CPV in $e^+e^-H$ at 1 TeV ILC

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Introduction

- Experimentally observed size of the CP violation (CPV) is insufficient to explain the baryon asymmetry of the Universe → search for new sources of the CPV beyond the SM is necessary
- Higgs boson is the only fundamental scalar discovered, related to quite a few unknowns (mass stabilization – hierarchy problem, contribution to the energy density of the Universe, connection to the dark matter and gravity, etc.)
- It is conceivable that new sources of CPV may be introduced in an extended Higgs sector.

- ILC precision to measure the CPV mixing angle (\( \psi_{CP} \)) between the Higgs scalar and pseudoscalar states seems to be the most promising in the fermionic \( H \rightarrow \tau \tau \) decay at 250 GeV (Table 1, JHEP 2020, 139 (2020)) – see D. Jeans talk
- Other possibilities (i.e. HVV vertices) are worth exploiting as well as the other center-of-mass energies offered by the ILC staged physics programme
- Here we report on the status of the on-going CPV analysis in the eeH production at 1 TeV ILC

<table>
<thead>
<tr>
<th>Collider</th>
<th>( \psi_{CP} )</th>
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<tbody>
<tr>
<td>HL-LHC</td>
<td>8°</td>
</tr>
<tr>
<td>HE-LHC</td>
<td>–</td>
</tr>
<tr>
<td>CEPC</td>
<td>–</td>
</tr>
<tr>
<td>FCC-ee(_{240})</td>
<td>10°</td>
</tr>
<tr>
<td>ILC(_{250})</td>
<td>4°</td>
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ILC & ILD

The International Linear Collider (ILC) is a high-luminosity linear $e^+e^-$ collider with center-of-mass-energy range of 250 - 500 GeV (extendable to 1 TeV) aimed for precision studies in the Higgs sector operating as a Higgs factory, detecting new physics phenomena in a direct or indirect way. It is designed to achieve a luminosity of $1.35 \cdot 10^{34}$ cm$^{-2}$s$^{-1}$ and provide an integrated luminosity of 400 fb$^{-1}$ in the first four years of running (2 ab$^{-1}$ in a little over a decade).

- The electron beam will be polarized to 80%, and the baseline plan includes an undulator-based positron source which will deliver 30% positron polarization.
- The well-defined collision energy at the ILC, highly polarized beams and low background levels, will enable these precision measurements.

- Excellent track momentum resolution: $\delta(1/p) = 2 \times 10^{-5}$ GeV$^{-1}$
- Very powerful vertex detectors: $\delta(SV) < 4 \mu$m
- Jet energy resolution: $\sigma_{E_{\text{jet}}} < 3.5$ % over 100 GeV
- Lepton (electron and muon) identification efficiency: above 99 %
- Good hermeticity down to $\cos(\theta) \approx 0.984$
SM-like Higgs boson as a CPV mixture of CP even and odd states

• SM-like Higgs boson could be a mixture of scalar ($H$) and pseudo-scalar state ($A$):

$$h = H \cdot \cos \psi + A \cdot \sin \psi$$

• Correlation between spin orientations of $VV$ carries information on the Higgs CP state

• Numerous Higgs production processes at linear machines can be exploited ($hZ$, $WW$-fusion, $ZZ$-fusion) at various c.m. energies

• Both Higgs production and decays can be studied
Ways to probe HVV vertices (V=Z, W) in Higgs production and decays

- hVV vertex (CPV at a loop level):
  \[ \mathcal{L}_{VHV} \sim M_Z^2 \left( \frac{1}{\sqrt{s}} + \frac{a_V}{\Lambda} \right) Z_\mu Z^\mu h + \left( \frac{b_V}{2\Lambda} \right) Z_{\mu\nu} Z^{\mu\nu} h + \left( \frac{\tilde{b}_V}{2\Lambda} \right) Z_{\mu\nu} \tilde{Z}^{\mu\nu} h \]

- hff vertex (CPV at a tree level):
  \[ \mathcal{L}_{fHF} \sim g f \left( \cos \psi_{CP} + i \gamma^5 \sin \psi_{CP} \right) h \]

- Suppressed effect in VV-fusion w.r.t. (i.e.) Higgs to \( \tau\tau \) decay, but relatively high statistics available (~27000 inclusively produced Higgs bosons in ZZ-fusion in 1 ab\(^{-1}\) at 1 TeV ILC, however approximately half in the central tracker)
Ways to probe HVV vertices (V=Z, W) in Higgs production and decays

- Information on spin orientations of $VV$ states is contained in the angle $\phi$ between production (decay) planes.

- Angle between planes is the angle between unit vectors orthogonal to those planes:

  $$\hat{n}_1 = \frac{q_e^- \times q_{e^-}}{|q_e^- \times q_{e^-}|} \quad \text{and} \quad \hat{n}_2 = \frac{q_e^+ \times q_{e^+}}{|q_e^+ \times q_{e^+}|}$$  

- There is more than one way (convention) to define $n_1$ and $n_2$ from 3 vectors forming the planes (1st plane: initial electron, final electron, $Z_{e^-}$; 2nd plane: initial positron, final positron, $Z_{e^+}$).

- Orientation of $n_1$ and $n_2$ could be in the same hemisphere (angle between $n_1$ and $n_2$ smaller than 180 deg.) or in the opposite (angle between $n_1$ and $n_2$ larger than 180 deg.).
• Since vectors $n_1$ and $n_2$ have the same direction, the angle between planes can be retrieved through the arccos function as:

$$\phi = a \arccos(\pm \mathbf{n}_1 \cdot \mathbf{n}_2)$$

• Sign $\pm$ retain natural domain of arccos function (which has a feature of returning angles from I and II quadrants also for angles larger than 180 deg.)

• $a$ defines how the second (positron) plane is rotated w.r.t. the first (electron) plane; if it falls backwards (as illustrated) $a=-1$, otherwise $a=1$. Direction of $Z$ in the $e^-$ plane regulates the notion of direction (fwd. or back.) by the right hand rule

$$a = \frac{q_{Z e^-} \cdot (\mathbf{n}_1 \times \mathbf{n}_2)}{|q_{Z e^-} \cdot (\mathbf{n}_1 \times \mathbf{n}_2)|}$$

Higgs production in ZZ-fusion
Examples of $\phi$ distributions

- We are correctly reproducing $\phi$ distributions at the generator level both for $hVV$ production and decay vertices ($V = Z, W$).
- All distributions are obtained for $\psi_{CP} = 0$

S. Bolognesi et al.,
On the spin and parity of a single produced resonance at the LHC,
arXiv:1208.4018 [hep-ph] for Higgs to ZZ* and WW* decays

<table>
<thead>
<tr>
<th>$J_{m}^{+}$ (red circles), $J_{h}^{+}$ (green squares), $J_{h}^{-}$ (blue diamonds)</th>
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</thead>
<tbody>
<tr>
<td><strong>scenario</strong></td>
</tr>
<tr>
<td>$0^{0}_{h}$</td>
</tr>
<tr>
<td>$0^{+}_{h}$</td>
</tr>
<tr>
<td>$0^{-}$</td>
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Method of the $\psi_{CP}$ measurement

- Consider $H \rightarrow bb$ and $H \rightarrow WW \rightarrow 4$ jets decays
  1. Cover most of the Higgs width ($\sim 80\%$)
  2. Avoid high cross-section $e^+e^- \rightarrow e^+e^-\gamma$ background present in inclusive reconstruction
  3. Combine results
- Select ZZ-fusion (signal is mixed with $HZ$) using $m(e^+e^-)$
- Isolate 2 leptons ($e^+e^-$)
- Reconstruct $\phi$
- Suppress background with MVA
- Describe $\phi$ of the signal and background with PDFs
- Reconstruct $\phi$ of the signal from pseudo-data ($S + B$)
- Fit $\psi_{CP}$ from the $\phi$ distribution
- Repeat pseudo experiments
- Combine channels
Higgs production in ZZ-fusion

- WHIZARD v1.95, 500GeV/0.5 ab⁻¹, 1 TeV/ 1 ab⁻¹, 1.4 TeV/1 ab⁻¹, unpolarized
- t-channel process, electrons (spectators) are scattered forward - not full statistics available in the tracker
- Due to this fact 1 TeV is the optimal energy for this study (already at i.e. 1.4 TeV the number of events with both electron is the tracker is ~1/5 of the available statistics). At 500 GeV i.e. x-section for ZZ fusion is relatively small (7.2 fb) and number of events in the tracker is order of magnitude smaller than at 1 TeV
- Around $7 \times 10^3$ eeh events with both e+ and e- in the tracker in 1 ab⁻¹ at 1 TeV ILC with (-0.8, +0.3) polarized beams
Preselection

• ILC samples at 1 TeV, assuming $\mathcal{L} = 1 \text{ ab}^{-1}$, generated with LR polarization (-1, 1) are normalized to polarization (-0.8, +0.3):

$$W_{\text{pol}} = \left(\frac{1 - P_{e+}}{2}\right) \cdot \left(\frac{1 + P_{e+}}{2}\right) = \left(\frac{1 - (-0.8)}{2}\right) \cdot \left(\frac{1 + 0.3}{2}\right) = 0.585$$

• Preselection: find 2 isolated electrons ($e^+ e^-$)

• Goal: find electrons spectators from ZZ-fusion and reduce high cross-section backgrounds

• Requirements:
  • Track energy: $E_{\text{track}} > 100 \text{ GeV}$ – spectators are energetic (3.3% loss)
  • Impact parameter: $d_0 < 0.1, z_0 < 1.0$
  • Ratio of deposition: $R_{\text{cal}} > 0.95$
  • Optimize cone vs. track energy
Isolation curve: $E_{\text{cone}}^2 < 40 E_{\text{track}} \text{ GeV} - 20 \text{ GeV}^2$
### Signal and background preselection efficiencies

<table>
<thead>
<tr>
<th>1 TeV/1 ab(^{-1}) /pol(−80%, +30%)</th>
<th>Sample</th>
<th>(\sigma) [fb]</th>
<th>Input</th>
<th>Output</th>
<th>Efficiency [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Signal:</strong> (e^+e^- \rightarrow e^+e^- H(H \rightarrow b\bar{b}))</td>
<td>15.1</td>
<td>(N_{\text{true}} = 1121^*) (N_{\text{norm}} = 3600)</td>
<td>(N_{\text{true}} = 875^*) (N_{\text{norm}} = 2800)</td>
<td>78 %</td>
<td></td>
</tr>
<tr>
<td><strong>Background samples:</strong> (e^-e^+ \rightarrow e^-e^+ q\bar{q}^{**} )</td>
<td>2577.3</td>
<td>(N_{\text{ev norm}} = 226160)</td>
<td>(N_{\text{true}} = 1447) (N_{\text{ev norm}} = 5470)</td>
<td>2.42 %</td>
<td></td>
</tr>
<tr>
<td>(e^-e^+ \rightarrow evqq^{***} )</td>
<td>8963.3</td>
<td>(N_{\text{ev norm}} = 1730000)</td>
<td>(N_{\text{true}} = 428) (N_{\text{ev norm}} = 346)</td>
<td>0.02 %</td>
<td></td>
</tr>
<tr>
<td>(e^-e^+ \rightarrow q\bar{q}^{**} )</td>
<td>9375.3</td>
<td>(N_{\text{ev norm}} = 877528)</td>
<td>(N_{\text{ev norm}} = 4)</td>
<td>0.0046 %</td>
<td></td>
</tr>
<tr>
<td>(\gamma\gamma \rightarrow q\bar{q}q\bar{q} )</td>
<td>126.0</td>
<td>(N_{\text{ev norm}} = 73835)</td>
<td>(N_{\text{true}} = 282) (N_{\text{ev norm}} = 930)</td>
<td>1.26 %</td>
<td></td>
</tr>
<tr>
<td>(\gamma\gamma \rightarrow e^-e^+ q\bar{q} )</td>
<td>3.1</td>
<td>(N_{\text{ev norm}} = 1817)</td>
<td>(N_{\text{ev norm}} = 5)</td>
<td>0.25 %</td>
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* Small current sample size, ** q=b, *** q=b,c

B:S=2.5:1
Reconstructed CPV observable for signal and background

After preselection
MVA selection

• MVA is trained with 14 sensitive variables: $p_{e^-}, p_{e^+}, E_{e^-}, E_{e^+}, p_T(e^-e^-), p_T(e^+e^+), p_T(q_1), p_T(q_2), E_{q_1}, E_{q_2}, m_H, E_H, p_T(H), p_T^{\text{miss}}$
• Three the most sensitive observables are: $m_H, E_{e^-}$ and $E_{e^+}$
• Best significance $\sim 42$ for $\text{BDT} > 0.013$ (training)
• BDT efficiency $\sim 70\%$, $B:S = 1:2.6$
• Approximately $\frac{1}{4}$ of the available signal statistics analyzed
After MVA

- MVA reverses background to signal ratio to 1:2.6
- Shapes maintained, yet large signal fluctuations
- Additional signal samples will be added
Summary

• Only few results of the CPV Higgs mixing angle measurements are available from the future projects. Primarily in the (more sensitive) Higgs fermionic decays and at lower center-of-mass energies.

• 1 TeV ILC offers optimal statistics (cross-section – pseudorapidity interplay) to probe CPV also in the HVV vertices.

• Sensitive angle \( \phi \) between Higgs production planes is reconstructed in ZZ-fusion with the expected behavior for \( \psi_{CP}=0 \). Polarized data samples are fully simulated with \( 1 \text{ ab}^{-1} \) (0.2 \( \text{ab}^{-1} \)) of integrated luminosity for background (signal). Result will be further improved since only \( \frac{1}{4} \) of available signal statistics is used.

• Background \( \phi \) distribution is CPV insensitive and it is effectively suppressed with the staged event selection.

• Further improvements are on the way (additional MVA observables, combination of results from samples with different polarization schemes).
Higgs decays: $H \rightarrow WW^*$ and $H \rightarrow ZZ^*$

- Unit vectors orthogonal to decay planes (one possible definition):
  $$\hat{n}_1 = \frac{q_f(V) \times q_f(V)}{|q_f(V) \times q_f(V)|} \quad \text{and} \quad \hat{n}_2 = \frac{q_f(V^*) \times q_f(V^*)}{|q_f(V^*) \times q_f(V^*)|}$$

- $n_1$ and $n_2$ are now in ‘the opposite’ directions, to preserve correct arcos output (in the range 0-180 deg.) define $\phi$ as:
  $$\phi = a \arccos(-\hat{n}_1 \cdot \hat{n}_2)$$

  where $a$ defines how the second (off-shell boson $V^*$) plane is rotated w.r.t. the first (on-shell boson) plane; If it falls backwards (as illustrated) $a = -1$, otherwise $a = 1$. Direction of the on-shell boson ($V$) regulates the notion of direction (fwd. or back.)

- $$a = \frac{q_V \cdot (\hat{n}_1 \times \hat{n}_2)}{|q_V \cdot (\hat{n}_1 \times \hat{n}_2)|}$$

- It is essential to distinguish between fermion and antifermion (jet-charge)
• Examples of possible definitions of $n_1$ and $n_2$ in ZZ-fusion:

1. $\phi_1 = \arccos(\hat{n}_1 \cdot \hat{n}_2)$ where $\hat{n}_1 = \frac{q e^- \times q e^-}{|q e^- \times q e^-|}$ and $\hat{n}_2 = \frac{q e^+ \times q e^+}{|q e^+ \times q e^+|}$

2. $\phi_2 = \arccos(-\hat{n}_1 \cdot \hat{n}_2)$ where $\hat{n}_1 = \frac{q Z e^- \times q e^-}{|q Z e^- \times q e^-|}$ and $\hat{n}_2 = \frac{q Z e^+ \times q e^+}{|q Z e^+ \times q e^+|}$

3. $\phi_3 = \arccos(\hat{n}_1 \cdot \hat{n}_2)$ where $\hat{n}_1 = \frac{q Z e^- \times q e^-}{|q Z e^- \times q e^-|}$ and $\hat{n}_2 = \frac{q Z e^+ \times q e^+}{|q Z e^+ \times q e^+|}$

• No matter how we define a unit vector orthogonal to a production (decay) plane, consistently defined $\phi$ leads to the same results (in production and decay).