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Probe CP violation in $H \to \gamma Z$ through forward-backward asymmetry

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ABSTRACT

We suggest that the forward-backward asymmetry (A_{FB}) of the charged lepton in $gg \to H \to \gamma Z \to \gamma \ell^- \ell^+$ process could be used to probe the CP violating $H\gamma Z$ coupling when the interference from $gg \to \gamma Z \to \gamma \ell^- \ell^+$ process is included. With CP violation in $H\gamma Z$ coupling, the interference effect leads to a non-vanishing A_{FB}, which is also sensitive to the strong phase differences. The resonant and non-resonant strong phases together make $A_{FB}(\hat{s})$ change sign around Higgs mass M_H. For phenomenology study, we suggest the integral over one-side mass region below M_H to magnify the A_{FB} strength.

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1 Introduction

To explain the observed matter-antimatter asymmetry in the universe, some CP-violation sources beyond Standard Model (SM) are needed [1]. The Higgs boson discovered five years ago with mass around 125 GeV may provide clues to study the source of CP violation. Many papers have studied CP violation in Higgs couplings such as $Ht\bar{t}$, HZZ, HWW couplings [2],[3]. In this work, we focus on $H\gamma Z$ coupling in the process $gg \to H \to \gamma Z \to \gamma \ell^- \ell^+$ at LHC. Since there are only three final state momenta, the direct method to construct a CP violation observable fail. After considering the interference from a background process, there are some new CP violation observables: the forward-backward asymmetry (A_{FB}) of the leptons in Z boson rest frame [4],[5], and the angle ϕ between the Z production and decay planes [6]. In this paper, we study the new CP violation observable A_{FB} with the interference from the process $gg \to \gamma Z \to \gamma \ell^- \ell^+$ and discuss the its impact at current and future hadron colliders. This paper is a short report, a more detailed analysis could be found in Ref. [7].

2 The effective model

We use the following dimension-5 effective operators to describe the $gg \to H \to \gamma Z$ process,

$$\mathcal{L}_{\rm h} = \frac{c}{v}\, h\, F_{\mu\nu} Z^{\mu\nu} + \frac{\tilde{c}}{2v}\, h\, F_{\mu\nu} \tilde{Z}^{\mu\nu} + \frac{c_g}{v}\, h\, G^a_{\mu\nu} G^{a\mu\nu} \ , \tag{1}$$

where F, G^a denote the γ and gluon field strengths, $a = 1, ..., 8$ are $SU(3)_c$ adjoint representation indices for the gluons, $v = 246$ GeV is the electroweak vacuum expectation value, the dual field strength is defined as $\tilde{X}^{\mu\nu} = \epsilon^{\mu\nu\sigma\rho} X_{\sigma\rho}$, c, $\tilde{c}$ and c_g are complex numbers.

For simplicity, we require

$$\mathrm{Arg}(c) = \mathrm{Arg}(\tilde{c}) \ \textit{or} \ \mathrm{Arg}(c) = \mathrm{Arg}(-\tilde{c}) \ . \tag{2}$$

After that it is convenient to define

$$\xi = tan^{-1}(\tilde{c}/c) \ , \tag{3}$$

where $\xi \in [0, 2\pi)$. ξ is a CP violation phase (weak phase) and we will show this when we discuss parity relation and CP transformation.

3 Interference

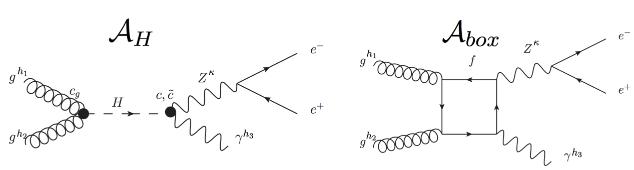

Figure 1: *The Feynman diagrams of $gg \to H \to \gamma Z \to \gamma \ell^- \ell^+$ and $gg \to \gamma Z \to \gamma \ell^- \ell^+$ processes. The amplitudes are noted as $\mathcal{A}_H$ and $\mathcal{A}_{box}$ respectively.*

The interference between the processes of $gg \to H \to \gamma Z \to \gamma \ell^- \ell^+$ and $gg \to \gamma Z \to \gamma \ell^- \ell^+$ are considered. Their Feynman diagrams are shown in Fig. 1. The intermediate Z boson is considered to be on-shell with a narrow-width approximation. After that the $2 \to 3$ process could be factorized into a $2 \to 2$ process times a $1 \to 2$ process and the total squared amplitude is

$$|\mathcal{A}|^2 = \sum_{h_i} \left| \sum_{\kappa=+,0,-} [\mathcal{A}_H^{2\to 2} + \mathcal{A}_{box}^{2\to 2}]^{h_1 h_2}_{h_3 \kappa} [\mathcal{A}^{1\to 2}]^{-\kappa}_{h_4 h_5} \right|^2 \ , \ [\mathcal{A}_H^{2\to 2}]^{h_1 h_2}_{h_3 \kappa} = [\mathcal{A}_H^{SM\ 2\to 2}]^{h_1 h_2}_{h_3 \kappa} \times e^{-i\kappa\xi} \ , \tag{4}$$

where h_is are the helicities of gluons and photon, κ is the helicity of Z boson.

$[\mathcal{A}_H^{2\to 2}]^{h_1 h_2}_{h_3 \kappa}$ has parity relations as

$$[\mathcal{A}_H^{2\to 2}]^{-h_1 - h_2}_{-h_3 -\kappa} = [\mathcal{A}_H^{2\to 2}]^{h_1 h_2}_{h_3 \kappa}\Big|_{\xi \leftrightarrow -\xi} \ , \tag{5}$$

which shows ξ changes sign under CP transformation and thus is a weak phase.

4 Kinematics and the Source of A_{FB}

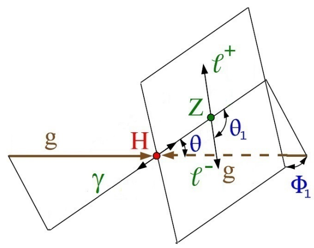

Figure 2: *The kinematic angles for $gg \to H \to \gamma Z \to \gamma \ell^- \ell^+$ process. θ is the polar angle of Z boson in H (or gg) rest frame. θ_1 is the angle of ℓ^- in Z boson rest frame. The z-axis of Z boson rest frame is defined as the Z boson production momentum direction in H rest frame. ϕ_1 is the angle between Z boson production and decay planes.*

We only need five variables to character the full kinematics. The independent variables are the two squared invariant masses $\hat{s}$ and s_{45}, and the three angles θ, θ_1 and ϕ_1. Fig. 2 illustrates the three angles.

The forward-backward asymmetry (A_{FB}) in proton-proton collision is

$$A_{FB} \equiv \frac{N_F - N_B}{N_F + N_B} = \frac{(\int_0^1 - \int_{-1}^0) d\cos\theta_1 \int_I d\sqrt{\hat{s}}\sqrt{\hat{s}} G(\hat{s}) \frac{d\hat{\sigma}(\hat{s},\theta_1)}{d(\cos\theta_1)}}{(\int_{-1}^1) d\cos\theta_1 \int_I d\sqrt{\hat{s}}\sqrt{\hat{s}} G(\hat{s}) \frac{d\hat{\sigma}(\hat{s},\theta_1)}{d(\cos\theta_1)}} \tag{6}$$

$$\propto \int_I d\sqrt{\hat{s}}\sqrt{\hat{s}} G(\hat{s}) \, \mathrm{Im}[\tilde{\sigma}^{2\to 2}_{H,box}]_{++} \sin\xi, \tag{7}$$

$$\mathrm{Im}[\tilde{\sigma}^{2\to 2}_{H,box}]_{++} = \mathrm{Im} \sum_{h_1,h_2,h_3} [\mathcal{A}_H^{2\to 2}]^{h_1 h_2}_{h_3 +}(\hat{s},\theta) [\mathcal{A}^{*2\to 2}_{box}]^{h_1 h_2}_{h_3 +}(\hat{s},\theta) \ , \tag{8}$$

where $\sqrt{\hat{s}} = M_{\gamma Z}$, s being the total hadronic c.m. energy and $G(\hat{s})$ is the gluon-gluon luminosity function, $\int_I$ represents an mass region to be integrated. Because of several non-zero strong phases, the integrand $\mathrm{Im}[\tilde{\sigma}^{2\to 2}_{H,box}]_{++}$ changes sign around resonance peak as shown in the simulation.

5 Simulation

Based on a modified `MCFM` package, the simulation are generated for a proton-proton collider with $\sqrt{s} =$ 14 TeV. The selection criteria include: $p_T^\gamma > 20$ GeV, $|\eta^\gamma| < 2.5$ and $M_{\ell^- \ell^+} \in [66, 116]$ GeV. In Figure 3, the left panel shows the integrand of A_{FB} numerator changes sign around the resonance peak, the right panel shows the slope (also A_{FB} numerator) is larger when integral region is half of the resonance region. Table .1 shows A_{FB} could be enhanced if integrate over the half resonance region.

Experimentally the invariant mass resolution could dilute the asymmetric component of interference and minify the A_{FB} value. The resonance mass uncertainty may make it difficult to get a half resonance region and thus the A_{FB} value would be also deviate to the theoretical prediction. Nevertheless, it is still better to consider the integral over one side of the resonance peak and the A_{FB} value would still be larger than if integrated over the whole resonance region.

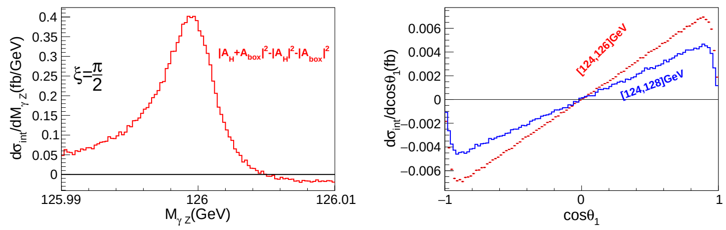

Figure 3: *Left panel: The $M_{\gamma Z}$ differential cross section of the interference part, which changes sign around the resonance peak. Right panel: $d\sigma_{int}/d\cos\theta_1$ versus $\cos\theta_1$ for* $[124, 126]$ *GeV and* $[124, 128]$ *GeV integral region. The slope is equal to the numerator value of A_{FB}.*

Integral mass region (GeV)	A_{FB}
[124, 126]	$0.008/1.4 \sim 0.57\%$
[124, 128]	$0.005/2.8 \sim 0.18\%$

Table 1: *A_{FB} values when integrating over half and whole resonance regions.*

6 Conclusion and discussion

In this work we construct a model with general CP violation phase ξ from $H\gamma Z$ coupling. By calculating the interference effect between $gg \to H \to \gamma Z \to \gamma\ell^-\ell^+$ and $gg \to \gamma Z \to \gamma\ell^-\ell^+$ processes, we confirm that the forward-backward asymmetry A_{FB} of charged leptons in the Z rest frame is a CP-violation observable, and is proportional to $\sin\xi$. By studying the lineshape of the integrand, we propose to do integral of $M_{\gamma Z}$ over half of the resonant mass region to enhance A_{FB}. After detailed simulations using modified `MCFM`, we estimate the A_{FB} could reach about 0.6%. Even though, the significance is relatively small and hard to be observed at the HL-LHC.

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