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OPTIMIZED PHYSICS PERFORMANCE EVALUATION OF MONOCHROMATIZATION INTERACTION REGION OPTICS FOR DIRECT *s*-CHANNEL HIGGS PRODUCTION AT FCC-ee

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Abstract

The measurement of electron Yukawa coupling (y_e) via direct *s*-channel Higgs production at ∼125 GeV centre-of-mass (CM) energy is significantly facilitated at the FCC-ee, provided that the CM energy spread can be reduced to a level comparable to the natural width of the Higgs boson. This reduction is possible through the "monochromatization" concept, which involves generating opposite correlations between spatial position and energy deviation in the colliding beams. Following initial parametric studies for this collision mode, three different interaction region (IR) optics designs, each featuring nonzero horizontal, vertical, or combined dispersion at the interaction point (IP), have been proposed based on the Version 2022 (V22) of the FCC-ee Global Hybrid Correction (GHC) optics. In this paper, we benchmark the upper limits contours on y_e with simulated CM energy spread and luminosity using Guinea-Pig, in order to assess, optimize, and compare their physics performances.

INTRODUCTION

Since the discovery of the Higgs boson [1,2], determining its Yukawa couplings is regarded as a crucial full confirmation of the Standard Model (SM) [3,4]. Measuring the Higgs Yukawa coupling to first-generation fermions presents to be experimentally challenging due to their low masses and consequently small Yukawa couplings to the Higgs field. The electron Yukawa coupling, $y_e = \sqrt{2}m_e/v = 2.9 \times 10^{-6}$ (with $m_e = 0.511 \times 10^{-3}$ GeV denoting the electron mass and $v = (\sqrt{2}G_F)^{-1/2} = 246.22$ GeV the Higgs field vacuum expectation value), is virtually impossible to access at hadron colliders because the $\mathrm{H} \to e^+e^-$ decay has an extremely small branching fraction, $\mathscr{B}(\mathrm{H} \to e^+e^-) = 5.22 \times 10^{-9}$, and is completely overwhelmed by the Drell-Yan dielectron continuum, which has a cross section many orders of magnitude larger. However, it was recognized that the FCC-ee, by delivering an unprecedented integrated luminosity ($\mathscr{L}_{\mathrm{int}}$) of ∼10 ab^{-1} per year at CM energy ($\sqrt{s}$) of ∼125 GeV [3,4], could enable observation of the resonant *s*-channel production of the scalar boson, namely the reaction $e^+e^- \to \mathrm{H}$ at the Higgs pole [5–7]. This prospect motivated physics [8,9] and accelerator [10–23] studies of the $e^+e^- \to \mathrm{H}$ process.

The feasibility of such a measurement would be substantially enhanced if the CM energy spread ($\delta_{\sqrt{s}}$) of e^+e^- collisions — ∼50 MeV due to energy spread from synchrotron radiation (SR) and further exacerbated by beamstrahlung under the standard operating condition — could be reduced to a level comparable to the natural width of the SM Higgs boson, $\Gamma_{\mathrm{H}} = 4.1$ MeV. To reduce the collision energy spread and improve the CM energy resolution in colliding-beam experiments, the concept of monochromatization has long been proposed [24]. The basic idea is to introduce opposite correlations between spatial position and energy deviation in the colliding beams, which could be accomplished in beam-optics terms by generating a nonzero IP dispersion function ($D^*_{x,y}$) with opposite signs for the two beams.

Proposed in 2016, the monochromatization implementation at the FCC-ee has since been progressively improved, beginning with comprehensive self-consistent parametric studies and physics performance evaluation [7,10–12,16,17]. Based on the FCC-ee GHC V22 optics [25–27], a detailed study of the monochromatization IR optics design was performed, exploring three alternative schemes that introduce, respectively, nonzero D^*_x, D^*_y, or both, while maintaining the crossing angle (θ_c) of 30 mrad [18–20,22,23]. This paper presents the optimized physics performance of these FCC-ee monochromatic optics comparatively, by establishing their working points on the upper limits contours for y_e, according to simulated $\delta_{\sqrt{s}}$ and luminosity per IP ($\mathscr{L}$) obtained using the tool Guinea-Pig [28].

OPTICAL PARAMETER OPTIMIZATION

Global performance parameters of all the monochromatization IR optics are summarized in Refs. [22,23]. The optics designs based on the "FCC-ee GHC V22 Z" optics (optimized for operation at the Z pole) are labeled "MonochroM ZH", "MonochroM ZV", and "MonochroM ZHV", corresponding to configurations with nonzero D^*_x, D^*_y, and com-

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bined D_x^*/D_y^*, respectively, implemented at all four IPs. Similarly, those developed from the "FCC-ee GHC V22 $\mathrm{t\bar{t}}$" optics (optimized for operation above the $\mathrm{t\bar{t}}$ threshold) are labeled "MonochroM TH", "MonochroM TV", and "MonochroM THV". To improve physics performance in collider experiments, the two critical optical parameters, $\delta_{\sqrt{s}}$ and $\mathscr{L}_{\mathrm{int}}$, are optimized taking into account the impacts of beamstrahlung and the hourglass effect.

Beamstrahlung

Beamstrahlung, the SR emitted in the electromagnetic field of the opposing beam during collisions, is negligible in low-energy e^+e^- colliders but becomes significant in future high-energy circular colliders such as the FCC-ee. Its impacts on relative beam energy spread (σ_δ), emittance ($\varepsilon_{x,y}$), and bunch length (σ_z) were calculated analytically [22, 23]. In the FCC-ee GHC monochromatization schemes with nonzero D_x^*, the σ_δ and σ_z remain nearly at their natural values in the absence of collisions thanks to the much-increased horizontal IP beam sizes (σ_x^*). The number of bunches per beam (n_b) was maximized to 12000 (constrained by the maximum SR power loss of 50 MW while assuming the minimum bunch spacing of 25 ns) to minimize bunch population and thereby reduce the ε_x blow-up from beamstrahlung. To mitigate the ε_y blow-up induced by beamstrahlung in the scheme with only nonzero D_y^*, σ_x^* was increased to a level comparable to that of the scheme with nonzero D_x^*. This was achieved by enlarging the horizontal IP beta function (β_x^*) through adjustments to the strengths of the final focus quadrupoles. The resulting impact on global optical parameters, as computed by the code MAD-X [29], was found to be negligible. Figure 1 shows the variation of $\mathscr{L}$ and $\delta_{\sqrt{s}}$ for the "MonochroM ZV" optics as a function of β_x^*. The original setting of $\beta_x^* = 0.1$ m appears sub-optimal, yielding low $\mathscr{L}$ and high $\delta_{\sqrt{s}}$. As β_x^* increases, $\mathscr{L}$ rises to a maximum at $\beta_x^* = 1.5$ m before gradually declining, whereas $\delta_{\sqrt{s}}$ continues to decrease. Evaluation of physics performance at various β_x^* values indicates an optimal benchmark of ~5 m [22]. A similar analysis was conducted for the "MonochroM TV" optics, indicating that the β_x^* should also be increased to ~50 times its original value for optimal physics performance in the presence of beamstrahlung.

Hourglass Effect

The other factor studied here that could have an impact on this collision scheme is the hourglass effect [13]. To accurately assess the performance of the monochromatization IR optics, we calculated their $\delta_{\sqrt{s}}$ and $\mathscr{L}$ using Guinea-Pig, incorporating an estimation of the hourglass effect. In this calculation, the particle distribution at the IP was not a realistic distribution generated by tracking simulations, but modeled as an ideal Gaussian distribution of 40000 particles, defined by the following global optical parameters: beam energy, σ_δ, $\varepsilon_{x,y}$, $\beta_{x,y}^*$, $D_{x,y}^*$, σ_z, and θ_c [22,23]. Since Guinea-Pig simulates collisions per bunch crossing without accounting for the n_b and revolution frequency, the result must be multiplied by these two parameters to obtain the actual $\mathscr{L}$. The variation of $\mathscr{L}$ as a function of β_y^* for all the monochromatization IR optics is depicted in Fig. 2. The original value of $\beta_y^* = 1$ mm is already optimal for maximizing $\mathscr{L}$ in the two configurations with only nonzero D_x^*. In contrast, for the four configurations with nonzero D_y^*, when β_y^* is below 2 mm, $\mathscr{L}$ increases with β_y^*. However, beyond 2 mm, $\mathscr{L}$ remains nearly constant. Therefore, the final choice of β_y^* was made by selecting the point with the minimum $\delta_{\sqrt{s}}$ in the region where $\mathscr{L}$ plateaus. Specifically, β_y^* was set to 4 mm for the "MonochroM ZV" and "MonochroM TV" optics, and to 2.5 mm for the "MonochroM ZHV" and "MonochroM THV" optics.

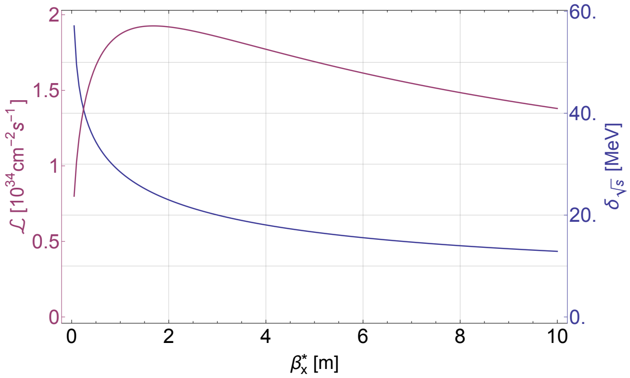

Figure 1: Trade-off between $\mathscr{L}$ (red curve) and $\delta_{\sqrt{s}}$ (blue curve) for the "MonochroM ZV" optics as a function of β_x^*.

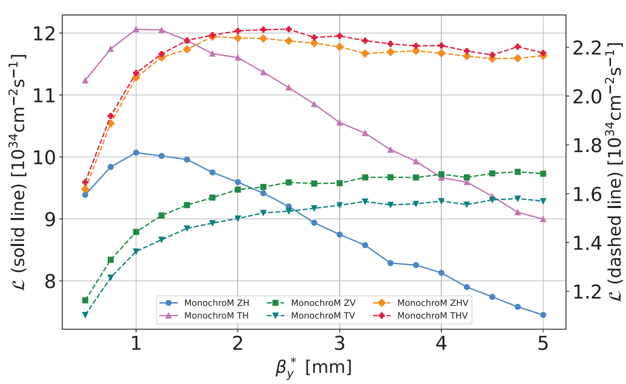

Figure 2: $\mathscr{L}$ as a function of β_y^* for various monochromatization IR optics, simulated using Guinea-Pig.

Optimized $\delta_{\sqrt{s}}$ and $\mathscr{L}$ of all the monochromatization IR optics, obtained using Guinea-Pig, are summarized in two tables: Table 1 for those based on the "FCC-ee GHC V22 Z" optics and Table 2 for those based on the "FCC-ee GHC V22 $\mathrm{t\bar{t}}$" optics. For reference, the first column in each of the two tables, labeled "Standard ZES" and "Standard TES", presents the energy-scaled optics configurations [23]. Regarding the $\mathscr{L}_{\mathrm{int}}$, a $\mathscr{L}$ of 10^{35} cm^{-2} s^{-1} yields 1.2 ab^{-1} per year per IP, based on the assumptions laid out in the FCC-ee CDR [4], which include 185 physics days per year and a physics efficiency of 75 %. Using this relation, the corresponding $\mathscr{L}_{\mathrm{int}}$ values were calculated and are listed in the two tables.

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Table 1: $\delta_{\sqrt{s}}$, $\mathscr{L}$, and $\mathscr{L}_{\text{int}}$ of the Monochromatization IR Optics Based on the "FCC-ee GHC V22 Z" Optics

Parameters	**Standard ZES**	**MonochroM ZH**	**MonochroM ZV**	**MonochroM ZHV**
CM energy spread $\delta_{\sqrt{s}}$ [MeV]	68.49	29.77	19.05	20.16
Luminosity/IP $\mathscr{L}$ [10^{34} cm^{-2} s^{-1}]	22.1	10.1	1.68	2.23
Integrated luminosity/IP/year $\mathscr{L}_{\text{int}}$ [ab^{-1}]	2.65	1.21	0.20	0.27

Table 2: $\delta_{\sqrt{s}}$, $\mathscr{L}$, and $\mathscr{L}_{\text{int}}$ of the Monochromatization IR Optics Based on the "FCC-ee GHC V22 $t\bar{t}$" Optics

Parameters	**Standard TES**	**MonochroM TH**	**MonochroM TV**	**MonochroM THV**
CM energy spread $\delta_{\sqrt{s}}$ [MeV]	67.25	29.59	15.85	19.08
Luminosity/IP $\mathscr{L}$ [10^{34} cm^{-2} s^{-1}]	57.9	12.1	1.57	2.21
Integrated luminosity/IP/year $\mathscr{L}_{\text{int}}$ [ab^{-1}]	6.95	1.45	0.19	0.27

PHYSICS PERFORMANCE EVALUATION

For physics performance evaluation of the FCC-ee monochromatization mode, large samples of simulated signal ($e^+e^- \to \text{H} \to \text{XX}$) and associated background ($e^+e^- \to \text{Z}^* \to \text{XX}$) events were generated with the Pythia 8 Monte Carlo code [7]. This was done for 11 Higgs decay channels, employing a multivariate analysis based on Boosted Decision Trees to discriminate between signal and background events. This analysis reveals two statistically significant final states: $\text{H} \to gg$ and $\text{H} \to \text{WW}^* \to \ell\nu 2j$. Taking a monochromatization benchmark that provides an ideal $\delta_{\sqrt{s}}$ of 4.1 MeV and a $\mathscr{L}_{\text{int}}$ of 10 ab^{-1}, an upper limit on the y_e was achieved at 1.6 times the SM Higgs s-channel cross section: $|y_e| < 1.6\,|y_e^{SM}|$ at a 95 % confidence level (CL) per IP per year, represented by the red star in Fig. 3. The black cross represents the benchmark of the FCC-ee monochromatization self-consistent parameters [16, 17], corresponding to a $\delta_{\sqrt{s}}$ of 25 MeV and a $\mathscr{L}_{\text{int}}$ of 2.76 ab^{-1}.

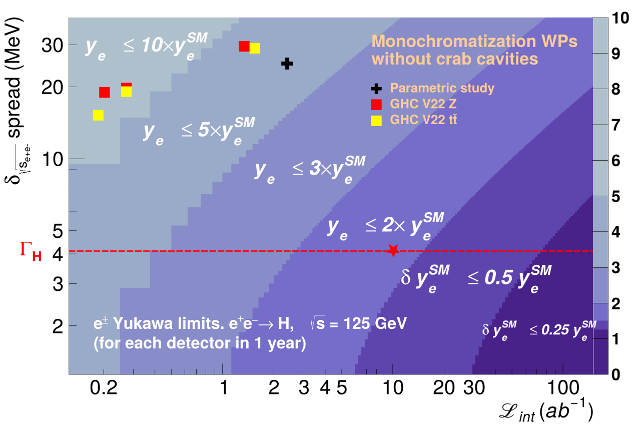

Figure 3: Upper limits contours (95 % CL) on y_e in the $\delta_{\sqrt{s}}$ vs. $\mathscr{L}_{\text{int}}$ plane, per FCC-ee IP and per year.

Working points of the proposed monochromatization IR optics, derived from the parameters listed in Table 1 and Table 2, are presented in Fig. 3. The red points refer to those based on the "FCC-ee GHC V22 Z" optics, while the yellow ones are based on the "FCC-ee GHC V22 $t\bar{t}$" optics. The "MonochroM TH" optics yields the best physics performance, achieving $\delta_{\sqrt{s}} = 29.59$ MeV and $\mathscr{L}_{\text{int}} = 1.45$ ab^{-1}. This corresponds to an upper limit (95 % CL) on the Higgs–electron coupling of $|y_e| < 4.2\,|y_e^{SM}|$ per IP per year. In contrast, although the configurations featuring nonzero D_y^* result in lower $\delta_{\sqrt{s}}$, the accompanying substantial decrease in $\mathscr{L}_{\text{int}}$ limits their overall performance.

SUMMARY AND OUTLOOK

The FCC-ee GHC V22 monochromatization IR optics design has been further refined through preliminary parameter optimization that accounts for beamstrahlung and the hourglass effect. Key performance indicators, $\delta_{\sqrt{s}}$ and $\mathscr{L}$, were evaluated using Guinea-Pig, and the results were used to compare the physics reach of different schemes in terms of their working points on the y_e upper limits contours. However, since Guinea-Pig was originally developed for linear colliders, in which beam dynamics are dominated by the pinch effect, such single-pass-based optimization provides only a relative performance estimate in the FCC-ee context, where the beam distribution is shaped by multi-turn dynamics. A more realistic evaluation is currently underway using multi-turn tracking simulations with the Xsuite code [30], which is expected to yield a more accurate assessment of the achievable monochromatization performance.

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