MEASURING THE CP PROPERTIES OF THE HIGGS SECTOR AT ELECTRON-POSITRON COLLIDERS

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on behalf of the ILD Concept Group

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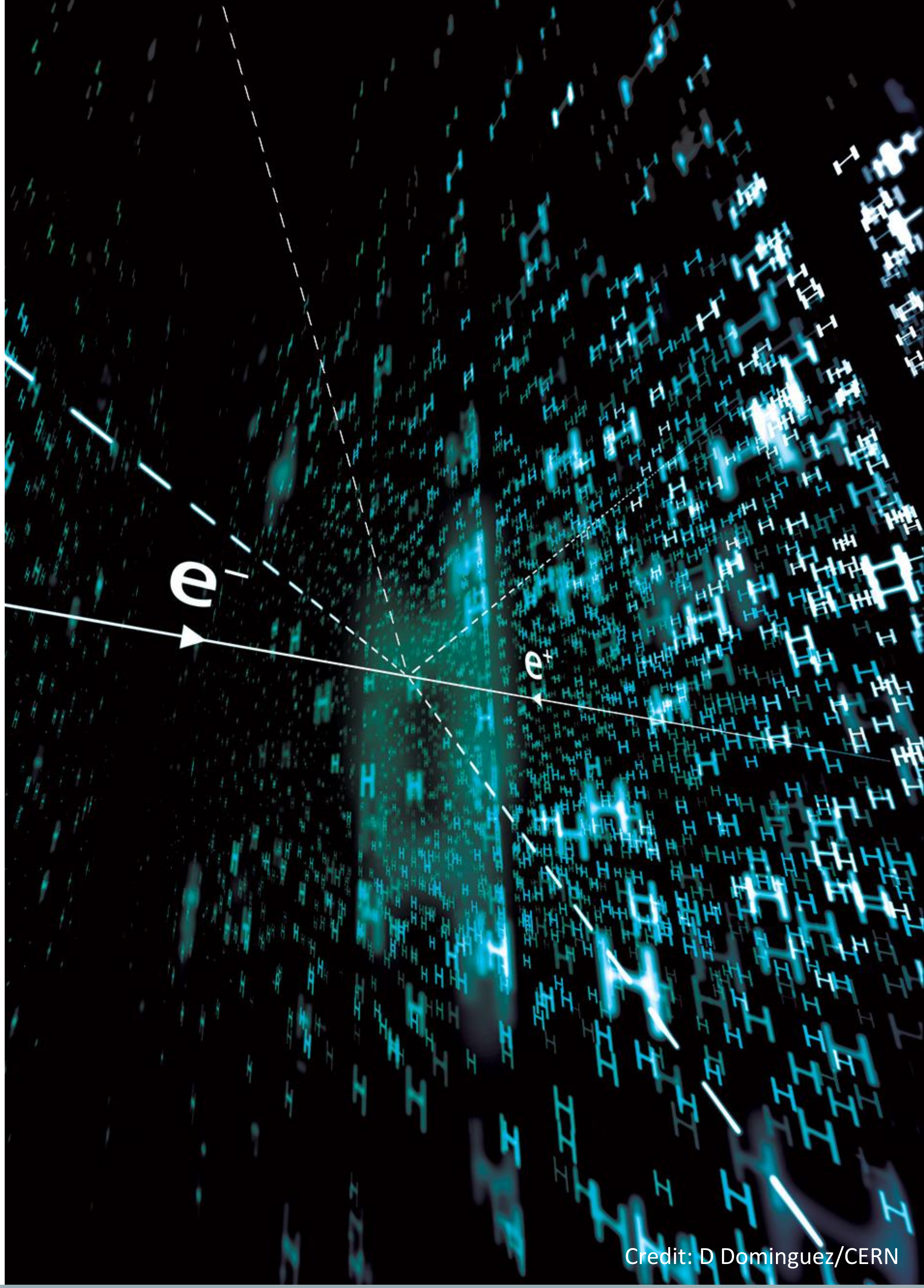
Credit: R Hori/KEK

OVERVIEW

- Motivation
- Ways to probe CP symmetry violation in the Higgs sector
- Current status of the study at the ILC
  - CPV in e^+e^-H (ZZ – fusion) at 1 TeV
- CPV in $H \to \tau^+\tau^-$ at 250 GeV ILC and other colliders
- Open questions – perspective of the study
- Summary



Credit: D Dominguez/CERN

MOTIVATION

TERRA INCOGNITA

CPV

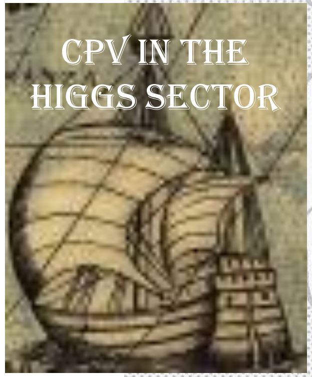
Necessary yet insufficient in the SM to explain baryon asymmetry of the Universe

Are they connected?

TERRA INCOGNITA

HIGGS

- Higgs mass – Hierarchy problem
- Higgs vacuum – energy of the Universe
- Higgs and DM – Higgs invisible decays
- Higgs and cosmic inflation – is Higgs the inflaton?



MOTIVATION

- CP symmetry violation (BSM physics) is required to explained baryogenesis
- CP symmetry violation provided in the SM (i.e. CKM matrix) is insufficient
- Could CP be violated in the Higgs sector?

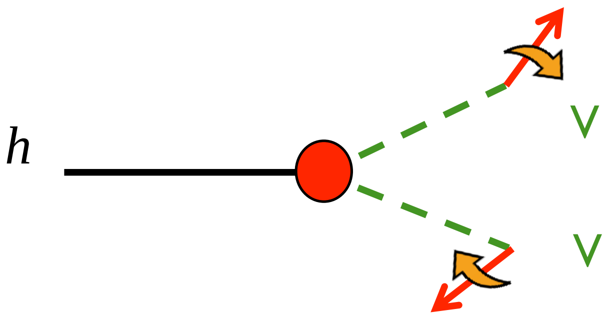
$$\mathscr{L}_{VVH} \sim M_Z^2 \left(1/v + a_V/\Lambda \right) Z_\mu Z^\mu h + \left(b_V/2\Lambda \right) Z_{\mu\nu} Z^{\mu\nu} h + \left(\tilde{b}_V/2\Lambda \right) Z_{\mu\nu} \tilde{Z}^{\mu\nu} h$$

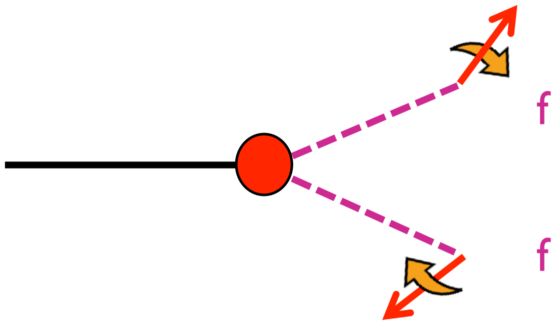
VV CPV at loop level

ff CPV at tree level

CP-violating terms

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



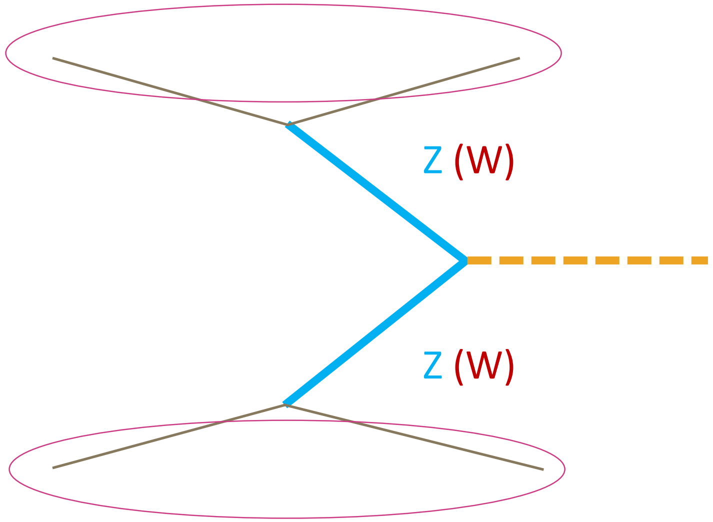


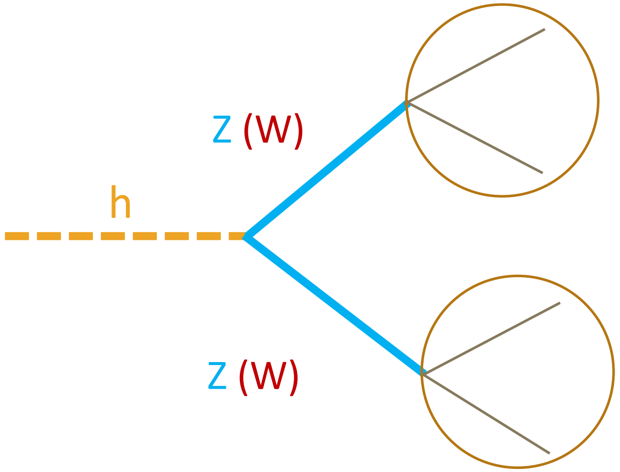
WAYS TO PROBE CPV IN THE HIGGS SECTOR

- 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 (or ff) carries information on the Higgs CP state
- Numerous Higgs production processes at linear machines (hZ, WW-fusion, ZZ-fusion) at various c.m. energies
- Both Higgs production and decays can be exploited



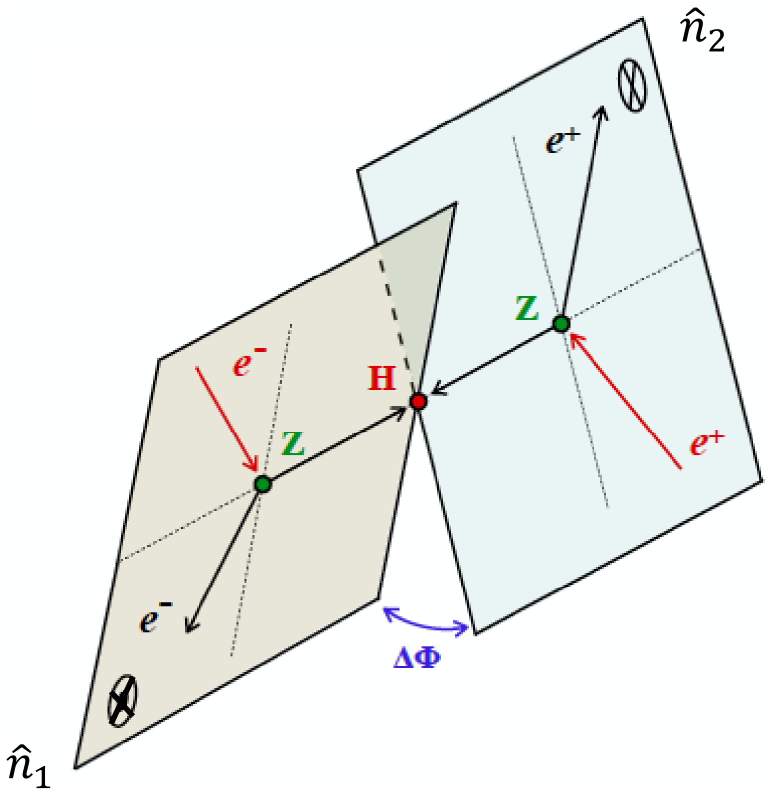


INCLUSIVE HIGGS PRODUCTION IN ZZ-FUSION

- Information on spin orientations of VV states is contained in the angle between production (decay) planes
- Angle between planes is angle between unit vectors orthogonal to those planes:

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

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

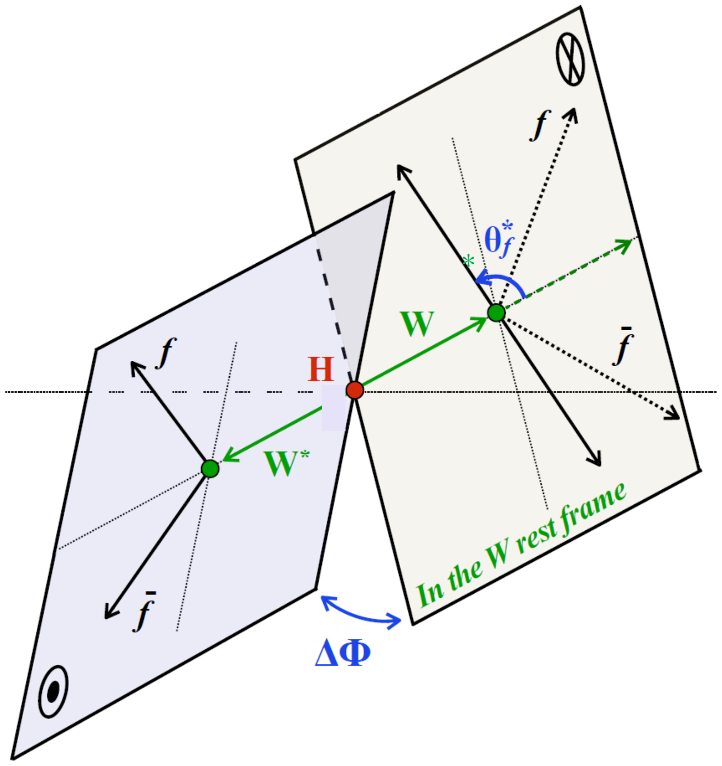


HIGGS DECAYS (AS A CROSS-CHECK): $H \to WW^*$ AND $H \to ZZ^*$

- Unit vectors orthogonal to decay planes are now opposite:

$$\hat{n}_1 = \frac{q_{f(V)} \times q_{\bar{f}(V)}}{\left|q_{f(V)} \times q_{\bar{f}(V)}\right|} \quad \text{and} \quad \hat{n}_2 = \frac{q_{f(V^*)} \times q_{\bar{f}(V^*)}}{\left|q_{f(V^*)} \times q_{\bar{f}(V^*)}\right|}$$

- $\phi = a \arccos(-\hat{n}_1 \cdot \hat{n}_2)$
- 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 in case of semileptonic ZZ decays)

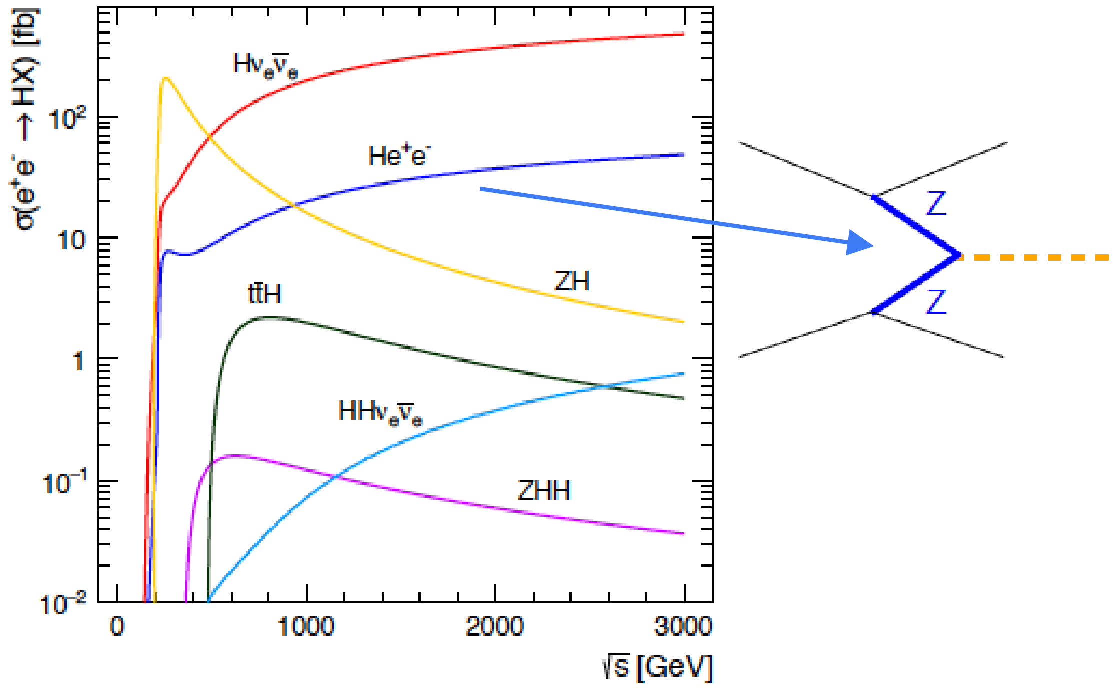


CURRENT STATUS OF THE CPV STUDIES AT ILC

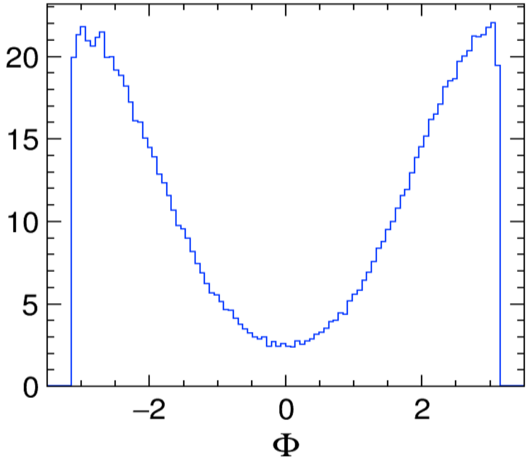
CPV in e^+e^-h (ZZ – fusion) at 1 TeV

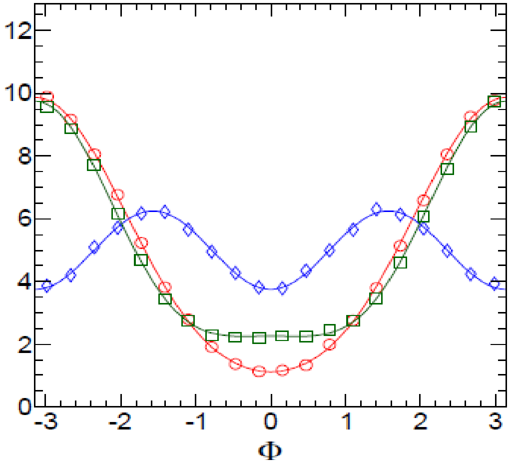
Method of the analysis:

- Definition of sensitive observable - ϕ ✓
- Event selection:
  - Preselection ✓
  - MVA analysis
- PDFs of the reconstructed CPV observable for signal and background
- Pseudo-experiment to extract CPV mixing angle from the reconstructed signal
- Multiple pseudo-experiments (with the fixed Higgs CPV mixing angle) to determine statistical uncertainty from the pull distribution



Φ DISTRIBUTIONS

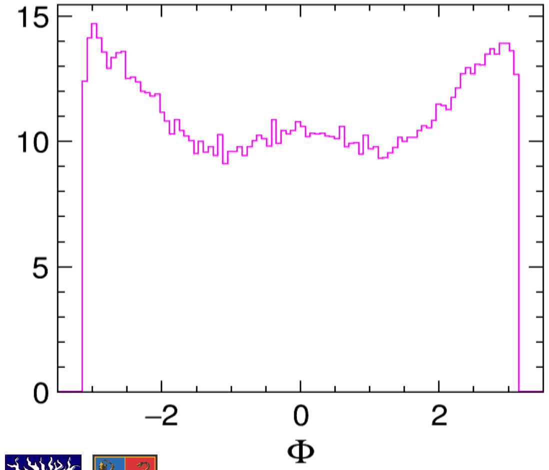


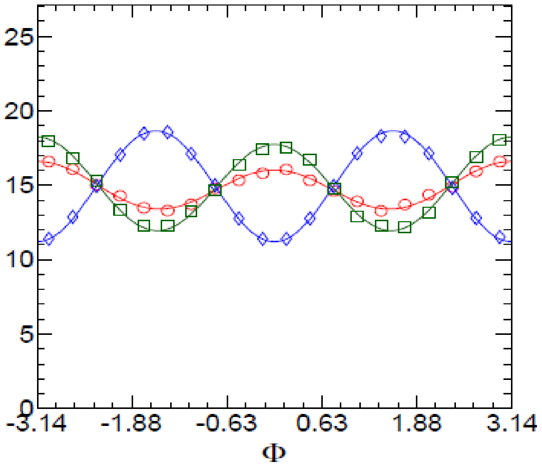


J_m^+ - red circles J_h^+ - green squares J_h^- - blue diamonds

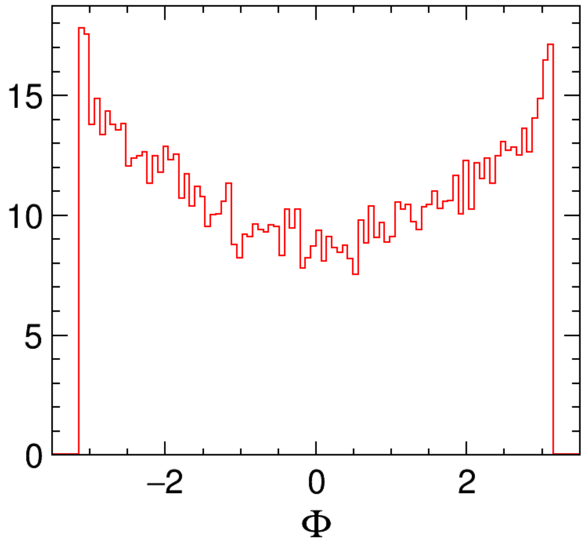
scenario	X production	$X \to VV$ decay	comments
0_m^+	$gg \to X$	$g_1^{(0)} \neq 0$ in Eq. (9)	SM Higgs boson scalar
0_h^+	$gg \to X$	$g_2^{(0)} \neq 0$ in Eq. (9)	scalar with higher-dimension operators
0^-	$gg \to X$	$g_4^{(0)} \neq 0$ in Eq. (9)	pseudo-scalar

We are correctly reproducing ϕ distributions at the generator level both for HVV decay vertices $(V = Z, W)$





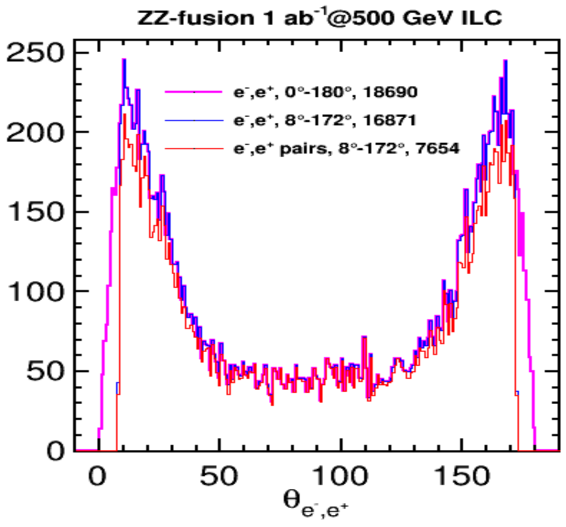
arXiv:1208.4018 [hep-ph]



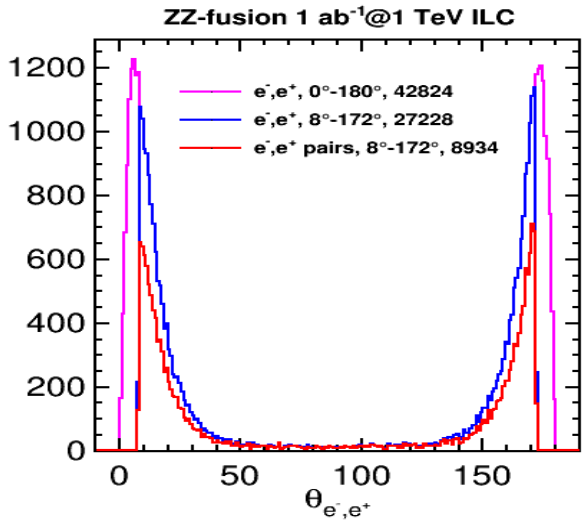
PRESELECTION - SAMPLES

- WHIZARD v3.0, $500\ \text{GeV}/\ 1\ \text{ab}^{-1}, 1\ \text{TeV}/\ 1\ \text{ab}^{-1}, 1.4\ \text{TeV}/\ 1\ \text{ab}^{-1}$
- t-channel process, electrons (spectators) are scattered forward - not full statistics available in the tracker

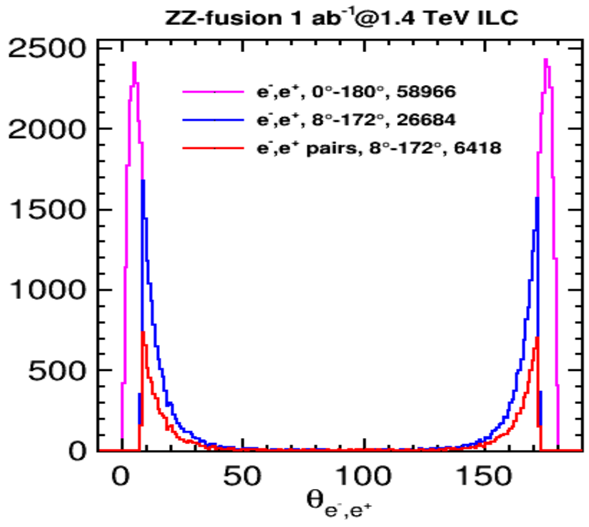
  ⇨ Due to this fact 1 TeV is the optimal energy for this study (already at i.e. 1.4 TeV the number of events with both electrons in the tracker is $\sim$1/5 of the available statistics). Around $8-9\cdot10^3$ events with both e^- and e^+ in the tracker, in 1 ab^{-1} at 1 TeV ILC.
- At 500 GeV i.e. x-section for ZZ-fusion is relatively small (7.2 fb) and assuming integrated luminosity of $0.5\ \text{ab}^{-1}$ number of events in the tracker is a factor 2 smaller than at 1 TeV



82 % @ 500 GeV



41.7 % @ 1 TeV

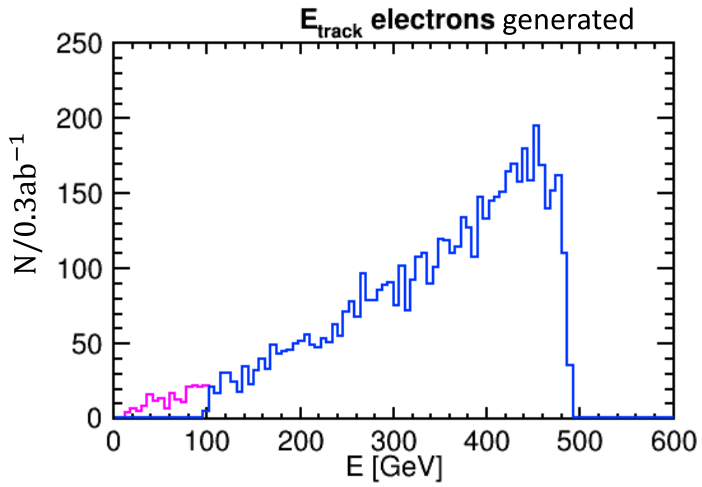


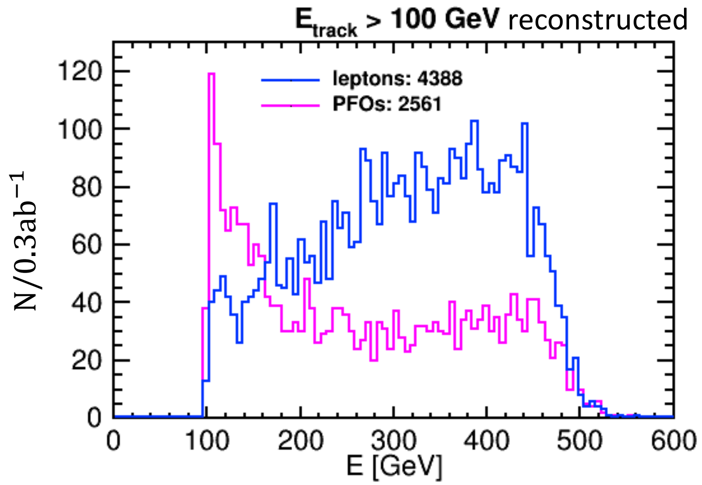
21.8 % @ 1.4 TeV

PRESELECTION - CUTS

- ILC sample at $1\ \mathrm{TeV}$, $\sim 0.3\ \mathrm{ab}^{-1}$
- Preselection: find 2 isolated electrons ($e^{+}e^{-}$)
- Goal: reduce high cross-section backgrounds
- Requirements:
  - Track energy: $E_{track} > 100\ \mathrm{GeV}$ – spectators are energetic ($\sim 6\ \%$ loss)
  - Impact parameter: $d_0 < 0.1\ \mathrm{mm}, z_0 < 1.0\ \mathrm{mm}$ – tracks from primary vertex
  - Ratio of deposition: $R_{cal} \geq 0.95$, where

    $R_{CAL} = E_{ECAL}/(E_{ECAL} + E_{HCAL})$ – select electrons
  - Optimize cone vs. track energy – electron isolation



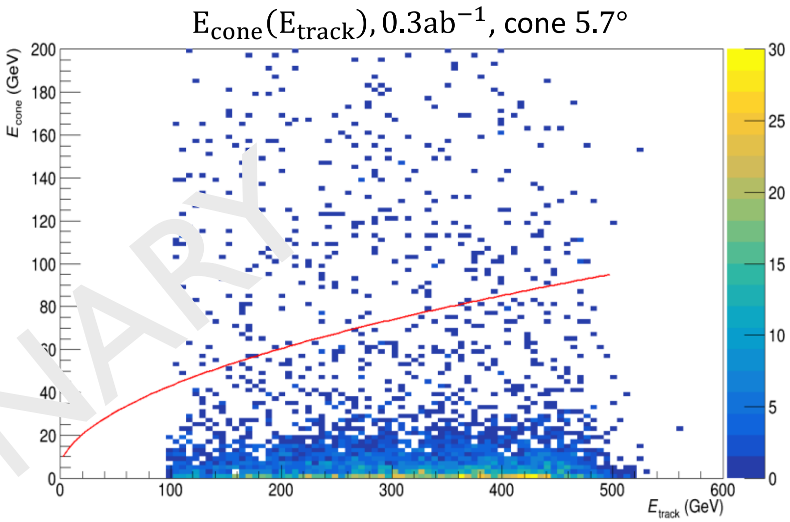


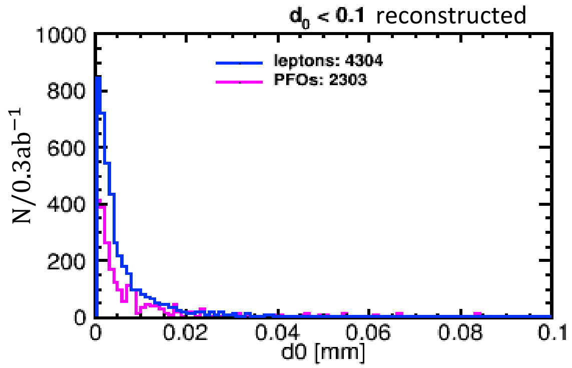
PRESELECTION EFFICIENCY

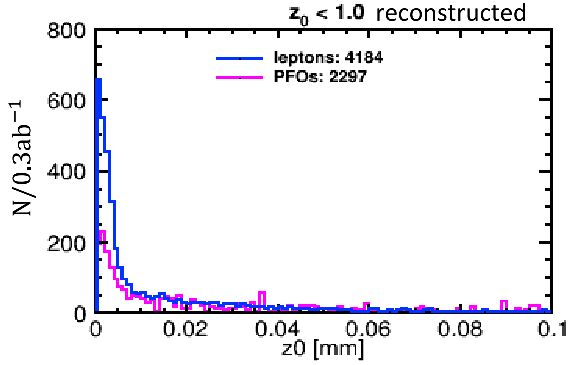
Requirements:

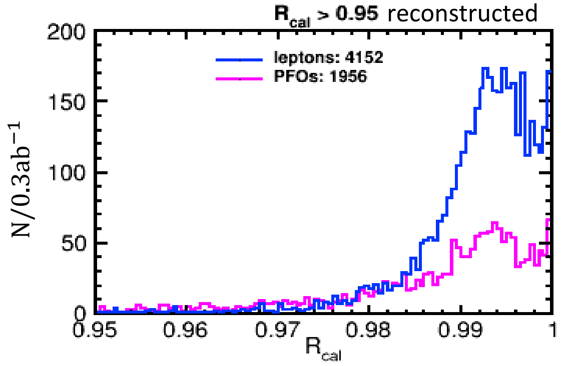
- Track energy: $E_{track} > 100$ GeV – spectators are energetic (~ 6 % loss)
- Impact parameter: $d_0 < 0.1$ mm, $z_0 < 1.0$ mm
- Ratio of deposition: $R_{cal} \geq 0.95$
- Optimize cone vs. track energy

(should be further optimized with the Breamstrahlung recovery to prevent event loss due to isolation)









@1 TeV @ 1 ab^{-1}	Input	E_{track}	E_{track} && d_0/z_0	E_{track} && d_0/z_0 && R_{CAL}	E_{track} && d_0/z_0 && R_{CAL} && $E_{cone} = f(E_{track})$
Number of ee events in the tracker	$N_{ev} = 8310$	$N_{ev} = 7814$ (6.0 %)	$N_{ev} = 7451$ (8.6 %)	$N_{ev} = 7394$ (9.2 %)	$N_{ev} = 5777$ (30.4 %, Eff ~ 70 %)

CPV IN $H \to \tau^+\tau^-$ AT 250 GEV ILC AND OTHER RESULTS

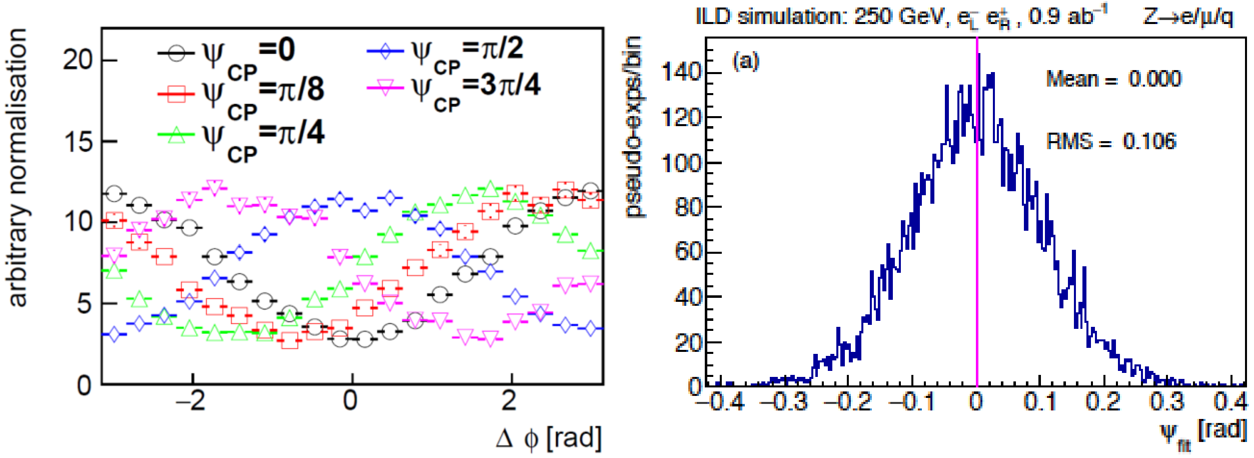
ILC

- $h\tau\tau$ vertex can probe CPV at a tree level
- ILC completed analysis in $h \to \tau^+\tau^-$ finding 75 mrad ($4.3°$) uncertainty in ψ_{CP} with 2 ab^{-1} of polarized data @ 250 GeV [LD-PHYS-2018-001]
- There is ongoing analysis in the same channel for SiD concept by J. Brau et al.

LHC

- No sign of CPV is observed with LHC (ATLAS data, 31.6 fb^{-1}, 13 TeV) in the $h \to \tau^+\tau^-$ channel [ATLAS-CONF-2019-050]
- Also, CMS results (137 fb^{-1}, 13 TeV) statistically consistent with the SM expectations in $h \to ZZ \to 4l$ [CMS-PAS-HIG-19-009]

arXiv:1804.01241v2 [hep-ex]



Upper bounds on the CP phase of the Yukawa coupling for τ leptons

Name	α_τ (ψ_{CP})
HL-LHC HE-LHC	8° -
CEPC $FCC-ee_{240}$ ILC_{250}	- 10° 4°

arXiv:1905.03764v2 [hep-ph]

OPEN QUESTIONS – PERSPECTIVE OF THE STUDY

- Possibility that CP is violated in the Higgs sector raises several intriguing questions :
  - What is a precision at the different colliders & energies?
  - What are critical or advantageous detector aspects? (e.g. quark charge identification)
  - How do these measurements all fit together, i.e. How does the experimental sensitivity at e^+e^- colliders compare to that at HL-LHC?
  - What is their relative importance?

We welcome collaborators to join us in the study of these and related questions.

Measuring the CP properties of the Higgs sector at electron-positron colliders

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(Vinca Institute of Nuclear Sciences, Belgrade)
J. Brau, L. Braun, C. Potter (University of Oregon)

August 31, 2020

Letter of Interest for SnowMass2021: Energy Frontier

The violation of the CP symmetry is one of Sakharov's conditions for the matter–anti-matter asymmetry of our universe. Currently known sources of CP violation in the quark and neutrino sectors are too small to account for this. Is CP also violated in the Higgs sector? Is the 125 GeV mass eigenstate a mixture of even and odd CP states of an extended Higgs sector, or is CP explicitly violated in Higgs interactions. With what precision could such effects be measured at future electron-positron colliders?

Several processes at e^-e^+ colliders are sensitive to the CP nature of the Higgs sector. Some are sensitive to fermionic, others to bosonic couplings; they also require different centre of mass energies, as summarised below.

fermion couplings	
$H \to \tau^-\tau^+$	250+ GeV
$e^-e^+ \to Ht\bar{t}$	500+ GeV
boson couplings	
$e^-e^+ \to HZ$	250+ GeV
$H \to ZZ$	250+ GeV
$H \to WW$	250+ GeV
$e^-e^+ \to He^-e^+$ (ZZ-fusion)	1000+ GeV

The results of recent related measurements at LHC can be found at e.g. [1], [2], [3]. What can measurements at future e^-e^+ colliders add? Thanks to the clean experimental

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SUMMARY

- **CP violation in the Higgs sector is tempting and well motivated possibility**
- **There are several analysis on CPV mixing in the Higgs sector at ILC**
- **Both hff and hVV vertices can be exploited in Higgs production and decays**
- **So far the utmost precision (in comparison to other future projects) of the Higgs mixing angle is foreseen at 250 GeV ILC in the Higgs to $\tau\tau$ decay channel**
- **Similar analysis ongoing at SiD**
- **Ongoing analysis in the Higgs inclusive production in ZZ-fusion at 1 TeV ILC targeting hZZ vertex**
- **These analyses are part of the Snowmass initiative – welcome to join us**