CP violation in the Higgs sector at ILC

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On behalf of the ILC International Development Team and Detector Working Group

CP Violation

- Experimentally observed size of the 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 are its CP properties. Higgs HVV or Hff 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 (Hff).
- SM-like Higgs boson could be a mixture of scalar (H) and pseudo-scalar state (A): $h = H \cdot \cos\psi_{CP} + A \cdot \sin\psi_{CP}$

$$\mathcal{L}_{VVH} \sim M_Z^2\,(1/v + a_V/\Lambda)\, Z_\mu Z^\mu h + (b_V/2\Lambda)\, Z_{\mu\nu} Z^{\mu\nu} h + (\tilde{b}_V/2\Lambda)\, Z_{\mu\nu} \tilde{Z}^{\mu\nu} h$$

VV CPV at loop level

ff CPV at tree level

CP-violating terms

$$\mathcal{L}_{ffH} \sim g\,\bar{f}\,(\cos\psi_{CP} + i\,\gamma^5 \sin\psi_{CP})\, f\, h$$

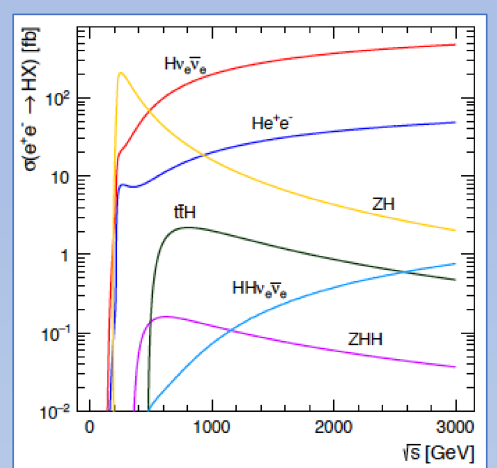
- How can we measure the CP effects in the Higgs sector and with what sensitivity?
- By measuring CP-sensitive couplings i.e. in the Effective Field Theory Framework, or by extracting information on the Higgs CP state from the correlation between spin orientations of vector bosons (fermions) either in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

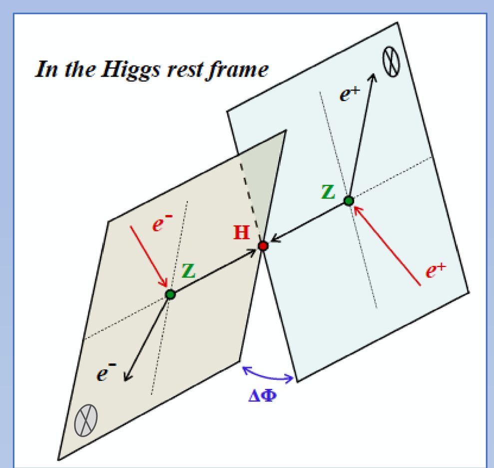
Table 1.

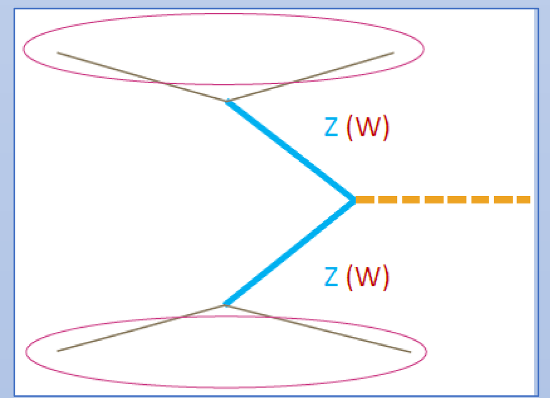
Collider	ψ_{CP}
HL-LHC	8°
HE-LHC	–
CEPC	–
FCC-ee$_{240}$	10°
ILC$_{250}$	4°

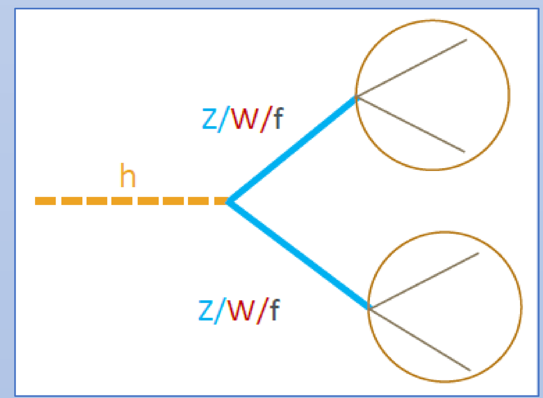
Probing CP Violation at ILC

- Correlation between spin orientations of vector bosons (or fermions) can be extracted from the angle ϕ between production or decay planes.
- Numerous Higgs production processes available at ILC (hZ, WW-fusion, 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, w.r.t. 500 GeV or 1.4 TeV center-of-mass energies, due to the interplay between pseudorapidity and the cross-section for the Higgs production in ZZ-fusion.









Inclusive Higgs boson production in ZZ boson fusion

- For the opposite orientation of the unit vectors orthogonal to the production planes, CP-sensitive angle between the planes can be defined as:

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

where the unit vectors are defined as:

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

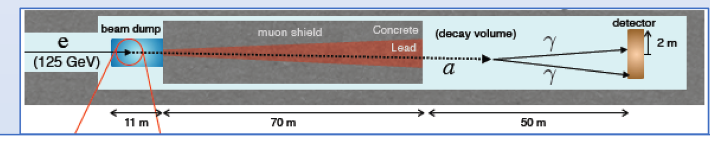
- Coefficient a defines how the second (positron) plane is rotated w.r.t. the first (electron) plane; If it falls backwards (as illustrated) $a = -1$, otherwise $a = 1$, and is defined as:

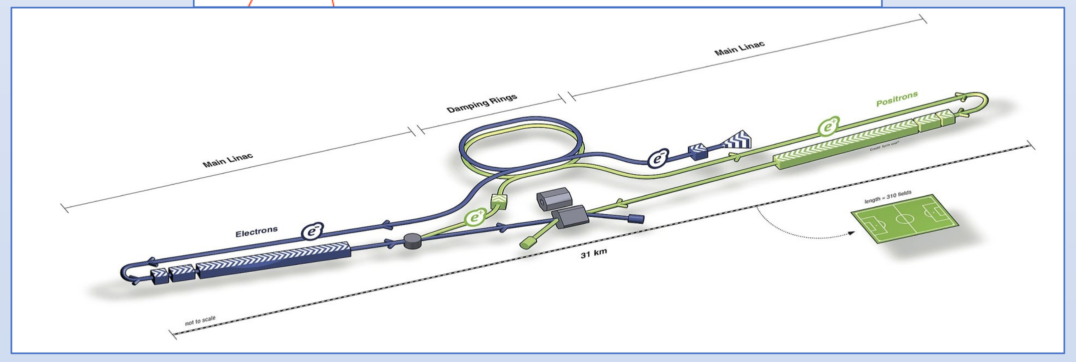
$$a = \frac{q_{Z_{e^-}} \cdot (\hat{n}_1 \times \hat{n}_2)}{|q_{Z_{e^-}} \cdot (\hat{n}_1 \times \hat{n}_2)|}$$

- Direction of Z boson in the e^- plane regulates the notion of forward and backward.

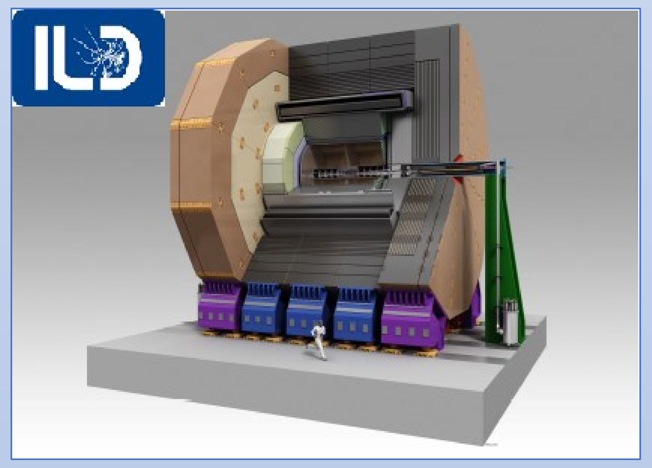
ILC Project

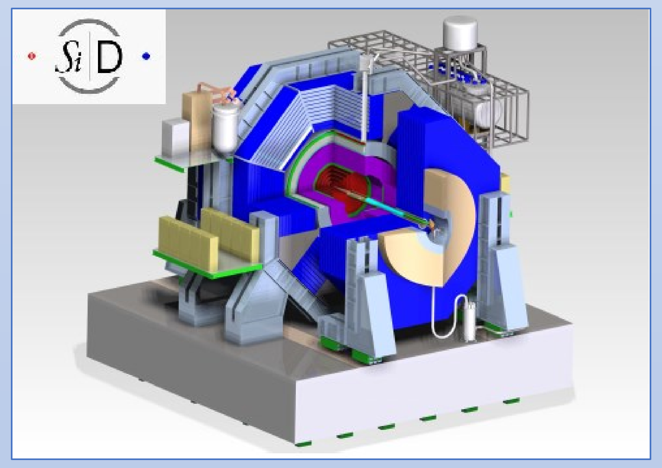
- The International Linear Collider (ILC) is a high-luminosity linear e^-e^+ collider with center-of-mass-energy range of 250 – 500 GeV (extendable to 1 TeV) aimed for precision studies in the Higgs sector operating as a Higgs factory, detecting new physics phenomena in a direct or indirect way. It is designed to achieve a luminosity of $1.35 \cdot 10^{34}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ 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.
- 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 dark sector, fixed-target and beam dump ILC eXperiments (ILCX) [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 ILCX physics 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 requiring highly granular calorimeters and excellent low material budget tracking and vertexing 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. ILD would aim for momentum resolution by making the detector large, while SiD keeps the detector more compact and compensates by using a higher central magnetic field (3.5 T at ILD versus 5 T at SiD) .



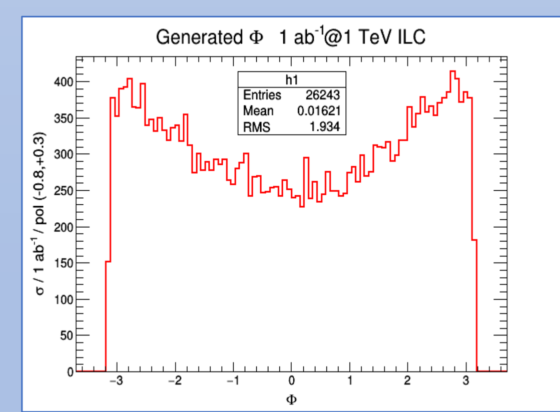


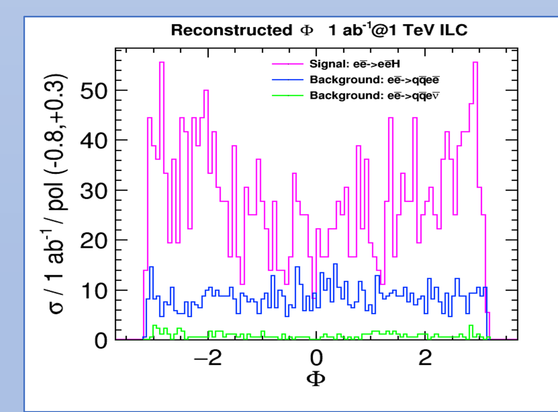
- Excellent track momentum resolution: $\delta(1/p) = 2 \times 10^{-5}\ \mathrm{GeV}^{-1}$
- Very powerful vertex detectors: $\delta(\mathrm{SV}) < 4\ \mu m$
- Jet energy resolution: $\sigma_{E,\mathrm{Jet}} < 3.5\ \%$ over 100 GeV
- Lepton (electron and muon) identification efficiency: above 99 %
- Good hermeticity down to $\cos(\theta) \approx 0.984$

Results

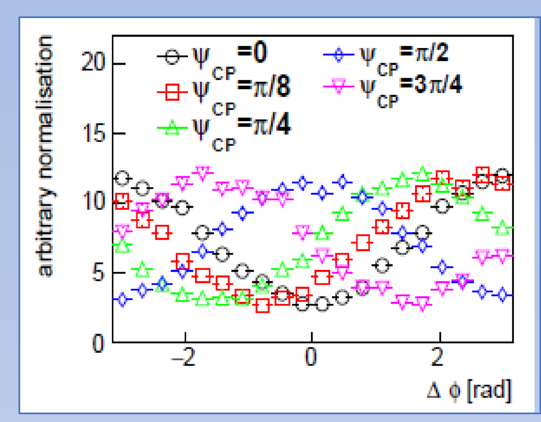
CP violation in ZZ boson fusion Higgs production at 1 TeV ILC

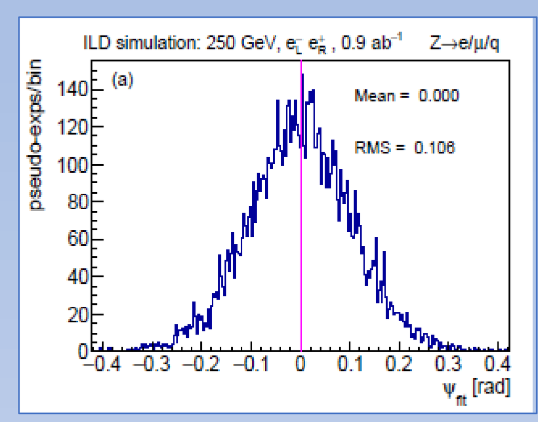
- Figures illustrates generated information on angle ϕ, in the full physical range of polar angles, expected with 1 ab^{-1} of integrated luminosity and $(-0.8, +0.3)$ beam polarization (left);
- On the right, reconstructed CP violating observable ϕ is given, in the central tracker acceptance, and for the exclusive $H \to b\bar{b}$ channel, against dominant backgrounds. Events are preselected with $\sim 80\ \%$ efficiency, to suppress high-cross section background processes. As expected, background distributions do not exhibit any structure;
- Analysis is ongoing aiming to estimate achievable precision on ψ_{CP} ($\psi_{CP} = 0$) from repeated pseudo-experiments reconstructing ϕ of the selected signal.
- The analysis is done with the fully simulated ILD detector for ILC.





CP violation in $H \to \tau^+\tau^-$ at 250 GeV ILC





- Higgs fermionic decay to $\tau^+\tau^-$ at 250 GeV center-of-mass-energy [4] provided excellent sensitivity of the ψ_{CP} measurement extracted from the shape of ϕ in repeated pseudo-experiments.
- Dependence of the φ distribution on various assumptions on the CP-mixing strength (ψ_{CP} value) is illustrated on the figure left.
- On the right, pull distribution for the generated $\psi_{CP} = 0$ mixing angle is illustrating the ILC precision on ψ_{CP} of order of a hundred of mrad. There is an ongoing analysis in the same channel, at 250 GeV center-of-mass energy with the SiD detector model [5].
- The analysis is done with the fully simulated ILD detector for ILC.

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