Probing CPV mixing in the Higgs sector in VBF at 1 TeV ILC

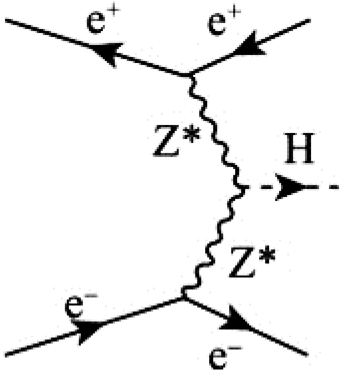
N. VUKASINOVIC, I. BOZOVIC JELISAVCIC, G. KACAREVIC

ON BEHALF OF THE ILD DETECTOR CONCEPT GROUP

VINCA Institute of Nuclear Sciences,
Belgrade, Serbia

OUTLINE

- We explore the possibility that CP is violated through mixing of CP eigenstates of opposite parities
- Generic assumption that 125 GeV Higgs mass eigenstate is a mixture of scalar and pseudoscalar via mixing angle Ψ_{CP} ($h_{125} = H \cdot \cos \Psi_{CP} + A \cdot \sin \Psi_{CP}$)?
- What is the precision to measure Ψ_{CP} in ZZ-fusion at 1 TeV e^+e^- collider - ILC ?
- The first fully simulated measurement in VBF (arXiv:2205.07715v3[hep-ex], only ZH scaled to higher E and $\mathcal{L}$)



SIGNAL AND BACKGROUND

$\sim$ 1 TeV energies are optimal due to interplay of x-section and centrality

1 TeV	σ (fb)	Expected in 8 ab^{-1} full range	Reconstructed with ILD
Signal: $\boldsymbol{e^+e^- \to Hee, H \to b\bar{b}}$	13	104000	$6\cdot10^5$ DELPHES ~ 46 ab^{-1}
			3495 full sim. ~ 0.27 ab^{-1}
$e^+e^- \to q\bar{q}e^+e^-$	$2.4\cdot10^3$	$19\cdot10^6$	$2\cdot10^5$
$e^+e^- \to q\bar{q}$	$3.6\cdot10^3$	$29\cdot10^6$	$4\cdot10^5$
$e^+e^- \to q\bar{q}e\nu$	$3\cdot10^3$	$24\cdot10^6$	$2.6\cdot10^6$
$e^+e^- \to llll$	$8\cdot10^3$	$64\cdot10^6$	$1.5\cdot10^6$
$e^+e^- \to eeqqqq$	37	$30\cdot10^4$	$1\cdot10^4$
$e^+e^- \to e\nu_e qqqq$	51	$4\cdot10^5$	$1\cdot10^6$
$e^+e^- \to qq\nu_e ee\nu_e$	5.6	$45\cdot10^3$	$5\cdot10^4$

- Unpolarized beams
- Generator level WHIZARD V2.8.3/UFO/Higgs characterization model signal and WHIZARD 1.95/SM background
- Higgs decays to 2 b-jets to avoid eeγ background

- CP-odd coupling to vector bosons at loop level

$$\mathcal{L}_0^V = \Big\{ c_\alpha \kappa_{\rm SM} \big[\tfrac{1}{2} g_{HZZ}\, Z_\mu Z^\mu + g_{HWW}\, W^+_\mu W^{-\mu} \big] - \frac{1}{4}\frac{1}{\Lambda} \big[c_\alpha \kappa_{HZZ}\, Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ}\, Z_{\mu\nu} \widetilde{Z}^{\mu\nu} \big] - \frac{1}{\Lambda} c_\alpha \big[\kappa_{H\partial\gamma}\, Z_\nu \partial_\mu A^{\mu\nu} + \kappa_{H\partial Z}\, Z_\nu \partial_\mu Z^{\mu\nu} + \big(\kappa_{H\partial W}\, W^+_\nu \partial_\mu W^{-\mu\nu} + h.c. \big) \big] \Big\} X_0$$

- Generator parameters are set in a way that production cross-section depends only on Ψ_{CP} – otherwise multidimensional analysis would be reqired including variations of κ_{AZZ}

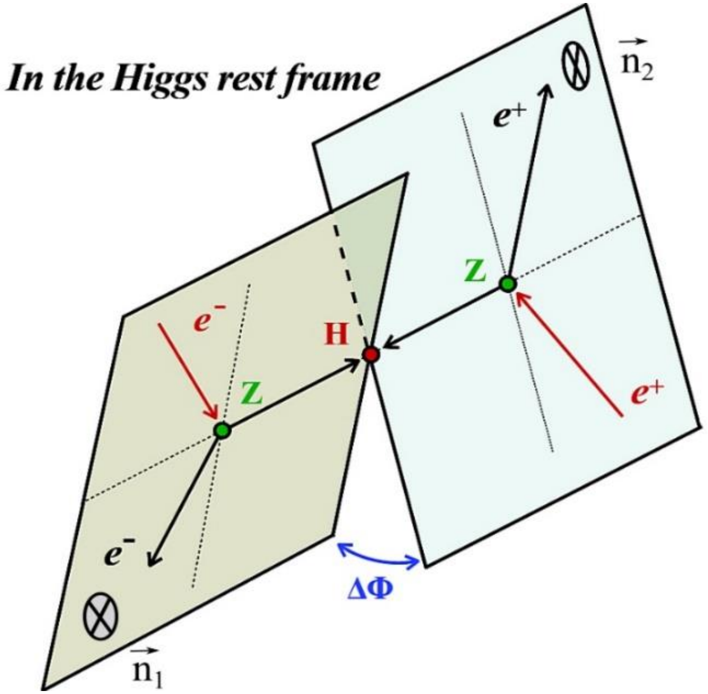
SENSITIVE OBSERVABLE

- CP-sensitive observable: angle between production planes $\Delta\Phi$
- $\Delta\Phi$ carries the most information on the Higgs CP state [arXiv:2203.11707]

$$\Delta\Phi = \mathrm{sgn}(\Delta\Phi) \cdot \mathrm{arcos}(\vec{n}_1 \cdot \vec{n}_2)$$

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

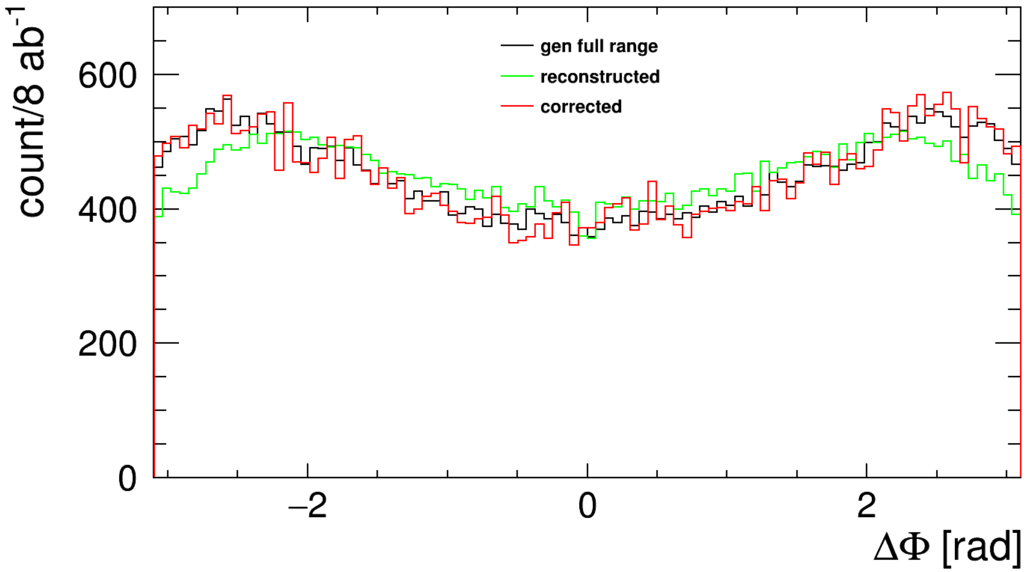
$$\hat{n}_1 = \frac{q_{e_i^-} \times q_{e_f^-}}{|q_{e_i^-} \times q_{e_f^-}|} \qquad \hat{n}_2 = \frac{q_{e_i^+} \times q_{e_f^+}}{|q_{e_i^+} \times q_{e_f^+}|}$$



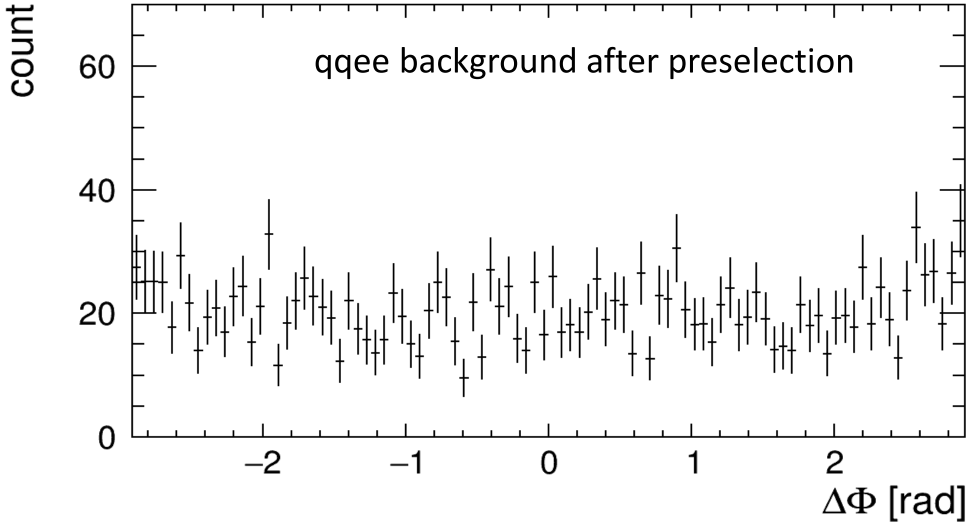
GENERATED AND RECONSTRUCTED SIGNAL

Measurement for the pure scalar $\Psi_{CP}=0$

- **Correction for detector acceptance in polar angles**
- Generated signal is well reproduced with corrected reconstructed data



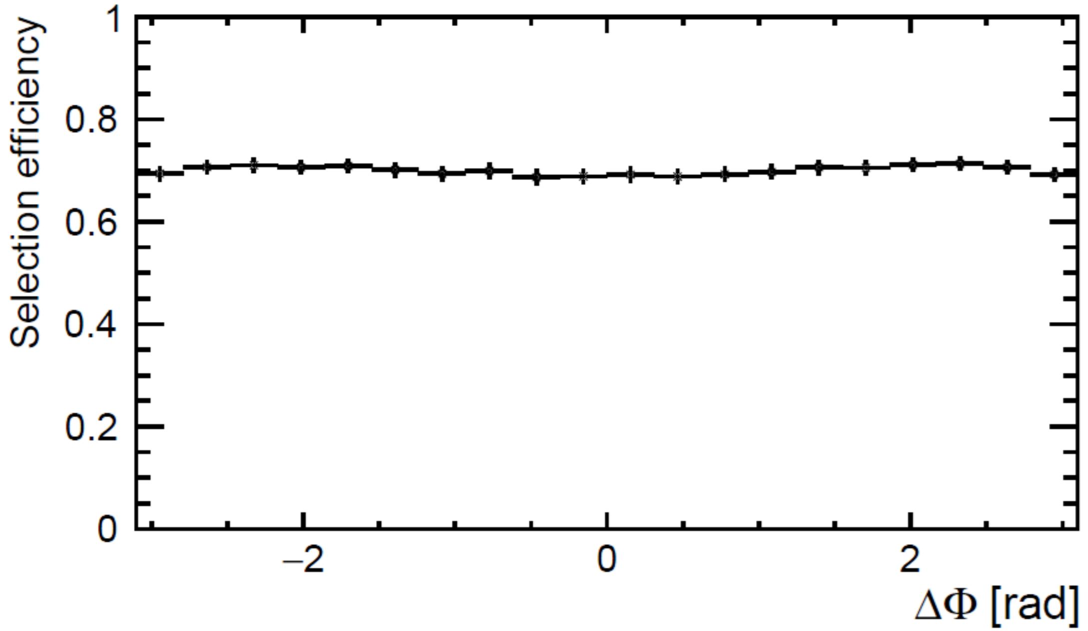
- **Preselection – electron isolation**:
- $m_{e^+e^-} > 200$ GeV (veto HZ)
- $E_{e\pm} > 60$ GeV
- DELPHES electron isolation
  - ΔRmax = 0.5
  - p_{Tmin} = 0.5 GeV
  - $I = \frac{\sum_{i \neq P}^{p_T(i) > p_T^{min}} p_T(i)}{p_T(P)}$ <0.12
- Signal preselection efficiency: ~85%
- **Background is CP insensitive**



EVENT SELECTION

- **Selection cuts:**
  - $m_{j\bar{j}} > 110\ GeV$,
  - $p_{T\,j_2} > 160\ GeV$,
  - $N_{PFO_{1,2}} > 10$,
  - Selection efficiency: 82%

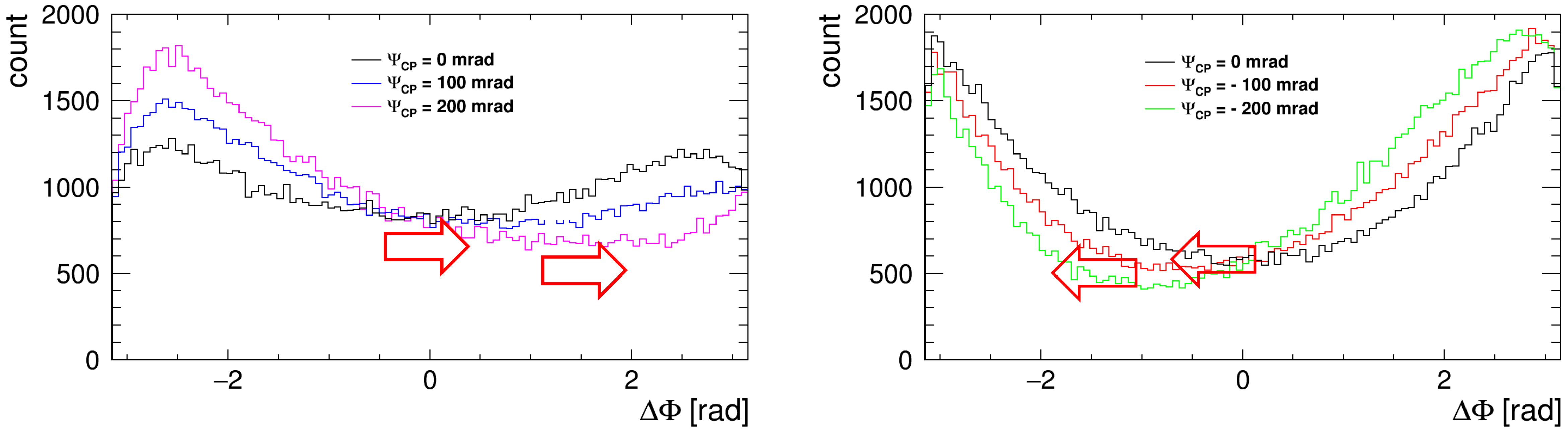
  - **Total signal efficiency with preselection: ~ 70%**
  - **Unbiased selection w.r.t. ΔΦ**
  - **Background is fully suppressed**



ANGULAR OBSERVABLE $\Delta\Phi$ AND MIXING ANGLE Ψ_{CP}

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

- Relation between Ψ_{CP} and $\Delta\Phi$ has to be extracted **empirically**

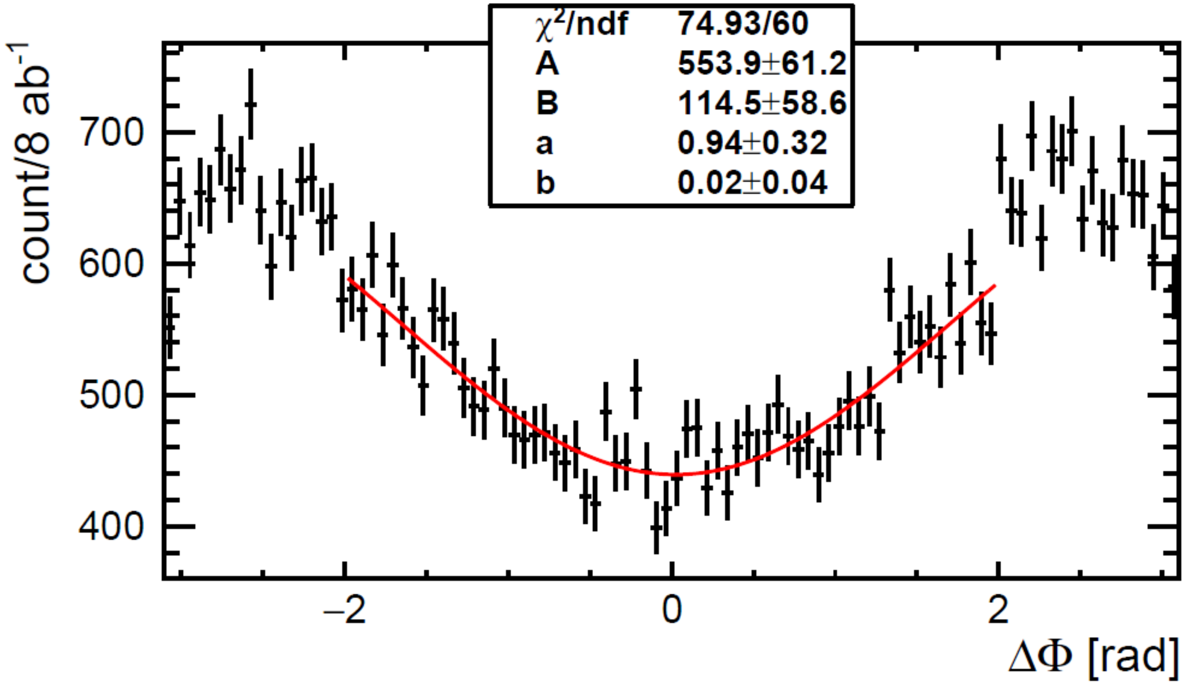


RECONSTRUCTION OF MIN($\Delta\Phi$)

1. **Determine position of the local minimum from experimental data (corrected, selected S+B):**

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

2. b/a defines minimum from the principle of the first derivative

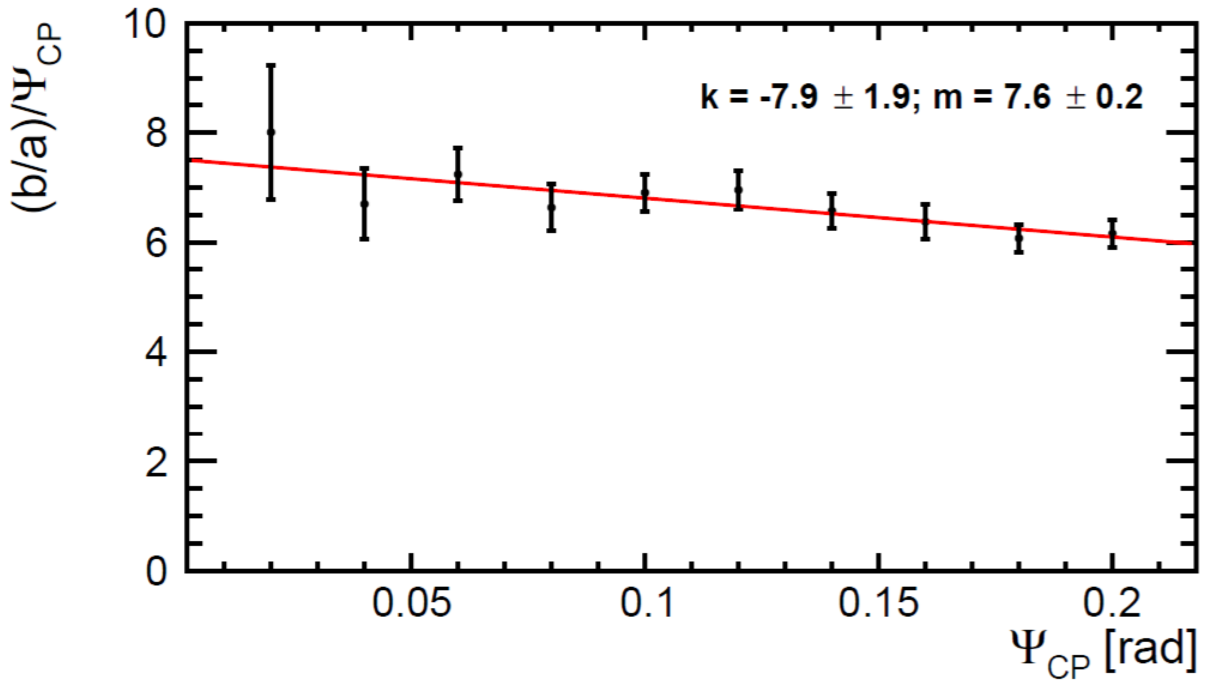


MIN($\Delta\Phi$) VS. MIXING ANGLE Ψ_{CP}

3. Position (b/a)/ Ψ_{CP} is a linear function of Ψ_{CP} ,

determine *k* and *m* from simulation

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



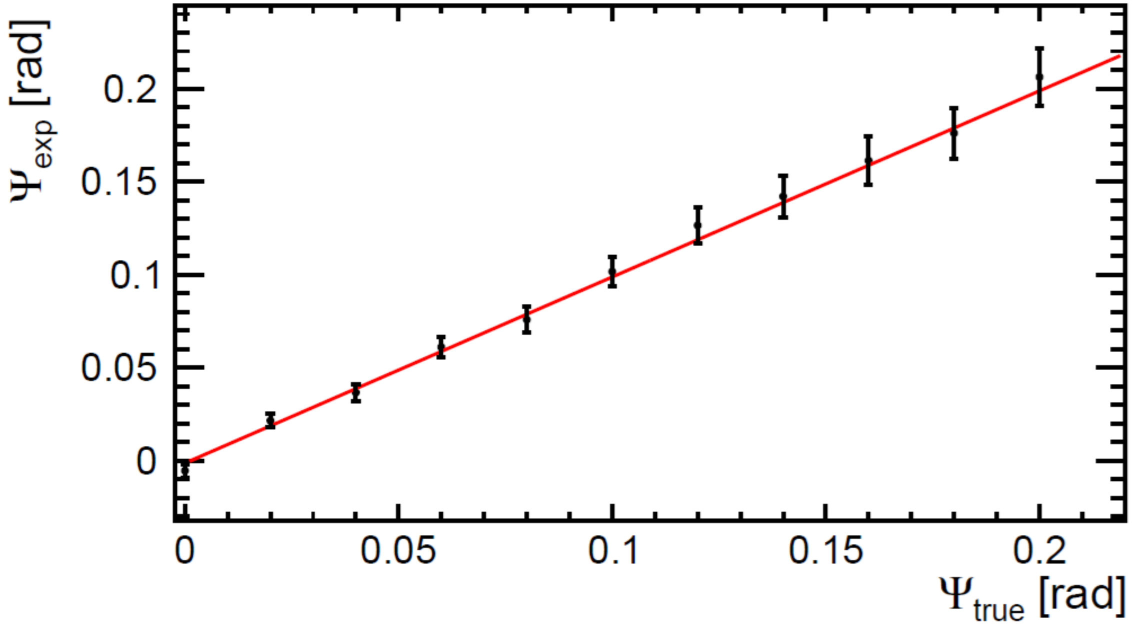
DETERMINATION OF Ψ_{CP} FROM MIN($\Delta\Phi$)

4. **Retrieve Ψ_{CP} by solving the quadratic equation**:

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

(*k, m* – fit parameters from simulation

b, a – fit parameters from the reconstructed data)

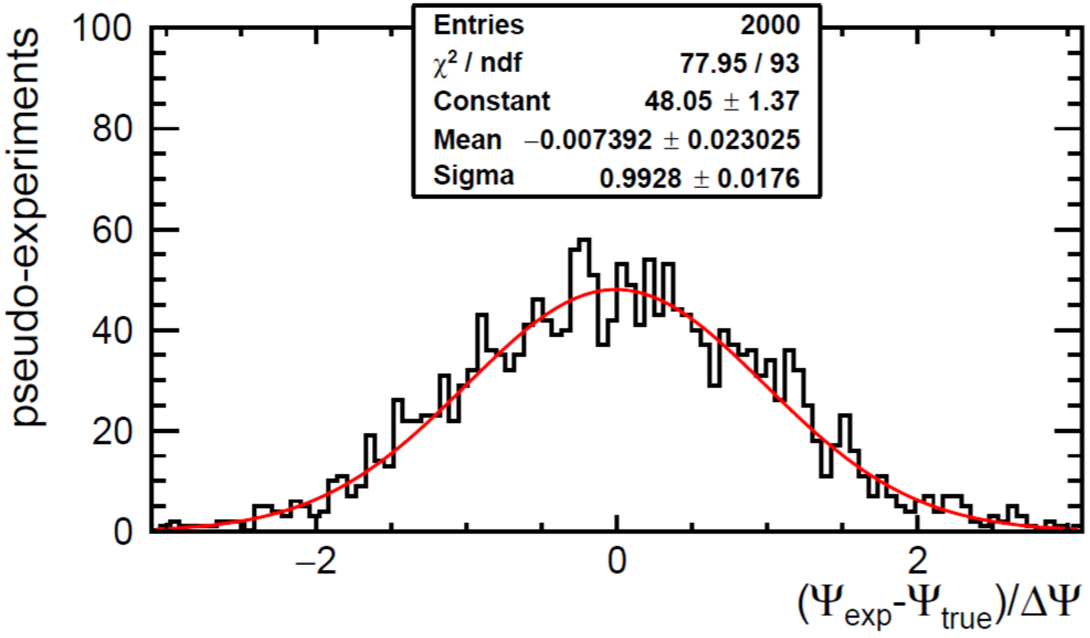


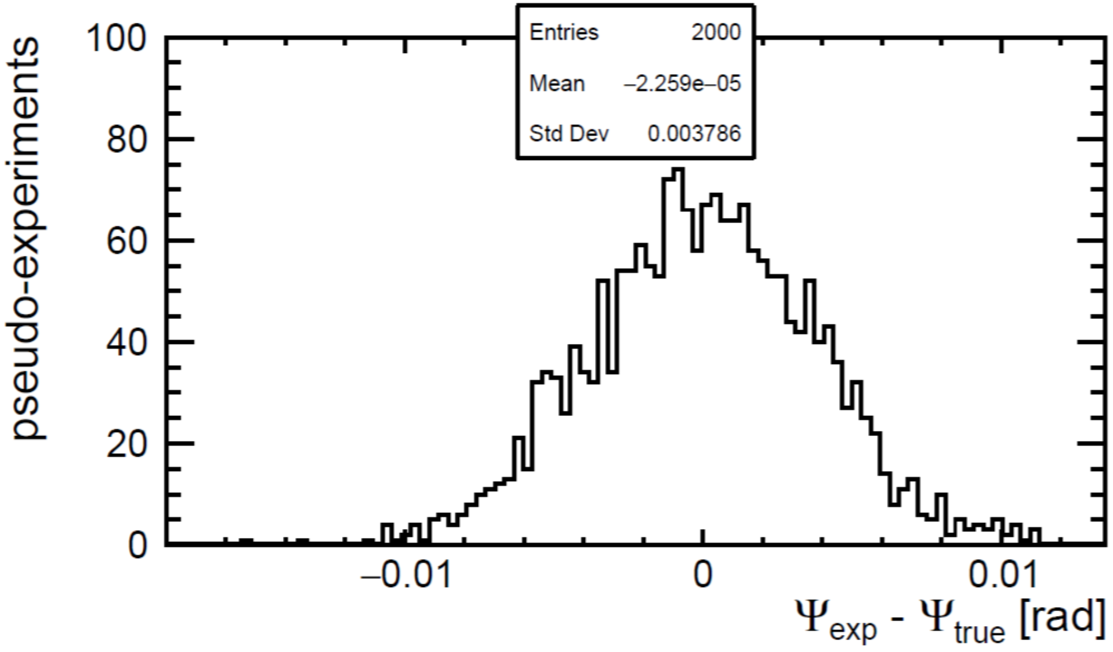
Generated values of Ψ_{CP} are correctly reproduced

PSEUDO-EXPERIMENTS

- 2000 pseudo-experiments at Ψ_{CP}= 0, with 8 ab^{-1} of unpolarised data
- Pull distribution indicates that uncertainties are correctly estimated
- Fit parameters' uncertainties give ~1 mrad systematic error

$\Delta\Psi_{CP\ (stat.)}$= (3.8 ± 0.4) mrad , 68% CL





DISCUSSION

$f_{CP} = sin^2(\Delta\Psi_{CP})$ = (1.44 ± 0.02) ·10^{-5} with 68% CL

- First measurement in VBF (HZZ vertex)
- Full background simulation of ILD detector and fast simulation of the signal, realistic ILC running scenario
- Sensitivity in line with the targeted precision from theory (benchmark point 2HDM to explain barion asymetry)

(f_{CP}, 68% CL, pure scalar) [arXiv:2205.07715v3]

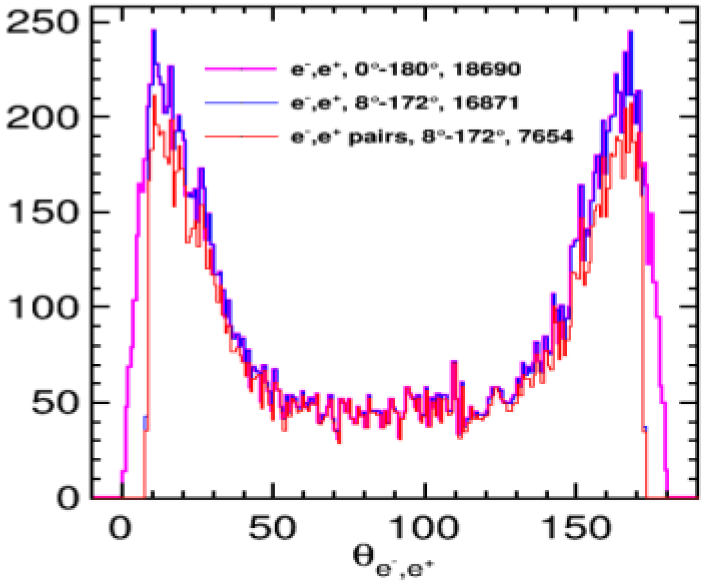
Collider	pp	pp	pp	e^+e^-	e^+e^-	e^+e^-	e^+e^-	e^-p	$\gamma\gamma$	$\mu^+\mu^-$	$\mu^+\mu^-$	target
E (GeV)	14,000	14,000	100,000	250	350	500	1,000	1,300	125	125	3,000	(theory)
$\mathcal{L}$ (fb^{-1})	300	3,000	30,000	250	350	500	8,000	1,000	250	20	1,000	
HZZ/HWW	$4.0\cdot10^{-5}$	$2.5\cdot10^{-6}$	✓	$3.9\cdot10^{-5}$	$2.9\cdot10^{-5}$	$1.3\cdot10^{-5}$	**$1.44\cdot10^{-5}$**	✓	✓	✓	✓	$< 10^{-5}$
$H\gamma\gamma$	–	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	–	✓	✓	✓	$< 10^{-2}$
$H\mu\mu$	–	–	–	–	–	–	–	–	–	✓	–	$< 10^{-2}$

SUMMARY

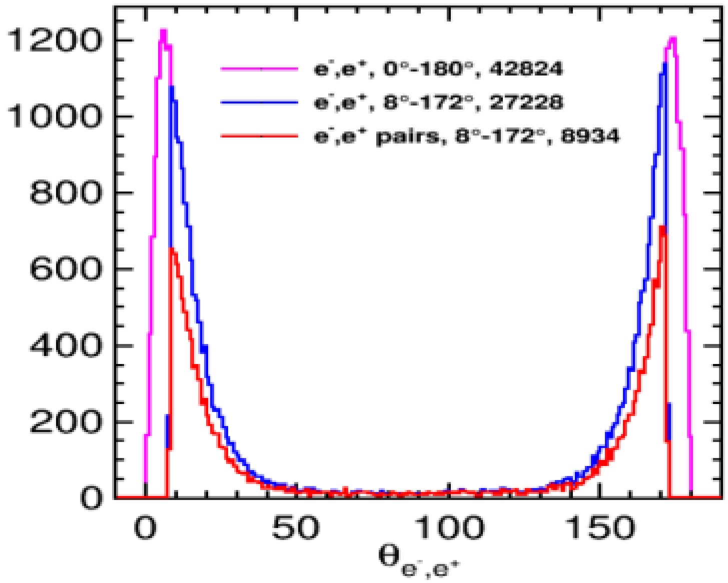
- First measurement in VBF in HZZ vertex (arXiv:2205.07715v3[hep-ex], only ZH scaled to higher E and $\mathcal{L}$)
- Realistic simulation of ILD experiment (luminositiy spectrum, machine background, event reconstruction)
- Demonstrating feasibility of linear e^+e^- colliders to probe CPV in VBF at high center-of-mass energies ($\sim$ 1 TeV)
- Input to the ECFA Study on Higgs/top/EW factories – ILD-PHYS-PUB–2024-002
- Published in Phys. Rev. D 110, 032011 (2024)

THANK YOU!

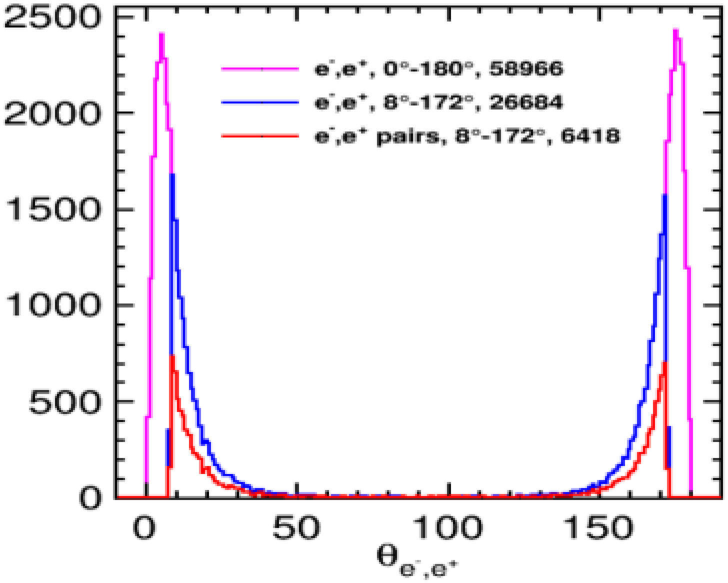
BACKUP



82 % @ 500 GeV



41.7 % @ 1 TeV



21.8 % @ 1.4 TeV