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Higgs physics at the Future Circular Collider

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Abstract

The unique Higgs physics opportunities accessible at the CERN Future Circular Collider (FCC) in electron-positron ($\sqrt{s} = 125$, 240, 350 GeV) and proton-proton ($\sqrt{s} = 100$ TeV) collisions, are succinctly summarized. Thanks to the large c.m. energies and enormous luminosities (plus clean experimental conditions in the e^+e^- case), many open fundamental aspects of the Higgs sector of the Standard Model (SM) can be experimentally studied:

(i) Measurement of the Higgs Yukawa couplings to the lightest fermions: u,d,s quarks (via rare exclusive $H \to (\rho, \omega, \phi) + \gamma$ decays); and $e^\pm$ (via resonant s-channel $e^+e^- \to H$ production); as well as neutrinos (within low-scale seesaw mass generation scenarios).

(ii) Measurement of the Higgs potential (triple λ_3, and quartic λ_4 self-couplings), via double and triple Higgs boson production in pp collisions at 100 TeV.

(iii) Searches for new physics coupled to the scalar SM sector at scales $\Lambda_{\rm NP} \gtrsim 6$ TeV, thanks to measurements of the Higgs boson couplings with subpercent uncertainties in $e^+e^- \to HZ$.

(iv) Searches for dark matter in Higgs-portal interactions, via high-precision measurements of on-shell and off-shell Higgs boson invisible decays.

All these measurements are beyond the reach of pp collisions at the Large Hadron Collider. New higher-energy e^+e^- and pp colliders such as FCC are thus required to complete our understanding of the full set of SM Higgs parameters, as well as to search for new scalar-coupled physics in the multi-TeV regime.

1 Introduction

Despite its tremendous success describing many phenomena with high accuracy —crowned with the discovery of its last missing piece, the Higgs boson, in 2012 [1, 2]— many fundamental questions of the Standard Model (SM) of particle physics still remain open today. Our lack of understanding of the nature of dark matter, the origin of matter-antimatter asymmetry, the generation of neutrino masses, or how to tame the quadratically-divergent virtual SM corrections affecting the running of the Higgs boson mass between the widely separated electroweak and Planck scales ("fine tuning" problem), among others, are questions which likely will *not* be fully answered through the study of proton-proton (pp) collisions at the Large Hadron Collider (LHC). Searching for solutions to such fundamental problems, together with a *complete* experimental confirmation of the SM Higgs sector —including the unknown Yukawa couplings of the lightest fermions, as well as the triple λ_3 and quartic λ_4 Higgs self-couplings— requires both a new pp collider at higher center-of-mass (c.m.) energies, as well as a new high-precision e^+e^- machine with unprecedented luminosities to very accurately study the H boson properties. The Future Circular Collider (FCC) is a post-LHC project in a new 100-km tunnel under consideration at CERN [3], designed to deliver pp at $\sqrt{s} = 100$ TeV with $\mathscr{L}_{\rm int} = 0.2$–$2$ ab^{-1}/yr integrated luminosities (FCC-hh) [4], as well as e^+e^- over $\sqrt{s} = 90$–350 GeV with up to 80 ab^{-1}/yr (FCC-ee) [5]. Both machines are truly competitive "Higgs factories". Figure 1

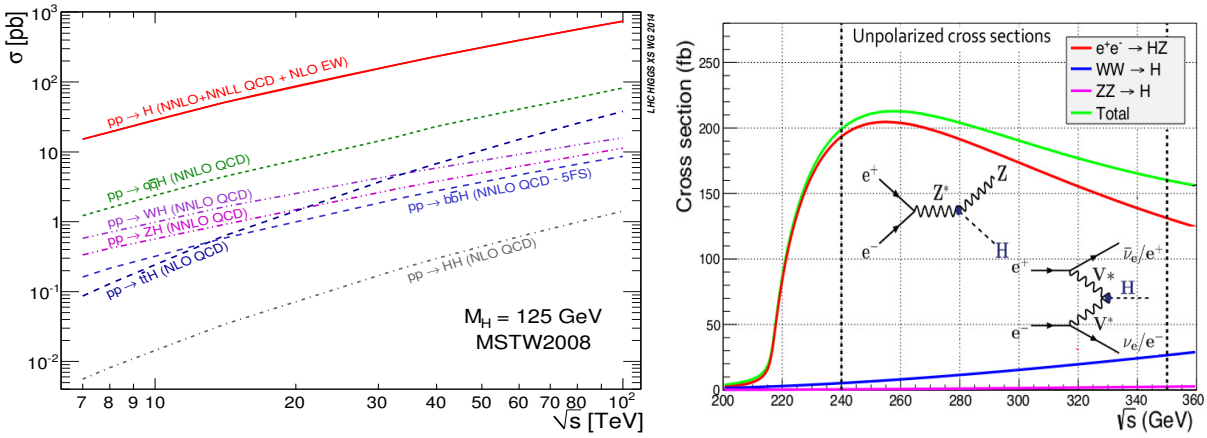

Figure 1: Higgs boson cross sections as a function of c.m. energy (total, and separated for different subprocesses) in pp (left) [6] and e^+e^- (right) [5] collisions.

shows the H boson production cross sections as a function of c.m. energy at FCC-hh (left) and FCC-ee (right). Higgs production in DIS at FCC-eh, not discussed here, is also possible [7]. At the FCC-hh, gluon-gluon fusion (ggF) dominates the cross section, followed by vector-boson-fusion (VBF), and associated $t\bar{t}$ production. The sum of all contributions amounts to $\sigma(pp \to H + X) \approx 0.9$ nb at $\sqrt{s} = 100$ TeV [6]. At the FCC-ee, the cross section (rates) peaks at $\sigma(e^+e^- \to H+X) \approx 200$ fb at $\sqrt{s} \approx 240$ (250) GeV [5], dominated by Higgsstrahlung ($e^+e^- \to HZ$) with small VBF contributions ($VV \to H\, e^+e^-, \nu\nu$). Both machines provide unparalleled opportunities to study the Higgs sector of the SM thanks to the enormous number of scalar bosons produced over ∼15 and ∼20 years of operation: up to $2{\cdot}10^6$ at FCC-ee with very low backgrounds and no pileup, and $2{\cdot}10^{10}$ at FCC-hh. Measurements of very precise Higgs couplings (with subpercent uncertainties), and of very rare and beyond the SM decays are thereby possible.

2 Generation of the lightest fermion (u, d, s; e; and ν's) masses

The SM Higgs boson couples to the fundamental fermions proportionally to their masses m_f, and thus its decays into the actual constituents of the stable visible matter in the Universe —formed by first generation fermions ($u\bar{u}$, $d\bar{d}$, $e^{\pm}$) with light masses $\mathscr{O}(0.5-10$ MeV)– have extremely reduced branching ratios and cannot be directly measured at the LHC. The large and clean Higgs boson samples at FCC-ee will allow the measurements of very rare exclusive decays into light vector-mesons (VM) plus a photon ($H \to \rho, \omega, \phi + \gamma$, with $\rho = (u\bar{u} - d\bar{d})/\sqrt{2}, \omega = (u\bar{u} + d\bar{d})/\sqrt{2}, \phi = s\bar{s}$) that are sensitive to the lightest quarks' Yukawas. The branching ratios for such processes are $\mathscr{O}(10^{-5} - 10^{-6})$ [6, 8]. The most promising one is $H \to \rho(\pi\pi)\gamma$, with about 40 counts expected with low backgrounds. Determining the corresponding sensitivity to the u/d quark Yukawa couplings requires dedicated studies given that the indirect $H \to \gamma\gamma^* \to VM + \gamma$ decays interfere with the direct $H \to VM + \gamma$ ones, and dilute the sensitivity to the latter. Of course, all these channels will be produced much more abundantly at FCC-hh, but the huge QCD (and pileup) backgrounds jeopardize a possible extraction of the corresponding u,d,s Yukawa couplings.

Measuring the electron Yukawa is even harder given the $e^{\pm}$ lightness, and the only direct method to extract it is through resonant s-channel e^+e^- production running at the Higgs pole mass [9]. The resonant cross section for a 125-GeV scalar of natural width $\Gamma_H = 4.1$ MeV is tiny, $\sigma(e^+e^- \to H) = 1.64$ fb. The actual cross section is further reduced accounting for the finite energy spread and initial state photon radiation (ISR) of the $e^{\pm}$ beams. For a c.m. energy spread commensurate with the Γ_H natural width (dashed line in Fig. 2), reachable using monochromatization [10], the cross section becomes $\sigma(e^+e^- \to H) = 290$ ab [11]. Under these conditions, a preliminary study based on counting the number of events for signal and backgrounds in 10 different decay final-states in e^+e^- at $\sqrt{s} = 125.000 \pm 0.004$ GeV, indicates that a 3σ observation requires $\mathscr{L}_{int} \approx 90$ ab^{-1} (Fig. 2) [9]. For the target $\mathscr{L}_{int} = 40$ ab^{-1}/yr at 125 GeV, the significance of the signal is 2.1σ which translates into limits on the $H \to e^+e^-$ branching ratio at $\times 1.2$ the SM expectation or, equivalently, a 95% CL upper bound on $\times 1.1$ the SM prediction for the $e^{\pm}$ Yukawa [9].

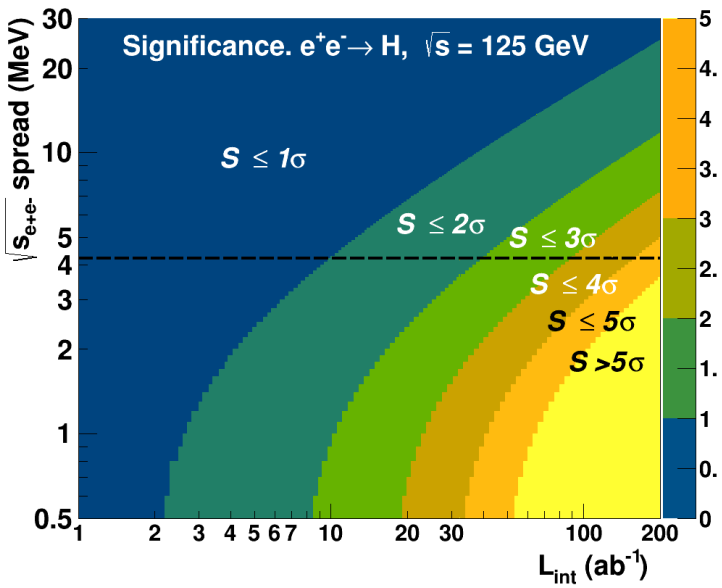

Figure 2: Significance contours for the $e^+e^- \to H$ observation at $\sqrt{s} = 125$ GeV (combining 10 Higgs boson decays) in the $\sqrt{s}$-spread vs. $\mathscr{L}_{int}$ plane at FCC-ee [9]. The dashed line shows the natural H boson width.

The generation of non-zero neutrino masses, called for by the observation of their flavor oscillations, is beyond the SM and requires new particles such as right-handed "sterile" ν's. Phenomenologically-attractive scenarios have been considered [12] where sterile neutrinos N_i have masses around the electroweak scale, and thereby can be produced at FCC-ee and observed via $N_i \to H + \nu$. Through the experimental study of mono-Higgs final states, FCC-ee has competitive sensitivities for $m_{N_i} \approx 100$–350 GeV and values of the active-sterile mixing parameter down to $|\theta_e|^2 \approx 10^{-5}$.

3 Determination of the Higgs potential (triple and quartic self-couplings)

The Higgs sector of the SM cannot be considered to be fully confirmed experimentally until the strength of the Higgs boson to itself is measured. The SM Lagrangian parametrizes the Higgs self-interaction through its triple (λ_3) and quartic (λ_4) self-couplings, and their determination is crucial to confirm the shape of the Higgs potential and the mechanism of electroweak symmetry breaking [13]. Their direct determination is only possible through the production cross sections of two and three Higgs bosons. At the LHC(14 TeV) and FCC(100 TeV), the cross sections amount to $\sigma(\text{HH}) \approx 0.05, 1.9$ pb and $\sigma(\text{HHH}) \approx 0.1, 5$ fb [6]. However, different production subchannels contribute to the HH and HHH cross sections that do not directly involve H self-couplings, thereby diluting the final sensitivity on $\lambda_{3,4}$. At the end of the high-luminosity LHC running (HL-LHC, 14 TeV, $\mathscr{L}_{\text{int}} = 3$ ab^{-1}), the uncertainties on λ_3 will be of the order of 50% [14], whereas the measurement of λ_4 is out of reach.

The FCC-ee has a sensitivity to the λ_3 parameter comparable to that of the HL-LHC, through the high-precision study of the dominant H+Z cross section which contains a small (energy-dependent) loop contribution involving the Higgs self-coupling [15]. However, a definite λ_3 measurement and constraints on λ_4, require a 100-TeV pp collider such as FCC-hh. The precision achievable in the measurements of double and triple Higgs cross sections at FCC-hh, and associated 68% CL intervals on the λ_3 and λ_4 self-couplings are listed in Table 1 [6]. The trilinear self-coupling can be measured with 3% uncertainties, whereas the quartic will be mildly constrained.

process	(statistical) precision on σ_{SM}	68% CL interval on Higgs self-couplings
$HH \to b\bar{b}\gamma\gamma$	3%	$\lambda_3 \in [0.97, 1.03]$
$HH \to b\bar{b}b\bar{b}$	5%	$\lambda_3 \in [0.9, 1.5]$
$HH \to b\bar{b}4\ell$	$O(25\%)$	$\lambda_3 \in [0.6, 1.4]$
$HH \to b\bar{b}\ell^+\ell^-$	$O(15\%)$	$\lambda_3 \in [0.8, 1.2]$
$HH \to b\bar{b}\ell^+\ell^-\gamma$	–	–
$HHH \to b\bar{b}b\bar{b}\gamma\gamma$	$O(100\%)$	$\lambda_4 \in [-4, +16]$

Table 1: Expected precision on SM cross sections for double and triple Higgs final-states reachable at FCC-hh (pp at 100 TeV, 30 ab^{-1}), and associated 68% CL ranges on λ_3 and λ_4 Higgs self-couplings. Details are provided in [6].

4 Searches for new scalar-coupled physics

With the Higgs boson discovered, the SM is now theoretically confronted to the hierarchy (aka. fine tuning or naturalness) problem, whereby quadratically-divergent SM virtual

corrections affect the running of the Higgs boson mass between the widely separated electroweak and Planck scales. New particles are required to stabilize such untamed quantum corrections. Since the Higgs boson couples directly to any massive particle, the presence of any new physics has large chances to affect its couplings to the rest of SM particles. A powerful model-independent method to encode the effect of new physics from higher energies on experimental observables, is provided by the SM Effective Field Theory (EFT), which parametrizes possible new physics via a systematic expansion in a series of higher-dimensional operators composed of SM fields: $\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm SM} + \sum_{d=5}^{\infty} \frac{1}{\Lambda^{d-4}} \mathscr{L}_d$ with $\mathscr{L}_d = \sum_i c_i^d \mathscr{O}_i$, and unknown Wilson coefficients c_i generated by decoupled new physics beyond the SM. Often, dim-6 operators $\mathscr{O}_i$ are the only ones considered (the Weinberg neutrino-mass is the unique dim-5 operator, and effects of $d > 6$ operators are subleading in the decoupling assumption), i.e. $\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2} \mathscr{O}_i$, where Λ represents the scale of new interactions, and the coefficients c_i depend on the details of its structure [16, 17]. In the case of indirect (loop) constraints on new physics coupled to the Higgs boson, a useful back-of-the-envelope formula can be derived which relates Λ to deviations of its couplings ($\delta g_{\rm HXX}$) with respect to the expected SM values:

$$\Lambda \gtrsim (1\ \text{TeV}) / \sqrt{(\delta \mathrm{g_{HXX}} / \mathrm{g_{HXX}})/5\%}; \qquad (1)$$

i.e. H couplings measurements of 5% precision are sensitive to new physics at $\Lambda \gtrsim 1$ TeV.

Parameter	Current* 7+8+13 TeV $\mathscr{O}$ (70 fb^{-1})	HL-LHC* 14 TeV (3 ab^{-1})	FCC-ee Baseline (10 yrs)	ILC Lumi upgrade (20 yrs)	CEPC Baseline (10 yrs)	CLIC Baseline (15 yrs)
σ(HZ)	–	–	0.4%	0.7%	0.5%	1.6%
$\mathrm{g_{ZZ}}$	10%	2–4%	0.15%	0.3%	0.25%	0.8%
$\mathrm{g_{WW}}$	11%	2–5%	0.2%	0.4%	1.6%	0.9%
$\mathrm{g_{bb}}$	24%	5–7%	0.4%	0.7%	0.6%	0.9%
$\mathrm{g_{cc}}$	–	–	0.7%	1.2%	2.3%	1.9%
$\mathrm{g_{\tau\tau}}$	15%	5–8%	0.5%	0.9%	1.4%	1.4%
$\mathrm{g_{t\bar{t}}}$	16%	6–9%	13%	6.3%	–	4.4%
$\mathrm{g_{\mu\mu}}$	–	8%	6.2%	9.2%	17%	7.8%
$\mathrm{g_{e^+e^-}}$	–	–	<100%	–	–	–
$\mathrm{g_{gg}}$	–	3–5%	0.8%	1.0%	1.7%	1.4%
$\mathrm{g_{\gamma\gamma}}$	10%	2–5%	1.5%	3.4%	4.7%	3.2%
$\mathrm{g_{Z\gamma}}$	–	10–12%	(to be determined)			9.1%
$\Delta \mathrm{m_H}$	200 MeV	50 MeV	11 MeV	15 MeV	5.9 MeV	32 MeV
$\Gamma_{\rm H}$	<26 MeV	5–8%	1.0%	1.8%	2.8%	3.6%
$\Gamma_{\rm inv}$	<24%	<6–8%	<0.45%	<0.29%	<0.28%	<0.97%

Table 2: Summary of the best statistical precision attainable for Higgs observables at future e^+e^- colliders (FCC-ee [5], ILC [18], CEPC [19], CLIC [20]) compared to (model-dependent*) current LHC [21] and expected HL-LHC [14] pp results.

At lepton colliders, precise and model-independent Higgs measurements can be carried

out using the recoil mass method in $e^+e^- \to HZ$, which allows an accurate determination of the H boson 4-momentum irrespective of its decay mode, from the $Z \to \ell^+\ell^-$ ($\ell = e, \mu$) decay reconstruction. At the FCC-ee, the high-precision ($\pm 0.4\%$) measurement of $\sigma_{e^+e^- \to HZ} \propto g^2_{HZ}$ provides a *model-independent* value of g_{HZ} to within $\pm 0.2\%$. The total Higgs boson width Γ_H can also be obtained with 1% uncertainty combining the measured value of $\sigma_{e^+e^- \to H(XX)Z} \propto \Gamma_{H \to XX}$ with the known branching fractions, $BR_X = \Gamma_{H \to XX}/\Gamma_H$, for different decays. The Higgs mass can be determined to within ± 11 MeV from the measured recoil mass. Table 2 provides a summary of the *best* precision attainable for most Higgs boson properties at future e^+e^- machines (FCC-ee [5], ILC [18], CEPC [19], and CLIC [20]) compared to those today [21] and reachable at HL-LHC [14]. Lepton colliders provide a factor of at least 50 (10) improvement with respect to the present (HL-LHC) results that, in addition and at variance with the latter, do not depend on any SM fit. Among future e^+e^- colliders, FCC-ee typically features the highest precision thanks to its expected higher luminosities. Farther, the $2{\cdot}10^{10}$ scalars bosons produced at FCC-hh will also systematically improve the precision of all H couplings, preliminary studies [6, 22] indicate a potential precision of 1% for those with lower rates at e^+e^- machines: $g_{t\bar{t}}$, $g_{\mu\mu}$, and $g_{Z\gamma}$.

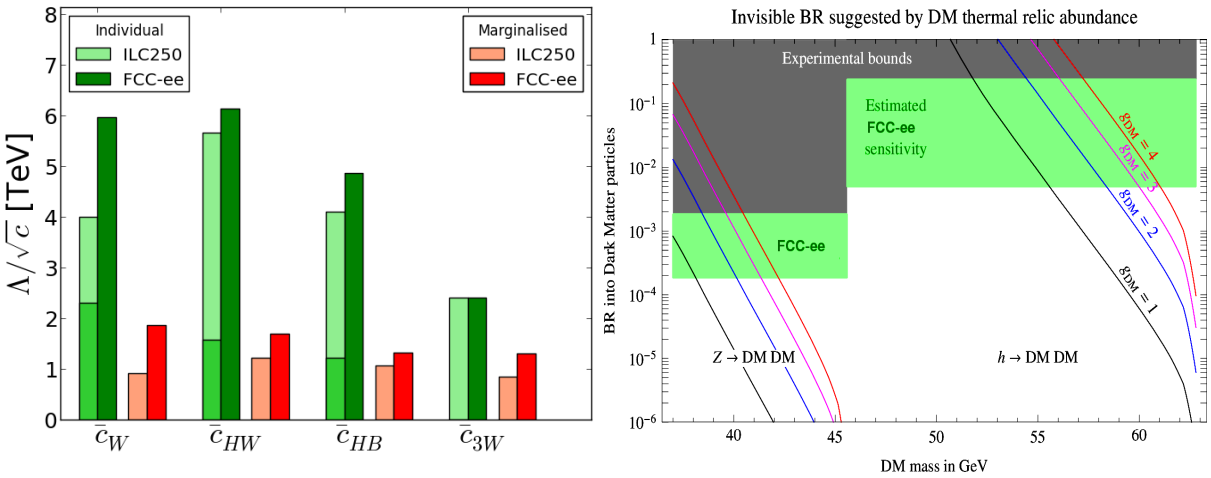

Figure 3: Left: Sensitivity reach to new physics scales ($\Lambda/\sqrt{c_i}$), encoded in four dim-6 operator c_i coefficients, of precision Higgs (and triple gauge boson couplings) measurements at FCC-ee and ILC [17]. Right: FCC-ee sensitivity for rare H (and Z) decays into DM pairs in the $BR_{H,Z \to \phi\phi}$ vs. m_ϕ plane [23].

The most precise coupling at FCC-ee ($\delta g_{ZZ}/g_{ZZ} \approx 0.15\%$) will allow setting limits on new scalar-coupled physics at $\Lambda \gtrsim 5.8$ TeV as per the simple estimate (1). Accurate theoretical analyses based on dim-6 EFT [17, 24] yield indeed $\Lambda \gtrsim 6$ TeV (Fig. 3, left). The same measurements can also be interpreted in terms of sensitivity to broad classes of SUSY models (such as the Constrained MSSM, or natural SUSY) effectively covering phase space corners beyond the LHC reach [25, 26].

5 Searches for Higgs-portal dark matter (DM)

The SM describes only 4% of the universe energy budget, the rest being in the form of unknown DM (and dark energy) contributions, pointing to the existence of new massive

particles (such as e.g. SUSY partners, heavy ν's, axions,...). In Higgs-portal models [27], the H boson acts as a mediator between the SM and DM particles, playing a central role in the evolution of the early universe. Attractive scenarios exist for DM candidates (ϕ) lighter than $m_{\mathrm{H,Z}}/2$, consistent with the measured DM thermal relic abundance in the universe, with DM freezing out through resonant H (or Z) exchanges. In such cases, the measurements of the invisible H and Z widths provide the best collider options to test such scenarios [23]. Current invisible H decays limits are BR(H→inv.) < 0.24 (95% CL) at the LHC [28], and are expected to reach BR(H→inv.) < 0.06 at HL-LHC (Table 2). At the FCC-ee, the $\mathrm{HZ}(\ell^+\ell^-)$ final state can be used to directly measure Γ_{inv} (a 5σ observation is possible down to BR = 1.7±0.1%) [29], in events where its decay products escape undetected. If unobserved, a 0.5% upper limit (95% CL) [5] can be set on this branching ratio (Fig. 3, right), placing DM bounds a factor of 50 (10) better than those at LHC (HL-LHC), and being also competitive with the reach of planned direct detection experiments for $\mathrm{m}_\phi < 10$ GeV [29].

For DM particles heavier than the Higgs boson, off-shell H decays into DM can be searched in pp events characterized by missing energy (from the $\mathrm{H}^\star \to \phi\phi$ decay) accompanied by extra particle production (gluon ISR in ggF, forward-backward jets in VBF, associated $\mathrm{t\bar{t}}$,...) as done at the LHC [21]. Theoretical studies indicate that the FCC-hh can place strong constraints on Higgs-portal couplings $|c_\phi| \approx 0$–3.5 for scalar DM masses $m_\phi = 150$–500 GeV (see details in [6, 30]).

6 Summary

The Future Circular Collider (FCC) will provide unparalleled luminosities $\mathscr{O}\,(1 - 20\ \mathrm{ab}^{-1})/\mathrm{yr}$ in pp ($\sqrt{\mathrm{s}} = 100$ TeV) and $\mathrm{e^+e^-}$ ($\sqrt{\mathrm{s}} = 125$–350 GeV) collisions, totalling $2{\cdot}10^{10}$ and $2{\cdot}10^6$ Higgs bosons produced over their respective expected operation times, and opening up measurements with $\mathscr{O}\,(50)$ ($\mathscr{O}\,(10)$) times better precision than those reachable at LHC (HL-LHC). The unique FCC Higgs physics opportunities include fully closing the SM scalar sector (measuring the unknown Yukawas of the first-generation fermions, as well as the triple and quartic Higgs self-couplings), and discovering (or placing bounds on) scalar-coupled new physics well into the multi-TeV regime.

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