APPENDIX 3.5.A

Next generation of e^+e^- colliders

The flagship of the modern particle physics is the Large Hadron Collider at CERN. Its main achievement so far was the discovery of Higgs boson in 2012. The LHC experiments produced more than a thousand publications covering a variety of topics, including Higgs boson properties, electroweak and strong interactions, physics of top and other heavy quarks, searches for new physics phenomena, and many others. With a series of luminosity upgrades LHC is planned to run for more than 10 years from now.

Although the LHC running will continue for many years, design studies for the next-generation colliders have already started. It is widely accepted that the next major machine should be an e^+e^- collider. In general, it is easier to reach high beam energies at hadronic machines and hence to discover new particles. However, e^+e^- machines are best suited for the precision studies of the newly discovered particles, with obvious advantages from well defined kinematics of the initial state and absence of the large QCD background typical for hadronic colliders. As an example, W and Z bosons have been discovered at SPS, and then studied with an enormous precision at the LEP collider. In a similar fashion, the top quark and the Higgs bosons, both discovered at hadronic machines, can be studied at a future e^+e^- collider with typically an order of magnitude improvement in precision.

The major problem of the high-energy e^+e^- collider design is to overcome the energy losses for synchrotron radiation emitted by electrons on a circular orbit. One has to build either a very long linear collider, or a circular collider of very large radius. Currently there are four projects of a future e^+e^- collider under consideration. Two of them are for linear colliders and two are for circular ones. Both circular projects have the advantage of re-using the tunnel and the infrastructure for the next-generation hadron collider at ultra-high energy.

There are several energy points that are crucial for e^+e^- collider running:

1. 91 GeV, "Z factory". Modern technology allows to overcome the LEP luminosity by 3 orders of magnitude, or even more. With many billions of reconstructed Z boson decays the precision of electroweak measurement and flavour physics can be improved by a huge factor.

2. 240-250 GeV, "Higgs factory". The "Higgsstrahlung" process $ee \to ZH$ has maximal cross-section at this energy. Very precise model-independent measurements of Higgs boson properties can be performed using the Z boson decays as tags which uniquely define a presence of the Higgs boson.

3. 350 GeV, "tt threshold scan". By measuring the energy dependence of the top pair production cross-section near the production threshold one can determine the top quark mass with extremely high precision (about ± 50 MeV, order of magnitude improvement of the current uncertainty)

4. $\sim$400 GeV, "top factory". This energy is close to the maximum of the top pair production cross-section. Huge statistics of the top pairs would allow a very precise measurement of the top quark properties

5. 500-3000 GeV, "new physics factory". At the maximum possible collision energy e^+e^- colliders get sensitive to various new physics phenomena, including the Supersymmetry and many "Exotica" models.

The projects of future e^+e^- colliders are summarized in Table 1. For each project the physics research program is mostly dictated by the energy reach of the given collider. CEPC and ILC are essentially the "Higgs factories", operating near the maximum of the Higgsstrahlung process. A "Giga-Z" running at 91 GeV is also planned for CEPC. At FCC, in addition

Table 1: Projects of future e^+e^- colliders

	CEPC	ILC	FCC	CLIC
Site	China	Japan	CERN	CERN
Type	Circular	Linear	Circular	Linear
Length	100 km	20 (30?) km	100 km	50 km
Energy (GeV)	91/240	250 (500?)	91/250/350	350/380/1500/3000
Int. Luminosity (ab^{-1})	5	0.5	15 (+10^{12} Z)	5

to Higgs physics it is possible to perform a precision measurement of the top quark mass at the top pair threshold. Other studies in the top sector are not foreseen, since both cross-section and luminosity are expected to be very small at the $e^+e^- \to tt$ threshold. An important feature of FCC project is the possibility to collect an enormous statistics of Z bosons (of the order of 10^{12} decays) from running near the 91 GeV peak.

The CLIC project offers the richest spectrum of physics research. At the first energy stage (350-380 GeV) model-independent measurements of Higgs boson properties will be performed via the Higgsstrahlung process. Top quark mass will be measured by the threshold scan at 350 GeV. Other top quark properties will be precisely determined using the high statistics to be collected at 380 GeV, close to the maximum of $e^+e^- \to tt$ cross-section. At the higher energy stages, 1.5 and 3 TeV, Higgs boson properties will be measured with an improved precision, thank to the high luminosity and high cross-section of the "W boson fusion" process $e^+e^- \to WW\nu\nu \to H\nu\nu$. The top pair cross-section drops as $1/s$ at high energies, however the top quark data here will be more sensitive to the tiny effect of the new physics. Finally, a variety of searches for effects beyond the Standard Model will be performed at high energy stages, including the searches for the Supersymmetry models and the so-called "Exotica models". In many cases the reach of a direct discovery is close to the kinematical limit, i.e. particles with a mass close to 1.5 TeV can be discovered with 3 TeV CLIC running. Even the phenomena at energy scales beyond the direct discovery limit can be indirectly observed at CLIC via the small deviations of the measured observables from the predictions of the Standard Model. The CLIC potential for such indirect discoveries extends to many tens of TeV.

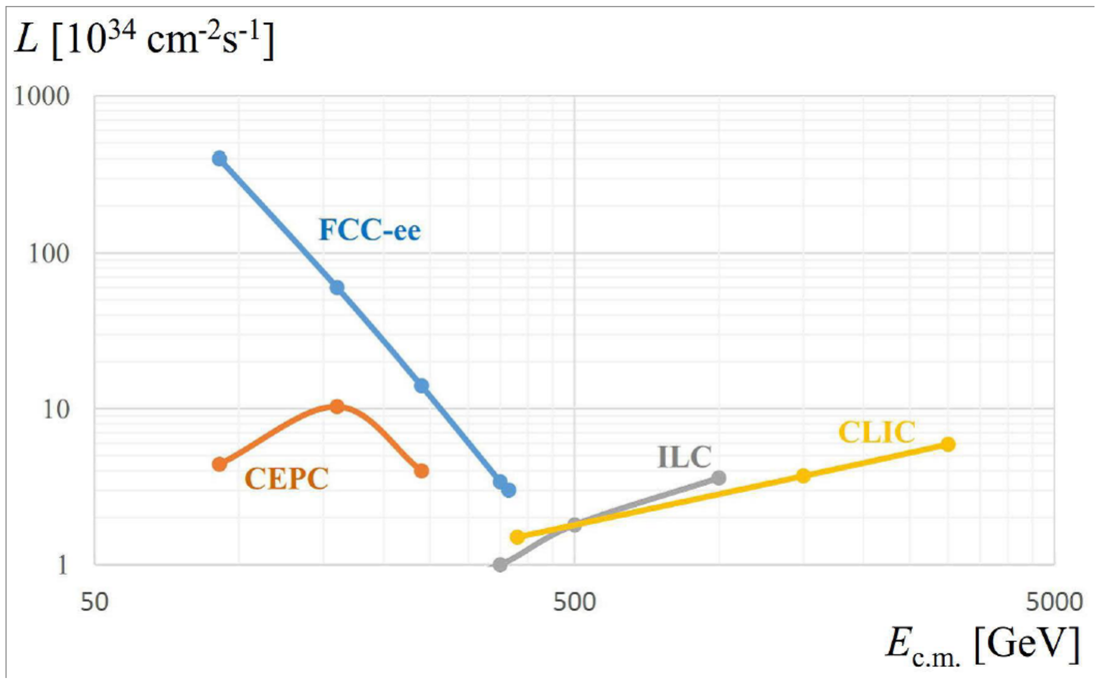

Figure 1: A comparison of different projects of e^+e^- collider.

The energy and luminosity ranges of different e^+e^- projects are illustrated in Fig.1. Note that currently ILC is planning to run at 250 GeV, an upgrade to 500 GeV is considered with a low priority. CLIC is expected to reach the energies much higher than any other project. On the other hand, FCC plan to deliver a very high luminosity at 250 GeV and especially at the Z boson peak.