Searches at LEP

Kiyotomo Kawagoe
Department of Physics, Faculty of Science, Kobe University,
1-1 Rokkodai-cho, Nada-ku Kobe, 657-8501 Japan
E-mail address : kawagoe@phys.sci.kobe-u.ac.jp

Searches for new particles and new physics were extensively performed at LEP. Although no evidence for new particle/physics was discovered, the null results set very stringent limits to theories beyond the standard model. In this paper, searches at LEP and anomalies observed in the searches are presented. Future prospect of searches at the new energy frontier machines is also discussed.

1 Introduction : Searches at LEP

Merits of e^+e^- colliders with respect to hadron colliders are well known. The merits include;

- As leptons are elementary, the center-of-mass energy ($\sqrt{s}$) of colliding particles is fully used for the interaction.
- Any charged particle can be produced in particle-antiparticle pairs, if the production is kinematically allowed.
- Any particle which couples to the Z^0 boson can be produced, if $\sqrt{s} \geq M_Z$ and the production is kinematically allowed.
- Observed events are relatively simple and easy to reconstruct.
- The standard model backgrounds are usually controlled to a very low level compared to the signal, as the behaviors are well understood and can be simulated with good precision.

The demerit of (circular) e^+e^- colliders is limited center-of-mass energy due to the energy loss caused by Synchrotron radiation. On the other hand, hadron colliders do not suffer from this problem, so that much higher center-of-mass energy can be achieved. Therefore e^+e^- colliders and hadron colliders have been both used to explore the world of particle physics. The development of the center-of-mass energies of e^+e^- and hadron colliders is shown in Figure 1 as a Livingston chart. In the chart major discoveries of new particles are also shown. There has been no discovery at e^+e^- colliders for more than 20 years since gluon was discovered at PETRA in 1979[1]. Weak gauge bosons ($W^\pm$ and Z^0) and the top quark were found at hadron colliders (S$\bar{\text{p}}$pS and Tevatron, respectively).

From 1989 to 2000, LEP, an e^+e^- collider constructed at CERN, was operated at the highest center-of-mass energy in the world. The LEP accelerator and the four LEP experiments (ALEPH, DELPHI, L3 and OPAL) are described elsewhere[2]. Physics studies at LEP may be classified into two categories;

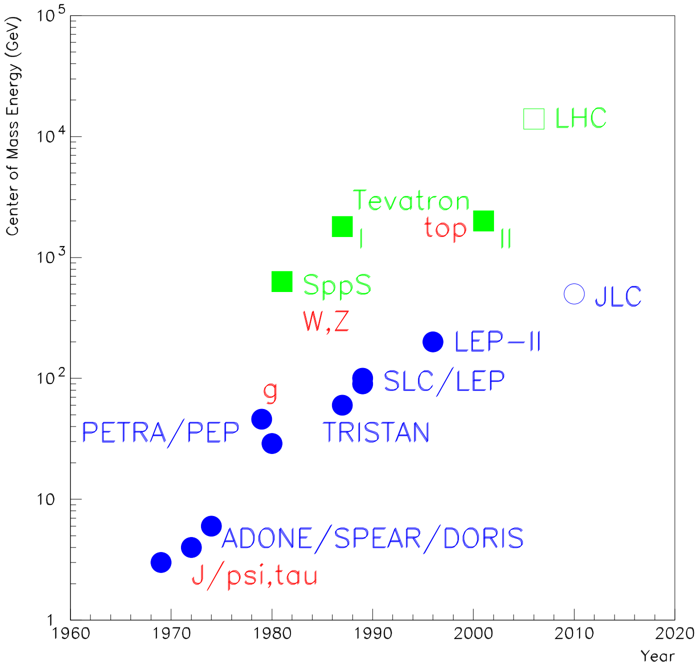


Figure 1: A Livingston chart of e^+e^- and hadron colliders. Discoveries of new particles are also shown.

- Tests of the standard model at the Z^0 resonance (LEP1) and above the W^+W^- production threshold (LEP2).
- Searches for new particles and new physics at the highest e^+e^- center-of-mass energy.

While tests of the standard model were extremely successful [3,4], LEP searches did not find any evidence for new particles in spite of all the efforts devoted by a large number of physicists. The reason is very simple : new particles do not exist within the reach of the LEP machine. This is “Nature”, which we cannot change. The null results, however, set very stringent limits on masses and couplings of new particles, providing important information to restrict theories beyond the standard model.

I do NOT intend to summarize the results of LEP searches here. Those who are interested in recent results may visit Web sites of the LEP experiments and the LEP working groups [5]. Instead, I am going to review “fake” anomalies observed at LEP, hoping to obtain some lessons for future energy-frontier experiments such as LHC [6,7] and JLC [8].

2 Anomalies observed at LEP

Since the beginning of the LEP physics run, several anomalies, which might be signals of new physics, have been reported. They can be classified into two types.

Type 1 Anomalies which are expected by the standard model (the Higgs boson) or theories beyond the standard model (for example, new particles predicted by Supersymmetry (SUSY) or composite models). In this case the characteristics of the signal such as production cross-section and event kinematics are well known before data taking.

Type 2 Anomalies which are not expected by a specific theory. This is very important, as any “UNKNOWN” or “UNEXPECTED” may happen at the world-highest energy that has

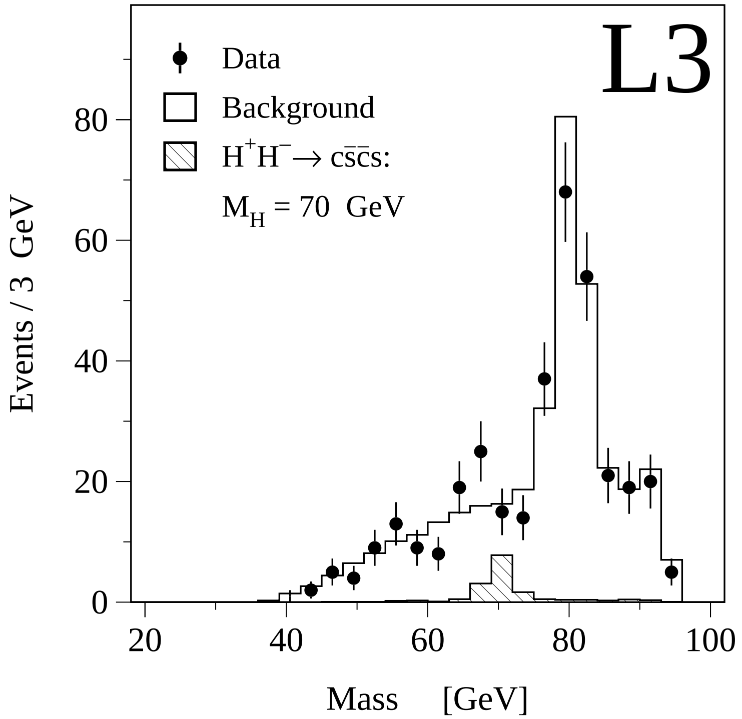


Figure 2: Distribution of the mass resulting from a kinematic fit, with assumed production of a pair of equal mass particles, for data and background events in the $H^+H- \to c\bar{s}\bar{c}s$ channel. The hatched histogram indicates the expected distribution for a 70 GeV charged Higgs boson at $Br(H^\pm \to \tau\nu) = 0$.

never been explored. The experimental data are thoroughly compared in a less model-independent way with the expectation of the standard model. If a significant difference were found in the cross-section or in the event kinematics, it might originate from new (unknown) physics beyond the standard model.

Anomalies observed at LEP are briefly described in the following.

2.1 Type 1 (expected anomalies)

- L3 observed a slight excess in search for the charged Higgs boson ($H^\pm$) in the data taken at $\sqrt{s} = 189$ GeV [10]. The area where the excess was observed corresponded to pair-production a charged Higgs boson with $M_{H^\pm} \sim 67$ GeV and a low $Br(H^\pm \to \tau\nu)$. The reconstructed mass distribution is shown in Figure 2. The anomaly was excluded by the data taken at higher energies. The current LEP-combined mass limit is $M_{H^\pm} > 78.6$ GeV at 95 % confidence level.

- A possible excess of acoplanar τ pair events, observed in the data taken at $\sqrt{s} \leq 202$ GeV in 1999, where a slight excess was observed by each of the four LEP experiments. The excess could be interpreted as the pair production of scalar tau lepton ($\tilde{\tau}$, the SUSY partner of tau lepton) with $M_{\tilde{\tau}} \sim 85$ GeV and $M_{\tilde{\chi}_1^0} \sim 22$ GeV. The possible signal was excluded by the data taken at $\sqrt{s} > 202$ GeV in 2000. Mass regions excluded by slepton searches at LEP are shown in Figure 3.

- We had a world-wide-spread rumor that ALEPH found a Higgs signal at $M_H \sim 105$ GeV in 1999 [12]. The possible signal shown in Figure 4 was soon excluded by full analysis of the

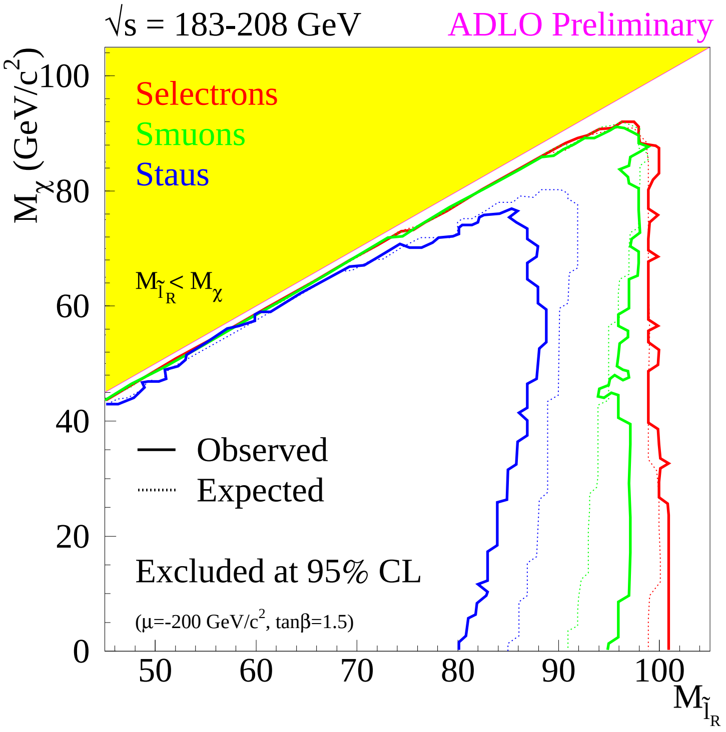


Figure 3: Excluded regions in the plane of the right-handed slepton mass ($M_{\tilde{\ell}_R}$) and the neutralino mass (M_χ).

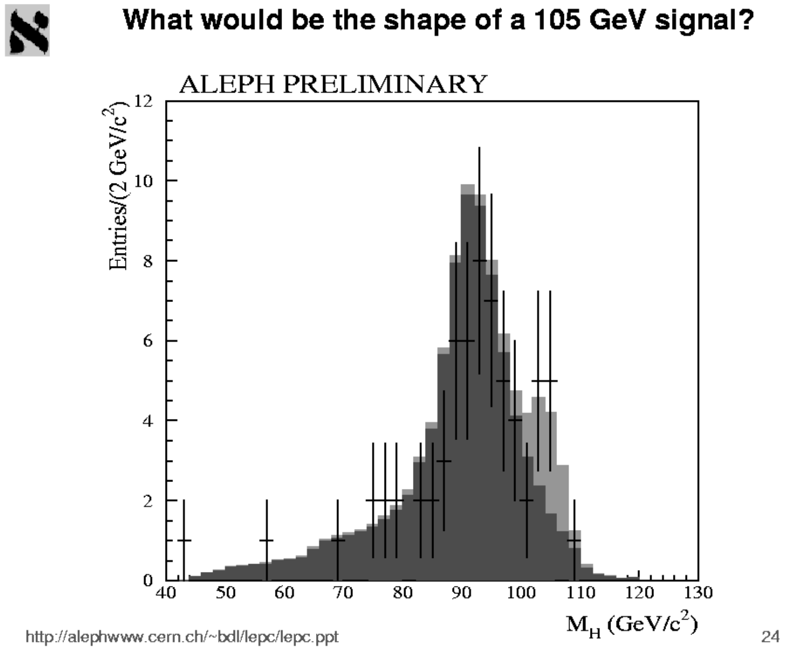
1999 data [13]. By including the 2000 data, the current LEP-combined mass limit of the standard model Higgs is set to be $M_H \geq 114.4$ GeV at 95 % confidence level.

- A possible Higgs signal at $M_H \sim 115$ GeV in the data taken in 2000, the last year of LEP run, as given in another talk in this symposium [9]. The possible excess was first reported by ALEPH. Other experiments also reported possible candidates [16]. At the LEPC held in November 2000 the LEP combined analysis still showed an excess of 2.7 σ. However, this excess was not convincing enough to extend the LEP run for one year in 2001. Therefore the signal will be kept "gray" until we accumulate enough LHC data to tell whether the signal for the 115 GeV Higgs boson was real or not.

2.2 *Type 2 (unexpected anomalies)*

- ALEPH reported an excess of $\tau^+\tau^-V$ events in the data taken in 1989 and 1990 [18] where V denotes a pair of charged particles, namely e^+e^-, $\mu^+\mu^-$, or $\pi^+\pi^-$. The data corresponded to about 2000,000 Z^0. One of the observed $\tau^+\tau^-V$ events is shown in Figure 5. The excess, compared with the electroweak expectation, was observed only in the $\tau^+\tau^-V$ channel (15 events observed and 3.2 events expected), and not in the e^+e^-V (10 events observed and 7.2 events expected) and $\mu^+\mu^-V$ channels (10 events observed and 6.6 events expected). The excess was not confirmed by other experiments, and was excluded by new data.

- In the data taken in 1990 and 1991 L3 observed four $\ell\ell\gamma\gamma$ events with the invariant mass of the photon pairs very close to 60 GeV [19]. The distribution of the invariant mass is shown in Figure 6. The four events could be, for example, an indication of a new scalar particle with a mass of about 60 GeV which decays into $\gamma\gamma$. The probability for all four events originating from QED is estimated to be $\mathcal{O}(10^{-3})$. However, the excess was not confirmed by other LEP experiments [20,21]. TRISTAN experiments, which searched for a



What would be the shape of a 105 GeV signal?

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Figure 4: The reconstructed Higgs mass distribution compared with the standard model and signal expectations. This is a preliminary plot shown at LEPC on 9th November 1999.

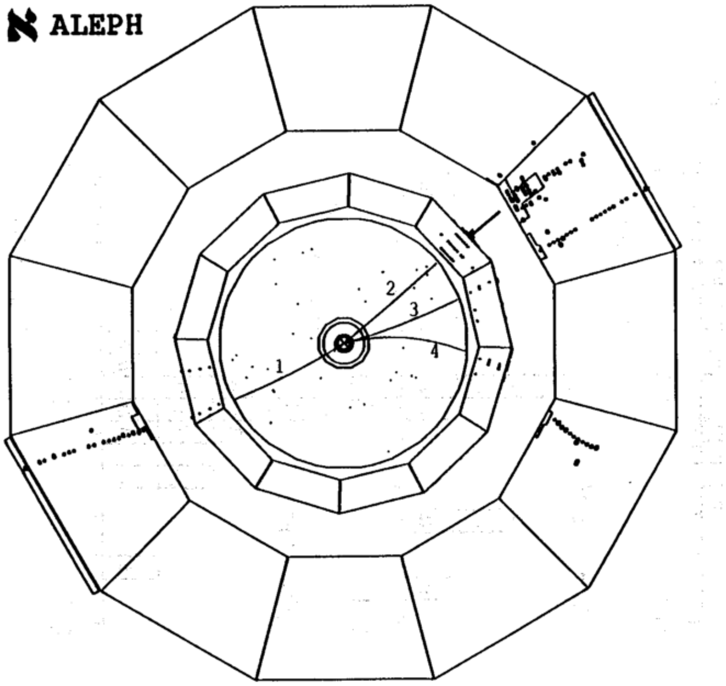

Figure 5: A four track $\tau^+\tau^-V$ candidate recorded by ALEPH, where $\tau^+ \to \mu^+\nu\bar{\nu}$, $\tau^- \to \pi^-\nu$ and $V \to \mu^+\mu^-$.

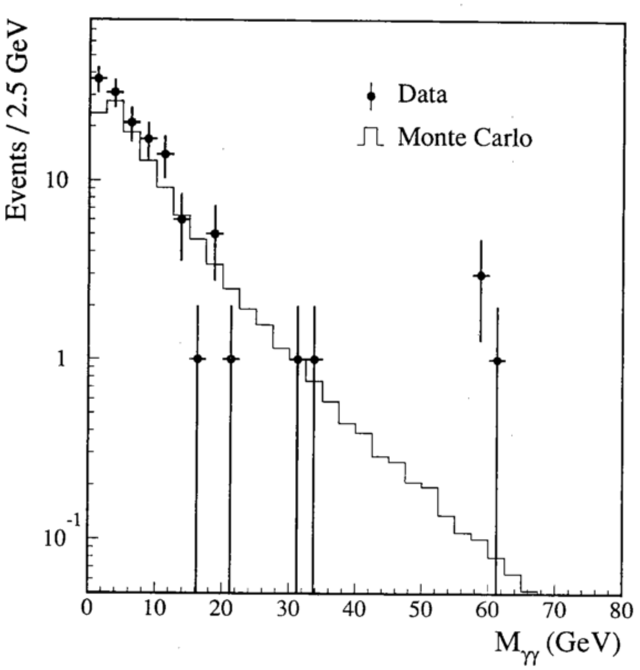

Figure 6: The distribution of the invariant mass of photon pair for $\ell\ell\gamma\gamma$ events compared to the expectation from the Monte Carlo (L3).

narrow resonance in the reaction $e^+e^- \to \gamma\gamma$ due to such a new scalar particle, also gave negative results [22,23].

- In 1995 after the end of LEP1, LEP was operated at $\sqrt{s} = 130$ and 136 GeV providing the integrated luminosity of about 6 pb^{-1} for each experiment (LEP1.5). ALEPH analyzed four-jet final state in the data to search for hadronic decays of pair-produced heavy particles [24]. In short, the analysis was as follows.

  - select four-jet events with a jet-finding algorithm,
  - calculate di-jet masses and choose a combination that minimizes the mass difference $\Delta m = |m_{ij} - m_{kl}|$,
  - and make a distribution of the sum of the two di-jet masses $m_{ij} + m_{kl}$.

  The distribution for the 1995 data is shown in Figure 7(a). The events exhibited an enhancement in the sum of the two di-jet masses around 105 GeV. An interpretation of the enhancement is the pair production of Higgs bosons, $e^+e^- \to hA$, with $m_h = m_A \sim$ 53 GeV.

  Other three experiments tried to confirm the enhancement applying very similar analyses to their data [25,26,27], but in vain. Furthermore any experiment did not observe the enhancement in higher energy data at LEP2. The contradiction had remained until LEP took data again at $\sqrt{s} = 130$ and 136 GeV in 1997 to obtain enough statistics for discovery/exclusion. This time none of the LEP experiments observed the enhancement at $m_{ij} + m_{kl} \sim 105$ GeV (see Figure 7b). The four-jet anomaly was completely killed [28,29].

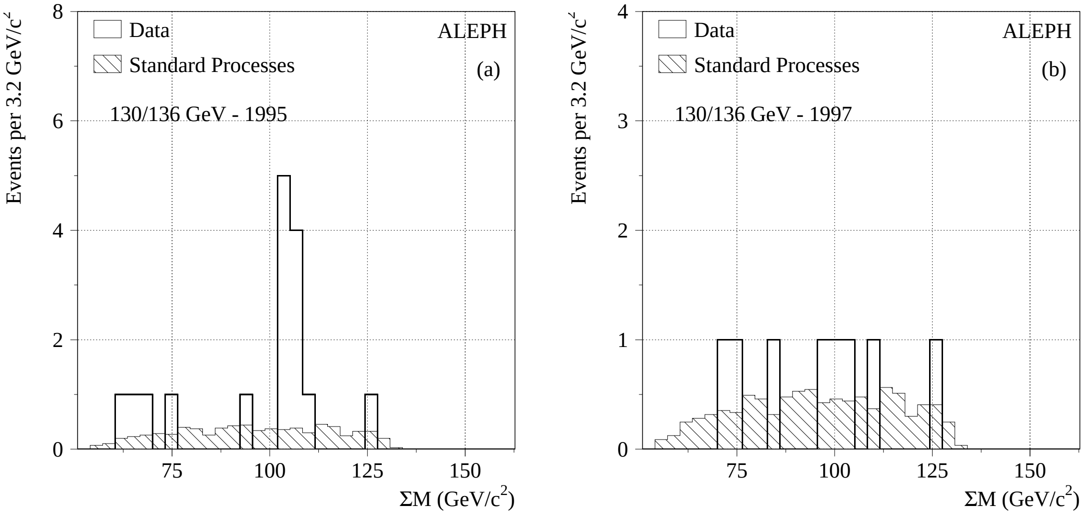

Figure 7: The distribution of the sum of the two di-jet masses for (a) data taken in 1995 and for (b) data taken in 1997.

2.3 Origin and effect of anomalies

The observed anomalies, except the possible signal of the 115 GeV Higgs boson, have been excluded. They are assumed to be statistical fluctuations. This is not a surprise at all.

- If one repeats a same measurement 1000 times, one observes $\geq 3\sigma$ anomalies 3 times on average.
- If one makes 1000 different measurements, one also observes $\geq 3\sigma$ anomalies 3 times on average.

This is a universal theorem of statistics. The four LEP experiments have compared their data with the standard model expectations in a huge number of different distributions at many different center-of-mass energies. Therefore it is statistically impossible to avoid happening anomalies. Physicists, not only experimental physicists but also theoretical physicists, should keep this in mind. A 3σ anomaly should not be regarded as an evidence of new physics. It may be regarded as just a “possible” sign of new physics, which must be further investigated with more data to have $\geq 5\sigma$ significance, or must be studied in a completely different way.

Observation of anomalies have made some by-products.

- In order to check if an observed anomaly was real, everything (detector status, calibration constants, reconstruction program, analysis algorithm, and etc.) was re-examined. As a result, quality of the analysis, not only for searches but also for measurements of the standard model, was much improved.
- Theorists could write many papers on the anomalies. This is especially true for unexpected anomalies.

3 Future prospects

The main objective of LEP, which ended its operation in November 2000, was the study of the electroweak interaction, and was extremely successful. What we particle physicists must to do next is to explore the origin of the electroweak symmetry breaking.

As the post-LEP experiment, a new energy frontier machine, LHC [6,7] is being constructed to replace the LEP machine in the LEP tunnel. The construction is expected to be completed in 2005, and experiments will start in 2006[a]. The main target of LHC is the discovery of the Higgs boson. For the standard model Higgs boson, the two pp collision experiments (ATLAS and CMS) will cover the whole mass region from the LEP limit (114.4 GeV) to about 1 TeV. The discovery potential of SUSY is expected also to be high, as colored SUSY particles (gluons and scalar quarks) can be copiously produced at LHC (if SUSY is the real theory and its mass scale is 1∼2 TeV).

However, LHC alone will not be enough to fully understand the physics of TeV energy scale. Similar to previous hadron colliders such as Sp̄pS (discovery of the $W^{\pm}$ and Z^0 bosons) and Tevatron (discovery of the top quark), LHC is good at discovery of new particles. In addition some precision measurements are possible at LHC according to recent Monte Carlo simulation studies. For example, some Higgs branching ratios and SUSY parameter studies may be performed. However, we will not be satisfied by the measurements, because we know that an e^+e^- collider with higher center-of-mass energy than the LEP energy can dominate in this area. Remember that precise measurements of the $W^{\pm}$ and Z^0 bosons, which Sp̄pS had discovered in 1983, became for the first time possible by the e^+e^- colliders, SLC and LEP.

Therefore linear collider projects [8] are enthusiastically discussed in Asia (JLC), United States (NLC), and Europe (TESLA/CLIC). We plan to start the JLC experiment at initial center-of-mass energy of 250∼300 GeV by ∼2010, and then extend the energy to $\mathcal{O}(1)$ TeV. First of all, such a linear collider will work as a Higgs factory at its first stage where the nature of the Higgs boson can be fully examined (I assume that the Higgs boson mass is less than about 200 GeV as the combined fit of the electroweak measurements tells us [3]). Discovery and detailed study of uncolored SUSY particles may also be possible. As for SUSY particle searches JLC reach is comparable with that of LHC, because uncolored SUSY particles (sleptons and charginos/neutralinos) are much lighter than colored SUSY particles in general.

We need both LHC and JLC to fully explore physics at TeV energy scale and to have perspectives to much higher energy scale (see a famous picture shown in Figure 8. While LHC is now under construction, the JLC project (and other linear collider projects) is still under discussion. In order to realize the JLC project, we have to make every effort to overcome technical/political/financial issues.

Acknowledgments

Thanks are due to the organizing staffs of this fruitful LEP symposium. I would like to thank all who have contributed to the LEP machine and the LEP experiments, one of the most successful project in the history.

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[a] According to more recent information start of the experiments is likely to be delayed to 2007.

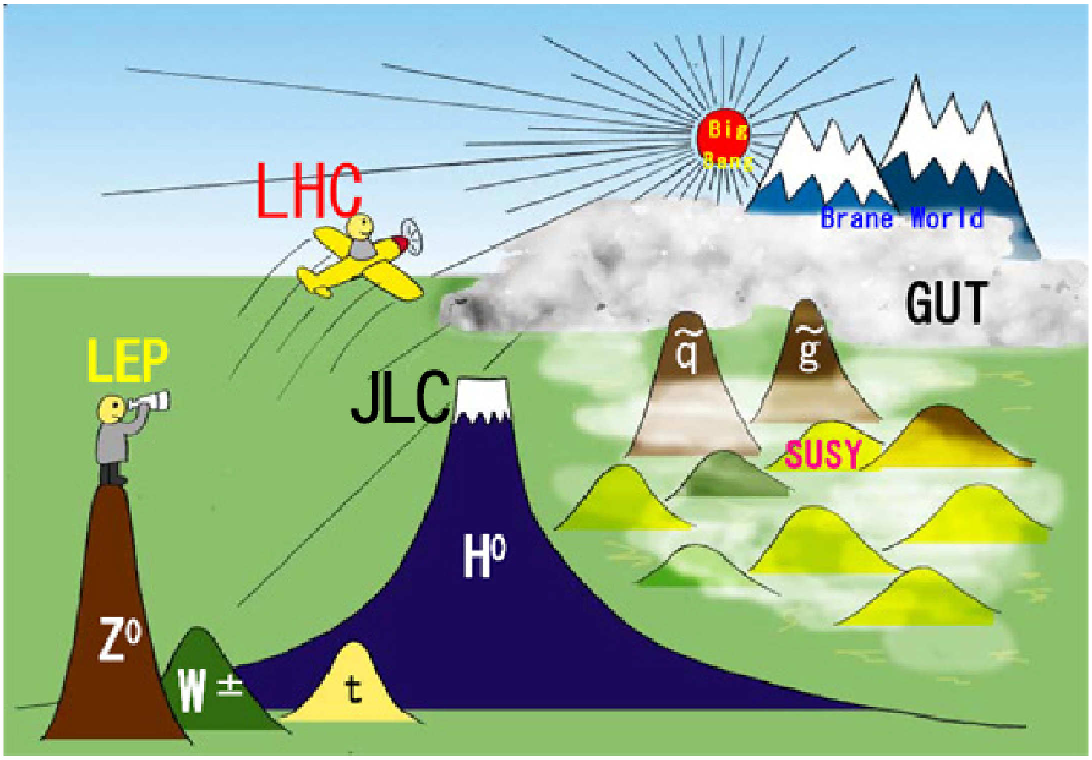

Figure 8: Perspectives from LHC and JLC toward the physics far beyond the electroweak scale.

http://www.cern.ch/Opal/
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