of the neutrino masses is different from that of the quark masses. Indeed, if neutrinos are Majorana fermions, their masses could be related to physics at extremely high energy scales, as predicted by the seesaw mechanism. While the neutrino mixing angle of $\theta_{13}$ has been measured by the T2K experiment and reactor neutrino experiments, there are still important questions in neutrino physics, including whether or not oscillations violate CP, whether neutrinos are Dirac or Majorana fermions, the absolute value of the neutrino masses and the nature neutrino mass hierarchy (that is, whether it is normal or inverted). The search for proton decay, which is considered a signature of GUT models, has been explored by Super-Kamiokande with the highest sensitivity in the world. So far a proton decay signal has not been observed and the lower limit on the proton lifetime has been established as $10^{34}$ years for the decay mode $p \to e^+ + \pi^0$.

Connections between cosmology and particle physics are ever increasing. Cosmology has reached the level of a precision science due to recent improvements in cosmological parameter measurements and starting with the results from the Planck project we have gained deep insight into the universe. In particular, the energy densities of dark energy and dark matter are known to be 69% and 26% of the total energy density of the universe, while baryonic matter accounts for only 5%. In addition, cosmic density fluctuations have been observed to be nearly scale-invariant, pointing strongly to inflation scenarios in the early universe. These results provide the basis for constructing the standard model of cosmology but pose new problems for particle physics at the same time. It is currently impossible to understand the generation of the observed matter-antimatter asymmetry in the universe, the origin of its dark matter, the mechanism of inflation, the nature of dark energy, as well as many other topics in cosmology within the framework of the standard model of particle physics. Clearly some new physics beyond the standard model must have played an important role in the evolution of the universe. In order to solve these cosmological problems, new knowledge of physics beyond the standard model from current and future experiments, such as the LHC and the ILC, is indispensable.

## 1.2 Prospects for Particle Physics

The standard model of particle physics, as an excellent effective theory up to the electroweak energy scale, has been completed by the discovery of the Higgs boson in 2012 and subsequent measurements of its mass, spin, and parity. At the same time, pathways to discover new particles and phenomena beyond the standard model and to elucidate physics at higher energy scales have have become clear. Energy-frontier experiments have adopted an extremely effective approach of seeking to discover new particles directly and to reveal the vacuum structure by precisely measuring the production and decay of the Higgs boson.

The direct discovery of new particles is the most important approach to pursue with energy-frontier accelerators. As the luminosity of the LHC increases, the frequency of collisions with partons carrying higher momenta increases and the ability to discover new particles, such as super-symmetric particles, is extended. The LHC experiments have a high potential to discover new colored particles, while the ILC, which will observe collisions in a cleaner environment, has better sensitivity to find new particles without color. It is necessary to exhaustively survey the widest possible parameter space using both the LHC and the ILC.

When new particles are discovered, their interactions and quantum numbers need to be determined to clarify the laws of physics behind them. In addition, the entire landscape of new physics should be explored by searching for as yet undiscovered particles predicted by the theoretical frameworks describing those laws. The ILC and the High-Luminosity LHC will be used to extract as much physics as possible, but if it turns out that the next generation of accelerators is necessary to reach beyond the standard model, the energy scale of those machine should be clearly determined, and the technical developments will be advanced in parallel.

The other important approach is to measure various Higgs particle production and decay processes and to determine the coupling constant of the Higgs boson with $W/Z$ bosons, the top, bottom, and charm quarks, as well as the $\tau$ and $\mu$ leptons. Such measurements will determine if there is a universal relationship between the mass of the elementary particles and the coupling constant as expected from the standard model, or if different relationships are seen between bosons and fermions, up and down-type fermions, or the second and third generation fermions. If the Higgs vacuum shows such an unexpected property, it will open up a path to elucidate physics beyond the standard model.

The LHC is only the accelerator that can currently generate Higgs particles, and the precision of its coupling constant measurements will be improved intermittently as the luminosity is increased in preparation for the High-Luminosity LHC project. The ILC project is going to measure the decay rates of Higgs boson produced by electron and positron collisions in an exceedingly clean environment and will thereby achieve the most precise coupling constant measurements. Now that the mass of Higgs particles has been revealed, the ILC accelerator is essential to the construction of tera-scale physics models beyond the standard model and therefore needs to be realized as soon as possible.

At energy-frontier experiments, the typical approach to search for new phenomena at high energy scales is the direct search for new particles. However, in terms of a complementary approach, there are various indirect ways to explore phenomena at high energy scales without increasing the energy of particle accelerators. It is possible to find quantum effects from new physics by increasing beam intensities and searching for rare phenomena that cannot be explained by the standard model. New physics can be identified over energies up to about 10 TeV with precise measurements of B meson, D meson, $\tau$-lepton and other decay processes, and CKM matrices using the Belle II and LHCb experiments. Furthermore, similar studies are possible with measurements of the rare kaon decay processes in the KOTO and NA 62 experiments. The full search for physics beyond the standard model will combine the results of these varied approaches.

Searching for symmetry breaking is an effective experimental technique to probe new physics at higher energy scales. Flavor symmetry is an imperfect symmetry, but lepton flavor is a conserved quantum number in the standard model. The branching fractions of charged-lepton-flavor-violating processes are very small even if the light neutrino mass is taken into account. An upper limit on the branching ratio of the $\mu \to e\gamma$ process, which is one of the charged-lepton-flavor-violating processes, has been produced by the MEG experiment. The discovery of new physics processes which break flavor symmetry as result of physics at higher energy scales is expected with the improved sensitivity of searches for $\mu \to e\gamma$ process with the MEG-II experiment, $\mu \to e$ conversion with the COMET and Mu2e experiments, and rare $\tau$ lepton decays with the Belle II and LHCb experiments. CP symmetry is not a strict symmetry, and the degree to which it is broken as introduced by the Kobayashi-Maskawa theory is too small to explain the matter-antimatter asymmetry of the universe. Though the standard model predicts a minuscule neutron electric dipole moment, there is no reason to expect CP violation is small at higher energy scales. Accordingly, there is the possibility to discover evidence of CP symmetry violation from new physics processes by precise measurements of $B$ decays with Belle II, rare kaon decays with KOTO, and precision measurements of the neutron electric dipole moment with experiments at TRIUMF, PSI, and J-PARC. Hints of baryon-number-violating processes predicted by GUT at even higher energy scales (i.e. greater than $10^{15}$ GeV) may be obtained from observations of proton decay with extremely large scale neutrino detectors. The decay process $p \to \bar{\nu} + K^+$ is predicted by various SUSY-GUT scenarios and will be searched for at the Hyper-Kamiokande and DUNE experiments with much higher sensitivity than the Super-Kamiokande experiment. Furthermore, the Hyper-Kamiokande experiment will be able to measure the lifetime of the proton via the $p \to e^+ + \pi^0$ process, which is predicted by many GUT models, with one order of magnitude better sensitivity than the current upper limit.

Observations of neutrino oscillations strongly support the presence of physics beyond the standard model. To understand the phenomenon in detail, further studies of the neutrino are necessary. Three-generation neutrino mixing has been established by recent measurements by the T2K and reactor neutrino experiments, and in addition, hints of CP violation in the neutrino sector have been reported by the T2K experiment. It is important to continually increase the intensity of the J-PARC neutrino beam and advance studies of neutrino oscillation, including the search for CP violation at the T2K extension T2K-II, on the way to realizing Hyper-Kamiokande. Precise measurements of CP violation and the determination of the neutrino mass hierarchy will be carried out by future experiments, namely Hyper-Kamiokande with the J-PARC neutrino beam and its competitor, the DUNE experiment in the U.S. A full picture of neutrino flavor mixing will be revealed with these experiments. Hyper-Kamiokande has better sensitivity to the CP violation search and has broader physics capabilities, including supernova neutrino observations, and an early start of the project is essential. It is important to proceed with further upgrades of the J-PARC neutrino beam while improving results from existing projects. It is considered as one of the major goals of future projects in particle physics to obtain a unified picture of the flavor structure and origin of CP violation through the combination of knowledge of flavor mixing in the lepton and quark sectors. In addition, searches for neutrinoless double $\beta-$decays ($0\nu\beta\beta$) by, for example, KamLAND-Zen are important to settle the issue of whether the neutrino mass is Majorana- or Dirac-type. If the neutrino mass is Majorana-type, it supports the notion that the tiny neutrino masses are a natural consequence of the seesaw mechanism, and the baryon-anti-baryon asymmetry can be explained by the leptogenesis scenario.

Significant progress is also expected in understanding the properties of dark matter. There are various dark matter candidates, including weakly interacting massive particles (WIMPs), coherent oscillation of scalar condensation, and others. Among them, there is also a scenario in which thermally produced WIMPs were not entirely annihilated in the early universe and left its thermal bath. In order for such thermally-produced WIMPs to be the main component of dark matter, their pair annihilation cross section should be at about 1 pb, which corresponds to the cross section obtained from exchanging a particle with a mass of order 100 GeV to 1 TeV. Accordingly, the dark matter particle may be embedded in a particle physics model that resolves the hierarchy problem. In fact, the cross section of supersymmetric dark matter particles scattering off nuclei may be large enough to be detected by current and future direct dark matter detection experiments. Hence, the determination of the nature of dark matter particles by future direct detection experiments with large-scale detectors, such as the XMASS, LZ and XENONnT is anticipated.

At the LHC, dark-matter particles may be found in measurements of missing transverse momentum. With the discovery of such a candidate, detailed studies of its properties will be necessary to confirm whether it is really consistent with the dark matter in the universe. For a weakly interacting dark matter candidate, those properties can be investigated in further detail with the ILC if the production cross section is large enough. Such studies provide important information to determine the production and interaction cross section of dark matter particle. This is essential for dark matter searches and to our understanding of the thermal history of the universe.

Progress is also expected in the understanding of the evolution of the universe through inflation, mainly from observations of the cosmic microwave background (CMB). Especially, the B-mode polarization of the CMB can be produced from primordial gravitational waves due to the oscillation of spacetime during inflation. Therefore, the observation of this polarization, if it is made, will strongly support the inflation scenario, and in addition, it will provide information on the energy scale of inflation. If the tensor-to-scalar ratio, which represents the intensity of primordial gravitational waves, is larger than 0.03 the Simons Array ground-based experiment is expected to discover the B-mode polarization. Future projects searching for this polarization are being considered both in and out of Japan using scientific satellites, which will enable all-sky observations without interference from atmosphere. These projects will search for B-mode polarization with sensitivity to tensor-to-scalar ratios of 0.001 and can potentially validate major inflation models. In Japan, the LiteBIRD project aims for an early realization of these measurements by focusing on specific scientific goals. In addition, progress in the study of dark energy and the origin of the accelerating expansion of the universe, is expected from the SuMIRe project, which is in operation at the Subaru Telescope, and from future wide sky survey projects on both the ground and in the space.

# 2 Energy Frontier Physics

## Overview

Research at energy frontier aims to discover new particles and phenomena as well as determine their properties and the laws of nature governing them using high energy particle accelerators. Numerous accomplishments in this area include the discovery of quarks, leptons, and gauge bosons as well as the measurement of their quantum numbers, coupling strengths, symmetries of their interactions and the number of particle generations. Precision measurements performed at the LEP, the SLC, and the Tevatron provided firm ground for the gauge sector that forms the basis of the standard model. After the discovery of the Higgs boson with a mass of 125 GeV in the year 2012, its spin-parity has been determined to be $0^+$ and the precision of the measurements of the couplings to the gauge bosons and the fermions has been improving. These efforts have advanced our understanding on the origin of the mass of elementary particles and the structure of the vacuum. The next targets for energy-frontier experiments are the direct search for new particles and phenomena and the precise measurement of the coupling constants of the Higgs boson to the elementary particles in order to determine whether there is any deviation from the prediction of the standard model.

In order to study higher energy phenomena at hadron colliders such as the LHC, either the beam energy must be increased with stronger bending magnets to keep particles on their circular trajectory or the luminosity must be increased to obtain higher collision rate of high-energy partons. In contrast, for lepton colliders, such as a linear collider, which do not suffer from acceleration losses due to synchrotron radiation, the collision energy must be increased, or alternatively a heavy lepton (muon) collider must be used.

Since the beams at hadron colliders consist of protons or antiprotons, which are composite particles, a wide variety of physics phenomena can be studied from a broad perspective depending on the energies carried by the colliding partons, including the standard model, the top quark, the production and decay of the Higgs boson, and searches for new particles. On the other hand, there are issues that come from multiple interactions occuring in the same beam bunch (pile-up) and large backgrounds coming from non-colliding partons. Since all the beam energy at lepton colliders is converted into the reaction, the final states are clean and thus precision measurements can be performed. Once new particles have been discovered, their properties can be studied in detail at such machines. In addition, the beam energy and the polarization can be adjusted to separate the intermediate and final states of the interactions, enabling the determination of the symmetry in the reaction as well as the quantum numbers of the new particles.

## 2.1 International Linear Collider

The ideal machine to further study the Higgs boson discovered at the LHC is considered to be the International Linear Collider (ILC). At the ILC linear accelerators will be installed in a tunnel to accelerate electrons and positrons in opposite directions and produce head-on collisions. Unlike circular colliders, the ILC can start with an accelerator length providing the energy required for the initial target of the physics study, and subsequently extend its length to increase the energy according to the results from the initial study. The center-of-mass energy of 250 GeV can be realized with a 20 km straight machine and 500 GeV can be reached if it is extended to 30 km. A future option to upgrade to 1 TeV or even higher is also within the ILC's scope when possible improvements in accelerator technologies are considered.

The initial target of the ILC is to clarify the Higgs boson. The properties of the Higgs, boson such as its couplings to other elementary particles will be studied in detail with a center-of-mass energy of 250 GeV, which will subsequently determine the future direction of searches for physics beyond the standard model.

The cross-section of $e^+e^- \to Zh$ is maximized at the center-of-mass energy of 250 GeV, and $5 \times 10^5$ Higgs bosons will be produced with an integrated luminosity of $2\,\mathrm{ab}^{-1}$ in a clean environment with a good signal-to-noise ratio. The Higgs couplings can be precisely measured in a model-independent manner through the analysis of the recoiling $Z$-boson from this process. The gauge couplings can be determined with a precision of 1% and the Yukawa couplings to the bottom quark, charm quark, and $\tau$ lepton can be determined to 1–2%. The $h\gamma\gamma$ coupling can also be determined to 1–2% by taking advantage of the synergy with the LHC. Even if the Higgs boson decays to invisible particles such as dark matter, the branching ratio sensitivity will be better than 0.3%. The mass and total width of the Higgs boson can be determined to within 15 MeV and 3%, respectively. The CP phase angle of the Higgs boson can be measured with a precision of 4°. Any deviation from the expected coupling constants of the standard model will be a clear evidence of new physics. Furthermore, the pattern of such a deviation will help pin down the new physics model. If the Higgs boson is a composite particle, its energy scale can be probed up to 3 TeV. If the Higgs boson is an elementary particle as in SUSY models, the mass of the heavy Higgs boson can be probed up to 1 TeV.

New particles that may escape detection at the LHC could be discovered at ILC through their direct production. For new particles that do not create a mass peak, such as supersymmetric particles and light dark matter particles with no color charge, it may be difficult to discover them at LHC due to overwhelming backgrounds. At a lepton collider, though, their discovery would be certain if the collision energy exceeds their production threshold. New particles without color charge can be discovered via their decay products or using initial state radiation and it may be possible to determine the properties of dark matter particles through detailed measurements of this kind. In addition, phenomena or particles that are not currently predicted in any model may also be discovered. Furthermore, new physics at energy scales much higher than the collision energy, such as the $Z'$ bosons up to and exceeding 10 TeV, can be studied indirectly through comparison with precise theoretical calculations. The possibilities to study fundamental physics which play an essential role in the very early universe, such as those predicted in Grand Unified Theory (GUT), are also being discussed.

The ability to extend the energy of the ILC is a great advantage it has over circular colliders. After detailed studies of the Higgs boson at a center-of-mass energy of 250 GeV, various physics can be studied by increasing the energy to exceed the energy thresholds for important processes, including top-pair production at around 350 GeV and $e^+e^- \to Zhh$ and $e^+e^- \to t\bar{t}h$ at around 500 GeV. The measurement of the triple Higgs self-coupling $\lambda_{hhh}$ performed mainly through the double Higgs radiative process $e^+e^- \to Zhh$ is considered to be one of the most important goals of the ILC since it would allow us to directly probe the origin of the electroweak symmetry breaking. It can be measured with a precision of 15–30% with an integrated luminosity of $4\,\text{ab}^{-1}$ around 500 GeV. The top-Yukawa coupling can also be determined through the reaction $e^+e^- \to t\bar{t}h$ with a precision of 6(3)% at a center-of-mass energy of 500(550) GeV.

Overall Plan, Framework, Budget and Schedule

ILC will be able to make significant progress, not only in the understanding of elementary particle physics and cosmology, but also in advanced technologies such as super-conducting accelerators. Furthermore, it would lead to the construction of a new international research center integrating academic, educational, and technological activities.

From 2000 to 2002, the world-wide high energy physics community, mainly represented by Asia, the U.S. and Europe, established a consensus with the aim to jointly constructing an electron-positron linear collider as a priority for its next main project. According to the agreement, the physics studies at ILC and the design of the accelerator and detectors have been performed as fully international activities. Notably, after the Global Design Effort (GDE) was established in 2005 by major particle physics laboratories operating high energy accelerators (KEK, DESY, Fermilab), global activities had been promoted intensively to further the detailed technical design of ILC. Consequently, the Technical Design Report (TDR) was published in June 2013. More than 1000 researchers and engineers, and more than 300 laboratories, universities (over 40 in Japan), and many private companies participated in these R&D efforts. As the Asian research center, the Japanese ILC team including KEK plays a leading role. Synchrotron light facilities, based on the similar superconducting accelerator technology to that is developed by the ILC project, are being constructed in Germany and the U.S. The facility in Germany started operation in July 2017. Detector R&D has been advanced by two large international collaborations, corresponding to two experimental proposals.

The GDE was dissolved with the completion of the TDR and two new organizations were set up in 2013. One is the Linear Collider Collaboration (LCC), which coordinates international R&D efforts for next-generation linear accelerator projects, and the other is the Linear Collider Board (LCB), which oversees the LCC. In 2013, the ILC site evaluation committee of Japan announced the result of their site assessment that the Kitakami site is evaluated to be the best domestic candidate site for the ILC. Accordingly, the LCC started site-specific design studies for Kitakami site. The construction of the ILC in Japan is supported in Europe, Asia and the U.S. as part of their respective particle physics research strategies.

The schedule of the ILC project aims to start the operations sometime in the late 2020s to the early 2030s following three development phases, the pre-preparation phase, the preparation phase and the construction phase. In the pre-preparation phase, which is the current phase, various issues are being tackled, including critical issues raised by MEXT-established ILC Advisory Panel, the detailed design of the accelerator and detectors, the site-specific design of the facility, beam acceleration tests and the development of the construction plan. All of these items are crucial for the approval of the ILC project and will be completed in 2017 or 2018. The project will enter the main preparation phase once it has been approved, followed by the construction phase, which will take about nine years. The ILC will then start operations thereafter.

The TDR published in 2013 is based on a reference design assuming a center-of-mass energy of 500 GeV which estimated construction and annual operation costs to be 7.78 billion USD and 390 million USD, respectively. Cost reduction efforts making use of possible technological innovations and technical design optimizations are underway.

Now that the Higgs boson has been discovered, the first issue to be targeted by the ILC is the detailed study of its properties. Therefore, a staging scenario is being seriously considered which starts with the construction of the accelerator for the center-of-mass energy of 250 GeV and is later followed by step-by-step increases in energy. This staging approach will lead to a significant reduction of the initial costs and is considered to be crucial for the early realization of the ILC.

The Japan Association of High Energy Physicists (JAHEP) proposed the staging approach to start with a 250 GeV-ILC in October 2012 and recently made this proposal again July 2017, calling for the early realization of the ILC as a Higgs factory.

Other Higgs Factory Projects

A center-of-mass energy of 250 GeV is now an important target after the discovery of the Higgs boson. A shorter version of the collider is being considered for the early realization of the project. The Compact Linear Collider (CLIC), which is an electron-positron linear collider at a multi-TeV center-of-mass energy exceeding that of ILC has been studied within the framework of a worldwide collaboration lead by CERN. As a Higgs factory, conventional normal-conducting X-band accelerator technology is being considered instead of the two-beam acceleration scheme that is the current baseline technology for CLIC.

The feasibility of the FCC-ee, an electron-positron circular collider installed in the 100 km FCC tunnel is being studied by CERN. Center-of-mass energies ranging from 250 GeV to 350 GeV are envisaged. Similarly, a circular collider using a 54 km tunnel (CEPC-SppC) is being considered in China, either as an electron-positron collider or a proton collider. Center-of-mass energies of 240 GeV and 100 TeV, respectively, are envisaged for these options.

Since the energy loss due to synchrotron radiation rapidly increases at higher beam energies in circular accelerators, it is not possible to significantly increase the center-of-mass energy for circular electron-positron colliders. Even if the ILC starts as a 250 GeV "Higgs Factory", the study of the Higgs self-coupling and searches for unknown particles and phenomena can be performed by extending the accelerator and increasing the collision energy. This energy extensibility is a great advantage over other Higgs factory projects based on circular colliders. In order to retain its significance as a "Higgs Factory", it is important to realize the ILC as soon as possible, while carefully watching the development of circular electron-positron colliders.

ILC Detector Technology R&D

ILC detector technology R&D is being undertaken by two international collaborations responsible for the designs, ILD and SiD. To improve the hadron jet reconstruction scheme (Particle Flow Algorithm) invented at the LEP experiments, a pixel vertex detector, a large-solid-angle tracking detector, and a fine-segmented calorimeter which is able to distinguish each showering particle, are being developed. In Japan, a version with a vertex detector surrounding the interaction point, a calorimeter, and a large TPC tracking detector are being developed. In close collaboration with theory groups, sensitivity studies and optimization of the detector concept are being advanced. Japanese physicists participate mainly in the ILD conceptual design, leading the ILC physics and detector studies in Asia and also organizing an international collaboration with our European and U.S. counterparts. Japanese detector operation experience with Belle II, ATLAS and the T2K near detector has provided useful information used to develop important components of ILC detectors.

ILC Accelerator R&D

In terms of ILC accelerator R&D, important technologies such as polarized electron sources, positron beams, flat ultra-low emittance beams, high gradient superconducting accelerating cavities, and nano-beam focusing are being developed.

The ILC 1.2 m long accelerating cavities formed from nine superconducting Nb nine-cell cavities are cooled down to 2 K and operated at 31.5 MV/m. ILC consists of 1700 cryomodules and 15000 cavities. In order to fabricate such a large number of cavities within a reasonable time period and at a reasonable cost, all while meeting the required performance specifications, the manufacturing process has to be tightly controlled. One of the goals set in 2012 is to achieve a cavity production yield greater than 90%, satisfying the 35 MV/m gradient requirement, which has almost already been met. The same manufacturing technology of superconducting cavity and cryomodule as ILC is being used at a synchrotron light facility now under construction in Germany (an x-ray free electron laser facility), and an average accelerating gradient of 27.5 MV/m has been achieved, exceeding the required 23.6 MV/m, for its 800 cavities. The main issue going forward is further cost reduction. The industrial fabrication of ILC components is being intensively advanced by design and optimization of cavity and cryomodule production lines and by constructing a pilot plant for production system engineering.

KEK operates key test facilities for ILC, including The Super-conducting RF Test Facility (STF) and the Accelerator Test Facility (ATF). The aim of the STF is to demonstrate the performance of the ILC's main linac cryomodule (a cryogenic chamber containing the super-conducting accelerator cavities). High-power RF tests were carried out using 12 nine-cell superconducting cavities in a cryomodule, where an acceleration gradient exceeding the ILC requirement of 31.5 MV/m was achieved in eight out of twelve cavities. Four of those showed a gradient higher than 35 MV/m. R&D work into thing such as the optimization of the cryomodule production process is now underway in order to achieve component stability while meeting performance requirements.

The aim of the ATF is to generate a ultra-low emittance beam using radiation damping, and to develop and demonstrate the beam diagnostic system with using the beam as well as the final focusing system. The ATF has already achieved a 0.015 mm·mrad normalized vertical-emittance, surpassing the ILC requirement. Furthermore, using this ultra-emittance beam a beam size as small as 41 nm and approaching the target of 37 nm, has already been achieved at the prototype ILC final focus system (ATF2). Precise control of the beam position is required for the stable beam collision at ILC. The beam position jitter has been successfully reduced from 410 nm to 67 nm using a feedback system developed at ATF2. The jitter is limited by the accuracy of the beam position monitor.

A polarized electron source has been developed by SLAC and Nagoya University and has already achieved 90% polarizations. The issues here are developing and demonstrating a laser drive system to generate a 1 ms long pulse train. Activities related to the production of positrons including, research and development towards a superconducting helical undulator and the prototyping of a generation target, are in progress. Further, an alternative positron source using an electron beam has been proposed in Japan.

## 2.2 LHC Upgrade

Introduction

The two large-scale detectors, ATLAS and CMS, were designed and constructed at two of the collision points of Large-Hadron-Collider (LHC) with the aim of discovering a Higgs boson and searching for physics beyond the standard model. The LHC accelerator has been running at a center-of-mass energy greater than 7 TeV since 2010. The Higgs boson was found in 2012 with a mass of 125 GeV and a spin-parity state of $0^+$. As the beam energy and the instantaneous luminosity of the LHC improves continuously, the reach of new physics searches are being extended and the precision of coupling constant measurements of the Higgs boson to both gauge bosons and fermions are also improving. The LHC has been developing the energy frontier since the beginning of its operations. The final focusing magnet of the LHC was designed and constructed by a collaboration of KEK (Japan) and Fermilab (USA) and it played a key role in achieving an instantaneous luminosity of $1.4\times10^{34}\text{cm}^{-2}\text{s}^{-1}$ in 2016, which is 40% higher than the design value. The performance and stability of the final focusing magnet is one of the most important components for success.

There are 16 Japanese universities and one laboratory in the ATLAS collaboration and they have been making significant contributions to the design, construction, commissioning, and operation of various systems including the solenoid magnet, the silicon-strip detector, and the muon-trigger system. In recent years, grid computing systems have become a vital tool for processing large scale data and obtaining physics results. Japan also makes significant contributions to the grid computing system. On top of these contributions, Japanese ATLAS collaborators are achieving outstanding physics results, an example of which is the discovery of the Higgs boson decaying to two photons. Further, several important physics topics have have been explored by young Japanese researchers and students, including contributions to searches for SUSY particles and precision measurements of the standard model particles.

Physics researches in the LHC upgrade project

After the discovery of the Higgs boson, a new era in the exploration of physics beyond the standard model has begun. Direct observations of new particles as well as precise measurements of the Higgs boson are considered to be effective approaches. In terms of precision measurements of the Higgs boson, its couplings to the $W/Z$-boson, top quark, bottom quark, $\tau$ and $\mu$ will be measured with a precision of 1 to 10% with an integrated luminosity of $3000\,\text{fb}^{-1}$. It is crucial to test whether the couplings of the Higgs boson with other elementary particles are consistent with the predictions given by the standard model or there are different rules governing the coupling to bosons and fermions, up-type and down-type fermions, or the second and the third generation fermions.

Direct searches for new particles is another main subject of the LHC upgrade program and the strategy is to extend their reach by increasing the instantaneous luminosity significantly. The targets of new physics searches are SUSY particles produced by the strong interaction, third-generation squarks, which are expected to be relatively light due to naturalness considerations, SUSY particles produced by the electroweak interaction, extra dimensions, and $Z'$. They may be observed as resonances or broad excesses over the standard model background. Taking the search for the SUSY gluino as an example, the mass region up to 2 TeV has been excluded (13 TeV , $10\,\text{fb}^{-1}$ ). By increasing the integrated luminosity to $300\,\text{fb}^{-1}$ with 14 TeV, the reach will be extended to 2.5 TeV, and then to 3.0 TeV with $3000\,\text{fb}^{-1}$.

The development of the High-Luminosity LHC

To realize the physics program with the High-Luminosity LHC (HL-LHC), the accelerator complex will be upgraded and operated according to the following schedule. An integrated luminosity of greater than $100\,\text{fb}^{-1}$ will be accumulated with a center-of-mass energy of 13 TeV by the end of 2018 (Run-2). During the subsequent two-year shutdown (1) a new LINAC (LINAC4) will be introduced (2) the PS-Booster energy will be increased from 500 MeV to 2 GeV for better emittance (3) the SPS will be upgraded to increase the RF power and mitigate the electron-cloud problem, and then the bunch current will be increased by a factor of two. In the three years from 2021 to 2023 (Run-3), the peak instantaneous luminosity will be increased to greater than $2.0\times10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and an integrated luminosity to $300\,\mathrm{fb}^{-1}$ at a center-of-mass energy of 14 TeV will be collected. During a two year shutdown thereafter, various major upgrades of the accelerator components, including the replacement of the final focusing magnets and the beam-separation dipole magnets, the upgrade of the main beam collimators, and the installation of new RF crab cavities, are scheduled to kick off the High-Luminosity LHC project (HL-LHC) by the year 2026. In terms of machine operation, the instantaneous luminosity is controlled to $5.0\times10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ by introducing the luminosity leveling techniques to maximize the integrated luminosity with longer beam lifetimes. The plan is to accumulate $3000\,\mathrm{fb}^{-1}$ in ten years. The HL-LHC project has been officially approved by the CERN council held in June 2016.

The key components for the success of the HL-LHC project are the performance of the magnets placed around the beam collision points, notably the final focusing quadrupole magnets and the beam separation dipole magnets, and the crab RF cavities. To increase the luminosity significantly, the beam will be defocused before the collision point and then strongly squeezed ($\beta^* = 0.40$ m , the 2016 value, will be changed to 0.15 m). To cope with this beam handling, the bore size of the final focusing magnet needs to be enlarged and at the same time the field strength needs to be increased from 8.6 Tesla to 11.4 Tesla. This will be done using a new superconducting material, $Nb_3Sn$, which will be applied as an accelerator component for the first time. A small scale prototype magnet with a length is 25% of the final model has been developed by a collaboration between CERN and and the U.S. that has successfully conducted a 18 kA electric current. This current corresponds to 108% of the 16.47 kA operation current and meets the criteria for acceptance. Concerning the beam separation dipole magnets, KEK has constructed a prototype magnet with 33% of the final design length and an operational 5.6 Tesla magnetic field has already been achieved. Crab RF cavities are used to rotate beam bunches and keep geometrical loss factors as low as possible even when the beam-crossing angle is large. This is the first time a crab RF cavity will be used in a proton machine. Based on the success on the crab cavity at the KEKB factory, further contributions from Japan are highly anticipated.

Detector developments for HL-LHC

There are two major upgrade tasks for the ATLAS spectrometer, one is to replace all the inner trackers and the other is to revise all the trigger and DAQ systems. Aiming to keep the performance as high as possible in a high radiation background, five layers of pixel detectors and four layers of strip detectors with highly radiation tolerant silicon sensors will be installed. Since the Japanese group has experience assembling the ATLAS silicon detector as well as the fact there is a major silicon sensor vendor in Japan, further contributions from Japan are highly anticipated. Accordingly, the Japanese group is currently focused on the pixel detector and is intensively developing the silicon sensor. Those efforts will be followed by the detector construction, installation and operation.

In terms of the triggering and DAQ, in order to efficiently record the target physics objects under high luminosity conditions, the system will be designed with the longer trigger latency, $10\,\mu$s, as well as an increased data storage rate of 1 MHz. The current numbers are $2.5\,\mu$s and 100 kHz, respectively. Due to the longer latency, sophisticated trigger algorithms that are usually used in the offline analysis will be introduced to the first stage hardware trigger. The ATLAS Japan group is focused on these subjects and is intensively working on the development of the silicon sensors, the triggers and the readout system.

<u>The plan to upgrade the LHC beam energy</u>

Technology developments for the HL-LHC project may open the door to upgrade the LHC beam energy. There is a plan to construct the High-Energy LHC (HE-LHC) with a center-of-mass energy of 33 TeV sometime after 2030 or preparing a large scale tunnel and increase the center-of-mass energy of 100 TeV (FCC). The key technology is strong magnetic fields. Improving the critical current density performance of the superconductor, $Nb_3Sn$, to enable field strengths of 16 Tesla is required all while enabling the magnets are robust enough for mass production. In parallel to the development of $Nb_3Sn$ alternative materials such as ReBCO should be studied. The development of the superconducting magnets for the HL-LHC project is considered an important milestone for future energy-frontier accelerators. It is further important to study various kinds of basic technologies related to accelerator magnets to make further improvements.

## 2.3 Future Accelerators and Novel Acceleration Techniques

<u>Compact LInear Collider (CLIC)</u>

The Compact Linear Collider (CLIC) is a potential future linear collider which aims to collide electrons and positrons at energies of several TeV. It has been proposed and developed as an international collaboration between CERN and other laboratories in the world. In order to produce an acceleration gradient of 100 MV/m, CLIC adopts a two-beam concept, which utilizes the microwave produced by the deceleration of a low energy drive beam instead of using conventional microwave sources such as klystrons. The total length of CLIC is planned to be about 50 km and the linac frequency will be 12 GHz (X-Band) in order to realize this compact size.

The technical challenges of CLIC are pulse compression of the drive beam, transmission of the microwave with high efficiency, fabrication of an accelerator tube which is free from discharge even in the 100 MV/m, and alignment of the acceleration tube to 10 $\mu$m precision over long distances among others. A number of cutting-edge R&D efforts are being pursued after the first conceptual design report (CDR) was published in 2012.

Muon Collider

A muon collider is another candidate for a future energy-frontier collider. The highest energy realizable by an electron-positron circular collider is limited by energy losses from synchrotron radiation. However, this problem can be mitigated by using muons, which are 200 times heavier mass than electrons, without losing the benefit of the clean collision leptons provide. On the other hand, there are still many technical difficulties to overcome in the production, cooling, acceleration, and collision of large numbers of muons before they decay.

Laser-plasma accelerator, novel accelerator technologies

A laser-plasma accelerator has a potential to realize much higher accelerating gradients than accelerators based on conventional techniques. Recently gradients of a few GV/m have been achieved. Plasma acceleration driven by protons seems to be a promising approach because of high efficiency of the beam. However, in order to apply such techniques to future high energy physics experiments, many technical obstacles need to be overcome in the production of high-current beams with multiple acceleration stages.

Advances in superconducting technologies have been remarkable in recent years. New multi-layer materials which enable high-gradient cavities or superconducting materials with higher transition temperature ($T_c$) than niobium have been proposed recently.

High energy physics experiments can reach much higher energy scales if these technologies become practical reality.

# 3 Neutrino Oscillation and Proton Decay

## Overview

One goal of neutrino physics is to reveal the full picture of neutrino mass and flavor mixing, and then getting insight into physics at ultra-high energy scales well beyond the standard model. In particular, measurements of CP violation in the lepton sector, when compared with that of quarks and the CP symmetry of QCD will provide insight into the underlying symmetry mechanisms and allow for the formulation of a complete picture of the physics at these scales. Non-zero values of three neutrino mixing angles have already been measured, opening the door to measure the CP phase in neutrino oscillations. Theoretical studies suggest that CP violation in the neutrino sector may hold clues to understanding the origin of the matter-antimatter asymmetry in the present universe. The verification (rejection) of grand unified theories (GUT) and baryon number violating processes are also important subjects, which will be investigated by proton decay searches at large-scale neutrino detectors with sensitivities far beyond current limits given by the Super-Kamiokande detector.

## 3.1 Status

Neutrino Oscillation

After the discovery of neutrino oscillations there has been significant progress in our understanding of the properties and a full picture of neutrino flavor mixing is being revealed. The squared mass differences of the three neutrino masses $(m_1, m_2, m_3)$ have been measured to be $|\Delta m^2_{32}| \sim 2.4 \times 10^{-3}\text{eV}^2$ and $\Delta m^2_{21} \sim 7.5 \times 10^{-5}\text{eV}^2$, and two among three neutrino mixing angles were first measured to be $\theta_{23} \sim 45^\circ$ and $\theta_{12} \sim 34^\circ$. The last mixing angle, $\theta_{13}$, was measured to be $\sim 9^\circ$ in 2012 by T2K and the reactor experiments, Double Chooz, Daya Bay, and RENO, and now all the mixing angles are known to be finite. On the other hand, CP violation in the neutrino sector is caused by an as-yet unmeasured CP phase ($\delta_{CP}$) in three neutrino mixing, although hints have been reported by T2K. If future projects find that $\theta_{23}$ is close to 45° and $\delta_{CP}$ is close 90°, or that unitarity is violated in neutrino mixing, these results could be taken as a hint of new physics at an ultra-high energy scale. In addition, the sign of the mass squared difference $\Delta m^2_{32} = m^2_3 - m^2_2$ is still unknown, that is it is not yet known whether the mass ordering is $m_3 \gg m_2 > m_1$ (normal hierarchy) or $m_2 > m_1 \gg m_3$ (inverted hierarchy). The ordering of the neutrino masses is an important ingredient to understand the origin of particle masses when taken in comparison with quarks and charged leptons.

Proton Decay

Searches for proton decay are currently dominated by the Super-Kamiokande detector, which has placed 90% C.L. limits on the proton lifetime as $1.6 \times 10^{34}$ years for $p \rightarrow e^+ + \pi^0$ and $5.9 \times 10^{33}$ years for $p \rightarrow \bar{\nu} + K^+$. Some GUT models predict $p \rightarrow e^+ + \pi^0$ as the dominant decay mode, while $p \rightarrow \bar{\nu} + K^+$ is considered as a major decay mode in supersymmetric GUT models. These models predict proton lifetimes from $10^{34}$ to $10^{35}$ years.

## 3.2 Future Plans

Based on the measured values of the three neutrino mixing angles, the largest possible CP asymmetry observable in long-baseline neutrino experiments is expected to be 27%. [1] There is currently a tremendous opportunity to study neutrino CP violation over a wide range of $\delta_{CP}$ with the combination of a large water Cherenkov detector, Hyper-Kamiokande, and and upgraded J-PARC neutrino beam. Therefore these two future projects should be advanced. A plan to upgrade the beam power of J-PARC to 1.3 MW has been proposed and has been identified as the highest priority project in the KEK Project Implementation Plan (KEK-PIP). The detector design proposed by the Hyper-Kamiokande (HK) international proto-collaboration has excellent sensitivity to proton decay and can thereby provide direct evidence of the GUT models. The next-generation neutrino detector, DUNE in the U.S., is in progress and as international competition is foreseen, the early realization of the HK project is extremely important.

CP Violation Measurement

The CP-violating phase in the neutrino mixing matrix, $\delta_{CP}$, can be determined by measuring the asymmetry between the $\nu_\mu \rightarrow \nu_\mathrm{e}$ appearance probabilities of neutrinos and antineutrinos. As the effect of $\delta_{CP}$ appears in a small difference on the the probability of $\nu_\mathrm{e}$ appearance, the $\nu_\mu \rightarrow \nu_\mathrm{e}$ channel needs to be measured with large statistics. The T2K experiment has reported a hint of CP violation from the measurement of neutrino and antineutrino oscillation probabilities using the J-PARC neutrino beam. It is necessary to upgrade the J-PARC neutrino beam and extend T2K's operation period in order to confirm the existence of CP violation with higher significance (T2K-II). T2K-II has the opportunity to measure CP violation at $3\,\sigma$ significance depending on the true value of $\delta_{CP}$. In the event that CP violation is not observed by T2K-II, the highest priority for the next-generation neutrino experiment

[1] This assumes three neutrino mixing as expressed by PMNS matrix. The asymmetry could be larger with new physics.

will be the its discovery. On the other hand, if CP violation is confirmed by T2K-II, the task of next-generation experiments will be to precisely measure the mixing parameters including $\delta_{CP}$ and investigate existence of any deviation from the standard three-neutrino mixing framework. In light of these prospects, Japan's future plans are unified in pursuit of the large water Cherenkov detector, Hyper-Kamiokande, and various preparations are proceeding for its construction.

J-PARC Accelerator and Neutrino Beam

The neutrino beam at J-PARC is produced from 30 GeV protons accelerated by its Main Ring (MR). The operation of the accelerator complex, including the neutrino beam facility, started in 2009 and it has been providing stable neutrino beams for the T2K experiment since January 2010. In early 2011 operations were interrupted due to the Great East Japan Earthquake but were resumed in December 2011. By 2016 the beam power reached $\sim 500$ kW. The KEK-PIP has attached the highest priority to the J-PARC accelerator upgrade plan, and consequently the upgrade is progressing toward a beam power of 1.3 MW for the MR, which exceeds its original design value of 750 kW. As a first step, the repetition rate will be increased by almost a factor of two from the current value of 2.5 sec with an upgrade of the power supplies for the main magnets and the introduction of higher gradient RF cavities. These upgrades will result in a beam power greater than 750 kW. Further upgrades of the RF power supplies, the Fast-Extraction Kicker and the beam monitors are scheduled and the proton beam will be further optimized and stabilized. The number of protons per spill will be increased and the beam power is expected to reach 1.3 MW by around 2026. Irreplaceable components of the J-PARC neutrino beam facility, such as the decay volume and beam dump, are designed to withstand beam powers greater than 3 MW, while the cooling capability of the target horns and the radioactive waste water handling system need to be upgraded to realize a 1.3 MW beam power.

For the long-term future, upgrades towards the realization of a few MW accelerator are being considered. One possibility is to construct a new 8 GeV booster ring between the current Rapid Cycling Synchrotron (RCS) and MR to allow more protons to be injected with smaller emittance. As a possible operational improvement, the parallel operation of the fast extraction beam for neutrino experiments and slow extraction beam for hadron experiments can be realized if a stretcher ring for the slow extraction is newly constructed as an addition to the current MR accelerator. There is also an idea to arrange linac accelerators in the KEKB tunnel to make a 10 MW-scale proton driver after the completion of the SuperKEKB project.

Hyper-Kamiokande

Hyper-Kamiokande (HK) is a next-generation large-scale water Cherenkov detector based on the technology established in Super-Kamiokande (SK) and represents and upgrade the detector scale and its performance. The physics capabilities of HK cover a broad range of topics such as the measurement of $\delta_{CP}$ using the J-PARC neutrino beam, searches for proton decay, the determination of the mass hierarchy with atmospheric neutrinos, and the observation of astrophysical neutrinos.

The detector is designed as a cylindrical structure with 74 m diameter and 60 m height, with a fiducial volume of about 200 kiloton (approximately 10 times larger than SK). It is estimated the construction of HK will be completed within 10 years of budget approval. On longer timescales, there is a staging plan to construct a second detector and carry out physics research with a detector approximately 20 times larger than SK. The HK proto-collaboration successfully developed a new photosensor with both improved photon detection performance and water pressure resistance in cooperation with Hamamatsu Photonics K.K. The detector structure was re-examined after taking into account the benefits of the new photosensor and the new design has enabled a significant cost reduction at no expense to the physics sensitivity.

HK will be able to precisely measure neutrino oscillation parameters using the J-PARC neutrino beam and has extremely high sensitivity to the measurement of $\delta_{CP}$. Accumulating data for 10 years with the 1.3MW J-PARC neutrino beam, the $\delta_{CP}$ measurement precision is estimated to be better than 21° (7° for $\delta_{CP} = 0$).

Determination of neutrino mass hierarchy is one of major physics targets of HK, not only because it may give hints toward the origin of the extremely light neutrino mass, but also it is also related to studies of Majorana neutrinos being explored by the neutrinoless double beta decay searches. For example, if the neutrino mass ordering is the inverted hierarchy, whether neutrinos are Majorana or Dirac fermions, may be determined on short time scales with improved searches for neutrinoless double beta decay. According to its projected sensitivities, HK will be able to determine the mass hierarchy at a significance of $3\sigma$ or more with observations of atmospheric neutrinos and J-PARC beam neutrinos in about three years of operations.

HK also unprecedented sensitivity to proton decays. In addition to the increased fiducial volume, atmospheric neutrino backgrounds will be largely suppressed by the improved performance of the detector. The $3\sigma$ discovery potential reaches to $1 \times 10^{35}$ years for the $p \to e^+ + \pi^0$ and $4 \times 10^{34}$ for $p \to \bar{\nu} + K^+$ decay modes, approximately one order better than the current limits, and can therefore be used to test various GUT models.

Because of its huge fiducial volume, HK's observations of astrophysical neutrinos, such as solar neutrinos, supernova neutrinos, as well as searches for dark matter can lead to new discoveries. For instance, solar neutrino observation will enable matter effect measurements with high precision via the variation of their oscillation probability. This will subsequently allow tests of models beyond standard neutrino oscillations that produce the observed deficit of solar neutrinos. In terms of the supernova neutrino observations, HK will not only be able to observe neutrinos from supernova bursts within the galaxy or its near surroundings, but is also expected to make the observation of as-yet unmeasured supernova relic neutrinos. As the flux of the supernova relic neutrinos depends on the frequency of supernova bursts in early universe, its observation may advance the study of the evolution of the universe.

The Hyper-K design report has been submitted by the Hyper-Kamiokande proto-collaboration and the project is ready for construction once its budget is approved. Hyper-K is the most pragmatic future project in neutrino research because its detector design is based on existing technologies, it has realistic cost estimates, it has an international collaboration, and it has sufficient potential for many discoveries, including the discovery of neutrino CP violation and proton decay.

Sterile Neutrino Search

The LSND experiment operated in the 1990's in U.S. reported the appearance of $\overline{\nu_e}$ from $\overline{\nu_\mu}$ after traveling a distance of 30 m. If this flavor transition is interpreted as neutrino oscillation, the mass squared difference, which corresponds to oscillation length, should be of order $1\,\mathrm{eV}^2$. This, together with the other measurements of neutrino oscillations, requires the existence of three different neutrino mass difference scales, which can not be explained by a three-flavor neutrino framework. For this reason, it suggests the existence of a new fermion which does not couple to the weak interaction nor the strong or electromagnetic interaction, known as a sterile neutrino, as the fourth neutrino. The MiniBooNE experiment also reported results which indicate a possible neutrino transition though the existence of a sterile neutrino. Since both experiments lack near detectors it has been pointed out that the excess may have been produced background.

In order to validate the results reported by LSND, several neutrino experiments are being planned throughout the world. One such experiment planned in Japan is JSNS$^2$, which aims to start data taking in 2018 at the J-PARC MLF facility to test the oscillation parameter regions suggested by LSND. Further, though the NuPRISM water Cherenkov detector is proposed as a near detector for T2K and HK to suppress systematic uncertainties in their long-baseline neutrino measurements, it will also be capable of searching for sterile neutrinos.

Overseas Future Projects

In order to discover neutrino CP violation and to determine the neutrino mass hierarchy, neutrino oscillation experiments using accelerator neutrino beams are of key importance and next-generation projects are being pursued in the world. The Deep Underground Neutrino Experiment, DUNE, is in progress in the U.S.. DUNE will use neutrino beam produced from a 1 MW or greater proton beam at Fermilab and observe neutrinos at the Sanford underground laboratory, located 1300 km away. A liquid argon TPC is employed as the far neutrino detector and an R&D program is ongoing to enlarge the size of the detector. As $\theta_{13}$ turned out to be relatively large, $\beta$ beams or neutrino factories are less urgent than previously thought and the plan of LAGUNA project in Europe is being re-examined. Under these world conditions, future projects for the measurement of $\delta_{CP}$ have converged on Hyper-Kamiokande (HK) and DUNE. In case both experiments start simultaneously, HK has superior sensitivity to neutrino CP violation as well as to the proton decay mode, $p \to e^+ + \pi^0$. DUNE is currently proceeding with R&D to establish the detector design (especially to enlarge the detector size), while a part of the budget for the facility has already been approved. Excavation is going to start in 2017. In order to achieve important physics goals in this situation, the early realization of HK is extremely important. A study devoted to building a second HK detector in Korea is currently ongoing. The detector observes the J-PARC neutrino beam at a different distance from the HK detector in Japan and is expected to provide improved sensitivity, especially to the mass hierarchy.

Various projects are moving forward to determine the neutrino mass hierarchy. In China the JUNO project aims to determine the mass hierarchy by measuring reactor neutrino oscillations with high precision, and is pursuing R&D in parallel with the detector construction. PINGU is a project which plans to improve the precision of IceCube by increasing the photosensor density in the ice. It will be sensitive to the neutrino mass hierarchy by observing atmospheric neutrinos in a same way as HK. DUNE in U.S. has a long baseline in which the neutrino oscillation probability changes due to matter effects and is therefore sensitive to the mass hierarchy. Though these projects, with the exception of HK, rely on new detector technologies meaning their sensitivities are still uncertain, it is thought that depending on the progress of the detector R&D campaigns the prospects for a measurement will be clear within ten years.

Concerning sterile neutrino searches, SOX, which uses an artificial neutrino source at Gran Sasso in Italy, and SBN, which uses accelerator neutrinos at Fermilab in the U.S., are both in preparation and are aiming for commissioning in 2017 and 2018, respectively. They will be international competitors with the JSNS$^2$ project at J-PARC in Japan.

# 4 Flavor Physics

## Overview

After the discovery of the Higgs boson and subsequent completion of the standard model (SM) the focus of particle physics has shifted to attempting to provide ultimate solutions to the mysteries of the universe that cannot be explained by the SM, including as grand unification, the hierarchy problem, and the nature of dark matter. While energy-frontier experiments seek for such solutions directly, flavor-physics experiments take indirect, but complementary approach. In flavor-physics experiments, the effect from the existence of a new particle on a certain decay process manifests as a discrepancy between measured physics parameters and the prediction from the SM. It is possible in these experiments to discover the effects of new physics even though they run at accelerator energies lower than the mass of the new particles. This is their main advantage over direct-searches at energy-frontier experiments.

In order to discover new physics at flavor-physics experiments it is essential that rare decay processes with sufficiently small backgrounds from SM processes are used, that the physics parameters relevant those decays are precisely estimated from the theoretical calculations, and that systematic uncertainties are well controlled and minimal. Further it is important that the accelerator luminosity and beam intensity on the target area as high as possible in order to find the rare decay event signal. For these reasons, flavor-physics experiments are often called luminosity-frontier experiments. The search for new physics is being pursued while opening the luminosity frontier through parallel efforts to develop both accelerators with high intensity beams and experiments that can record rare decay events under the difficult experimental conditions posed by those beams.

Japan is leading the world in the field of flavor experimentation, as represented by the KEKB factory and it is important that Japan maintains this position over the long term. Several 2-4$\sigma$ discrepancies from the theoretical prediction have already been observed in measurements of the muon anomalous magnetic moment ($g-2$) and a variety of measurements at the B-factories and the LHCb experiment. Whether these discrepancies can be interpreted as an indication of a new physics is still under discussion.

Concluding this discussion by improving the precision of both theoretical calculations and of experimental measurements is critical going forward. In addition, it will be crucial to measure size of such discrepancies in several physics processes as well. With knowledge of which discrepancies are enhanced and which are suppressed relative to the expectation, it is possible to identify the framework of any new physics.

This method is a particular advantage of flavor-physics experiments. Accordingly, it is important to maintain a basic strategy of covering many physics processes with diverse set of projects in future.

The following sections describe the physics targets for experiments using $B$ mesons, $D$ mesons, $\tau$ leptons, muons, kaons, and neutrons.

## 4.1 SuperKEKB / Belle-II Experiment

Since the discovery of the $CP$ violation in the $B$ meson system in 2001 by the Belle and BaBar experiments, a number of achievements in flavor physics have been delivered by B-factory experiments at high-luminosity lepton colliders. In 2010, the LHCb experiment, which analyzes large numbers of $b$-quark events produced in proton collisions, began to report several results in flavor physics, triggering intense competition in the search for new physics throughout the world.

The operation of the KEKB accelerator was completed in 2010 after delivering an integrated luminosity of more than 1 $\mathrm{ab}^{-1}$. Since then the upgrade of the accelerator to the SuperKEKB, whose luminosity will be 40 times higher than KEKB, is being carried out through the installation of new final focusing magnets, strengthening the injector-linac, and reducing the beam size to $O(1\ \mathrm{nm})$. SuperKEKB successfully circulating and storing beams in the electron and positron rings in February 2016, and the phase-1 commissioning of the accelerator was finished by June of the same year. Physics data taking will start by March 2018 after rolling the Belle-II detector into the collision point, activating the solenoid and superconducting quadrupole magnets, and finishing the phase-2 commissioning using colliding electrons and positrons. The final commissioning of the detector will take place in 2018 by including silicon detectors located near the collision point, and physics data taking with complete detector will start by March 2019.

The Belle-II experiment will collect 50 $\mathrm{ab}^{-1}$ of data in about 10 years. It aims for the radical development of flavor physics by precisely analyzing the decays of $b$-quarks, $c$-quarks, and $\tau$ leptons with the high statistics data. Sensitivity to new physics up to $O(10)$ TeV is expected due to quantum effects in Belle-II's indirect searches. The experiment will look for such quantum effects, which potentially originate from as-yet undiscovered charged Higgs boson($\mathrm{H}^{\pm}$) decaying into the $b$-quark and $\tau$ lepton, both third generation particles, or from other new particles. Belle-II will open up searches for new physics to a new level in the next few years with its ultra-precise measurements. It will also make a definitive measurement of the lepton universality violating process $b \to s\ell^+\ell^-$ as suggested by the LHCb experiment. Several anomalies observed in Belle will be resolved by Belle-II with the clean experimental environment afforded by its $e^+$-$e^-$ collisions. The $CP$-violating phases in the quark sector will be determined with precision measurements of the CKM matrix elements to the $O(1\%)$ level and enable the detection of possible contributions from the new physics as well as the estimation of the relevant energy scales. Furthermore, contributions from new physics, such as a charged Higgs boson, SUSY particles, or right-handed currents, will be probed through precision measurements of the $B$ meson decays to $D^{(*)}\tau\nu$, $\tau\nu$, $K_S^0\pi^0\gamma$, and $K^{(*)}\nu\nu$, the lepton flavor violation in $\tau$ decays to $\ell\gamma$, $3\ell$, and the branching fraction of $B \to X_s\gamma$. Such probes will provide a foothold to elucidate the structure of the new physics behind the observed parameters. The integrated luminosity of SuperKEKB will reach 50 ab$^{-1}$ in about 10 years after the start of the experiment. Belle-II is expected to discover several new phenomena and provide limits on several physics parameters. It will be important to develop the successor to Belle-II while watching the evolution of flavor physics.

## 4.2 Kaon

Kaon experiments have also been playing an important role in establishing the standard model of particle physics, including the first observation of CP violation which suggested the existence of the third quark generation. The $V_{us}$ element of the CKM matrix is determined most precisely from kaon decays and the parameter $\varepsilon_K$ in $K^0$–$\overline{K^0}$ mixing constrains the quark unitarity triangle. Taken together with B Factory measurements, kaon experiments have provided many important results in the quark sector.

Flavor changing neutral current (FCNC) processes are sensitive proves to explore new physics since they are strongly suppressed in the standard model. Among quark FCNC processes, the $s \to d$ transition is suppressed the most strongly by CKM matrix elements and therefore the kaon decays could be the most powerful tool for exploring new physics with generic quark flavor-transitions.

Measurements of the branching ratios of the decays $K_L \to \pi^0\nu\overline{\nu}$ and $K^+ \to \pi^+\nu\overline{\nu}$ are among the most important in the search for new physics with rare kaon decays. Since those branching ratios are extremely small and precisely predicted in the standard model, if the effects of new physics are comparatively large they could be easy to observe experimentally. Depending on the model of the new physics, such as SUSY or Z', the kaon decay processes are sensitive to energy scales between 10 and 100 TeV and could be detected as a change in these branching ratios of a factor of a few to one order of magnitude.

In Japan, the KOTO experiment is currently searching for the decay $K_L \to \pi^0\nu\overline{\nu}$ with the high-intensity proton beam from J-PARC. The experiment started the physics running in 2013 and set an upper limit of $5\times10^{-8}$ on this process that is comparable to the current upper limit $2.6 \times 10^{-8}$ set by the KEK-PS E391a experiment. With the large amount of data taken in 2015, the KOTO experiment will approach the sensitivity of the Grossman-Nir bound ($1.5\times10^{-9}$), which is an indirect limit based on the measured branching ratio of $K^+ \to \pi^+\nu\overline{\nu}$. KOTO will further increase the sensitivity via background suppression with improvements in the analysis, upgrades to the detector, and by using a more intense primary proton beam with smaller intensity fluctuations. Sensitivity to the standard model branching ratio $3 \times 10^{-11}$ will be reached at the beginning of the 2020s.

Internationally, the NA62 experiment at CERN is studying the branching ratio of the decay $K^+ \to \pi^+\nu\overline{\nu}$ and aims to observe $\mathcal{O}(100)$-events. The experiment is both complementary to the KOTO experiment and a competitor as well, since it will place an indirect limit on the branching ratio of $K_L \to \pi^0\nu\overline{\nu}$ using the Grossman-Nir bound.

To go beyond the goals of the current KOTO experiment and explore the effects of new physics at the level of 10% deviations from the standard model prediction, the detector needs to be significantly upgraded. Additionally, a new beam line must be built, which requires an extension of the hadron experimental facility at J-PARC. Competition is further expected with another experiment that is currently under consideration at CERN that will measure the branching ratio of the same decay process starting in 2026. The extension plan of the hadron experimental facility at J-PARC includes an experiment to search for violations of the time-reversal symmetry with $K^+$ decays as well as various experiments designed for hadron and nuclear physics. This plan is supported by the KEK Project Implementation Plan and should be realized in cooperation with the nuclear physics community.

## 4.3 Muon

Lepton flavor may also be violated in the charged lepton sector and is being studied seriously after the discovery of neutrino oscillation. Changed lepton flavor violating processes are suppressed at the level of $10^{-40}-10^{-50}$ even taking into account neutrino oscillation. However if there is a contribution to such processes from new physics, it might become realistic to observe this phenomena by experiments currently under preparation. Discovery of charged lepton flavor violation would be a clear signature of new physics and such experiments should be advanced intensively.

Flavor violation in the $\tau$ lepton decay would be seen as mixing between the third and the first or the second generation fermions, while the decay process $\mu \to e\gamma$ and $\mu - e$ conversion represent mixing between the second generation and the first generations. As a result the two are complementary. The MEG experiment reported the final upper limit on the branching ratio of the $\mu \to e\gamma$ process at $4.2 \times 10^{-13}$, which is 30 times more stringent than the previous limit from MEGA experiment. An upgraded experiment, MEG II, will be ten times more sensitive and is expected to start soon.

The double ratio of the branching ratios of the two processes, $\mu \to e\gamma$ and $\mu - e$ conversion, is estimated to be $\mathcal{O}(10^2)$ in various physics models. However it is dependent upon the framework of the new physics and the individual measurements are therefore complementary. Preparations for experiments searching for $\mu - e$ conversion at a sensitivity of $10^{-14} \sim 10^{-17}$ are underway both in Japan and in the U.S.. The DeeMe experiment at the MLF facility in J-PARC is aiming at the early realization of $\mathcal{O}(10^{-14})$ sensitivities and beamline construction is on-going. The COMET experiment at J-PARC and the Mu2e experiment at Fermilab are now in the R&D phase and they are aiming for sensitivities of $\mathcal{O}(10^{-17})$. This may be enough to reach the predicted level of the $\mu - e$ conversion process in various physics models beyond the standard model. COMET, a flagship experiment of J-PARC, employs a staging approach and the first phase of the experiment, which is aiming for a sensitivity of $\mathcal{O}(10^{-15})$, is currently under construction

The muon anomalous magnetic moment, $(g-2)$, was measured by the BNL-E821 experiment with a precision of 0.54 ppm and deviates from the standard model prediction by $3.3\sigma$. It is essential that this discrepancy be verified with more sensitive experiments together with a better evaluation of the hadronic contribution to the vacuum polarization of the muon $(g-2)$. A planned experiment aiming at 0.1 ppm precision will transport the muon storage ring from the BNL-E821 experiment to Fermilab. Another experiment, which will measure $g-2$ and the electric dipole moment simultaneously, has been proposed at J-PARC. It employs a completely new method which uses an ultra-cold muon beam. It is technically possible to achieve a precision of 0.4 ppm and the project is aiming for a final precision of 0.1 ppm. Since two independent measurements with completely different systematics are of great importance, both experiments should be advanced toward their early realization.

## 4.4 Neutron

The combination of an accelerator-driven high intensity neutron source and high-performance neutron optics enables various neutron physics experiments with far superior statistics than previous measurements. As a result a new era of particle physics with neutrons is dawning.

An upper limit on the neutron electric dipole moment (EDM) of $|d_n| = 3 \times$

$10^{-26}\,e$·cm, which is close to theoretical predictions of various models, e.g. for SUSY : $10^{-27}$ – $10^{-28}\,e$·cm, SM : $10^{-32}\,e$·cm, was obtained by experiments using ultra-cold neutrons (UCNs). In order to suppress systematic uncertainties, an extremely uniform magnetic field over the neutron storage cell is required to measure their spin precession. It is highly important to increase the spatial density of UCNs to improve statistics in the limited storage area and to thereby improve the precision of the EDM measurement. The development of high-density UCN sources to study the neutron EDM of $10^{-27}$ to $10^{-28}\,e$·cm are becoming a ground for international competition. An experiment to measure the EDM with UCNs produced by solid deuterium converter has started at PSI. Even though the intensity of the UCNs was less than the design value due to technical problems, the statistical sensitivity of $10^{-27}\,e$·cm was achieved in 2017. There are plans to upgrade the apparatus and restart EDM measurements in 2020. At TRIUMF, the construction and commissioning of a beamline to produce UCNs in 2017 and then measure the neutron EDM in 2018 is underway. A collaboration between the Japanese institutes KEK and RCNP is in charge of the development of a superfluid helium converter for high density UCNs at TRIUMF. Though the average intensity of the proton beam at J-PARC is low, the instantaneous pulse intensity is higher than other facilities. In order to take this advantage of this feature research and development into a new method of transporting UCNs produced in a solid deuterium converter while maintaining their density is underway. It is essential to quickly achieve the design value of the UCN density as well as to understand and suppress systematic uncertainties in the EDM measurements for the discovery of new physics.

There are various other experiments using intense neutron beams that are either planned or underway. The neutron lifetime is an important parameter in big bang nucleosynthesis and calculations of the CKM matrix elements, but at present the measured values differ widely depending on the experimental method. Experiments aiming for better than one second precision measurements of the neutron lifetime are being pursued at J-PARC and throughout the world. Following the theoretical suggestion that there is a possibility of enhanced CP violation in resonant neutron-nuclei capture process, a feasibility study has been carried out for a high sensitivity search for new physics using the J-PARC beam. Using the fact that the neutron is a massive neutral particle, there are various experiments being considered that would be sensitive to exotic interactions coupled to mass.

Innovative neutron sources for the next generation of experiments. In Europe, construction of the European Spallation Source (ESS) is in progress and is planned to start operation in year 2020. Long-baseline neutron beam would allow for searches for neutron-antineutron oscillation, which is a test of baryon number violation. In

Japan, the discussion of a second target station at J-PARC has started. A neutron source with an order of magnitude higher flux will open up new possibilities for research. Key technologies for such an innovation may be the development of both new neutron moderators dedicated to very cold neutrons and high-efficiency reflectors to surround the source.

# 5 Non-accelerator Particle Physics

## 5.1 Particle Physics in Underground Laboratories

Overview

Rare events predicted by new physics are currently being searched for in underground laboratories. Underground environments are beneficial for these experiments because they provide shelter from cosmic rays, low radioactive backgrounds, and stable experimental conditions. Underground laboratories are important for exploring new physics at extremely high energy scales, which cannot be accessed with accelerators but may be revealed through naturally occurring rare events. In particular, experimental searches for dark matter particles and neutrinoless double beta ($0\nu\beta\beta$) decay have become highly competitive fields. Domestic activities stemming from neutrino experiments have concentrated in underground laboratories in the Kamioka mine, forming a research community of variously sized projects. Although the site is only moderately deep, the projects proposed by that community will realize world-leading sensitivities at low cost and over short time periods and can be performed using existing research facilities. A new academic field that aims to accelerate cooperative work across different projects is emerging is being advance and will prosper under continuous promotional support.

At present, projects involving 10 – 50 researchers are developing unique experimental approaches in the Kamioka mine. While it is important to recognize the importance of such diversity, it is necessary to identify common priorities for the direction of the field so that effort can be concentration on a larger project when an important discovery is made. Researchers working in underground laboratories belong to various fields spanning high energy, cosmic ray, and nuclear physics. Communication and cooperation among these fields will ensure that research is properly evaluated and strongly promoted.

Dark Matter Searches

Recent cosmological observations have established the existence of dark matter that cannot be explained by the currently known particles. The mass density of dark matter has been evaluated as 0.3 GeV/cm$^3$ in the vicinity of the Earth. However, the masses and interaction strengths of dark matter particles as predicted by various theories range over tens of orders of magnitude. Supersymmetric theories predict the existence of weakly interacting massive particles (WIMPs) which emerges in theories describing phase transitions in the electroweak interactions. Direct detection of WIMP dark matter is the goal of many experimental efforts around the world.

Using NaI (Tl) inorganic scintillators the experimental group DAMA/LIBRA detected an annually modulated signal caused by the rotation of the Earth around the Sun. However, this signal is absent in liquid xenon experiments such as XMASS. A recent result from the XENON1T experiment excluded WIMP models with a nucleon interaction cross section greater than $7.7 \times 10^{-47}\text{cm}^2$ at 35 $\text{GeV/c}^2$, far smaller than the cross section that naturally explains the DAMA/LIBRA result. Furthermore, no WIMP-like signal has been observed in accelerators or in indirect searches with cosmic ray data. Once the direct-detection sensitivity to the cross section improves to $10^{-48}\text{cm}^2$, most of the parameter region predicted by supersymmetric theories will be covered. Although solar neutrinos will begin contributing to the background when that happens, their effects could be removed by studying the differences in the energy spectrum for heavy-mass WIMP searches. Under these conditions, the sensitivity of experiments must be steadily improved beyond $10^{-47}\text{cm}^2$ while enhancing sensitivity to smaller masses and it is important to extend experimental capabilities beyond WIMPs to other types of dark matter.

Direct detection of dark particles is a top priority for future projects and the construction of a large-scale detector with improved sensitivity is the most important. The XENONnT and LZ experiments, scheduled to start in 2019 and 2020 respectively, are the representative large-scale dark matter experiments. Each experiment will require almost 10 tons of liquid xenon, and will measure cross sections down to $3 \times 10^{-48}\text{cm}^2$ for 50 $\text{GeV/c}^2$ WIMPs. Larger detectors with ultimate sensitivities exceeding $10^{-48}\text{cm}^2$ are also within reach. One example is the DARWIN experiment, which plans for a 50 ton liquid xenon target. For detectors of this size, atmospheric neutrinos start to contribute to the background and are difficult to distinguish from a heavy WIMP signal. However, if most of the dark matter consists of Wino particles, the neutralinos predicted in supersymmetric theories, a discovery is expected. A global cooperative effort toward realizing a large-scale detector is necessary in future.

Once a dark matter signal is observed, the underlying physics of the dark matter particles must be further investigated and confirmed. To that end, various measurements using different target materials and technologies, those using direction-sensitive detectors, and those studying inelastic scattering channels will become important.

The PICO-LON group aims to confirm the modulated signal obtained by the DAMA/LIBRA experiment. The group has developed ultra-low-background NaI(Tl) crystals and achieved the second-lowest background rate in the world. To surpass the sensitivity of the DAMA/LIBRA experiment, they are planning for larger crystals with even lower background. The ANKOK group is developing gas-liquid dual-phase argon detectors to search for low mass WIMPs. The group is planning to start data collection in an underground laboratory within the next few years, and is expected to test the DAMA/LIBRA results using an argon-based detector for the first time. Research into developing a liquid helium detector to search for low mass WIMPs is also underway.

Directional dark matter measurements particles would provide "smoking gun" evidence of their existence, as well as important information on the physics of their motion and scattering. The NEWAGE and NEWSdm groups are actively developing direction-sensitive detectors using TPC technology and emulsion methods, respectively. Direction-sensitive scintillators are also being developed. New technological approaches are expected to be further developed for these purposes.

The experiments above are devoted to WIMPs with masses ranging from 10 GeV/c$^2$ to a few TeV/c$^2$. Other experiments are searching for non-WIMP dark matter candidates such as axions. For instance, the CARRACK experiment is planning to search for axions with masses of $50 - 100$ $\mu$eV/c$^2$. Recent technologies will enable sensitive searches for axion-like particles or hidden photon dark matter. Searches for unknown particle interacting with electrons can (and should) be pursued with existing large-scale dark matter detectors. For example, super-WIMPs can be searched for in the low-background data of the XMASS-I detector. It is also argued that WIMPs with masses below 10 GeV/c$^2$ can scatter electrons and be identified through the electron recoils the produce. By reducing major background sources such as radon, various types of dark matter will be explored at current and planned experiments.

$0\nu\beta\beta$ decay

At present, the Majorana properties of neutrinos can only be investigated by observing $0\nu\beta\beta$ decay. Irrespective of the underlying physics, the observation of this process would provide evidence that the neutrino is a Majorana particle and that lepton number is violated. Since the decay rate should be proportional to the square of the effective Majorana mass of the neutrinos, the absolute masses of the neutrinos can be determined as well.

The absolute masses of the neutrinos will be explored in $0\nu\beta\beta$ decay experiments, which target masses greater than 200 meV. Cosmological measurements are sensitive to masses exceeding 50 meV at present, and are predicted to improve to 20 meV in future. Neutrino oscillation experiments have determined the range of the Majorana mass as $>$50 meV for a quasi-degenerate mass ordering, $20 - 50$ meV for an inverted ordering, and $<$20 meV for a normal ordering of the neutrino masses. Experimental studies at these mass scales represent milestones for the development of $0\nu\beta\beta$ decay experiments. Owing to recent rapid improvements in the sensitivity of the KamLAND experiment, the lower bound of Majorana mass has placed at $60 -$ 170 meV, which almost excludes quasi-degenerate ordering. The uncertainty on the lower bound is dominated by theoretical uncertainties and is expected to be improved in future. Though an experimental observation of $0\nu\beta\beta$ decays in $^{76}$Ge corresponding to an effective Majorana mass of approximately 320 meV has been reported (the KKDC claim), this mass range has been already excluded by the KamLAND-Zen results with $^{136}$Xe and the GERDA results with $^{76}$Ge.

After excluding quasi-degenerate mass ordering, the KamLAND-Zen experiment aims to probe the inverted mass ordering. For this purpose, the detector sensitivity will be improved to 20 meV. If the inverted mass-ordering is confirmed in neutrino oscillation experiments but no positive signal appears in $0\nu\beta\beta$ decay experiments with this sensitivity, it is possible to exclude the Majorana neutrino hypothesis. To improve sensitivities to below 20 meV, two neutrino double beta decays must be discriminated from the target signal and therefore both the size and performance of detector must be markedly improved.

To cover the inverted ordering mass range, an effective mass of one ton of the target material must be procured and must also have low radioactive backgrounds. As the major background originates from two neutrino double beta decay events, sufficiently high energy resolution to distinguish these from the signal is required. The next phase of the KamLAND-Zen experiment, KamLAND2-Zen, is aiming to explore the inverted ordering by improving the energy resolution. To this end, the group will replace their photomultiplier tubes with higher sensitivity ones, implement light-collection mirrors, and improve their liquid scintillator.

On the other hand, due to uncertainties in the nuclear matrix elements and difficulty in reducing the unpredictable background, it is essential to establish the existence of $0\nu\beta\beta$ decay using a variety of nuclei and experimental methods to understand the underlying physics. Several ongoing projects, including some in the Japanese community, have adopted different detection principles and target nuclei. The CANDLES experiment takes advantage of the high $Q$ value of $^{48}$Ca to realize a low-background experiment. However, enriching the $^{48}$Ca isotope is indispensable for this project due to its low natural abundance (0.2%). Recent studies have demonstrated the principle of isotope-enrichment methods, but further optimization is required for mass production. The energy resolution of the detector needs to be improved, and research and development on the use of low-temperature detectors is starting.

In parallel with the above achievements, detectors with particle tracking capability for measuring angular distributions are being developed. However, particle-tracking detectors are much less sensitive than large-scale calorimetric detectors at present. Scaling up the size of these detectors and improving their performance are their top priorities.

Progress more than ten years in the future is difficult to envision for these projects.

However, early-stage conceptual designs are necessary for realizing large-scale detectors with the 100 tons of target mass, which will enable investigation of both the inverted and normal mass orderings. When the Hyper-Kamiokande experiment is realized, Super-Kamiokande might be employed as a dark matter or $0\nu\beta\beta$ decay experiment. For example, combining Super-Kamiokande with the techniques of KamLAND-Zen might achieve the sensitivity required to probe $0\nu\beta\beta$ decay under the normal ordering.

## 5.2 Cosmological Observations

Introduction

In recent years, the importance of cosmological observations for elementary particle physics has increased dramatically. While harmonizing with accelerator experiments and in cooperation with neighboring fields, the active promotion of projects using space as a laboratory is expected. In particular, the exploration of inflation and dark energy is an important topic for which cosmological observations are the primary experimental method, and observations of the CMB polarization and researches with the Subaru telescope are underway. Both of these observations have high sensitivity to the sum of the neutrino masses and the number of neutrino generations, and it is expected that each observation can determine the former an accuracy of 100 meV or better. This means that it is possible to explore down to the lower limit of the inverted neutrino mass hierarchy and therefore these observations carry great significance. By measuring the number of neutrino generations to an accuracy of a few percent, it is possible to measure the abundance of light relativistic particles, such as hot axions, generated in the early universe.

Verifying inflation using Cosmic Microwave Background radiation (CMB)

Observations of the B-mode in the CMB polarization will provide direct evidence for inflation and further inform about its energy scale. The search for this polarization is essential as it is possible to probe ultrahigh energy physics that can not be reached directly using accelerators. The intensity of the B-mode polarization is proportional to the tensor-to-scalar ratio ($r$), which represents the intensity of primordial gravitational waves generated by space-time quantum fluctuations at the time of inflation. The value of $r$ is directly related to the distance ($\Delta\phi$) traversed by the inflaton, which is a hypothetical field responsible for inflation. If $r$ is greater than 0.002, $\Delta\phi$ becomes larger than the Planck mass and no field theory is able to calculate inflaton's potential from first principles [2]. In this case, a new physics framework

[2]Assuming single-field inflation, to be precise.

describing energy scales higher than the Planck mass, such as quantum gravity or string theory, will be necessary, making the observation results gravely important to the determination of the direction needed to explore the fundamental physical law.

The ground-based CMB polarization observation group in Japan participates as a core in POLARBEAR, which is an international experiment. POLARBEAR set up a telescope in Atacama, Chile and started observations in 2012. Projects competing with POLARBEAR include ACTpol in Atacama, Chile, and BICEP2/KECK and SPTpol, which are conducted at the South Pole. These ground-based experiments have polarization sensitivity beyond Planck in a limited area of the sky and are capable of detecting the B-mode polarization caused by gravitational lensing and foreground radiation (dust). On the other hand, the B-mode polarization originating from the primordial gravitational waves has not yet been observed. An upper limit on $r$ has been established by Planck-BICEP2-KECK as $r < 0.07$ at 95 % C.L. If the true value of $r$ is close to this upper limit, the discovery of the B-mode polarization originating from primordial gravitational waves can be expected within the next 5 years or so.

The KEK group is advancing the POLARBEAR-2 project, which aims to discover primordial gravitational waves with a sensitivity about 6 times higher than that of the current POLARBEAR. POLARBEAR-2 plans to see its first light during the 2017 fiscal year. With the construction of two more POLARBEAR-2 telescopes by fiscal year 2018, Simons Array plans to achieve 20 times the sensitivity of POLARBEAR with a total of three telescopes. It is expected that the error $\sigma(r = 0.1) = 6 \times 10^{-3}$ of $r$ be obtained by separating foregrounds using the results of Planck and C-BASS, and also the error $\sigma(\sum m_\nu)$ =40 meV in the sum of neutrino masses by combining the DESI [3] results of baryon acoustic oscillations. Meanwhile, Japan's unique technology development is progressing. The GroundBIRD experiment is scheduled to begin observation in the near future and will demonstrate proprietary technologies including a high-speed rotation scanning method for measuring large angular scales and the superconducting MKIDs developed in Japan. Simons Array and ACTpol groups have joined forces to start Simons Observatory, which has already been funded in the U.S. and its telescope design has begun. Japanese researchers are also participating in the Simons Observatory. As a plan for the further future, the CMB Stage-4 project is being studied by the U.S. DOE and aims to start observation in the middle of 2020s with expected measurement precisions of $\sigma(r) = 0.001$ and $\sigma(\sum m_\nu) =$ 20 meV. Japanese researchers are also considering participating in the project.

The scientific satellite program LiteBIRD aims for launch in the middle of the

[3] DESI as an observational experiment scheduled to start in 2019 for the purpose of making a 3 dimensional map of galaxies in the universe.

decade beginning in 2020 and is being studied in Japan in order to further improve its sensitivity on the large angular scales. LiteBIRD will observe the whole sky without being influenced by the atmosphere, achieve $\sigma(r) < 0.001$, and examine the main inflation models in further detail. The high precision observation of the B-mode polarization with the large angular scales afforded by LiteBIRD is considered to be important to narrow down the cosmological model, even in the event of an earlier discovery by ground-based observations or others. Further, it is possible to precisely measure the optical depth of the CMB by measuring the E-mode polarization with the ultimate sensitivity, and combining them with results from DESI, the precision on the sum of the neutrino mass measurements is expected to be reduced down to $\sigma(\sum m_\nu) = 15\,\mathrm{meV}$.

The LiteBIRD program has been developed mainly as an international collaboration between Japan and the U.S. The Japanese group applied for JAXA's strategic mid-size scientific satellite program in 2015 and was selected as one of the candidates. In September 2016, the conceptual design phase (Phase-A1) of the JAXA Institute of Space and Astronautical Science began. LiteBIRD is the only CMB B-mode polarization satellite program in the world that has progressed to the conceptual design phase at the present time (March 2017). The U.S. group has obtained funding from NASA for technology development for LiteBIRD. The promotion of LiteBIRD is expected to proceed while balancing the independence of Japanese community. LiteBIRD has been adopted as a priority project of the Science Council Master Plan 2014 and of the Master Plan 2017. It has also been selected as one of ten plans on the MEXT Road Map 2014, and one of the seven plans on the Road Map 2017.

Exploration of dark energy [4]

The observation at the end of the 20th century of non-inflationary accelerated expansion of the universe as suggested by supernova data marked an important discovery. The physical model behind this accelerated expansion is unknown, and the energy responsible is termed "dark energy". In order to understand the essence of dark energy, it is important to investigate how the cosmic expansion has changed with the passage of time, using cosmological observations to constrain its equation of state. There are mainly two methods to achieve this: a method of measuring the cosmic expansion directly and a method to investigate evolutionary history of structure formation in the universe born from the competition between the cosmic expansion and gravitational attraction. Regarding the former, methods based on type Ia supernova and baryon acoustic oscillations are being studied, while studies for the latter use

[4] Space observation - Exploration of dark energy: contribution from Kavli IPMU Prof. Masahiro Takada.

methods based on clustering statistics of the galaxy and weak gravitational lensing effects.

The next-generation project of Japanese dark energy exploration is the SuMIRe project, which upgrades the Subaru telescope to simultaneously perform deep space imaging and spectroscopy over a broad area. The Hyper Suprime-Cam (HSC) project, which measures weak gravitational lensing effects from imaging data, was launched in 2014. It carries a wide field of view using a focal plane consisting of a CCD with about 900 million pixels and observes billions of galaxies over about 1400 square degrees. Based on these measurements and the analysis of gravitational lensing effects, the time evolution of the distribution of dark matter will be revealed and the effects of dark energy will be investigated.

Another observational instrument is a new spectroscopic device called Prime Focus Spectrograph (PFS), which is scheduled to be installed around 2019. It will start scientific observations from 2020 and measure the red shift of more than 4 million galaxies in the HSC observation area in order to uncover the three-dimensional spatial distribution of galaxies. Since HSC will reveal the dark matter distribution and PFS will measure the detailed galaxy distribution, both observations will reduce uncertainties in the galaxy bias, thus providing a substantial synergistic effect to the exploration of dark energy's properties. Other capabilities include the measurement of neutrino mass, verification of inflation theory using measurements of non-Guassianity, verification of general relativity at cosmological distances, and verification of the properties of dark matter. Scenarios in which primordial black holes generated in the early universe can also be explored.

HSC will help monitor stars in Andromeda galaxy in the time domain with high density, and explore gravitational micro-lensing effects due to primordial black holes. With these observations, stringent limits can be placed on the number of existing primordial black holes generated in the early universe at thermal temperatures greater than TeV scales and with masses of about $10^{-10} M_{\odot}$. Furthermore, the combination of small angular scale observations of the CMB and baryon oscillations observed by galaxy survey experiments can provide measurements of the abundance of light relativistic particles that were thermally generated in the early universe in units of the number of neutrino generations with a few percent precision. This can help determine whether or not hot axions frozen following the reheating just after inflation exist.

A wide range cosmic surveys such as these are planned and ongoing all over the world. The European Space Agency's Euclid satellite is scheduled for launch around 2021 and will perform wide area imaging and spectroscopic surveys for about six years. Around the same time, LSST, a ground-based telescope that will undertake the ultimate visible light survey, is being lead by the U.S. and will start operations and conduct wide sky area imaging surveys for about ten years. Further, the U.S. National Aeronautics and Space Administration (NASA) is planning to launch the WFIRST-AFTA satellite to perform wide-area imaging and spectroscopic surveys with high sensitivity and a wide field of view in around 2025. There is no doubt that these wide area space surveys will advance fundamental physics research from 2020 to early 2030. The SuMIRe project aims to obtain results ahead of other observational projects and is highly competitive internationally.

# 6 Human Resource and Technology Development

High energy physics research aims to achieve the world's best results by combining various cutting-edge technologies. Experiments are consequently full of forefront technologies and are thus a fascinating research field for young researchers especially as regards technology. Continuous development of technology and training of young researchers are essential for high energy experiments as they create positive feedback loops for further development of the field. However, several concerns about human resources and technological developments have arisen recently.

- Span of experiments: the size of high energy physics experiments is growing larger and are taking longer to complete. It is difficult for even a competent student or young researcher to experience the entirety of an experiment from its project design, the R&D and construction of detectors, commissioning and operation, to the eventual data collection and physics analysis. More and more young researchers miss opportunities to work on technological developments and it may prevent smooth transfer of technology between generations.

- Specialization and subdivision of technology: there are many driving-force technologies in high energy physics, such as accelerator technology, detector technology, analog and digital electronics, software and large-scale distributed data processing systems, superconducting technology, and mechanical engineering among others. These cutting-edge technologies have become more and more specialized and subdivided in recent years, and it is difficult for individuals to obtain broad experience in the various technologies used in present high energy physics experiments. This also causes difficulties in the exchange of human resources among subdivided fields of expertise.

- Lack of resources: Due to the decline of the economy and heavy pressure for short-term outcomes, budgets for basic research are suffering significant reductions. This leads to the closure of electronics workshops at universities, a decrease of technical support staff at universities and laboratories, and other problems which results in the deterioration of the research environment for the development of cutting-edge technologies. Further, the mass retirement of the baby-boomer generation disrupts the transfer of technological inheritance to rising generations.

The active exchange of human resources at various levels is important to the mitigation of these problems. Further efforts to increase the exchanges of personnel between projects and institutes will be necessary. Providing young researchers with opportunities to work on small- or medium-size experiments at the beginning of their careers, and employing young researchers inclined toward challenging cutting-edge technologies may be effective on this front. Also necessary measures should be seriously considered and undertaken to help to continuously develop forefront technologies and train young researchers who will support those technologies in the future. Future large-scale projects cannot be realized without further technological development and the existence of sufficient human resources.

# 2 Report by the Committee on the Scientific Case of the ILC Operating at 250 GeV as a Higgs Factory

# Report by the Committee on the Scientific Case of the ILC Operating at 250 GeV as a Higgs Factory

**July 22, 2017**

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## Preface

In July 2012, a Higgs boson with 125 GeV mass was discovered at the LHC. The discovery of new phenomena and new principles that can (naturally) explain the electroweak symmetry breaking (EWSB) including the existence of this Higgs boson is now the most important and urgent target of research. In order to attain this goal, the LHC is performing direct searches for new phenomena and new principles with a center-of-mass (CM) energy increased to 13 TeV. So far, there is no evidence of new physics beyond the Standard Model (SM). The purpose of this committee is to investigate and compare, under the current circumstances, the capability to determine the energy scale of new phenomena and new principles and the capability to uncover the origin of matter-antimatter asymmetry for the following three cases: (i) an ILC operating at 250 GeV as a "Higgs Factory" (ILC250); (ii) an ILC operating up to 500 GeV (ILC500); and (iii) the case of no ILC construction. The committee members consist primarily of members of the ATLAS collaboration, the Belle II collaboration, and theorists. The committee aimed to give an assessment on the physics case of the ILC250 in a way that is independent from the ILC community.

This report consists of the following five chapters:

1. Introduction
2. Precise measurements of Higgs and other SM processes: Determination of the energy scale of new phenomena via precise measurements.
3. EWSB and the origin of matter-antimatter asymmetry.
4. Direct search for dark matter and new particles based on "Naturalness".
5. Summary: Comparison of the ILC operating at 250 GeV and 500 GeV

Different approaches are summarized in Chapters 2 and 3 to probe the next energy scale beyond EWSB through precise measurements. Chapter 4 discusses searches to elucidate dark matter (DM) and probes to test the idea of "naturalness".

## 1. Introduction

For the purpose of this discussion, the following points are assumed for the timeline and the conditions of the ILC operation.

1. The operation will start around 2028-2030. It will run concurrently with the High-Luminosity LHC (HL-LHC) experiment and produce complementary results.
2. The CM energy is fixed at 250 GeV. No energy scan is performed. The integrated luminosity is 200 $fb^{-1}$ per year, accumulating 2 $ab^{-1}$ by 2040.

3. Beam polarization is used (30% for positrons, 80% for electrons).

The key is the synergy with other experiments, including the HL-LHC, SuperKEKB, Hyper-Kamiokande, electric dipole moment (EDM) searches, lepton flavor violation (LFV) searches, and satellite probes to detect gravitational waves (LISA, DECIGO, etc.), as well as theory development in Lattice QCD and higher-order corrections. Various implications are considered combining rich outputs from these experiments with the ILC results, and we elucidate the role of the ILC with respect to the other experiments.

## 2. Higgs and Other Standard Model Processes: Determination of the New Energy Scale via Precision Measurements

### 2.1. Precise measurements of Higgs couplings

The precise measurements of the couplings between Higgs boson and other elementary particles can be performed at the 0.6-1.8% level at the ILC250. The measurement precisions are summarized in Tables 1 and 2. It is the important task of ILC to measure the total decay width model-independently. The previous strategy is as follows, the HWW coupling is measured using the vector boson fusion process, and decay branching fraction Br(H→WW) can be measured precisely. Then total decay can be determined model-independently. The vector boson fusion process enables the precise measurement of the HWW coupling at higher energies. At the ILC250, however, this cross section is small. It was one of motivations for higher center of mass at ILC.

As an alternative approach, we can measure Higgs decay branching fraction at the HL-LHC to examine the symmetry between the HWW and HZZ couplings (custodial symmetry) at the 2% level. By taking this symmetry as an assumption, the ee→ZH cross section (HZZ coupling) and the H→WW decay branching ratio measurements can be combined for the model-independent determination of the total decay width. This idea can be further extended in the framework of effective field theories to determine the coupling (denoted as g), in a model-independent way (Ref. airXiv 1708.09079).

The estimated precisions of various Higgs boson couplings are shown in Table 1, combining ILC250 and HL-LHC results. The precisions are at the 10% level with the HL-LHC alone, less than 1% accuracies can be obtained as shown in Table 1. The comparison between ILC250 and ILC500 shown in Fig.1 shows that the differences in the achievable precisions are small for the same total integrated luminosity of 2 $ab^{-1}$. This illustrates the importance of the combination of the HL-LHC and the ILC250 results. These combined results are comparable to those at ILC500 (combined with HL-LHC). Table 2 summarizes the precision of the coupling ratios from the direct determination at ILC250. Many experimental systematic uncertainties cancel by taking the ratios. These ratios are useful for the precise comparison between the SM predictions and the experimentally observed values.

Table 1: Precision of Higgs boson couplings in the effective field theory framework. Combination of the ILC250 and the HL-LHC measurements

| | g(HZZ) | g(HWW) | g(Hbb) | g(Hττ) | g(Htt) | g(Hμμ) | g(Hcc) |
|---|---|---|---|---|---|---|---|
| Δg/g | 0.63% | 0.63% | 0.89% | 1.0% | 7% (LHC) | 6.2% | 1.8% |

Table 2: Precision of Higgs coupling ratios from the direct measurements at the ILC250.

| | g(HWW)/g(HZZ) | g(Hbb)/g(HWW) | g(Hττ) /g(HWW) | g(Hcc) /g(HWW) |
|---|---|---|---|---|
| Δ | 1.9% | 0.64% | 0.84% | 1.7% |

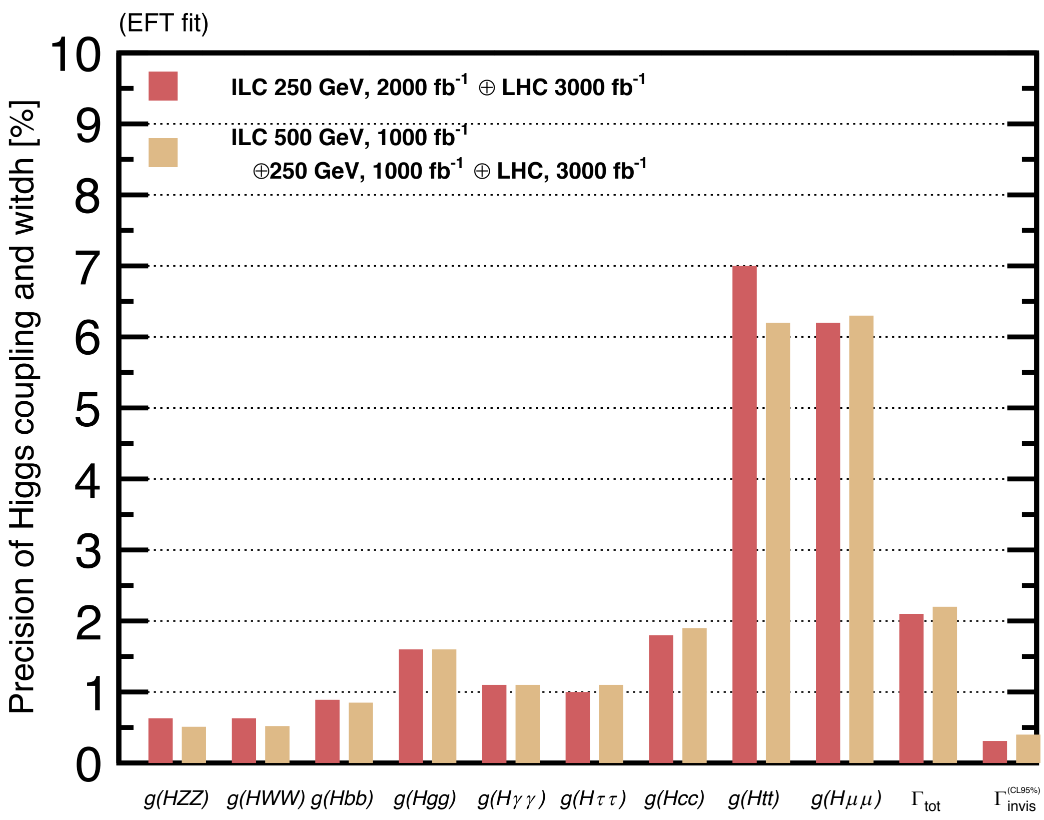


Figure 1: Precision of coupling measurements.

It will be possible to measure the Yukawa couplings of the second-generation leptons and quarks with about 2-6% precision. This will show that the differences in the Higgs boson couplings give rise to the generations, providing insight into our understanding of generations. Furthermore, the measurement of the Higgs boson coupling with the Z boson and the differential cross section can be done model-independently and provides sensitivity to new phenomena with a mass scale of up to 2.5 TeV for CP-even states and 3.9 TeV for CP-odd states using the effective Lagrangian approach.

Among the various new phenomena and new principles, the supersymmetry is the most promising theory. There are three approaches to discover supersymmetric particles, as described below. The capability of these three approaches depends on the model and the parameter space. Thus it is crucial to be able to cover all three approaches.

(a) Direct search for supersymmetric partners with SU(3) color charge, such as the squarks and the gluino. The HL-LHC has good sensitivities to search for the squarks and gluino up to about 3 TeV.
(b) Search for supersymmetric partners with SU(2) and U(1) charge, such as the electroweak gauginos and higgsinos. In contrast to (a), the mass spectrum can be naturally highly compressed. The ILC will play an important role as described in Chapter 4.
(c) There are at least two Higgs doublets (2HD) in all supersymmetric models, in which multiple Higgs bosons exist. These signatures can be accessed even if the supersymmetric partners as described in (a) and (b) are beyond the reach of the experiments.

The precise measurement of the Higgs couplings at the ILC250 provides an important input to the approach (c) above. The Minimal Supersymmetric Standard Model (MSSM) is considered first among the 2HD models. The HL-LHC has a high discovery potential for parameter regions with large tan$\beta$. In contrast, the deviation of the Higgs boson coupling with the gauge bosons, g(HZZ) or g(HWW), becomes larger for smaller tan$\beta$, which is favorable for the ILC. The sensitivity of direct searches at the LHC and the ILC250 sensitivity are thus complementary. Heavy Higgs bosons (or SUSY breaking scale $\Lambda$) can be discovered almost up to 1.5–2 TeV by combining the ILC250 and the HL-LHC results, even if the supersymmetric partners are heavy. In the extended models such as the Next-to-Minimal Supersymmetric Standard Model (NMSSM), in which the relation between the neutral and charged Higgs bosons become model-dependent, the large tan$\beta$ region is covered by neutral Higgs boson searches at the HL-LHC and the charged Higgs boson searches at Belle II; the small tan$\beta$ region is covered by the ILC250.

The energy scale of new phenomena can be probed up to $\Lambda$~2 TeV in more general 2HD models not restricted to supersymmetry, through coupling deviations. The Kaluza-Klein (KK) gluon can be probed up to a mass of 10–20 TeV (corresponding to a KK scale of 3–7 TeV).

Furthermore, a physics model behind the discovered new phenomena at $\Lambda$ can be identified through the deviation pattern. These sensitivities are determined by the precision of the Higgs couplings, and do not depend highly on the CM energy (250 GeV or 500 GeV). It will be crucial to reduce the systematic uncertainties (coming from experimental uncertainties, and determining the quark mass and $\alpha_s$) through the collaboration between the experimental and theory communities.

## 2.2. Precision measurement of the Higgs boson properties

The total decay width $\Gamma_H$ can be determined with an accuracy of 2.1% by fitting the both results at ILC250 and HL-LHC in the effective field theory framework as mentioned in Section 2.1. This will allow for the search for decays to unknown particles with decay branching ratios down to 0.3%. Detail is discussed in Chapter 4. The CP phase in the coupling between the Higgs boson and fermions can be measured to 3.8 degree precision, which provides an important clue to the origin of the matter-antimatter asymmetry, whether it is baryogenesis or leptogenesis (See Chapter 3). The discovery of CP violation in the Higgs sector will be an important achievement, as it implies that the SM Higgs field (1HD) is not the correct description of nature, and that the Higgs sector must be more complicated (such as general 2HD models or addition of singlet fields).

From the angular distribution of the decay particles, the compositeness of the Higgs boson can be probed up to a scale of 2.2 TeV.

## 2.3. Precision observables in the Standard Model: $M_W$ / $M_t$ / $\sin\theta_{eff}$

At ILC250, the W boson mass ($M_W$) and weak mixing angle ($\sin\theta_{eff}$) can be measured with accuracies of 3 MeV and $3\times10^{-5}$ (relative precision), respectively. Although the top quark mass ($M_t$) cannot be measured directly at the ILC250, the HL-LHC is expected to determine the top quark mass with an accuracy of 0.2–0.3 GeV. The contribution of various systematic uncertainties such as $\Delta M_Z$ and $\Delta\alpha_s$ and a top quark mass precision of 0.3 GeV are roughly equal to check the Standard Model precisely. Thus, from the point of view of precise observables in the SM, the HL-LHC precision of 0.3 GeV is sufficient. Supposing that the current central values for $M_W$, $M_t$, and $\sin\theta_{eff}$ remain fixed, the improved precision from the ILC250 and the HL-LHC will yield a 3–4$\sigma$ deviation from the SM. This will indicate that new physics such as supersymmetry exists around the TeV scale. If an excess is seen at the HL-LHC or if deviations of Higgs couplings are seen at the ILC, it will be crucial to identify the principles behind these anomalies. This will be one of the important achievements expected from the ILC250.

The stability of our vacuum can be computed from the Higgs boson mass ($M_h$) and $M_t$. An upper limit on the energy scale of new physics can be also determined with the assumption that our vacuum is stable. Combining the ILC precision of $\Delta M_h$=14 MeV and the HL-LHC precision of $\Delta M_t$=0.3 GeV will determine that our universe is metastable or that new physics should exist at a scale below $10^{12}$ GeV to make our universe stable, if the central values are the same as the current values. These results are crucial to understand the early universe, including implications about the possibility of leptogenesis, as described in Chapter 3.

2.4. New phenomena can be discovered up to $\Lambda$=2–3 TeV with synergy among the ILC250, HL-LHC and the SuperKEKB. The ILC250 has high sensitivity in the region that cannot be covered with the HL-LHC (heavy higgs boson in the 2HD models with small tan$\beta$ and the electroweak gaugino). The ILC is therefore complementary to the HL-LHC. If an excess is found at the HL-LHC, ILC can play an important role to reveal the physics behind it.

Figure 2 shows a flowchart of overview. If a deviation from the Standard Model prediction is observed in the Higgs coupling, the EW precise measurements or searches, the new energy scale $\Lambda$ for the new phenomena and new principles is determined. It also fixes the technology and the CM energy of the next-generation accelerators, such as Future Circular Colliders (FCC, HE-LHC) and the energy upgrade of the ILC.

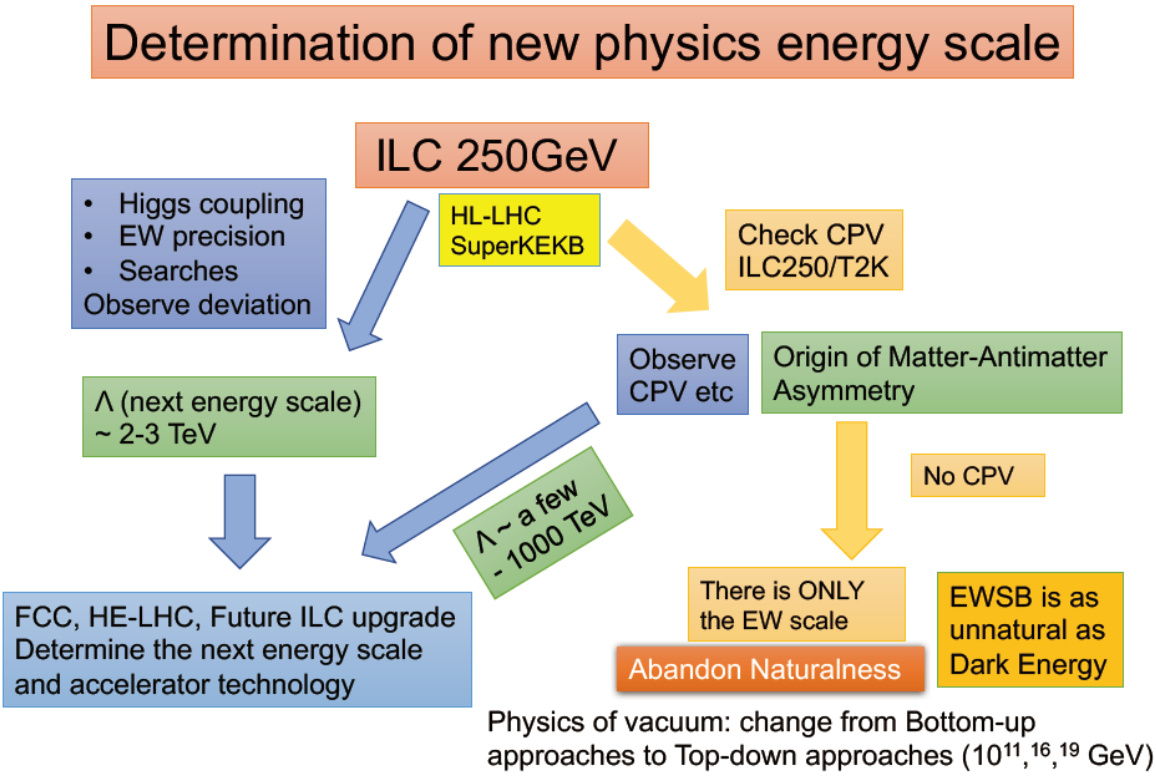


Figure 2: Precision measurements and the energy scale $\Lambda$.

The right side of Figure 2 illustrates the different approach, in which the probing for the origin of the matter-antimatter asymmetry will lead to the next new phenomena (where $\Lambda$ is the new energy scale). As discussed in Chapter 3, it can be determined that the origin of matter is either electroweak baryogenesis ($\Lambda$=10–1000 TeV) or leptogenesis ($\Lambda$<10 TeV) with the observation of CP violation (in Higgs or neutrino sectors), the precise measurement of the Higgs boson, and measurements of gravitational waves in space.

If the results from the ILC250 and other experiments are found to be consistent with the SM, and no new sources of CP violation are found, it will be determined that the energy scale for the physics behind the EWSB mechanism is O(10) times higher than the EWSB scale itself. It will be found to be at least O(10) times "unnatural" , and the electroweak phase transition (EWPT) will be an as unnatural phenomenon as dark energy. The EWPT is related to the vacuum physics, as the same as the inflation and dark energy, whose scales are also not naturally explained. This will lead to a paradigm shift in our research direction, from the traditional bottom-up approach to the top-down approach.

## 3. Electroweak Symmetry Breaking and the Origin of Matter-Antimatter Asymmetry

There are two promising scenarios for the origin of matter-antimatter asymmetry; leptogenesis and electroweak baryogenesis (EWBG). Figure 3 shows a flowchart for approaching these scenarios. EWBG can be probed at the ILC250 in two phases as discussed below.

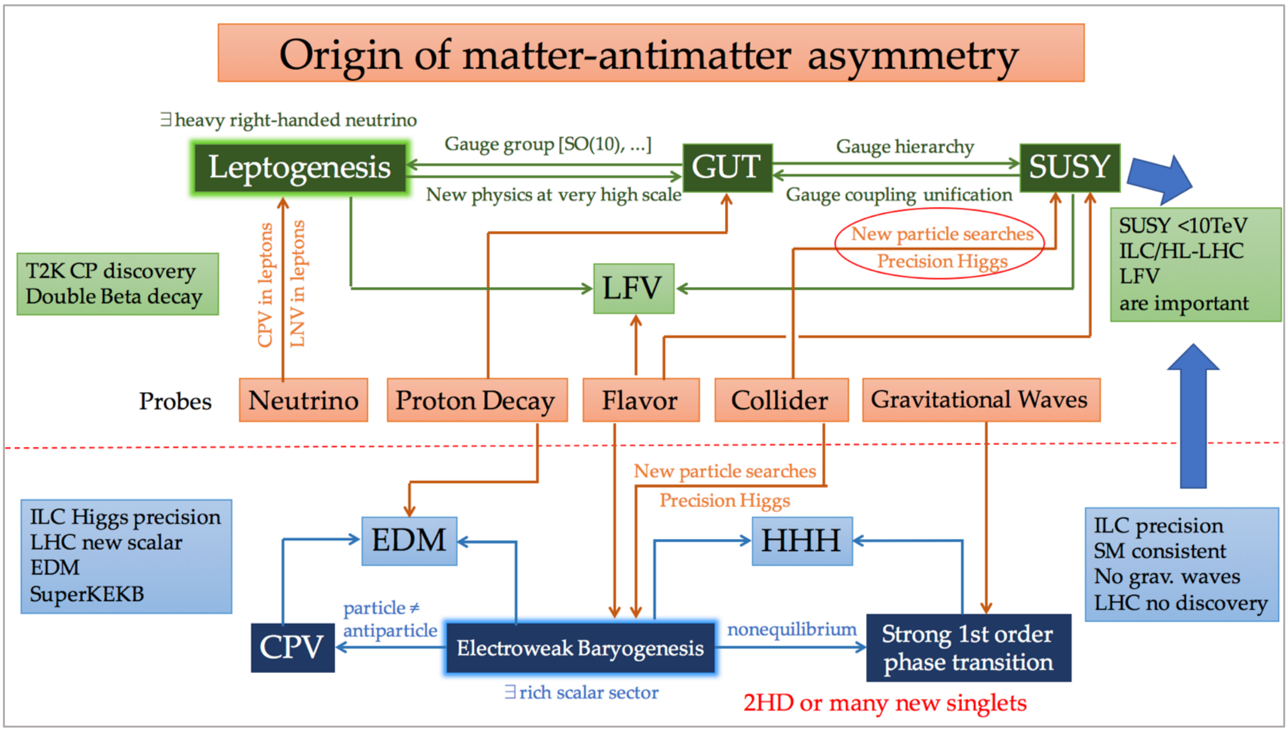


Figure 3: Origin of matter-antimatter asymmetry.

As described in Section 2.2, the phase of the couplings between the Higgs boson and fermions can be measured to 3.8-degree precision. Together with the precise measurements of the HZZ coupling and Yukawa couplings, it can be determined whether or not the Higgs boson is responsible for the origin of matter-antimatter asymmetry. These results can be cross-checked with experiments searching for the electric dipole moment of the neutron and the electron. This is the first step to examine EWBG (left-lower side of Figure 3) .

Furthermore, the electroweak symmetry breaking should be a strong first-order phase transition and in non-equilibrium in order to retain the asymmetry produced by the Higgs sector. For this to occur, it is necessary to introduce additional Higgs fields as in 2HD models or an additional singlet. These new scalar fields result in large deviations (>20%) in the trilinear Higgs coupling and most probably a few-percent deviation in Higgs couplings with gauge bosons as well (right-lower side of Figure.3). The ILC250 can investigate these couplings at sufficient precision. Gravitational waves are also emitted during the EWPT in Strong $1^{st}$ order transition. They can be detected at satellite probes (such as LISA and DECIGO) which are expected to begin operation around 2040. This is the second step to examine EWBG. The Higgs potential demands that new phenomena must be present in the range up to Λ=a few–1000 TeV in the case of EWBG. The energy of the next energy frontier experiment and its accelerator technology can be also determined in this case (as shown in Fig.2)

The ILC250 can examine EWBG scenarios from many sides. The key to probe EWBG scenarios is the precise measurement of CP violation, the Higgs couplings with the gauge bosons, and the Yukawa couplings. The precisions of these measurements are largely similar between the ILC250 and the ILC500 results. Although the Higgs trilinear coupling (HHH coupling) cannot be measured at the ILC250, the precise measurement of the Higgs boson couplings with the gauge bosons and the gravitational wave probes can be used to elucidate the origin of matter. The crucial test of EWBG can be performed at the ILC250.

If the EWBG scenarios are disfavored at the ILC250, or if CP violation is observed in neutrino sector at the T2K experiment and neutrino-less double-beta decay is discovered, the leptogenesis scenario becomes favorable. This implys the existence of a right-handed neutrino at a very high energy scale as well as grand unification (GUT). The most attractive scenario for GUT is supersymmetry with gauginos and higgsinos under 10 TeV. This scenario can be examined with the search for lepton number violation, the search for proton decays at the HyperKamiokande experiment, and the search for gauginos and higgsinos under 10 TeV at the next hadron collider (FCC, HE-LHC, etc.) or at a higher energy lepton collider. The favorability of the leptogenesis scenario is important input for the discussion of the accelerator technology and the CM energy of the next-generation facility. This is the path labeled “Λ~ a few–1000 TeV” in Figure 2. Since this is an important scenario, it is in the interest of Japan's long-term strategy to construct a linear collider which can easily accommodate the next-generation technology.

## 4. Direct Search for Dark Matter and New Particles Based on Naturalness

Naturalness has played an important role in the history of particle physics. The discovery of the 125 GeV Higgs boson has started to cast some doubt to this idea in the current situation that no new physics is found. The claim is that using supersymmetry to explain a 125 GeV Higgs boson nominally requires fine-tuning on the order of around O(100)–O(1000). However, there are possibilities where squarks become naturally heavy like focus point models. The Higgs boson becomes also naturally heavy in extensions of the MSSM, with additional singlets for example. Before giving up on the idea of naturalness, these possibilities (Higgsino/Wino/Singlet-like ) must be probed. They are also scenarios that provide natural candidates of dark matter (DM). Figure 4 summarizes the candidates of WIMP DM and their searches.

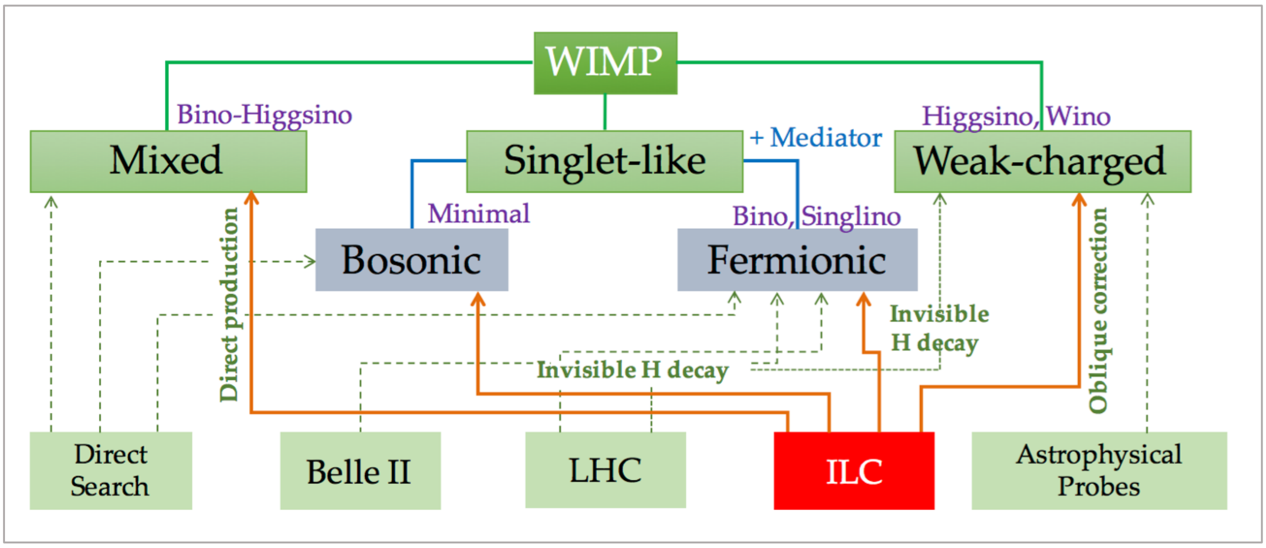


Figure 4: WIMP dark matter candidates and searches.

For the electroweak gauginos and higgsinos, the mass differences from the lightest particle among them (wino, higgsino) are generally small as described in Section 2.1(b). Such compressed spectra are challenging to search for at the LHC. It is also possible that the existence of a singlet particle could suppress the couplings with the gauge bosons. The investigation of these two possibilities are important. Taking together the HL-LHC searches (having a sensitivity for the bino) and the approach of 2.1(b) will make the search strategy complete.

It should be noted that the higgsino mass should be naturally around the Higgs mass; thus the search for the higgsino is particularly important. The ILC250 can probe higgsinos indirectly up to about 200 GeV, corresponding to the test of naturalness of about 10%. This is the higgsino path shown in Figure 4. Since it is challenging to search for higgsinos at the HL-LHC, the ILC searches are indispensable.

In the case of a singlet-like DM as in the middle of Figure 4, there are bosonic and fermionic DM (bino-like or singlino-like). A bino-like DM can be covered by gaugino searches at the HL-LHC. For singlino-like DM or for bosonic DM, the Higgs invisible decays to unknown particles is important. The ILC250 is sensitive to Higgs invisible decays with a branching ratio of 0.3%. This will be a tight constraint for DM candidates lighter than 62 GeV. Such light DM is challenging for underground direct detection experiments because the recoiling energy is small. The ILC will provide coverage for such particles, which makes the search strategy for DM complete.

In the case of a mixed bino and higgsino (Figure 4, left), the strategy depends on its mass. For a heavy mixed bino-higgsino, it can be covered through the gaugino search at the HL-LHC as well as at direct DM detection experiments. If it is light, it will become challenging for the HL-LHC (due to the compressed spectrum) and direct detection experiments (small recoil energy). The ILC250 is able to cover most of the remaining parameter space for these particles by the direct search.

For DM searches based on the “naturalness”, the ILC250 will be able to cover regions that cannot be covered by the HL-LHC and direct detection experiments (up to 200 GeV higgsinos and up to 62 GeV singlet-like DM). The ILC250 together with these experiments make the approach of 2.1(b) and the search strategy for WIMP DM complete.

The ILC will play a crucial role in the search for electroweak gauginos and higgsinos and singlet particles motivated by naturalness and dark matter. It plays a complementary role to the HL-LHC and the DM direct detection experiments. Combining these three approaches makes the search strategy complete. The necessary CM energy of the ILC depends on how much fine-tuning one can test for the naturalness.

## 5. Summary

The contributions of each project are summarized in Table 3. As discussed in Chapter 2, the ILC250 will be able to explore the phase space of new physics that cannot be covered by the HL-LHC or the Belle II experiments. It will be able to probe the new phenomena in a robust way. In particular, the ILC250 has an excellent sensitive to the heavy Higgs bosons in 2HD models, which is the 3$^{rd}$ approach as mentioned in Section 2.1(c). The ILC250 has also a good sensitivity to search for dark matter based on naturalness described in Section 2.1(b). Combining three approaches ((a)-(c)) by the ILC250 and the HL-LHC will establish a comprehensive search network, capable of probing the energy scale of new phenomena and new principles (up to $\Lambda$~2–3 TeV). Thus the ILC250 will play an important role.

Table 3: The role of each project.

| | |
|---|---|
| ILC | Higgs & other SM precision measurements; electroweak baryogenesis; 2.1(b): higgsinos, and DM ligher than 62 GeV; 2.1(c): small tan$\beta$. |
| HL-LHC | Higgs couplings; direct search of new phenomena; top quark mass; 2.1(a),(b): bino, wino; 2.1(c): large tan$\beta$. |
| SuperKEKB | Additional CP violation in quark-sector; bottom quark mass; tau LFV (GUT); 2.1(c): large tan$\beta$. |
| T2K, HK | CPV in neutrino-sector; leptogenesis; GUT. |
| LFV | Leptogenesis; right-handed neutrinos; GUT. |
| EDM | Flavor-conserving additional CP violation; electroweak baryogenesis. |
| LISA, DECIGO | First-order phase transition for electroweak baryogenesis: an alternative to the HHH coupling measurement. |
| Underground experiments | DM direct search; 2.1(b): heavy regions. |

The ILC250 will also be able to elucidate the origin of matter. It can perform a crucial test of the electroweak baryogenesis models, and probe the energy scale of new phenomena and new principles (up to $\Lambda\sim$ a few–1000 TeV).

Table 4 summarizes the list of measurements that become challenging by lowering the ILC starting energy to 250 GeV. As far as the precision measurements of the Higgs and other SM observables are considered, the ILC250 operating together with the HL-LHC and the SuperKEKB experiments will be able to play a sufficient role, with precisions not too far from the ILC500.

Table 4: List of measurements that become challenging
by making the ILC starting energy 250 GeV.

| Observable | Solutions with synergy |
|---|---|
| Higgs Full Width | From HL-LHC, use custodial symmetry ($K_W/K_Z = 1$) to replace $\Gamma_{HZZ}$ with $\Gamma_{HWW}$ in $\Gamma_{total}=\Gamma_{HWW}/Br(H\rightarrow WW)$<br>→ becomes **comparable to ILC500 precision** |
| Self-coupling HHH (also challenging for ILC500) | Baryon number violation → EWBG or leptogenesis **(T2K, neutrino-less double beta decay).** EWBG covered by **HL-LHC, ILC250, SuperKEKB, LISA.**<br>Although direct measurement of self-coupling is not possible, ILC250 can contribute to examine EWBG through CPV in Higgs sector and the precise measurements of Higgs couplings. |
| Higgs couplings | **HL-LHC** (Top Yukawa coupling)<br>**Lattice** ($m_b$, $m_c$, $\alpha_s$ uncertainty) → **comparable to ILC500**<br>**SuperKEKB** (Lattice examination) |
| Searches | Electroweak gauginos/higgsinos based on naturalness: higgsino (< ~200 GeV); dark matter (<62 GeV). |
| Top mass | HL-LHC (0.2–0.3 GeV) sufficient precision for test of SM; roughly sufficient for vacuum stability; **(if a detailed study of high scale physics becomes necessary, upgrade to 350 GeV)** |

Some of the main merits of the ILC operating at 350 GeV, 500 GeV, or above are

(a) When the energy scale of the new phenomena and new principles is discovered by the combined results of the ILC250 and HL-LHC, this energy scale becomes the next target for an energy upgrade of ILC.

(b) Top quark mass precise measurement: The HL-LHC precision of 0.2–0.3 GeV is sufficient for the test of the SM and the vacuum stability. If the results from the HL-LHC and ILC250 point to physics at very high energy scales such as GUT and the necessity to study the vacuum stability in further detail, then the ILC350 becomes important.

(c) When only the electroweak scale seems to exist (the scenario in Figure 2 (right)), it becomes important to directly study the breaking of the electroweak symmetry and the Higgs potential in detail. In this case, the measurement of the Higgs self-coupling (HHH) becomes important, irrespective to the indirect measurement by gravitational waves. The precise measurement at CM energy of 500 GeV (positive interference) and 1 TeV (negative interference) will be both important.

Future energy upgrade scenarios should be discussed based on the findings of the energy scale of new phenomena and new principles as in point (a) above, or the CM energy will be upgraded, as before, upto 350, 500 GeV or 1TeV based on points (b) and (c).

## Conclusions

The conclusions of this committee are the following four points:

- In order to maximally exploit the potential of the HL-LHC measurements, concurrent running of the ILC250 is crucial.
- LHC has not yet discovered new phenomena beyond the Standard Model. The ILC250 operating as a Higgs Factory will play an indispensable role to fully cover new phenomena up to Λ~2–3 TeV and uncover the origin of matter-antimatter asymmetry, combing all the results of ILC250, HL-LHC, the SuperKEKB, and other experiments. Synergy is a key.
- Given that a new physics scale is yet to be found, ILC250 is expected to deliver physics outcomes, combined with those at HL-LHC, SuperKEKB and other experiments, that are nearly comparable to those previously estimated for ILC500 in precise examinations of the Higgs boson and the Standard Model.
- The inherent advantage of a linear collider is its energy upgradability. The ILC250 has the potential, through an energy upgrade, to reach the energy scale of the new physics discovered by its own physics program.

Many thanks to T.Tanabe (ICEPP, U.Tokyo), T.Nakada (EPFL) , H.Aihara (U.Tokyo) and S.Komamiya (U.Tokyo) for useful discussions and suggestions to translate the original document into English.

# 3 Scientific Significance of ILC and Proposal of its Early Realization in Light of the Outcomes of LHC Run 2

2017/07/22
revised 2017/08/16
Japan Association of High Energy Physicists

Scientific Significance of ILC and Proposal of its Early Realization
in light of the Outcomes of LHC Run 2

The International Linear Collider (ILC) is a linear electron-positron collider, a key experimental facility that enables forefront research at the energy frontier in high energy physics. The ILC has been developed through an international collaboration overseen by the International Committee for Future Accelerators (ICFA). The international team of physicists, Global Design Effort, published in 2013 the Technical Design Report of a 200-500 GeV (extendable to 1TeV) center-of-mass collider. In October 2012, the Japan Association of High Energy Physicists (JAHEP) proposed to construct ILC in Japan under a global collaboration with consensus of the international community and active participation from each country. This proposal received many positive responses from the international community. In particular, it garnered support from European countries and the United States, who were also developing their future particle physics projects, as well as from the ICFA. Upon the launch of JAHEP's proposal, the Science Council of Japan and a panel of experts under the Ministry of Education, Culture, Sports, Science and Technology discussed the proposal. They noted that the large expense and cost sharing are issues that must be solved. Subsequently, a research and development project was initiated to reduce the costs associated with ILC based on the discussions between the governments of Japan and United States. Meanwhile, the Large Hadron Collider (LHC) Run 2 experiments at CERN have continued to progress, and new results have been published. In this context, JAHEP has deliberated the scientific significance of ILC and has come to a conclusion; JAHEP proposes to construct a 250 GeV center-of-mass ILC promptly as a Higgs factory.

The driving force for JAHEP's proposal released in October 2012 is that particle physics entered a new phase following the discovery of a Higgs boson. Research in the 20th century particle physics focused on elucidating fundamental forces, save gravity, of nature: strong, weak and electromagnetic forces. The existence of a Higgs boson was predicted by the Standard Model, which successfully describes these three forces in a unified way. A Higgs boson was discovered as predicted, indicating that our understanding of these three forces has greatly advanced. On the other hand, the real nature of the Higgs boson remains unknown. Candidate theories to explain the origin of Higgs bosons include new forces, new hierarchies of matter, and extension of the space-time structure. In this light, studying the Higgs boson is definitively important to determine the future of elementary particle physics. The ILC, with additional advantage of energy-extendable and beam-polarization capabilities due to being a linear accelerator, would be the best suited facility for this purpose.

The LHC experiments have an excellent ability to explore new physics by observing new strongly-interacting particles and their decays. The LHC Run 2 experiment, where the center-of-mass energy was increased from 8 TeV to 13 TeV, began in 2015 and the accelerator operated smoothly throughout 2016. The exploratory area (or mass scale) of the Run 2 has, indeed, significantly expanded compared to that under 8-TeV-energy operations. The results reported in 2016 showed that new particles anticipated by physics beyond the Standard Model are unlikely to exist below the mass scale of 1 TeV. This important finding at LHC underscores that the most imminent and important goal of ILC is to explore new physics by precision measurements of the Higgs boson and search for a class of new particles that ILC could directly produce but LHC has difficulty to observe.

JAHEP has established the "Committee on the Physics Significance of ILC 250 GeV Higgs Factory." The charge to this committee is to verify the significance of a 250 GeV center-of-mass energy ILC ("ILC250"), in particular, by comparing with the case for a 500 GeV center-of-mass ILC ("ILC500") and the case for no ILC at all. The roles that ILC250 should play were examined from the following perspectives: determination of the energy scale of new physics by precision measurement of the Higgs boson and thorough examination of the Standard Model, elucidation of electroweak symmetry breaking and the origin of matter and antimatter asymmetry, and searching for particles that are candidates of the dark matter. In the Committee's deliberation, possible synergies with the High-Luminosity LHC (HL-LHC) and SuperKEKB /Belle II were taken into account.

The Committee's conclusions are summarized as follows:

- ILC250 should run concurrently with HL-LHC to enhance physics outcomes from LHC.
- Given that a new physics scale is yet to be found, ILC250 is expected to deliver physics outcomes that are nearly comparable to those previously estimated for ILC500 in precise examinations of the Higgs boson and the Standard Model.
- The ILC250 Higgs factory, together with HL-LHC and SuperKEKB, will play an indispensable role in the discovery of new phenomena originating from new physics with the energy scale up to 2–3 TeV and the elucidation of the origin of matter-antimatter asymmetry.
- A linear collider has a definite advantage for energy-upgrade capability. ILC250 possesses a good potential for its upgrades to reach the higher energy of new physics that the findings of ILC250 might indicate.

As discussed above, the scientific significance and importance of ILC has been further clarified considering the current LHC outcomes. ILC250 should play an essential role in precision measurement of the Higgs boson and, with HL-LHC and SuperKEKB, in determining the future path of new physics. Based on ILC250's outcomes, a future plan of energy upgrade will be determined so that the facility can provide the optimum experimental environment by considering requirements in particle physics and by taking advantage of the advancement of accelerator technologies. It is expected that ILC will lead particle physics well into the 21st century.

To conclude, in light of the recent outcomes of LHC Run 2, JAHEP proposes to promptly construct ILC as a Higgs factory with the center-of-mass energy of 250 GeV in Japan.