

Role of angular observables in probing nonstandard HZZ couplings at an electron-proton collider

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In this study, we explore various lab-frame angular observables at the Large Hadron-electron Collider (LHeC) to test their sensitivity to the most general structure of the Higgs (H) to neutral weak boson (Z) coupling (HZZ) via the process $e^-p \rightarrow e^-Hj$ at the center of mass energy $\sqrt{s} \approx 1.3$ TeV. The most general Lorentz structure of the HZZ coupling beyond the standard model is composed of two CP -even (λ_{1Z} and λ_{2Z}) and one CP -odd ($\tilde{\lambda}_Z$) component. In a previous study, we investigated the absolute value of azimuthal correlation ($|\Delta\phi|$) between the final state electron and the jet to derive constraints on the nonstandard HZZ couplings. This choice of observable is motivated by its potential to discriminate between CP -odd and CP -even couplings in the $e^-p \rightarrow \nu_e H j$ process. Since the process $e^-p \rightarrow e^-Hj$ has an electron in the final state, one can construct more angular observables. In addition to $|\Delta\phi|$, we identify new angular observables: the sign-sensitive azimuthal correlation ($\Delta\phi$) and the polar angle of the final state electron (θ), which are suitable for constraining nonstandard HZZ coupling. Our analysis shows that these new angles improve the constraints on λ_{2Z} and $\tilde{\lambda}_Z$ in the range of 48%–67%. We also study the potential of the asymmetry in $\Delta\phi$ to constrain the parameters corresponding to the CP -odd coupling.

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I. INTRODUCTION

The discovery of a fundamental scalar with a mass of 125 GeV at the Large Hadron Collider (LHC) is consistent with the Higgs boson (H) predicted in the minimal electroweak standard model. Its characterization by the ATLAS and CMS Collaborations [1,2] has significantly improved our understanding of its coupling to other standard model particles. In the kappa framework, the coupling of H with the Z boson has been measured with an accuracy below 7% using LHC Run 2 data in CMS [3] and ATLAS [4] experiments, and it is expected to reach 1.5% at HL-LHC [5] and 1.2% at LHeC [6]. The combined results from LHeC+HL-LHC are expected to bring it down to $\sim 0.82\%$ [6]. There remains scope for potential new physics beyond the Standard Model to be hidden in the LHC data on the Higgs boson. Understanding the possible nature of new physics arising from hidden symmetries requires going beyond the kappa framework in collider searches. In this regard, a new physics parametrization based on higher-dimensional operators,

constructed from standard model fields, provides a consistent theoretical framework. Such higher-dimensional operators often lead to non-trivial modifications in standard model couplings. This framework is particularly suitable for capturing new physics effects that may appear at high energy scales and are hard to detect directly.

The most general HZZ interaction vertex takes the form [7–12],¹

$$\begin{aligned} \Gamma_{HZZ}^{\mu\nu}(q_1, q_2) = & g_Z m_Z \kappa_Z g^{\mu\nu} - \frac{g}{m_W} [\lambda_{1Z} (q_1^\nu q_2^\mu - g^{\mu\nu} q_1 \cdot q_2) \\ & + \lambda_{2Z} (q_1^\mu q_1^\nu + q_2^\mu q_2^\nu - g^{\mu\nu} q_1 \cdot q_1 - g^{\mu\nu} q_2 \cdot q_2) \\ & + \tilde{\lambda}_Z \epsilon^{\mu\nu\alpha\beta} q_{1\alpha} q_{2\beta}]. \end{aligned} \quad (1)$$

In the above equation, we use the prescription $\epsilon^{0123} = 1$. Here, (q_1, q_2) and (μ, ν) represent the momenta and Lorentz indices of the two Z bosons, respectively. Clearly, the standard model can be recovered from the above by setting $\kappa_Z = 1$ and $\lambda_{1Z} = \lambda_{2Z} = \tilde{\lambda}_Z = 0$. The presence of momentum-dependent couplings is typical of higher-dimensional operators, and high-energy particle colliders are suitable experiments to probe momentum-dependent couplings. Such coupling structure has been

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¹The nonstandard HVV terms in Eq. (1.2) of [13] should have an overall negative sign.

extensively investigated in Higgs decays at various colliders [14–24]. In particular, the collider phenomenology of couplings of the Higgs boson with vector bosons given in Eq. (1), has been studied at the LHC by the ATLAS [25,26] and CMS [27–32] experiments via the Higgs production in VBF and VH processes, as well as the four-lepton decay channel of Higgs. The latest constraint from ATLAS [26] is $[-0.33, 0.48]$ on $\tilde{\lambda}_Z$ at 95% C.L., and from CMS [32], the constraints on λ_{1Z} , λ_{2Z} , and $\tilde{\lambda}_Z$ are $[-0.13, 0.09]$, $[-0.01, 0.01]$, and $[-0.13, 0.07]$, respectively, at 68% C.L.

An electron-proton (e^-p) collider has advantages over both e^-e^+ and pp colliders. It provides an opportunity to study high-energy interactions with relatively low backgrounds. In this work, we present a cut-based analysis to probe the structure of the non-standard HZZ couplings given in Eq. (1) at a proposed electron-proton collider [33] via the $e^- + p \rightarrow e^-Hj + X$ scattering process. At the parton level, this process proceeds via the so-called neutral current (NC) interaction in which Z bosons from the incoming electron and quark fuse to produce a Higgs boson.

One of the challenges in new physics searches at colliders is to identify observables that can efficiently distinguish among various Lorentz structures present in a coupling. In Ref. [9] it was found that CP -even and CP -odd nonstandard HWW coupling structures can be probed efficiently in the $e^- + p \rightarrow \nu_e H j + X$ (led by a charge current interaction) process using the $|\Delta\phi_{\not{e}j}|$ angular observable defined as the azimuthal angle between missing transverse energy and the light jet. The same angular observable involving e^- and j has been studied in detail for the neutral current process as well using the BSM framework given in Eq. (1) [13]. Unlike the case of the charged current process, in the neutral current process, we have access to the four momenta of all final-state particles. This situation allows us to construct new angular observables and investigate their efficiency in probing nonstandard HZZ coupling structures. The aim is to identify BSM parameter-specific angles that can provide the best constraints on individual parameters of Eq. (1).

II. EVENT SIMULATION

In this work, we perform a parton-level analysis, using MadGraph5_aMC@NLO (MG5) [34] to generate signal and background events. The NC process was analyzed in Refs. [13,35] using the $|\Delta\phi_{ej}|$ distribution to constrain the HZZ coupling. The simulation setup from that study is briefly summarized in this section, as it is used to produce the results in Sec. III. We refer the reader to Ref. [13] for a detailed discussion of the simulation methodology. We consider the NN23LO1 parton distribution function with the default MadGraph dynamical scales for renormalization and factorization. Signal events are identified with an e^- ,

two b jets, and one light jet in the final state of the neutral current process. Contributions to the background come from the processes $e^-p \rightarrow e^-b\bar{b}j$, e^-jjj , and $e^-b\bar{b}jj$, where j represents a jet originating from a light quark (u, d, s, c) or gluon. For our present study, we choose $E_e = 60$ GeV and $E_p = 7$ TeV, which corresponds to a center-of-mass energy of 1.3 TeV at the proposed LHeC. At this energy, the cross section for the SM signal is 16 fb, while the background cross sections are 77.3 pb for the one-jet process, 20.6 pb for the two-jet process, and 20.5 pb for the three-jet process. These values are obtained with the basic cuts: $p_T(e) > 20$ GeV, $p_T(j) > 20$ GeV, $|\eta_j| < 5$, $|\eta_e| < 2.5$, and $\Delta R(e, j) > 0.4$. Our kinematic selections to improve the significance of the SM signal over all the backgrounds are as follows:

- (1) To suppress the two-jet background, we impose a veto on the less forward jet in rapidity by requiring $p_T(j) > 30$ GeV. Additionally, we apply $p_T(e) > 20$ and $p_T(b) > 30$ GeV to account for detector resolution. These cuts reduce nearly 99% of the background, albeit at the cost of losing approximately half of the signal events.
- (2) An invariant mass window cut on the b -jet pair, $|M(b, \bar{b}) - M_H| < 15$ GeV, is found to be highly effective in suppressing all background processes.
- (3) To target the forward jet signature, we require $2 < |\eta_j| < 5.0$, which helps reduce one-jet background. Further kinematic selections, $|\eta_e| < 2.5$ and $0.5 < \eta_b < 3$, are applied to optimize signal efficiency in accordance with detector acceptance.
- (4) Finally, we impose a cut on the invariant mass of the Higgs and jet system, $M(H, j) > 300$ GeV, which reduces the total background to 16% of that remaining after the previous selection stage.

Several of the selection criteria are inspired by those used in the VBF analyses at the LHC. At an integrated luminosity of 1 ab^{-1} , the SM signal yields approximately 5340 events before any selection cuts, compared to nearly 30×10^6 events from background processes. After applying the full set of cuts, the signal is reduced to 760 events, while the background is significantly suppressed to 1850 events. This cut optimization increases the signal-to-background ratio (S/B) to 0.41. In the event selections, the tagging efficiency of a b jet is 0.6. The probabilities of miss-tagging a c jet and a light jet (u, d, s, g) as a b jet are 0.1 and 0.01, respectively. These tagging and miss-tagging rates substantially reduce backgrounds with light jets in the final state. So we do not consider the $3jet$ background in our analysis. We also use smearing of partonic energy by the formula $\frac{a}{E} = a/\sqrt{E} \oplus b$ to include hadronization effects at the detector where $a = 0.6$, $b = 0.04$ for parton jets and $a = 0.12$, $b = 0.02$ for electrons are chosen from Ref. [6].

III. ANGULAR OBSERVABLES

CP -even and CP -odd observables for lepton and hadron colliders for couplings between standard model particles, have been studied in Refs. [18,36–51]. *Genuine* CP -even and CP -odd observables cannot be constructed for the ep collider studies, since the initial state in this collider is not a CP eigenstate [39]. In this case, we can construct observables sensitive to the Lorentz structure of the couplings. Such observables have been used in Refs. [9,52,53]. We are interested in angular observables over radial observables, as the former are known for being sensitive to the spin and parity of particles. In this section, we discuss angular observables sensitive to the momentum-dependent structure of the HZZ coupling. These distributions are produced using the generation-level cuts, $p_T(j) > 10$ GeV, $p_T(e) > 10$ GeV, $\Delta R(e, j) > 0.4$, $\Delta R(b, \bar{b}) > 0.4$, $\Delta R(e, b) > 0.4$, $\Delta R(b, j) > 0.4$ in MG5.

The angular distributions defined in Eqs. (2)–(5) are θ_e , the angle made by the scattered e^- with the direction of the incident e^- beam; α_{ej} , the angle between the scattered e^- and the jet; and β_{ejH} , the angle between the Higgs boson and the normal to the plane of e^- and jet. We also consider $\Delta\phi_{ej}$ in the range $-\pi$ to π instead of $|\Delta\phi_{ej}|$ which is defined between 0 and π and has been studied in Ref. [13]. We have chosen final-state particles e^- and jet in distributions since these particles are directly related to the momenta of the legs involved in the nonstandard HZZ coupling. Therefore, distributions with combinations of these two particles are likely to capture the most sensitivity.

$$\theta_e = \cos^{-1} \left(\frac{\vec{p}_e \cdot \hat{z}}{|\vec{p}_e|} \right), \quad (2)$$

$$\alpha_{ej} = \cos^{-1} \left(\frac{\vec{p}_e \cdot \vec{p}_j}{|\vec{p}_e| |\vec{p}_j|} \right), \quad (3)$$

$$\begin{aligned} \Delta\phi_{ej} &= \tan^{-1} \left(\frac{p_{ey}}{p_{ex}} \right) - \tan^{-1} \left(\frac{p_{jy}}{p_{jx}} \right) \\ &= \tan^{-1} \left[\frac{(\vec{p}_e \times \vec{p}_j) \cdot \hat{z}}{\vec{p}_{Te} \cdot \vec{p}_{Tj}} \right], \end{aligned} \quad (4)$$

$$\begin{aligned} \beta_{ejH} &= \cos^{-1} \left(\frac{(\vec{p}_e \times \vec{p}_j) \cdot \vec{p}_H}{|\vec{p}_e \times \vec{p}_j| |\vec{p}_H|} \right) \\ &= \cos^{-1} \left(\frac{(\vec{p}_e \times \vec{p}_j) \cdot \hat{z} (E_1 - E_2)}{|\vec{p}_e \times \vec{p}_j| |\vec{p}_H|} \right). \end{aligned} \quad (5)$$

Here, $\vec{p}_i (i = e(\not{E}_T), j, H)$ denotes the momenta of the final-state particles—the electron (missing energy), jet, and Higgs boson—in the NC (CC) process. The quantities E_1 and E_2 represent the energies of the initial-state electron and quark, respectively.

Since the κ_Z parameter only scales the SM coupling, it cannot capture deviations with respect to the SM in

differential distributions. Therefore, we do not consider this parameter in our study. In Fig. 1, we show the sensitivity of the angular observables to the Lorentz structures associated with the parameters λ_{1Z} , λ_{2Z} , and $\tilde{\lambda}_Z$. In order to test the effects of each BSM coupling on the kinematic observables, only one parameter is taken to be nonzero at a time. We have selected benchmark values ($\lambda_{1Z} = \pm 0.4$, $\lambda_{2Z} = \pm 0.3$, $\tilde{\lambda}_Z = \pm 0.5$) for these parameters. These values are motivated by constraints on the BSM parameters that we obtained from a previous analysis [13]. These values are only used to demonstrate deviations from the SM, while the rest of the analysis is independent of these specific choices of values of parameters. When the value of these parameters is set to zero, it replicates the SM distribution, as indicated by the green line in Fig. 1. In this demonstration, the SM contribution corresponds purely to the SM signal process, $e^- p \rightarrow e^- H j$. All angular distributions, in the presence of BSM parameters, include SM + interference + quadratic contributions.

As shown in Fig. 1(a), the θ_e distribution is more sensitive to the λ_{2Z} parameter than to the other BSM parameters. In the case of the SM, like the jet, the electron should be emitted along the beam directions due to the kinematics dictated by the weak boson propagator associated with the electron. However, the boost of the center-of-mass frame along the proton beam forces the electron to scatter away from its incident beam direction. Because of this, a significant number of events with θ_e away from zero also occur.² This behavior remains the same in the presence of λ_{1Z} and $\tilde{\lambda}_Z$. In the case of λ_{2Z} , the θ_e distribution is shifted more towards π .

Similarly, in Fig. 1(b), the α_{ej} distribution corresponding to λ_{2Z} is characteristically very different from the SM prediction, while in the case of λ_{1Z} and $\tilde{\lambda}_Z$, it follows behavior similar to the SM contribution. This can be understood from the polar angle distributions of the electron [Fig. 1(a)] and the jet. The jet is produced in the direction of the incident proton beam for the SM and all three BSM coupling scenarios. However, the electron is mostly transverse for λ_{1Z} , $\tilde{\lambda}_Z$, and the SM. For these two BSM couplings, electrons in the transverse direction and jets along the proton beam lead events to largely favor the angle α_{ej} around $\pi/2$. In the case of $\lambda_{2Z} = 0.3$, the polar angle distribution of electron peaks around $\theta_e = \pi/3$ and $4\pi/5$, while for jet it peaks along the proton beam direction. The correlation between θ_e and α_{ej} suggests that the two observables should be equally sensitive to the BSM parameter λ_{2Z} .

The $\Delta\phi_{ej}$ distribution in Fig. 1(c), ranging from $-\pi$ to π , contains more differential information than the $|\Delta\phi_{ej}|$ distribution used in [9,13]. This motivates us to examine

²With a higher beam energy of the electron, θ_e starts peaking in the forward direction.

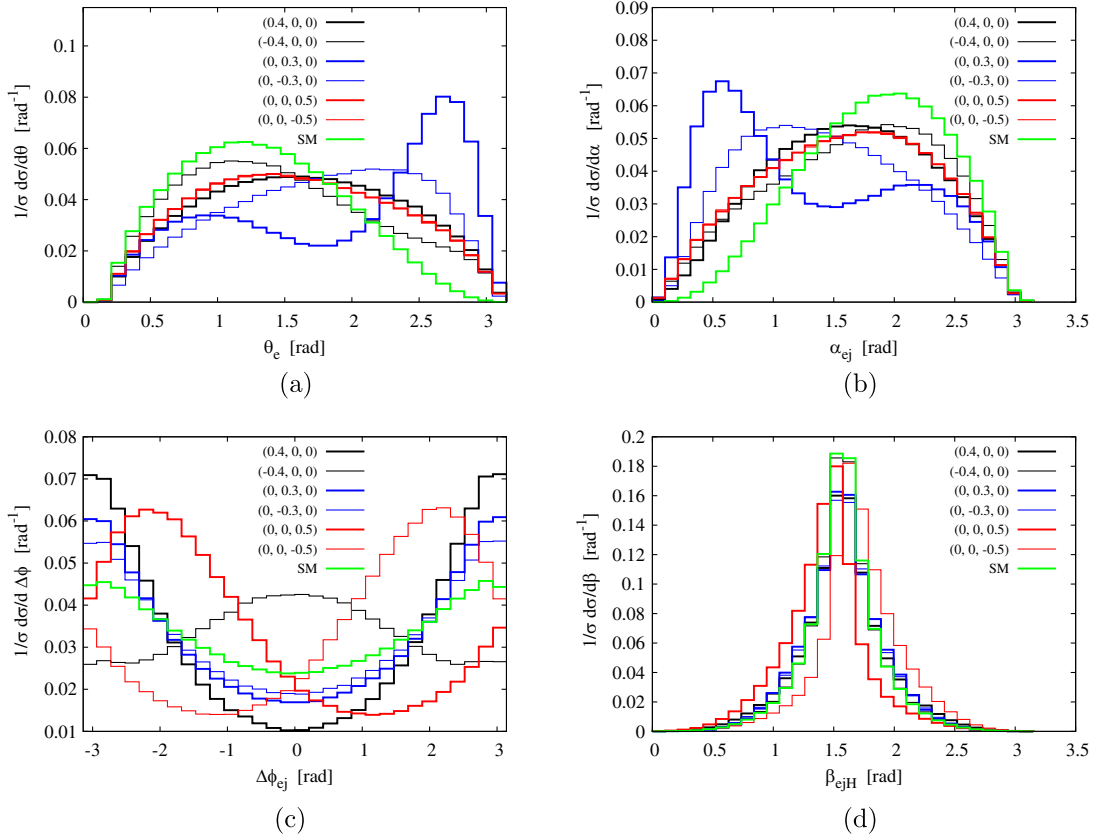


FIG. 1. Angular observables at the parton level, sensitive to BSM coupling associated with parameters $(\lambda_{1Z}, \lambda_{2Z}, \tilde{\lambda}_Z)$. All observables are normalized to unity.

the $\Delta\phi_{ej}$ distribution, which can be constructed without any ambiguity.³ The $\Delta\phi_{ej}$ distribution is defined using the $\tan^{-1}$ (quadrant inverse tangent) function, as it covers all four quadrants from 0 to 2π in the azimuthal angle. This function properly accounts for all possible directions of outgoing particles in the transverse plane of the detector. For most of the couplings, the $\Delta\phi_{ej}$ distribution peaks at values around $\pm\pi$. The transverse momentum distribution of the Higgs boson indicates that most of the events lie at low p_T for the Higgs boson; therefore, the electron and jet pairs are likely to be produced back-to-back. However, the $\Delta\phi_{ej}$ distribution for $\lambda_{1Z} = -0.4$ peaks at $\Delta\phi_{ej} = 0$. Such behavior in the $\Delta\phi_{ej}$ distribution arises because the interference term is large and negative in the central bins of the distribution for λ_{1Z} , which results in a positive contribution in those bins for negative values of λ_{1Z} . In contrast, for λ_{2Z} , the interference term is negative and small with respect to the quadratic term across all bins. Consequently, the quadratic term primarily dictates the shape of the $\Delta\phi_{ej}$ distribution for λ_{2Z} , as illustrated in Fig. 1(c).

³In the case of VBF, where a similar angle between two jets can be constructed, only $|\Delta\phi_{jj}|$ is meaningful.

The interference term for the CP -odd contribution plays a crucial role in shaping the behavior of the $\Delta\phi_{ej}$ distribution. The interference between the CP -odd term and the SM amplitude is given by

$$\begin{aligned} \text{Re}(\mathcal{M}_{\text{SM}}^* \mathcal{M}_{\tilde{\lambda}}) &\propto \tilde{\lambda}_Z \epsilon^{\mu\nu\alpha\beta} p_{1\mu} p_{2\nu} p_{e\alpha} p_{j\beta} \\ &\propto -\tilde{\lambda}_Z \sin \Delta\phi_{ej}. \end{aligned} \quad (6)$$

We can also observe in Fig. 1(c) that the $\Delta\phi_{ej}$ distribution is asymmetric about $\Delta\phi_{ej} = 0$ when the CP -odd coupling $\tilde{\lambda}_Z$ is nonzero. The interference term in Eq. (6) does not contribute at $\Delta\phi_{ej} = 0$. We note that for positive values of $\tilde{\lambda}_Z$, the interference term provides a positive contribution for $\Delta\phi_{ej} < 0$ and a negative contribution for $\Delta\phi_{ej} > 0$. This leads to an asymmetry around $\Delta\phi_{ej} = 0$. The behavior of this distribution is exactly the opposite for negative values of $\tilde{\lambda}_Z$. The asymmetry also remains when one of the CP -even couplings is present along with the CP -odd coupling. This feature offers the advantage of constraining the CP -odd coupling even in the presence of CP -even couplings.

Following the discussion on the vector boson fusion process at the LHC [53], we note that the $|\Delta\phi_{ej}|$ distribution for pure CP -even and CP -odd couplings (where

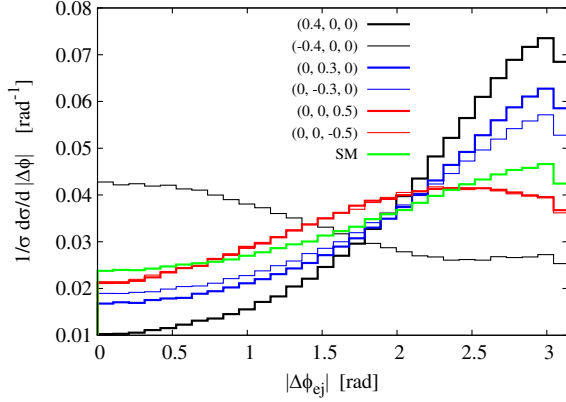


FIG. 2. $|\Delta\phi_{ej}|$ distribution at the parton level, for benchmark values of $(\lambda_{1Z}, \lambda_{2Z}, \tilde{\lambda}_Z)$. Distribution is normalized to unity.

“pure” means the Standard Model contribution is not considered) exhibits distinct behaviors: it peaks at $|\Delta\phi_{ej}| = 0, \pi$ for CP -even couplings, while for CP -odd couplings, it dips at $|\Delta\phi_{ej}| = \pi/2$. In contrast, the pure SM contribution results in a relatively flat $|\Delta\phi_{ej}|$ distribution. This demonstrates that the distribution is highly sensitive to pure CP -even and CP -odd coupling structures. However, when the CP -odd coupling is present in addition to the SM contribution, the distribution becomes insensitive to the sign of the CP -odd parameter $\tilde{\lambda}_Z$, as shown in Fig. 2. This effect arises due to the sign of the azimuthal correlation between the outgoing electron and the jet present in the interference term.

The interference term linear in the CP -odd coupling is an odd function of $\Delta\phi_{ej}$, as shown in Eq. (6). In contrast, for the CP -even coupling, including the SM case, the amplitudes are even functions of $\Delta\phi_{ej}$, as discussed in Refs. [38,52,53]. This implies that the interference with CP -odd coupling is the only term in the amplitude-squared that is sensitive to the sign of $\Delta\phi_{ej}$. When obtaining $|\Delta\phi_{ej}|$ from $\Delta\phi_{ej}$ via phase space integration, the interference term cancels. Therefore, the distributions presented in Ref. [13] and Fig. 2 in this work are insensitive to the sign of the CP -odd parameter. However, the interference terms proportional to the CP -even parameters λ_{1Z} and λ_{2Z} remain intact under phase space integration and show presence in both $|\Delta\phi_{ej}|$ and $\Delta\phi_{ej}$ distributions. Therefore, in order to recover sensitivity to the sign of the CP -odd coupling, it is important to consider the signed azimuthal angle difference rather than its absolute value.

Constraints on the CP -odd coupling of HWW have been obtained via the charged current process in Refs. [9,13] using $|\Delta\phi_{\not{e}j}|$. Similar to $\Delta\phi_{ej}$ given in Eq. (4), one can also define the correlation $\Delta\phi_{\not{e}j}$ between the missing energy and the jet of the CC process, as the missing energy information in the transverse plane can be reconstructed from the final state particles.

A similar argument applies to understanding the asymmetric nature of the β_{ejH} distribution. The β_{ejH} distribution is related to the angle made by the normal to the e^- and jet plane and the electron beam direction, as defined in Eq. (5). Since the jet is predominantly produced along the proton beam direction, the plane formed by the scattered e^- and the jet passes through the beam axis. Consequently, a large number of events in the β_{ejH} distribution accumulate around $\beta_{ejH} = \pi/2$. Moreover, the β_{ejH} and $\Delta\phi_{ej}$ distributions exhibit similarities due to their dependence on the common factor $(\vec{p}_e \times \vec{p}_j) \cdot \hat{z}$, which appears in both observables and also contributes to the amplitude for the CP -odd coupling. As a result, both observables provide similar sensitivity to the $\tilde{\lambda}_Z$ coupling, making it reasonable to expect similar constraints on $\tilde{\lambda}_Z$ from these two distributions. Due to the similarity between θ_e and α_{ej} , as well as between $\Delta\phi_{ej}$ and β_{ejH} , we focus our discussion on the comparatively simpler distributions of θ_e , $|\Delta\phi_{ej}|$, and $\Delta\phi_{ej}$ in the rest of the analysis.

IV. BOUNDS ON BSM PARAMETERS

We use χ^2 analysis to estimate constraints on the BSM parameters λ_i assuming the standard model hypothesis. The χ^2 as a function of the BSM couplings λ_i and λ_j (where λ_i and λ_j are λ_{1Z} , λ_{2Z} , and $\tilde{\lambda}_Z$) for any observable ($\mathcal{O}$) defined in Eqs. (2)–(5) is given by,

$$\chi^2(\lambda_i, \lambda_j) = \sum_{k=1}^n \left(\frac{\mathcal{O}_k^{\text{BSM}}(\lambda_i, \lambda_j) - \mathcal{O}_k^{\text{SM}}}{\Delta\mathcal{O}_k} \right)^2. \quad (7)$$

Here, n is the total number of bins in which an observable is distributed. $\mathcal{O}_k^{\text{SM}}$ and $\mathcal{O}_k^{\text{BSM}}$ are the values of the observables of Eqs. (2)–(5) in the k th bin for the SM and BSM, respectively. $\Delta\mathcal{O}_k$ consists of the statistical uncertainty and systematic uncertainty in the k th bin. In the χ^2 analysis, we have included the contributions from the 1 jet and 2 jet background processes that survive the selection cuts discussed in Sec. II, and their effects are incorporated in the uncertainties $\Delta\mathcal{O}_k$.

First, we take into account the scenario where only one of the three BSM parameters is taken to be nonzero at a time. The analysis considering more than one bin of an angular observable is expected to be more efficient than a one-bin analysis. We use a bin width of 9° for all observables. This means 20 bins for the θ_e and $|\Delta\phi_{ej}|$ distributions, while 40 bins for $\Delta\phi_{ej}$. Figure 3 presents χ^2 plots assuming an integrated luminosity of $L = 1 \text{ ab}^{-1}$ and no systematic uncertainty in bins. The $\Delta\phi_{ej}$ distribution provides the strongest bound on λ_{1Z} , as shown in Fig. 3(a). In the case of λ_{2Z} , Fig. 3(b) shows that the most stringent bounds are obtained from the θ_e distribution. For both CP -even parameters λ_{1Z} and λ_{2Z} , the constraints provided by $\Delta\phi_{ej}$ are slightly tighter than those obtained by $|\Delta\phi_{ej}|$. This is mainly due to the larger number of bins that go into the

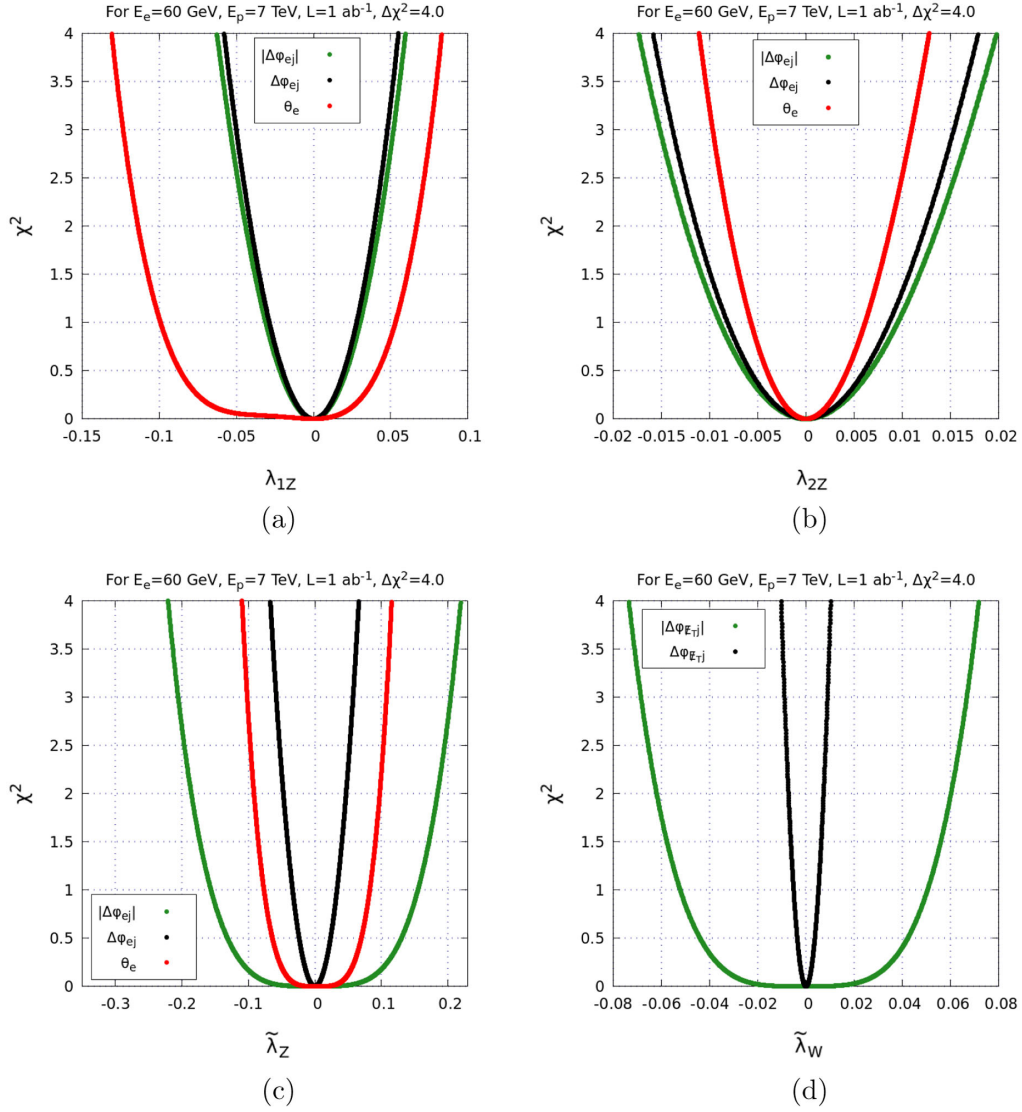


FIG. 3. Constraints on nonstandard HZZ coupling parameters and $\tilde{\lambda}_W$ assuming $L = 1 \text{ ab}^{-1}$. The constraints correspond to (a) λ_{1Z} , (b) λ_{2Z} , (c) $\tilde{\lambda}_Z$, and (d) $\tilde{\lambda}_W$.

analysis using $\Delta\phi_{ej}$ distribution. Figure 3(c) demonstrates that the asymmetric distribution $\Delta\phi_{ej}$, which is sensitive to the CP -odd structure of the HZZ coupling, puts the most stringent limits on $\tilde{\lambda}_Z$ compared to the other angular observables considered in this analysis. The expected effectiveness of $\Delta\phi_{\not{j}}$ over $|\Delta\phi_{\not{j}}|$ in constraining $\tilde{\lambda}_W$, analyzing the charged current process can also be seen in Fig. 3(d). We also examine the impact of a 5% systematic uncertainty applied to each bin on the constraints shown in Fig. 3. While the constraint from θ_e is affected minimally, with an increment below 0.7%, the constraints from the $\Delta\phi_{ej}$ and $|\Delta\phi_{ej}|$ distributions are weakened by approximately 3%–6% and 8%–17%, respectively.

Using new observables, Table I shows that the constraints on λ_{2Z} and $\tilde{\lambda}_Z$ improve by 48% and 67%,

respectively, compared to those obtained from the $|\Delta\phi_{ej}|$ distribution discussed in Ref. [13]. It is worth noting here that the HL-LHC projections [5,19] for λ_{1Z} , λ_{2Z} , and $\tilde{\lambda}_Z$ are 1%, 0.5%, and 12% at 95% C.L. with an integrated luminosity of 3 ab^{-1} . In the same table, we also compare

TABLE I. Comparison of constraints obtained from $|\Delta\phi|$ (second column) with those from new observables $\Delta\phi$ and θ (third column). Systematic uncertainty is not included.

Couplings	$ \Delta\phi $	New observables
λ_{1Z}	$[-0.07, 0.07]$	$[-0.07, 0.07]$ ($\Delta\phi_{ej}$)
λ_{2Z}	$[-0.02, 0.02]$	$[-0.01, 0.01]$ (θ_e)
$\tilde{\lambda}_Z$	$[-0.22, 0.22]$	$[-0.07, 0.07]$ ($\Delta\phi_{ej}$)
$\tilde{\lambda}_W$	$[-0.07, 0.07]$	$[-0.01, 0.01]$ ($\Delta\phi_{\not{j}}$)

constraints from $\Delta\phi_{\#j}$ and $|\Delta\phi_{\#j}|$ on the CP -odd component $\tilde{\lambda}_W$ of the nonstandard HWW coupling. We find an improvement of about 85% when using $\Delta\phi_{\#j}$ over $|\Delta\phi_{\#j}|$ in the analysis. All these numbers are expected to change with the inclusion of systematic uncertainties.

The constraints on λ_{1Z} , λ_{2Z} , and $\tilde{\lambda}_Z$ as a function of luminosity, varying from 10 to 1000 fb^{-1} , are presented in Fig. 4 at 95% C.L. In this plot, constraints on each BSM parameter are taken from the most sensitive observable to that parameter. The variation of the bounds with luminosity follows a similar trend for all couplings. The constraints on λ_{1Z} , λ_{2Z} , and $\tilde{\lambda}_Z$ change by 74%, 83%, and 74%, respectively, as the luminosity increases from 10 fb to 10^3fb^{-1} .

The asymmetric nature of $\Delta\phi_{ej}$, as shown in Fig. 1(c) for $\tilde{\lambda}_Z$, allows us to construct an asymmetry observable that is less sensitive to systematic uncertainty. The asymmetry is defined as

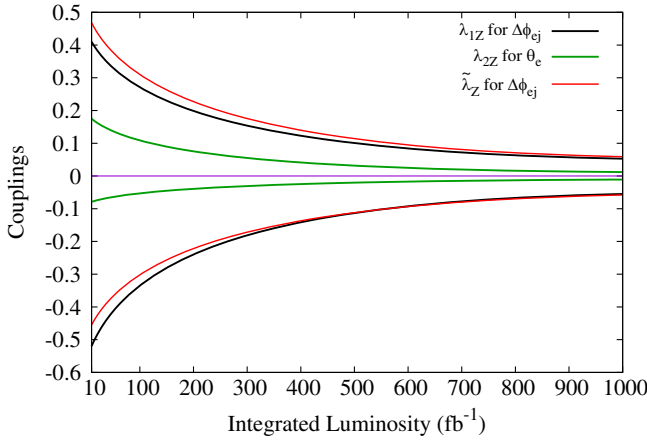


FIG. 4. Variation of constraints on HZZ parameters using the best observables obtained at 95% C.L. as a function of integrated luminosity.

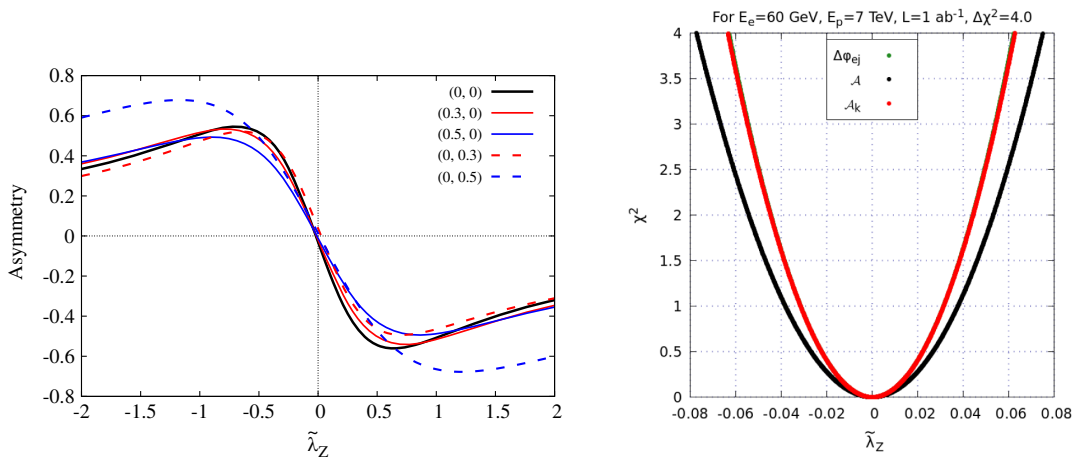


FIG. 5. Asymmetry in $\Delta\phi_{ej}$ as a function of $\tilde{\lambda}_Z$ for fixed values of CP -even couplings ($\lambda_{1Z}, \lambda_{2Z}$) (left), and the corresponding χ^2 plot based on asymmetry in $\Delta\phi_{ej}$ (right) with $\delta = 0$.

$$\mathcal{A} = \frac{\mathcal{O}_{\Delta\phi>0} - \mathcal{O}_{\Delta\phi<0}}{\mathcal{O}_{\Delta\phi>0} + \mathcal{O}_{\Delta\phi<0}}. \quad (8)$$

When using $\mathcal{A}$ in the χ^2 analysis, the statistical uncertainty is given by

$$\Delta\mathcal{O}_{\text{stat}} = \sqrt{\frac{1 - (\mathcal{A}^{\text{SM}})^2}{\mathcal{O}^{\text{SM}} \cdot L}}.$$

Here, L is the integrated luminosity. The systematic uncertainty in asymmetry, assuming no correlation between systematic uncertainties in the bins of $\Delta\phi_{ej}$ distribution, is given by

$$\Delta\mathcal{O}_{\text{sys}} = \delta \sqrt{\frac{1 - (\mathcal{A}^{\text{SM}})^2}{2}}.$$

Since the amplitude-squared is an even function of $\Delta\phi_{ej}$ for CP -even coupling and an odd function for CP -odd coupling, the asymmetry has a linear dependency on the CP -odd coupling in its numerator. However, its denominator can depend on all three couplings λ_{1Z} , λ_{2Z} , and $\tilde{\lambda}_Z$. Consequently, for small values of the CP -even couplings, the asymmetry varies linearly, as shown in Fig. 5. This makes the observable particularly suitable for constraining the CP -odd coupling when the CP -even parameters are already tightly constrained by theoretical or experimental means. Using this asymmetry in the χ^2 formula given in Eq. (7), we first obtain constraints on $\tilde{\lambda}_Z$ under the assumption that the other BSM parameters are zero. In Fig. 5, we have plotted χ^2 as a function of $\tilde{\lambda}_Z$ using the asymmetry $\mathcal{A}$ defined in Eq. (8), bin-wise asymmetry $\mathcal{A}_k$, and $\Delta\phi_{ej}$ as observables considering zero systematic uncertainty. The bin-wise asymmetry $\mathcal{A}_k$ is constructed by applying the definition of $\mathcal{A}$ for each pair of

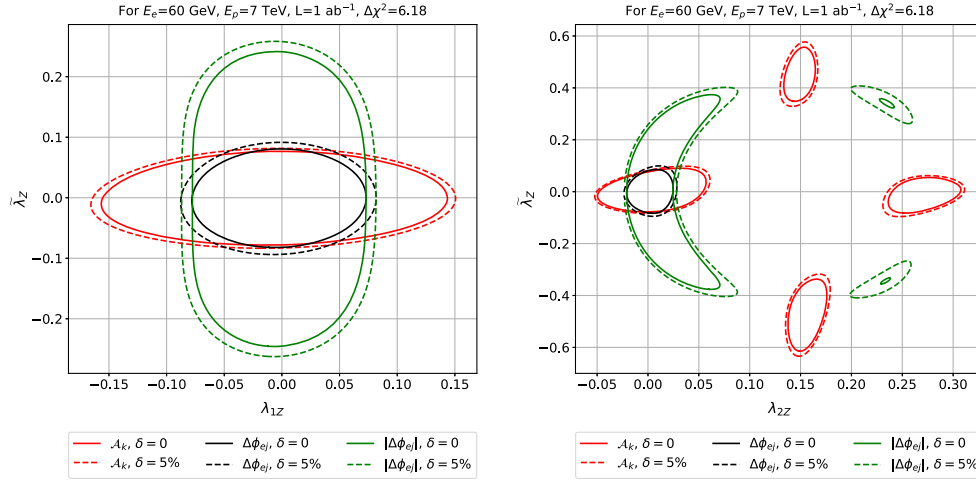


FIG. 6. Comparison of constraints in the two parameter space based on $\Delta\phi_{ej}$, $|\Delta\phi_{ej}|$, and the asymmetry in $\Delta\phi_{ej}$, with $\delta = 0$ (solid) and $\delta = 5\%$ (dashed) systematic uncertainty per bin of distributions.

symmetrically located bins about $\Delta\phi_{ej} = 0$. Thus, a total of 20 values of $\mathcal{A}_k$ is used in the analysis. As expected, the constraints using $\mathcal{A}_k$ are tighter than those obtained using $\mathcal{A}$. However, there is no improvement in constraints when comparing them with the analysis based on $\Delta\phi_{ej}$. In the presence of a 5% systematic uncertainty, the constraints on $\tilde{\lambda}_Z$ obtained from $\mathcal{A}_k$ and $\Delta\phi_{ej}$ observables weaken by approximately 6%, while the constraint from the asymmetry $\mathcal{A}$ nearly doubles. These qualitative trends also hold for the χ^2 analysis of $\tilde{\lambda}_W$ in the charged-current process.

As discussed in the previous section, the $\Delta\phi_{ej}$ distribution is more efficient than the $|\Delta\phi_{ej}|$ distribution in capturing CP -odd coupling effects when CP -even couplings are present. Considering this fact, we present the constraints on $\tilde{\lambda}_Z$ in Fig. 6, assuming the presence of one CP -even coupling at a time, with either 0% or 5% systematic uncertainty applied to each bin of the $\Delta\phi_{ej}$ distribution. From this figure, it is evident that the constraints on $\tilde{\lambda}_Z$ are considerably stronger for $\Delta\phi_{ej}$ (black) than $|\Delta\phi_{ej}|$ (green). Around smaller values of CP -even couplings, the asymmetry (red) performs slightly better than $\Delta\phi_{ej}$. However, as discussed above, for larger values of λ_{1Z} and λ_{2Z} , the sensitivity of asymmetry is reduced compared to the angular distribution. We also observe that the parameter space constrained by $\mathcal{A}_k$ is least impacted by systematic uncertainties, compared to those obtained using other observables.

V. CONCLUSIONS

A general Lorentz-invariant HZZ coupling, parametrized by the three parameters λ_{1Z} , λ_{2Z} , and $\tilde{\lambda}_Z$, is studied via the NC process at an ep collider. We analyze the

sensitivity of various angular observables— θ_e , α_{ej} , $|\Delta\phi_{ej}|$, β_{ejh} , and $\Delta\phi_{ej}$ —to each coupling by setting the remaining parameters to zero. It is found that $\Delta\phi_{ej}$ and θ_e are the most sensitive angular observables. We have compared the constraints on each parameter using these observables. The strongest bound on λ_{1Z} comes from the $\Delta\phi_{ej}$ distribution, which is the same as obtained in our previous study [13]. The observables θ_e and $\Delta\phi_{ej}$ provide the strongest limits on the λ_{2Z} and $\tilde{\lambda}_Z$ parameters, respectively. At an integrated luminosity of 1 ab $^{-1}$, these limits now fall within the ranges of $[-0.02, 0.02]$ for λ_{2Z} and $[-0.22, 0.22]$ for $\tilde{\lambda}_Z$, representing improvements of 48% and 67%, respectively, compared to our previous study. The angular observable $\Delta\phi_{ej}$ shows an asymmetry around $\Delta\phi_{ej} = 0$ in the presence of the CP -odd coupling $\tilde{\lambda}_Z$, which arises due to the four-rank epsilon tensor structure. The constraints on $\tilde{\lambda}_Z$ derived from this asymmetry are closely comparable to those obtained from the $\Delta\phi_{ej}$ distribution when the other parameters are set to zero. Furthermore, we present constraints on the CP -odd coupling in scenarios where one of the CP -even couplings is nonzero. In such cases, the asymmetry in the $\Delta\phi_{ej}$ distribution provides stronger constraints on $\tilde{\lambda}_Z$ compared to the $\Delta\phi_{ej}$ observable when λ_{1Z} is nonzero. However, $\Delta\phi_{ej}$ sets a tighter parameter space for $\tilde{\lambda}_Z$ in the presence of λ_{2Z} . The constraints on $\tilde{\lambda}_Z$ obtained from the new observable are stronger than the HL-LHC projections, whereas those on λ_{1Z} and λ_{2Z} are weaker for the achievable integrated luminosities at HL-LHC and LHeC. We have noted that, like $\Delta\phi_{ej}$ in the neutral current process, $\Delta\phi_{\not{j}}$ (ranging between $-\pi$ to π) can be constructed in the charged-current process without any ambiguity, leading to an improved constraint on $\tilde{\lambda}_W$, the CP -odd parameter of HWW coupling.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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