Future e^+e^- Colliders at the Energy Frontier

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Abstract. A future giant electron-positron collider, operating at the energy frontier, is a natural proposal in order to push particle physics into new regime of precise measurements, in particular in the sectors of electroweak observables and Higgs boson parameters. The four projects of such accelerators: two linear (ILC and CLIC) and two circular (FCC and CEPC) are currently in various stages of development. In view of the update of European HEP strategy for particle physics and expectations of important decisions from Japan, China and USA, the next few years will be critical as far as the decisions about the construction of such colliders are concerned. The paper concisely reviews the relevant aspects and challenges of the proposed accelerators and detectors along with the presumed schedules of construction and operation. The motivation and very attractive physics program for new e^+e^- colliders, spanning in particular perspectives in Higgs, electroweak, and neutrino sectors, together with expectations of searches for New Physics, will be discussed as well.

1 Introduction

The progress in understanding the realm of fundamental building blocks and interactions was, to a large extent, driven by the synergic operation of proton-proton and electron-positron colliders. Thus, the landmark Higgs boson discovery in 2012, taking place in pp collisions at Large Hadron Collider (LHC) [1, 2], gave impetus to the projects of new giant e^+e^- colliders, intended to collect data at the energy frontier. Two accelerators are proposed in each of the two possible geometries: circular and linear. The former are Circular Electron Collider (CEPC) [3] in China and Future Circular Collider (FCC) [4] in CERN area. The latter are Compact Linear Collider (CLIC) [5] at CERN and International Linear Collider (ILC) [6] in Japan. All four projects will be discussed briefly in chapter 2. The rest of this article (Chapter 3) will be devoted to the discussion of the physics program which could be undertaken at new electron-positron colliders at the energy frontier.

2 Projects of future e^+e^- colliders

The Large Electron Collider (LEP) [7], the largest circular electron-positron collider built so far, was decommisioned in 2000 together with the conviction that any future e^+e^- collider should realize linear collisions. This was motivated by the fact that for circular accelerators, the beam energy losses due to synchrotron radiation (and operation costs as well) grow

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rapidly with the centre-of-mass (CM) energy. At the same time the luminosity of such machines was limited by the level of the beam's squeezing (β_y^* - the vertical beta function at the interaction point), which was available at the LEP time ($\beta_y^* \approx 50$ mm). Thus, in view of the absence of synchrotron radiation and with the promise of the longitudinal beam polarisation, the linear geometry of e^+e^- collisions was seriously considered for new accelerator' projects. However for linear colliders, the beams are accelerated and collided only once. In order to reach the appropriate high-luminosity, the beam size must be reduced enormously (even to the order of nanometer in the vertical direction), which comprises the technological challenge. In addition, in such conditions the beam-beam electromagneting interaction and the associated beamstrahlung radiation losses are becoming an issue.

In parallel with these developments of linear colliders, a substantial progress in the technology of circular electron-positron accelerators took place, mainly due to the successful operation of B-factories. In particular, it opened the possibility to reduce significantly the β_y^* parameter (by a factor exceeding 50). At the same time the luminosity could be kept high by harnessing the so called top-up or continuous injection. In this scheme, the additional collider ring, so called booster, periodically top-ups the main rings of the accelerator (adding typically $\sim$ 10% of beam particles every $\sim$10 s). In such a way the booster compensates for the short beam lifetime caused by Bhabha scattering and the loss of particles in collisions and thus constantly keeps the instantaneous luminosity close to the optimal level. With other advances, like e.g. the crab-waist crossing, and assuming a large circumference collider of the order of 100 km, the overall increase of luminosity by a factor exceeding a 1000 (to compare with LEP), is feasible. As a result, the circular geometry is currently considered as a viable option for a future e^+e^- collider, in parallel with the linear one. The brief discussion of the two projects of linear colliders (ILC and CLIC) and two circular ones (FCC and CEPC) is given below.

2.1 Linear colliders

Parameter	Symbol [unit]	ILC	ILC	CLIC	CLIC
CMS energy	E_{cm} [GeV]	250	500	380	3000
Luminosity	L [10^{34} cm^{-2}s^{-1}]	1.35	1.8	1.5	6
Gradient	G [MV/m]	31.5	31.5	72	100
Repetition rate	f_r [Hz]	5	5	50	50
Bunches per train	n	1312	1312	352	312
Particles/bunch	N [10^9]	20	20	5.2	3.72
Bunch length	σ_z [μm]	300	300	70	44
Energy spread	[%]	0.1-0.2	0.1-0.2	0.35	0.35
Emittances	$\varepsilon_{x,y}$ [nm]	5x10^3/35	5x10^3/35	950/30	660/20
IP beam size	$\sigma_{x,y}$ [nm/nm]	520/8	474/6	149/3	40/1
Beta-functions	$b_{x,y}$[mm]	13/0.41	22/0.48	8/0.1	6/0.07
Assumed effective running time	[10^7 s/year]	1.6	1.6	1.08	1.08

Figure 1. The most relevant parameters of projects of linear colliders [8].

The International Linear Collider (ILC) [6] is put forward as a 250 GeV machine with the site in Japan. The Technical Design Report (TDR) [9–11] of ILC, issued in 2013, assumed maximum CM energy of 500 GeV. Since 2017, the project was downgraded to 250 GeV with the motivation of cost reduction (by $\sim$40%). At the same time, the opportunity of future extensions of the linacs with the associated increase of the collision energy up to 1 TeV, is preserved. This so called ILC250 with the total length of 20 km would concentrate on the studies of the Higgs boson, with the potential of reaching the $t\bar{t}$ threshold in the upgraded machine. The ILC would be based on superconducting RF structures with the acceleration gradient of 31.5 MV/m. This would be a unique new e^+e^- collider with longitudinal polarisation of both beams (80% for electron and 30% for positron beam). The basic parameters of the ILC are collected in Fig. 1. It is worthwhile to mention that with the successful commissioning of the European Free Electron Laser (E-XFEL) [12] at DESY (Germany) this acceleration technology has passed the practical test. The decision of Japanese government about the realization of the ILC is awaited by the end of 2018.

The Compact Linear Collider (CLIC) [5] is conceived as a staged accelerator with CM energies ranging from 380 GeV up to 3 TeV with a corresponding length from 11 km to 50 km. The CLIC machine is envisioned in the CERN area and it would be based on a novel two-beam acceleration scheme. The first one, so-called drive-beam is a high-current, low-energy electron beam with a bunch repetition rate of 12 GHz. This beam passes through Power Extraction and Transfer Structures (PETS). Their role is to decelerate the drive-beam and thereby to generate the powerful RF pulse (at 12 GHz). The former accelerates the second so called main-beam, operating at room temperature with the gradient of 100 MV/m. Such scheme appears to be more efficient and less costly to compare with a classical, klystron based, RF powering scheme. The CLIC Conceptual Design Report [13] foresees 80% polarisation of the electrons at collision. The most relevant characteristics of CLIC can be found in Fig. 1.

2.2 Circular colliders

The Future Circular Collider (FCC) project [4] aims at the construction of a 100 km circumference accelerator tunnel in the Geneva area. The first phase of the project, labelled as FCC-ee, would comprise the instrumentation of the tunnel with a high-luminosity e^+e^- collider. This machine would operate with CM energies ranging from the Z^0 mass up to beyond the $t\bar{t}$ threshold. The flagship part of the overall project is a 100 TeV proton-proton collider FCC-pp, which is to be commissioned after the e^+e^- phase. The electron-proton collisions are envisioned as well with the e^- beam from the Electron Recovery Linac (ERL). The FCC-ee would collect data in four working points, corresponding to the relevant physics thresholds for the Z, WW, HZ and $t\bar{t}$ production. The collider's parameters are collected in Fig. 2.

The Circular Electron-Positron Collider (CEPC) [3] is proposed with the setup and parameters very similar to FCC. The six potential sites in China have been proposed so far.

2.3 Complementarity of circular and linear colliders

The pattern of expected luminosities vs the CM energies is shown in Fig. 3. Clearly the luminosities of circular colliders seem to be superior to compare with linear ones in the region of relatively low energies, roughly to the $t\bar{t}$ threshold. Above this working point, the linear colliders seem to be the only viable option. Thus the Fig. 3 clearly illustrates the complementarity of both geometries of electron-positron collisions.

The typical timelines of potential future e^+e^- colliders at the energy frontier encompass first the few years of preparatory work devoted in particular to the final R&D work. Next the period of construction would come, spanning the range of 6-8 years. Finally the data taking is expected to take at least a decade with various strategies of the time order of different working points.

parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1390	147	29	5.4
no. bunches/beam	16640	2000	393	48
bunch intensity [10^{11}]	1.7	1.5	1.5	2.3
SR energy loss / turn [GeV]	0.036	0.34	1.72	9.21
total RF voltage [GV]	0.1	0.44	2.0	10.9
long. damping time [turns]	1281	235	70	20
horizontal beta* [m]	0.15	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horiz. geometric emittance [nm]	0.27	0.28	0.63	1.46
vert. geom. emittance [pm]	1.0	1.7	1.3	2.9
bunch length with SR / BS [mm]	3.5 / 12.1	3.0 / 6.0	3.3 / 5.3	2.0 / 2.5
luminosity per IP [10^{34} cm^{-2}s^{-1}]	>200	>25	>7	>1.4

Figure 2. The most relevant parameters of projects of circular colliders [8] (the numbers referring to the FCC-ee are given as example).

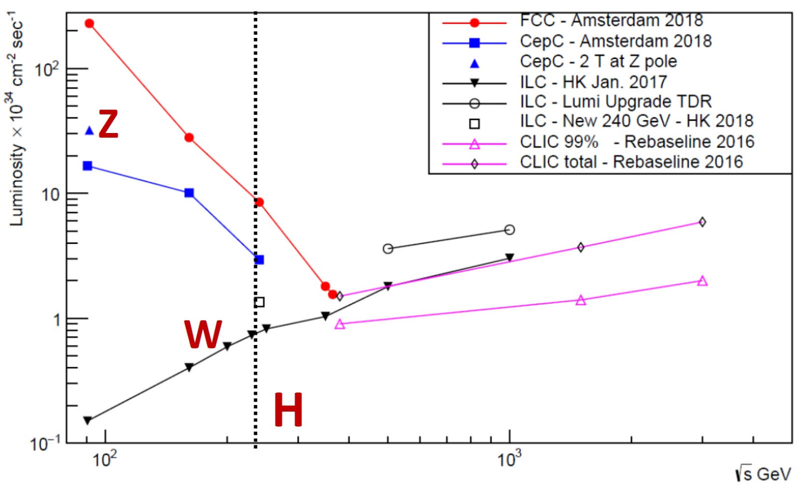

Figure 3. The luminosities vs the CM energies (cf. [8]) for all four projects of electron-positron colliders discussed in the paper.

2.4 Detectors for new e^+e^- colliders

Each of the abovementioned projects of future e^+e^- colliders envisions one-two interaction points instrumented with the general purpose, 4π-barrel type detectors. They will follow the footpaths of the predecessors, designed and built for LEP. The overall scheme of such spectrometer is shown in Fig. 4. The proposal of the CLICdp collaboration [14] is shown there for illustration. The generic spectrometer for new e^+e^- should be lightweighted in terms of the material content and hermetic, providing also precise tracking and fine-grained calorimetry.

The tracker system is usually proposed in Silicon technology with the alternative of the modern drift chamber. The critical part is the system of calorimeters which should allow for the application of the Particle Flow Algorithms [15] with the overall goal of around 3 GeV resolution of jet reconstruction. The fullfilment of such requirement would allow to discriminate between jets originating from the W and Z bosons. The intense R&D efforts of the

CALICE collaboration [16] are ongoing in these directions with several proposed setups of calorimeters. It should be stressed that data taking will be trigger-free i.e. all collisions can be safely recorded for further studies.

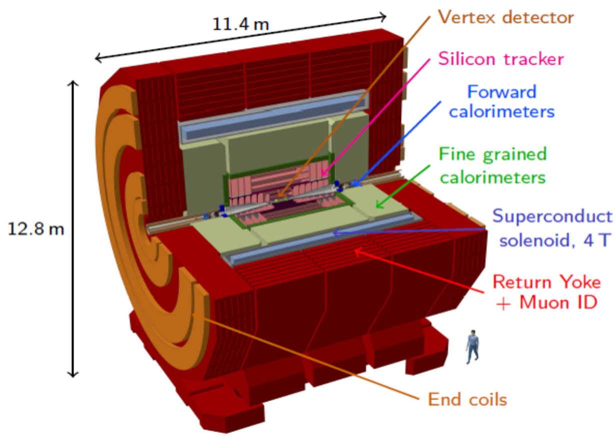

Figure 4. The layout of the CLICdp detector.

3 Physics program of future e^+e^- colliders

All four projects of future electron-positron colliders put a considerable efforts in order to optimize the data taking in terms of working points (cf. Fig. 3) and their timeline. The following four working points are clearly motivated by the relevant thresholds in the cross-sections, corresponding to Z mass peak and to W^+W^-, HZ and $t\bar{t}$ production. For the CLIC, which offers a very attractive opportunity of collecting data at higher energies, the three working points at the CM energies of 380 GeV, 1.4 TeV and 3 TeV are considered. This chapter is devoted to the concise discussion of the most important physics studies which can be undertaken at the abovementioned working points. It is appropriate to underline that neither Higgs boson nor top quark physics have been studied so far in a clean environment of electron-positron collisions.

3.1 Physics at the Z pole

At the Z pole the huge statistics of data assumed for circular colliders (5×10^{12} Z events for the FCC-ee [17]), corresponding to the increase by five orders of magnitude to compare with LEP1, will improve the drastically statistical accuracies of electroweak observables. As a result, for almost every observable the overall precision will be dominated by systematic uncertainties. Thus, several working groups have already undertaken more precise theoretical calculations, aimed at the reduction of the respective systematic errors [20].

The lineshape scan in the vicinity of the Z mass can yield, in particular, a very accurate determination of mass and width of that boson. The expected total precision of 100 keV is claimed by the FCC-ee for both abovementioned parameters (to compare with ΔM_Z = 2.1 MeV and $\Delta\Gamma_Z$ = 2.3 MeV at LEP1). The crucial limitation here is the systematic uncertainty due to the CM energy calibration (realized, as for LEP, via resonant depolarisation). The similar gain in the precision (by a factor of 20) is expected for the determination of the normalized partial widths $R_l = \Gamma_{\rm had}/\Gamma_{l\bar{l}}$, $l = e, \mu, \tau$ and $R_q = \Gamma_{q\bar{q}}/\Gamma_{\rm had}$, $q = b, c$, where $\Gamma_{\rm had}$ is the total hadronic width.

The set of forward-backward and polarisation asymmetries at the Z pole can be measured precisely by future e^+e^- colliders for charged leptons and heavy quarks. It is expected that the experimental precision on these parameters can, for the first time, be limited not by statistics but by systematics. Of particular importance is the production of tau lepton pairs in Z decays, where the polarisation of the final state fermion, and the respective asymmetry as well, can be measured through the angular distributions and momenta of the decay products.

From the abovementioned sets of asymmetries and normalized partial widths, the respective coupling-ratio factors

$$\mathcal{A}_f = \frac{2g_V^f g_A^f}{(g_V^f)^2 + (g_A^f)^2}, \quad f = e, \mu, \tau, b, c \tag{1}$$

can be evaluated. They are dependent on the vector (g_V^f) and axial (g_A^f) couplings of the neutral current to fermions, which thus can be extracted. The relative uncertainties on g_V^f and g_A^f parameters, as expected for the FCC-ee, are collected in Table 1. These quantities in turn allow for the determination of the effective Weinberg electroweak mixing angle as:

$$\sin^2\theta_{W,\rm eff} = \frac{1}{4}\left(1 - \frac{g_V^f}{g_A^f}\right). \tag{2}$$

For the FCC-ee the expected gain in the precision on $\sin^2\theta_{W,\rm eff}$ amounts to 75 (100) for the tau polarisation (muon forward-backward asymmetry) measurements, respectively.

Table 1. The relative uncertainties on fermion vector and axial neutral couplings to Z, as expected at the FCC-ee [17].

fermion	$\Delta g_V/g_V$	$\Delta g_A/g_A$
e	2.5×10^{-4}	1.5×10^{-4}
μ	2.0×10^{-4}	2.5×10^{-5}
τ	3.5×10^{-4}	0.5×10^{-4}
b	1.0×10^{-2}	1.5×10^{-3}
c	1.0×10^{-2}	2.0×10^{-3}

The excellent experimental precision on the $A_{FB}^{\mu\mu}$ would allow also for a more precise and direct determination of the electromagnetic coupling constant at the Z mass scale ($\alpha_{\rm QED}(m_Z^2)$). The approach of [18] is based on the measurement of the muon-muon forward-backward asymmetry by taking data in two one-year runs in the optimal working points at $\sqrt{s_-}$ = 87.9 GeV and $\sqrt{s_+}$ = 94.3 GeV. As the relative uncertainty of the $\alpha_{\rm QED}(m_Z^2)$ is proportional to the one of $A_{FB}^{\mu\mu}$, the electromagnetic coupling constant at the Z mass scale can be determined without the necessity of extrapolation from low mass region. Moreover this would yield to the relative precision on $\alpha_{\rm QED}(m_Z^2)$ of 3×10^{-5} which was estimated to be fully adequate for future precision electroweak physics fits.

4 Physics at the WW production threshold

For the future circular e^+e^- collider, even a relatively short period of data taking ($\sim$ one year) on and above the W boson pair production threshold would allow to pick up an enormous sample of W^+W^- events. The FCC-ee expects 3×10^7 of such events [17] to compare with 4×10^4 events at LEP2. The scan of the WW cross-section in the close proximity of the production threshold would allow to extract the mass and width of the W boson with expected precisions of $\Delta M_W \approx 1$ MeV and $\Delta\Gamma_W \approx 1.5$ MeV. The trilinear gauge couplices (TGCs) of the WWZ and $WW\gamma$ vertices can be determined as well, with the expected limits improved by the factor of ~50 to compare with PDG [19]. Moreover, The measurements of W branching ratios to hadrons and $l\bar{\nu}$, $l = e, \mu, \tau$ would comprise an important test of the lepton and lepton-quark universalities, since the anticipated accuracies are below the permill level to compare with current precision of few percent.

4.1 Higgs Physics

Studies of the properties of Higgs boson are a flagship part of physics program of every future e^+e^- collider discussed in this paper. They should bring accurate determination of Higgs mass and couplings to SM particles and possibly be sensitive to new phenomena at energy scales that cannot be accessed directly at a given future accelerator.

The Higgs boson production in e^+e^- collisions is dominated by three contributions (cf. Fig 5, left plot). The dominant one is the associated production of a Higgs and a Z boson. The remaining two are WW and ZZ fusion.

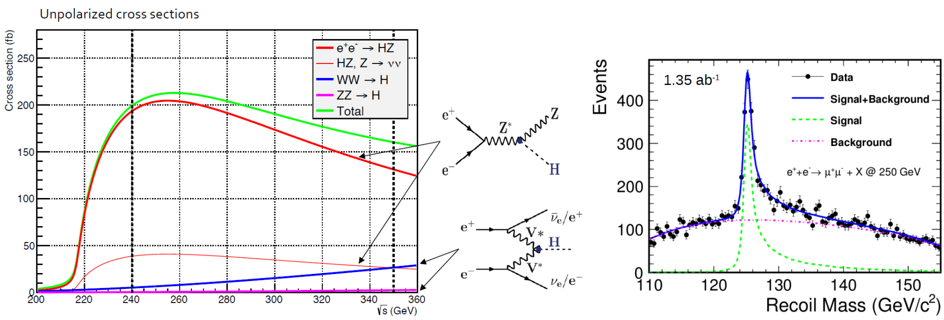

Figure 5. The Higgs boson [production cross-section as a function of CM energy (left plot, from [21]). Distribution of the mass recoiling against the muon pair in the process $e^+e^- \to HZ(\to \mu^+\mu^-)$ (right plot, from [22]).

The Higgs mass, together with the H-Z-Z (g_{HZZ}) and H-W-W (g_{HWW}) couplings can be extracted using the recoil mass technique. In e^+e^- collisions the initial state's four-momentum is well defined. As a result, the cross section of $e^+e^- \to HZ$ can be measured inclusively i.e. by reconstructing the Z boson (preferably in the decays to l^+l^- pairs, $l = e, \mu$). Then the Higgs mass (Fig. 5,right plot) can be evaluated as

$$m^2_{\text{recoil}} = (\sqrt{s} - E_{ll})^2 - |\vec{p}_{ll}|^2. \tag{3}$$

With the typical assumed statistics of 1 million HZ events, the expected precsion of the Higgs mass amounts to $\sim$ 10 MeV. The cross section for the process $e^+e^- \to HZ$ is proportional to the coupling g_{HZZ}, thus allowing for its direct determination. The H-W-W coupling can be extracted by measuring the ratio of WW fusion to HZ processes (preferably at $\sqrt{s} \sim 350$ GeV) using Higgs decay to the given final state e.g. $H \to b\bar{b}$

$$\frac{\sigma(e^+e^- \to H\nu_e\bar{\nu}_e) \times BR(H \to b\bar{b})}{\sigma(e^+e^- \to HZ) \times BR(H \to b\bar{b})} \propto \frac{g^2_{HWW}}{g^2_{HZZ}}. \tag{4}$$

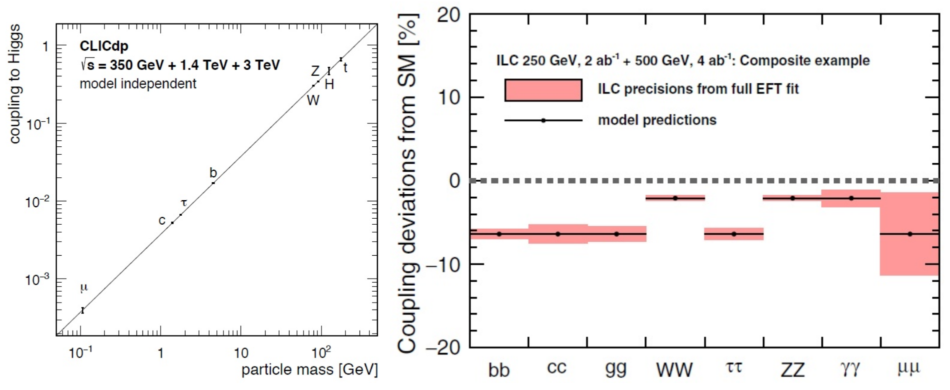

Figure 6. The precision of Higgs couplings, as expected by CLIC [23]). The solid line represents the SM prediction. Visualization of the deviations of Higgs couplings from the SM on the example composite Higgs model (right plot, from [22]) as estimated for the ILC [24].

By tagging the individual Higgs decays, the couplings to fermions of the second and third generations can be determined with the expected precision spanning the permill-percent level i.e. better by one order of magnitude, to compare with High Lumi LHC program. According to the Standard Model the Yukawa couplings should be proportional to the fermion (intermediate boson) mass (cf. Fig. 6, left plot). If the measured couplings would exhibit any deviations from the SM expectations, their pattern can help substantially to discriminate between various models of New Physics (Fig 6, right plot).

The Higgs physics at energies above 1 TeV is a natural domain of the CLIC project. It is described in detail in [23].

4.2 Top Quark Physics

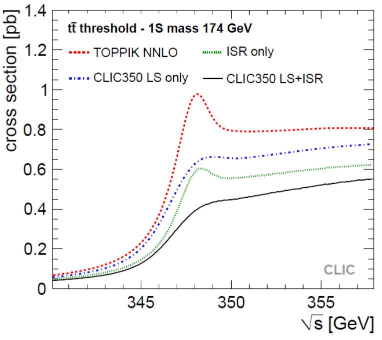

Figure 7. Top pair production cross-section from theory calculations, with the luminosity spectrum (LS) of CLIC at 350 GeV and initial state radiation (ISR) effects included [25].

The future e^+e^- colliders offer a very attractive opportunity of precise studies of the top quark properties. In particular the threshold scan at the $t\bar{t}$ production threshold (Fig. 7) would yield an enormous leap in the precision of the top mass - up to 10 MeV. The lineshape of the $t\bar{t}$ production is also sensitive to the strong coupling constant and top Yukawa coupling.

The electroweak couplings of the top quark can be determined using the longitudinal polarisation of the beams (linear colliders case, [26]) or by exploiting the final state polarisation which is maximally transfered to the top decay products (circular colliders case, [27]).

4.3 Neutrino physics

The future electron-positron colliders can address the question of the number of light neutrino species by measuring the Z invisible width (Γ_{inv}) in at least two ways. The first approach will be based on the determination of the hadronic cross section at the Z peak ($\sigma_{\text{had}}^{\text{peak},0}$) via the threshold the scan as

$$N_\nu = \left(\frac{\Gamma_{l\bar{l}}}{\Gamma_{\nu\bar{\nu}}}\right)_{\text{SM}} \cdot \left(\sqrt{\frac{12\pi R_l}{M_Z^2 \sigma_{\text{had}}^{\text{peak},0}}} - R_l - 3\right). \tag{5}$$

Its expected accuracy amounts to 0.00008(stat.) ± 0.0001(syst.) (cf. the LEP1 result $N_\nu = 2.991 \pm 0.007$ [19]) with the basic limitation due to the systematic uncertainty on luminosity determination (evaluation of the low-angle Bhabha cross-section).

For the second approach, the radiative return process $e^+e^- \to Z\gamma,\ \ Z \to \nu\bar{\nu}$ measured at CM energies above the Z peak is harnessed to determine the number of light neutrino species according to the formula

$$N_\nu = \left(\frac{e^+e^- \to \gamma Z_{\text{inv}}}{e^+e^- \to \gamma Z_{l\bar{l}}}\right)^{\text{meas}} / \left(\frac{\Gamma_{\nu\bar{\nu}}}{\Gamma_{l\bar{l}}}\right)^{\text{SM}}. \tag{6}$$

Thus the number of $\nu\bar{\nu}\gamma$ events is normalized to the number of events observed in the final state $l\bar{l}\gamma$, which reduces significantly the systematic uncertainties. The statistical accuracy of this method is anticipated at 4×10^{-4} (LEP: 2.92 ± 0.05, [19]).

The future e^+e^- colliders offer also an unprecented sensitivity for searches for right-handed sterile neutrinos, in particular for those labelled as Heavy Neutral Leptons (HNLs) [28]. Such particles should mix with the SM light neutrinos with the overall ν-HNL coupling denoted as $|U|^2$. They are expected to decay at macroscopic lengths (even of the order of meters) and with distinct experimental signatures like 2 jets/leptons and missing energy (neutral current case) and 2 jets and lepton/(missing energy) for the charged current. The sensitivity claimed by the FCC-ee reaches $|U|^2 \sim 10^{-11}$ [29] to compare with 10^{-4} obtained at LEP [19]. The former surpasses the expectations from the dedicated beam-dump experiments like SHiP [30].

5 Summary and Acknowledgements

The four projects of future electron-positron colliders at the energy frontier, which are currently under consideration, have been briefly reviewed. Few selected highlights of the physics program of such colliders, have been presented.

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