International Workshop on Future Linear Colliders

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MEASUREMENT OF THE CPV HIGGS MIXING ANGLE IN ZZ-FUSION AT 1 TEV ILC

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OPENING QUESTIONS

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]?

Common framework is defined in the Snowmass CPV White paper: Benchmark parameter $f_{CP}^{HX} \equiv \frac{\Gamma_{H\to X}^{CP\,\mathrm{odd}}}{\Gamma_{H\to X}^{CP\,\mathrm{odd}} + \Gamma_{H\to X}^{CP\,\mathrm{even}}}$;

quantifying contributions from CP-odd and CP-even amplitudes;

- Assuming ≤10% admixture of CP-odd state, sensitivity target on f_{CP} is set from theory;
- Common interpretation for LHC/HL-LHC, EFT and CP-sensitive measurements; $f_{CP} \sim \sin^2(\Delta\Psi_{CP})$

STATE OF THE ART (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	f_{CP}
HZZ/HWW	$4.0\cdot10^{-5}$	$2.5\cdot10^{-6}$	✓	$3.9\cdot10^{-5}$	$2.9\cdot10^{-5}$	$1.3\cdot10^{-5}$	$3.0\cdot10^{-6}$ EFT HZ	✓	✓	✓	✓	$< 10^{-5}$
$H\gamma\gamma$	–	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	–	✓	✓	✓	$< 10^{-2}$
$H\mu\mu$	–	–	–	–	–	–	–	–	–	✓	–	$< 10^{-2}$

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	f_{CP}
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	✓	–	–	–	–	–	–	–	–	$< 10^{-2}$
$Ht\bar{t}$									–	–	✓	$< 10^{-2}$
$H\tau\tau$										✓	✓	$< 10^{-2}$
$H\mu\mu$										✓	–	$< 10^{-2}$

$\Delta\Psi_{CP}$:

≤4 mrad

≤100 mrad

arXiv:2205.07715v3

Collider	pp	pp	e^+e^-	e^+e^-	e^+e^-	e^+e^-	$\gamma\gamma$	$\mu^+\mu^-$	target
E (GeV)	14,000	14,000	250	350	500	1,000	126	126	(theory)
$\mathcal{L}$ (fb^{-1})	300	3,000	250	350	500	1,000	250		
spin-2^+_m	$\sim10\sigma$	$\gg10\sigma$	$>10\sigma$	$>10\sigma$	$>10\sigma$	$>10\sigma$			$>5\sigma$
$VVH^\dagger$	0.07	0.02	✓	✓	✓	✓	✓	✓	$< 10^{-5}$
$VVH^\ddagger$	$4\cdot10^{-4}$	$1.2\cdot10^{-4}$	$7\cdot10^{-4}$	$1.1\cdot10^{-4}$	$4\cdot10^{-5}$	$8\cdot10^{-6}$	–	–	$< 10^{-5}$
$VVH^\diamond$	$7\cdot10^{-4}$	$1.3\cdot10^{-4}$	✓	✓	✓	✓	–	–	$< 10^{-5}$
ggH	0.50	0.16	–	–	–	–	–	–	$< 10^{-2}$
$\gamma\gamma H$	–	–	–	–	–	–	0.06	–	$< 10^{-2}$
$Z\gamma H$	–	✓	–	–	–	–	–	–	$< 10^{-2}$
$\tau\tau H$	✓	✓	0.01	0.01	0.02	0.06	✓	✓	$< 10^{-2}$
ttH	✓	✓	–	–	0.29	0.08	–	–	$< 10^{-2}$
$\mu\mu H$	–	–	–	–	–	–	–	✓	$< 10^{-2}$

† estimated in $H \to ZZ^*$ decay mode

‡ estimated in $V^* \to HV$ production mode

$^\diamond$ estimated in $V^*V^* \to H$ (VBF) production mode

HZ

arXiv:1310.8361v2

No estimates in VBF

ZZ-FUSION AT 1TeV ILC

- ✓ Most of the measurements are EFT
- ✓ EFT: based on assumptions to reduce number of free parameters
- ✓ EFT: fit experimental information which is not necessarily truly CP-sensitive

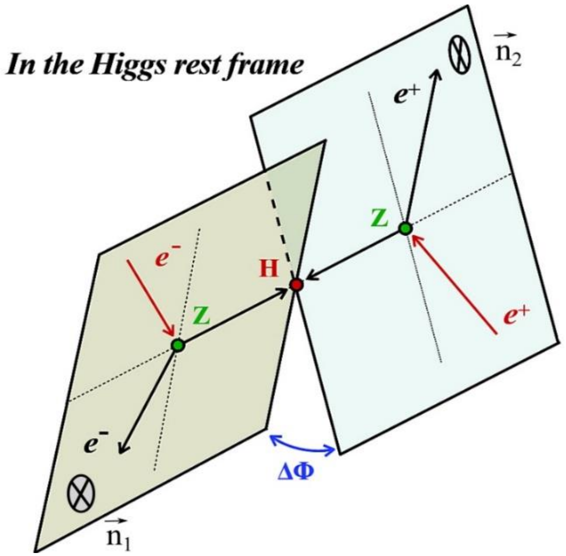
⇨

- ✓ Use CP-sensitive observables
- ✓ There are more than one
- ✓ Angle between production/decay planes is the most sensitive (arXiv:2203.11707v2)

- ✓ Limitation in precision by statistics (forward t-channel process)
- ✓ Background

⇨

- ✓ ~ 1TeV energies are better than 500GeV/3TeV due to interplay of x-section and centrality
- ✓ Chose exclusive qq final state, to avoid high x-section ee(γ) processes



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

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

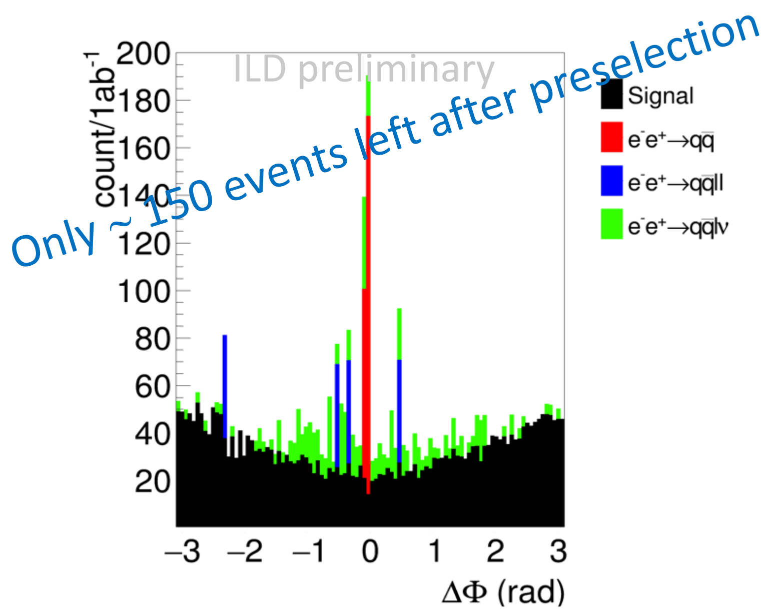
$$\sin\Phi = \frac{q_1 \cdot (\hat{n}_1 \times \hat{n}_2)}{|q_1 \cdot (\hat{n}_1 \times \hat{n}_2)|}$$

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

Similar approach in arXiv:1208.4018, T. Ogawa, PhD, 2018.

EVENT SAMPLES AND SELECTION STRATEGIES

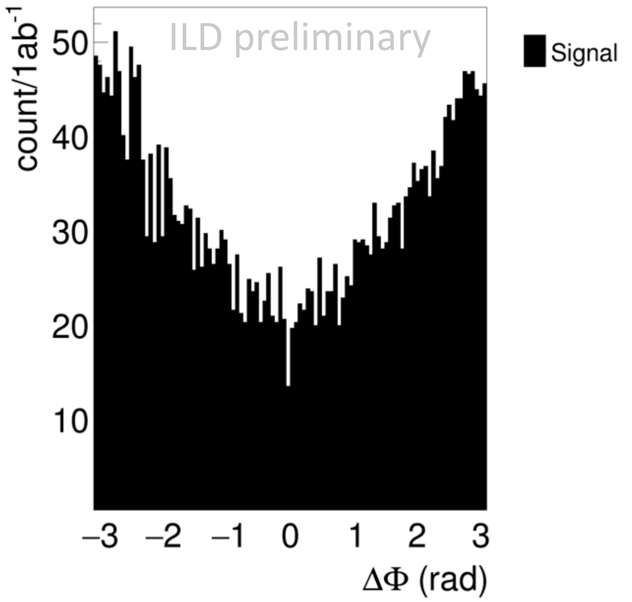
1 TeV	σ (fb)	Expected in 1 ab^{-1}	Simulated/ILD	Events after final selection (1 ab^{-1})
SIGNAL: $\boldsymbol{e^+e^- \to Hee, H \to b\bar{b}}$	16	16016/8231^{tracker}	27911 DELPHES v3.4.2 (*with ILD delphes card*) 3495 MC	5658
$e^+e^- \to q\bar{q}l^+l^-$	255	255000	5886 (1/43)	/
$e^+e^- \to q\bar{q}$	9375	9375000	120343 (1/78)	/
$e^+e^- \to q\bar{q}l\nu$	4116	4116000	955058 (1/4)	/



+ Generator study: WHIZARD V2.8.3, UFO framework to import Higgs Characterization model

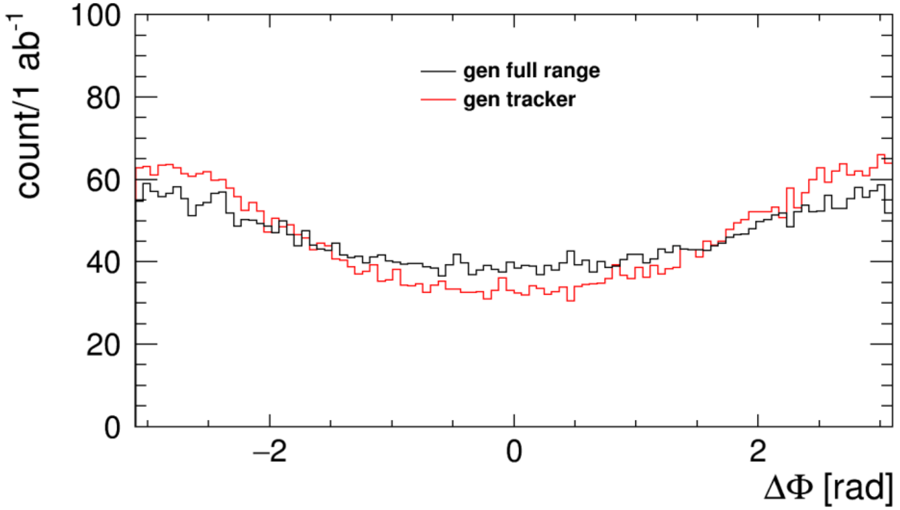
- ✓ **Selection cuts:**
  - ✓ $80\ GeV < m_{q\bar{q}} < 160\ GeV$
  - ✓ $m_{Z_1,Z_2} > 30\ GeV$
  - ✓ $p_{T\,ee} > 15\ GeV,$
  - ✓ $p_{T\,miss} > 150\ GeV$
  - ✓ Selection efficiency: **96%**
  - ✓ **Total signal efficiency: ~ 68%**
  - ✓ **Background fully suppressed**

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

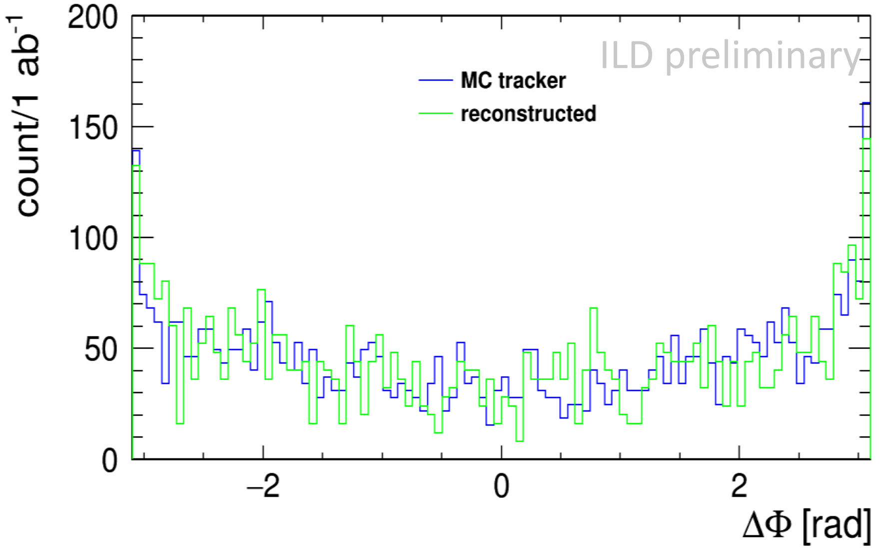


1 ab^{-1}, 1 TeV ILC

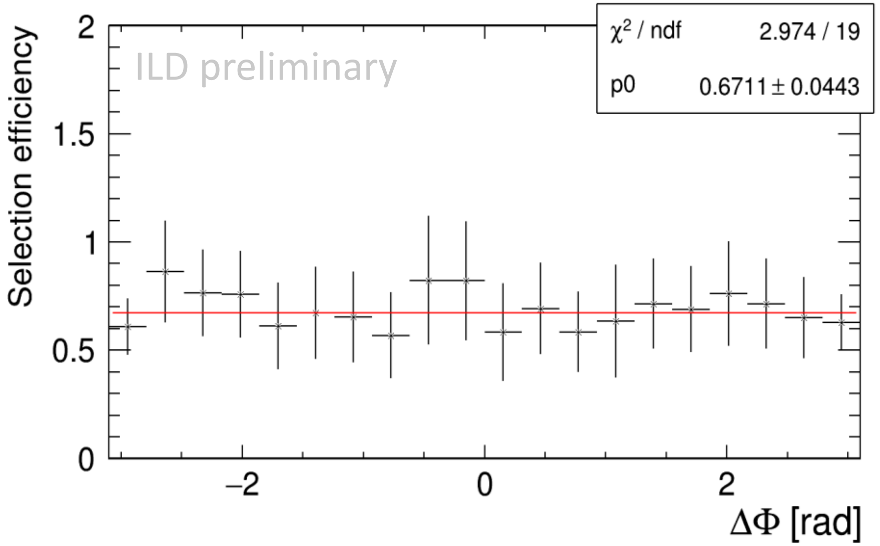
(H→bb, 100% $e_L^- e_R^+$ polarization /simulated sample tracker: 14345 DELPHES, 1619 full reconstruction)



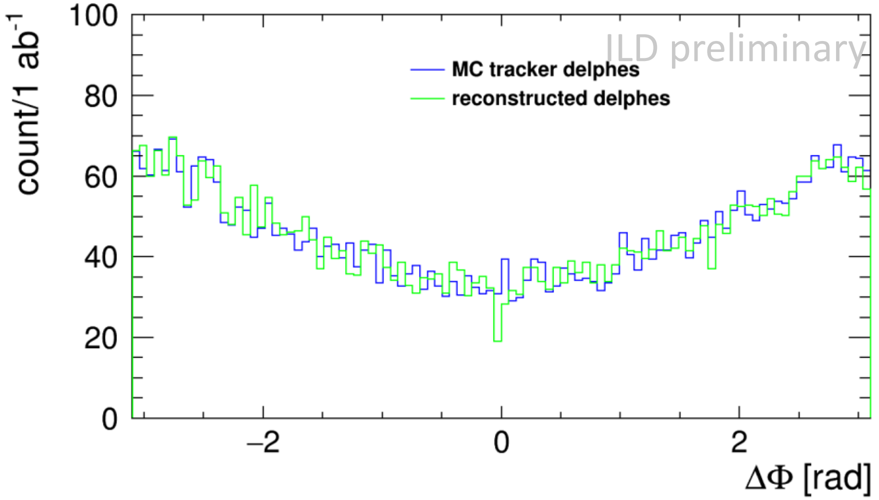
- ✓ Major effect (on Φ shape) comes from the acceptance;



- ✓ MC matches reconstructed information (negligible detector effects)



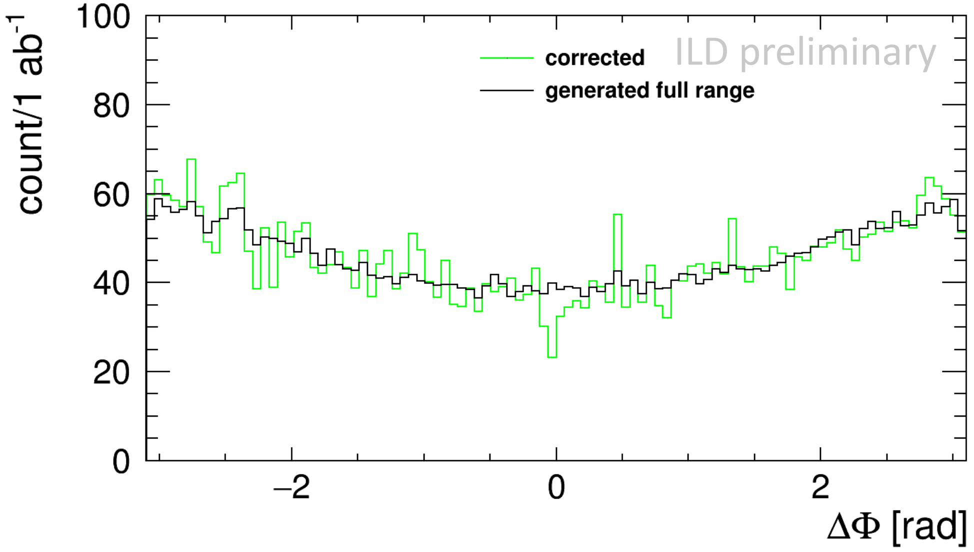
- ✓ Event selection does not biases ΔΦ



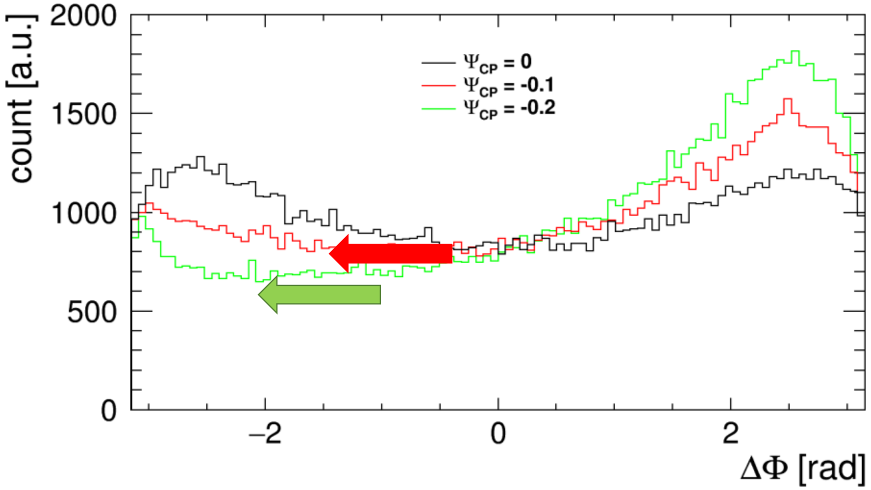
ACCEPTANCE CORRECTION AND Ψ_{CP} DETERMINATION

Corrected signal for pure scalar Ψ_{CP}=0

Reasonably reproduced full physical information



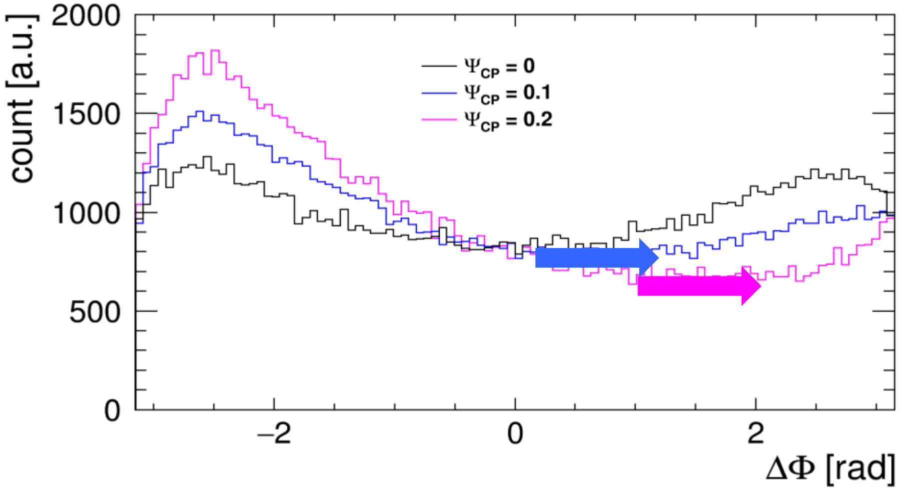
1. Minimum of ΔΦ is sensitive to Ψ_{CP}



HOW TO EXTRACT ψ_{CP}?

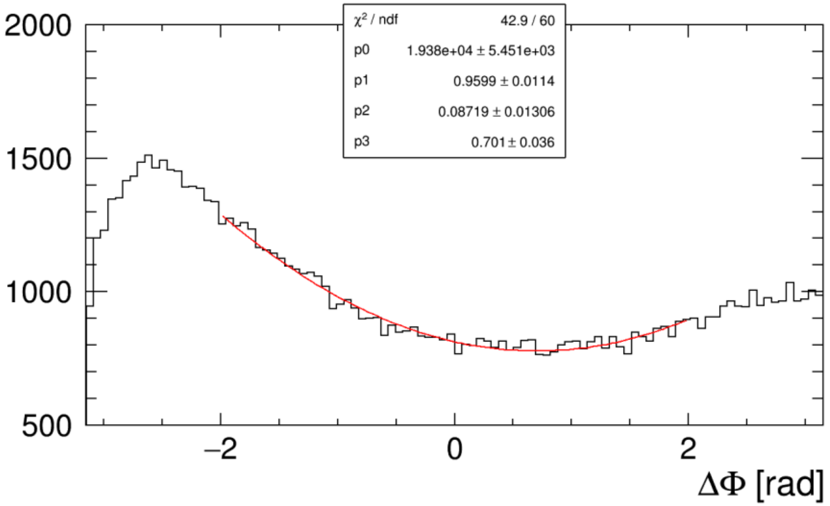
- There is not (known) exact dependence of ΔΦ on Ψ_{CP} in HVV vertices (differently from Hff);

1. Minimum of ΔΦ is sensitive to Ψ_{CP};
2. Perform a local fit around the minimum b/a: $f(\Delta\Phi, \Psi_{CP}) = A + B \cdot \cos(a \cdot \Delta\Phi - b)$
3. Position of minimum (b/a)/ Ψ_{CP} is a linear function of Ψ_{CP}: $(b/a)/\Psi_{CP} = k \cdot \Psi_{CP} + m$
4. Determine (from simulation) coefficients of that function (*k*, *m*) in a certain interval of Ψ_{CP} ;
5. Measure the minimum (b/a) from the fit of experimental data;
6. Ψ_{CP} can be retrieved from quadratic equation: $k \cdot \Psi^2_{CP} + m \cdot \Psi_{CP} - (b/a) = 0$



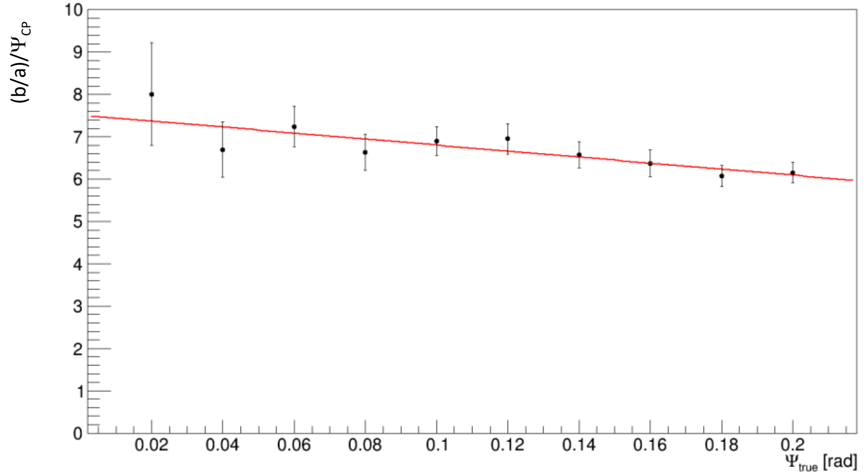
2. Perform a local fit around the minimum b/a, generator 10^5 events

$\Delta\Phi$ fit for Ψ_{CP}=0.1
(b/a)=0.70± 0.4

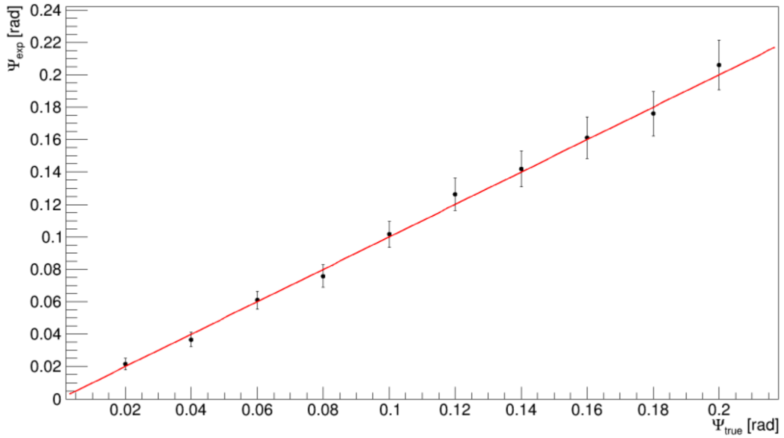


3, 4. Position of minimum (b/a)/ Ψ_{CP} is a linear function of Ψ_{CP}

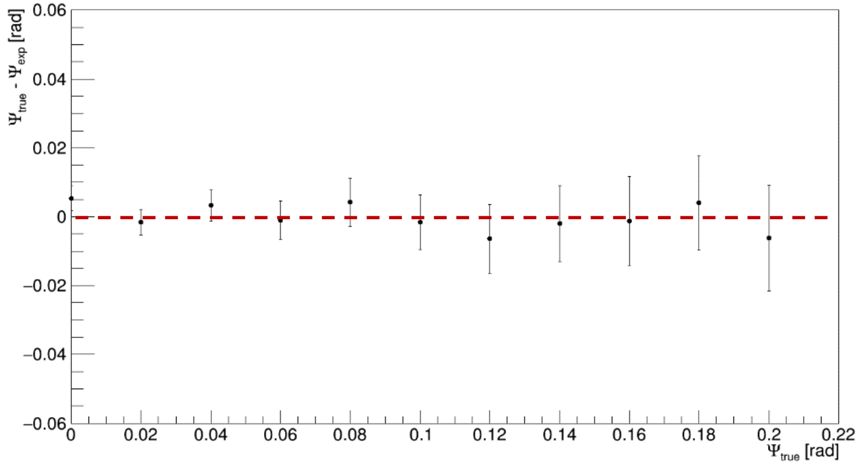
k=-7.9 ± 1.9; m=7.6 ± 0.2



5. Retrieved vs. true values of Ψ_{CP} (generator) + uncertainties from fit parameters

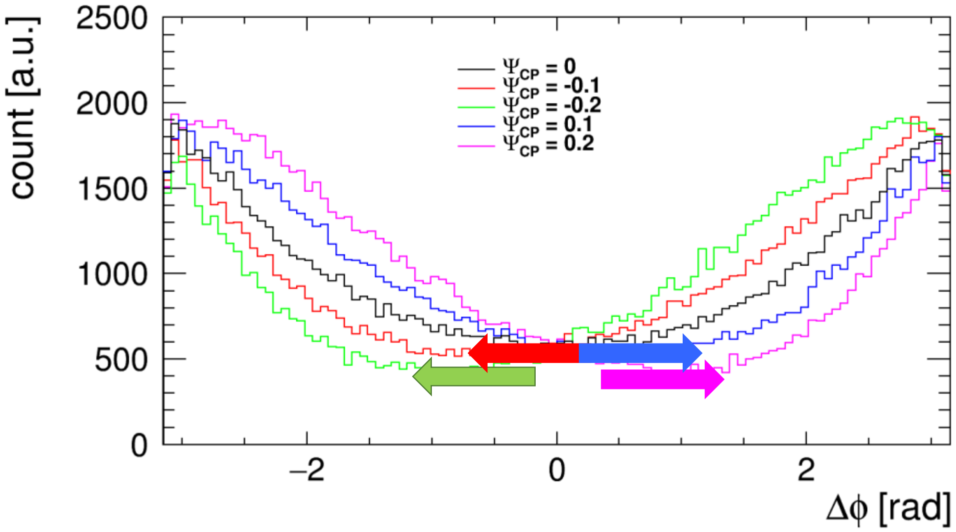


Dissipation of extracted Ψ_{CP} around true Ψ_{CP} values
$\Delta\ \Psi_{CP}$=5 mrad for Ψ_{CP} =0



ANOTHER (CORELATED) OBSERVABLE

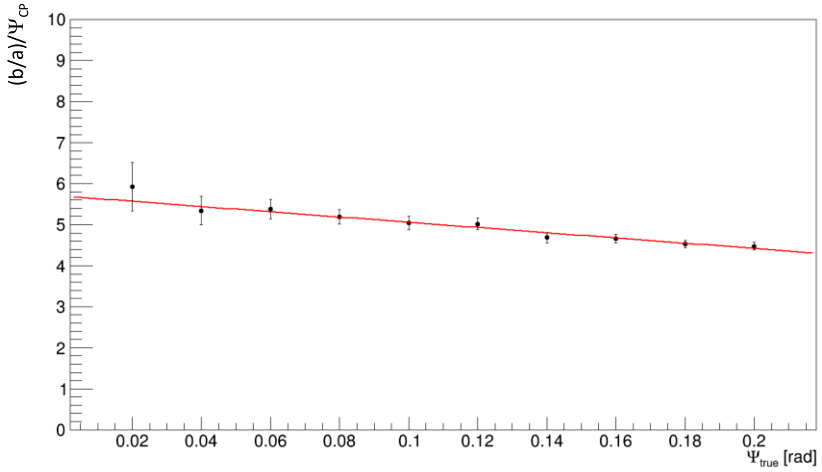
$\Delta\phi$ for Ψ_{CP}: -0.2, -0.1, 0, 0.1, 0.2



EXTRACT ψ_{CP} (at ψ_{CP} =0)

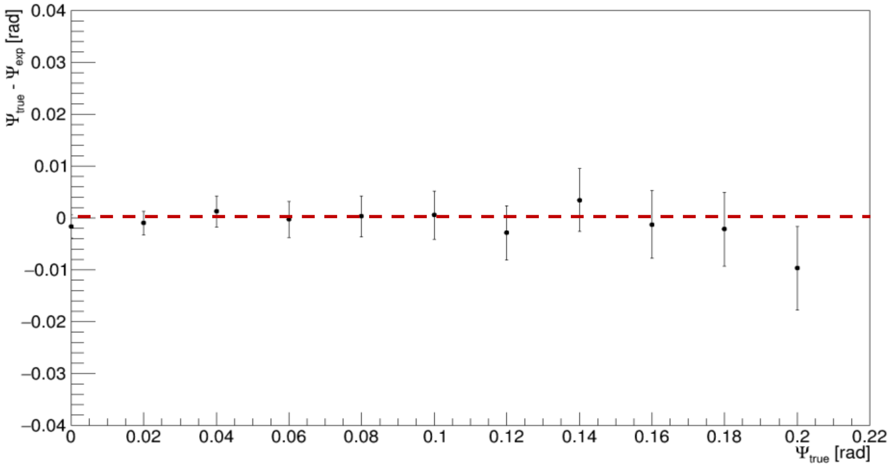
- Instead of the angle between Higgs production planes ($\Delta\Phi$), azimuthal angle $\Delta\phi$ between final state e^+ and e^- can be measured (F. Zarnecki)
- Minimum of $\Delta\phi$ is sensitive to Ψ_{CP};
- Do the same as with $\Delta\Phi$

Position of minimum (b/a)/ Ψ_{CP} is a linear function of Ψ_{CP}



Dissipation of extracted Ψ_{CP} around true Ψ_{CP} values

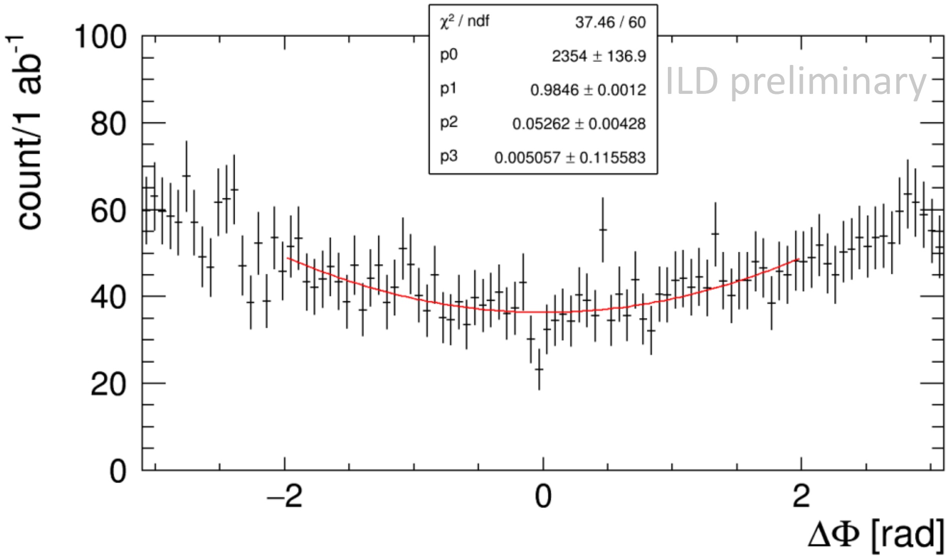
$\Delta\ \Psi_{CP}$=2 mrad for Ψ_{CP} =0



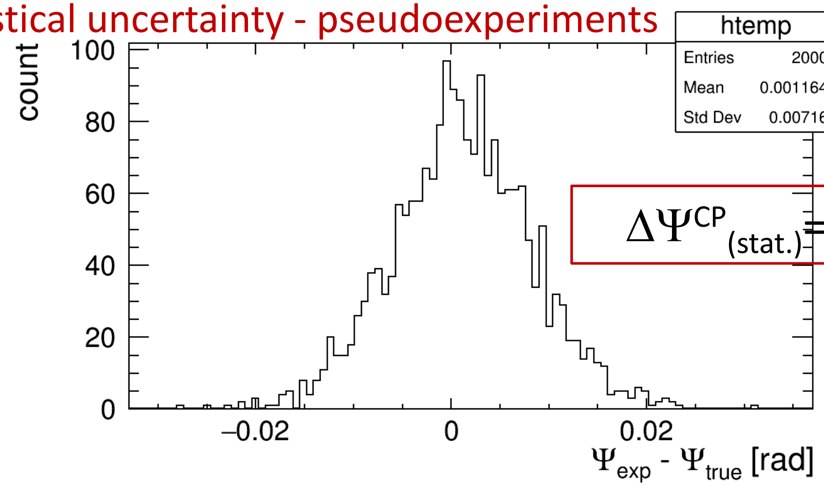
5. Ψ_{CP} FROM RECONSTRUCTED DATA, SCALAR

$\Delta\Phi$ reconstructed, corrected, local fit

Ψ_{CP}=0.0009 rad, $|\Psi_{true}-\Psi_{CP}|$ =0.9 mrad



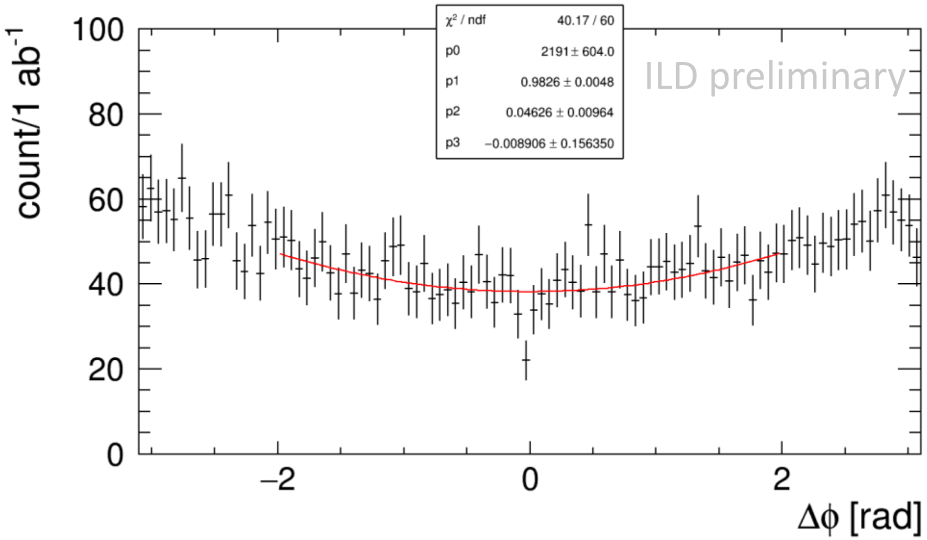
Statistical uncertainty - pseudoexperiments



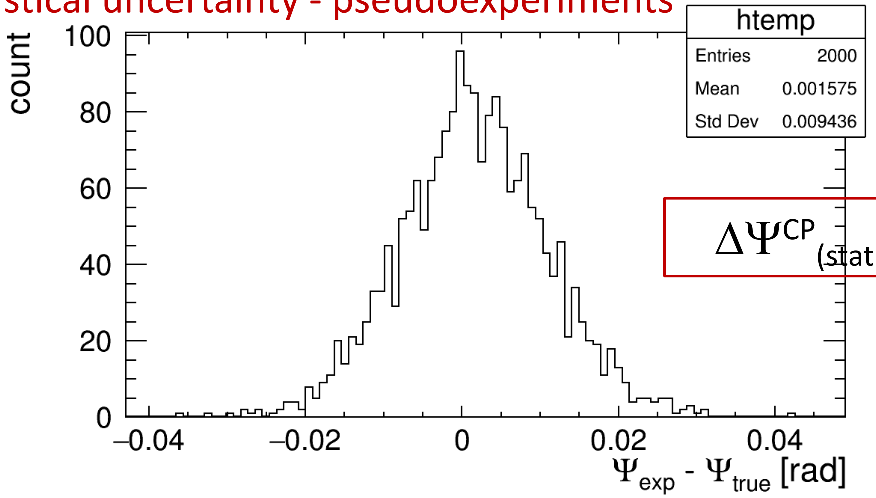
$\Delta\Psi^{CP}_{(stat.)}$ = 7 mrad

$\Delta\phi$ reconstructed, corrected, local fit

Ψ_{CP}=0.0016 mrad, $|\Psi_{true}-\Psi_{CP}|$ =1.6 mrad



Statistical uncertainty - pseudoexperiments



$\Delta\Psi^{CP}_{(stat.)}$ = 9 mrad

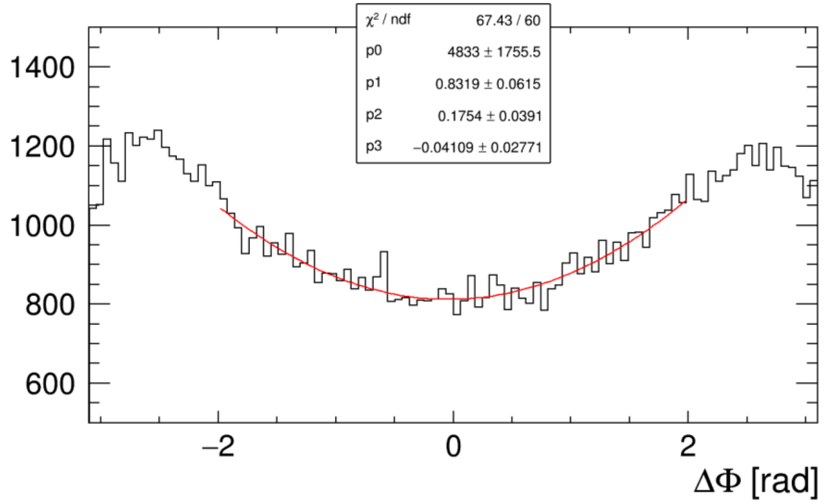
SUMMARY

- ✓ We have performed a complete simulation of CPV Higgs mixing angle measurement Ψ_{CP};
- ✓ This is the first result in VBF fusion based on angular observable(s);
- ✓ Fit can be performed around local minima sensitive to Ψ_{CP}. Knowing the dependence of the minima to Ψ_{CP} from simulation, Ψ_{CP} can be determined from (experimental) data;
- ✓ Individual measurement on fully simulated data gives deviation of 0.9 mrad from the truth value. The method is stable for Ψ_{CP} variations up to 0.2 rad;
- ✓ From 1 ab^{-1} of 1 TeV ILC data, pure scalar state should be measured with 7 mrad statistical uncertainty of Ψ_{CP} for $\Psi_{CP}=0$ (68% CL); Systematic uncertainty from the fit is found to be smaller (< 1 mrad);
- ✓ The above uncertainty corresponds to $f_{CP} \approx 4.5 \cdot 10^{-5}$;
- ✓ The study is ongoing.

BACKUP

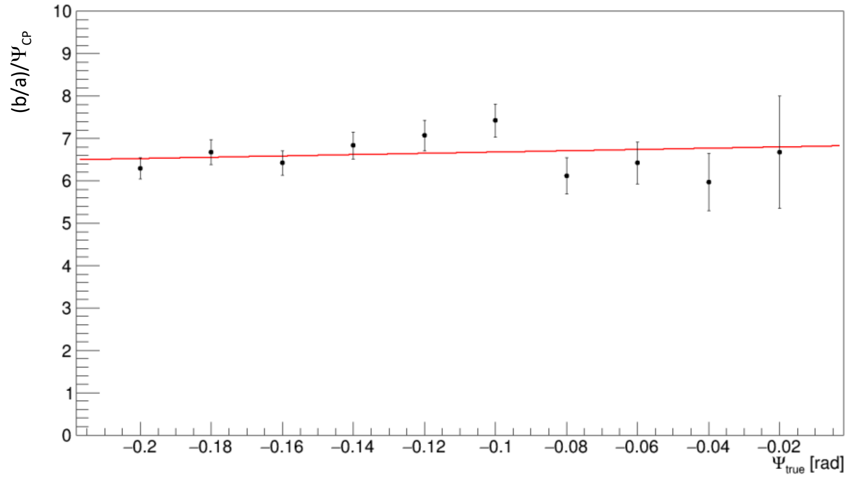
2. Perform a local fit around the minimum b/a, generator 10^5 events

$\Delta\Phi$ fit for Ψ_{CP}=0.
(b/a)=-0.04$\pm$ 0.03

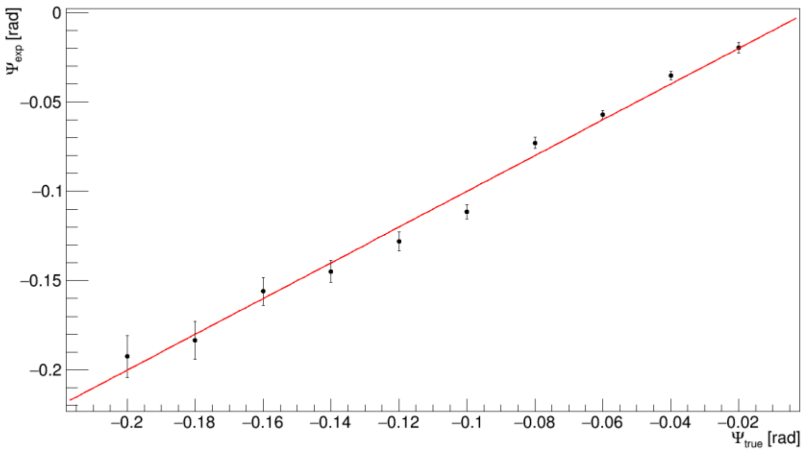


3, 4. Position of minimum (b/a)/ Ψ_{CP} is a linear function of Ψ_{CP}

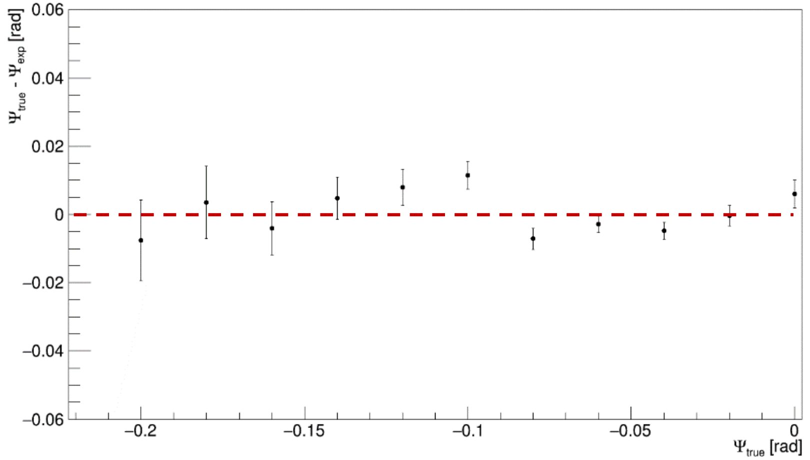
k=1.5 $\pm$ 2.4; m=6.8 $\pm$ 0.4



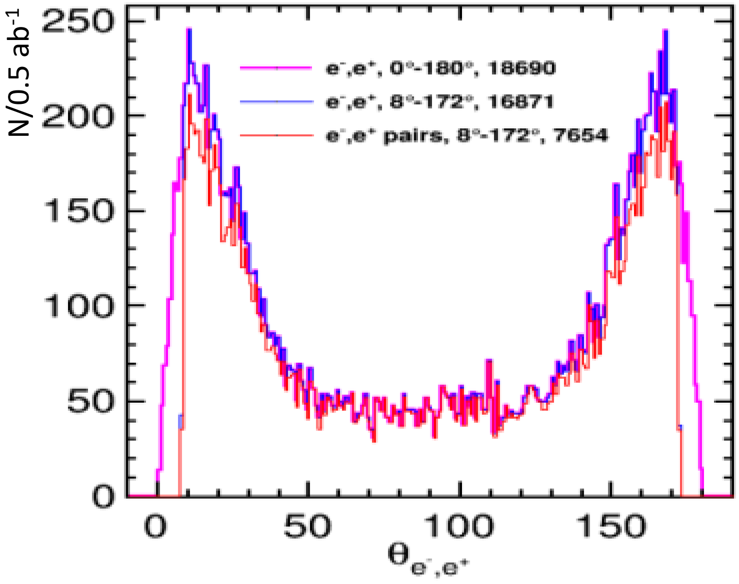
5. Retrieved vs. true values of Ψ_{CP} (generator) + uncertainties from fit parameters



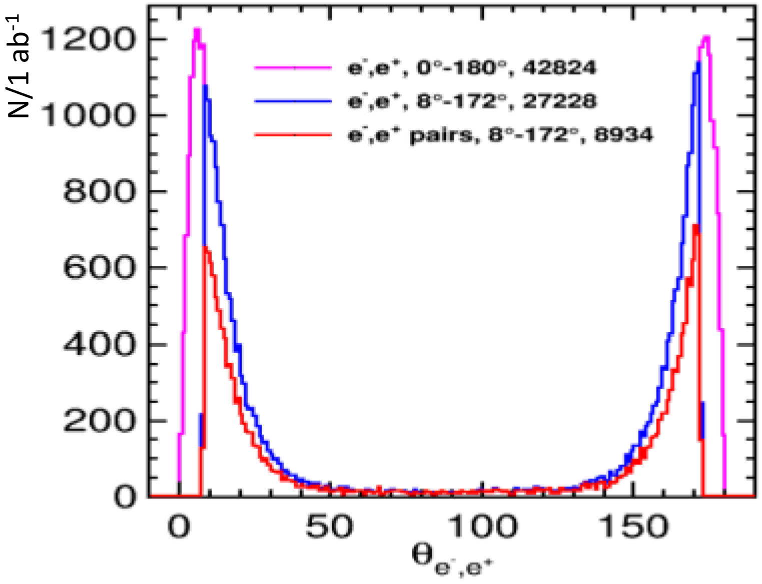
Dissipation of extracted Ψ_{CP} around true Ψ_{CP} values
$\Delta\ \Psi_{CP}$=6 mrad for Ψ_{CP} =0



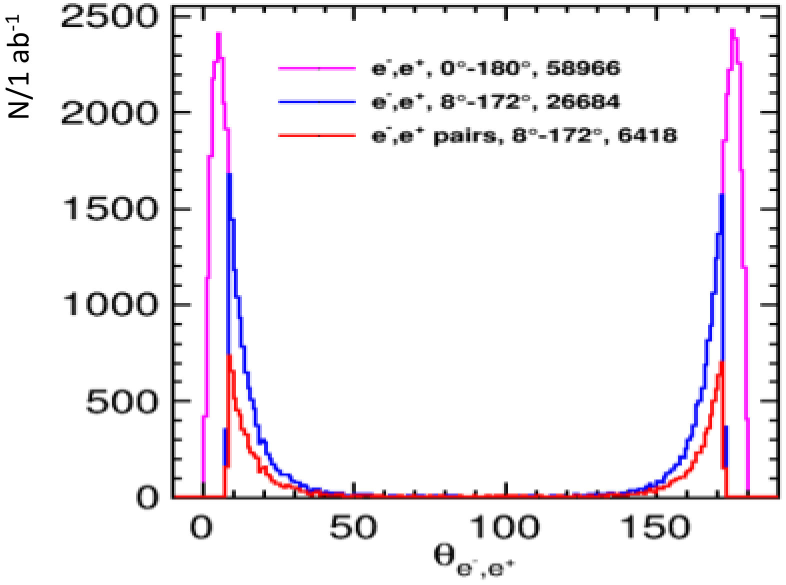
- ✓ WHIZARD v1.95, 500 GeV/0.5 ab^{-1}, 1 TeV/1 ab^{-1}, 1.4 TeV/1 ab^{-1}, unpolarized
- ✓ 1 TeV is the optimal energy for this study (already at i.e. 1. 4 TeV the number of events with both electron in the tracker is ~1/5 of the available statistics). At 500 GeV i.e. x-section for ZZ fusion is relatively small (7.2 fb) and number of events in the tracker is order of magnitude smaller than at 1 TeV
- ✓ Around 8 - 9 · 10^3 events with both e^+ and e^- in the tracker in 1 ab^{-1} at 1 TeV ILC



82 % @ 500 GeV



41.7 % @ 1 TeV



21.8 % @ 1.4 TeV