Probing the CP properties of Higgs bosons via transverse polarization at e^+e^- collider

Work in progress

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Motivation

1. The Baryogenesis can be accommodated by the 2HDM with CP-violating vacuum expectation value
2. One can test the CP properties of ZZH coupling via Z decay at the future collider e^+e^- collider
3. The CP-violating structure can be sensitive to the angular distribution of final state particles, particularly the azimuthal distribution with initial transversely polarized beams

> The idea of using transverse polarization to probe the CP properties of ZZH coupling came from [S. Biswal et al. '09]

The CP violation in the extended Higgs model

> 2HDM with CP violation

$$\Phi_1 = \begin{pmatrix} \chi_1^+ \\ \frac{v_1+\rho_1+i\eta_1}{\sqrt{2}} \end{pmatrix}, \Phi_2 = \begin{pmatrix} \chi_2^+ \\ \frac{v_2 e^{i\Phi_{CP}}+\rho_2+i\eta_2}{\sqrt{2}} \end{pmatrix} \tag{1}$$

CP-even Higgs mix with CP-odd Higgs:

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \\ G^0 \end{pmatrix} = R \begin{pmatrix} \rho_1 \\ \rho_2 \\ \eta_1 \\ \eta_2 \end{pmatrix} \tag{2}$$

The CP mixing Higgs to fermion couplings:

$$c_{h_i f\bar{f}} = c_f + i\gamma_5 \tilde{c}_f \tag{3}$$

CP violation in Higgs to gauge bosons interaction

- At tree level, $c_{h_i VV}$ is purely CP-even

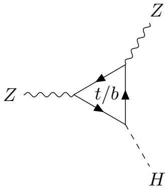
$$c_{h_i VV} = \cos\beta R_{i1} + \sin\beta R_{i2} \tag{4}$$

- At one loop level, the CP mixing $c_{h_i f\bar{f}}$ provide the CP-odd structure of $c_{h_i VV}$

$$\Gamma_{h_i VV} = \frac{i g m_Z}{\cos\theta_W}\left[c_{h_i VV} g_{\mu\nu} + \frac{\kappa_V}{m_Z^2}(p_{1\nu}p_{2\mu} - g_{\mu\nu} p_1 \cdot p_2) + \frac{\tilde{\kappa}_V}{m_Z^2}\epsilon_{\mu\nu\alpha\beta}p_1^\alpha p_2^\beta \right] \tag{5}$$

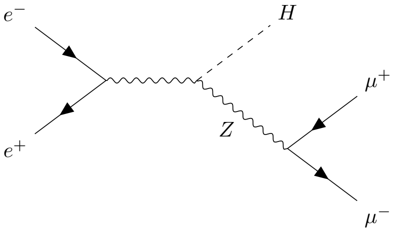
We only take the Leading-order CP-odd term into account

$$\mathcal{L}_{\text{EFT}} \propto Z_{\mu\nu}\tilde{Z}^{\mu\nu}H \tag{6}$$



Probing the CP violation at e^+e^- collider

- Probing the CP-violation of 2HDM via Higgs decay had been studied
- One can look at the Z decay of the Higgs strahlung at e^+e^- collider



$$e^+e^- \to HZ, Z \to \mu^+\mu^-$$

- The effect of the initial polarized electrons can be carried by the Z boson and transferred to the $\mu^+\mu^-$ pair by the Z decay

Initial beams polarization

Polarization matix for the initial beams:

$$\frac{1}{2}(1-\sigma\cdot P)_{\lambda\lambda'} = \frac{1}{2}\begin{pmatrix} 1-P^3 & P^1-iP^2 \\ P^1+iP^2 & 1+P^3 \end{pmatrix} = \frac{1}{2}\begin{pmatrix} 1-f\cos\theta_P & f\sin\theta_P e^{-i\phi_P} \\ f\sin\theta_P e^{i\phi_P} & 1+f\cos\theta_P \end{pmatrix} \tag{7}$$

where:

- f is the polarization degree
- if $\theta_P = 0$, the beam is longitudinally polarized
- if $\theta_P = \frac{\pi}{2}$, the beam is transversely polarized
- ϕ_P is the azimuthal angle of transverse polarization

$$P^1 = f\sin\theta_P\cos\phi_P \tag{8}$$

$$P^2 = f\sin\theta_P\sin\phi_P \tag{9}$$

$$P^3 = f\cos\theta_P \tag{10}$$

Spin density matrix

Bouchiat-Michel formula:

$$u(p,\lambda')\bar{u}(p,\lambda) = \frac{1}{2}(1+2\gamma_5)\not{p}\delta_{\lambda\lambda'} + \frac{1}{2}\gamma_5(\not{s}^1_-\sigma^1_{\lambda\lambda'} + \not{s}^2_-\sigma^2_{\lambda\lambda'})\not{p} \tag{11}$$

$$v(p,\lambda')\bar{v}(p,\lambda) = \frac{1}{2}(1-2\gamma_5)\not{p}\delta_{\lambda\lambda'} + \frac{1}{2}\gamma_5(\not{s}^1_+\sigma^1_{\lambda\lambda'} + \not{s}^2_+\sigma^2_{\lambda\lambda'})\not{p} \tag{12}$$

Spin density matrix for Higgs strahlung:

$$\begin{aligned}\rho^{ii'}(e^+e^- \to ZH) =& \frac{1}{2}(\delta_{\lambda_r\lambda_r'} + P_-^m\sigma^m_{\lambda_r\lambda_r'})\frac{1}{2}(\delta_{\lambda_u\lambda_u'} + P_+^n\sigma^n_{\lambda_u\lambda_u'})M^i_{\lambda_r\lambda_u}M^{*i'}_{\lambda_r'\lambda_u'} \\ =&(1-P_-^3P_+^3)A^{ii'} + (P_-^3 - P_+^3)B^{ii'} + \sum_{mn}^{1,2} P_-^m P_+^n C^{ii'}_{mn}\end{aligned} \tag{13}$$

where C_{mn} is the part with transversely polarized electron beams.

Cross section calculation

Spin density matrix for $Z \to \mu^+\mu^-$ decay: $\rho^{i'i}(Z \to \mu^+\mu^-)$

- The total scattering amplitude can be obtained by narrow width approximation:

$$
\begin{aligned}
&\mathcal{M}(e^+e^- \to HZ, Z \to \mu^+\mu^-) \approx \frac{1}{m_Z\Gamma_Z}\sum_{ii'}\rho^{ii'}(e^+e^- \to ZH)\rho^{i'i}(Z \to \mu^+\mu^-) \\
=&(1 - P_-^3P_+^3)\mathcal{M}_A + (P_-^3 - P_+^3)\mathcal{M}_B + \sum_{mn}^{1,2} P_-^m P_+^n \mathcal{M}_{C_{mn}}
\end{aligned}
\tag{14}
$$

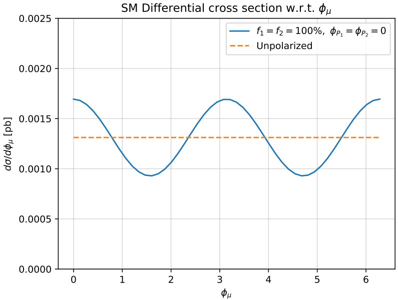
- The cross section can be obtained by integrating over the whole phase space:

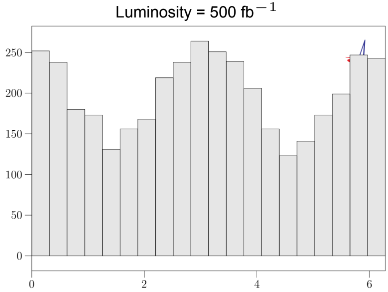
$$
\sigma = \int \frac{\mathcal{M}(e^+e^- \to HZ, Z \to \mu^+\mu^-)}{4sm_Z} dQ_{\text{LIPS}}(\phi_H, \theta_H, \phi_{\mu^-}, \theta_{\mu^-}) \tag{15}
$$

SM Differential cross section ($\sqrt{s} = 250$ GeV)

with respect to the ϕ_H

The total cross section with transverse polarization is always the same as the unpolarized totoal cross section, if the leptonic chiral symmetry is preserved.*[K. Kolodziej et al. '93.]*

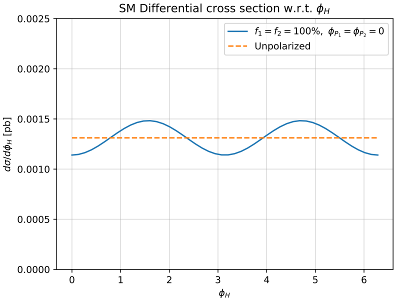


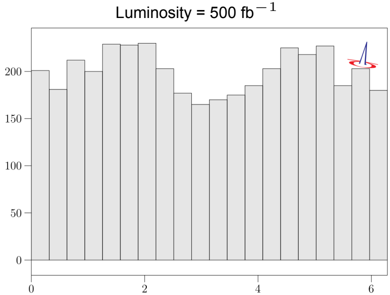


- The transverse polarization will only have the effect on the azimuthal distribution of the cross section
- The analytical result is consistent with the `Whizard` simulation.

SM Differential cross section ($\sqrt{s} = 250$ GeV)

with respect to the ϕ_{μ^-}



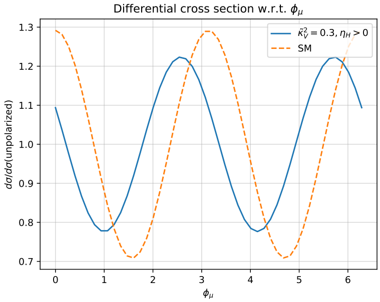


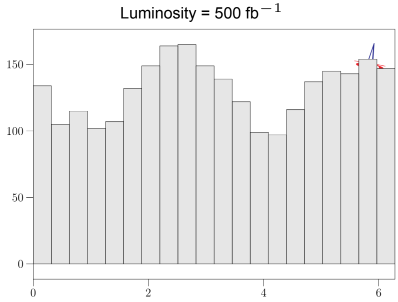
- The azimuthal angular distribution of μ^- from Z decay would be different from the Higgs azimuthal distribution.
- Both distributions for the SM are CP symmetric

Differential cross section for CP-mixing case

We set:

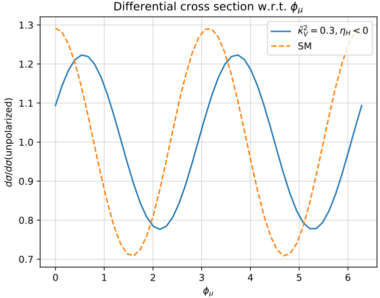
$$c_{hVV}^2 + \tilde{\kappa}_V^2 = 1 \quad (16)$$

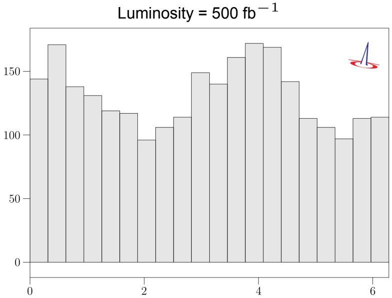




- The BSM case (blue line) with 30% CP-odd component has the CP asymmetric distribution
- The azimuthal distribution with forward Higgs is shifted to the left compared to the SM symmetric distribution

Differential cross section for CP-mixing case





- The azimuthal distribution with backward Higgs is shifted to the right compared to the SM symmetric distribution
- The distributions generated by the `Whizard` are consistent with the analytical results

Azimuthal asymmetry

Analytical results

Construct a CP-odd observable:

$$\mathcal{C} = \eta_H \,\text{sin}\, 2\phi_{\mu^-} \propto [\vec{s}_1 \cdot \vec{p}_{\mu^-}] \cdot [(\vec{s}_1 \times \vec{p}_1) \cdot \vec{p}_{\mu^-}] \cdot [\vec{p}_1 \cdot \vec{p}_H] \tag{17}$$

We can define the following azimuthal asymmetries:

$$\mathcal{A} = \frac{\sigma(\eta_H \,\text{sin}\, 2\phi_{\mu^-} < 0) - \sigma(\eta_H \,\text{sin}\, 2\phi_{\mu^-} > 0)}{\sigma_{\text{tot}}} \tag{18}$$

For the muon azimuthal asymmetry (analytical):

$$\mathcal{A}(\text{SM}) = 0 \qquad\qquad \mathcal{A}(\tilde{\kappa}_V^2 = 0.3) \approx 12.9\% \tag{19}$$

Azimuthal asymmetry

`Whizard` simulation

Obtain the asymmetry by summing up the events of different signal region:

$$\mathcal{A} = \frac{N(\eta_H \,\text{sin}\, 2\phi_{\mu^-} < 0) - N(\eta_H \,\text{sin}\, 2\phi_{\mu^-} > 0)}{N_{\text{tot}}} \tag{20}$$

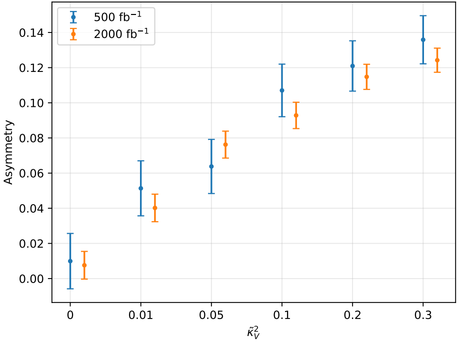
Uncertainty of the Asymmetry:

$$\Delta A = 2\sqrt{\frac{\epsilon(1-\epsilon)}{N_{\text{tot}}}}, \epsilon = \frac{N(\eta_H \,\text{sin}\, 2\phi_{\mu^-} < 0)}{N_{\text{tot}}} \tag{21}$$

Asymmetry results from `Whizard` simulation (500 fb^{-1})

$$\mathcal{A}(\text{SM}) \approx (0.99 \pm 1.57)\% \qquad \mathcal{A}(\tilde{\kappa}_V^2 = 0.3) \approx (13.59 \pm 1.37)\% \tag{22}$$

Azimuthal asymmetry



- With only taking the statistical uncertainties into account, the CP-mixing case with $\tilde{\kappa}_V^2 = 0.01$ can be resolved by the ILC with a luminosity of 500 fb^{-1}
- The luminosity of 2000 fb^{-1} can improve the resolution of the CP-odd component.

Summary

Work done

- We calculated the cross section of $e^+e^- \to HZ, Z \to \mu^+\mu^-$ analytically with taking the initial polarization into account
- We evaluated the differential cross section with respect to the azimuthal angles of the Higgs boson and the muon.
- We constructed the CP-odd observables and calculated the asymmetry
- We use `Whizard` for the Monte Carlo simulation and calculate the uncertainties of the asymmetry for a specific luminosity

Next step

- Estimating systematic uncertainties for this asymmetry

Thank you!

Contact

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Backup

Other study of Higgs CP-properties

- The study of $H \to 4\ell$ [1707.00541] at LHC constrained the anomalous higgs gauge bosons coupling in $\tilde{\kappa}_V^2 \sim \{-0.38, 0.46\}$ with 95% C.L.
- CP-violating effects in $H \to \tau^+\tau^-$ had been investigated at LHC [1903.06973]
- The CP-properties of the Higgs–top quark coupling at the HL-LHC had been studied by [2202.11753]
- One had also studied the CP-violation via $H \to \tau^+\tau^-$ at ILC by [1804.01241,2105.06530,2110.12830]