Sensitivity of 1 TeV ILC to measure CP-odd Higgs interactions in ZZ-fusion

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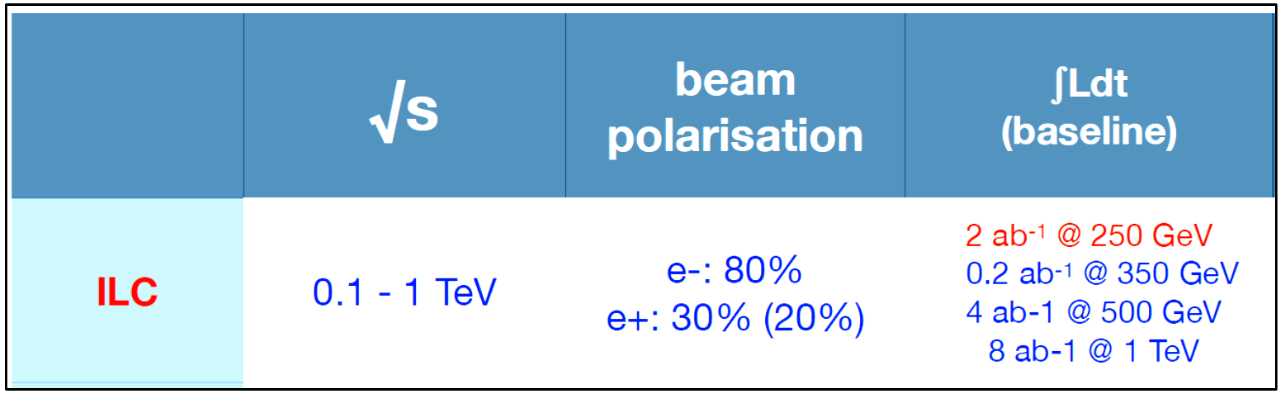
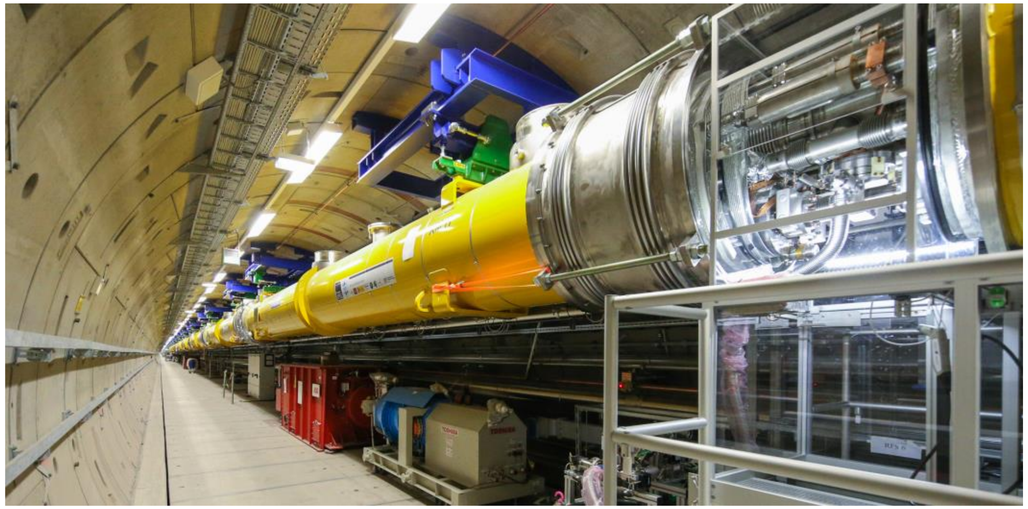
OPENING QUESTIONS/OUTLINE

1. Could 125 GeV Higgs mass eigenstate be a 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 the measurement sensitivity (in the context of Snowmass CPV White paper [arXiv:2205.07715v3])?

A WORD ON ILC



	$\sqrt{s}$	beam polarisation	$\int L dt$ (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



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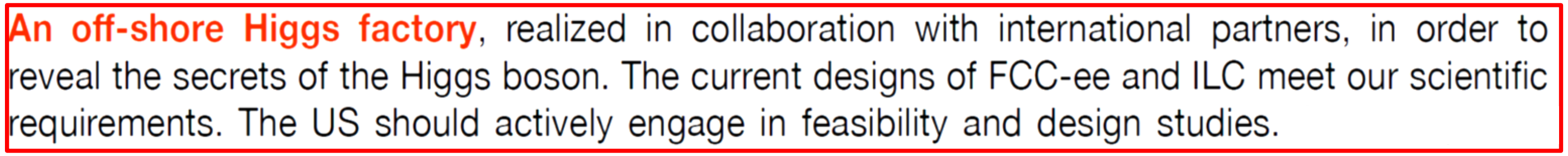


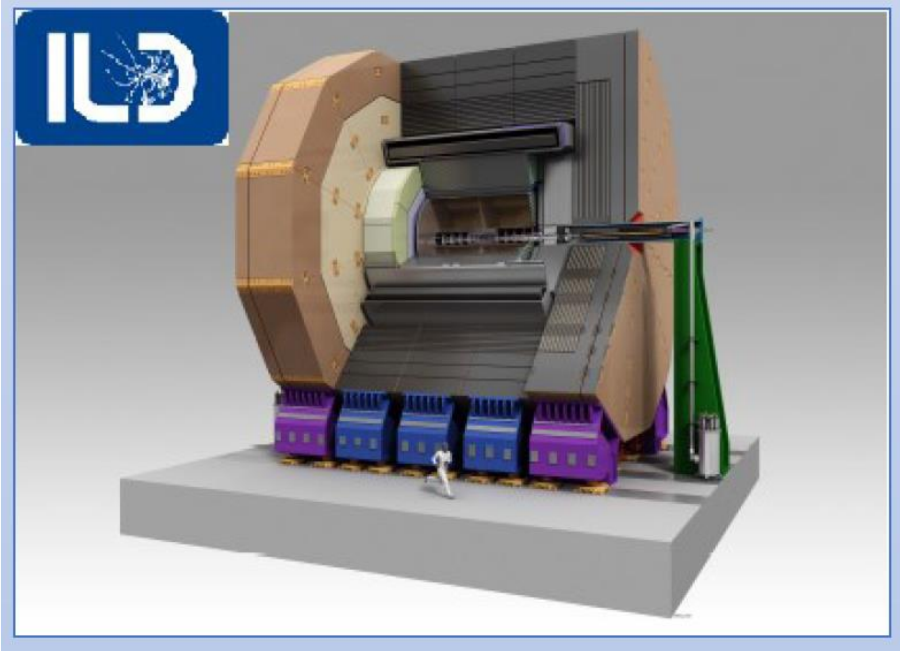
An off-shore Higgs factory, realized in collaboration with international partners, in order to reveal the secrets of the Higgs boson. The current designs of FCC-ee and ILC meet our scientific requirements. The US should actively engage in feasibility and design studies.

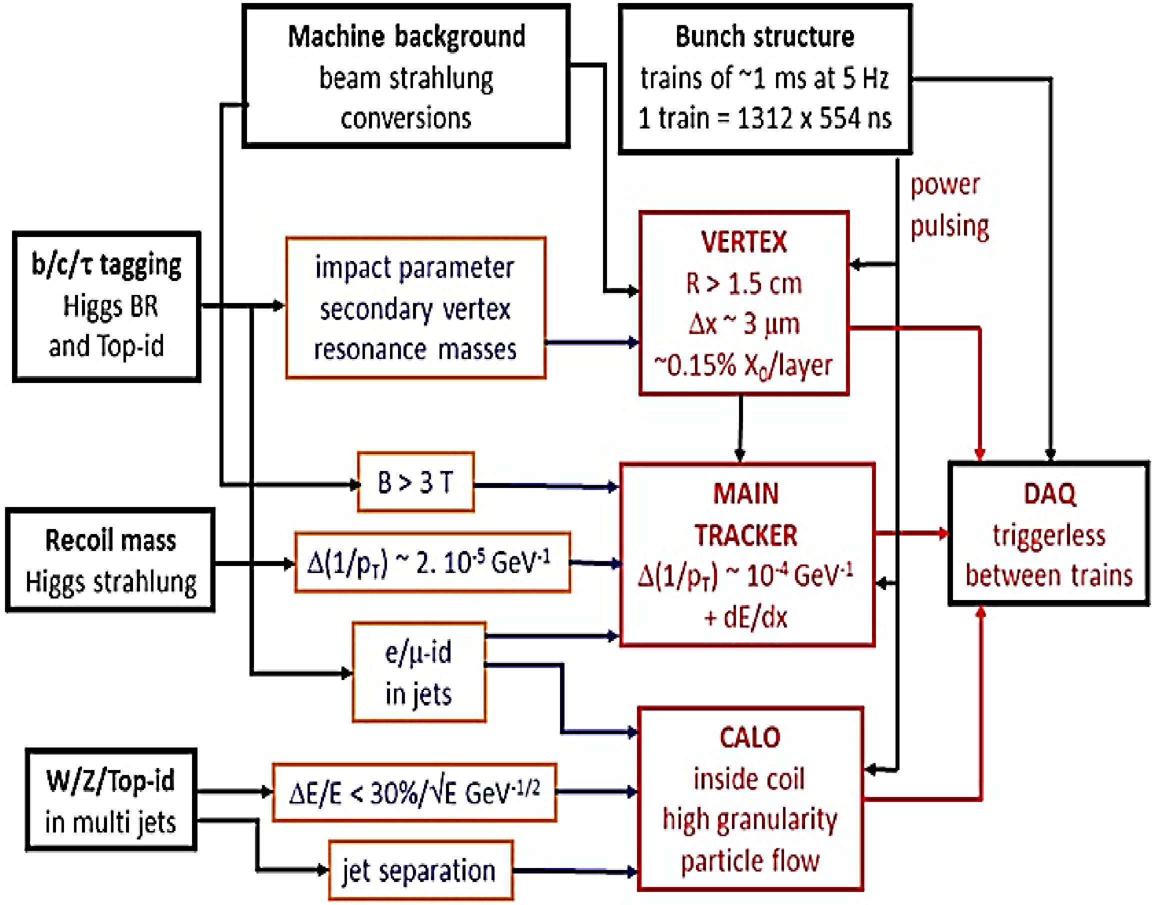
P5 Panel Recommendation 2

- Comes as a ‘ready to take’ project (mature design, proven technologies)
- Largest ever accelerator prototype (operating now as E-XFEL), full industrialization of ILC-type SCRF cavity production
- Tunable, upgradeable (from Z-pole, via Higgs factory mode, 500 GeV up to 1 TeV, or by replacing accelerating structures with advanced technologies)
- Numerous benefits from the high energy phases (≥500 GeV) and beam polarization

A WORD ON ILD

- Two validated detector concepts:
  ILD and SiD
- <u>Physics driven requirements</u>
- Decades of extensive detector R&D ⇒ mature design (& available technologies)
- Multiple R&D collaborations involved (CALICE, FCAL, LCTPC,..)





Machine background
beam strahlung
conversions

Bunch structure
trains of ~1 ms at 5 Hz
1 train = 1312 x 554 ns

power pulsing

b/c/τ tagging
Higgs BR
and Top-id

impact parameter
secondary vertex
resonance masses

VERTEX
$R > 1.5$ cm
$\Delta x \sim 3\ \mu m$
~0.15% X_0/layer

$B > 3$ T

Recoil mass
Higgs strahlung

$\Delta(1/p_T) \sim 2.\ 10^{-5}\ GeV^{-1}$

MAIN TRACKER
$\Delta(1/p_T) \sim 10^{-4}\ GeV^{-1}$
+ dE/dx

DAQ
triggerless
between trains

e/μ-id
in jets

W/Z/Top-id
in multi jets

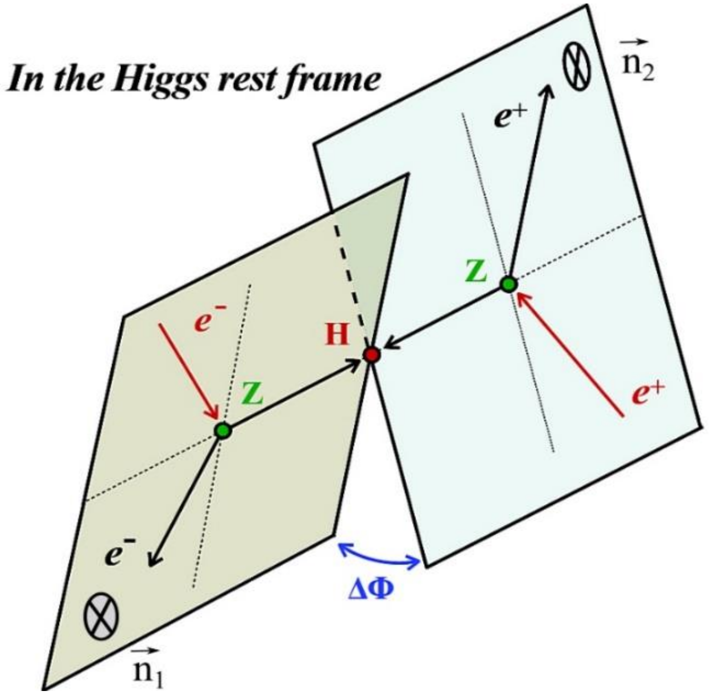
$\Delta E/E < 30\%/\sqrt{E}\ GeV^{-1/2}$

jet separation

CALO
inside coil
high granularity
particle flow

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] $\Delta\Phi$ carries the most information on the Higgs CP state



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

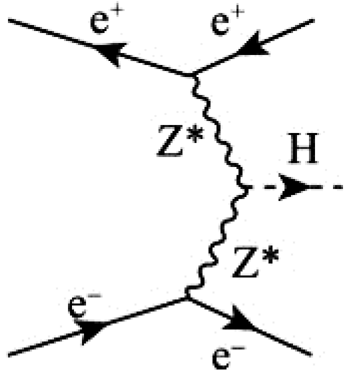
$$\cos \Phi = (\hat{n}_1 \cdot \hat{n}_2)$$

$$\mathrm{sgn}\,(\sin\ \Phi): \frac{q_1 \cdot (\hat{n}_1 \times \hat{n}_2)}{|q_1 \cdot (\hat{n}_1 \times \hat{n}_2)|}$$

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

SIGNAL AND BACKGROUND

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	$2 \cdot 10^5$ DELPHES~36.6 ab^{-1}
			3495 full sim. ~0.22 ab^{-1}
$e^+e^- \rightarrow q\bar{q}l^+l^-$	255	$2 \cdot 10^6$	$1 \cdot 10^6$ DELPHES
			5886 full sim.
$e^+e^- \rightarrow q\bar{q}$	9375	$75 \cdot 10^6$	120343 full sim.
$e^+e^- \rightarrow q\bar{q}lv$	4116	$32.9 \cdot 10^6$	955058 full sim.



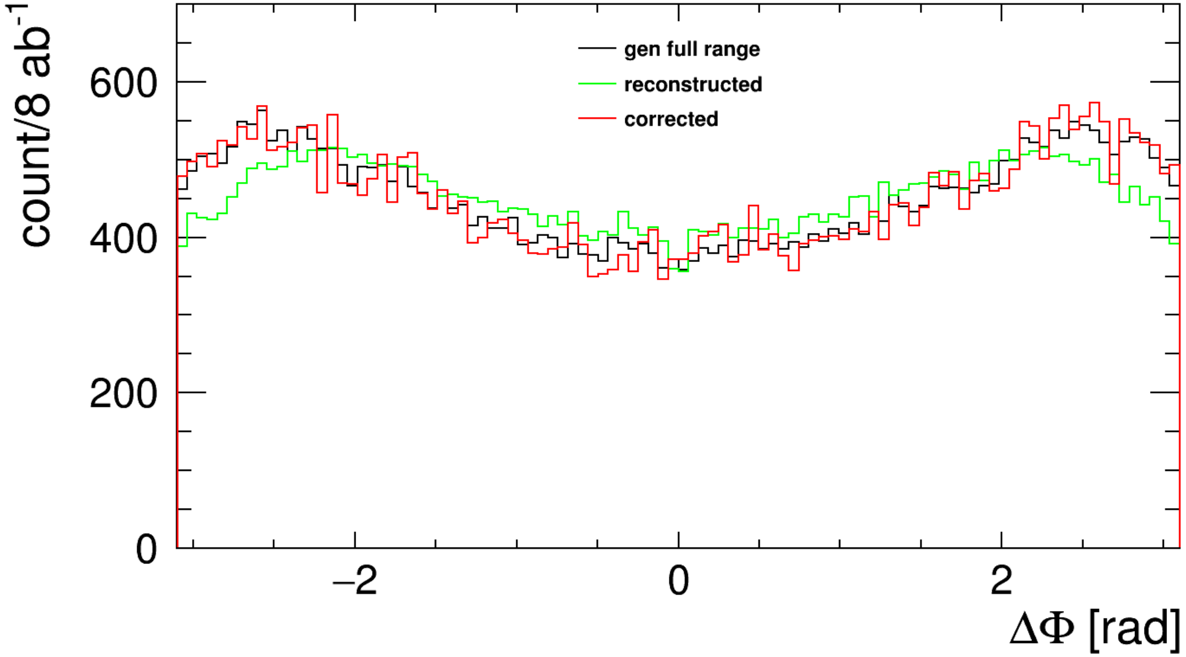
- Generator level WHIZARD V2.8.3/UFO/Higgs characterization model signal and WHIZARD 1.95/SM background
- Unpolarized beams

- $H \rightarrow b\bar{b}$ (to suppress eeγ background)
- b-tagging efficiency is idealized to 100%)

500 GeV, 1 TeV energies are optimal due to interplay of x-section and centrality

GENERATED AND RECONSTRUCTED SIGNAL

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

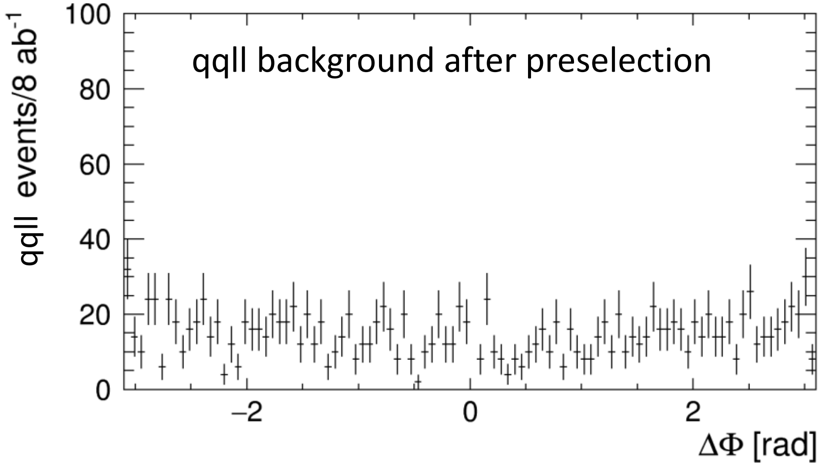


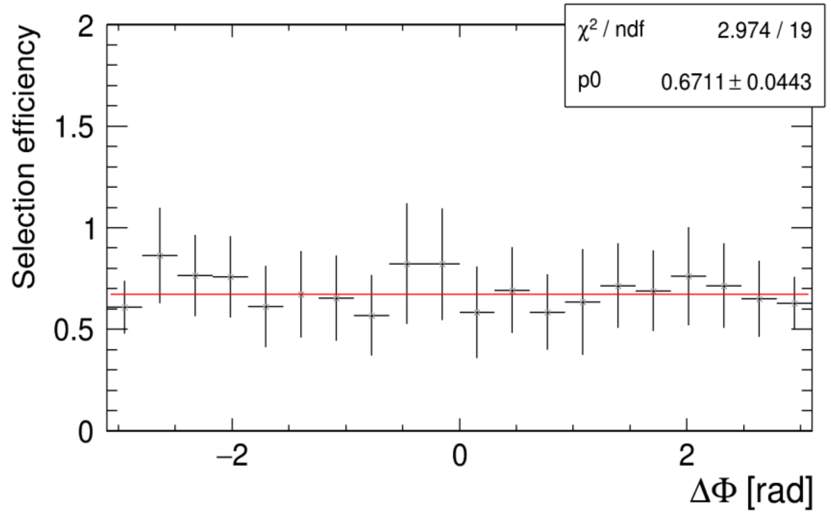
- ○ Acceptance correction needed to retrieve full physical information
- ○ Generated information is reasonably well reproduced with corrected reconstructed data

EVENT SELECTION

- **Preselection – electron isolation**:
  - $m_{e^+e^-} > 200$ GeV (veto HZ)
  - $E_{e\pm} > 60$ 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: **~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%**



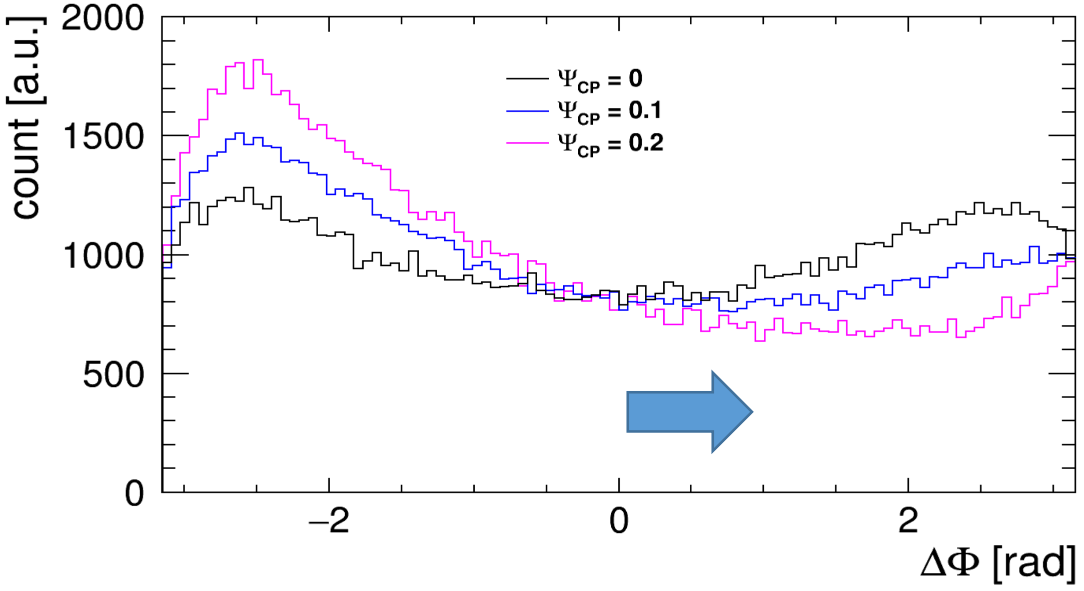


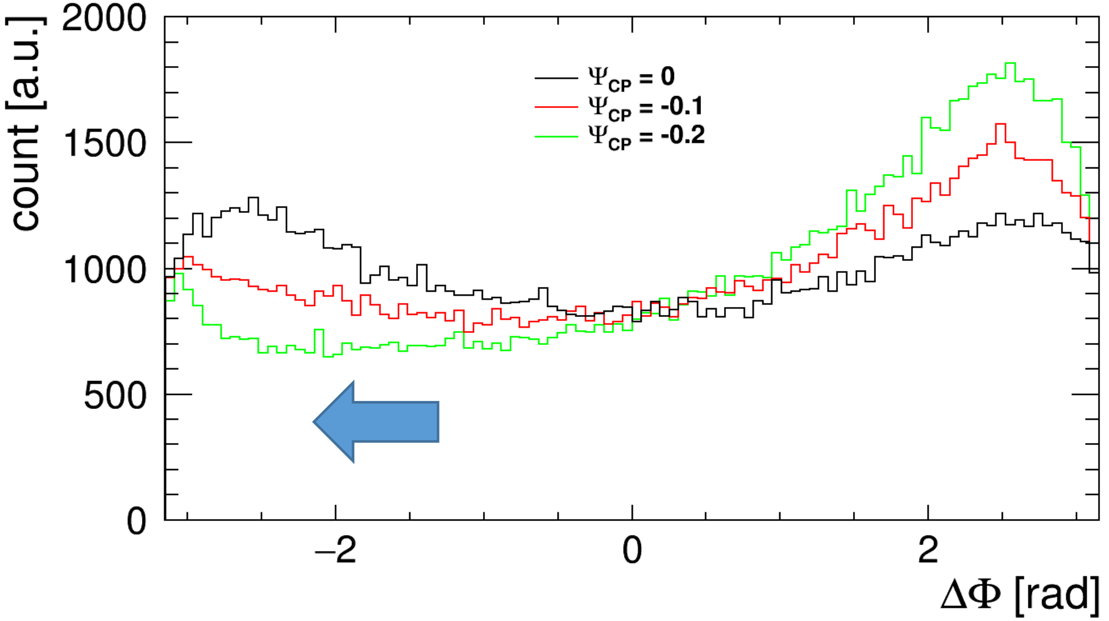
- **Unbiased selection** w.r.t. $\Delta\Phi$
- Background is CP insensitive, fully suppressed (preselection efficiency $\leq 10^{-4}$)

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:

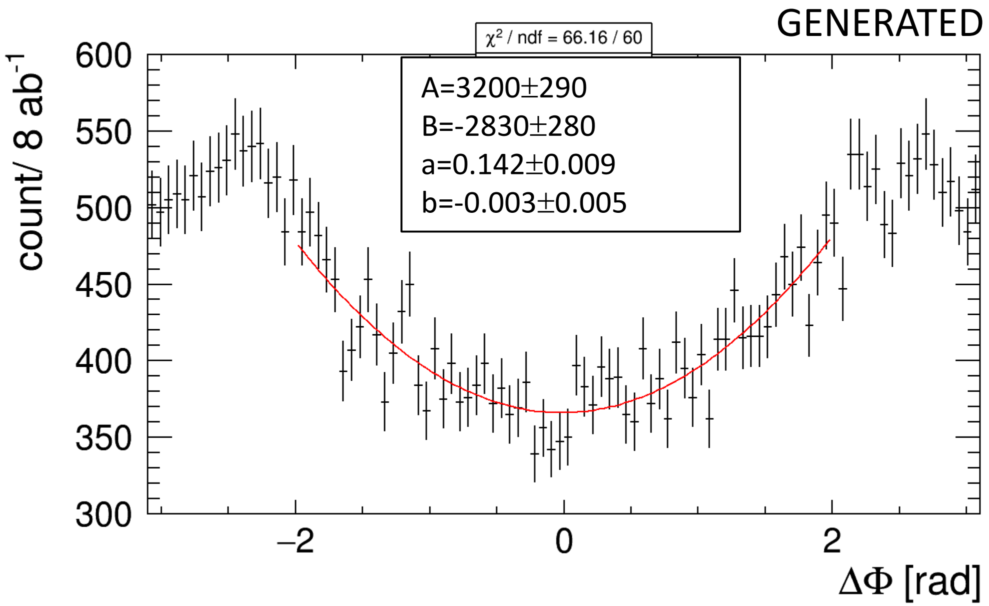
   $f(\Delta\Phi,\ \Psi_{CP})=A+B\cdot\cos(a\cdot\Delta\Phi-b)$

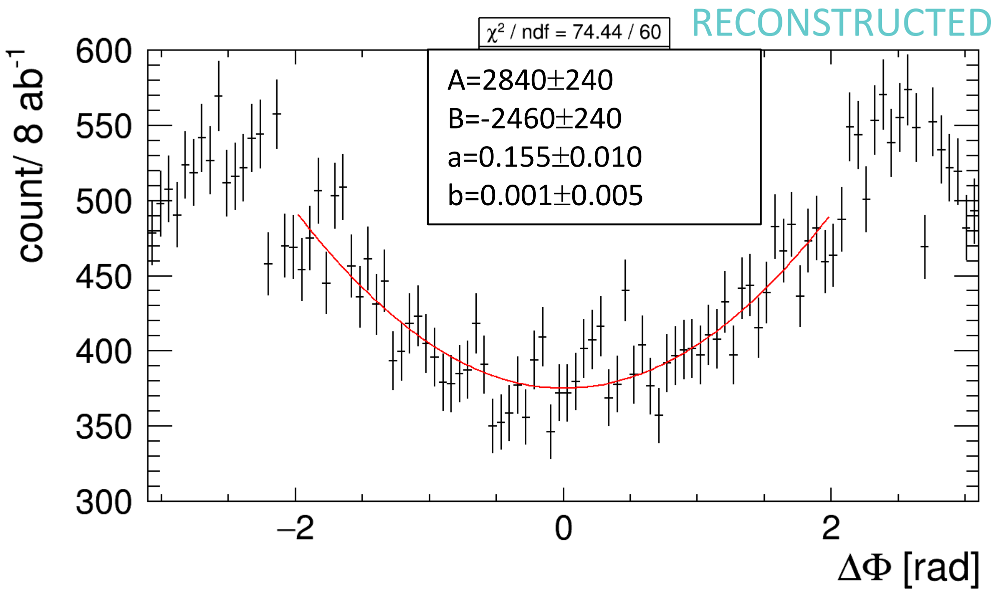
2. Position (b/a)/ Ψ_{CP} is a linear function of Ψ_{CP}:

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

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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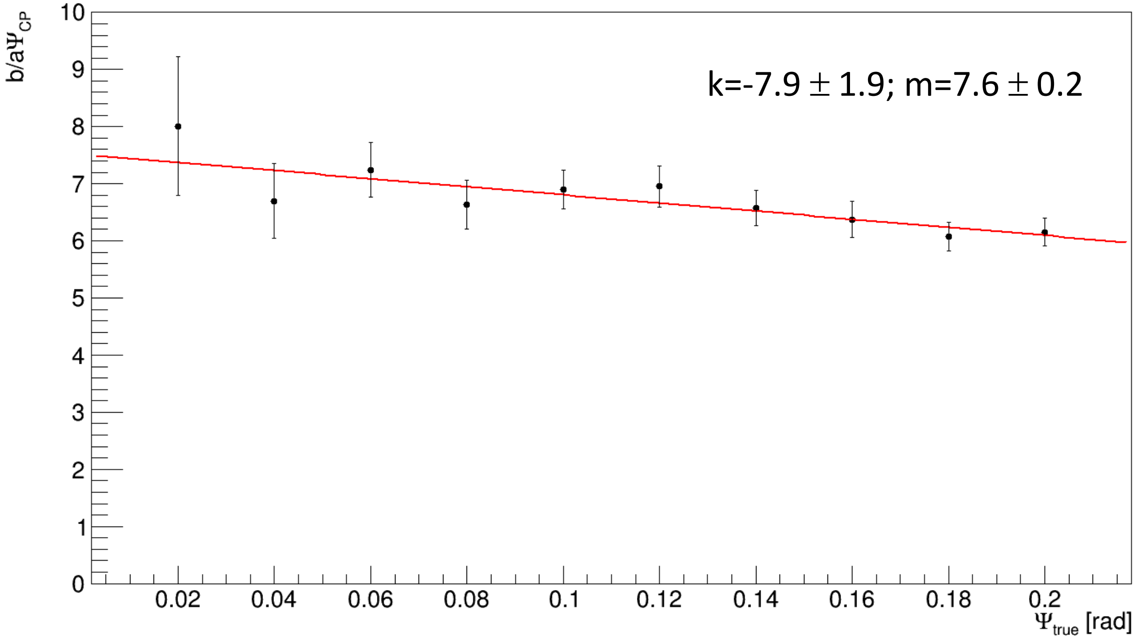

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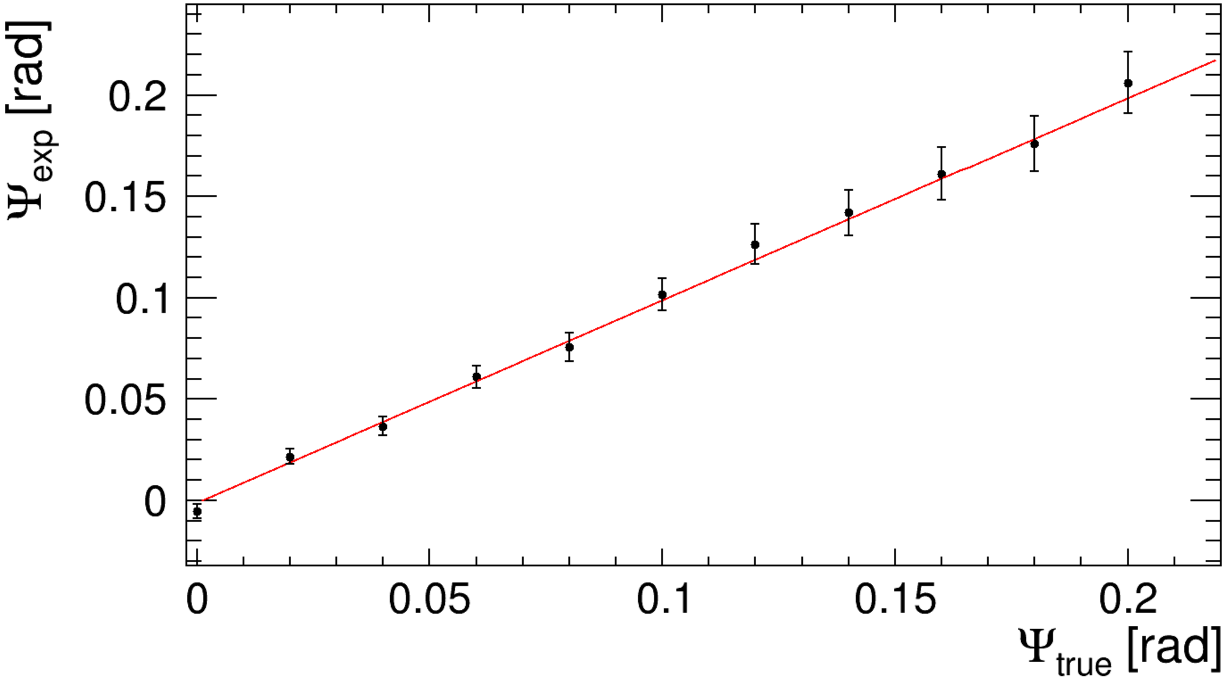

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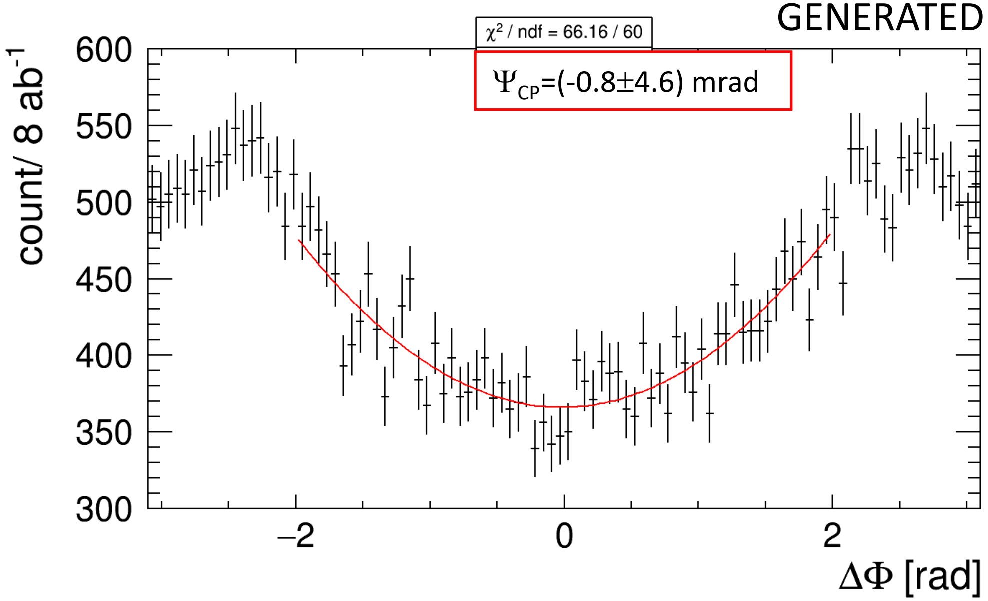
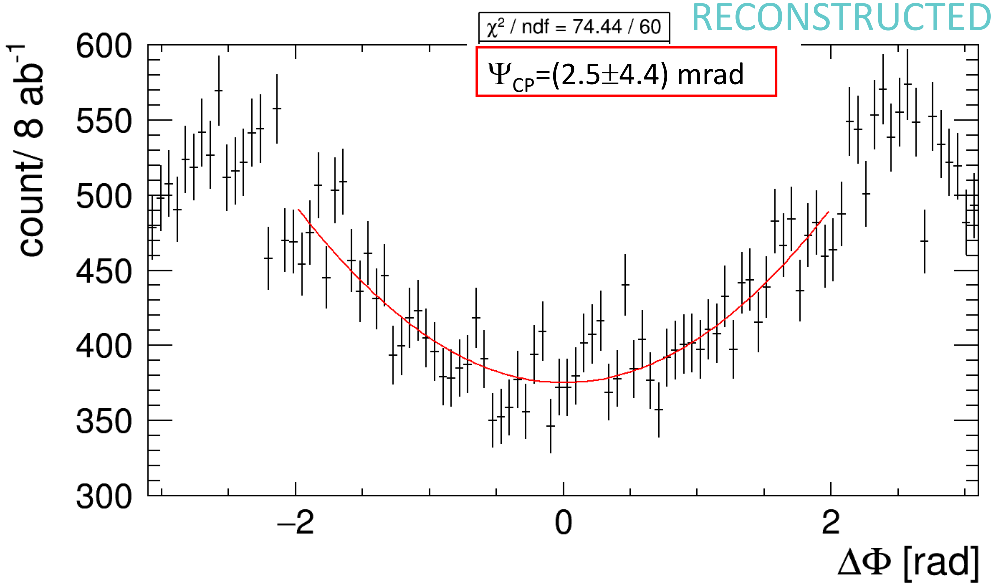
GENERATED

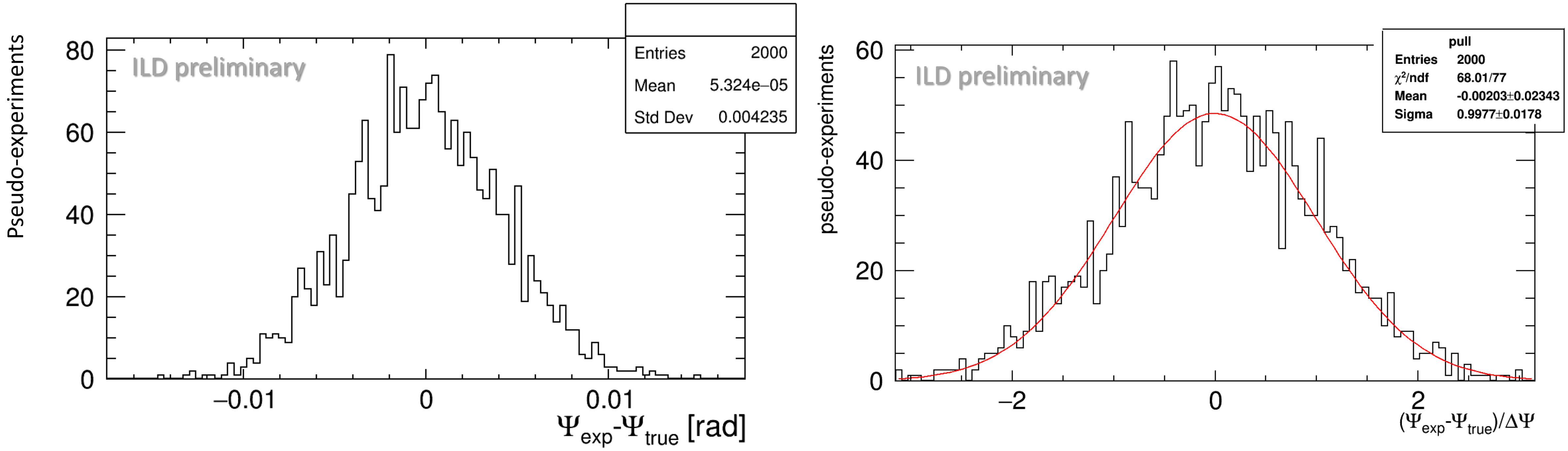


RECONSTRUCTED



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

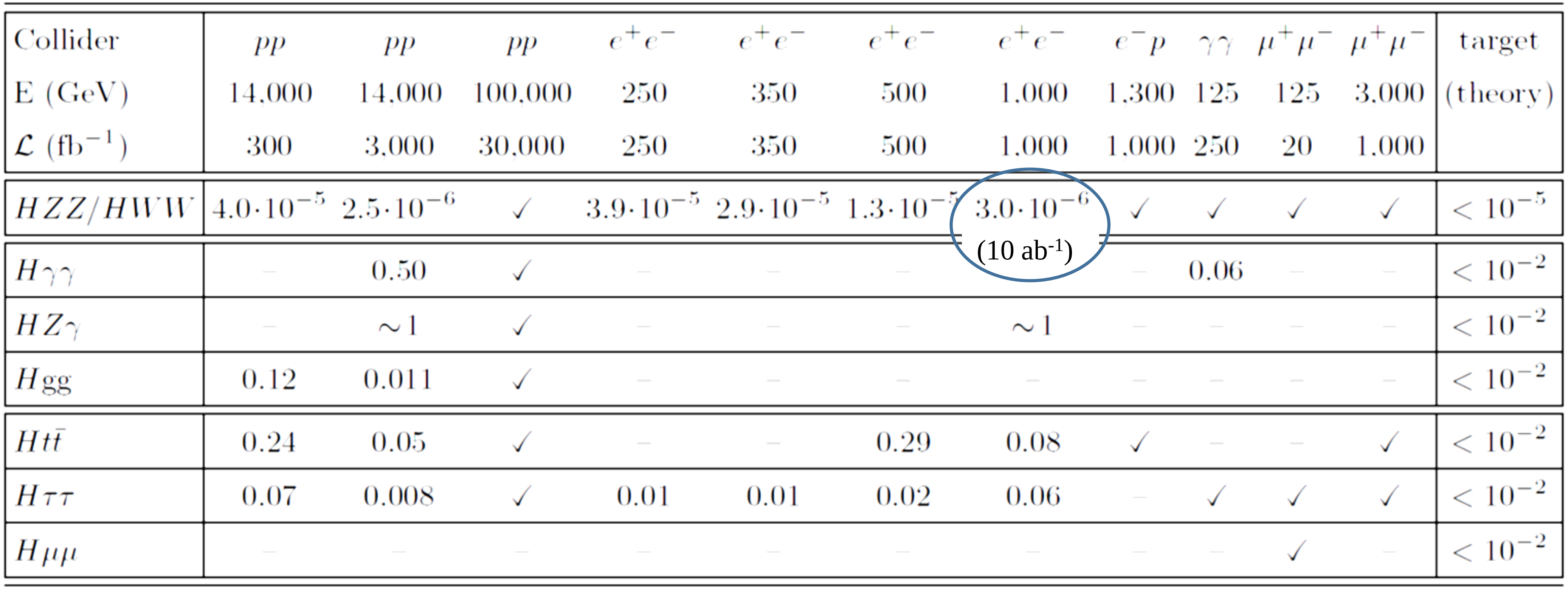
INTERPRETATION

- Common framework 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 $f_{CP}^{hX} \equiv \frac{\Gamma_{h\to X}^{CP\,\mathrm{odd}}}{\Gamma_{h\to X}^{CP\,\mathrm{odd}} + \Gamma_{h\to X}^{CP\,\mathrm{even}}}$

- Interpretation for LHC/HL-LHC and future Higgs factories, for EFT and CP-sensitive observable based measurements

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

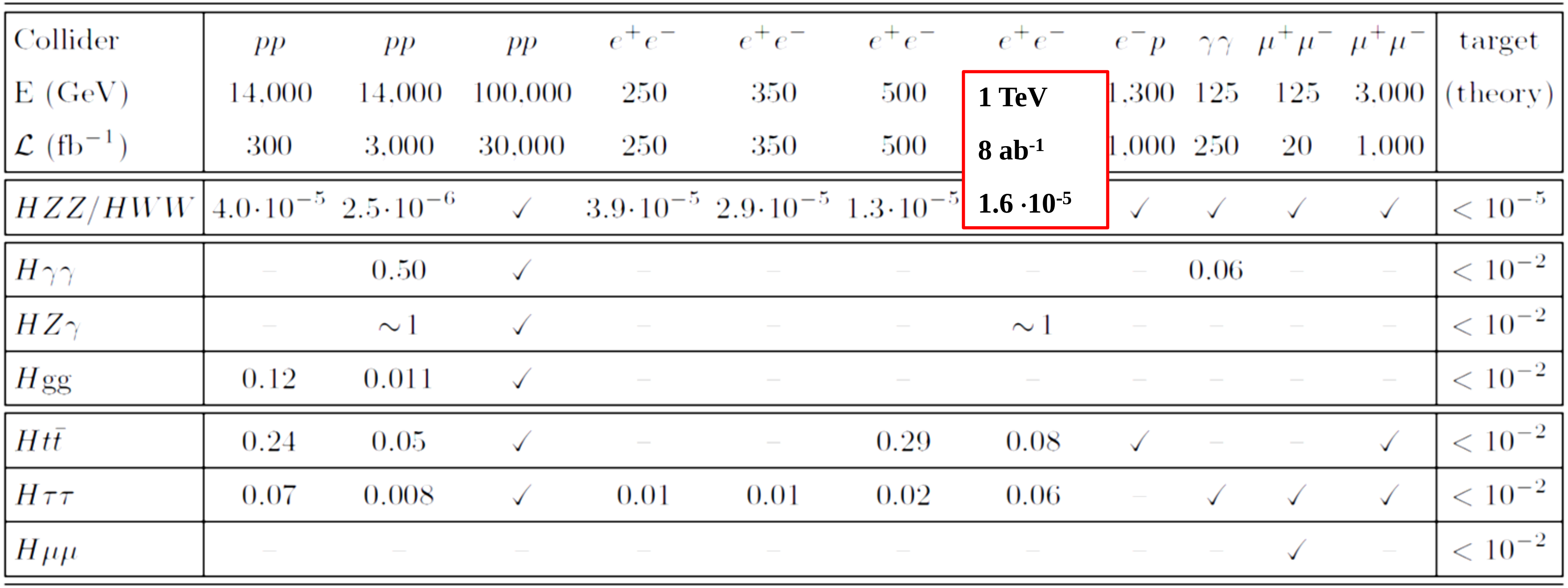


Collider	pp	pp	pp	e^+e^-	e^+e^-	e^+e^-	e^+e^-	e^-p	$\gamma\gamma$	$\mu^+\mu^-$	$\mu^+\mu^-$	target
E (GeV)	14,000	14,000	100,000	250	350	500	1,000	1,300	125	125	3,000	(theory)
$\mathcal{L}$ (fb^{-1})	300	3,000	30,000	250	350	500	1,000	1,000	250	20	1,000	
HZZ/HWW	$4.0\cdot10^{-5}$	$2.5\cdot10^{-6}$	✓	$3.9\cdot10^{-5}$	$2.9\cdot10^{-5}$	$1.3\cdot10^{-5}$	$3.0\cdot10^{-6}$ (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
- ✓ Full background simulation of ILD detector and fast simulation of the signal
- ✓ Realistic ILC running scenario

INTERPRETATION

(68% CL, pure scalar)



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 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	$4.0\cdot10^{-5}$	$2.5\cdot10^{-6}$	✓	$3.9\cdot10^{-5}$	$2.9\cdot10^{-5}$	$1.3\cdot10^{-5}$	**$1.6\cdot10^{-5}$**	✓	✓	✓	✓	$< 10^{-5}$
$H\gamma\gamma$	–	0.50	✓	–	–	–	–	–	0.06	–	–	$< 10^{-2}$
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$H\mu\mu$	–	–	–	–	–	–	–	–	–	✓	–	$< 10^{-2}$

SUMMARY

- ✓ Complete simulation of CP 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 precision can be improved in combination with other Higgs decay channels (i.e. $H \rightarrow WW \rightarrow$4-jets).