Determination of CPV Higgs mixing angle in ZZ-fusion at 1 TeV ILC

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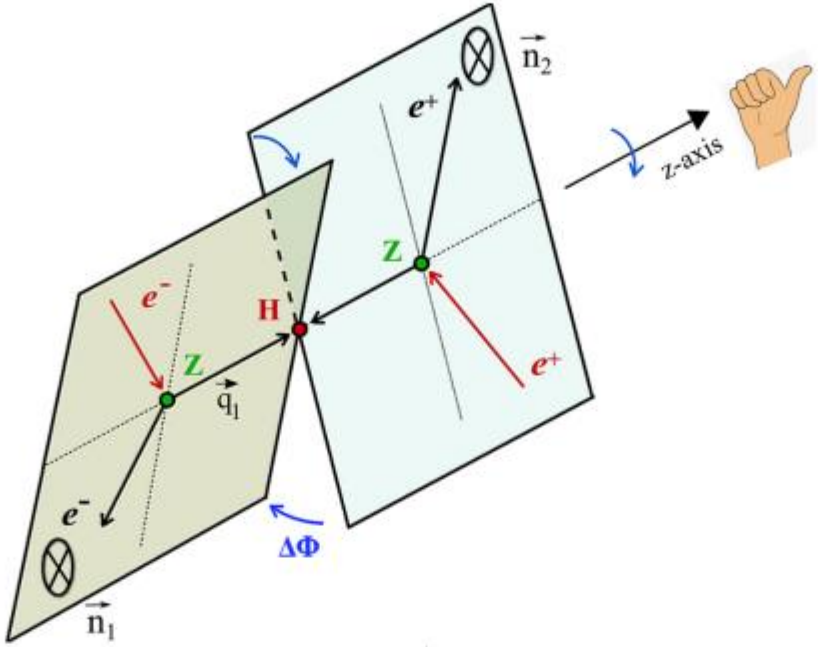
Outline

1. Could 125 GeV Higgs mass eigenstate be a CPV mixture of CP-odd and CP-even states of the extended Higgs sector via mixing angle Ψ_{CP}?
2. If so, with what precision can this effect be measured at ILC (1 TeV e^+e^- linear collider)?
3. What is the interpretation of measurement sensitivity in the context of Snowmass CPV White paper [arXiv:2205.07715v3]?

CP-sensitive observable

Generic model of CPV mixing: $h_{125} = H \cdot \cos \Psi_{CP} + A \cdot \sin \Psi_{CP}$

- CP-sensitive observable: angle between production planes $\Delta\Phi$
- As shown in arXiv:2203.11707v3 (S. Qiyu et al.) $\Delta\Phi$ carries the most information on the Higgs CP state
- $\Delta\Phi$ can be retrieved in the following way:

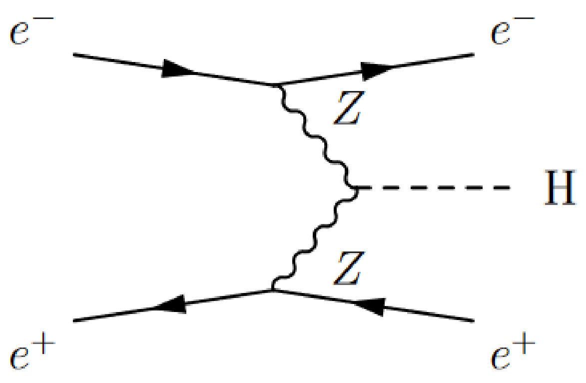


$$\Delta\Phi = sgn\,(\Delta\Phi) \cdot arccos(\vec{n}_1 \cdot \vec{n}_2)$$

$$sgn\,(\Delta\Phi) = \frac{\vec{q}_1 \cdot (\vec{n}_1 \times \vec{n}_2)}{|\vec{q}_1 \cdot (\vec{n}_1 \times \vec{n}_2)|}$$

$$\vec{n}_1 = \frac{\vec{q}_{e_i^-} \times \vec{q}_{e_f^-}}{\left|\vec{q}_{e_i^-} \times \vec{q}_{e_f^-}\right|} \qquad \vec{n}_2 = \frac{\vec{q}_{e_i^+} \times \vec{q}_{e_f^+}}{\left|\vec{q}_{e_i^+} \times \vec{q}_{e_f^+}\right|}$$

Event samples



1 TeV	σ (fb)	Expected in 8 ab^{-1} full range	Reconstructed MC events
SIGNAL: $\boldsymbol{e^+e^- \to Hee, H \to b\bar{b}}$	13	104000	$2 \cdot 10^5$ DELPHES 3495 full sim.
$e^+e^- \to b\bar{b}l^+l^-$ $e^+e^- \to q\bar{q}l^+l^-$	255	$2 \cdot 10^6$	$1 \cdot 10^6$ DELPHES 5886 full sim.
$e^+e^- \to q\bar{q}$	9375	$75 \cdot 10^6$	120343 full sim.
$e^+e^- \to q\bar{q}l\nu$	4116	$32.9 \cdot 10^6$	955058 full sim.

Energies up to 1 TeV are optimal due to interplay of x-section and centrality

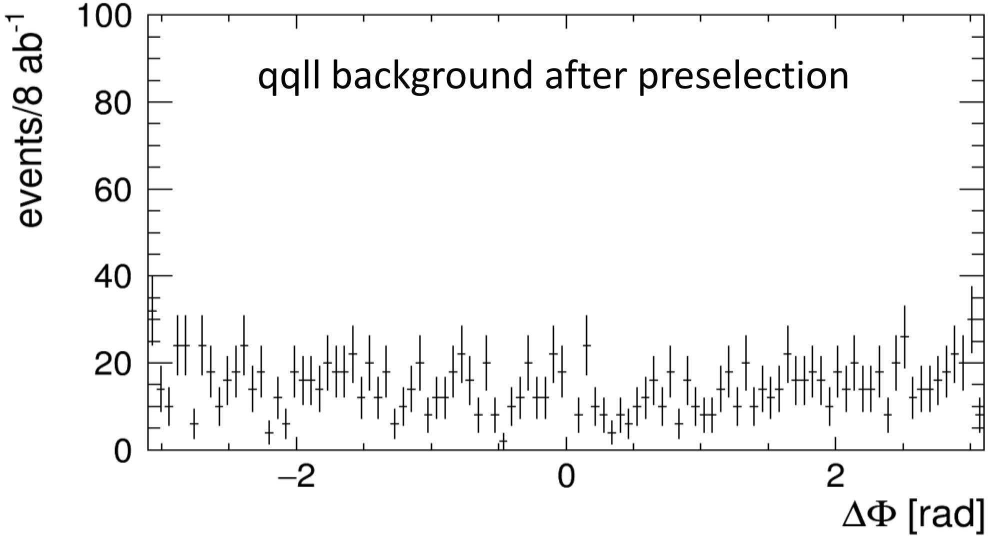
ILC	$\sqrt{s}$	$\int \mathcal{L}dt$ (baseline)
	0.1 - 1 TeV	2 ab^{-1} @ 250 GeV 0.2 ab^{-1} @ 350 GeV 4 ab^{-1} @ 500 GeV 8 ab^{-1} @ 1 TeV

- Generator level WHIZARD V2.8.3/UFO/Higgs characterization model for signal and WHIZARD 1.95/SM for background events
- Beams are unpolarised

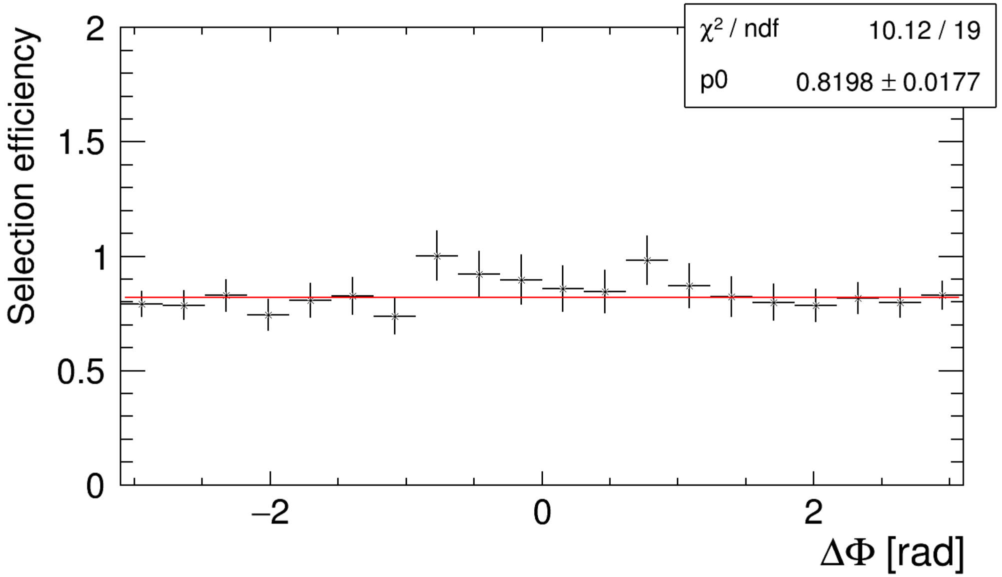
Event selection

- Preselection – electron isolation:
  - $m_{e^+e^-} > 200$ GeV (exclude HZ)
  - $E_{e^\pm} > 60$ GeV
  - DELPHES electron isolation:
    - $\Delta R_{\max} = 0.5$
    - $p_{T\,\min} = 0.5$ GeV
    - $I = \frac{\sum_{i \neq P}^{p_T(i) > p_{T\,\min}} p_T\,(i)}{p_T(P)} < 0.12$
- Signal preselection efficiency: ~ 71%

- Selection cuts:
  - 80 GeV < $m_{q\bar{q}}$ < 160 GeV
  - $m_{Z_1,Z_2} > 30$ GeV
  - $p_{Tee} > 15$ GeV
  - $p_{T\,\mathrm{miss}} < 150$ GeV
- Selection efficiency: 96%
- Total signal efficiency: ~ 68%



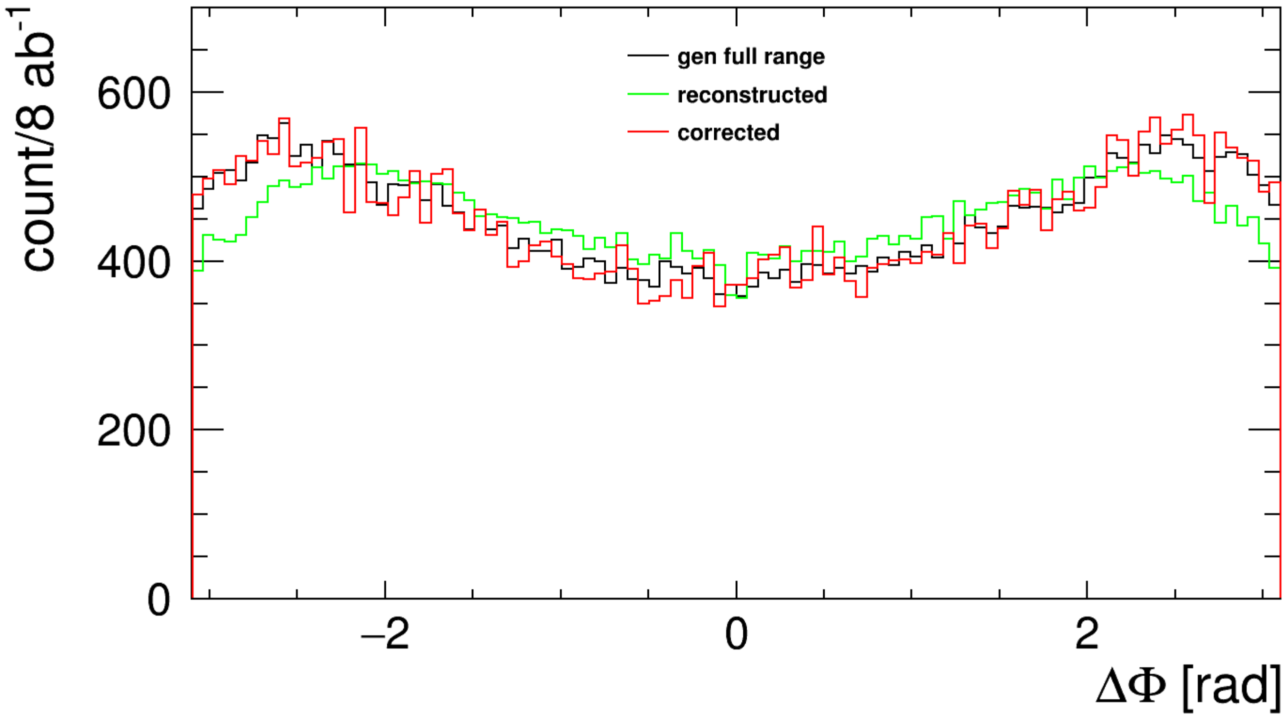
Background is CP insensitive.



Unbiased selection w.r.t ΔΦ

Generated and reconstructed signal

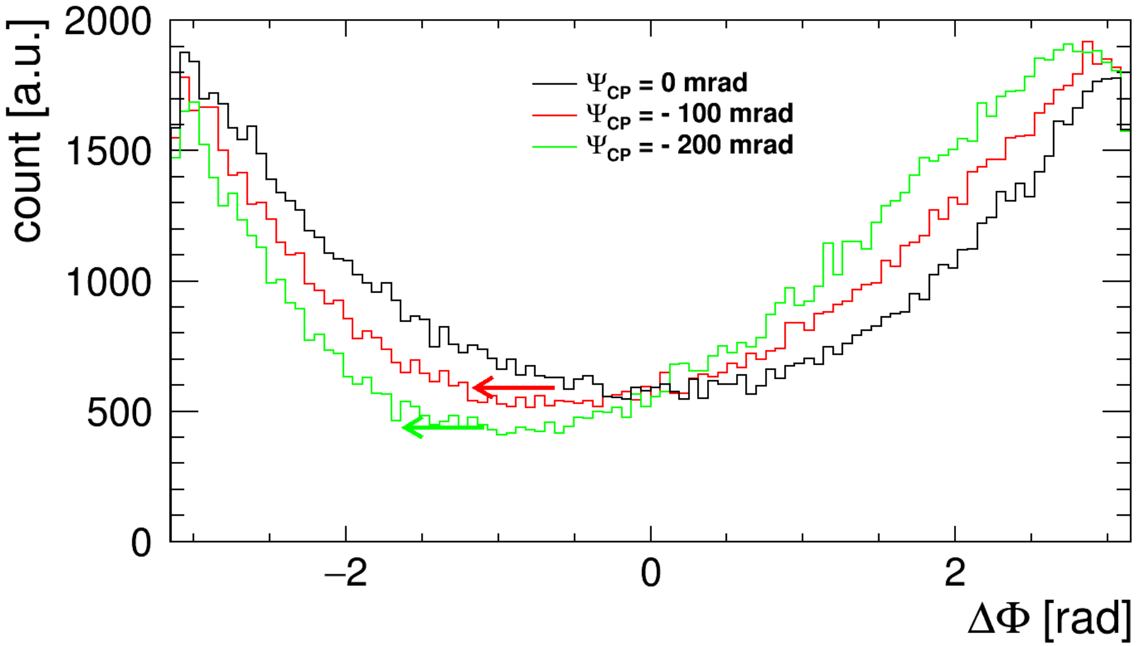
Generated information (WHIZARD), uncorrected and corrected reconstructed signal

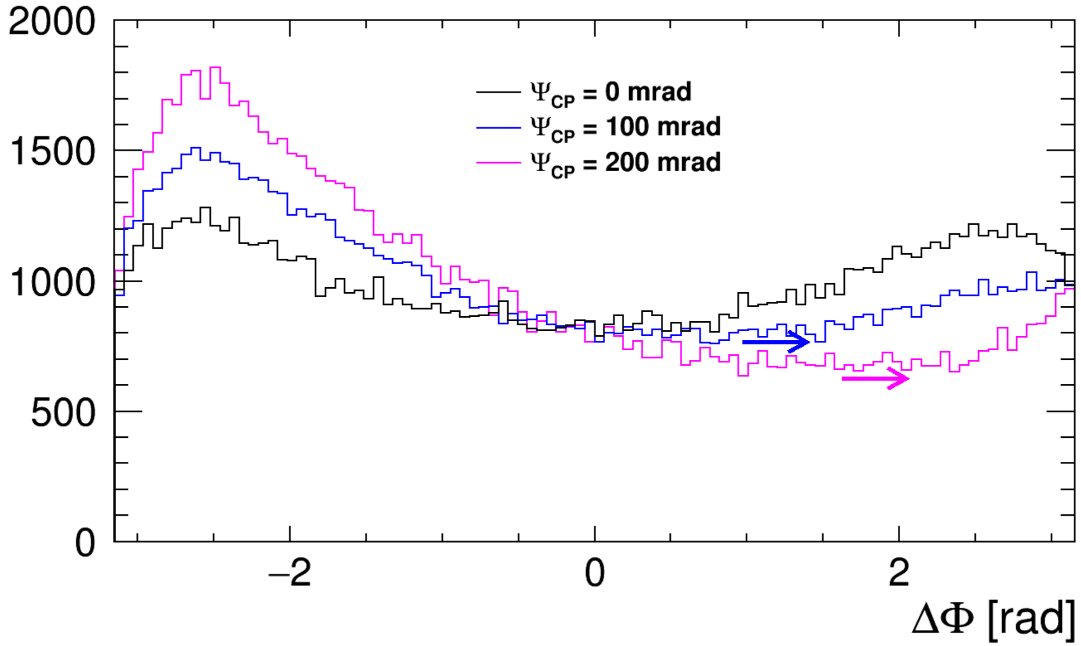


- Acceptance correction needed to retrieve full physical information
- Generated information is reasonably well reproduced with corrected reconstructed data

CP-observable $\Delta\Phi$ and mixing angle Ψ_{CP}

Minimum of $\Delta\Phi$ shifts for non-zero Ψ_{CP} values





- Differently from the $H \rightarrow \tau\tau$ angular observable whose dependence on Ψ_{CP} can be derived from the differential x-section, here is no simple analytical dependence, which has to be extracted **empirically**

How to extract Ψ_{CP}?

Position of local minimum of $\Delta\Phi$ is sensitive to Ψ_{CP};

1. Determine position of the minimum b/a by performing the fit function:

$$f(\Delta\Phi, \Psi_{CP}) = A + B \cdot \cos(a \cdot \Delta\Phi - b)$$

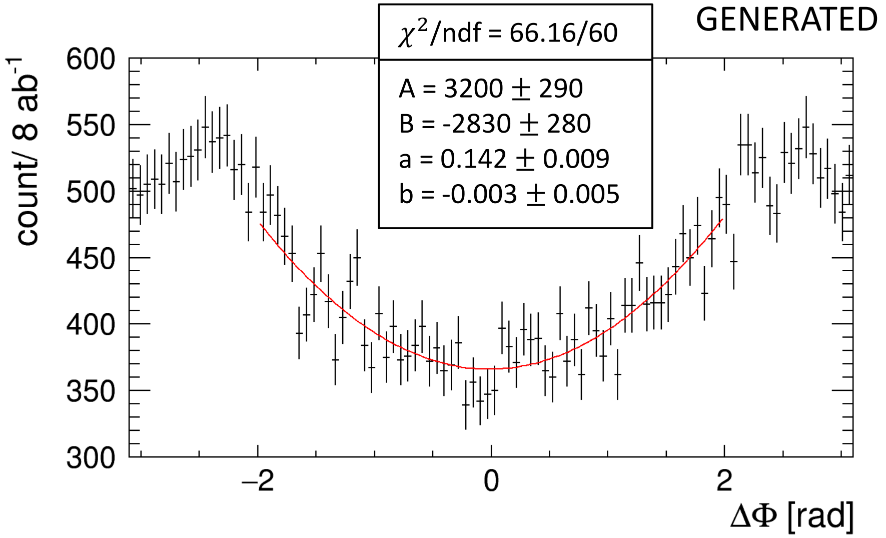
2. Position (b/a)/ Ψ_{CP} is a linear function of Ψ_{CP}:

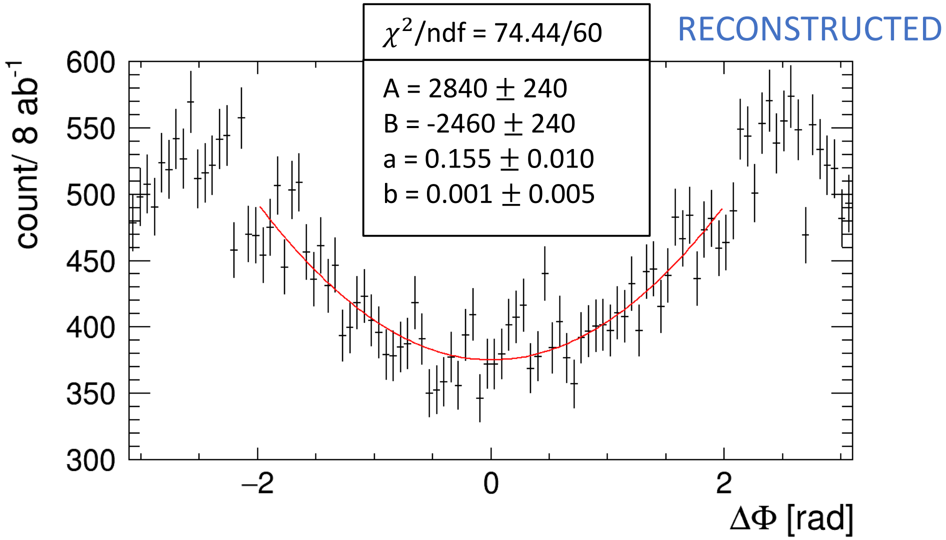
$$(b/a)/\Psi_{CP} = k \cdot \Psi_{CP} + m$$

3. Determine (from simulation) coefficients of the linear function (k, m);

4. Ψ_{CP} can be retrieved from quadratic equation:

$$k \cdot \Psi^2_{CP} + m \cdot \Psi_{CP} - (b/a) = 0$$





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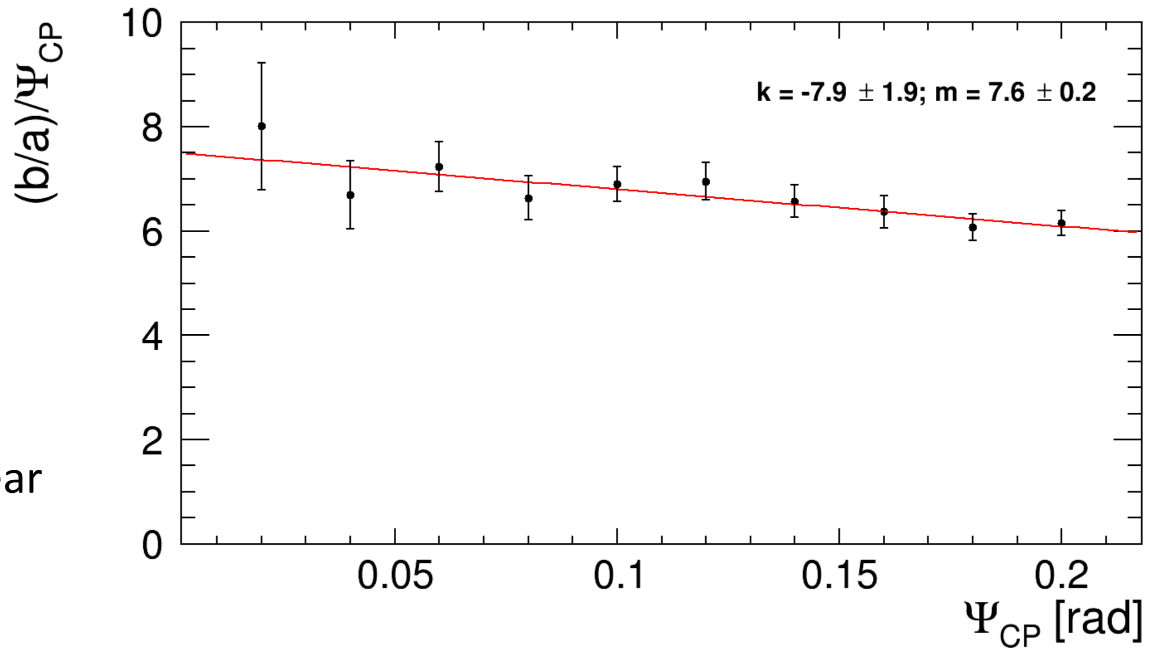

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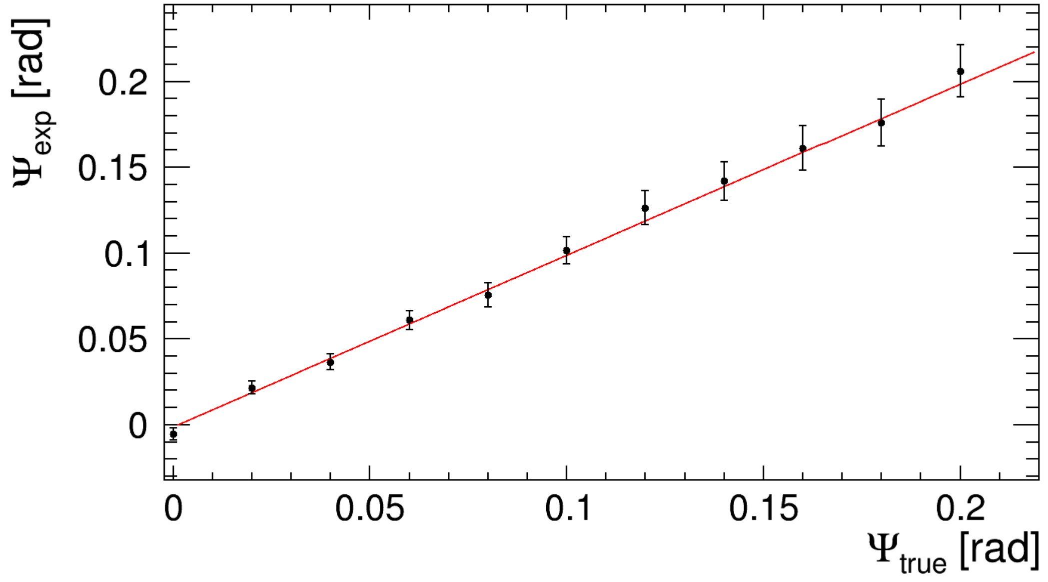

Red line illustrates dependence $\Psi_{exp} = \Psi_{true}$

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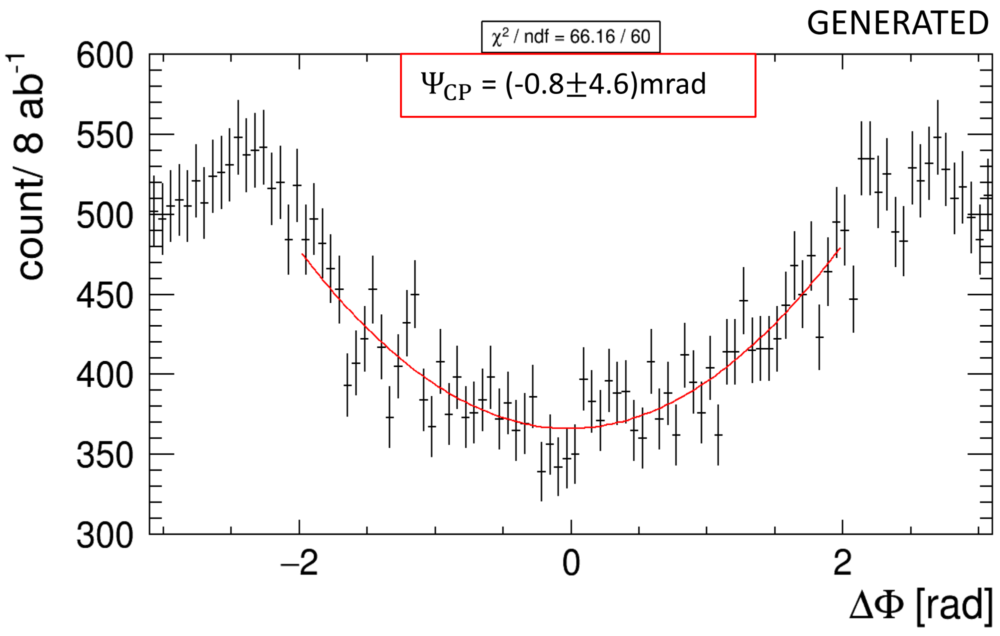
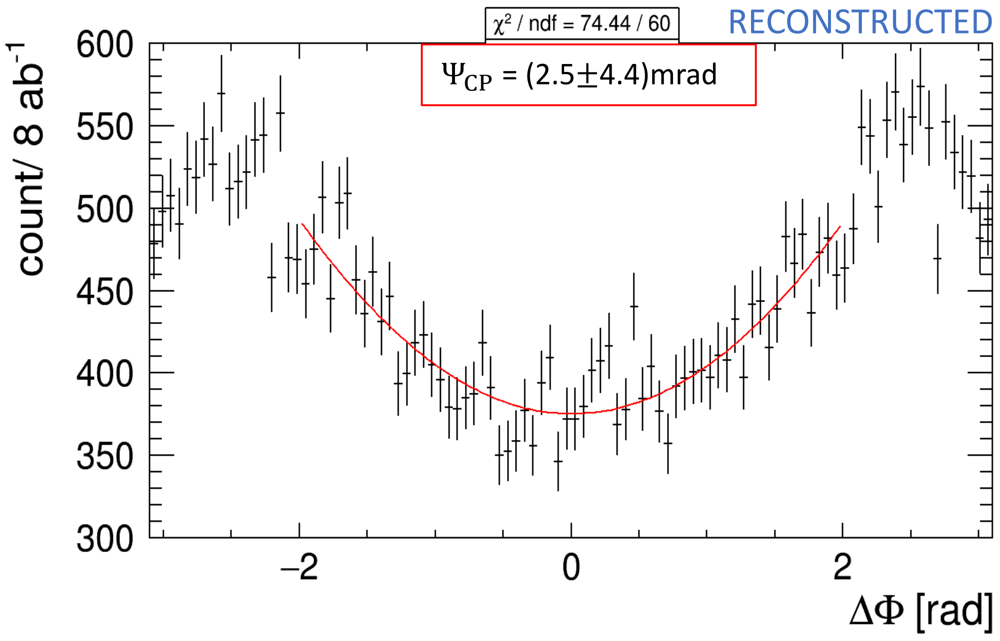
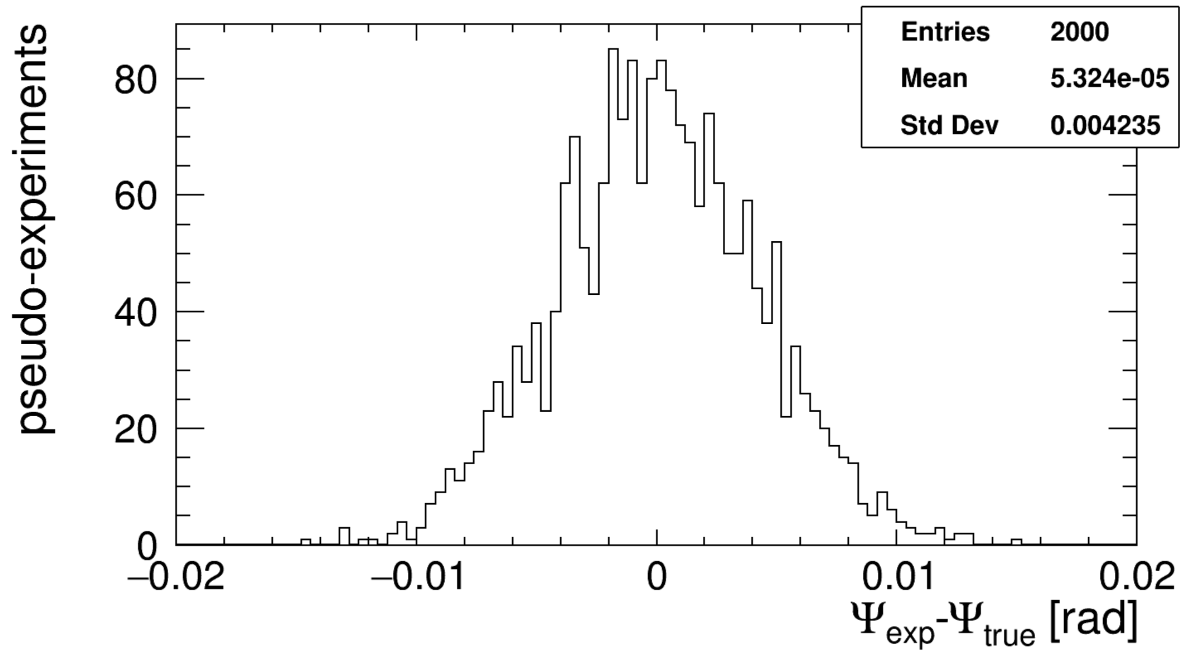
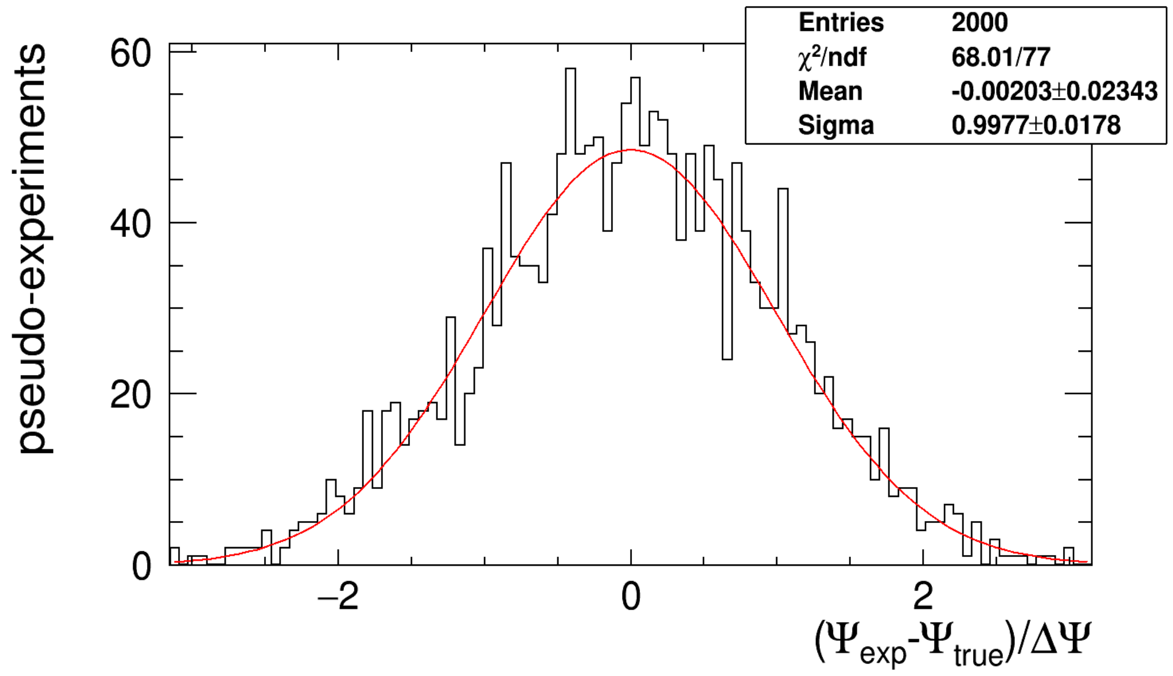




Pseudo-experiments

$\Delta\Psi^{CP}_{(stat.)}$ = 4 mrad





- 2000 pseudo-experiments give 4 mrad for statistical dissipation of the mean
- Pull distribution indicates that uncertainties are correctly estimated
- Systematic error from the fit parameters uncertainties gives $<$ 1 mrad

Interpretation

- Common framework for interpretation of CPV results is defined in the Snowmass CPV White paper
- Benchmark parameter f_{CP} quantifies relative contribution from CP-odd amplitude

$$f_{CP}^{HX} \equiv \frac{\Gamma_{H\to X}^{CP\,\text{odd}}}{\Gamma_{H\to X}^{CP\,\text{odd}} + \Gamma_{H\to X}^{CP\,\text{even}}}$$

$$f_{\text{CP}}^{hVV} = \frac{|a_3^{hVV}|^2}{\sum_i |a_i^{hVV}|^2(\sigma_i/\sigma_3)}.$$

- For the pure scalar state $f_{CP} \sim \sin^2(\Delta\Psi_{CP})$
- Interpretation for LHC/HL-LHC and future Higgs factories, for EFT and CP-sensitive observable based measurements

(68% CL, pure scalar) arXiv:2205.07715v3

Collider E(GeV) $\mathcal{L}$ (fb^{-1})	pp 14.000 300	pp 14.000 3.000	pp 100.000 30.000	e^-e^+ 250 250	e^-e^+ 350 350	e^-e^+ 500 500	e^-e^+ 1.000 1.000	e^-p 1.300 1.000	$\gamma\gamma$ 125 250	$\mu^+\mu^-$ 125 20	$\mu^+\mu^-$ 3.000 1.000	target (theory)
HZZ/HWW	$4.0\cdot10^{-5}$	$2.5\cdot10^{-6}$	✓	$3.9\cdot10^{-5}$	$2.9\cdot10^{-5}$	$1.3\cdot10^{-5}$	$3.0\cdot10^{-6}$	✓	✓	✓	✓	$< 10^{-5}$
$H\gamma\gamma$		0.50	✓						0.06			$< 10^{-2}$
$HZ\gamma$		~ 1	✓				~ 1					$< 10^{-2}$
Hgg	0.12	0.011	✓									$< 10^{-2}$
$Ht\bar{t}$	0.24	0.05	✓			0.29	0.08	✓			✓	$< 10^{-2}$
$H\tau\tau$	0.07	0.008	✓	0.01	0.01	0.02	0.06		✓	✓	✓	$< 10^{-2}$
$H\mu\mu$										✓		$< 10^{-2}$

Interpretation

1 TeV ILC, ILD
- ✓ First measurement in VBF at an e^+e^-
- ✓ Full background simulation of ILD detector and fast simulation of the signal
- ✓ Realistic ILC running scenario

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HZZ/HWW	$4.0 \cdot 10^{-5}$	$2.5 \cdot 10^{-6}$	✓	$3.9 \cdot 10^{-5}$	$2.9 \cdot 10^{-5}$	$1.3 \cdot 10^{-5}$	$3.0 \cdot 10^{-6}$	✓	✓	✓	✓	$< 10^{-5}$
$H\gamma\gamma$		0.50	✓						0.06			$< 10^{-2}$
$HZ\gamma$		~ 1	✓									$< 10^{-2}$
Hgg	0.12	0.011	✓									$< 10^{-2}$
$Ht\bar{t}$	0.24	0.05	✓			0.29		✓			✓	$< 10^{-2}$
$H\tau\tau$	0.07	0.008	✓	0.01	0.01	0.02	0.06		✓	✓	✓	$< 10^{-2}$
$H\mu\mu$										✓		$< 10^{-2}$

1 TeV
8 ab^{-1}
$1.6 \cdot 10^{-5}$

Summary

- This is the first result in VBF fusion at an e^+e^- collider;

- Complete simulation of CP Higgs mixing angle (Ψ_{CP}) measurement, at 1 TeV ILC with the ILD detector;

- From 8 ab^{-1} of 1 TeV ILC data, pure scalar state should be measured with 4 mrad statistical uncertainty of Ψ_{CP} at 68% CL;
  Systematic uncertainty from the fit is found to be smaller (< 1 mrad);

- CP factor f_{CP} can be mesured down to $1.6 \cdot 10^{-5}$ approaching the theoretical target corresponding to the 10% admixture of the CP-odd state.

Backup

Reconstructed signal