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

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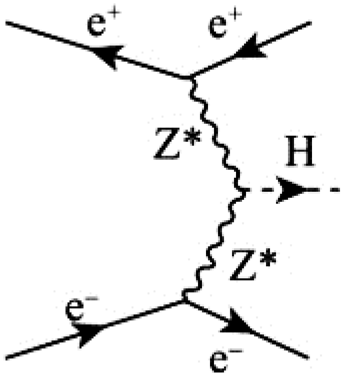
OPENING QUESTIONS/OUTLINE

- Is CP violated in Higgs interactions (with Z bosons)?
- Could 125 GeV Higgs mass eigenstate be a mixture of CP-odd and CP-even states 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 ILC ?
- The first fully simulated measurement in VBF at an e^+e^- collider



SIGNAL AND BACKGROUND

~ 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: $e^+e^- \rightarrow Hee, H \rightarrow b\bar{b}$	13	104000	$6{\cdot}10^5$ DELPHES~46 ab^{-1} 3495 full sim. ~0.27 ab^{-1}
$e^+e^- \rightarrow q\bar{q}e^+e^-$	$2.4{\cdot}10^3$	$19{\cdot}10^6$	$2{\cdot}10^5$
$e^+e^- \rightarrow q\bar{q}$	$3.6{\cdot}10^3$	$29{\cdot}10^6$	$4{\cdot}10^5$
$e^+e^- \rightarrow q\bar{q}e\nu$	$3{\cdot}10^3$	$24{\cdot}10^6$	$2.6{\cdot}10^6$
$e^+e^- \rightarrow llll$	$8{\cdot}10^3$	$64{\cdot}10^6$	$1.5{\cdot}10^6$
$e^+e^- \rightarrow eeqqqq$	37	$30{\cdot}10^4$	$1{\cdot}10^4$
$e^+e^- \rightarrow e\nu_e qqqq$	51	$4{\cdot}10^5$	$1{\cdot}10^6$
$e^+e^- \rightarrow qq\nu_e ee\nu_e$	5.6	$45{\cdot}10^3$	$5{\cdot}10^4$

- Unpolarized beams
- Generator level WHIZARD V2.8.3/UFO/Higgs characterization model signal and WHIZARD 1.95/SM background
- Generator parameters are set in a way that production cross-section depends only on Ψ_{CP}
- Higgs decays to 2 b-jets to avoid eeγ background

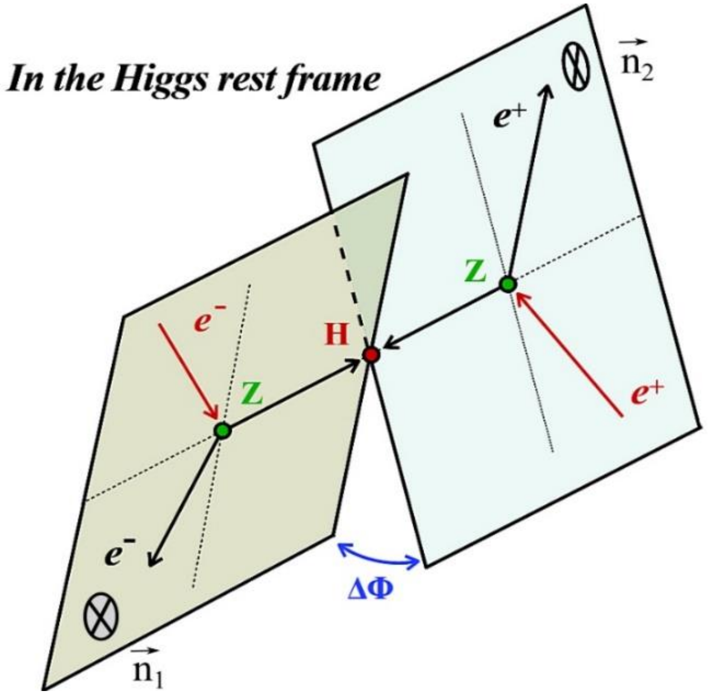
ANGULAR OBSERVABLE

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

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

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

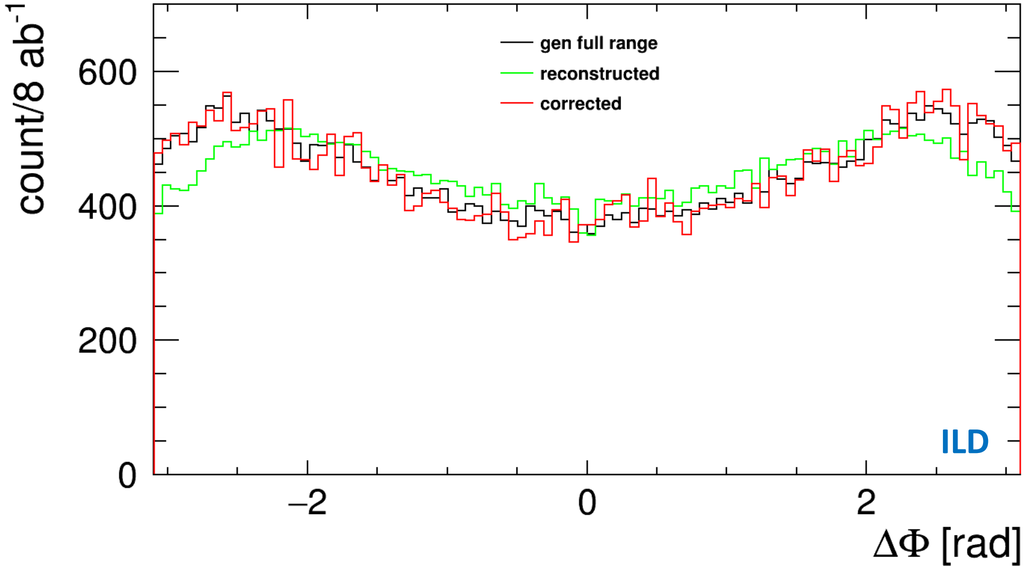
$$\hat{n}_1 = \frac{q_{e_i^-} \times q_{e_f^-}}{|q_{e_i^-} \times q_{e_f^-}|} \qquad \hat{n}_2 = \frac{q_{e_i^+} \times q_{e_f^+}}{|q_{e_i^+} \times q_{e_f^+}|}$$



GENERATED AND RECONSTRUCTED SIGNAL

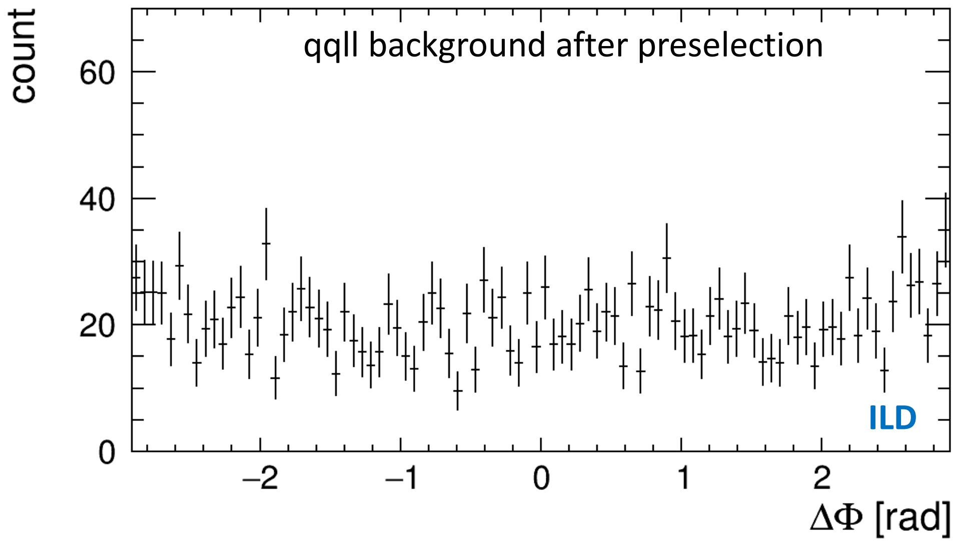
Measurement for the pure scalar $\Psi_{CP}=0$

- **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
  - $\Delta R_{max} = 0.5$
  - $p_{Tmin} = 0.5$ 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%

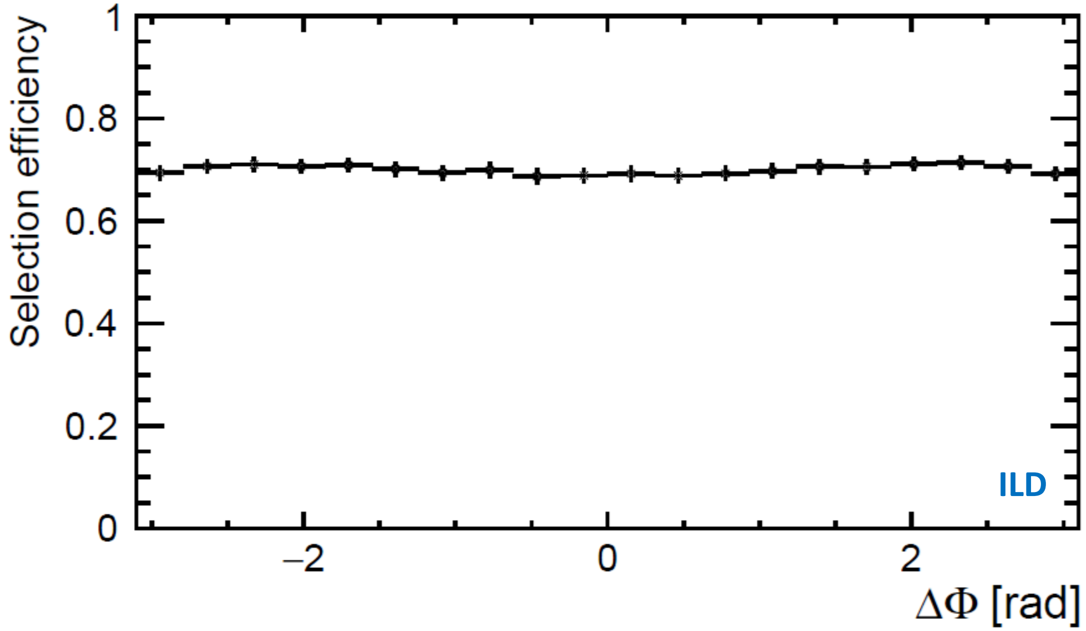
- **Background is CP insensitive**



EVENT SELECTION

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

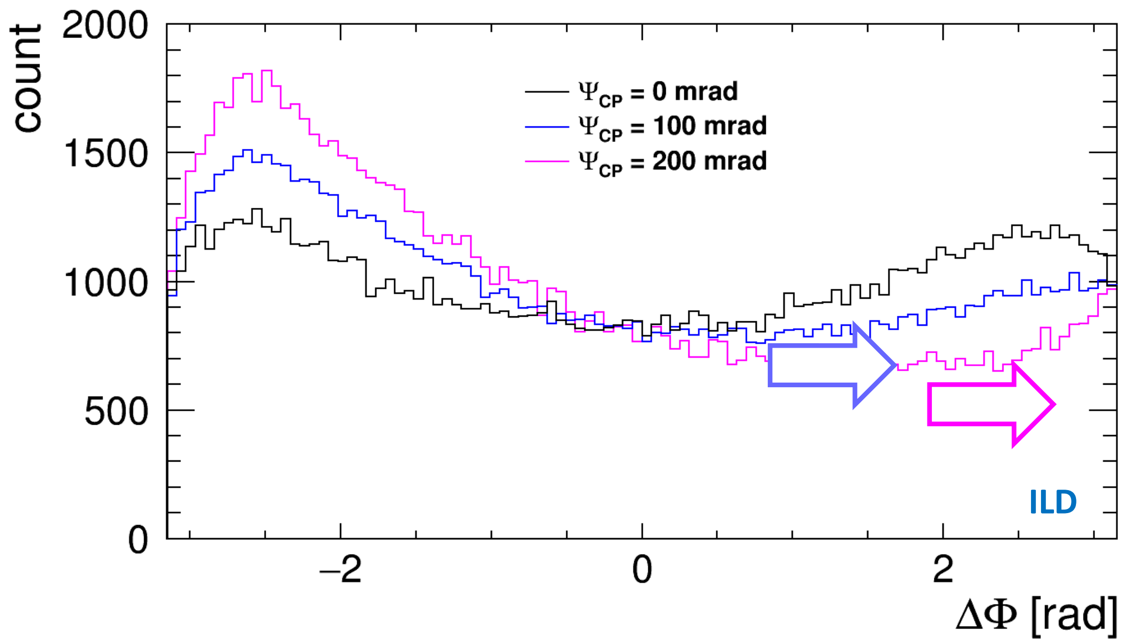
  - **Total signal efficiency: ~ 70%**
  - **Unbiased selection w.r.t. ΔΦ**
  - **Background is fully suppressed**

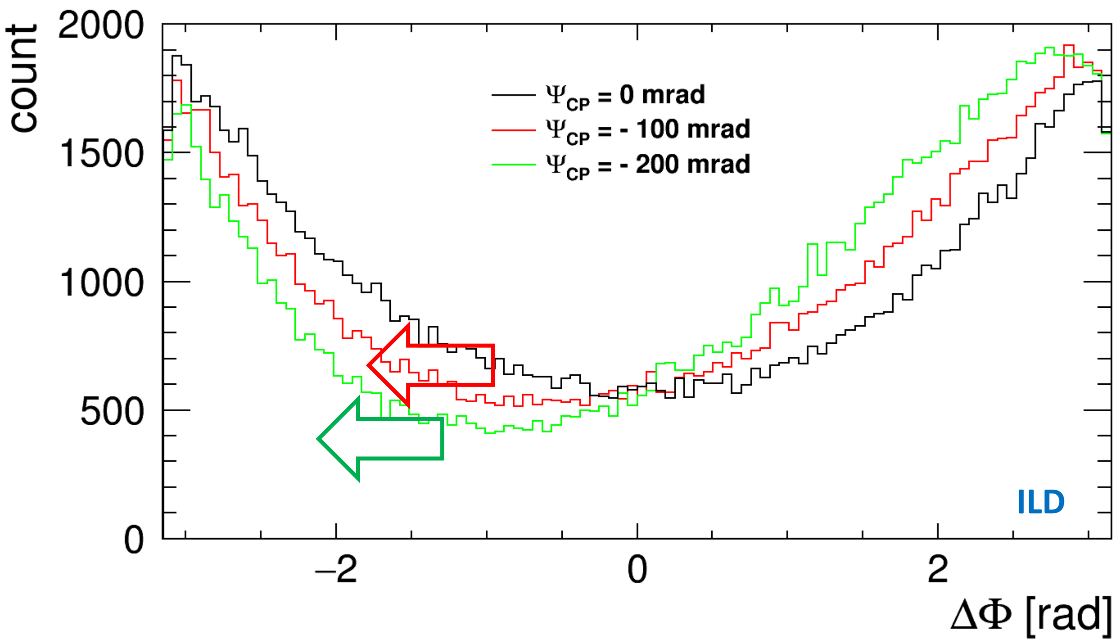


ANGULAR OBSERVABLE $\Delta\Phi$ AND MIXING ANGLE Ψ_{CP}

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

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



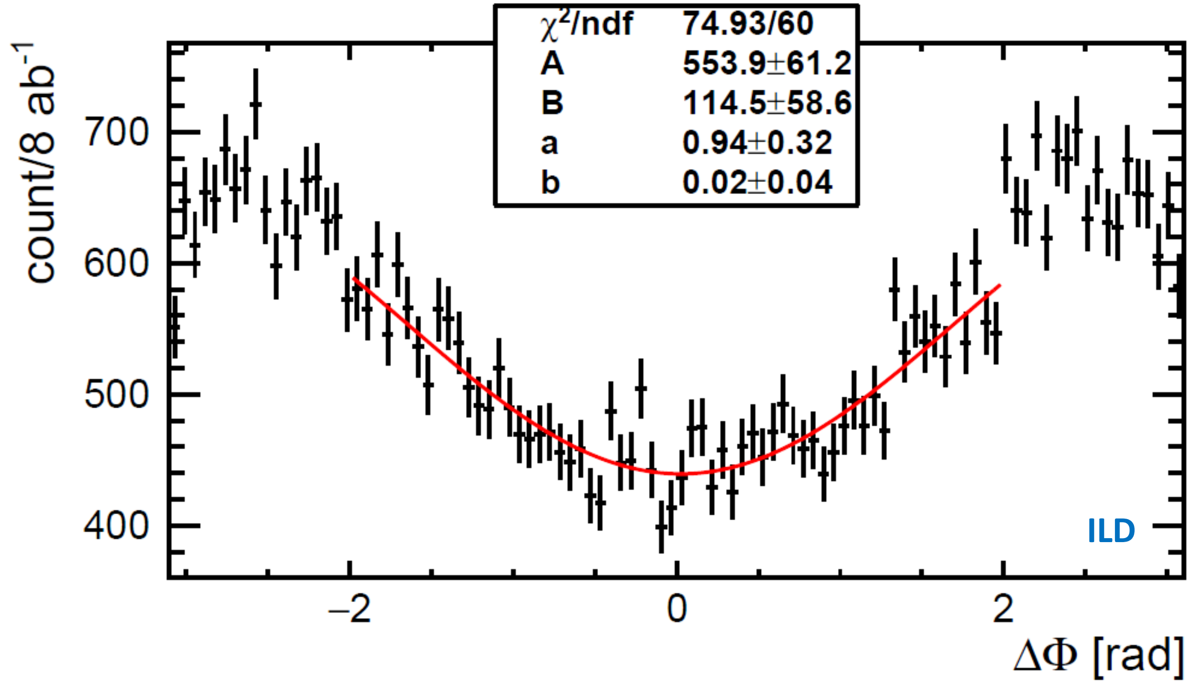


1. EXTRACTION OF ψ_{CP} FROM MIN ($\Delta\Phi$)

1. **Determine position of the local minimum (b/a)**

   from experimental data (corrected, selected S+B):

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

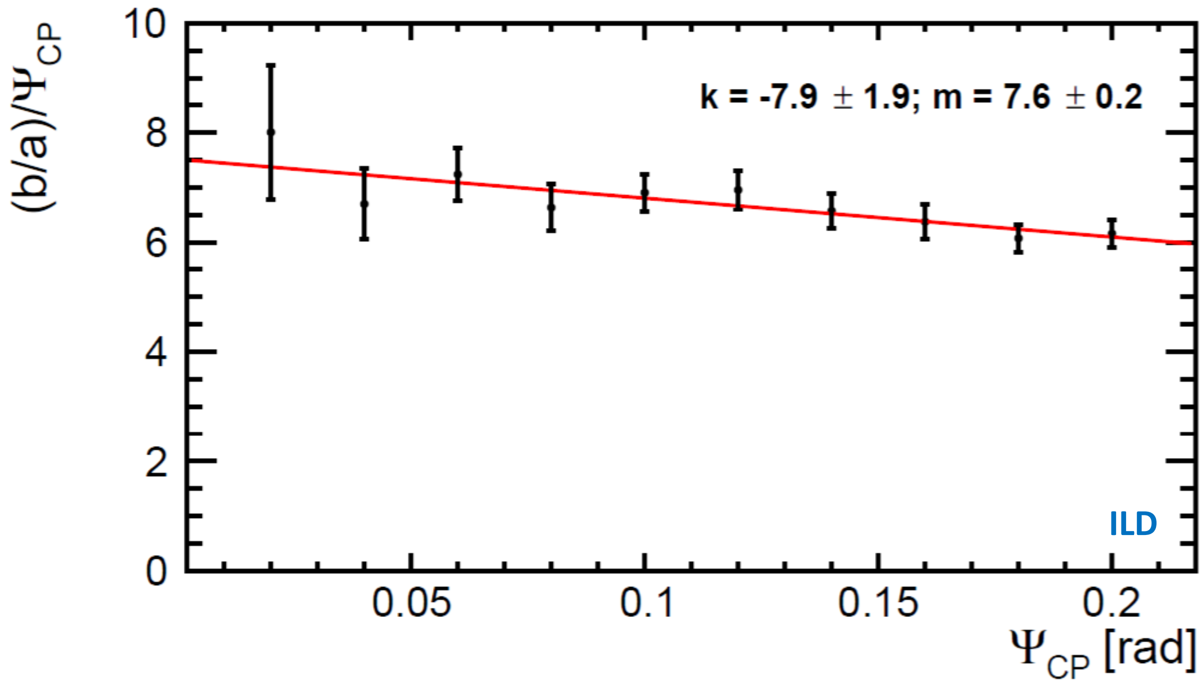


2. EXTRACTION OF ψ_{CP} FROM MIN ($\Delta\Phi$)

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

determine *k* and *m* (from simulation)

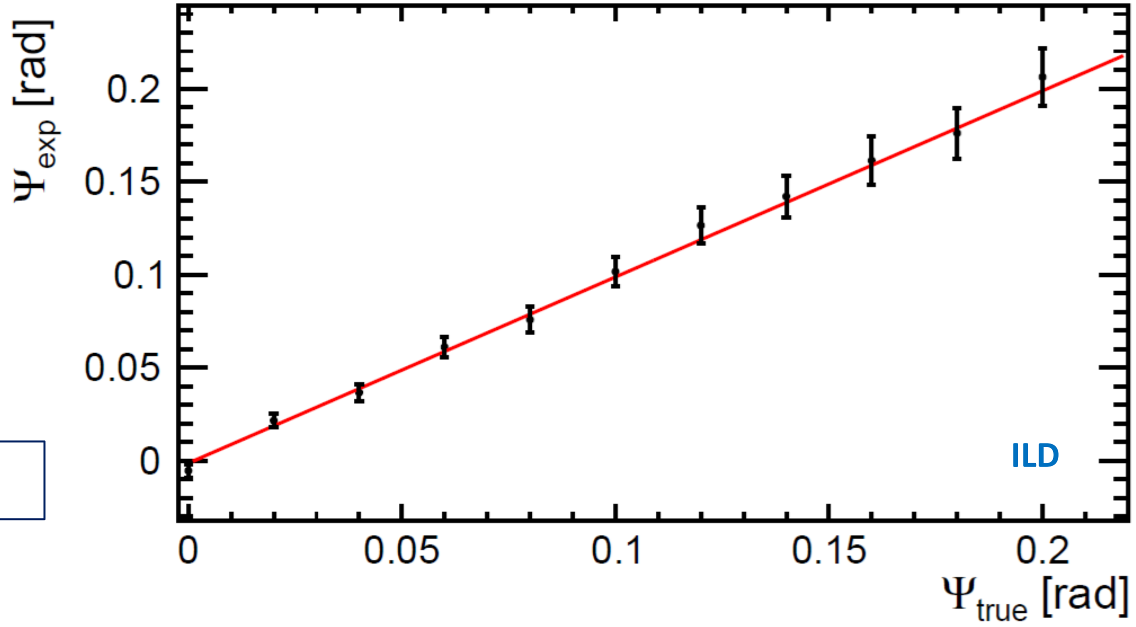
$$(b/a)/\ \Psi_{CP} = k \cdot \Psi_{CP} + m$$



3. EXTRACTION OF ψ_{CP} FROM MIN ($\Delta\Phi$)

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

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

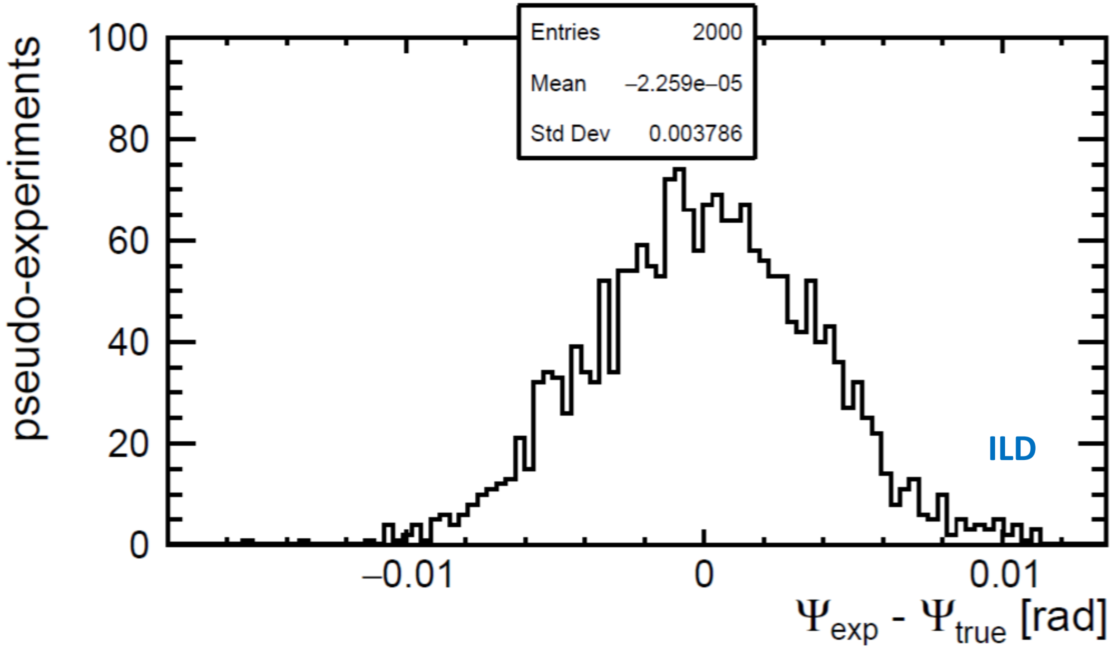


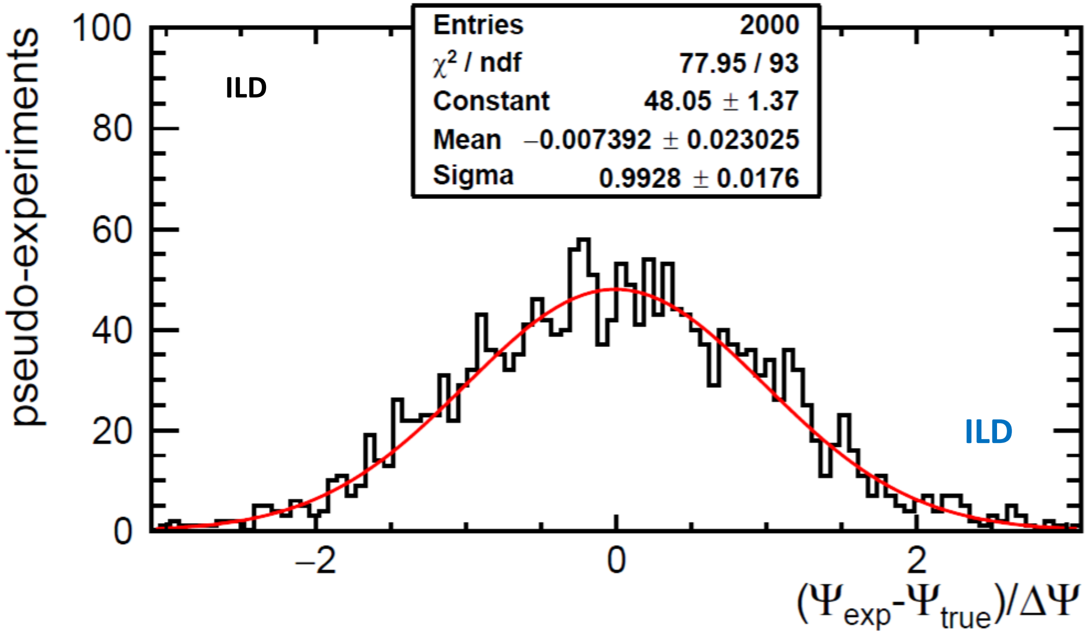
Generated values of Ψ_{CP} are correctly reproduced

PSEUDO-EXPERIMENTS

- 2000 pseudo-experiments at Ψ_{CP}= 0
- Pull distribution indicates that uncertainties are correctly estimated
- Fit parameters' uncertainties give < 1 mrad systematic error

$\Delta\Psi_{CP(stat.)}$= 3.8 mrad, 68% CL
$f_{CP} = sin^2(\Delta\Psi_{CP})$ = 1.44 $\cdot 10^{-5}$





DISCUSSION AND SUMMARY

- First (simulated) measurement in VBF (HZZ vertex), accepted for publication by the Phys.Rev.D (arXiv:2405.05820)
- Realistic ILC running scenario, full background simulation of ILD detector and fast simulation of the signal
- In line with the targeted precision from theory

(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	1,000	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	–	✓	✓	✓	$< 10^{-2}$
$H\mu\mu$	–	–	–	–	–	–	–	–	–	✓	–	$< 10^{-2}$