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

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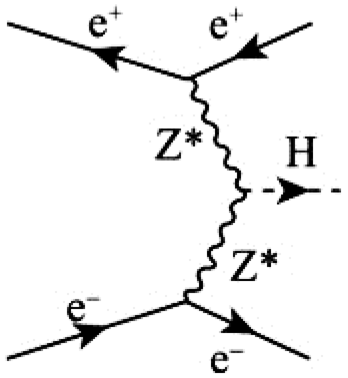
OPENING QUESTIONS/OUTLINE

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

SENSITIVE OBSERVABLE

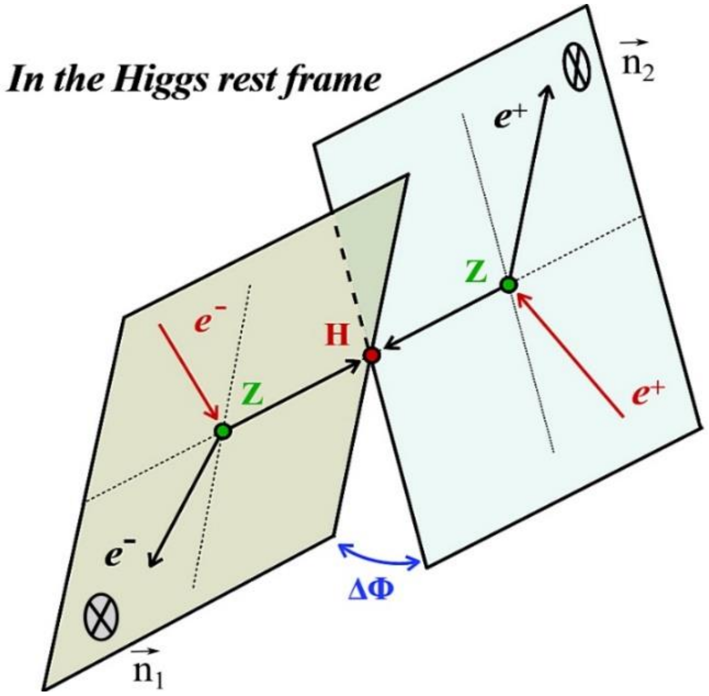
- Generic model of CPV mixing: h_{125}=H·cos Ψ_{CP} + A·sinΨ_{CP}
- CP-sensitive observable: angle between production planes $\Delta\phi$
- As shown in [arXiv:2203.11707v2] $\Delta\Phi$ carries the most information on Higgs CP state



$$\Delta\Phi = \begin{cases} \arccos(\cos\Delta\Phi), & sgn(\sin)\ \Phi \geq 0 \\ 2\pi - \arccos(\cos\Delta\Phi), & sgn(\sin)\ \Phi \leq 0 \end{cases}$$

$$\cos\Phi = (-\hat{n}_1 \cdot \hat{n}_2)$$

$$sgn(\sin\Phi): \frac{q_1 \cdot (\hat{n}_1 \times \hat{n}_2)}{|q_1 \cdot (\hat{n}_1 \times \hat{n}_2)|} \qquad \hat{n}_1 = \frac{q_{e_i^-} \times q_{e_f^-}}{|q_{e_i^-} \times q_{e_f^-}|} \qquad \hat{n}_2 = \frac{q_{e_i^+} \times q_{e_f^+}}{|q_{e_i^+} \times q_{e_f^+}|}$$



SIGNAL AND BACKGROUND

~ 1 TeV energies are optimal due to interplay of x-section and centrality

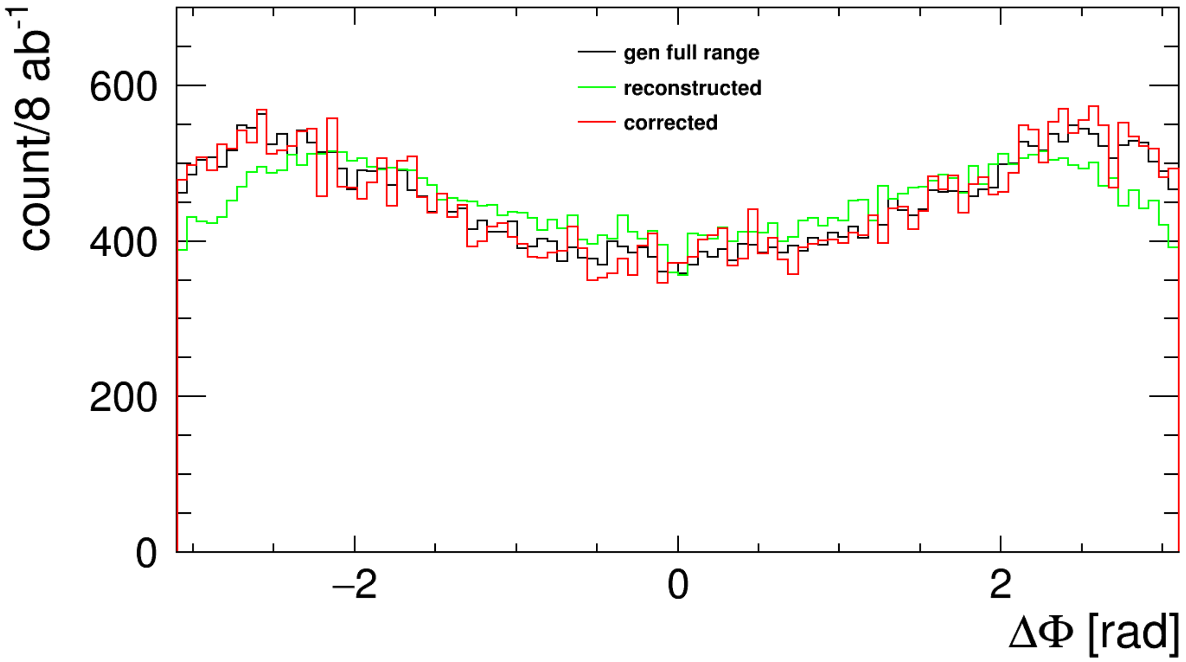
1 TeV	**σ (fb)**	**Expected in 8 ab^{-1}**	**Reconstructed with ILD**
SIGNAL: $\boldsymbol{e^+e^- \to Hee, H \to b\bar{b}}$	13	104000	200000 DELPHES 3495 full sim.
$e^+e^- \to q\bar{q}l^+l^-$	255	$2\cdot10^6$	5886
$e^+e^- \to q\bar{q}$	9375	$75\cdot10^6$	120343
$e^+e^- \to q\bar{q}l\nu$	4116	$32.9\cdot10^6$	955058

	√s	**beam polarisation**	**∫Ldt (baseline)**
ILC	0.1 - 1 TeV	e-: 80% e+: 30% (20%)	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 signal and WHIZARD 1.95/SM background
- Unpolarized beams

GENERATED AND RECONSTRUCTED SIGNAL

Corrected reconstructed signal for pure scalar Ψ_{CP}=0, **generated** information (WHIZARD) and **uncorrected** reconstructed signal

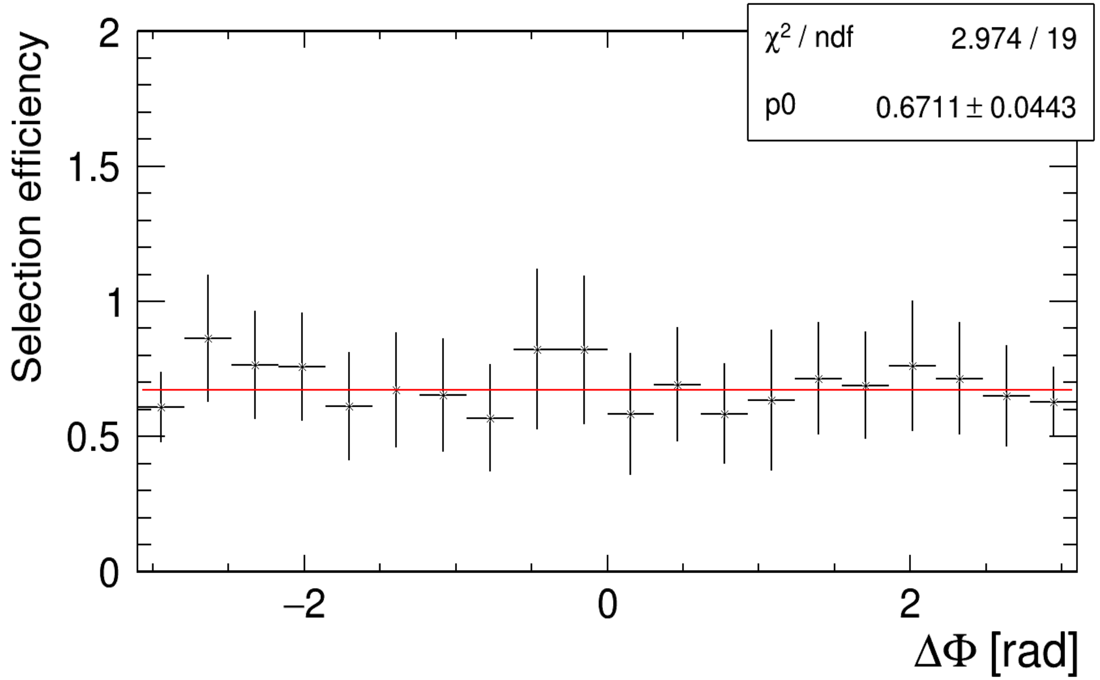


- Acceptance correction needed to retrieve full physical information
- Generated information is reasonably well reproduced with corrected reconstructed data

EVENT SELECTION

- **Preselection – electron isolation**:
  - $m_{e^+e^-} > 200$ GeV (veto HZ)
  - 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: **~71%**

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

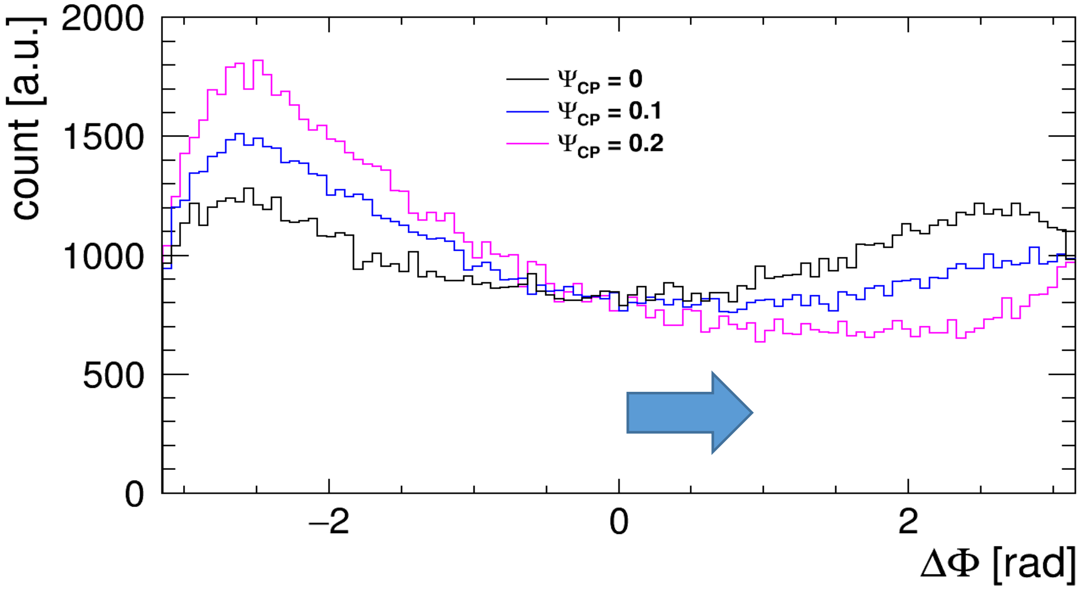


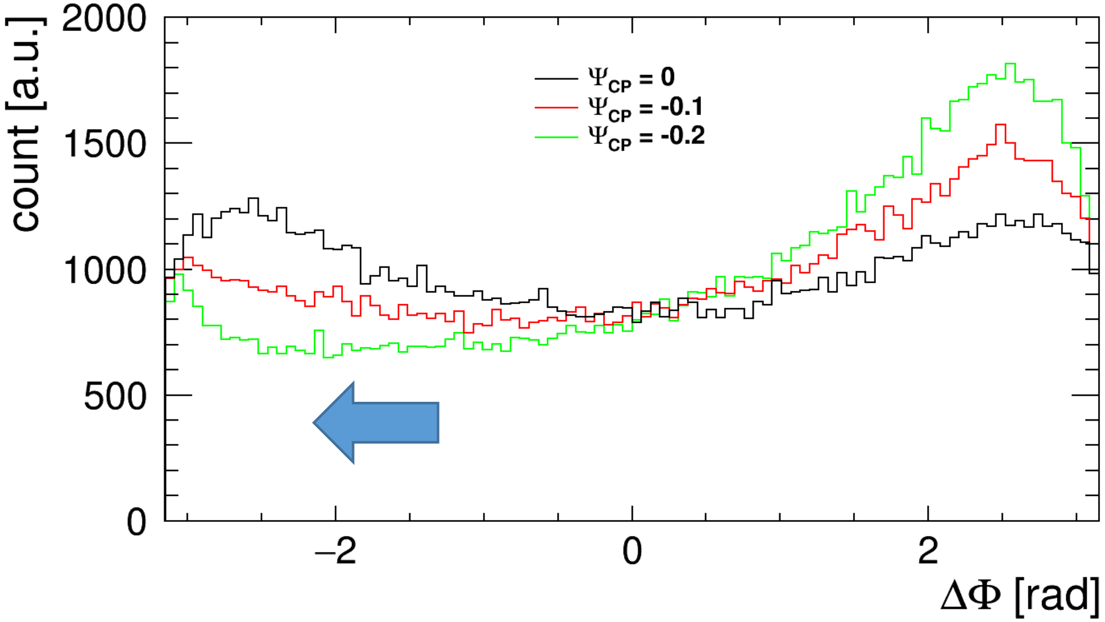
- **Unbiased selection** w.r.t. ΔΦ
- Background fully suppressed, but needs additional simulation effort: sample rather small (~1% of the full size), not all flavors contained

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

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

- Differently from the $H\rightarrow\tau\tau$ angular observable whose dependence on Ψ_{CP} can be derived from the differential x-section, here Ψ_{CP} has to be extracted **empirically**





HOW TO EXTRACT ψ_{CP}?

✓ Minimum of $\Delta\Phi$ is sensitive to Ψ_{CP};

1. Determine position of the local minimum (b/a) from experimental (pseudo) data:

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

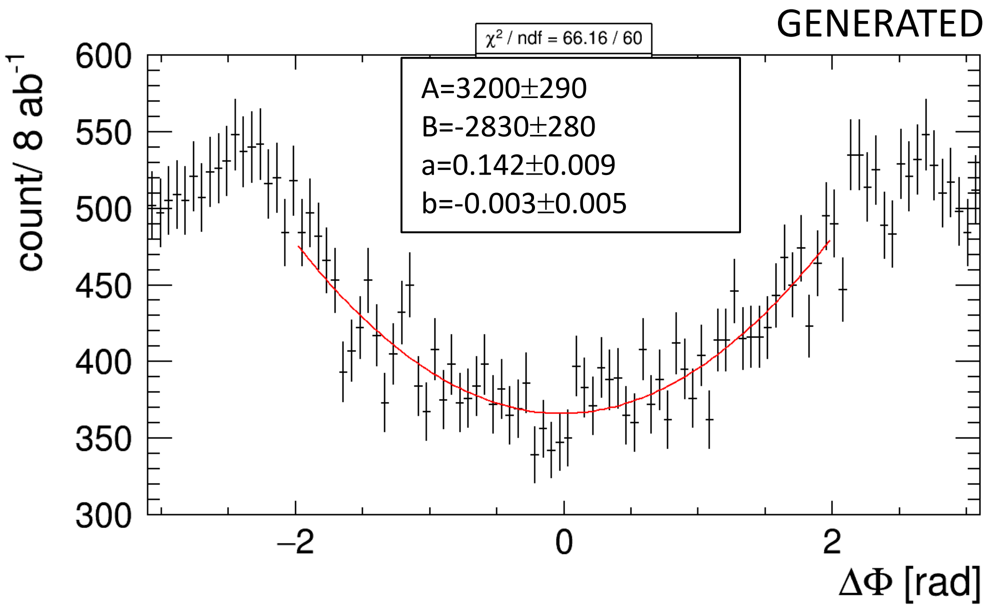
2. Position (b/a)/ Ψ_{CP} is a linear function of Ψ_{CP}:

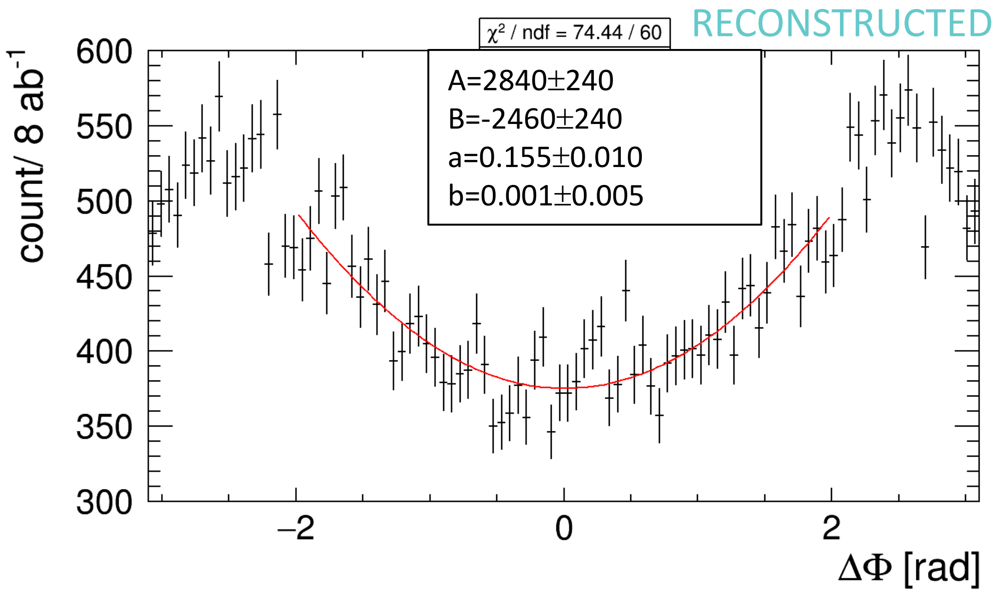
   $(b/a)/\Psi_{CP}=k\cdot\Psi_{CP}+m$

3. Determine from simulation coefficients *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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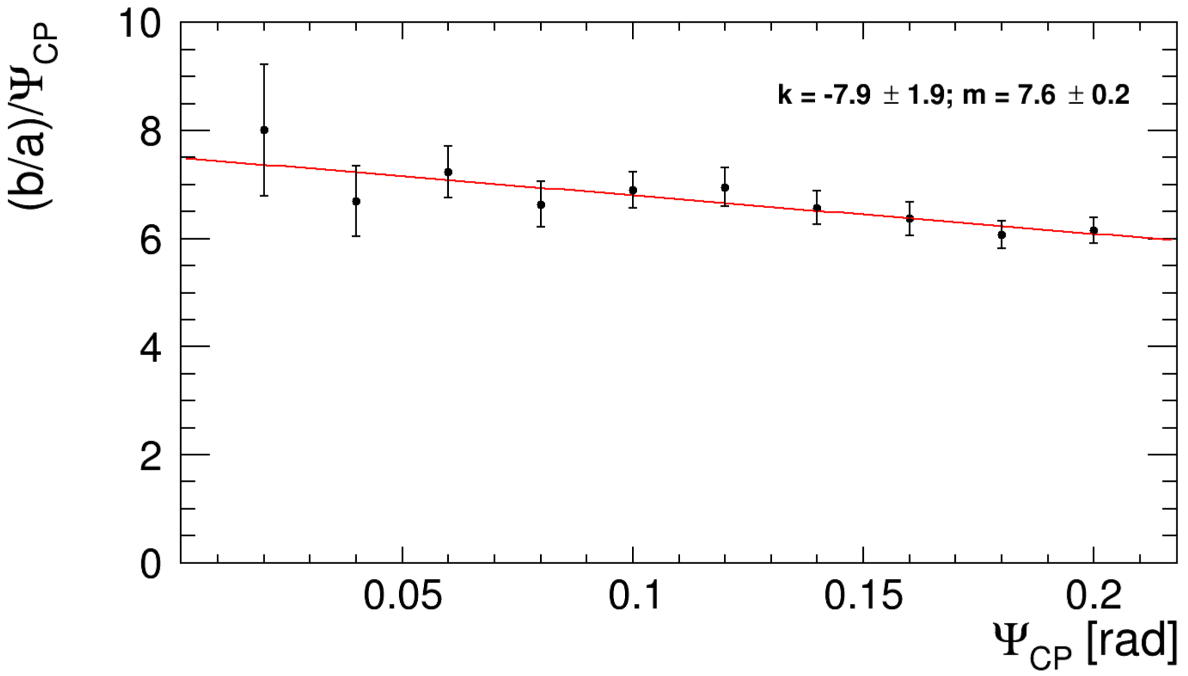

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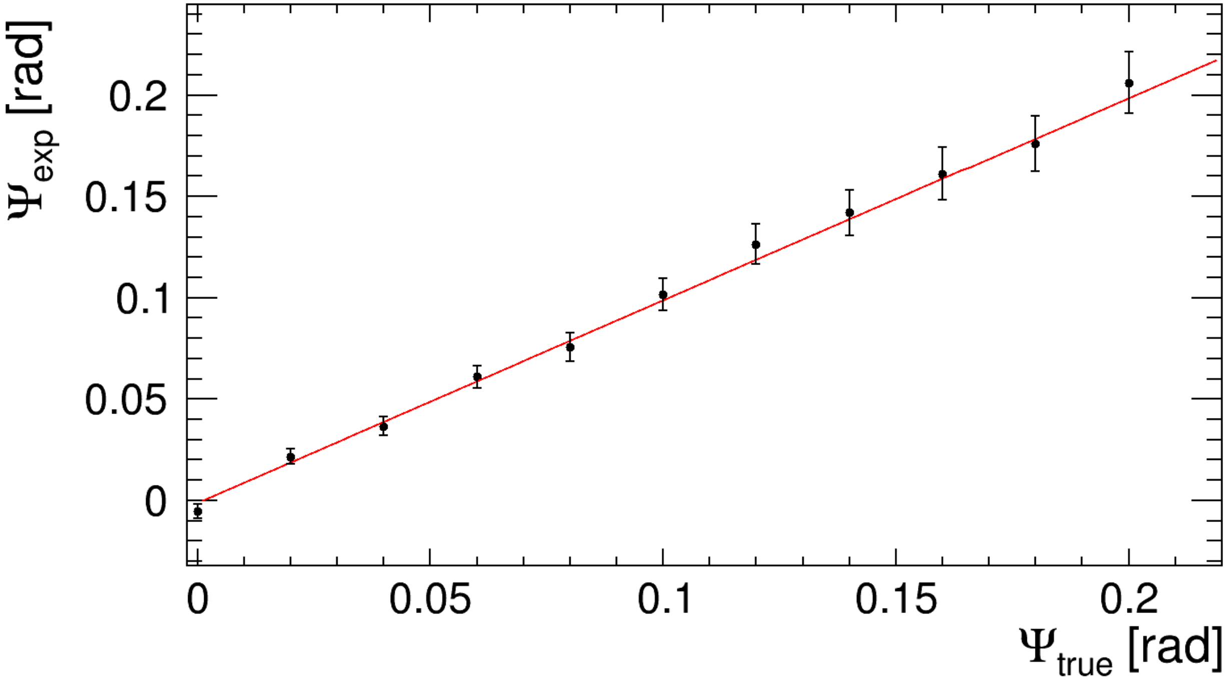

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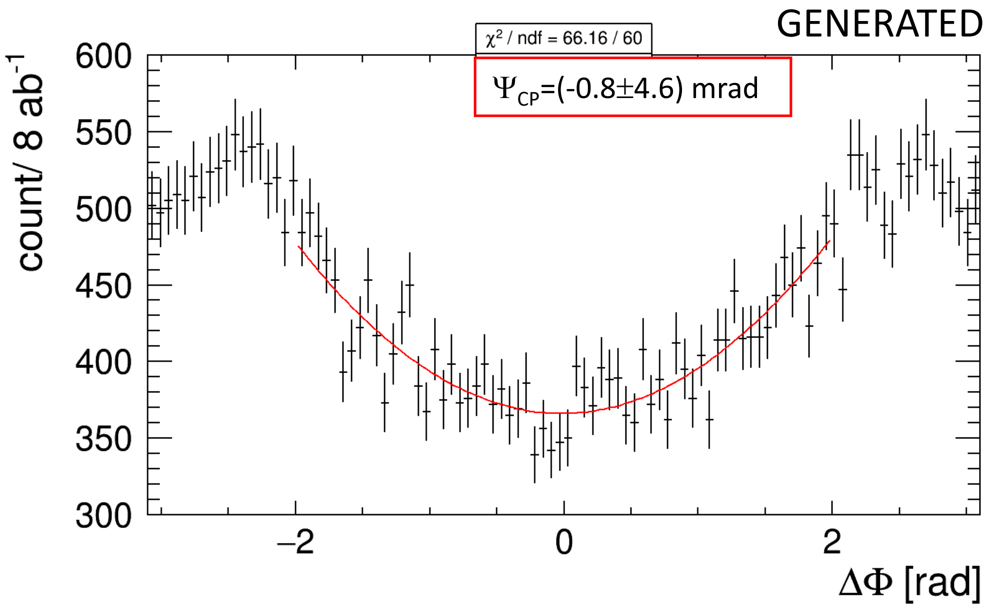
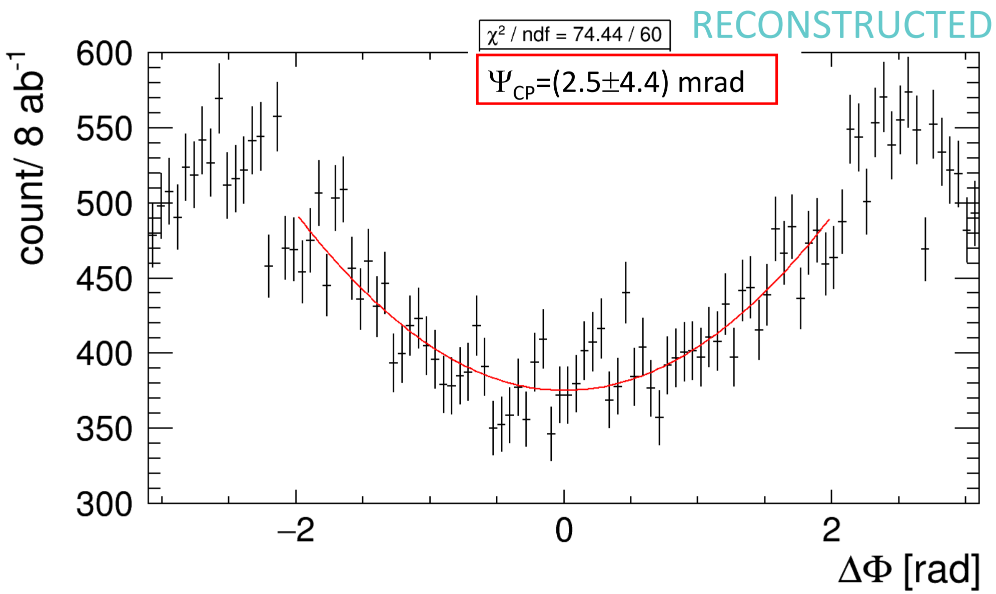
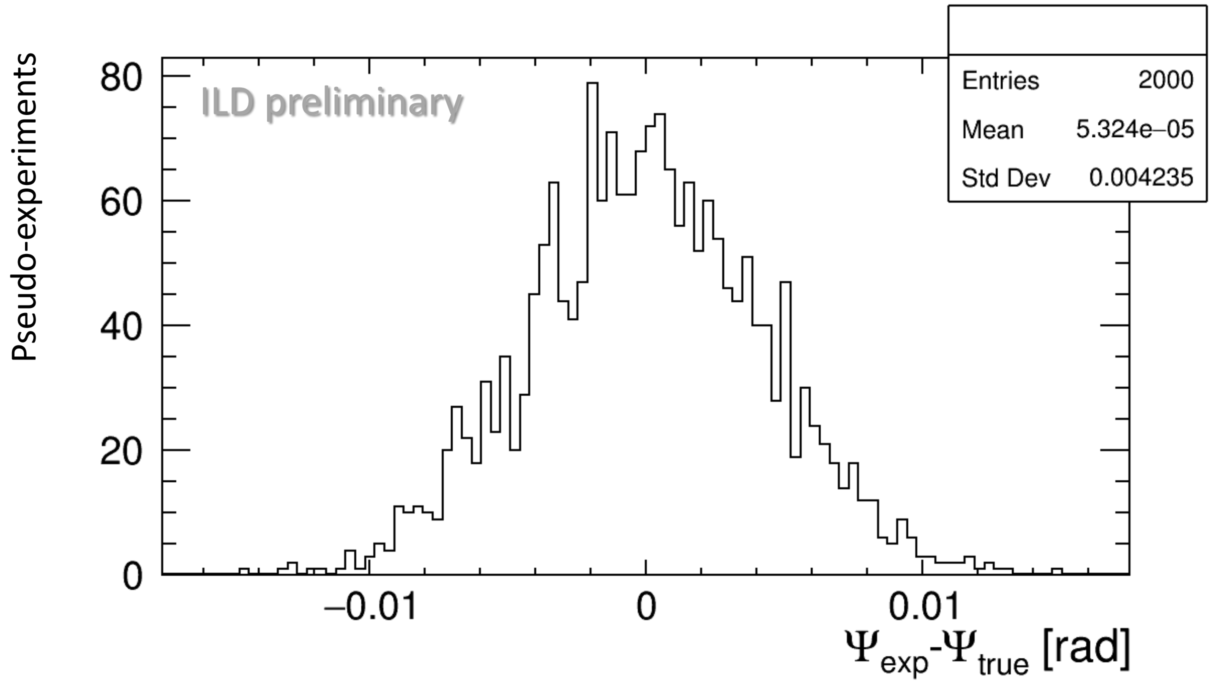
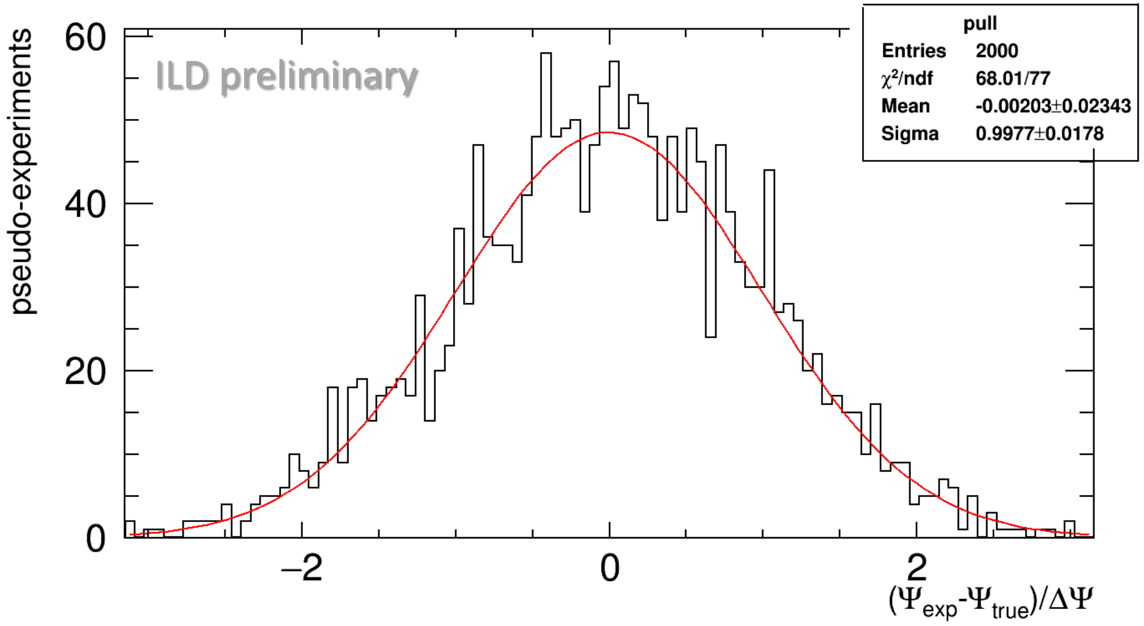




PSEUDO-EXPERIMENTS

$\Delta\Psi^{CP}_{(stat.)}$= 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 parameter uncertainties gives ~1 mrad

INTERPRETATION

- Common framework is defined in the Snowmass CPV White paper: benchmark parameter $f_{CP} \sim sin^2(\Delta\Psi_{CP})$ quantifying relative contribution from CP-odd amplitude
- 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	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	$4.0\cdot10^{-5}$	$2.5\cdot10^{-6}$	✓	$3.9\cdot10^{-5}$	$2.9\cdot10^{-5}$	$1.3\cdot10^{-5}$	$3.0\cdot10^{-6}$ (10 ab^{-1})	✓	✓	✓	✓	$< 10^{-5}$
$H\gamma\gamma$	–	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	–	✓	✓	✓	$< 10^{-2}$
$H\mu\mu$	–	–	–	–	–	–	–	–	–	✓	–	$< 10^{-2}$

1 TeV ILC

- ✓ First measurement in VBF
- ✓ First measurement in HZZ vertex based on angular observable

INTERPRETATION

(68% CL, pure scalar)

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E (GeV)	14,000	14,000	100,000	250	350	500	**1 TeV**	1,300	125	125	3,000	(theory)
$\mathcal{L}$ (fb^{-1})	300	3,000	30,000	250	350	500	**8 ab^{-1}**	1,000	250	20	1,000	
HZZ/HWW	$4.0 \cdot 10^{-5}$	$2.5 \cdot 10^{-6}$	✓	$3.9 \cdot 10^{-5}$	$2.9 \cdot 10^{-5}$	$1.3 \cdot 10^{-5}$	**$1.6 \cdot 10^{-5}$**	✓	✓	✓	✓	$< 10^{-5}$
$H\gamma\gamma$	–	0.50	✓	–	–	–	–	–	0.06	–	–	$< 10^{-2}$
$HZ\gamma$	–	~ 1	✓	–	–	–	~ 1	–	–	–	–	$< 10^{-2}$
Hgg	0.12	0.011	✓	–	–	–	–	–	–	–	–	$< 10^{-2}$
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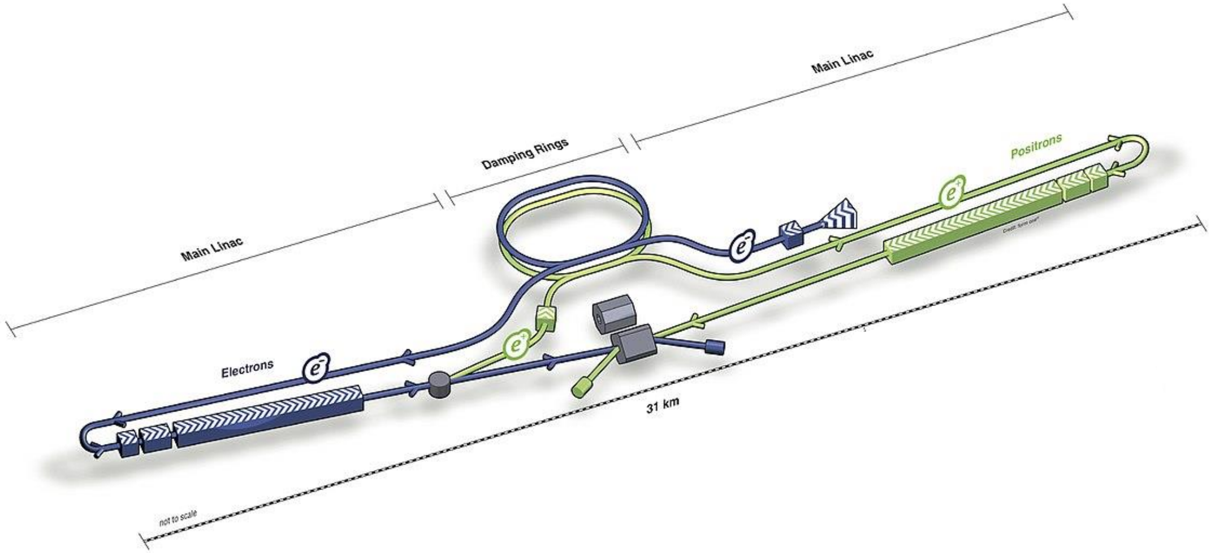
$H\tau\tau$	0.07	0.008	✓	0.01	0.01	0.02	0.06	–	✓	✓	✓	$< 10^{-2}$
$H\mu\mu$	–	–	–	–	–	–	–	–	–	✓	–	$< 10^{-2}$

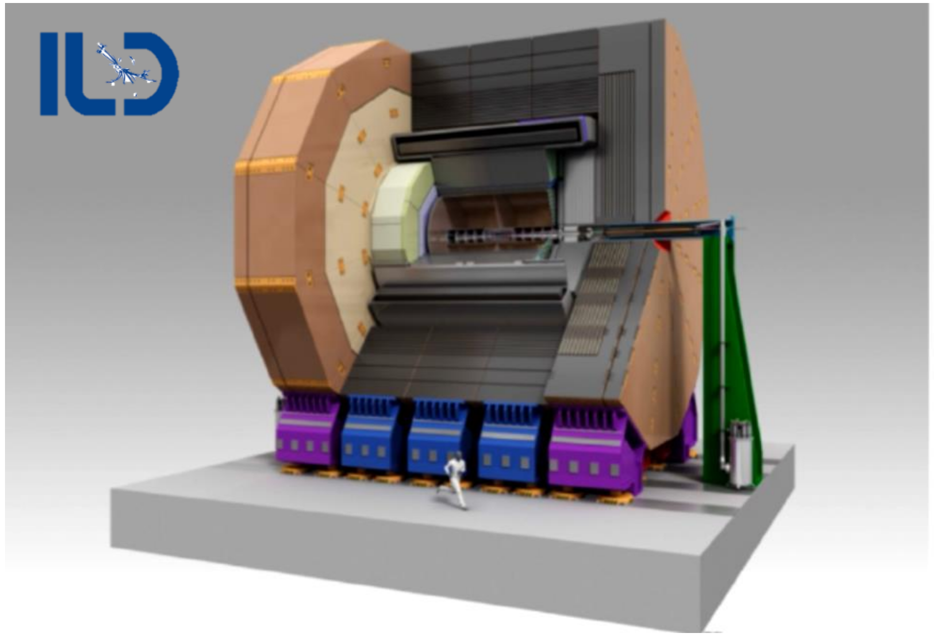
SUMMARY

- ✓ Complete simulation of CPV Higgs mixing angle (Ψ_{CP}) measurement is performed at 1 TeV ILC with the ILD detector
- ✓ This is the first result in VBF fusion based on angular observable ($\Delta\Phi$);
- ✓ Knowing the dependence of $\Delta\Phi$ minimum to Ψ_{CP} from simulation, Ψ_{CP} can be determined from (experimental) data;
- ✓ 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);
- ✓ The above uncertainty corresponds to $f_{CP} \approx 1.6 \cdot 10^{-5}$ approaching theoretical target;
- ✓ The study is ongoing in terms of further refinements in background simulation.

BACKUP

ILC AND ILD





- Mature e^+e^- collider project (TDR in 2013)
- Currently led by the IDT
- Superconducting technology (prototyped for E-XFEL)
- Tunable and upgradeable (1 TeV)
- Comes with numerous options for auxiliary experiments (beam-dump, fixed target)

- Jet energy resolution 3-4%
- Asymptotic transverse momentum resolution = $2 \cdot 10^{-5}$ GeV^{-1}
- Impact parameter resolution < 5 µm
- Hermeticity down to 5 mrad
- Triggerless operation
- Current status summarized in IDR

arXiv:2003.01116