Probing the CP-violating HZZ coupling at e^+e^- collider

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Motivation

In light of the future e^+e^- collider, how can one probe the CP properties of the HZZ coupling?

At 250 GeV for Higgs Strahlung Cheng Li showed that this is possible with transverse polarized beams [EPS-HEP 2023: Cheng Li].

What happens at higher energies?

How can we probe the CP properties of the HZZ coupling for Z-Fusion?
Can we make use of transverse polarized beams for Z-Fusion?

CP-violating HZZ coupling

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

$$\mathcal{L}_{eff} = c_{SM} Z_\mu Z^\mu H + \frac{c_{HZZ}}{v} Z_{\mu\nu} Z^{\mu\nu} H + \frac{\tilde{c}_{AZZ}}{v} Z_{\mu\nu} \tilde{Z}^{\mu\nu} H \tag{1}$$

To simplify the analysis, we ignore the CP-even term $Z_{\mu\nu} Z^{\mu\nu} H$.

At LHC: $H \longrightarrow 4\ell$

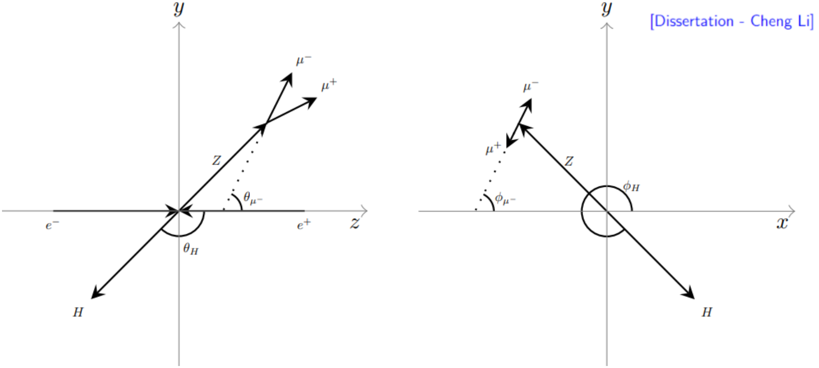
$$(\tilde{c}_{AZZ})_{CMS} \sim [-1.65, 0.63] \qquad \text{[CMS-HIG-17-034]} \tag{2}$$

$$(\tilde{c}_{AZZ})_{ATLAS} \sim [-1.2, 1.75] \qquad \text{[CERN-EP-2023-030]} \tag{3}$$

Higgs Strahlung

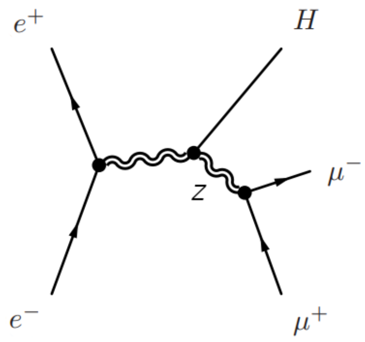
With transverse polarized beams, we can construct an observable sensitive to CP-Mixing [EPS-HEP 2023: Cheng Li]:

$$\mathcal{O}_{HS} \propto \eta_H \sin(2\phi_{\mu^-}) \propto [\vec{s}_{e^-} \cdot \vec{p}_{\mu^-}][(\vec{s}_{e^-} \times \vec{p}_{e^-}) \cdot \vec{p}_{\mu^-}][\vec{p}_{e^-} \cdot \vec{p}_H] \quad (4)$$



$\vec{s}_{e^-}$ is the direction of the transverse polarization of the e^- beam. In the Figure $\vec{s}_{e^-} \parallel \vec{e}_y$.

Higgs Strahlung



The initial polarization is carried by the Z boson and transferred to the $\mu^+\mu^-$ pair after it has passed the HZZ coupling. CP-Mixing now leads to an asymmetry in the azimuthal angle ϕ_{μ^-}.

Higgs Strahlung - Asymmetry

$$\mathcal{O}_{HS} \propto \eta_H \sin(2\phi_{\mu^-}) \tag{5}$$

We define the asymmetry:

$$\mathcal{A}_{HS} = \frac{N(\mathcal{O}_{HS} < 0) - N(\mathcal{O}_{HS} > 0)}{N_{tot}} \tag{6}$$

Statistical uncertainty of the asymmetry:

$$\Delta\mathcal{A}_{HS} = \sqrt{\frac{1 - \mathcal{A}_{HS}^2}{N_{tot}}} \tag{7}$$

For a CP-conserving result:

$$\mathcal{A}_{HS}(2000\ \text{fb}^{-1}, 250\ \text{GeV}) = (0 \pm 0.0078) \tag{8}$$

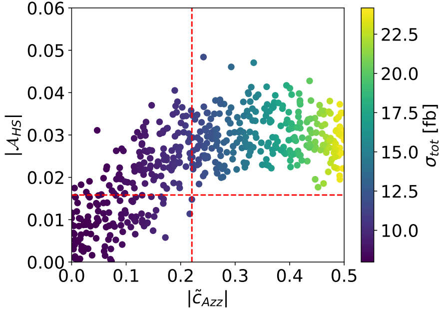
$$\mathcal{A}_{HS}(2000\ \text{fb}^{-1}, 300\ \text{GeV}) = (0 \pm 0.009) \tag{9}$$

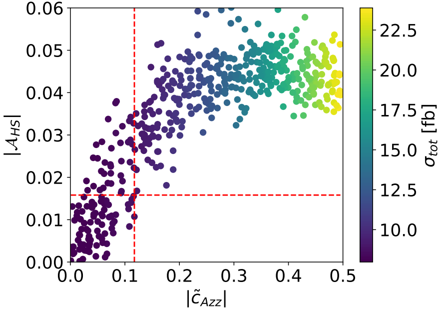
Higgs Strahlung - Monte Carlo simulation

Simulations were done with Whizard and the Modell: HC_NLO_X0.
We fix $c_{SM} = 1$ and vary $\tilde{c}_{AZZ}$ to look for the $|\tilde{c}_{AZZ}|$ value after which $|\mathcal{A}_{HS}|$ is above $2\Delta\mathcal{A}_{HS}$ for every point.

$L = 2000\ \text{fb}^{-1}$ $\sqrt{s} = 250$ GeV
$P^T_{e^-} = 80\%$ $P^T_{e^+} = 30\%$

$L = 2000\ \text{fb}^{-1}$ $\sqrt{s} = 250$ GeV
$P^T_{e^-} = 90\%$ $P^T_{e^+} = 40\%$



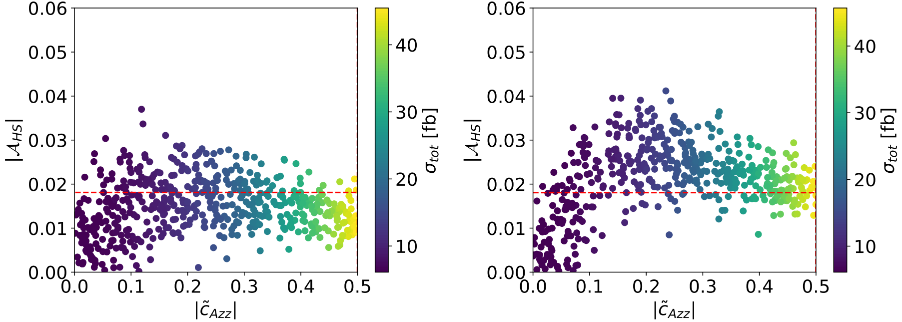


Higher polarization improves the determination of CP-odd coupling.

Higgs Strahlung - Monte Carlo simulation

$L = 2000\ \text{fb}^{-1}$ $\sqrt{s} = 300$ GeV $P^T_{e^-} = 80\%$ $P^T_{e^+} = 30\%$

$L = 2000\ \text{fb}^{-1}$ $\sqrt{s} = 300$ GeV $P^T_{e^-} = 90\%$ $P^T_{e^+} = 40\%$



At higher energies, it becomes difficult to determine the CP-odd coupling. This is probably a result of the decreasing cross-section.

Higgs Strahlung - Summary

We have defined an observable

$$\mathcal{O}_{HS} \propto \eta_H \sin(2\phi_{\mu^-}) \tag{10}$$

and used the asymmetry

$$\mathcal{A}_{HS} = \frac{N(\mathcal{O}_{HS} < 0) - N(\mathcal{O}_{HS} > 0)}{N_{tot}} \tag{11}$$

to detirmen the $|\tilde{c}_{AZZ}|$ limit, for which CP-mixing is detectable.

$(P^T_{e^-}, P^T_{e^+})$	$\sqrt{s}$	$\lvert\tilde{c}_{AZZ}\rvert$ limit
(80%,30%)	250 GeV	< 0.22
(90%,40%)	250 GeV	< 0.12
(80%,30%)	300 GeV	-
(90%,40%)	300 GeV	-

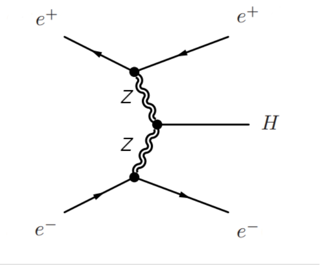
Z-Fusion

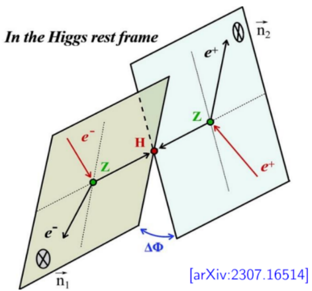
Looking at Z-Fusion, we can construct an observable that only uses longitudinal polarization [arXiv:2307.16514].

$$\mathcal{O}_{ZF} = \Delta\Phi = sgn(\sin(\Delta\Phi)) \cdot \arccos(\cos(\Delta\Phi)) \quad (12)$$

$$\cos(\Delta\Phi) = -\vec{n}_1 \cdot \vec{n}_2 \qquad sgn(\sin(\Delta\Phi)) = \frac{\vec{q}_Z \cdot (\vec{n}_1 \times \vec{n}_2)}{|\vec{q}_Z \cdot (\vec{n}_1 \times \vec{n}_2)|} \quad (13)$$

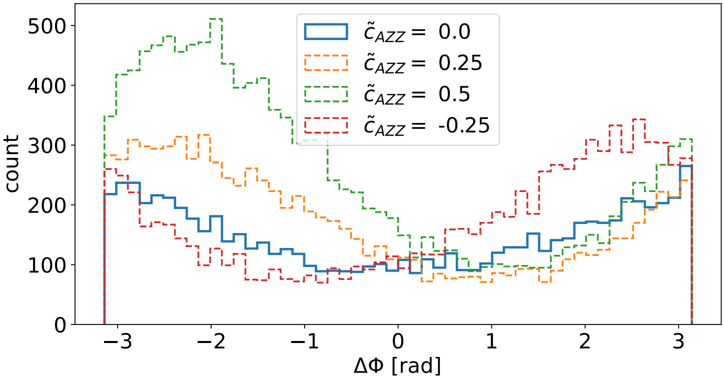
$$\vec{n}_1 = \frac{\vec{q}_{e_i^-} \times \vec{q}_{e_f^-}}{|\vec{q}_{e_i^-} \times \vec{q}_{e_f^-}|} \qquad \vec{n}_2 = \frac{\vec{q}_{e_i^+} \times \vec{q}_{e_f^+}}{|\vec{q}_{e_i^+} \times \vec{q}_{e_f^+}|} \quad (14)$$





Z-Fusion - Histogram of $\mathcal{O}_{ZF}$

The Histogram of $\mathcal{O}_{ZF}$ shows, that for $\tilde{c}_{AZZ} \neq 0$ the minimum of the distribution moves off center.



The magnitude of the offset depends on the magnitude of $\tilde{c}_{AZZ}$.

Z-Fusion - Asymmetry

Using the previous observation, we define the asymmetry

$$\mathcal{A}_{ZF} = \frac{N(\mathcal{O}_{ZF} < 0) - N(\mathcal{O}_{ZF} > 0)}{N_{tot}} \tag{15}$$

Statistical uncertainty:

$$\Delta\mathcal{A}_{ZF} = \sqrt{\frac{1 - \mathcal{A}_{ZF}^2}{N_{tot}}} \tag{16}$$

For a CP-conserving result[1]:

$$\mathcal{A}_{ZF}(2000 \text{ fb}^{-1}, 250 \text{ GeV}) = (0 \pm 0.026) \tag{17}$$

$$\mathcal{A}_{ZF}(2000 \text{ fb}^{-1}, 300 \text{ GeV}) = (0 \pm 0.018) \tag{18}$$

[1]For $P^L_{e^-} = P^L_{e^+} = 0$. Changes due to polarization have to be taken into account.

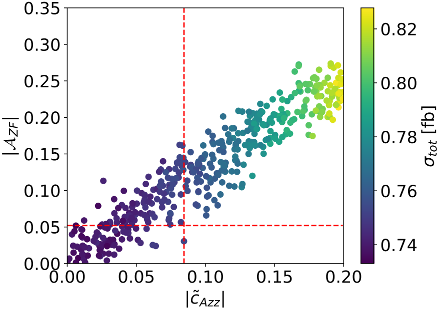
Z-Fusion - Monte Carlo simulation

$$\mathcal{L}_{eff} = c_{SM} Z_\mu Z^\mu H + \frac{c_{HZZ}}{v} Z_{\mu\nu} Z^{\mu\nu} H + \frac{\tilde{c}_{AZZ}}{v} Z_{\mu\nu} \tilde{Z}^{\mu\nu} H \qquad (19)$$

We fix $c_{SM} = 1$ and vary $\tilde{c}_{AZZ}$.

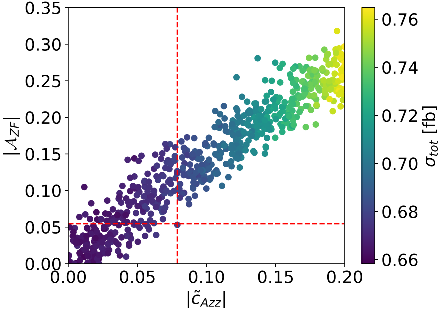
$L = 2000\ \text{fb}^{-1}$ $\quad \sqrt{s} = 250$ GeV

$P^L_{e^-} = 0\%$ $\quad P^L_{e^+} = 0\%$



$L = 2000\ \text{fb}^{-1}$ $\quad \sqrt{s} = 250$ GeV

$P^L_{e^-} = 80\%$ $\quad P^L_{e^+} = 30\%$



The polarization slightly improves the determination of the $|\tilde{c}_{AZZ}|$ limit.

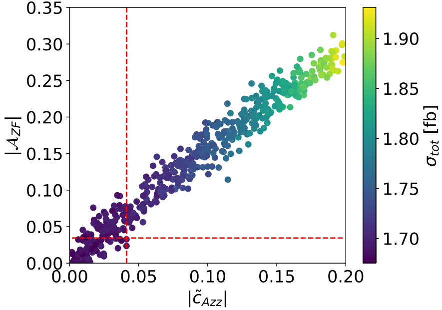
Z-Fusion - Monte Carlo simulation

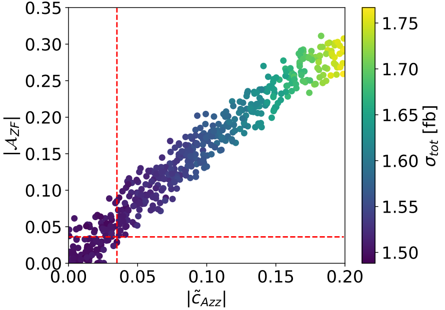
$L = 2000\ \text{fb}^{-1}$ $\sqrt{s} = 300\ \text{GeV}$

$P^L_{e^-} = 0\%$ $P^L_{e^+} = 0\%$

$L = 2000\ \text{fb}^{-1}$ $\sqrt{s} = 300\ \text{GeV}$

$P_{e^-} = 80\%$ $P_{e^+} = 30\%$





The higher energy improves the determination of the $|\tilde{c}_{AZZ}|$ limit.

Z-Fusion - Summary

Similar to Higgs Strahlung, we defined an observable

$$\mathcal{O}_{ZF} = \Delta\Phi = sgn(\sin(\Delta\Phi)) \cdot \arccos(\cos(\Delta\Phi)) \tag{20}$$

and an asymmetry

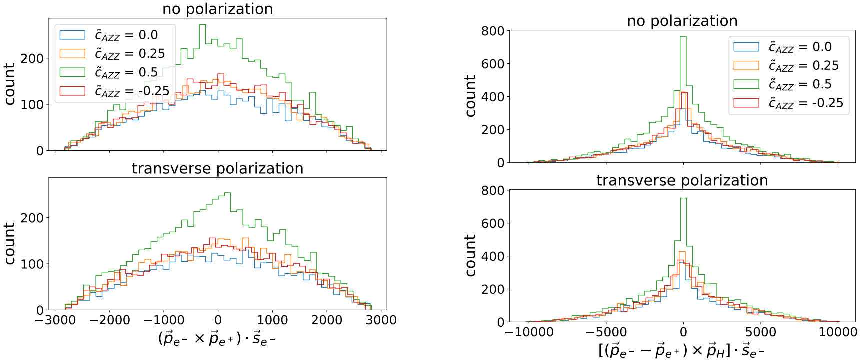
$$\mathcal{A}_{ZF} = \frac{N(\mathcal{O}_{ZF} < 0) - N(\mathcal{O}_{ZF} > 0)}{N_{tot}} \tag{21}$$

to detirmen the $|\tilde{c}_{AZZ}|$ limit, for which CP-mixing is detectable.

$(P^L_{e^-}, P^L_{e^+})$	$\sqrt{s}$	$\|\tilde{c}_{AZZ}\|$ limit
(0%,0%)	250 GeV	< 0.084
(80%,30%)	250 GeV	< 0.079
(0%,0%)	300 GeV	< 0.041
(80%,30%)	300 GeV	< 0.035

Z-Fusion - Transverse polarization

Constructing an observable dependent on transverse polarized beams (like for Higgs Strahlung) to detect the CP-Mixing yielded no result.

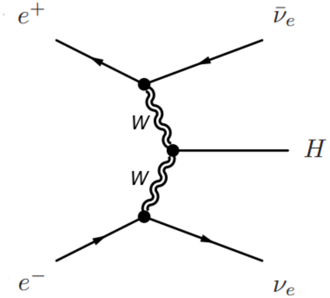


Possible explanation: the spin information is not transferred by the virtual Z bosons. Hence, initial transverse polarization is unable to probe the CP-violation of the *HZZ* coupling.

Analytical analysis is needed.

W-Fusion

W-Fusion has neutrinos in the final state. Since our previous considerations are dependent on the final state momenta, this makes our analysis impossible to fit onto W-Fusion.



Only the Higgs decay products could be used for detecting CP-Mixing.

Summary

Higgs Strahlung
(transverse polarization)

$(P^T_{e^-}, P^T_{e^+})$	$\sqrt{s}$	$\lvert\tilde{c}_{AZZ}\rvert$ limit
(80%,30%)	250 GeV	< 0.22
(90%,40%)	250 GeV	< 0.12
(80%,30%)	300 GeV	-
(90%,40%)	300 GeV	-

Z-Fusion
(longitudinal polarization)

(P_{e^-}, P_{e^+})	$\sqrt{s}$	$\lvert\tilde{c}_{AZZ}\rvert$ limit
(0%,0%)	250 GeV	< 0.084
(80%,30%)	250 GeV	< 0.079
(0%,0%)	300 GeV	< 0.041
(80%,30%)	300 GeV	< 0.035

We have two asymmetries to test at the future collider.
Both, for Higgs Strahlung and Z-Fusion, we are able to improve the $|\tilde{c}_{AZZ}|$ limit compared to the experimentally determined range of $\tilde{c}_{AZZ}$ at LHC:

$$(\tilde{c}_{AZZ})_{CMS} \sim [-1.65, 0.63] \qquad \text{[CMS-HIG-17-034]} \qquad (22)$$

$$(\tilde{c}_{AZZ})_{ATLAS} \sim [-1.2, 1.75] \qquad \text{[CERN-EP-2023-030]} \qquad (23)$$

Outlook

- Analytical analysis of Z-Fusion with transverse polarized beams.
  - could confirm our hypothesis
  - could yield another observable to detect CP-Mixing
  - (consistency check for Whizard)
- The CP-even operator $Z_{\mu\nu}Z^{\mu\nu}H$ can be included.
- The Z-Fusion analysis can be done for a constant σ_{tot}.