Monochromatized direct s-channel Higgs production in e^+e^- at $\sqrt{s}$=125 GeV

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Abstract

The FCC-ee could allow the measurement of the electron Yukawa coupling, k_e, in a dedicated run at ~125 GeV center-of-mass (CM) energy, provided that the CM energy spread, σ_{ecm}, can be made comparable to the width of the standard model Higgs boson itself $\Gamma_H \approx 4.2$ MeV, and that enough luminosity is integrated under such conditions. The natural collision-energy spread at 125 GeV, due to synchrotron radiation, is about 50 MeV. Its reduction to the desired level can be accomplished by means of monochromatization, e.g., through introducing nonzero horizontal dispersion of opposite sign at the interaction point (IP), for the two colliding beams. Such nonzero IP dispersion leads to an increase of the transverse horizontal emittance from beamstrahlung. Self-consistent IP parameters need to be determined and optimized for maximum sensitivity to the k_e coupling. Modifications of the standard final-focus optics are required for generating the required IP dispersion and for the possible accommodation of crab cavities. Alternative monochromatization scenarios, as well as improvements of the (simulated) data analysis, can also be explored. This effort addresses the only known pathway to measure an important property of the Higgs boson and to understand the origin of the electron mass.

The FCC-ee schedule can accommodate a few years of operation optionally spent at a CM energy in the immediate vicinity of the Higgs boson pole mass, $\sqrt{s} \simeq 125.09$ GeV [1,2]. At this energy, the resonant production of the Higgs boson in the s channel, $e^+e^- \rightarrow H$, has a tree-level peak cross section of 1.64 fb, reduced to ~0.6 fb when initial-state radiation is included, and to ~0.3 fb if, in addition, the CM energy spread is equal to the Higgs boson width of $\Gamma_H \approx 4.2$ MeV [3]. A much larger spread, typically of the order of 50-100 MeV, is expected when the machine parameters are tuned to deliver the maximal luminosity, rendering the resonant Higgs production invisible. The energy spread can, however, be reduced with monochromatization schemes [4-17] potentially reaching values of ~5 MeV.
According to a preliminary study of ten different Higgs decay channels (on top of the corresponding order-of-magnitude larger backgrounds) [18], the resonant Higgs boson production is expected to yield a significance of ~1σ for each 10 ab^{-1} of integrated luminosity at a value of $\sigma_{ecm} \approx \Gamma_H$, thereby allowing to set 95% C.L. upper limits on k_e at least 100 times better than those accessible at the LHC [19]. Depending on the number of IPs and of operation years, the SM sensitivity on k_e can be reached [18,19]. The FCC-ee therefore offers a unique opportunity to probe the electron Yukawa coupling, and thereby interpreting electron electric dipole measurements and placing constraints on new physics. E.g., the bounds on top CP-violating couplings discussed in Ref. [20], would be invalid if k_e was neither fixed to its SM value nor constrained independently.

The FCC-ee natural collision-energy spread at 125 GeV due to synchrotron radiation is about 46 MeV. Monochromatization can be achieved, for example, by introducing nonzero horizontal dispersion of opposite sign at the IP for two beams, in collisions without a crossing angle. The need to generate significant IP dispersion implies a change of beamline geometry in the interaction region and the use of crab cavities to compensate for the existing, or remaining, crossing angle. Nonzero dispersion at the crab cavities could also lead to monochromatization while the dispersion at the collision point is kept at zero [16]. Alternative or modified monochromatization schemes may also be possible in the presence of a crossing angle without crabbing [17]. The decrease in relative energy spread $(\sigma_w/W)_{standard}=\sigma_\delta/\sqrt{2}$, with CM energy $W=2E_0$ (for E_0 = 62.5 GeV and $\sigma_\delta = 5.2\times10^{-4}$), is described by the monochromatization factor λ, $(\sigma_w/W)_{monochrom}=\sigma_\delta/(\sqrt{2}\,\lambda)$, without crossing angle or with crab cavities, where $\lambda^2= 1 + (D_x^*\sigma_\delta)^2/(\varepsilon_x\ \beta_x^*)$ denotes the ratio between synchrotron and betatron horizontal beam sizes at the IP. The dependence of the Higgs event rate (N_H) on luminosity L and σ_w can be expressed by the function f_H [2]:

$$\acute{N}_H \propto f_H = \frac{L}{\sqrt{\Gamma_H^2+\sigma_w^2}}.$$

The experiment needs an energy calibration using resonant depolarization, which imposes a requirement on the synchrotron tune: $Q_s \geq 0.05$. To get this value, a 60°/60° lattice is required with an RF voltage $V_{RF} > 0.5$ GV. The lattice determines the natural emittance $\varepsilon_x \approx 510$ pm, and the RF voltage constrains the natural bunch length to $\sigma_z \leq 2.4$ mm. The optimum vertical emittance is $\varepsilon_y \approx 1.1$ pm [2]. β_y^* should be equal or slightly less than σ_z to avoid having a strong hour-glass effect, so ~2 mm could be chosen. Another possibility is to increase V_{RF}, which makes the bunches shorter so that β_y^* can be reduced. On the other hand, beamstrahlung is amplified for short bunches, and, with nonzero dispersion at the collision point, the beamstrahlung blows up the horizontal emittance [21,22]. Other beam-beam effects in the presence of a large IP dispersion were considered in [23]. For D_x^*, values in the range 10-50 cm are tentatively considered. The bunch charge is another important parameter to be optimized, again taking into account the beamstrahlung [13-15,21,22]. The anticipated monochromatized luminosity per IP exceeds 10^{35} cm^{-2} s^{-1} [15]. This translates into an integrated luminosity of at least 2 ab^{-1} per IP per year. For a CM energy spread commensurate with the SM Higgs boson width, the $e^+e^- \rightarrow H$ cross section is about 290 ab [3], and the FCC-ee would produce at least 600 s-channel Higgs bosons per IP per year.
To successfully embark on a program to measure the electron Yukawa coupling at the FCC-ee, numerous further studies are required. The optimum set of IP parameters and details of the monochromatization scheme should be further elaborated and optimized. In particular, optical lattices producing the required large D_x^*, along with target values for β_x^* and β_y^*, need to be developed. The running mode should be devised, including the continuous monitoring of the collision energy and of its spread, at the 10^{-5} level; the operation procedures; and the diagnostics, provided both by the accelerator instrumentation and by the particle physics detectors [24]. Further improvements in the data analyses (for the s-channel Higgs event selection and background reduction, as well as for the few-MeV Higgs mass precision required beforehand) should be carried out.

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