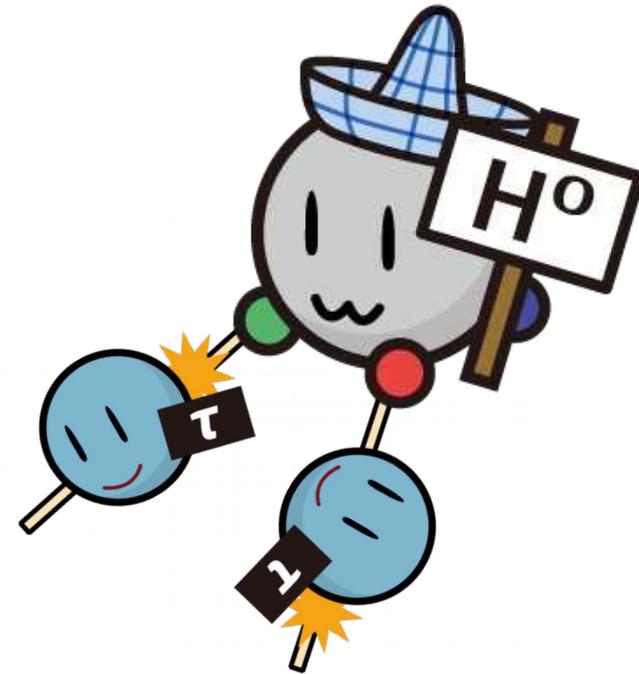


Measuring the CP state of tau lepton pairs from Higgs decay at the ILC

Phys.Rev. D98 (2018) no.1, 013007



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Motivation

Is the 125 GeV Higgs a CP eigenstate ?

$$h_{125} = \cos \psi_{CP} h^{CP\text{even}} + \sin \psi_{CP} A^{CP\text{odd}}$$

pure CP even: $\psi_{CP} = 0$ [Standard Model]

odd: $\psi_{CP} = \pi/2$ [excluded at LHC]

or a mixture?

Do Higgs couplings conserve CP ?

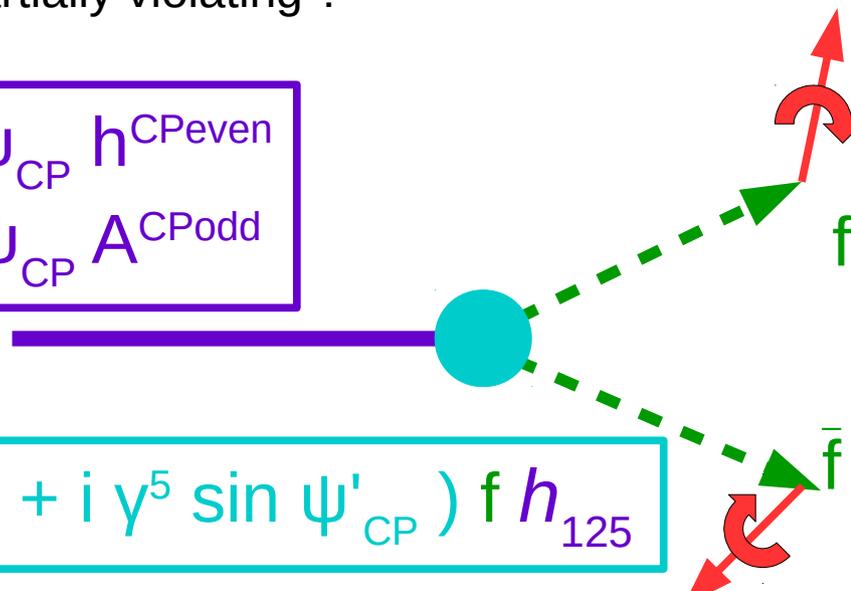
e.g. coupling to fermions: $\mathcal{L} \sim g \bar{f} (\cos \psi_{CP} + i \gamma^5 \sin \psi_{CP}) f H$

CP conserving coupling
maximally violating
or partially violating ?

$\psi_{CP} = 0$ [Standard Model]

$\psi_{CP} = \pi/2$

$$h_{125} = \cos \psi_{CP} h^{CP\text{even}} + \sin \psi_{CP} A^{CP\text{odd}}$$



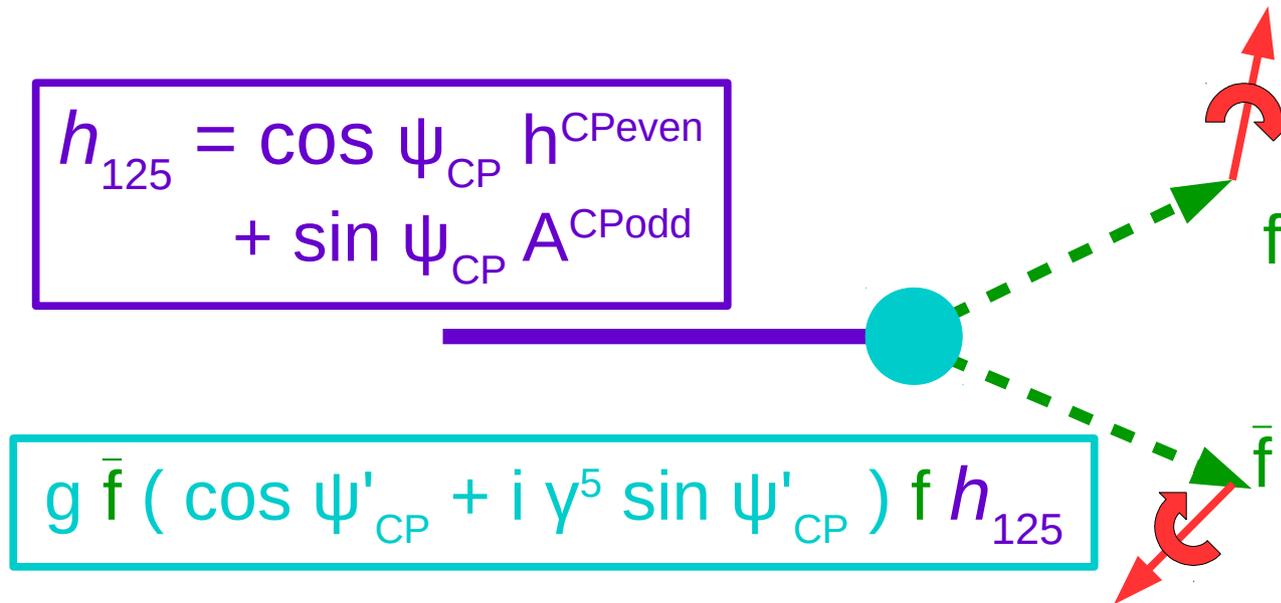
$$g \bar{f} (\cos \psi'_{CP} + i \gamma^5 \sin \psi'_{CP}) f h_{125}$$

h is a spin 0 state:

$$|f \bar{f}\rangle = |\uparrow\downarrow\rangle + e^{2i\psi} |\downarrow\uparrow\rangle$$

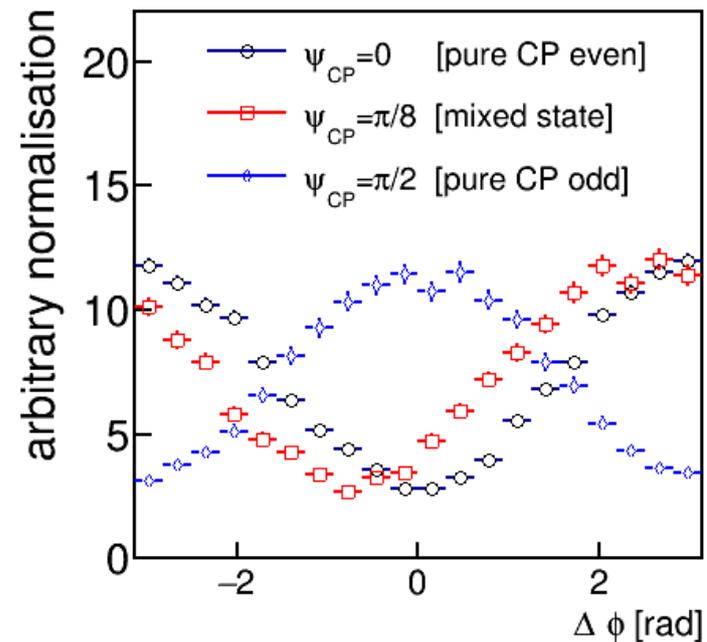
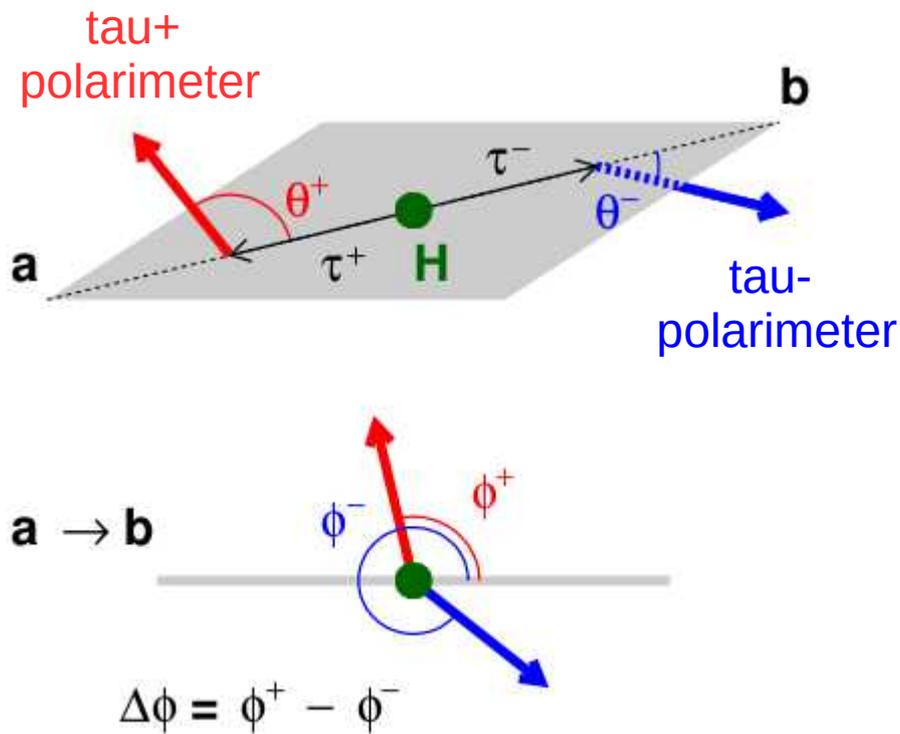
[$\psi =$ 0 CP even,
 $\pi/2$ CP odd]

The **correlation** between spins of Higgs decay products
 is sensitive to their **CP state** [in particular, the transverse correlation]



why use **tau leptons** to measure CP in Higgs sector?

- **fermion**: tree-level CP effects possible
 (H \rightarrow WW, ZZ only via loops)
- **unstable** fermion:
 distribution of tau decay products gives
 access to tau spin direction
 optimal estimator = “polarimeter vector”
 easy to extract for $\tau^+ \rightarrow (\pi^+ \nu)$ and $\tau^+ \rightarrow (\pi^+ \pi^0 \nu)$ decay modes
- reasonable 6% **branching ratio**
- clean separation of the two fermion decays (no colour string as in H \rightarrow bb)



distribution of $\Delta\phi$ is sensitive to CP mixing angle ψ_{CP}

amplitude of modulation in $\Delta\phi$ varies from event to event, depending on θ^\pm , according to contrast function:

$$c(\theta^+, \theta^-) \equiv \sin\theta^+ \sin\theta^- / (1 + \cos\theta^+ \cos\theta^-)$$

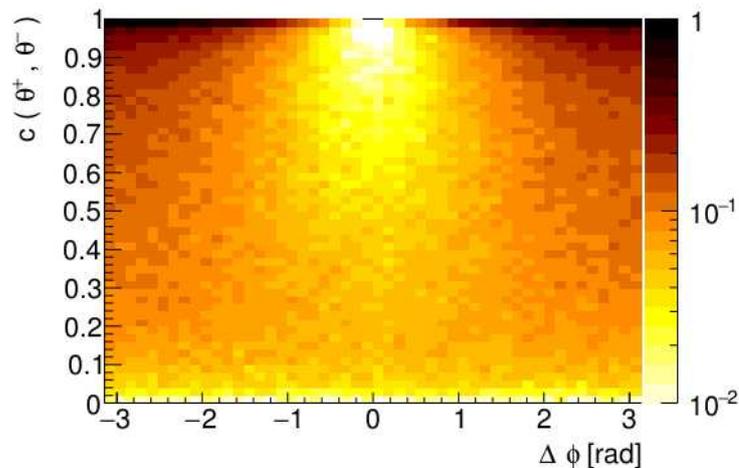
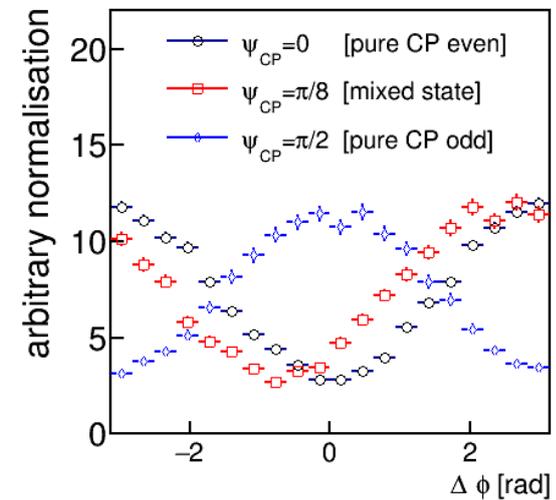


FIG. 3. Two-dimensional distribution of events in $\Delta\phi$ and $c(\theta^+, \theta^-)$ at MC truth level, for the case $\psi_{CP} = 0$.

In this analysis, we measure ψ_{CP} of the **tau pair** from **Higgs** decay
in a model-independent way,
by measuring the phase of this
 $\Delta\phi$ distribution



we don't try to understand which mechanism creates the mixing:
explicitly CP violating coupling, mixed CP mass eigenstate, ...
→ requires combination with other measurements,
model assumptions, ...

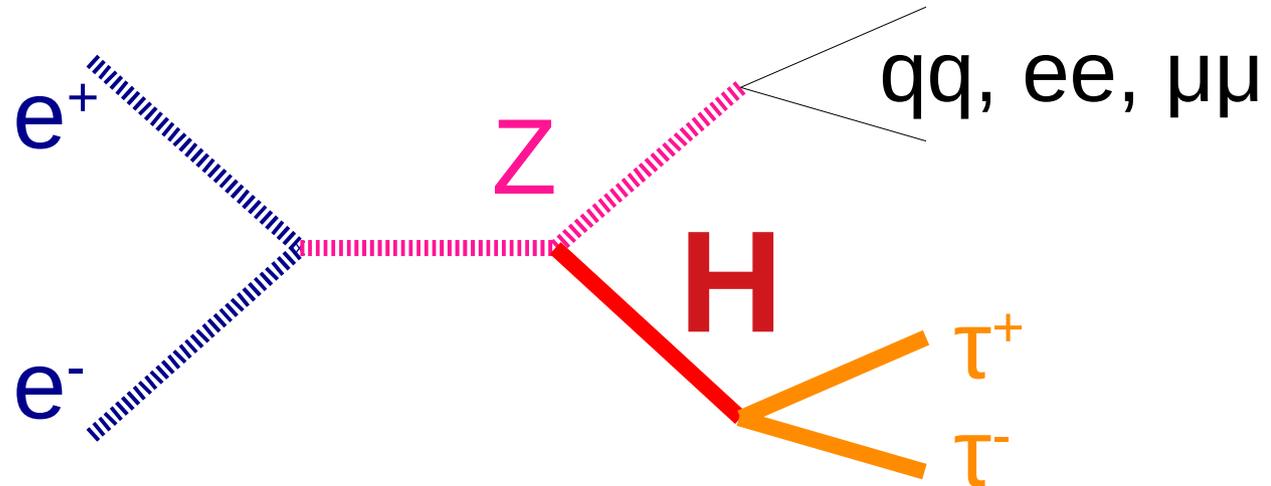
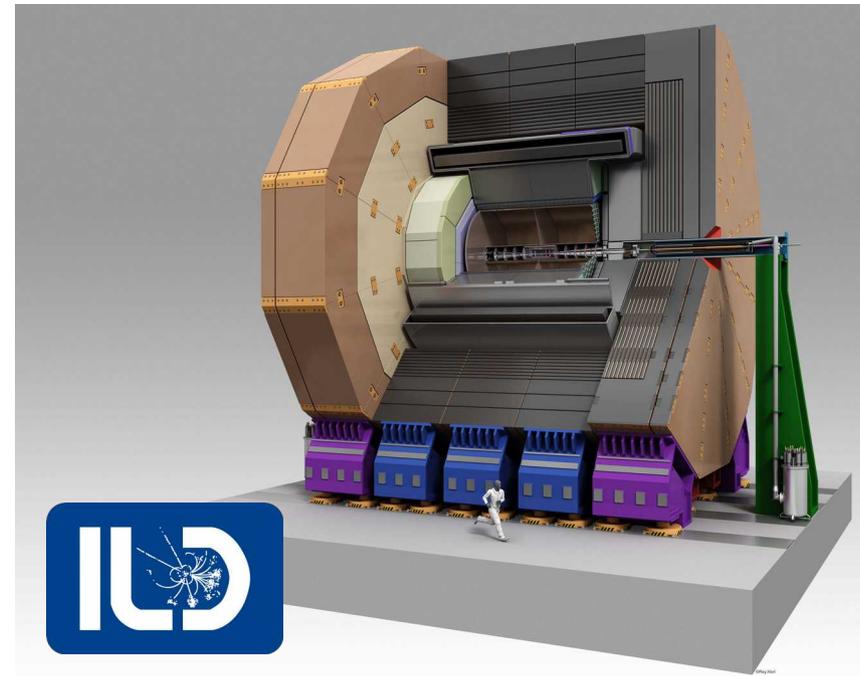
Analysis uses full ILD simulation
signal and SM backgrounds
standard data reconstruction
(ilcsoft v01-16-02)

SIGNAL: $e^+ e^- \rightarrow Z H$

$Z \rightarrow$ electrons, muons, quarks

$H \rightarrow \tau^+ \tau^-$

$\tau^\pm \rightarrow (\pi^\pm \nu)$ or $(\pi^\pm \pi^0 \nu)$



SM backgrounds:

$e^+ e^- \rightarrow ff H, 4f, 2f$

assume 2 ab^{-1} of 250 GeV data: “H20-staged”

Full tau reconstruction

NIM A810 (2016) 51

[arXiv:1507.01700](https://arxiv.org/abs/1507.01700)

to reconstruct tau **polarimeter**, need
full reconstruction of tau decay products,
including the neutrino(s)

in hadronic tau decays (# neutrino = 1), if we know
the tau **production vertex**,
the **impact parameters** of charged tau decay products,
the \mathbf{p}_T of the tau-tau system,

then the neutrino momenta can be reconstructed:

6 **unknowns**/event:

2 x neutrino 3-momenta

6 **constraints**/event:

2 x impact parameter defines plane of tau momentum

2 x tau invariant mass

2 from event \mathbf{p}_T [p_x , p_y] \rightarrow insensitive to ISR / beamstrahlung

[+ solve two-fold ambiguities from quadratic constraints using tau lifetime,
and, only if necessary, using reconstructed tau-tau mass]

vertex detector
tracking
photon reco.
Jet En. Res.

reconstruct $Z \rightarrow e e, \mu \mu, \text{jets} + 2 \times (1\text{-prong tau jets})$

simple preselection

some distributions after reconstruction and preselection:

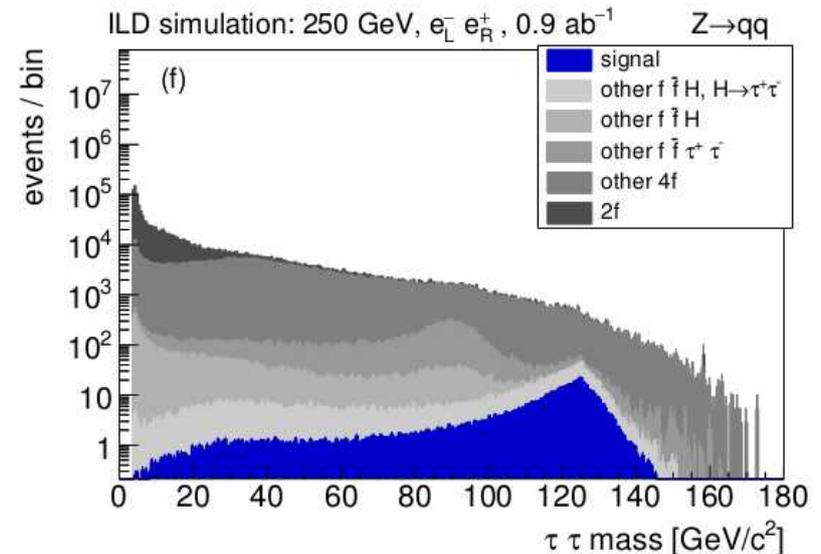
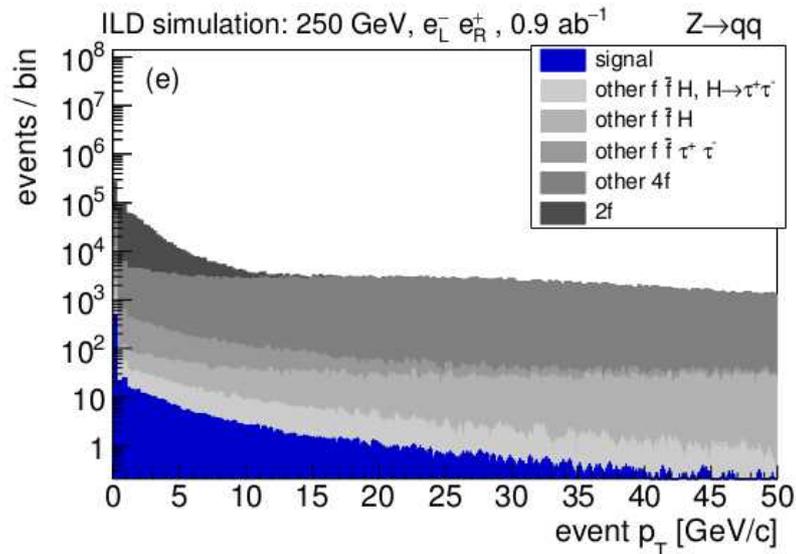
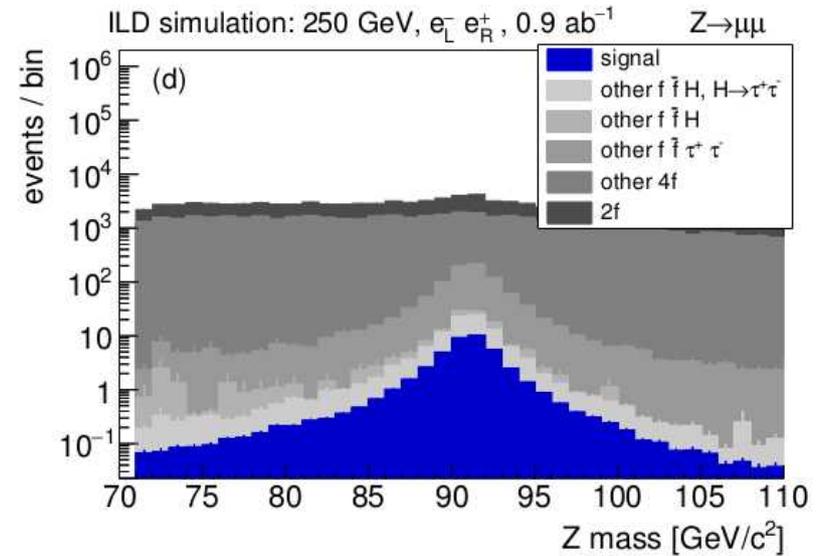
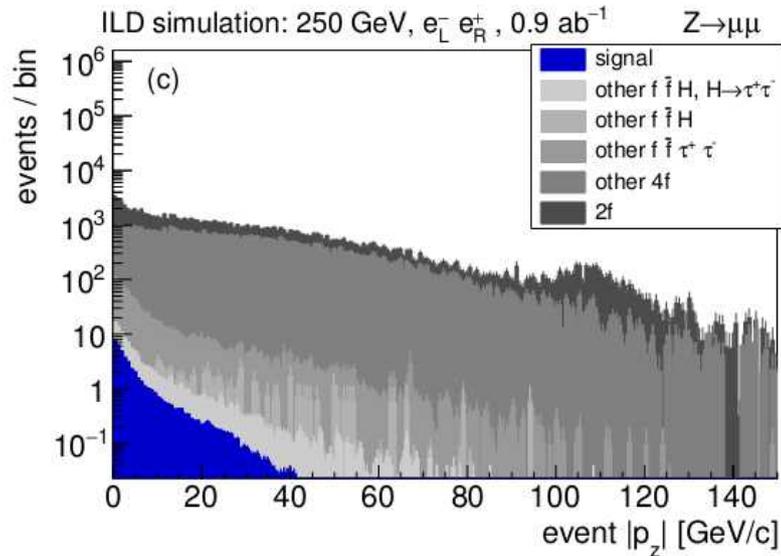


TABLE II. Selection cuts [see text for details; (energies, momenta, and masses) in $\text{GeV}/c^{(0,1,2)}$], signal selection efficiencies ϵ (in %), and number of expected background events (BG) at various stages of the selection in the three selection channels e, μ, q . Event numbers are scaled to the 2 ab^{-1} of 250 GeV data of the “H20-staged” running scenario.

event property	leptonic preselection			hadronic preselection				
	requirement	ϵ_e	ϵ_μ	BG _{lep}	requirement	ϵ_q	BG _{had}	
		100	100	142 M		100	142 M	
chg. PFOs	$4 \rightarrow 7$	91	93	10.1 M	≥ 8	98	95.7 M	
$Z \rightarrow ll$ candidate	≥ 1	88	90	1.03 M				
isolated prongs					≥ 2	91	45.8 M	
opp. chgd. prongs		84	87	903 k		84	33.5 M	
min. prong score					> 0.8	77	14.5 M	
impact par. error	$< 25\mu m$	76	79	491 k	$< 25\mu m$	74	13.2 M	
extra cone energy		72	75	438 k				
m_Z					$60 \rightarrow 160$	72	5.58 M	
m_{recoil}					$50 \rightarrow 160$	71	4.90 M	
τ decay mode		63	65	236 k		64	1.99 M	
full selection		$Z \rightarrow ee$		$Z \rightarrow \mu\mu$		$Z \rightarrow qq$		
event property	requirement	ϵ_e	BG _e	ϵ_μ	BG _{μ}	requirement	ϵ_q	BG _q
good $\tau^+\tau^-$ fit		57	112 k	59	99.5 k		58	1.64 M
$m_{\tau\tau}$	$100 \rightarrow 140$	46	618	52	366	$100 \rightarrow 140$	42	43.5 k
event p_T	< 5	43	309	50	268	< 20	42	31.6 k
m_{recoil}	> 120	42	252	50	162	> 100	41	23.5 k
m_Z	$80 \rightarrow 105$	41	186	49	136	$80 \rightarrow 115$	38	6.93 k
$ \cos\theta_Z $	< 0.96	40	168	47	124	< 0.96	37	6.22 k
event p_z	< 40	40	144	47	105	< 40	37	5.26 k
$ \cos\theta_P _{\text{min}}$	< 0.95	40	140	47	102	< 0.95	37	5.26 k
Sample purity (%)		19		26		11		

ability to identify tau decay modes

TABLE I. Migrations among τ -pair decay modes, for preselected and reconstructed signal events in which the Z boson decays to either muons or light quarks. All numbers are given in %.

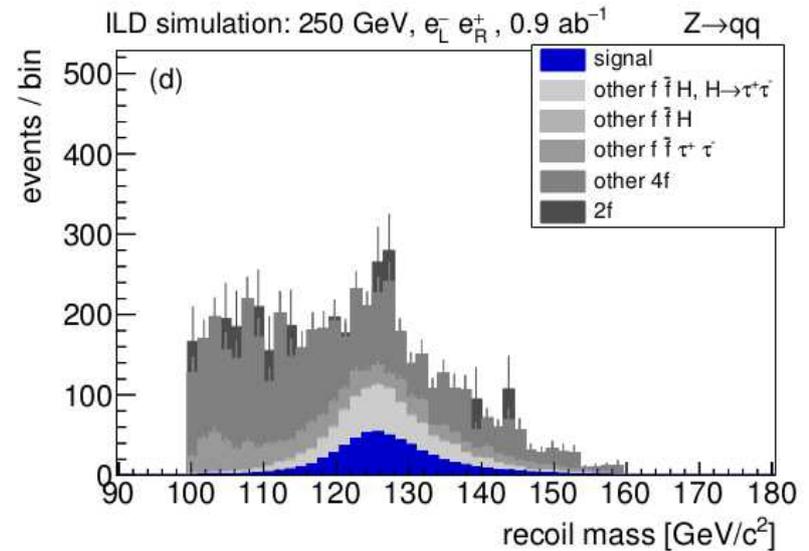
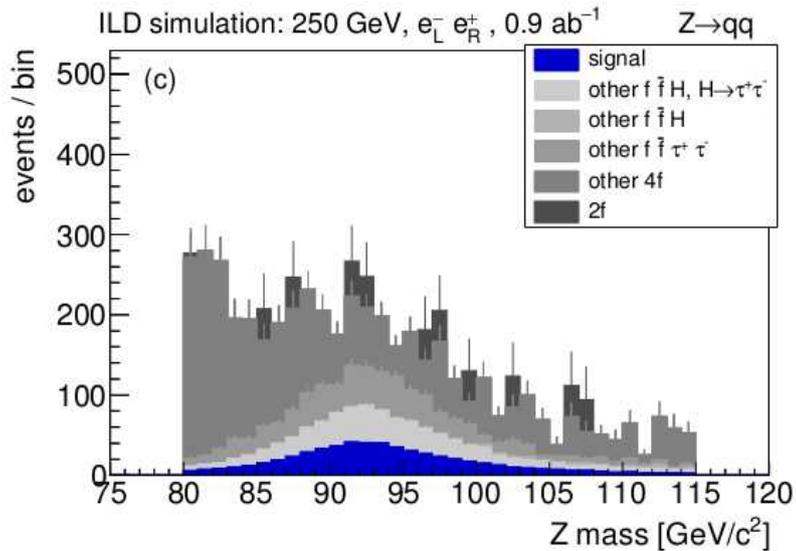
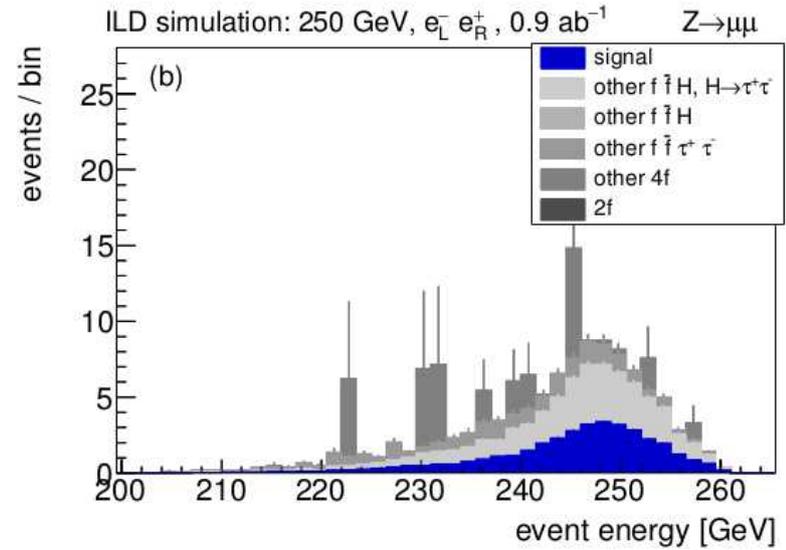
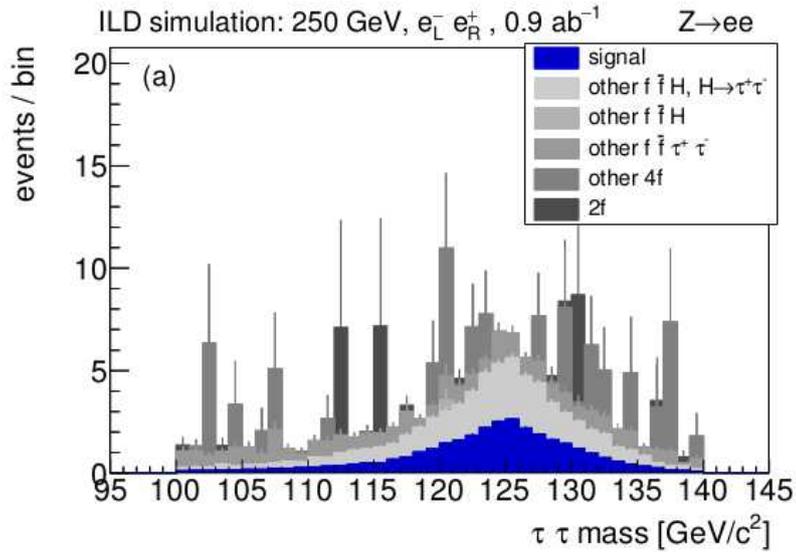
Reco. decay	True decay		
	$(\pi\nu, \pi\nu)$	$(\pi\nu, \rho\nu)$	$(\rho\nu, \rho\nu)$
$Z \rightarrow \mu^+ \mu^-$			
$(\pi\nu, \pi\nu)$	93	3	< 1
$(\pi\nu, \rho\nu)$	7	93	6
$(\rho\nu, \rho\nu)$	< 1	4	94
$Z \rightarrow \text{qq(uds)}$			
$(\pi\nu, \pi\nu)$	89	6	< 1
$(\pi\nu, \rho\nu)$	11	89	12
$(\rho\nu, \rho\nu)$	< 1	5	87

reconstructing polarimeter vectors: in tau rest frame

$$\mathbf{h}(\tau^\pm \rightarrow \pi^\pm \nu) \propto \mathbf{p}_{\pi^\pm} \quad (6)$$

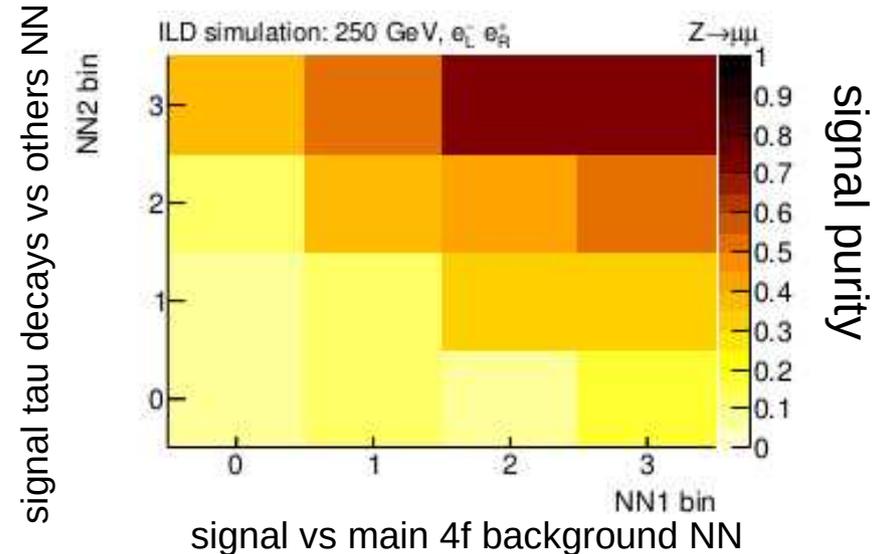
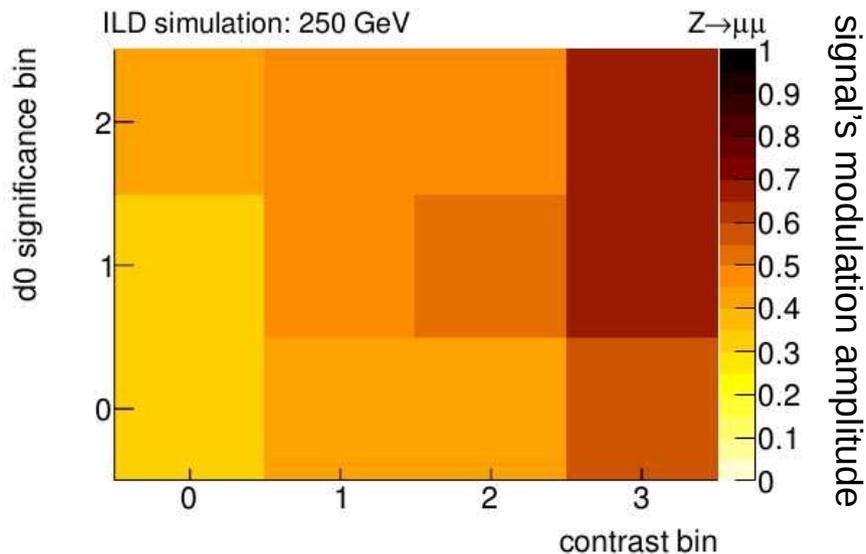
$$\mathbf{h}(\tau^\pm \rightarrow \pi^\pm \pi^0 \nu) \propto m_\tau (E_{\pi^\pm} - E_{\pi^0}) (\mathbf{p}_{\pi^\pm} - \mathbf{p}_{\pi^0}) + 2(p_{\pi^\pm} + p_{\pi^0})^2 \mathbf{p}_\nu, \quad (7)$$

some distributions after selection



group events according to expected sensitivity, based on:

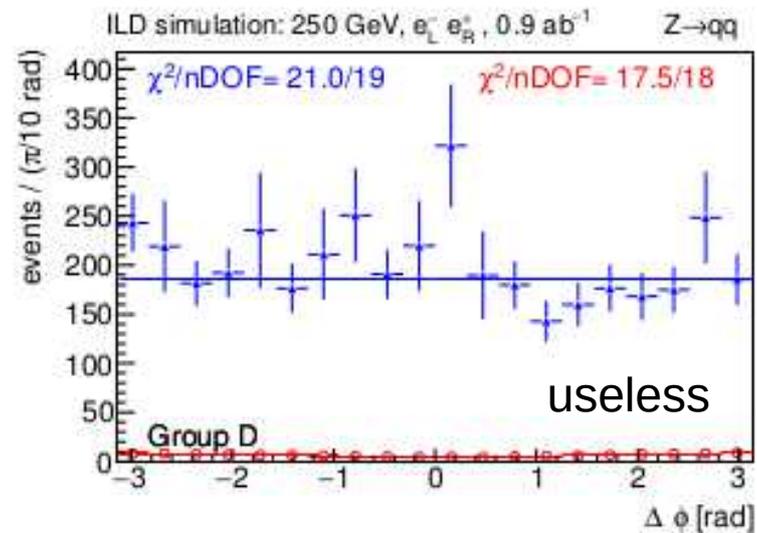
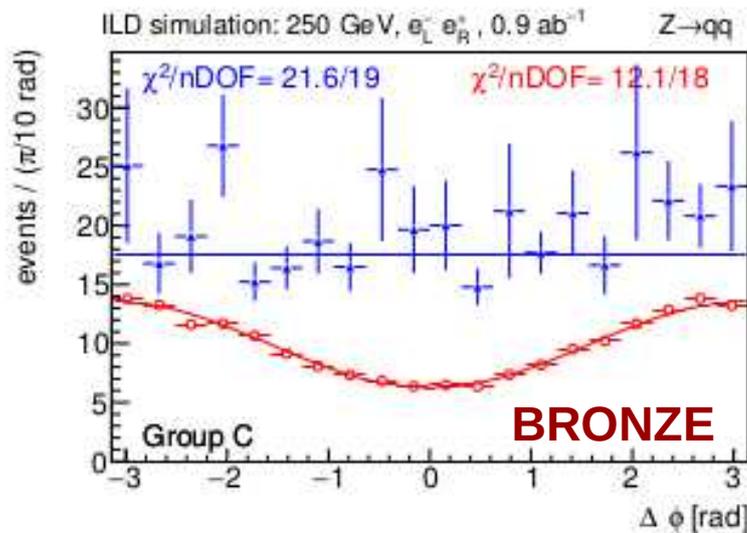
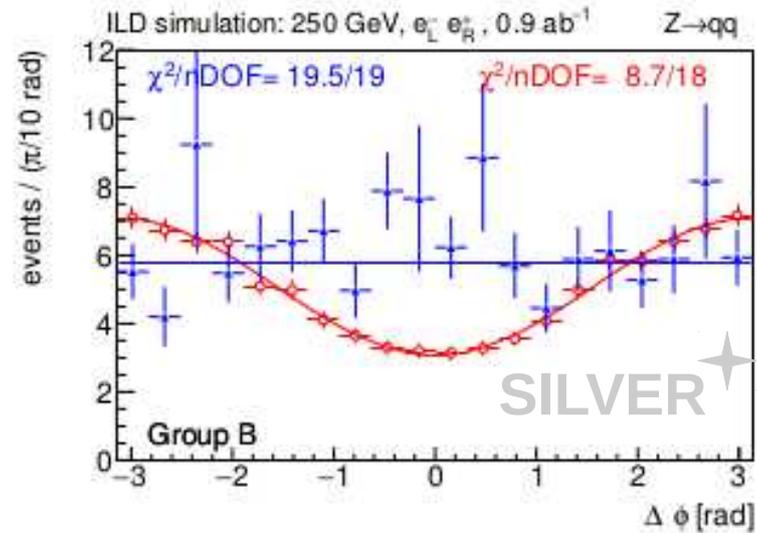
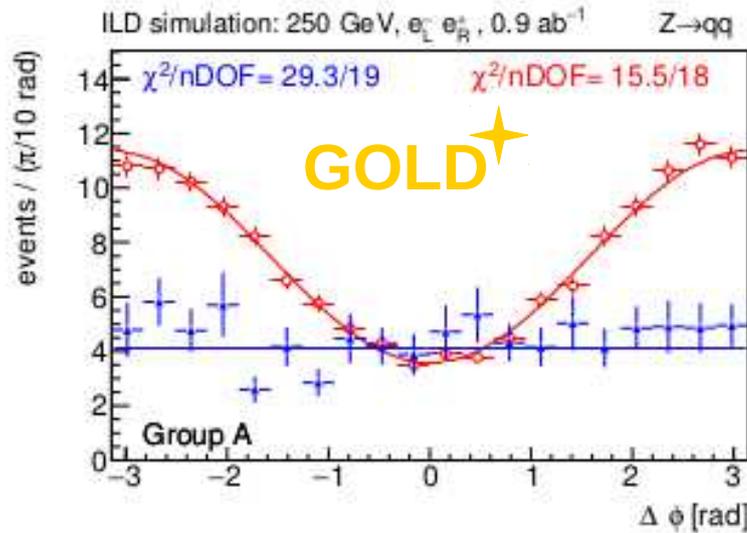
- longitudinal component of polarimeters (contrast function) → intrinsic sensitivity
- tau decay prongs' d0 measurement significance → reconstruction quality
- output of simple NN [6 inputs] (signal vs. main 4f bgs) → background contamination
- output of simple NN [4 inputs] (signal tau decays vs. others) → tau decay mis-identification



CP sensitive observable $\Delta\phi$ in different event sensitivity bins

signal background

error bars:
MC statistics



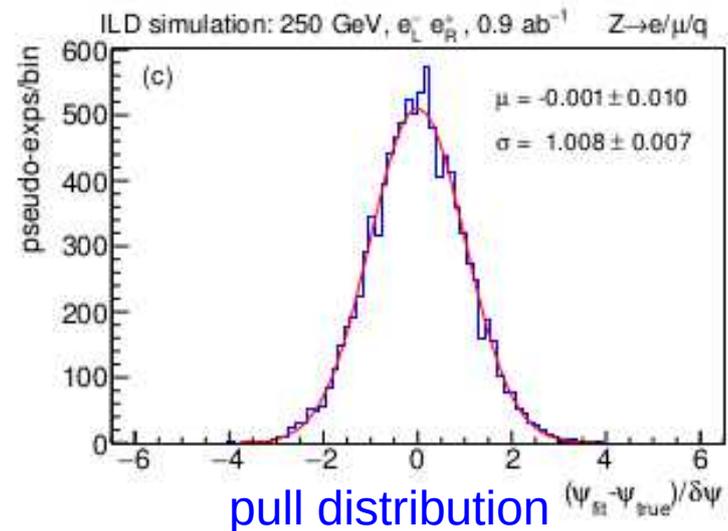
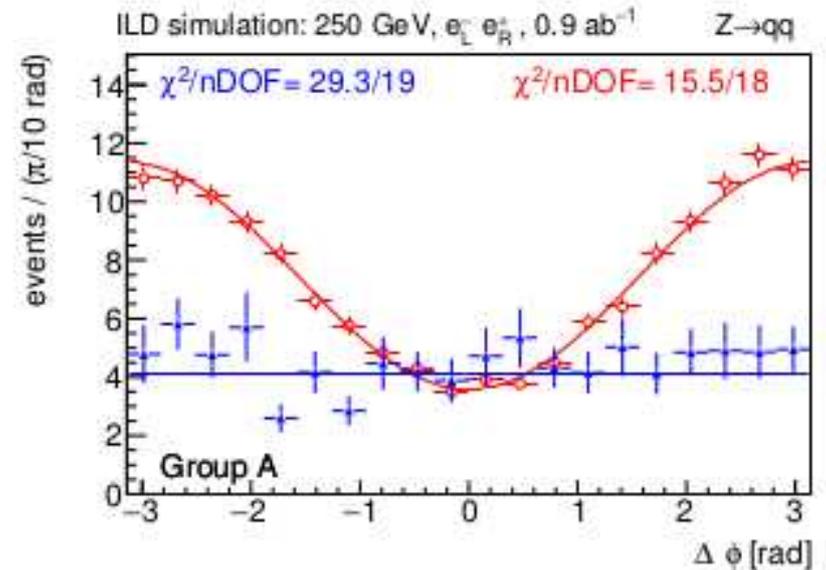
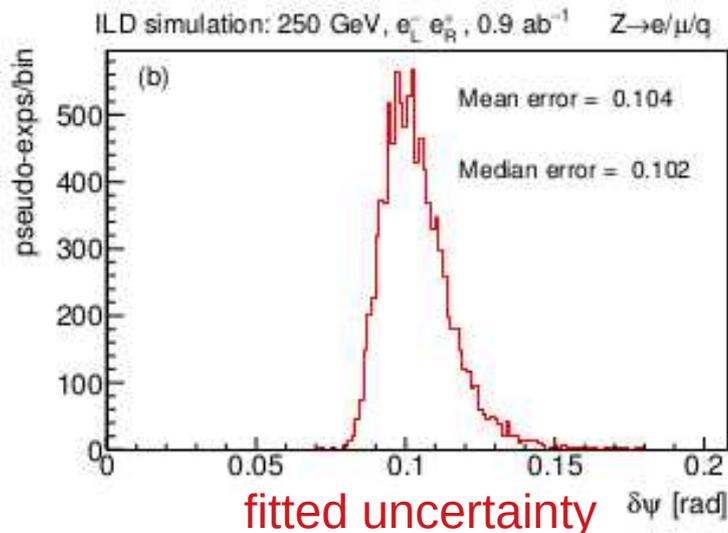
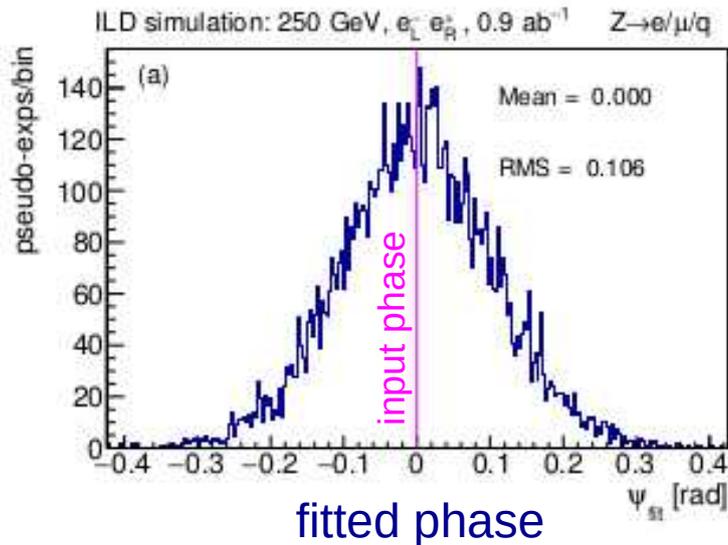
phase of **signal distributions** is sensitive to CP¹³

estimating measurement sensitivity

unbinned maximum likelihood fit: simultaneously in all sensitivity bins and selection channels
fit a single parameter: the phase of $\Delta\phi$ distribution

perform series of toy pseudo-experiments using simulated distributions

results of 10k pseudo-exps

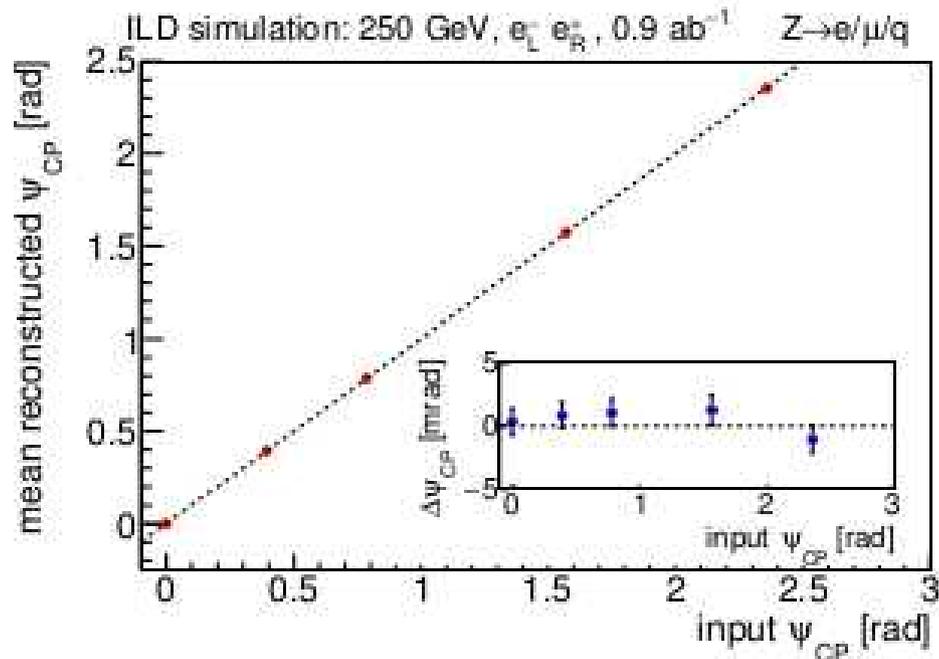


predicted sensitivity on ψ_{CP} under various conditions

TABLE IV. Estimated experimental precision $\delta\psi_{CP}$ on the CP phase in different scenarios.

$\int \mathcal{L}$ [ab ⁻¹]	beam pol.		notes	$\delta\psi_{CP}$ [mrad]
	e ⁻	e ⁺		
1.0	0	0	full analysis	116
1.0	0	0	only $Z \rightarrow ee$	450
1.0	0	0	only $Z \rightarrow \mu\mu$	412
1.0	0	0	only $Z \rightarrow qq$	122
1.0	0	0	only $(\pi\nu, \pi\nu)$	387
1.0	0	0	only $(\pi\nu, \rho\nu)$	198
1.0	0	0	only $(\rho\nu, \rho\nu)$	166
1.0	-1.0	+1.0	pure e _L ⁻ e _R ⁺	97
1.0	+1.0	-1.0	pure e _R ⁻ e _L ⁺	113
1.0	0	0	$\sigma_{ZH} + 20\%$	104
1.0	0	0	$\sigma_{ZH} - 20\%$	133
1.0	0	0	no bg.	76
1.0	0	0	perf. pol.	100
1.0	0	0	no bg., perf. pol./eff.	25
H20-staged: 250 GeV, 2 ab ⁻¹				
0.9	-0.8	+0.3	only e _L ⁻ e _R ⁺	102
0.9	+0.8	-0.3	only e _R ⁻ e _L ⁺	120
0.1	-0.8	-0.3	only e _L ⁻ e _L ⁺	359
0.1	+0.8	+0.3	only e _R ⁻ e _R ⁺	396
2.0	mixed		full analysis	75

sanity check: output = input phase



sensitivity on ψ_{CP} :

2/ab, all channels: 75 mrad

dominated by events with hadronic Z decay

perfect reconstruction, selection:
25 mrad sensitivity @ 1 ab⁻¹

summary

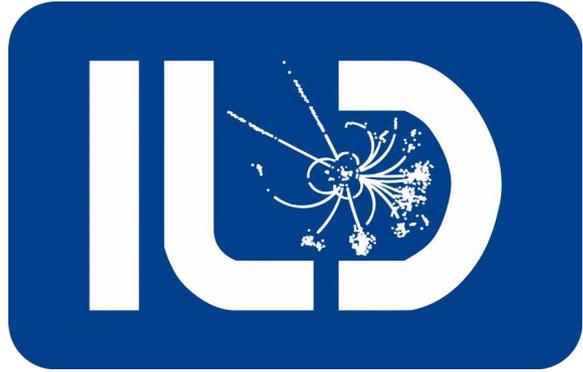
demonstrated, using full detector simulation and backgrounds,
that CP mixing in tau-pair from Higgs decays
can be determined to 75 mrad \sim 4.3 deg
using 2 ab^{-1} of ILC250 data

Measurement relies on many aspects of detector:
impact parameter reconstruction
reconstruction of photons/ π^0 from tau decays
jet energy resolution

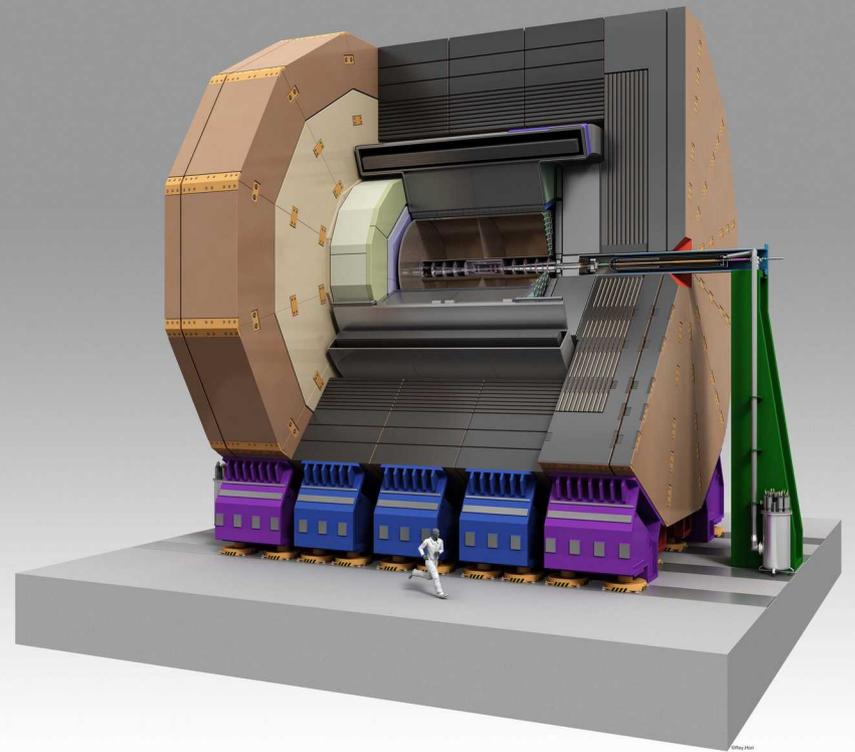
potential for improved analysis methods
to significantly improve results [ultimately < 20 mrad for 2 ab^{-1}]

using only a few tau decay modes
→ can also increase sensitivity by including other modes

backup



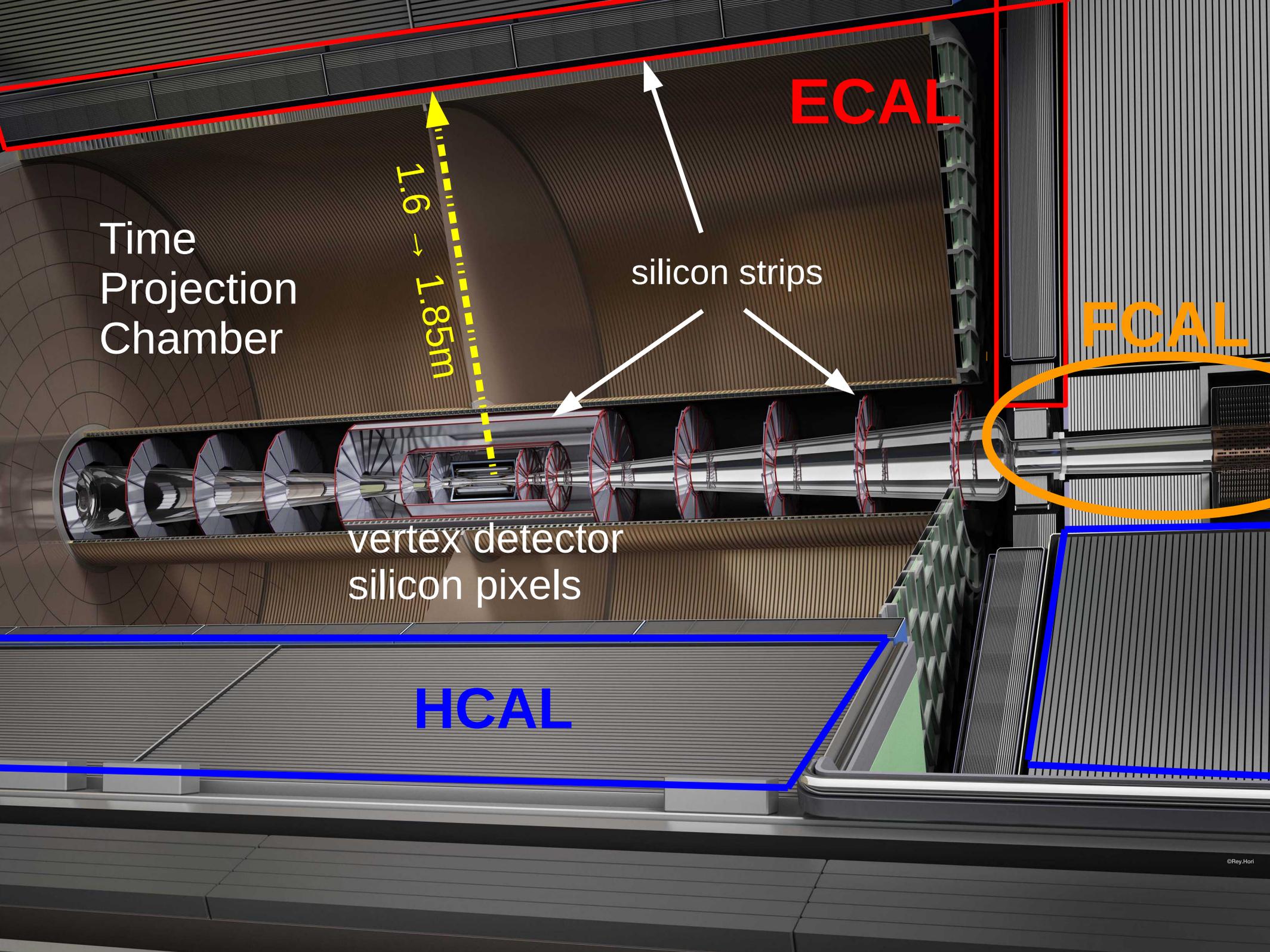
International Large Detector



One of two detector designs being studied for the ILC
dominated by groups from Europe and Japan

Design principles

- excellent vertexing: identification of b , c , τ
 - high precision and lightweight vertex detector
- highly efficient and precise charged particle tracking
 - large TPC in ~ 3.5 T field
- excellent jet energy resolution
 - make best use of dominant hadronic decays of W , Z , H
- highly granular calorimeters



ECAL

Time
Projection
Chamber

1.6 → 1.85m

silicon strips

FCAL

vertex detector
silicon pixels

HCAL

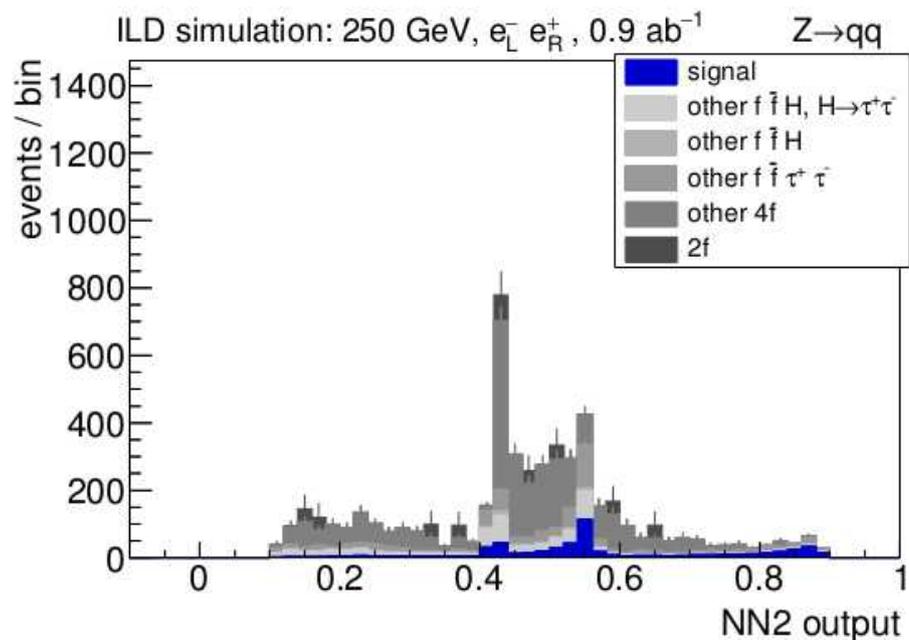
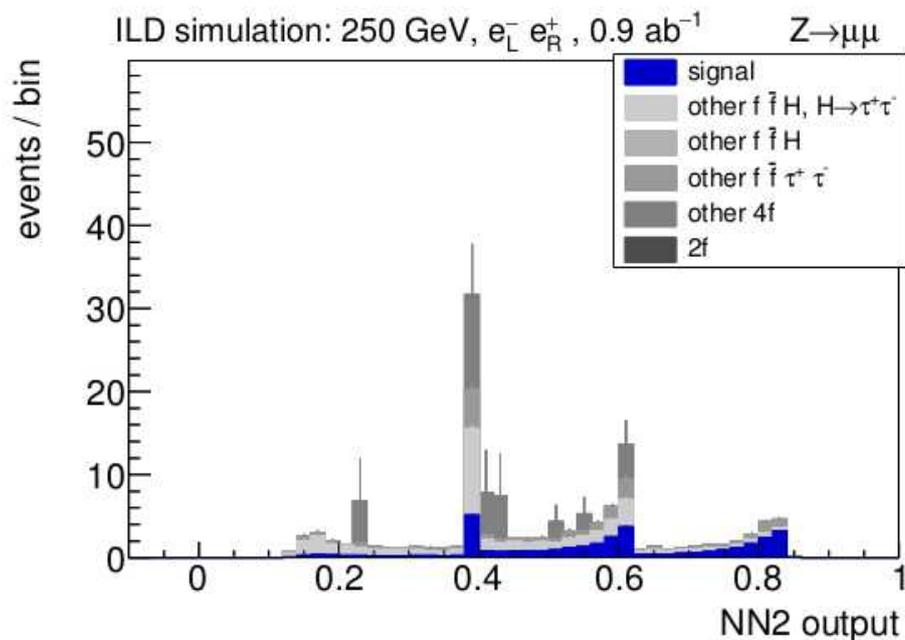
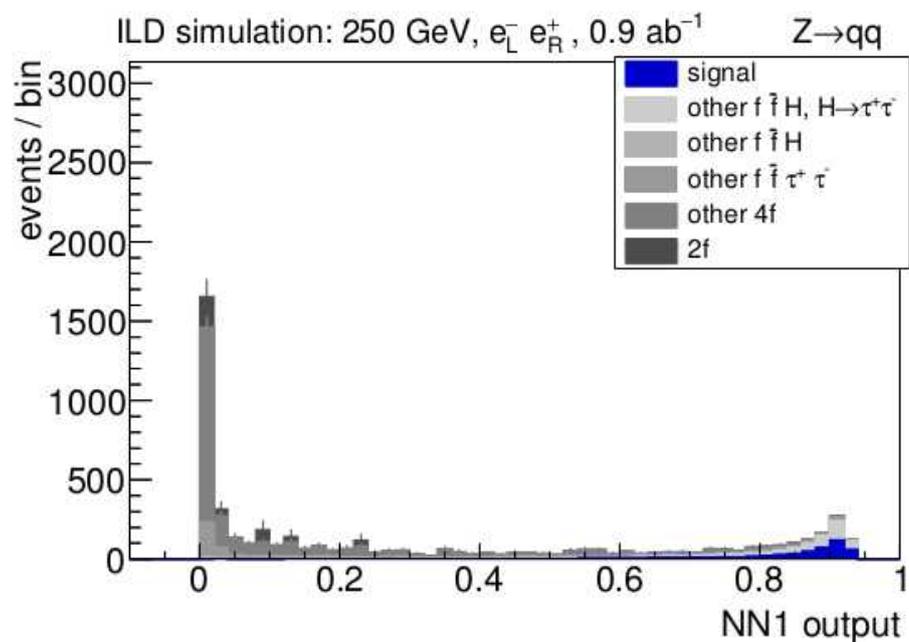
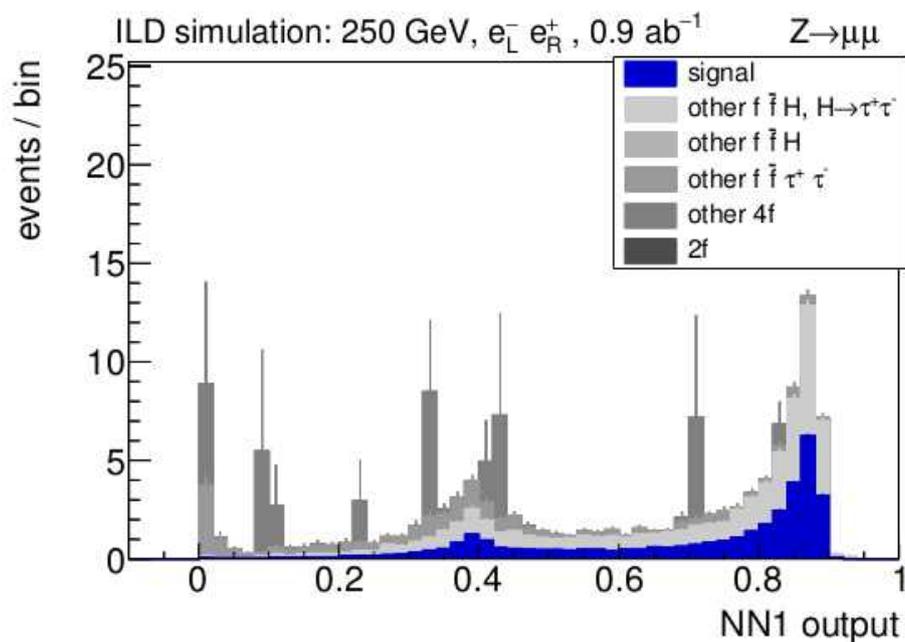


FIG. 7. Distributions of the two Neural Network outputs in the muon and hadronic selection channels. The structure in the output of NN2 is due to the three different combinations of τ lepton decay modes. Distributions are normalized to 0.9 ab^{-1} of data in the $e_L^- e_R^+$ beam polarization.