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The LEP Collider

LEP is the energy frontier e^+e^- collider at CERN. The circumference of the LEP is about 27 km which is almost the same length as the Yamanote-line (loop rail line in Tokyo).

LEP started its operation in summer 1989 at the 200 anniversary of the French Revolution. It was 15 years after the November Revolution on particle physics (discovery of J/ψ). Although we could not discover new particles which would open up the new revolution on elementary particle physics, the LEP collider contributed a lot to determine the direction of the revolution of particle physics in the near future.

From 1989 to 1995 the LEP collider was operated on or around the Z-boson resonance (LEP-I), where the unified electro-weak gauge theory was precisely tested just at the electro-weak energy scale. The most important but theoretically unexplained result from LEP-I is that the number of quark-lepton generations was determined to be three. It was determined from the number of neutrino species extracted through the precise measurements of the Z-resonance cross sections. Also the top quark mass was indirectly determined from the top-quark loop effects which was also extracted from the analysis of the Z-boson. In 1995 TEVATRON experiments directly discovered the top quark. Since they knew the top mass from LEP-I results, it was obvious that their signal was actually due to the top quark. After top quark mass was more precisely determined by the TEVATRON experiments, it was included into the electro-weak analysis to dig up the Higgs boson loop effect from the Z-boson data. The upper limit of the Standard Model Higgs boson mass thus obtained was about 200 GeV. This shows the direction of particle physics towards the TeV-scale supersymmetry, if we trust the majority of theorists. The history of LEP and TEVATRON proves that a concurrent running of energy-frontier e^+e^- and hadron colliders is essential to understand the underlying physics.

From 1995 to 2000 LEP beam energy was gradually increased by inserting superconducting acceleration cavities in the straight section of the LEP collider. In 1996 the center of mass energy exceeded W-boson pair production threshold, hence LEP-II was started. In 1999 the LEP energy exceeded 200 GeV and in the year 2000 finally reached 209 GeV. At these highest energies we extensively searched for the Higgs boson and supersymmetric particles. In these energy regions W-bosons are amply pair produced, so we studied the W-boson properties including mass, width and couplings. Now the lower mass limit of the Higgs boson is 114 GeV obtained from the direct searches at LEP. Therefore, after combining the upper mass limit from the precise electro-weak measurements, the Standard Model Higgs boson mass was confined in a narrow region of 114 GeV – 196 GeV (95% C.L.).

The success of the LEP experiments owes a lot to the excellent team of accelerator physicists at CERN as well as the international teams of experimentalists. In the OPAL experiment ICEPP constructed the electro-magnetic calorimeter which is a heart of OPAL together with the central tracker. Also powerful young physicists from ICEPP and universities lead the most important parts of data analyses, such as Higgs boson searches, SUSY particle searches and precision tests of electro-weak interactions.

Trends of Elementary Particle Physics

For more than two decades, much experimental effort has been undertaken to establish the Standard Model, which is based on two fundamental concepts, namely the gauge principle and the Higgs mechanism. Although our understanding on the gauge structure of the Standard Model has greatly improved from the discovery of the weak bosons at CERN and the precise electroweak measurements at LEP and SLD, little is known about the mechanism of electro-weak symmetry breaking. The direct search for the Higgs boson has been carried out at LEP, and will be continued by LHC experiments. On the other hand, there is already a strong constraint on the possible range of the mass of the Higgs boson from studies on the precise electro-weak measurements at LEP and other colliders as described above.

To determine the future direction, the most crucial step is a definite proof or disproof of TeV scale SUSY. Although each experimental indication is not strong, several independent experimental facts taken as a whole indicate the direction of a light Higgs boson with SUSY.

(1) As mentioned above, the upper bound on the mass of the Standard Model Higgs boson is estimated to be 196 GeV. This is consistent with the Minimal Supersymmetric Standard Model (MSSM) where the mass of the light Higgs boson is expected to be less than 130 GeV. The upper bound cannot exceed about 200 GeV even in more general SUSY models.

(2) From the values of the SU(3), SU(2) and U(1) gauge couplings measured at LEP, it is shown that the three coupling constants are unified at a mass scale around 10^{16} GeV for SU(5) SUSY GUT. The simple SU(5) GUT without SUSY cannot unify these couplings at any mass scale.

(3) There is definitive evidence that the dark matter exists in our galaxy with a density of 0.3 GeV/cm^3. The lightest SUSY particle is a theoretically well-motivated candidate for the dark matter.

The first indication of supersymmetric particle production may be obtained at LHC, since the cross sections of the strongly interacting supersymmetric particles (gluinos and squarks) are large at LHC. To disentangle the complicated cascade decay of these heavy SUSY particles, the determination of the masses and the couplings of the lighter colorless SUSY particles at the e^+e^- Linear Collider is essential. Experimental determination of these observables can resolve the mechanism of SUSY breaking, which is one of the most important and mysterious issues in the SUSY theories.

Recent progress in flavor physics (quark and lepton masses and flavor mixing) is remarkable. Belle and BaBar groups clearly measured the CP violation in the bottom-sector. The direct CP violation parameter ϵ'/ϵ in the kaon sector was most precisely measured at CERN and Fermilab. In coming years the Kobayashi-Maskawa mechanism of CP violation will be tested experimentally and the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements will be precisely determined.

In the leptonic sector, Superkamiokande observed the flavor oscillation of the muon neutrino, probably with the tau neutrino, from the measurement of atmospheric neutrinos. The measurements of solar neutrinos by Homestake, Kamiokande, Superkamiokande, Gallium experiments, and SNO, strongly suggest the oscillation of the electron neutrino with a large mixing angle. In the Maki-Nakagawa-Sakata (MNS) matrix of the neutrino flavor mixing, the off-diagonal component of θ_{23} is measured to be large, which presents a striking contrast to the hierarchical structure of the CKM matrix.

There are stringent limits on the mixing in the charged lepton sector. New experiments to observe $\mu^+ \to e^+\gamma$ decay and $\mu^- \to e^-$ conversion are planned, and $\tau \to \mu\gamma$ will be searched at B factories and tau-charm factories. Together with baryon number violation which continue to be searched for at the Superkamiokande experiment, these lepton flavor violating processes are sensitive probes of the physics beyond the Standard Model, including SUSY GUT.

At a fundamental level, these flavor physics has deep connection with Higgs physics. The masses and the flavor mixing of quarks and leptons are determined by the interaction of the fermions and the Higgs field, and all quarks and leptons remain massless without the vacuum expectation value of the Higgs field. The direct measurements of the Yukawa couplings at the future Linear Collider are important to understand the fermion mass generation mechanism.

If the lightest SUSY particle is the dark matter, the discovery and studies of SUSY by collider experiments and/or the direct observation of the dark matter may solve the fundamental problem in Cosmology.

Recent measurement on the acceleration of the expansion rate of the universe suggests the existence of the cosmological constant (dark energy). The origin of the dark energy may have a profound relation to the Higgs potential. The inflation of the universe may be due to the latent heat filled in the universe from the super-cooling which is caused by the delay of the phase transition of some Higgs field. Although these Higgs fields may not be the same one which causes the electro-weak symmetry breaking, the essential ingredients are the existence of an elementary scalar field and its dynamical properties. The discovery of the Higgs boson and the reconstruction of the Higgs potential from the measurement of the self-coupling constant will provide us with the first experimental evidence that an elementary scaler field plays a fundamental role in Particle Physics and the formation of the universe, and give tremendous impact to both Particle Physics and Astrophysics.

In this way, the present knowledge of Elementary Particle Physics suggests scenarios with a light Higgs boson, which could include SUSY and/or GUT. If this is correct, a new paradigm beyond the Standard Model must show up in the near future at the energy frontier colliders.

The ICEPP will continue pursuing the discovery physics at energy frontier wherever the frontier accelerator will be.