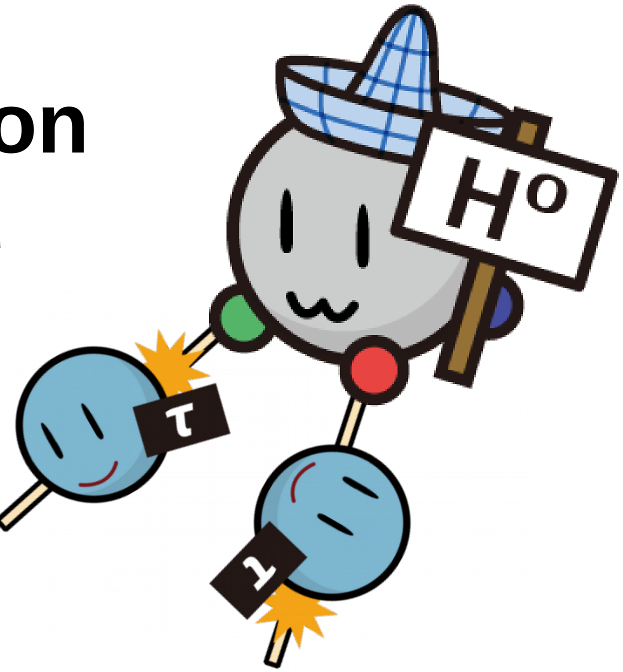
Measuring the CP state of tau lepton pairs from Higgs decays using tau spin correlations at the ILC



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

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Graham Wilson, Univ. of Kansas

Snowmass EF01, June 24, 2020

This study was done mostly by Daniel Jeans

Motivation

Is the 125 GeV Higgs a CP eigenstate ?

$$h_{125} = \cos\ \psi_{CP}\ h^{CPeven} + \sin\ \psi_{CP}\ A^{CPodd}$$

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

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

or a mixture?

Do Higgs couplings conserve CP ?

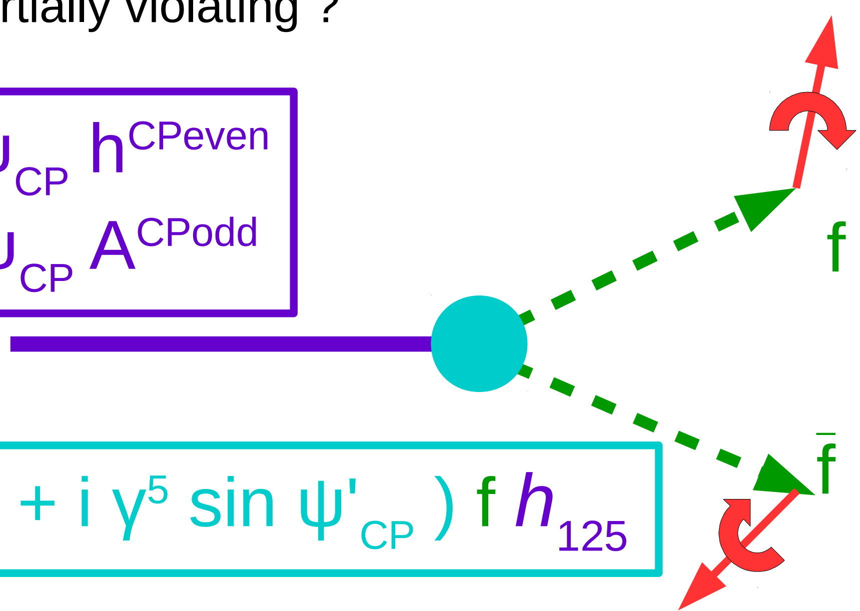
e.g. coupling to fermions: $\mathcal{L} \sim g\ \bar{f}\ (\ \cos\ \psi_{CP} + i\ \gamma^5 \sin\ \psi_{CP}\ )\ f\ H$

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

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

or partially violating ?

$h_{125} = \cos\ \psi_{CP}\ h^{CPeven} + \sin\ \psi_{CP}\ A^{CPodd}$



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

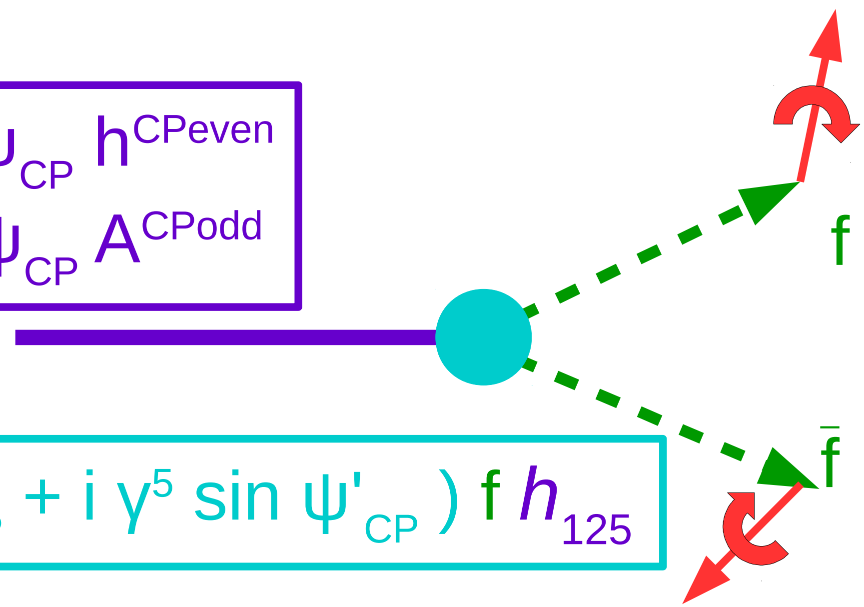
h is a spin 0 state:

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

[ψ = 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]

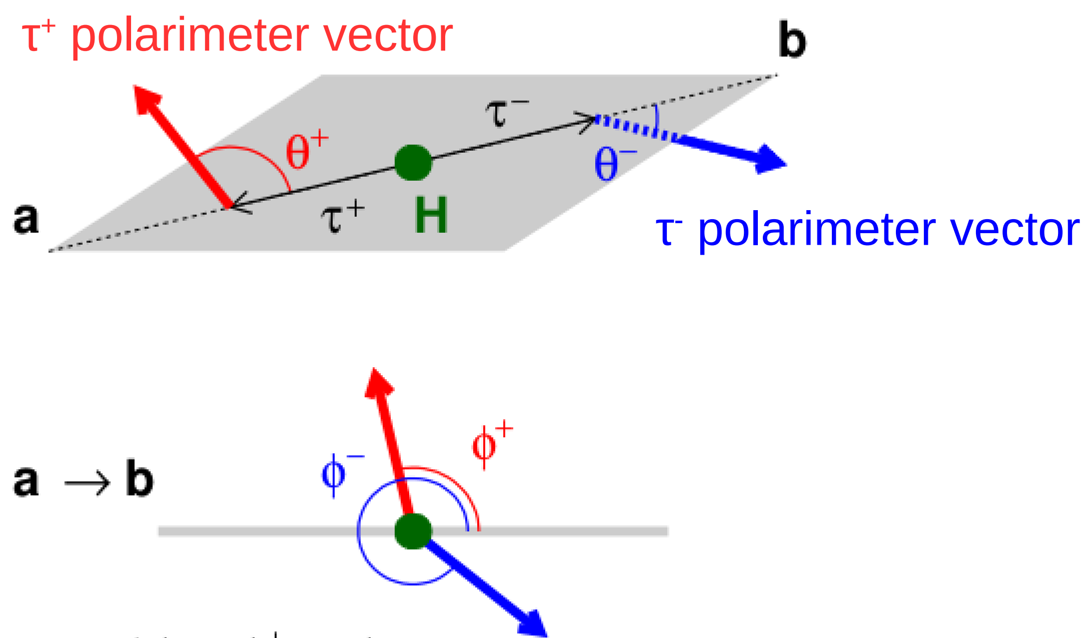
$$h_{125} = \cos\psi_{CP}\, h^{CPeven} + \sin\psi_{CP}\, A^{CPodd}$$



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

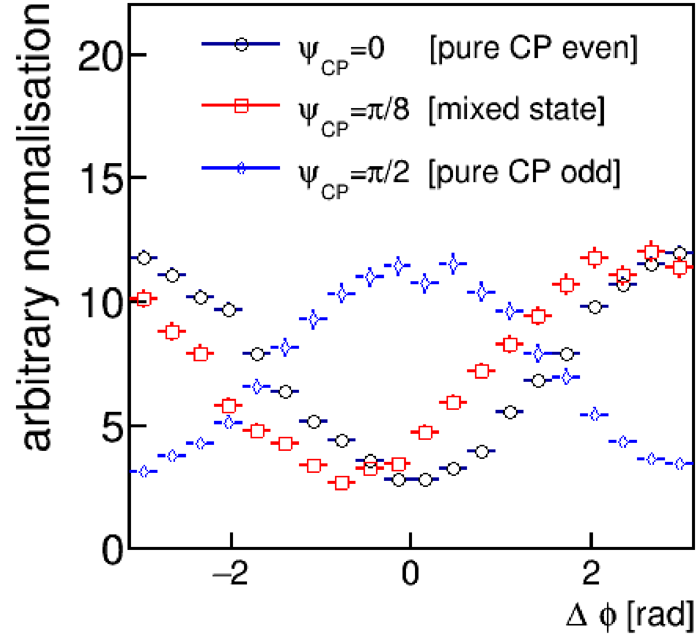
why use tau leptons to measure CP in Higgs sector?

- fermion: tree-level CP effects possible
  (H → 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 $\tau^{\pm} \rightarrow (\pi^{\pm}\nu)$ or $(\pi^{\pm}\pi^{0}\nu)$ decay modes
- reasonable Higgs branching fraction (6.3%)
- clean separation of the two fermion decays (no color string as in H→bb)



$\Delta\phi = \phi^+ - \phi^-$

Angles defined in the $\tau^\pm$ rest frames relative to $\mathbf{p}_H$



distribution of Δϕ is sensitive to CP mixing angle, ψ_{CP}

amplitude of modulation in Δϕ varies from event to event, depending on $\theta^\pm$, according to the contrast function:

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

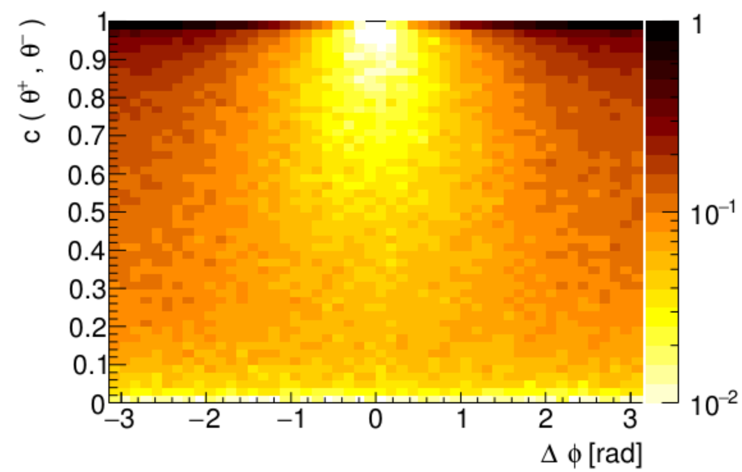
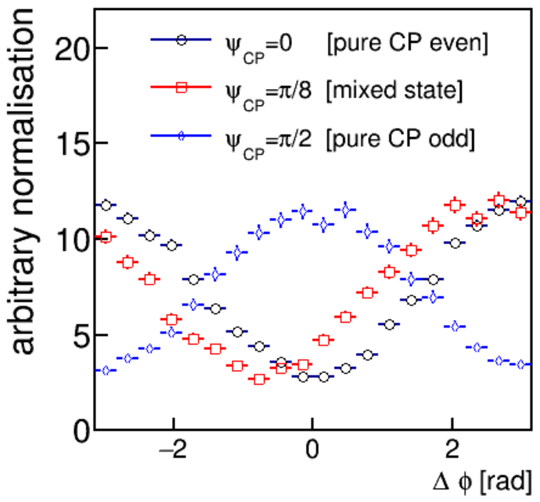


FIG. 3. Two-dimensional distribution of events in $\Delta\phi$ and $c(\theta^+,\theta^-)$ at MC truth level, for the case $\psi_{CP} = 0$.

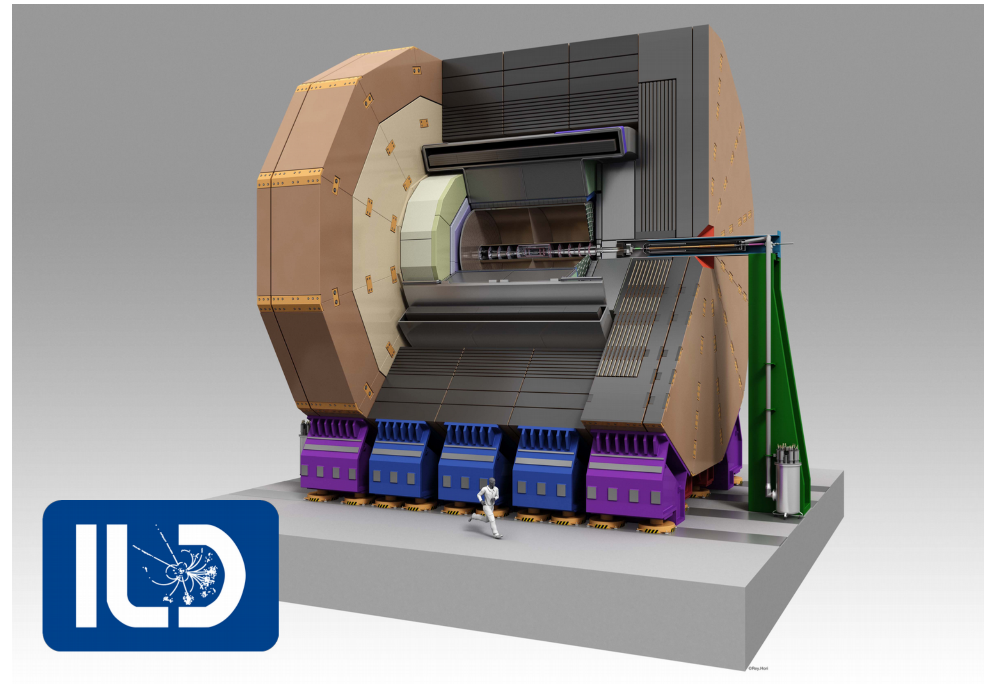
A. Rougé, PLB 619 (2005) 43 and refs. for more details

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 or mixed CP mass eigenstate, …
→ requires combination with other measurements (eg σ_{ZH}),
model assumptions, ...

Analysis uses full ILD simulation signal and SM backgrounds with standard ilcsoft based reconstruction (ILD_o1_v05 detector model)

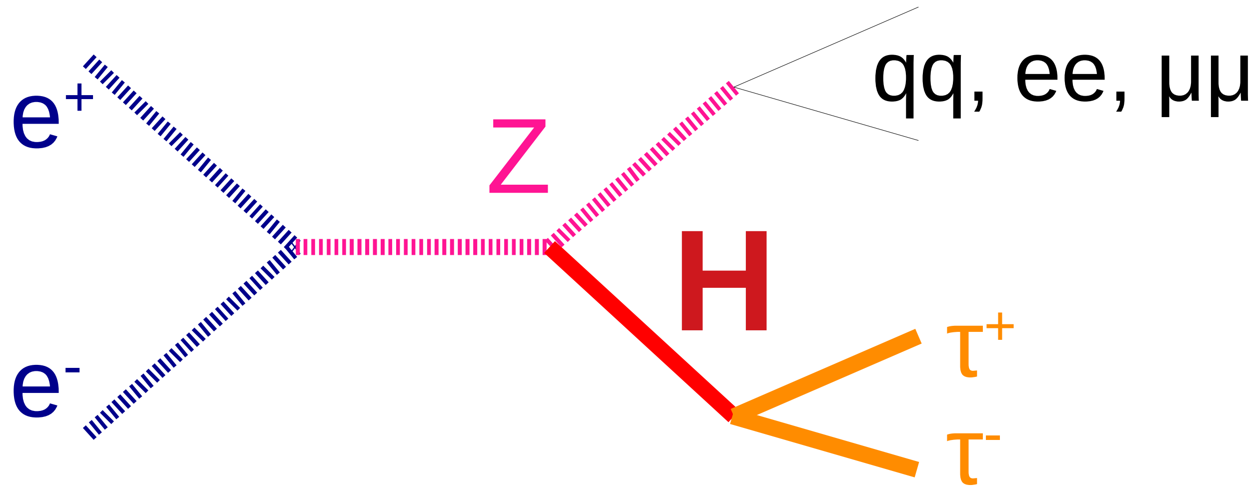


SIGNAL: $e^+ e^- \rightarrow Z\,H$

$Z \rightarrow e^+e^-, \mu^+\mu^-$, quarks

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

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



SM backgrounds:

$e^+ e^- \rightarrow$ ffH, 4f, 2f

assume 2 ab^{-1} of 250 GeV data: “H20-staged” with standard (80%, 30%) beam polarization mix (see arXiv:1903.01629)

Full tau reconstruction

D. Jeans, NIM A810 (2016) 51

arXiv:1507.01700

to reconstruct tau polarimeter vectors, 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 p_T of the tau-tau system,

vertex detector
tracking
photon reco.
Jet En. Res.

then the neutrino momenta can be reconstructed
6 unknowns/event:
2 x neutrino 3-momenta
6 constraints/event:
2 impact parameters define the tau momenta plane
2 invariant mass of each tau
2 from event p_T [p_x, p_y] → insensitive to ISR / beamstrahlung

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

(Quite sensitive to production vertex reconstruction – not yet using ILC nano-beam constraint)

reconstruct Z → e^+e^-, $\mu^+\mu^-$, jets + 2 x (1-prong tau jets)

simple preselection

some distributions after reconstruction and preselection:

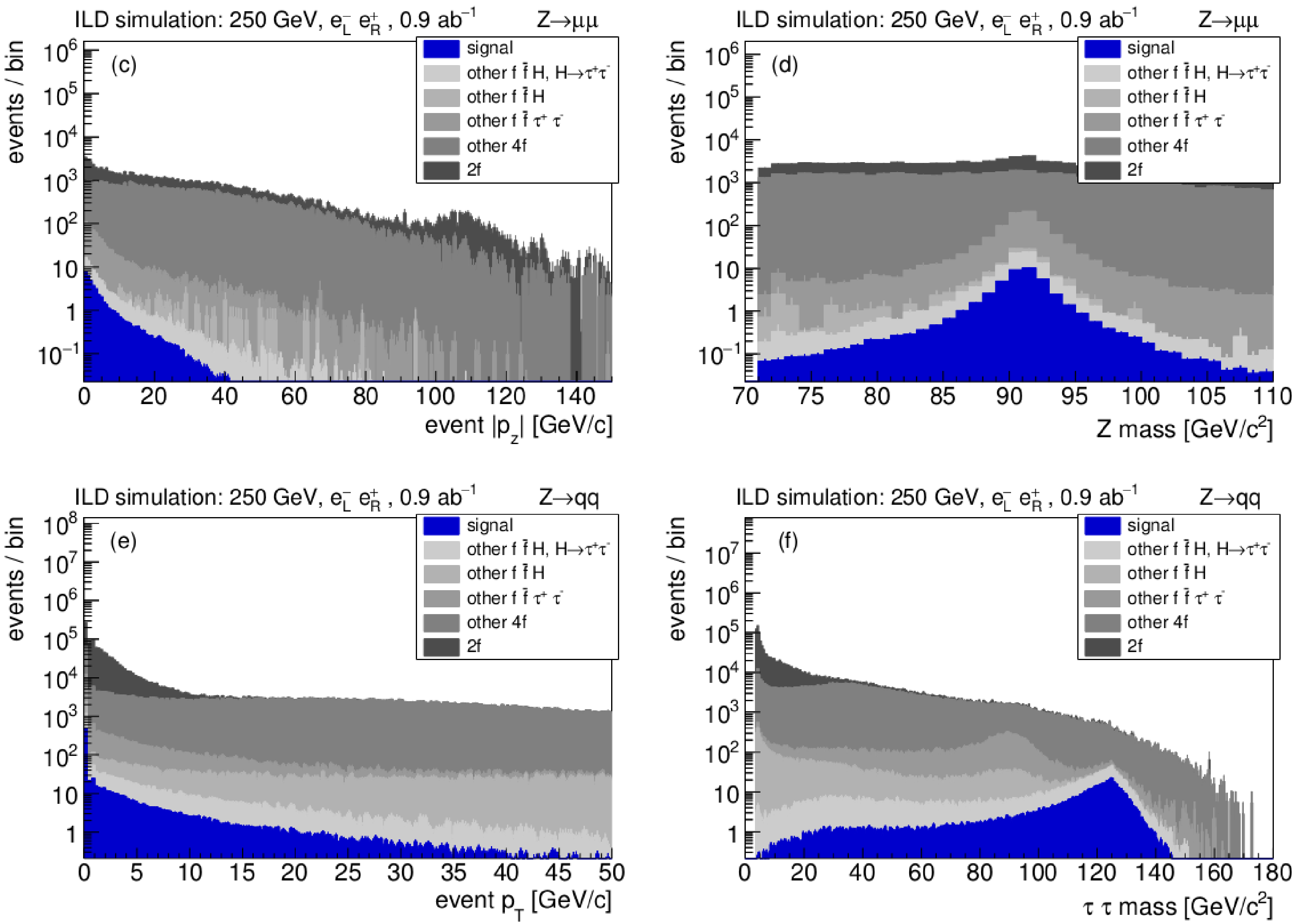


TABLE II. Selection cuts [see text for details; (energies, momenta, and masses) in $\mathrm{GeV}/c^{(0,1,2)}$], signal selection efficiencies ϵ (in %), and number of expected background events (BG) at various stages of the selection in the three selection channels e, μ, q. Event numbers are scaled to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

	Leptonic Preselection				Hadronic Preselection		
Event Property	Requirement	ϵ_e	ϵ_μ	$\mathrm{BG_{lep}}$	Requirement	ϵ_q	$\mathrm{BG_{had}}$
		100	100	142 M		100	142 M
Charged PFOs	$4 \to 7$	91	93	10.1 M	≥ 8	98	95.7 M
$Z \to ll$ candidate	≥ 1	88	90	1.03 M			
Isolated prongs					≥ 2	91	45.8 M
Oppositely charged prongs		84	87	903 k		84	33.5 M
Minimum prong score					>0.8	77	14.5 M
Impact parameter error	$<25\ \mu m$	76	79	491 k	$<25\ \mu m$	74	13.2 M
Extra cone energy		72	75	438 k			
m_Z					$60 \to 160$	72	5.58 M
m_{recoil}					$50 \to 160$	71	4.90 M
τ decay mode		63	65	236 k		64	1.99 M

Full selection		$Z \to ee$		$Z \to \mu\mu$			$Z \to qq$	
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
$m_{\tau\tau}$	$100 \to 140$	46	618	52	366	$100 \to 140$	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	$80 \to 105$	41	186	49	136	$80 \to 115$	38	6.93 k
$\lvert\cos\theta_Z\rvert$	<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
$\lvert\cos\theta_P\rvert_{\mathrm{min}}$	<0.95	40	140	47	102	<0.95	37	5.26 k
Sample purity (%)		19		26			11	

Expected sample composition (signal and background)

TABLE III. Breakdown of remaining signal and background events after the three full selections. Each line excludes processes which contribute to an earlier one. Event numbers are scaled to the 2 ab^{-1} of 250 GeV data of the "H20-staged" running scenario, and are rounded to the nearest integer.

Process	e	μ	q
Signal	32	36	575
Other $f\bar{f}H, H \to \tau^+\tau^-$	39	43	627
Other $f\bar{f}H$	1	0	58
Other $f\bar{f}\tau^+\tau^-$	32	24	766
Other $4f$	51	35	2834
$2f$	18	0	403
Signal purities:	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 %.

	True Decay		
Reconstructed Decay	$(\pi\nu, \pi\nu)$	$(\pi\nu, \rho\nu)$	$(\rho\nu, \rho\nu)$
		$Z \to \mu^+\mu^-$	
$(\pi\nu, \pi\nu)$	93	3	<1
$(\pi\nu, \rho\nu)$	7	93	6
$(\rho\nu, \rho\nu)$	<1	4	94
		$Z \to qq(uds)$	
$(\pi\nu, \pi\nu)$	89	6	<1
$(\pi\nu, \rho\nu)$	11	89	12
$(\rho\nu, \rho\nu)$	<1	5	87

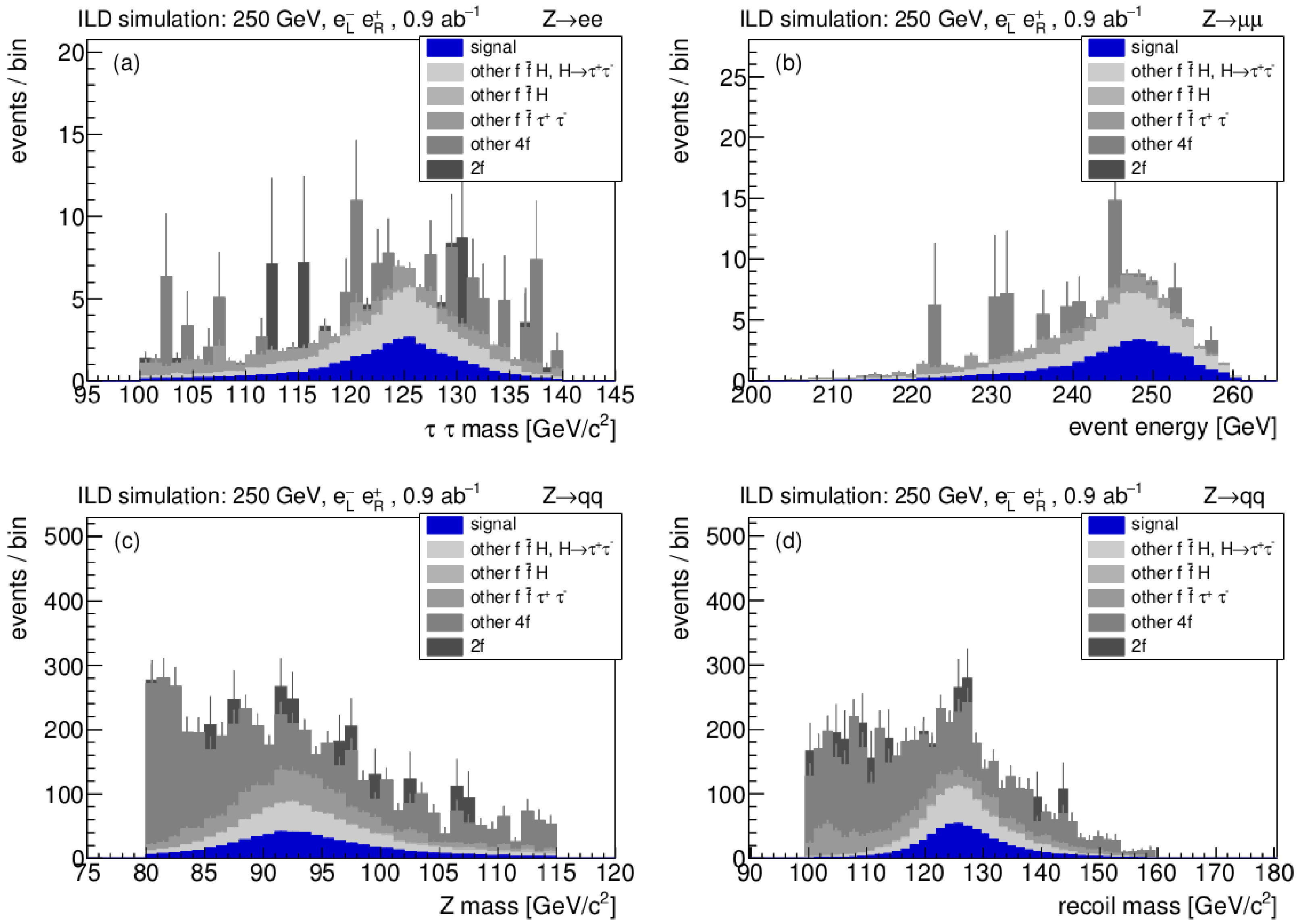
reconstructing polarimeter vectors in tau rest frame

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

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

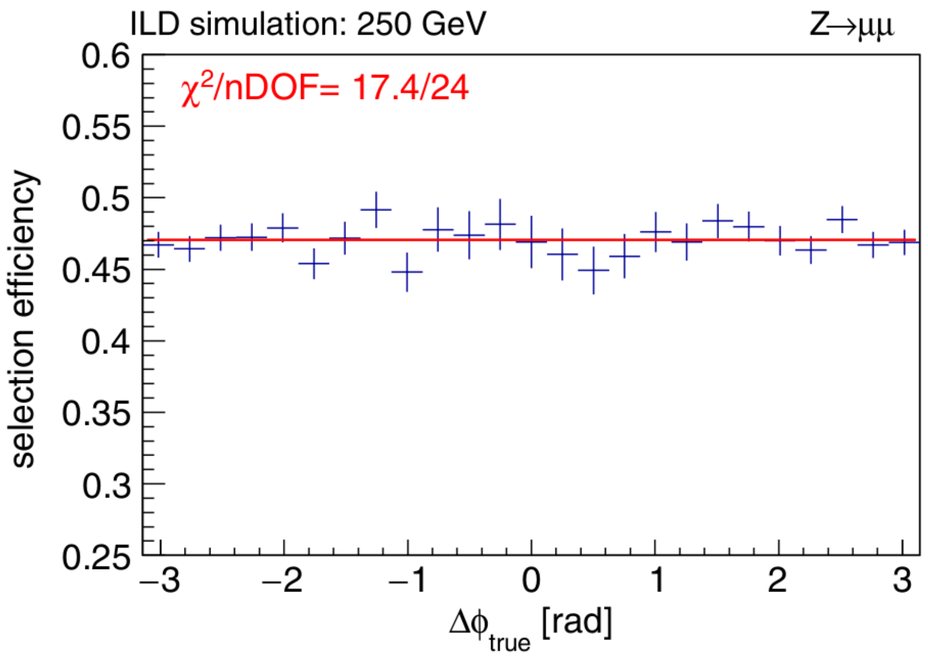
These two channels have maximal spin analyzing power.
Other channels feasible including leptons. (leptons have less analyzing power)

Some distributions after selection

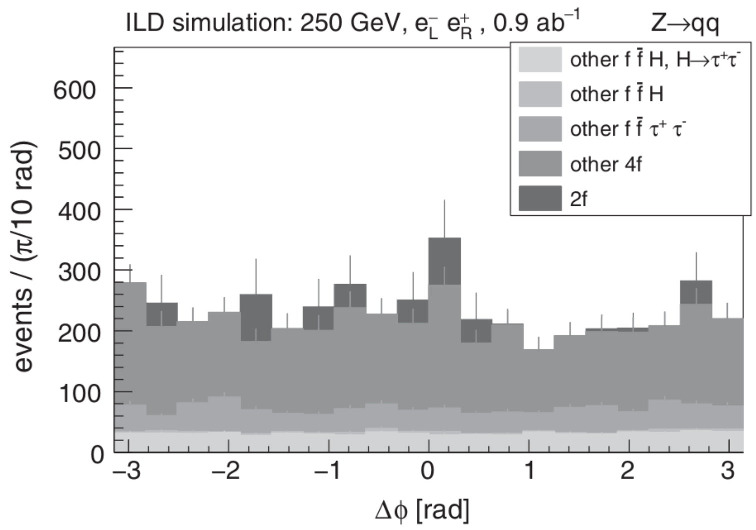


Peaks near 125 GeV for tau-tau mass and mass recoiling against the Z

Δϕ reconstruction crucial



Selection efficiency uniform in Δϕ as expected

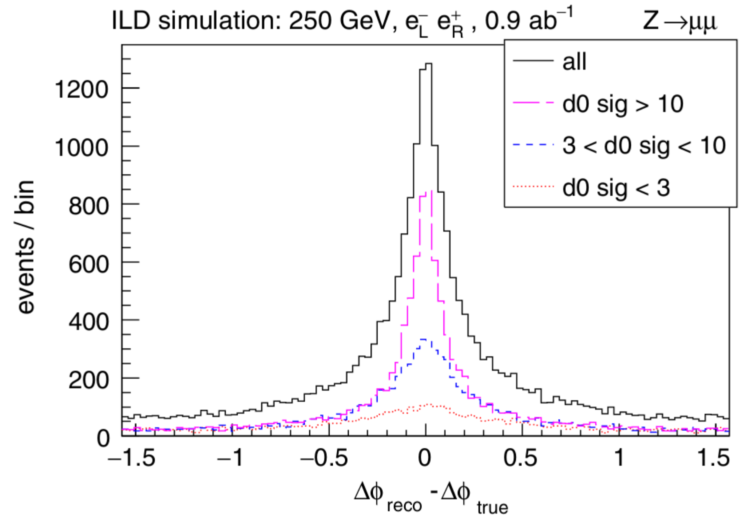


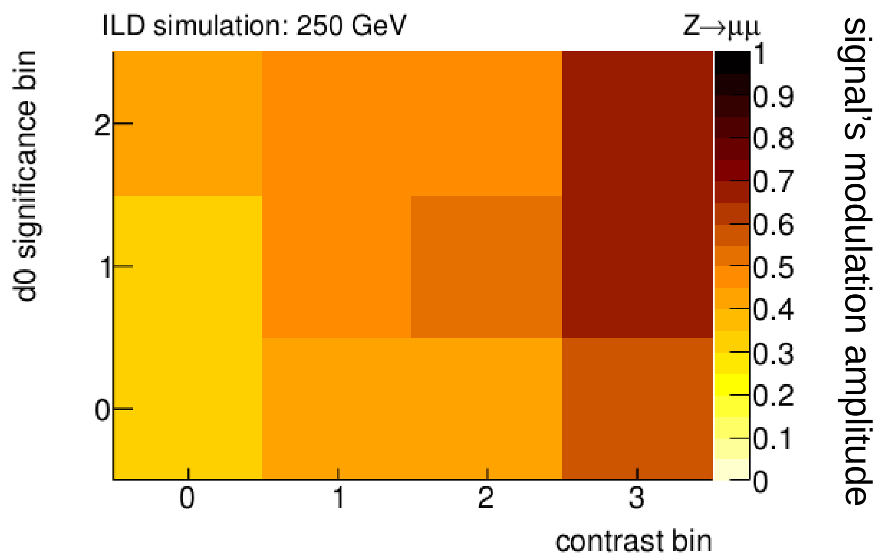
Backgrounds are uniform in Δϕ as expected (even the misIDd ττ component)

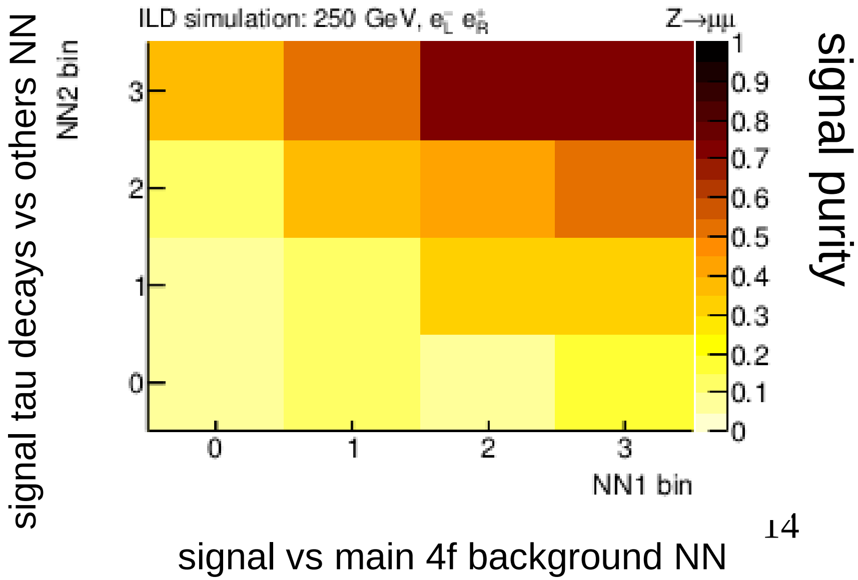
Group events according to expected sensitivity, based on:

- polarimeter vectors contrast function: $f(\theta^+,\theta^-)$ → intrinsic sensitivity
- tau decay track's d0 measurement significance → reconstruction quality
- simple NN [6 inputs] (signal vs. main 4f bkgs) → background contamination
- simple NN [4 inputs] (signal τ decays vs. other τ decays) → tau decay mis-identification

(NN variable details in backup)



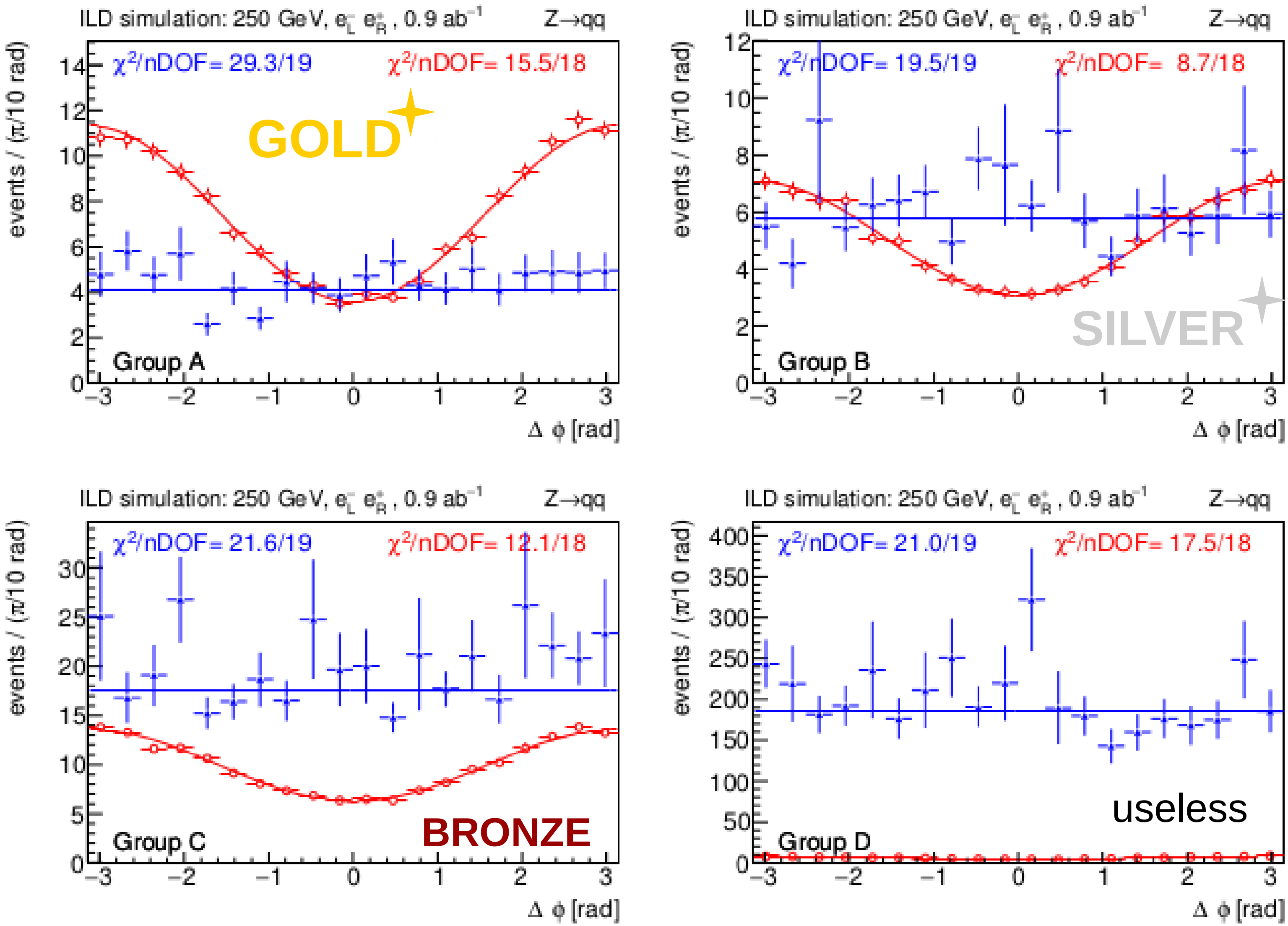




CP sensitive observable Δϕ in different event sensitivity bins

signal background

error bars:
MC statistics

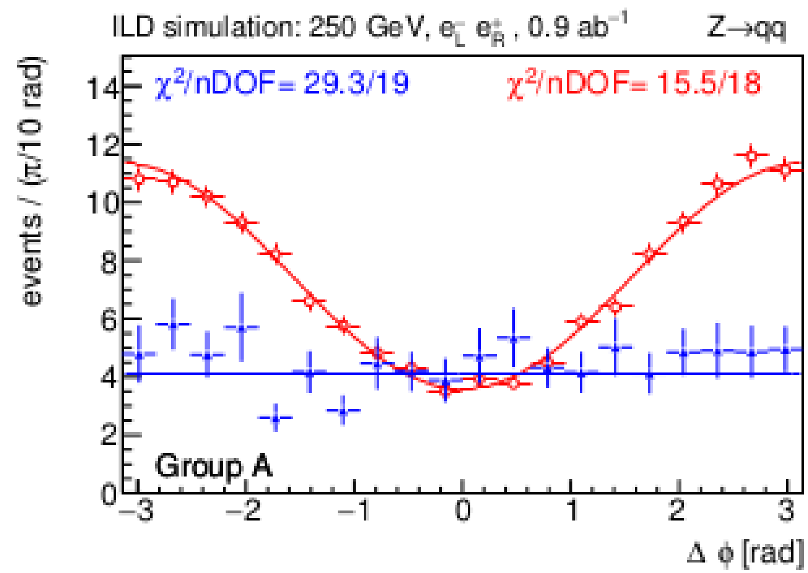


phase of signal distribution is sensitive to CP

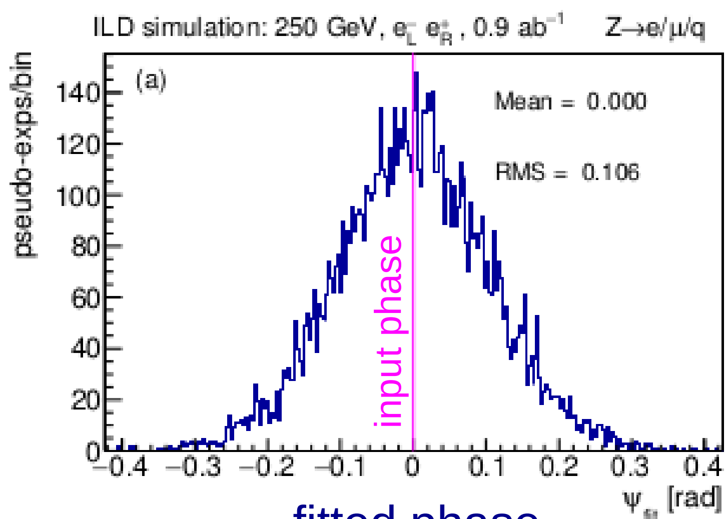
Estimating measurement sensitivity

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

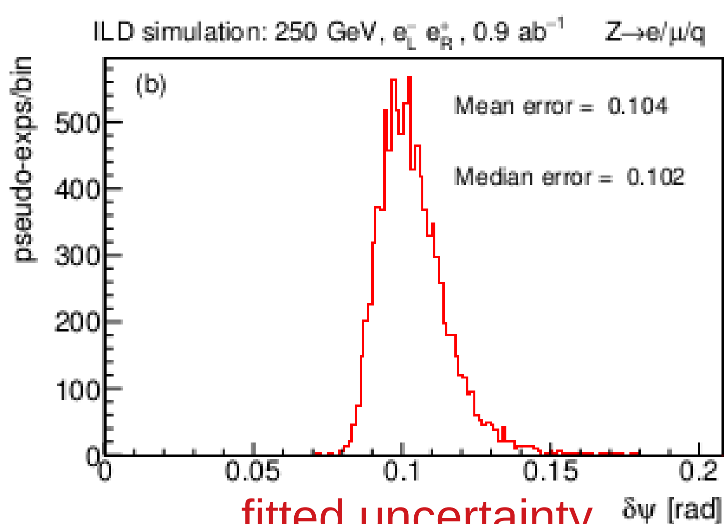
perform series of toy pseudo-experiments using
simulated distributions



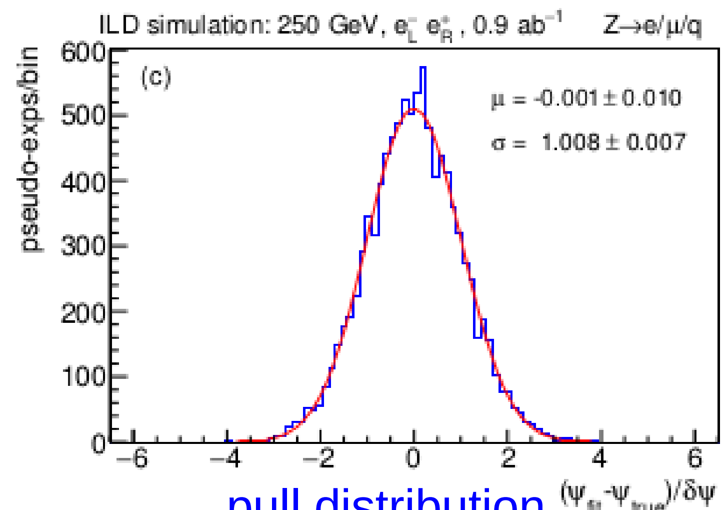
results of 10k pseudo-exps



fitted phase



fitted uncertainty



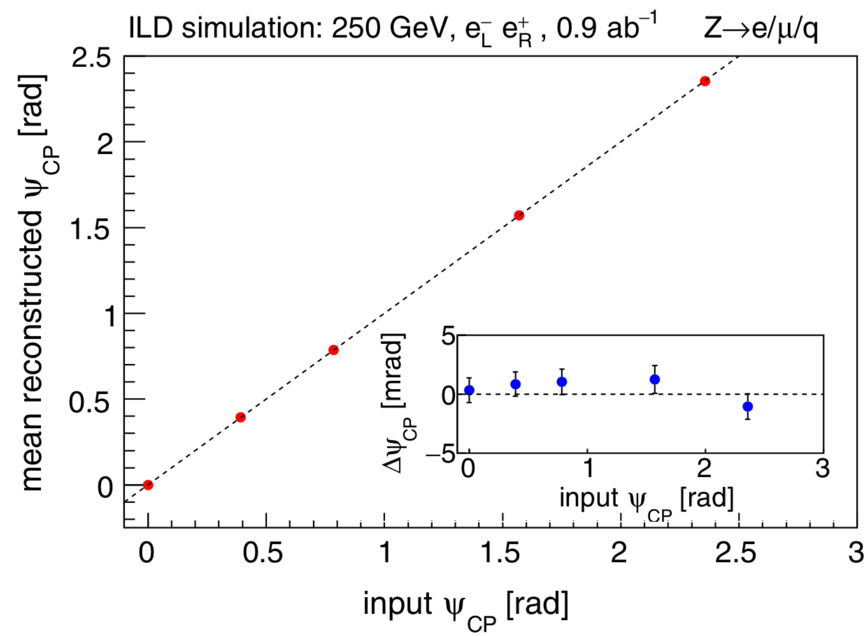
pull distribution

Predicted sensitivity on ψ_{CP} under various conditions

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

	Beam Polarization			
$\int \mathcal{L}$ [ab^{-1}]	e^-	e^+	Notes	$\delta\psi_{CP}$ [mrad]
1.0	0	0	full analysis	116
1.0	0	0	only $Z \to ee$	450
1.0	0	0	only $Z \to \mu\mu$	412
1.0	0	0	only $Z \to qq$	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^{-1}, all channels: 75 mrad

dominated by events with hadronic Z decay

perfect reconstruction, selection: 25 mrad sensitivity @ 1 ab^{-1}

Summary

Using full detector simulation and backgrounds, we demonstrated that the CP mixing angle from Higgs decays to $\tau^+\tau^-$ can be determined to 75 mrad ≈ 4.3° using 2 ab^{-1} of ILC250 data

Measurement relies on many aspects of the detector:

- impact parameter reconstruction
- reconstruction of photons/π^0 from tau decays
- jet energy resolution

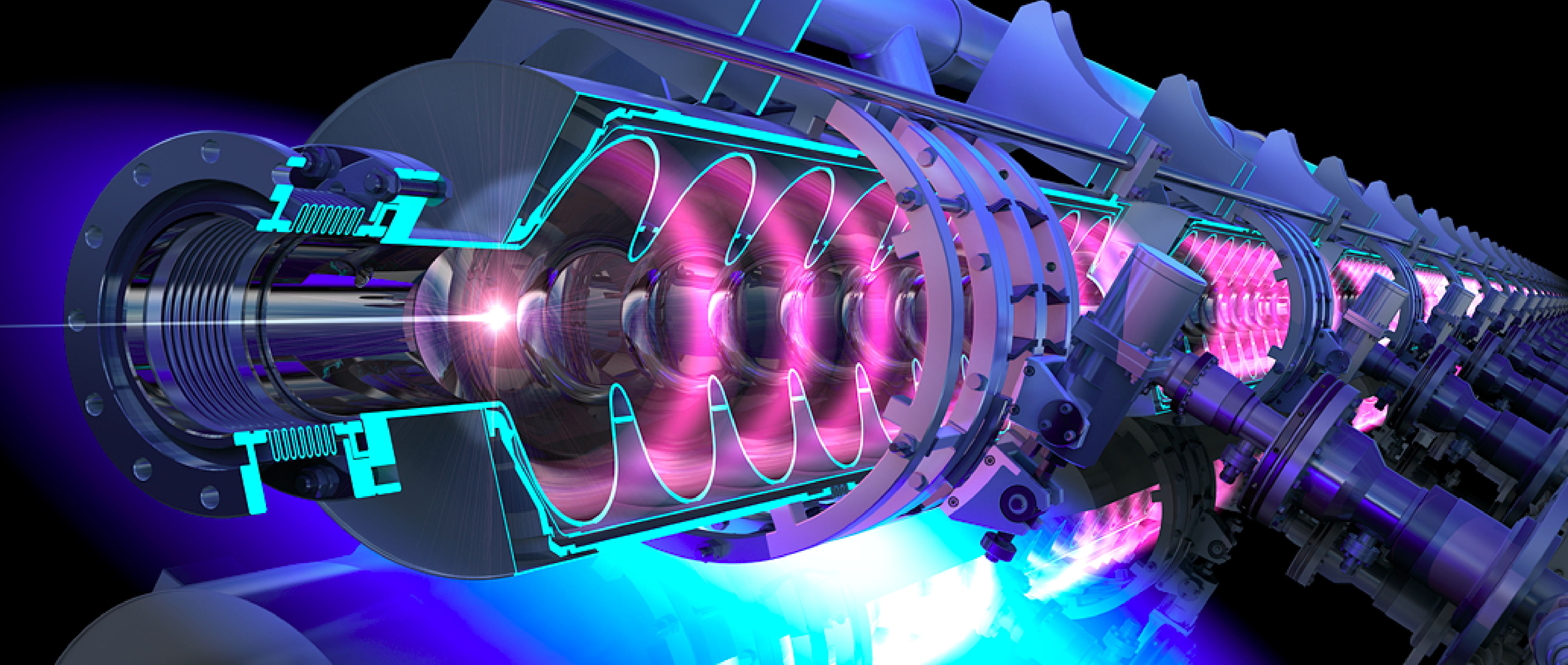
Much potential to significantly improve prospective results with improved analysis methods, improved detector reconstruction, and even detector design [ultimately < 20 mrad for 2 ab^{-1}]. Interesting projects!

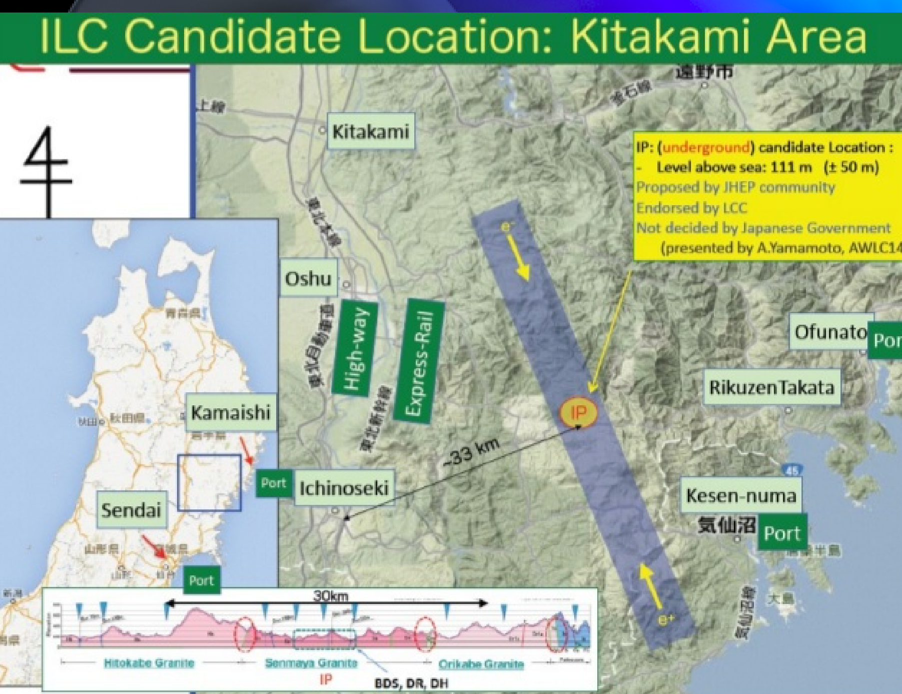
So far, used only the single-prong $\pi^\pm\nu$ and $\pi^\pm\pi^0\nu$ decay modes of the tau (37%)
→ can increase sensitivity by including other tau decay modes

Method should also be applicable to ZH at 350 GeV and 500 GeV.

Including $Z\to\tau^+\tau^-$ and, ($Z\to\nu\nu$ and WW-fusion production) may be feasible especially with at least one 3-prong τ decay and nano beam-constraints.

See backup for links to VVH anomalous couplings study backup





Kaname Kodashima

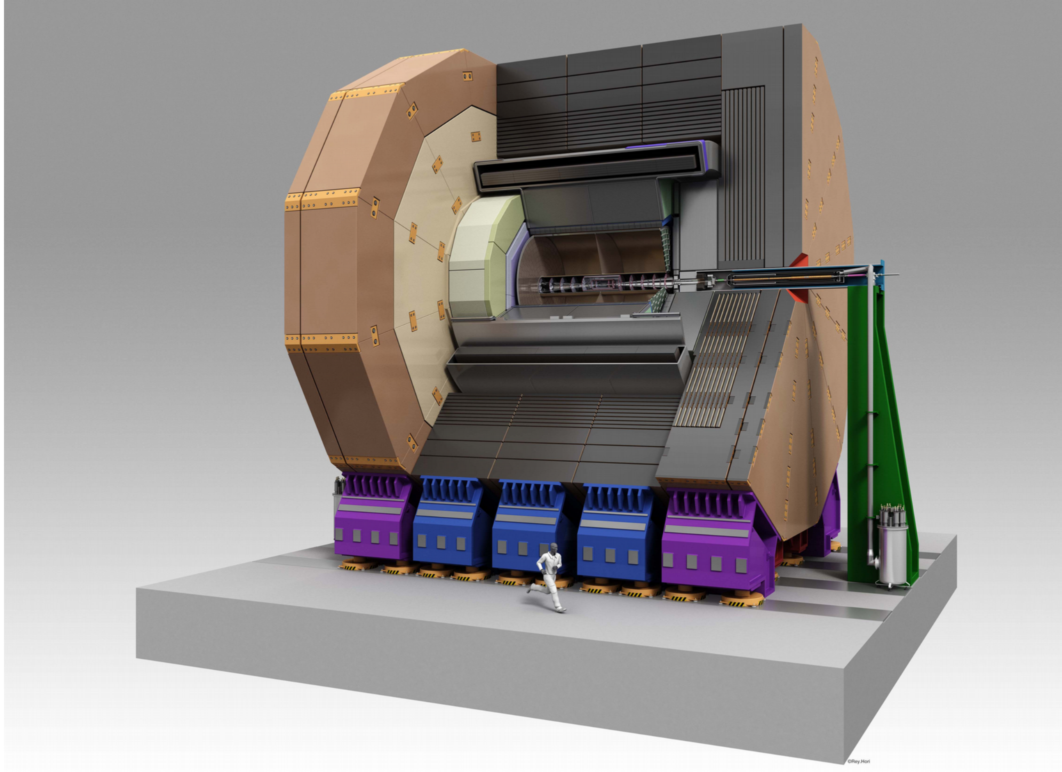
"Lots of encounters through the ILC"

Futago Elementary School, Kitakami City

Comment: "I drew my wish that there would be a lot of new encounters through the ILC everyone is hoping for."

2016 ILC Poster Contest
Merit Award
(1st~3rd grade entries)

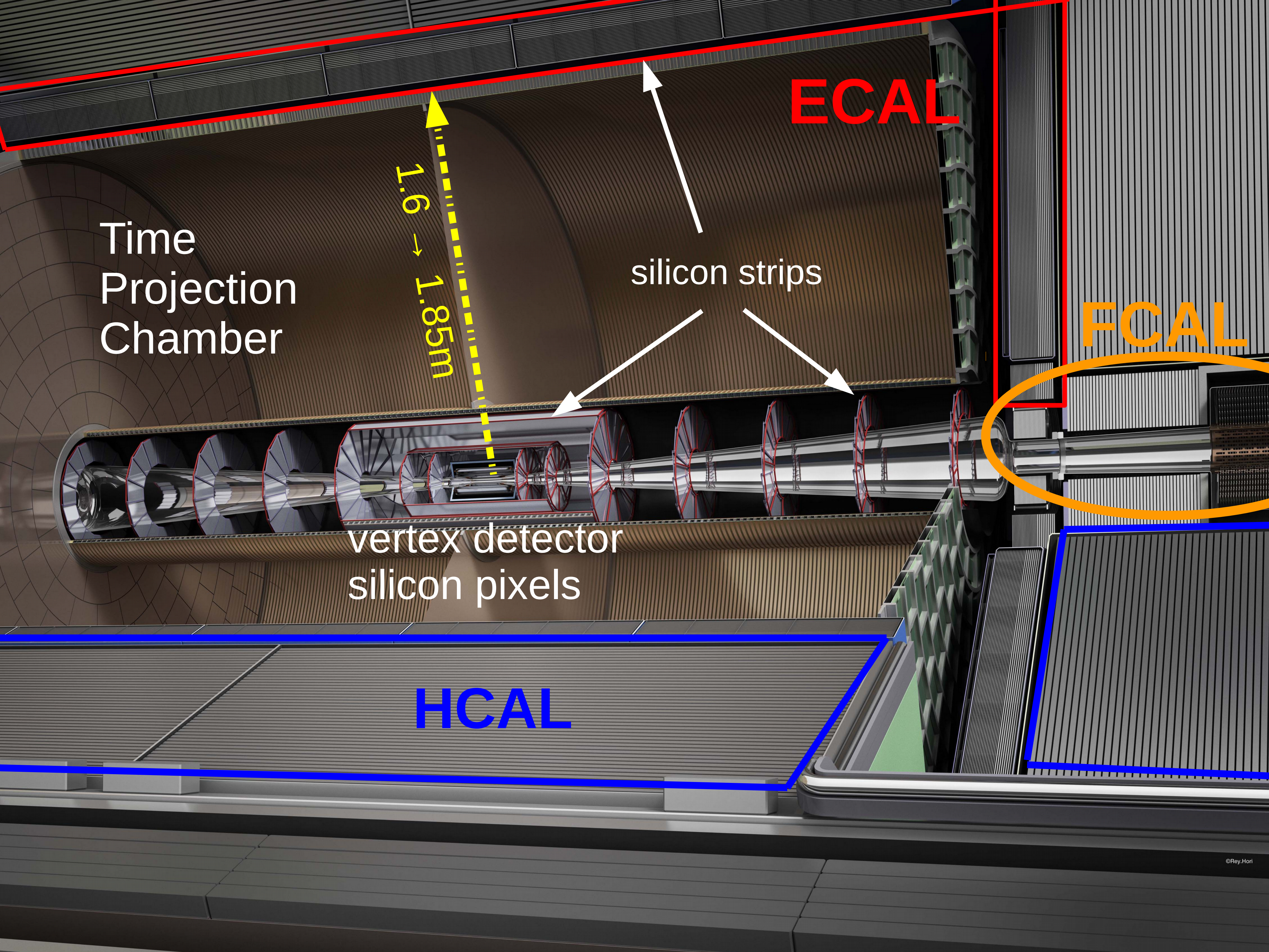
International Large Detector



One of two detector designs being studied for the ILC

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
©Rey.Hori

Neural Network Details

Variables for ZH / 4f separation (NN1):
1. tau tau invariant mass
2. event energy
3. invariant mass of the Z
4. recoil mass to the Z
5. tau+ cone (±20°) excess energy
6. tau- cone excess energy

Variables for distinguishing ZH events from signal tau decay modes from other tau decay modes (NN2):
1. tau+ cone excess energy
2. tau- cone excess energy
3. tau+ visible mass
4. tau- visible mass

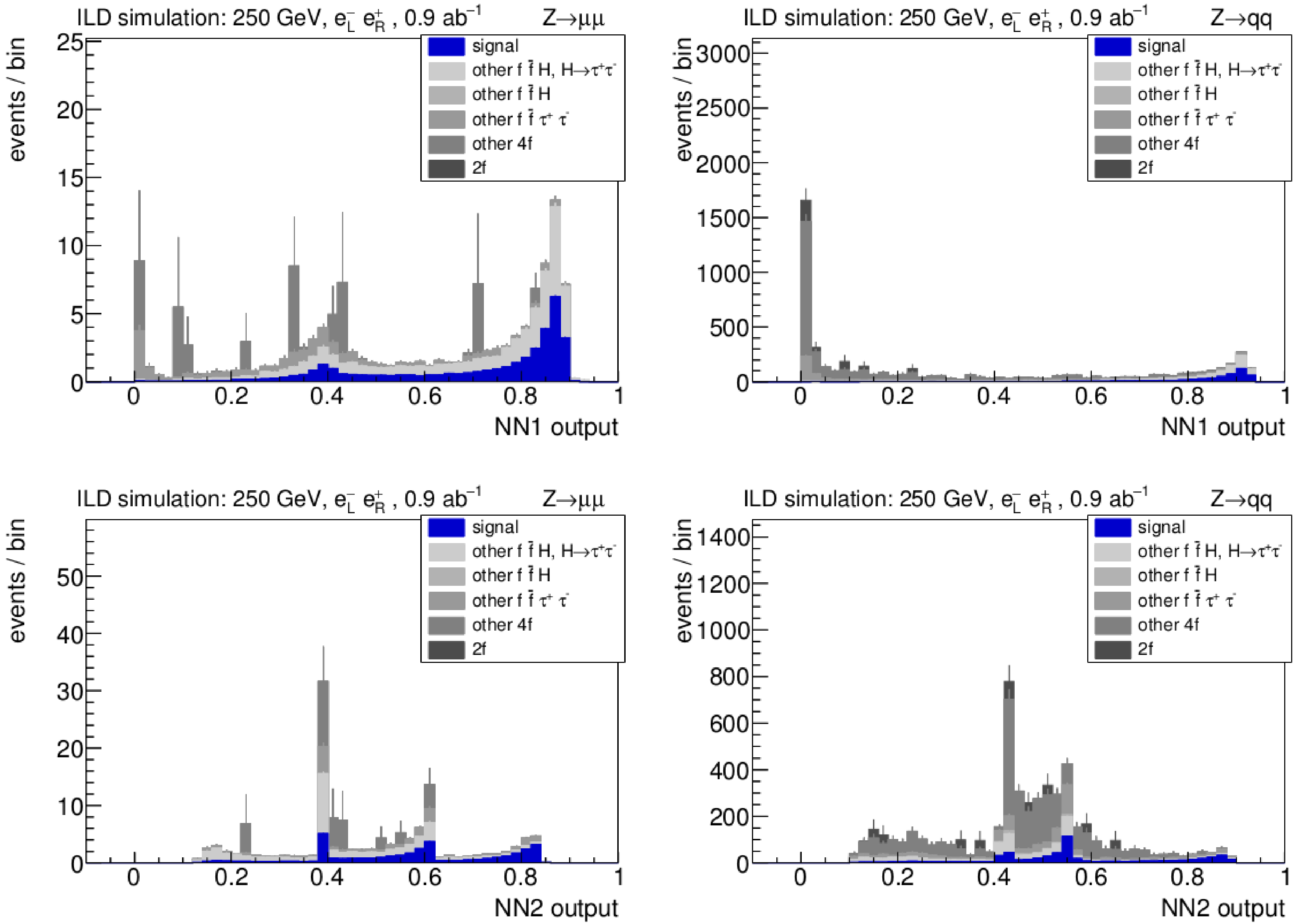


FIG. 7. Distributions of the two Neural Network outputs in the muon and hadronic selection channels. The structure in the output of NN2 is due to the three different combinations of τ lepton decay modes. Distributions are normalized to 0.9 ab^{-1} of data in the $e^-_L e^+_R$ beam polarization.

VVH CP-violating coupling studies

See Tomohisa Ogawa,
https://agenda.linearcollider.org/event/7826/contributions/41558

https://indico.cern.ch/event/732102/contributions/3146945