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PHYSICS AT FUTURE e^+e^- COLLIDERS*

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This article gives a short overview of the future high-energy e^+e^- collider projects. Both, linear and circular colliders offer an excellent potential for precision physics and are shortly discussed.

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1. Introduction

The discovery of the Higgs boson strengthened the general consensus among the particle physicists worldwide that a high-energy e^+e^- collider is necessary to allow precision measurements better than LEP [1] and which is complementary to the LHC. Besides the high priority of Higgs boson measurements, future e^+e^- collider offers a rich physics program to test the Standard Model (SM) and physics beyond. During the next years, the LHC physics program will be continued at highest luminosities and energies. It will be exciting to see how complementary results obtained with e^+e^- collisions will improve our insight in particle physics interactions.

In this paper, the future e^+e^- collider projects as well as their physics potential for selected topics are presented.

2. Future e^+e^- collider projects

In 2000, the Large Electron Positron Collider LEP [1] ceased operation at a center-of-mass energy of 208 GeV. Running at higher beam energies was highly inefficient due to synchrotron radiation which causes an energy loss per turn proportional to E^4/r, where r is the effective bending radius of the collider. Very large radii are needed to operate e^+e^- circular colliders at high energies. Besides the power consumption also the length of the tunnel is a

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decisive cost factor. Linear colliders are an alternative: With high accelerating gradients, the desired energy can be reached with reasonable tunnel length. However, for physics measurements also the luminosity counts. While in circular colliders the beams are used repeatedly, the beams at a linear collider are dumped after collision. To achieve high luminosities, extremely small beam sizes are required. Thus, the final decision for the realization of future e^+e^- collider projects depends on the performance and energy range of the machine as well as on the physics prospects.

Currently, four projects are under discussion, the International Linear Collider ILC, the Compact Linear Collider CLIC, the Future Circular Collider FCC-ee and the Chinese Electron Positron Collider CEPC. Projects such as the muon collider and plasma coliders are not yet mature enough and need substantial R&D. They are not discussed here.

2.1. The linear e^+e^- collider projects

2.1.1. The International Linear Collider

The International Linear Collider ILC [2] is the most mature e^+e^- project; it is a world-wide project with contributing labs from Europe, Asia and Americas. At a first stage, an energy of 250 GeV is planned to operate the ILC as Higgs factory. The energy is tunable; upgrades to 500 GeV and 1 TeV are foreseen, also the running at the Z-boson resonance is possible (so-called GigaZ option). The ILC uses 1.3 GHz superconducting RF cavities (2 K) with an average accelerating gradient of 31.5 MV/m so that the total length of a 250 GeV machine amounts to 20.5 km and for a 500 GeV machine to 31 km. The technology is already successfully applied by the European XFEL. At a center-of-mass energy of 250 GeV, the luminosity is $1.35 \times 10^{34}\,\mathrm{cm^{-2}s^{-1}}$, upgradable to $2.7 \times 10^{34}\,\mathrm{cm^{-2}s^{-1}}$ by doubling the number of bunches per pulse and further to $5.4 \times 10^{34}\,\mathrm{cm^{-2}s^{-1}}$ by increasing also the pulse repetition rate from 5 Hz to 10 Hz. The total power consumption amounts to 130 MW at 250 GeV center-of-mass energy. The electron beam is longitudinally polarized to at least 80%; the positron beam is polarized to about 30% which can be upgraded to 60%. The polarized positrons are produced with a circularly polarized photon beam created by the high-energy electron beam before it is directed to the interaction point. To achieve with the GigaZ option a precision of electroweak measurements, which is at least one order of magnitude better than LEP, the polarization of both beams, electrons and positrons, is essential. Since the efficiency of the positron production scheme decreases substantially for electron beam energies below 120 GeV, an optimized scheme using a second electron beam for photon production is planned. A luminosity of $2.05 \times 10^{33}\,\mathrm{cm^{-2}s^{-1}}$ at the Z pole can be achieved [3] — a factor 100 better than LEP. The collisions are recorded by two detectors which are operated in an alternating push–pull system. Currently, Japan is in the decision process to host the ILC and to construct it at the Kitakami site.

2.1.2. The Compact Linear Collider

The Compact Linear Collider CLIC [4] is designed for center-of-mass energies starting with 380 GeV, to be upgraded to 1.5 TeV and 3 TeV. The total length is 11 km for 380 GeV, 30 km for 1.5 TeV and 50 km for 3 TeV. CLIC utilizes normal-conducting acceleration structures with a 2-beam acceleration scheme: the radiofrequency power for the main linac is extracted from a high-intensity, low-energy electron drive beam which runs parallel to the colliding beams. This drive beam is decelerated and the power is transferred by special structures to the low current main beam for acceleration to high energy. The required average gradient is 72 MV/m for 380 GeV and 100 MV/m for energies above 1.5 TeV. The luminosity is $1.5 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ at 380 GeV and $3.7 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ at 1.5 TeV. The polarization of the electron beam is at least 80%; the positron beam is unpolarized in the baseline option. The power consumption amounts to 168 MW at the 380 GeV center-of-mass energy. CLIC is intended to be constructed in the CERN region.

2.2. Circular colliders projects

The international FCC (Future Circular Colliders) Collaboration is studying collider options at the energy and intensity frontier. An ultimate goal is the realization of proton–proton collisions at 100 TeV in a ring of about 100 km circumference (FCC-hh). Possible first steps towards a such collider could be an e^+e^- collider operated with very high luminosities at energies between 90 GeV and 400 GeV (FCC-ee) or a high-energy LHC (HE-LHC). The latter aims for energies up to about 50 TeV achieved in the LHC tunnel using new magnets of 16 T. Such magnets are required for FCC-hh. Another option is a proton–electron collider (LHeC and FCC-he). The FCC accelerator complex would be the next large research facility after accomplishment of the HL-LHC program at CERN. A project similar to the FCC is under consideration to be realized in China. This paper focuses on the e^+e^- options; hadron–hadron and electron–hadron are not considered.

2.2.1. FCC-ee

The e^+e^- option of the FCC collider allows running at the Z-boson resonance, at the WW threshold (160 GeV), at 240 GeV to produce Higgs bosons by the Higgsstrahlung process and at 350 GeV and 365 GeV to produce top-quark pairs. The technology is at hand and similar to that of LEP, for details, see [5]. The operation at energies beyond 300 GeV increases the level of synchrotron radiation beyond that of LEP. To keep the power consumption in acceptable limits, the synchrotron radiation power should not exceed 50 MW per beam for each of the energies.

FCC-ee consists of a double-ring for the electrons and the positrons. With a booster synchrotron for top-up injection, the beam current and luminosity are maintained. Two collision points are planned but four would also be possible. The layout and the optics of the interaction region is asymmetric to limit the synchrotron radiation towards the detector. With a special 'crab-waist' mode, the luminosity at the Z pole is $1.5 \times 10^{36}\,\mathrm{cm}^{-2}\mathrm{s}^{-2}$ per interaction point, roughly 5 orders of magnitude larger than at LEP. That is reached with the high number of 16 640 bunches per beam, and a smaller beam size w.r.t. LEP. The beams are unpolarized. However, for the energy calibration, the method of resonant depolarization will be used.

2.2.2. Chinese Electron Positron collider

The Chinese Electron Positron collider CEPC project [6] is similar to FCC-ee project: it is planned as intermediate stage towards the Super proton proton Collider SppC. SppC will be installed in the same tunnel for collisions at 75 TeV up to 100 TeV. The circumference of the ring is 100 km. The e^+e^- collisions are planned at the Z pole, at 160 GeV and at 240 GeV. As the FCC-ee, CEPC is designed as double-ring collider with an additional booster ring for top-up injection to maintain the beam current and luminosity. The layout and optics of the two interaction regions is asymmetric to limit the synchrotron radiation towards the detectors. At the Z pole and at the WW threshold, the 'crab-waist' scheme will allow high luminosities. The synchrotron radiation power is limited to 30 MW per beam at all energies; an upgrade to 50 MW per beam as it is planned for FCC-ee is possible. The construction could start as soon as the project is confirmed, *i.e.* the CEPC physics operation could start earlier than the FCC-ee.

2.3. Luminosity at future e^+e^- colliders

In figure 1, a comparison of the designed luminosities for the e^+e^- projects is shown. At low energies, the luminosity of circular e^+e^- colliders is orders of magnitude higher than at linear colliders but it drops at high energies due to synchrotron radiation. At high energies, linear colliders are the best; the luminosity per beam power is almost constant over a long energy range. At the energy of Higgs factories, *i.e.* around 250 GeV center-of-mass energy, the luminosity per beam power of circular colliders is close to that of linear colliders.

The high luminosities at the Z pole and also the WW threshold allow measurements with an extremely small statistical error. This requires to measure the integrated luminosity with a precision of 10^{-4}, *i.e.* about factor 10 better than at LEP. Studies are ongoing to achieve this ambitious goal. It concerns the experimental procedure as well as the theoretical calculation of the low angle Bhabha cross section with a precision below 10^{-4} [7].

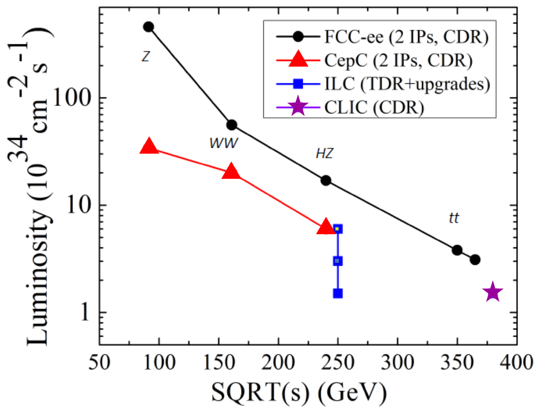

Fig. 1. Comparison of the luminosities depending on the energy as planned for the different e^+e^- collider projects (see also references [2, 4–6]).

3. Higgs boson measurements at future e^+e^- colliders

The LHC is a Higgs factory. So far, at the LHC already more Higgs bosons have been produced than expected at most e^+e^- Higgs factory projects. However, the Higgs boson production and decay at the LHC yields combinations of couplings

$$\sigma(H) \times \mathrm{BR}(H \to a + b) \propto \frac{\Gamma_{\mathrm{prod}}\Gamma_{\mathrm{decay}}}{\Gamma_{\mathrm{tot}}}\,, \tag{1}$$

and $\Gamma_{\mathrm{prod,decay}} \propto g^2_{\mathrm{prod,decay}}$. The total Higgs boson width cannot be determined without further assumption, *i.e.* with measurements at the LHC, only coupling ratios can be determined.

In the e^+e^- collisions, the Higgs boson properties can be studied with high precision. Table I gives an overview of the expected number of Higgs boson events for FCC-ee and ILC250. For CEPC, they can be scaled according to the luminosity. It is a unique feature of lepton colliders that the Higgsstrahlung process, $ee \to ZH$, can be measured without seeing the Higgs boson decay. At the center-of-mass energies around 250 GeV, the Higgs boson is tagged with the Z boson, the recoil mass corresponds to the Higgs boson mass. The cross section, $\sigma_{HZ} \propto g^2_{HZ}$, is measured

TABLE I

Approximate number of Higgs boson events expected for different collider scenarios based on [2, 5].

Center-of-mass energy	[GeV]	FCC-ee 240	FCC-ee 365	ILC 250 GeV
Integrated luminosity	[ab^{-1}]	5	1.5	2
No. Higgs bosons from $e^+e^-\to$HZ	[10^3]	1 000	180	600
No. Higgs bosons from fusion process	[10^3]	25	45	10

independently of the Higgs boson decay and allows the absolute determination of g_{HZ}. The result is used to infer the total Higgs boson width from $\sigma_{HZ} \times \mathrm{BR}(H \to ZZ) \propto g^4_{HZ}/\Gamma_H$. By measuring the invisible Higgs decay ('empty' recoil mass), $\sigma_{HZ} \times \mathrm{BR}(H \to \text{invisible})$, and the exclusive decays, $\sigma_{HZ} \times \mathrm{BR}(H \to XX)$, the Higgs coupling g_{HX} and Γ_H can be fitted in a model-independent manner combining the measurements at different energies. The relative precision [%] for the κ parameters, $g_{HXX} = \kappa_X g^{\mathrm{SM}}_{HXX}$ are at the percent level and below. The specified precision is slightly better for the prospective FCC-ee results. Details for the analyses and the resulting numbers can be found in reference [8]. The prospects for the Higgs mass measurements are also given in the reference. Considering the statistical error only, the high-luminosity option of the LHC expects an uncertainty $\delta m_H = 10$–20 MeV, ILC250 expects 14 MeV and FCC-ee 11 MeV. The corresponding relative statistical error on the width $\Gamma_{ZZ^\star}$ is 0.12–0.24% for HL-LHC, 0.17% for the ILC and 0.13% for FCC-ee.

4. Higgs boson self coupling

The triple Higgs boson coupling, κ_λ, determines the shape and evolution of the Higgs potential. Its measurement is important to understand whether the SM is true and whether new physics is beyond. However, these measurements are a challenge at any collider. At the linear e^+e^- colliders with the center-of-mass energies above 500 GeV, direct measurements of the triple Higg boson couplings are possible using the processes $e^+e^-\to Zhh$ and $e^+e^-\to \nu\nu hh$. These channels are complementary, so the measurements at energies ≥ 500 GeV and ≥ 1 TeV are important. The expectations are $\delta\kappa_\lambda = 26\%$ for ILC500 and $\delta\kappa_\lambda = 19\%$ for ILC1000; for CLIC3000 $\delta\kappa_\lambda = 9\%$ is predicted.

At FCC-ee and CEPC, the large data sample allows indirect measurements via loop contributions to the processes $e^+e^-\to Zhh$ and $e^+e^-\to \nu\nu h$ at the center-of-mass energies 240 GeV–350 GeV [9]. With a global fit, model-independent bounds on κ_λ and the coupling to the Z boson can be obtained. The results of the measurements at the HL-LHC can be used to exclude extreme values of $\lambda/\lambda_{\rm SM}$. As described in reference [8], a precision of $\delta\kappa_\lambda = \pm 42\%$ can be reached for FCC-ee data alone, including the HL-LHC data, $\delta\kappa_\lambda = \pm 34\%$ is expected and $\delta\kappa_\lambda = \pm 12\%$ if, in addition, the coupling to the Z boson is fixed to the SM value. The best precision of $\delta\kappa_\lambda = \pm 5\%$ is expected if all data of the FCC accelerator complex, *i.e.* FCC-ee, FCC-hh and FCC-eh, are included in the analysis.

5. Electron Yukawa coupling

With the excellent precision at FCC-ee arouse the question whether a measurement of the electron Yukawa coupling is possible. The Born cross section of the s-channel Higgs production is $\sigma_{\rm Born}(e^+e^- \to H) = 1.64\,{\rm fb}$ but including a realistic scenario including bremsstrahlung, beamstrahlung, the usual beam energy spread of about 100 MeV and the detector resolution, the measurement seems hopeless. However, in reference [10], the possibility of special beam monochromatization scenarios is studied [11]. According to references [10] and [11], a running period of one year with $2\,{\rm ab}^{-1}$ at $E_{\rm cm} = 125.09\,{\rm GeV}$ with a beam energy spread of $\delta E_{\rm beam} = 6(10)\,{\rm MeV}$ yields 0.4σ significance corresponding to an upper limit of $\kappa_e < 2.5\kappa_e({\rm SM})$. The sensitivity to the SM Yukawa coupling is reached after five years running.

6. Precision top-quark measurements in e^+e^- collisions

At the future e^+e^- colliders, for the first time, the top quark will be studied based on a precisely defined leptonic initial state. This will substantially improve the precision of the top-quark parameters, *i.e.* the mass, the width, the couplings. With the LHC, the top-quark mass and width are already determined with high precision [12], the pole mass extracted from cross-section measurements is $m_t = 173.1 \pm 0.9\,{\rm GeV}$ and the full width $\Gamma_t = 1.42^{+0.19}_{-0.15}\,{\rm GeV}$. However, the conversion of the top-quark mass measured at hadron colliders to the pole mass includes nonperturbative corrections, theoretical and experimental systematic uncertainties, each of which is about 200 MeV.

At the e^+e^- colliders, a scan of the $t\bar{t}$ threshold cross section as a function of the center-of-mass energy allows to extract the value of the top-quark mass. This mass is a short-distance quantity and very close to the mass which is used as theoretical input. The conversion uncertainties are below 10 MeV. So, the e^+e^- colliders allow the most precise measurement of the top-quark mass. The threshold scan is also sensitive to the total width, to the strong coupling constant, and the top Yukawa coupling. The shape of the threshold cross section is affected by initial-state radiation and the luminosity spectrum. Taking into account only the statistical uncertainty, a threshold scan at the ILC ($200\,\mathrm{fb}^{-1}$) results in $\delta m_t < 20\,\mathrm{MeV}$. The corresponding values for FCC-ee are $\delta m_t < 17\,\mathrm{MeV}$ and $\delta\Gamma_t < 47\,\mathrm{MeV}$. More details can be found in reference [2] for the ILC and [5] for FCC-ee and references therein.

7. Electroweak measurements at the Z pole

The operation of LEP and SLD in the 1990s was a story of success and confirmed the SM at one-loop level. The Z-boson mass was measured with a relative precision of 2×10^{-5} and electroweak precision observables were determined with uncertainties at the percent and even at the per mill level. Running the ILC at the Z pole (GigaZ) results in 10^9 Z bosons but FCC-ee provides even $10^5 \times$ LEP, the so-called TeraZ option. Although most measurements will be limited by systematic uncertainties, among them beam energy calibration and the luminosity measurement, FCC-ee-TeraZ offers excellent opportunities to test the SM with unprecedented accuracy up to higher loop corrections.

Facing the factor 10^3 higher number of Z-boson events obtained at FCC-ee, one may ask whether ILC-GigaZ makes sense. A comparison of these options can be found in reference [13]. However, ILC-GigaZ is one part in the ILC physics program which exploits a large energy range up to TeV. The combination of all ILC measurements will provide electroweak precision measurements wich are comparable and also complementary to FCC-ee.

7.1. Effective electroweak mixing angle

The effective weak mixing angle was measured at LEP/SLD to $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}} = 0.23153 \pm 0.00016$ [1]. It was determined including all pseudoobservables depending on the leptonic coupling, *i.e.* forward–backward asymmetries for leptonic and hadronic final states and including the left–right asymmetry measured at SLD. The latter is sensitive to leptonic coupling independent of the final state and dominates the global average derived from leptonic data. The analysis of LEP/SLD data shows a discrepancy of more than 2σ between results derived from leptonic and hadronic final states [1] which waits for explanation.

ILC-GigaZ anticipates an uncertainty of 10^{-5} for $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$, supposed that both electron and positron beam are polarized. With both beams polarized, systematic effects are better controlled, and the effective polarization is measured with substantially higher precision. This yields a more precise measurement of the left–right asymmetry at the Z pole and hence of $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$.

FCC-ee expects a precision of 10^{-6} for the $\sin^2\theta_{\rm eff}^{\rm lept}$, one order of magnitude better than ILC-GigaZ. This precision is beyond the current accuracy of theoretical calculations. Recently, the calculation of the two-loop electroweak corrections has been completed [14, 15, 17].

7.2. Does the theory match the experimental precision?

The unprecedented precision of the measurements — highest integrated luminosity and small systematic errors — requires theoretical calculation that meet this level. The TeraZ option of FCC-ee will allow to study the SM with at least one more perturbative order compared to LEP/SLD. Currently, the necessary precision of theoretical calculations is not yet given. However, the situation is identified and first steps to introduce new methods, techniques and tools are done. One crucial issue is a critical review of the precise QED unfolding and the correct calculation of SM pseudo-observables. References [14–17] specify which theoretical calculations are needed and present the achievements so far: The two-loop electroweak radiative corrections to the SM pseudo-observables are completed and progress in analytical and numerical calculations of multiloop and multiscale Feynman integrals is anticipated. Taking into account the timescale of more than one decade until a start of measurements at FCC-ee or CEPC, a dedicated effort by the community will provide the necessary level of accuracy also for theoretical calculations.

8. Summary

Four e^+e^- collider projects with strong physics potential exist: ILC, CLIC, FCC-ee and CEPC, where ILC and CLIC are extendable up to the TeV range, and in the case of FCC-ee and CEPC, the tunnel and infrastructure are reusable for the subsequent hadron colliders at highest energies. All e^+e^- projects are feasible; ILC is the most mature project, the community expects a decision statement for realization in Japan. An important issue in the ongoing strategy discussion on the future collider projects is the physics potential in comparison to the costs. The costs are high in all cases: 5.9 GCHF for 380 GeV CLIC, 4.8–5.3 GILCU for ILC250 ('ILCU' is defined as U.S. dollar in January 2012), 4 GCHF for the FCC-ee accelerator and injector, but 11.6 GCHF including the costs for the tunnel and technical infrastructure which would be reused for the FCC-hh, and 5 G$ for CEPC. However, besides the costs, also the long timescale of more than 40 years for construction and operation counts. Finally, the effort for a Higgs factory must not fail. The particle physics community awaits exciting results from a machine complementary to the LHC.

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