CP Violation

- Experimentally observed size of CP violation (CPV) is insufficient to explain the baryon asymmetry of the Universe, thus a search for new sources of the CPV beyond the SM to explain this phenomenon 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.) and it is conceivable that new sources of CPV may be introduced in an extended Higgs sector.
- Thus, one of the most important aspects of the Higgs boson interactions is its CP properties. Higgs HVV or HVH vertices may be modified in terms of CPV in the form of additional terms to the SM Lagrangian, describing the CPV effect at the loop (HVV) or at the tree level (Hf).
- SM-like Higgs boson can be a mixture of scalar (H) and pseudo-scalar state (A): $\mathcal{L}_{\text{HVV}} \sim M_t^2 \left( \lambda_{1V} + \lambda_{A1} Z \bar{Z}^* h + (\lambda_{12}^A / 2) Z \bar{Z}^* h + (\lambda_{12}^A / 2) Z \bar{Z}^* h \right)

How can we measure the CP effects in the Higgs sector and with what sensitivity?

- By measuring CP-sensitive couplings i.e. in the Effective Field Theory Framework, or by extracting information on the Higgs CP state from the correlation between spin orientations of vector bosons (fermions) either in the Higgs production or decay vertices.
- Projected sensitivities of the future projects to measure the CP mixing angle ($\phi_{HZZ}$) between the Higgs scalar and pseudoscalar states seems to be the most promising at ILC in the fermionic $H \rightarrow \tau\tau$ decay (Table 1, [1]).

Probing CP Violation at ILC

- Correlation between spin orientations of vector bosons (or fermions) can be extracted from the angle $\phi$ between production or decay planes.
- Numerous Higgs production processes available at ILC (ILC, WW, ZZ-fusion), at various center-of-mass energies offers plethora of possibilities for individual measurements and combinations. Both Higgs production and decays can be exploited.
- An example is given for the Higgs production in ZZ-fusion at 1 TeV ILC. It turns out that 1 TeV is the optimal energy for this particular study, with 500 GeV or 1.4 TeV center-of-mass energies, due to the interplay between pseudoscalar and the cross-section for the Higgs production in ZZ-fusion.

ILC Project

The International Linear Collider (ILC) is a high-luminosity linear $e^+ e^-$ collider with center-of-mass-energy range of 250 – 5000 GeV (extendable to 3 TeV) aimed for precision studies in the Higgs sector and Higgs factory, detecting new physics phenomena in a direct or indirect way. It is designed to achieve a luminosity of $1.35 \times 10^{35} \text{cm}^{-2} \text{s}^{-1}$ 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 20 % positron polarization. The fully defined collision energy at the ILC, highly polarized beams and low background levels, will enable these precision measurements.

Energy upgrades will allow the ILC to remain a powerful discovery vehicle for decades, bringing new processes into play, going along with the overall physics program of auxiliary detector, target and beam dump ILC experiments (ILC-X) [2].

ILC physics goals: ILC aims to significantly extend knowledge beyond the current limits of the Standard Model and to drive innovative technological developments through realization and upgrade of ILC accelerator, detectors and the ILCPHYS program. ILC physics searches in the Higgs sector - serving as a Higgs factory, EW and DM searches, extensive top and QCD physics program, set exciting and ambitious scientific goals that will drive technological and scientific exploration into new and uncharted territories. Realization of the ILC as a Higgs factory goes in line with the 2020 Update of the European Particle Physics Strategy [3].

Two detector concepts have been developed, ILD and SiD, general-purpose detectors designed to optimally address the ILC physics goals, operating in a push-pull configuration with the particle-flow technique that will play a central role in the event reconstruction requires highly granular calorimeters and excellent low-material budget tracking and vetting systems. The two concepts differ in the choice of the central tracker technology, where ILD is based on a gaseous central tracker (TPC), combined with silicon detectors inside and outside the TPC, while SiD relies on an all-silicon solution. ILC would aim for momentum resolution by making the detector larger, while SiD keeps the detector more compact and minimizes by using a higher central field (3.5 T at ILC versus 5 T at SiD).

Results

- Excellent track momentum resolution: $\Delta f(p) = 2 \times 10^{-4} \text{ GeV}$
- Jet energy resolution: $\sigma_{E_{\text{jet}}} < 3.5 \%$ over 100 GeV
- Lepton (electron and muon) identification efficiency: above 99 %
- Good hermiticity down to $\cos(\theta) = 0.984$

Table 1. CP violating terms

<table>
<thead>
<tr>
<th>Collider</th>
<th>$\phi_{CP}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILHMC</td>
<td>10°</td>
</tr>
<tr>
<td>HE-LHC</td>
<td>–</td>
</tr>
<tr>
<td>FCC-ep</td>
<td>10°</td>
</tr>
<tr>
<td>ILCPS</td>
<td>4°</td>
</tr>
</tbody>
</table>

References: