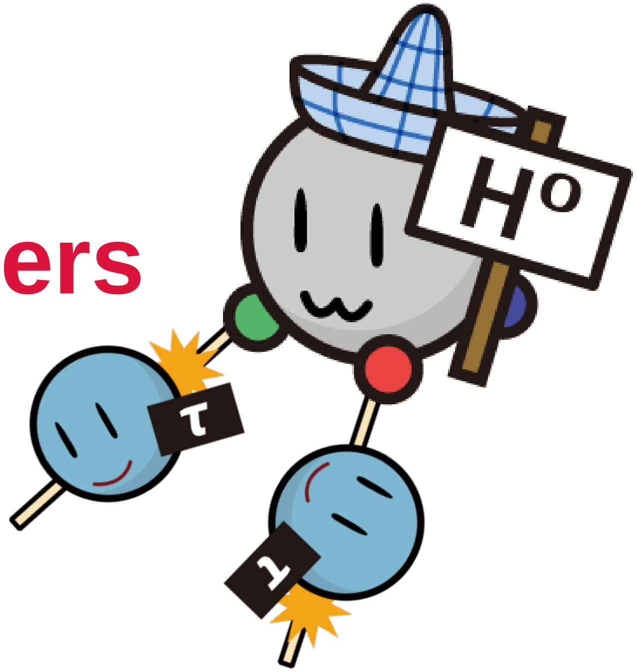
Measuring the CP state of tau lepton pairs from Higgs decay at ~~the ILC~~ e+e- colliders



https://higgstan.com/

Phys.Rev. D98 (2018) no.1, 013007
arXiv:1804.01241 [hep-ex]

Nucl.Instrum.Meth.A 810 (2016)
51-58 arXiv:1507.01700 [hep-ex]

Daniel Jeans, KEK/IPNS

FCC physics zoom meeting, 2021/11/29

known sources of CP violation are insufficient to explain our universe's matter – anti-matter asymmetry

→ motivates search for CP effects in the Higgs sector

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

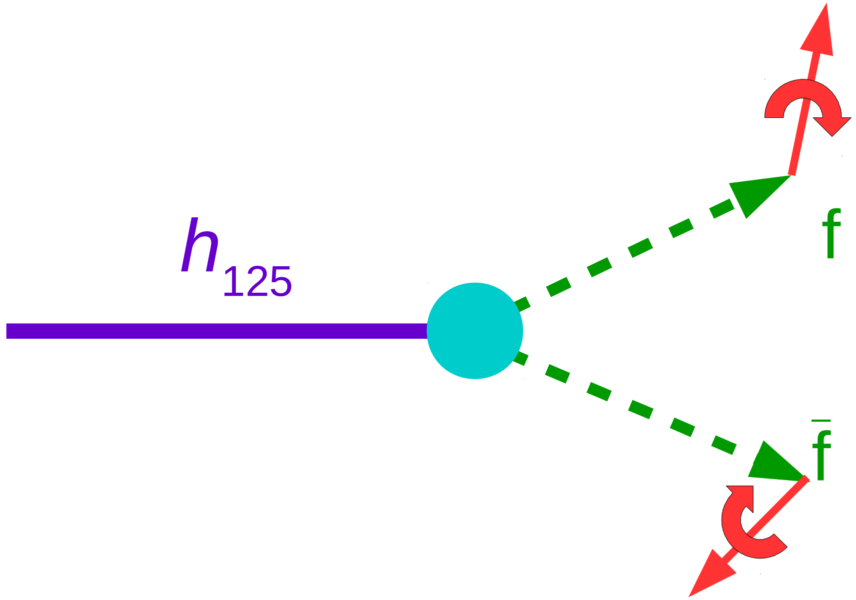
or a mixture?

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 ?		

we can also probe CP nature of Higgs couplings to gauge bosons



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

to probe CP, we consider the correlation between
the spins of fermions produced in Higgs boson decay

Higgs decays to tau leptons:
- large branching ratio (~6%)
- sensitivity to tau spin orientation
  - → reflected in distribution of decay products

use tau decay products to reconstruct **polarimeter**

→ estimator of tau spin orientation

straightforward to extract in $\tau^\pm \to (\pi^\pm \nu)$ [BR~11%]

or $(\pi^\pm \pi^0 \nu)$ [~25%]

optimal polarimeter vectors **h** in terms of

tau decay product momenta in the tau rest frame:

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

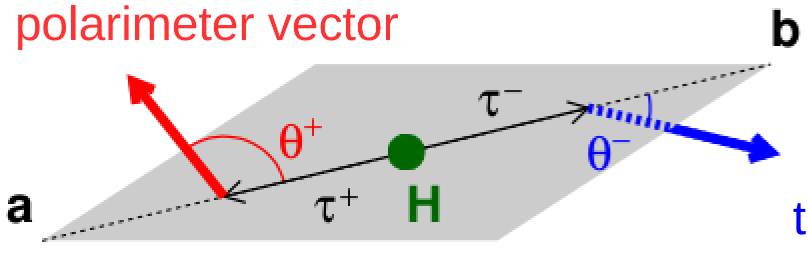
$$\mathbf{h}\ (\tau^\pm \to \pi^\pm \pi^0 \nu) \sim m_\tau\,(E_{\pi\pm} - E_{\pi0})\,(\mathbf{p}_{\pi\pm} - \mathbf{p}_{\pi0}) + 0.5\,(p_{\pi\pm} + p_{\pi0})^2\,\mathbf{p}_\nu$$

for optimal sensitivity, require knowledge of tau rest frame

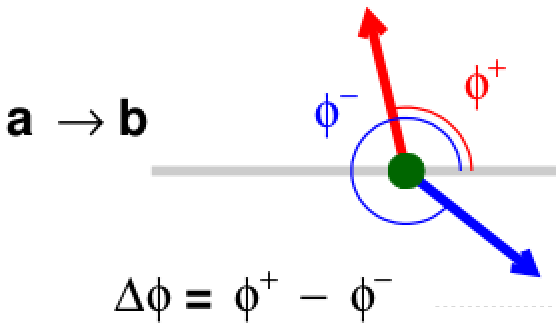
(or equivalently the **neutrino momentum**)

correlation between transverse polarimeter components is sensitive to CP mixing

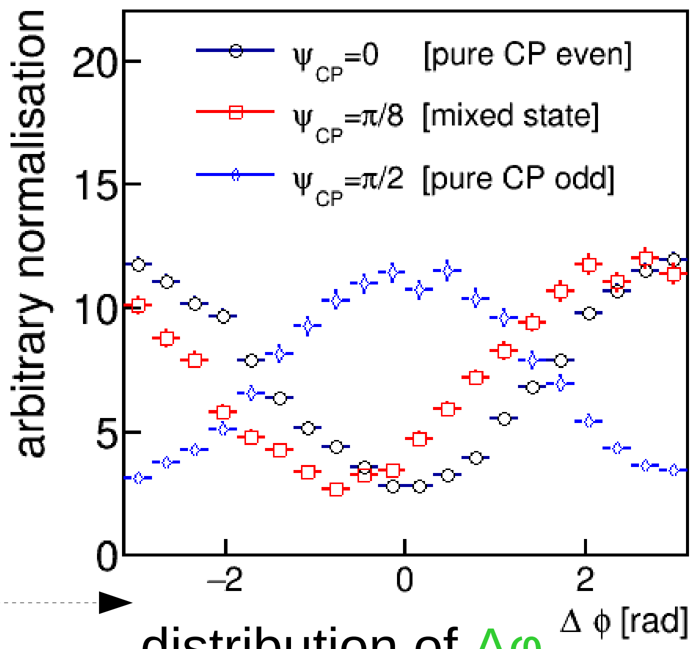
tau+
polarimeter vector



tau-
polarimeter vector



MC truth



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

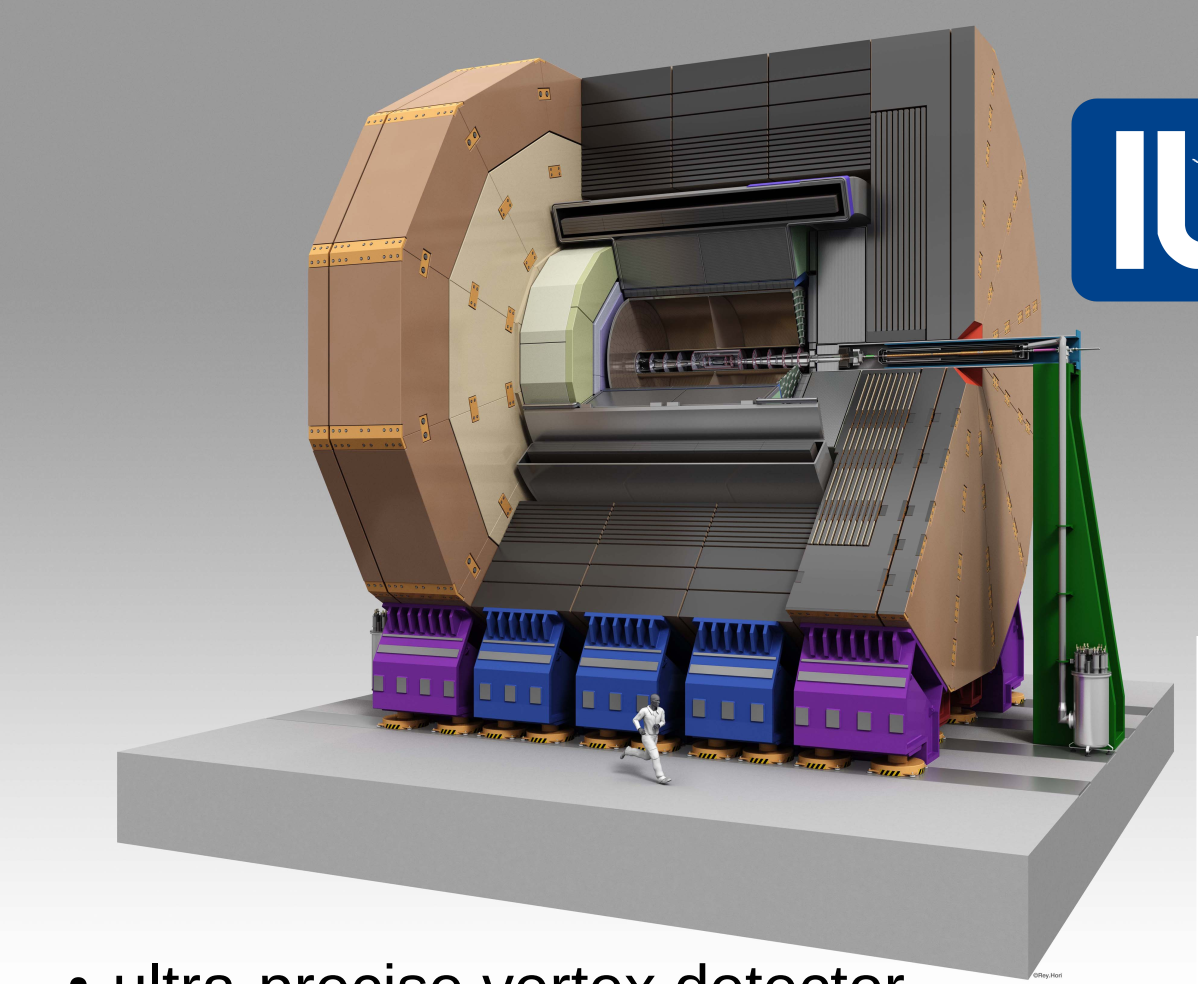
$$dN \sim (1+\cos\theta^+\cos\theta^-)\,\{1-\boxed{\sin\theta^+\sin\theta^- /(1+\cos\theta^+\cos\theta^-)}\}\,\cos(\,\Delta\varphi - 2\,\psi_{CP})$$

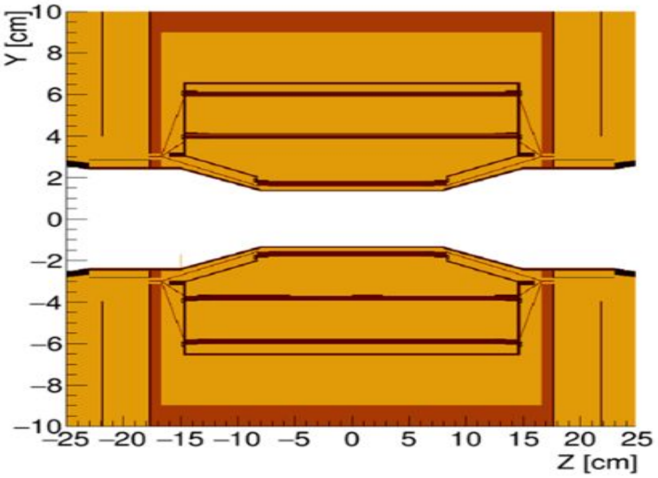
“contrast” → determines event-by-event modulation

if polarimeters aligned with tau momentum ($\sin\theta \to 0$),
transverse correlations are less strong

International Large Detector

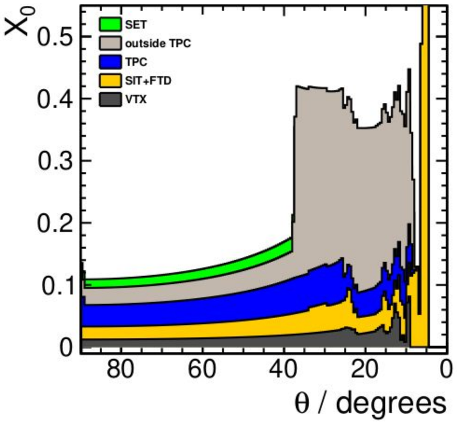
detector concept being developed for ILC
arXiv:2003.01116





- ultra-precise vertex detector
  - first layer @ r = 16 mm
  - impact parameter resolution ~3µm

- low mass tracker
  - few interactions → helps tau decay mode identification



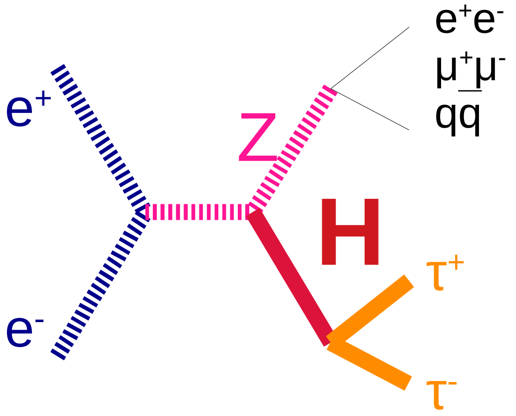
- highly segmented “PFA” calorimeters
  - 30 layers of 5x5 mm^2 cells in ECAL
  - pi0 & tau decay mode reconstruction

Full tau reconstruction

NIM A810 (2016) 51
arXiv:1507.01700

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

event with two hadronic tau decays (1 neutrino per tau),
6 unknowns: 2 × neutrino 3-momenta



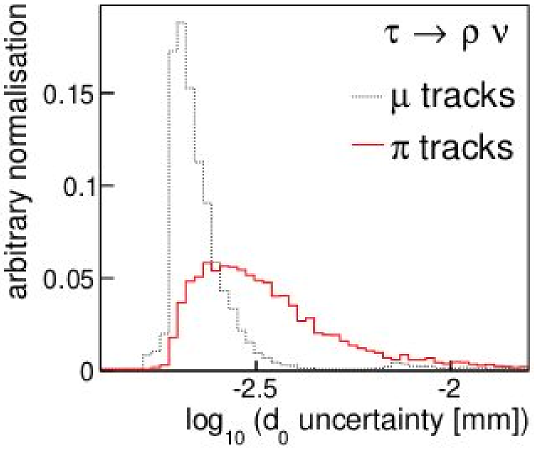
neutrino momenta can be reconstructed if we know:
visible tau momenta
tau production vertex (from Z decay products)
impact parameters of charged tau decay products
p_T of the tau-tau system (balance the Z p_T)

6 constraints:
2 × impact parameters define the tau momenta plane
2 × tau invariant mass
2 from tau-tau p_T [p_x, p_y]

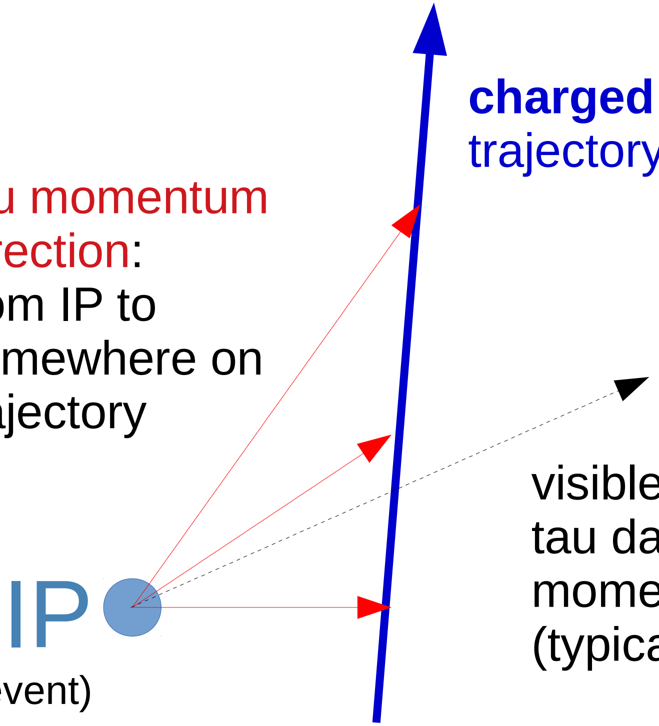
requires excellent detector performance:
charged particle and photon reconstruction,
impact parameter measurement, jet energy measurement

e.g. single-prong hadronic tau decays

tracks from H → tau tau
@250 GeV



3 10 um



charged tau daughter trajectory

tau momentum direction: from IP to somewhere on trajectory

trk-plane defined by IP and trajectory

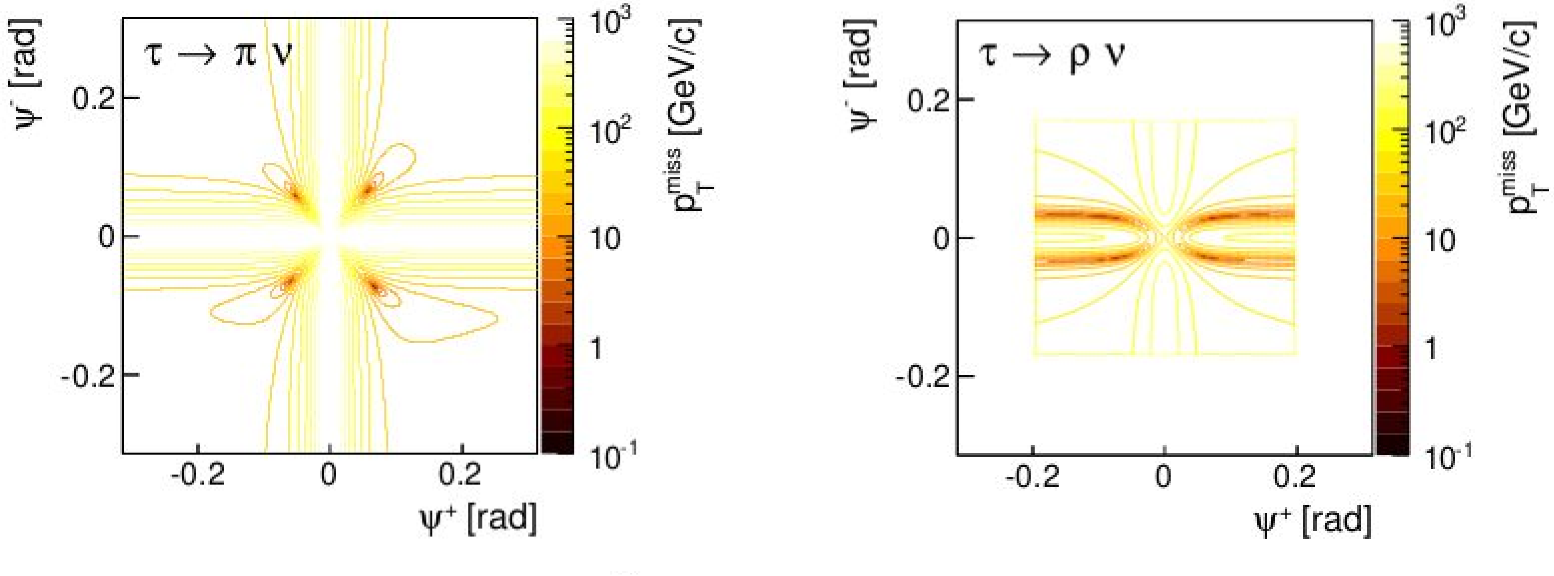
(event-by-event)

visible **neutral** tau daughter momentum (typically not in trk-plane)

→ out-of-plane mom. must be balanced by neutrino

one free parameter: orientation of the in-plane neutrino momentum (angle ψ)
once orientation is defined, tau mass constraint provides its magnitude

scan neutrinos’ orientation to minimise event p_T

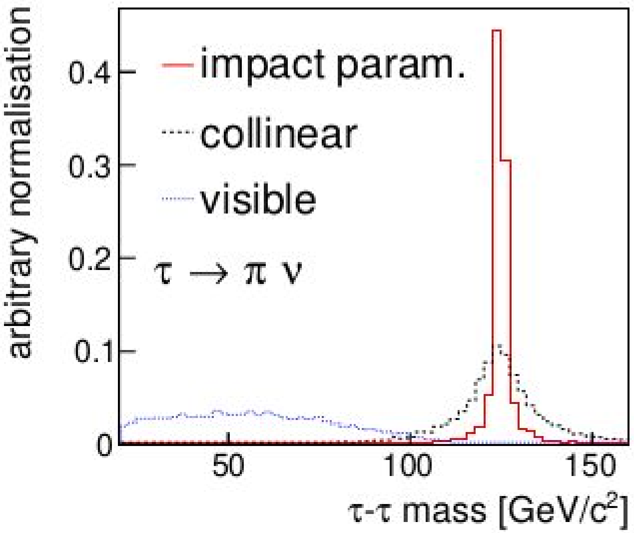


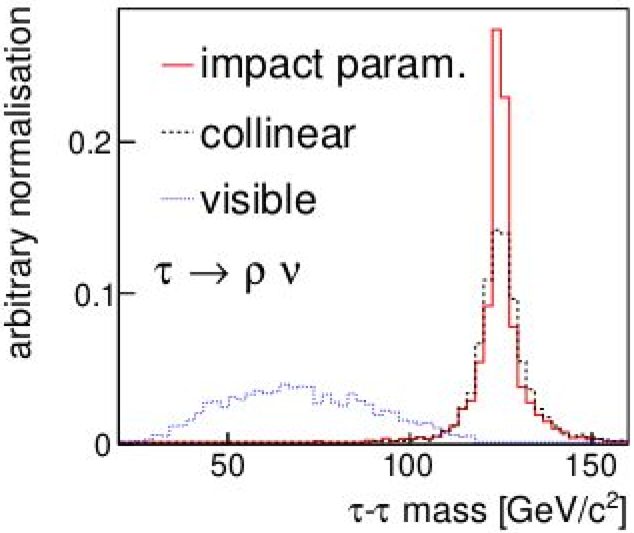
typically several solutions

reject solutions with negative reconstructed tau proper lifetime

choose remaining soln. with smallest event p_T

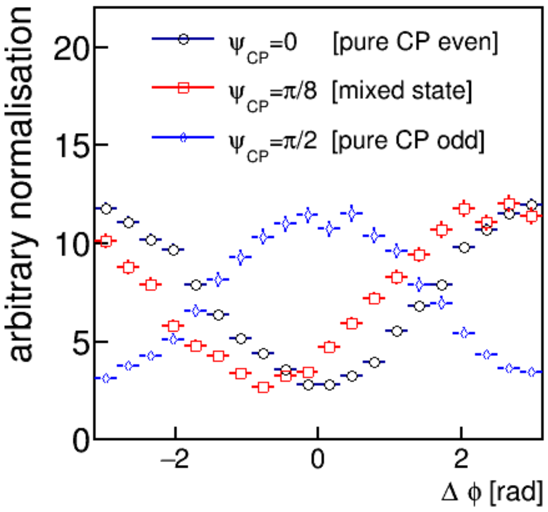
reconstructed di-tau mass





reconstruct CP-sensitive $\Delta\varphi$ distribution at ILC 250GeV

MC truth

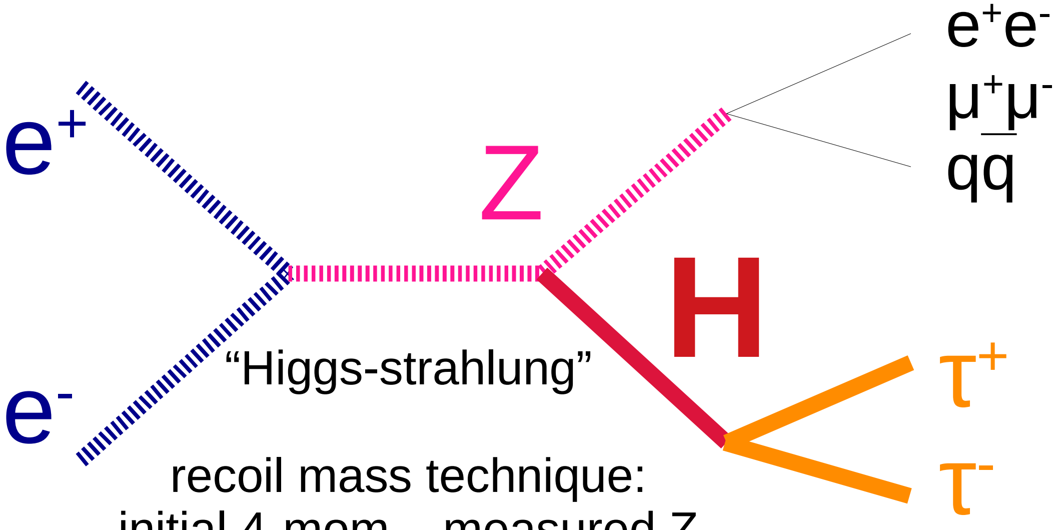


full Geant4 simulation of ILD

realistic reconstruction processing
ilcsoft, MarlinReco, PandoraPFA, ...

Signal: $e^+ e^- \to Z\,H$
$Z \to e^+e^-, \mu^+\mu^-, q\bar{q}$
$H \to \tau^+ \tau^-$
$\tau^\pm \to (\pi^\pm \nu)$ or $(\pi^\pm \pi^0 \nu)$

Backgrounds:
$e^+ e^- \to$ ffH, 4f, 2f

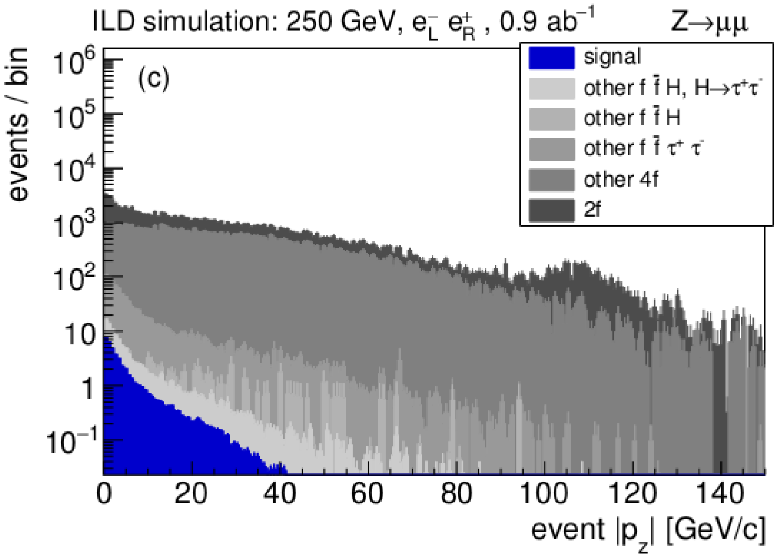


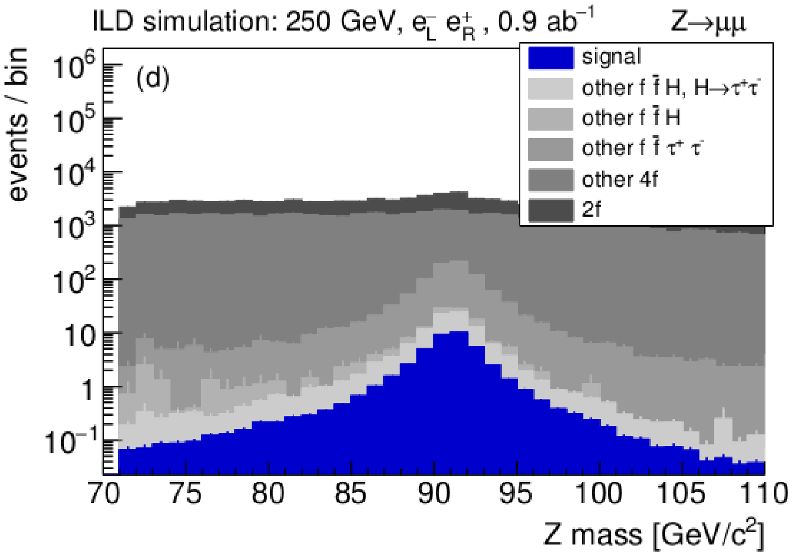
recoil mass technique:
initial 4-mom – measured Z
→ Higgs 4-momentum

assume 2 ab^{-1} of 250 GeV data : after 11 years ILC operation [arXiv:1903.01629]

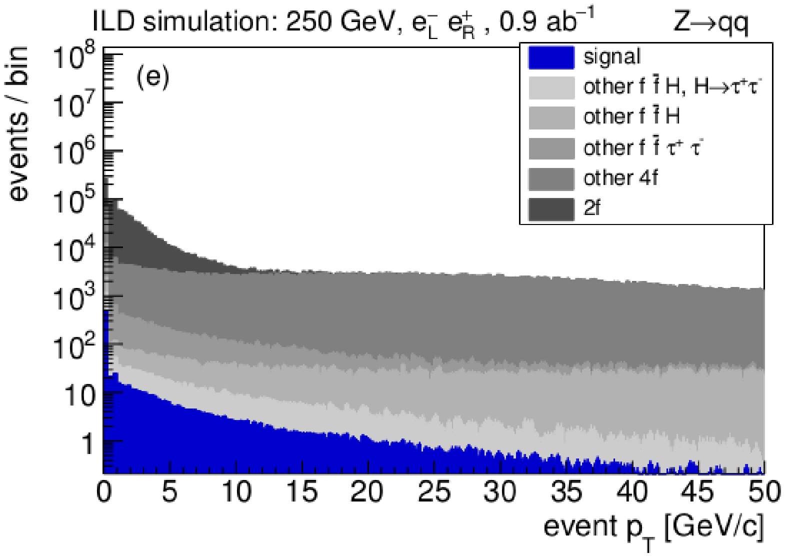
some distributions after full simulation and reconstruction and a simple preselection:

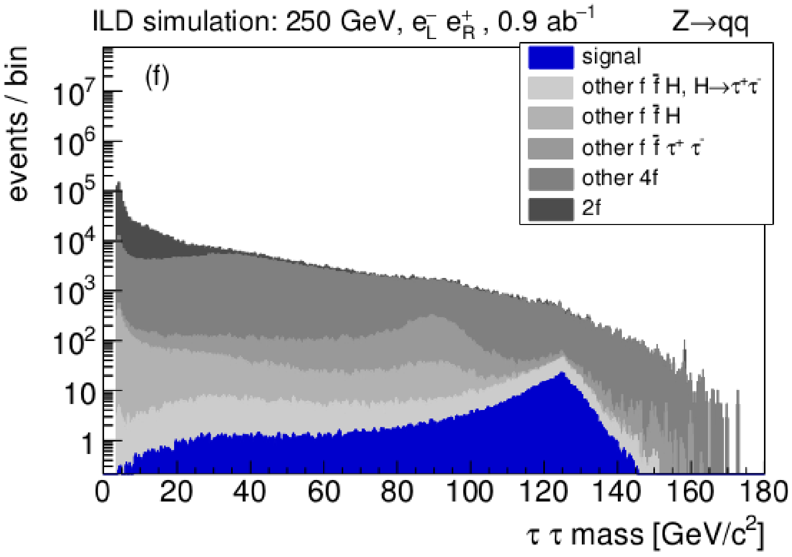
$Z \rightarrow \mu^+\mu^-$





$Z \rightarrow q\bar{q}$



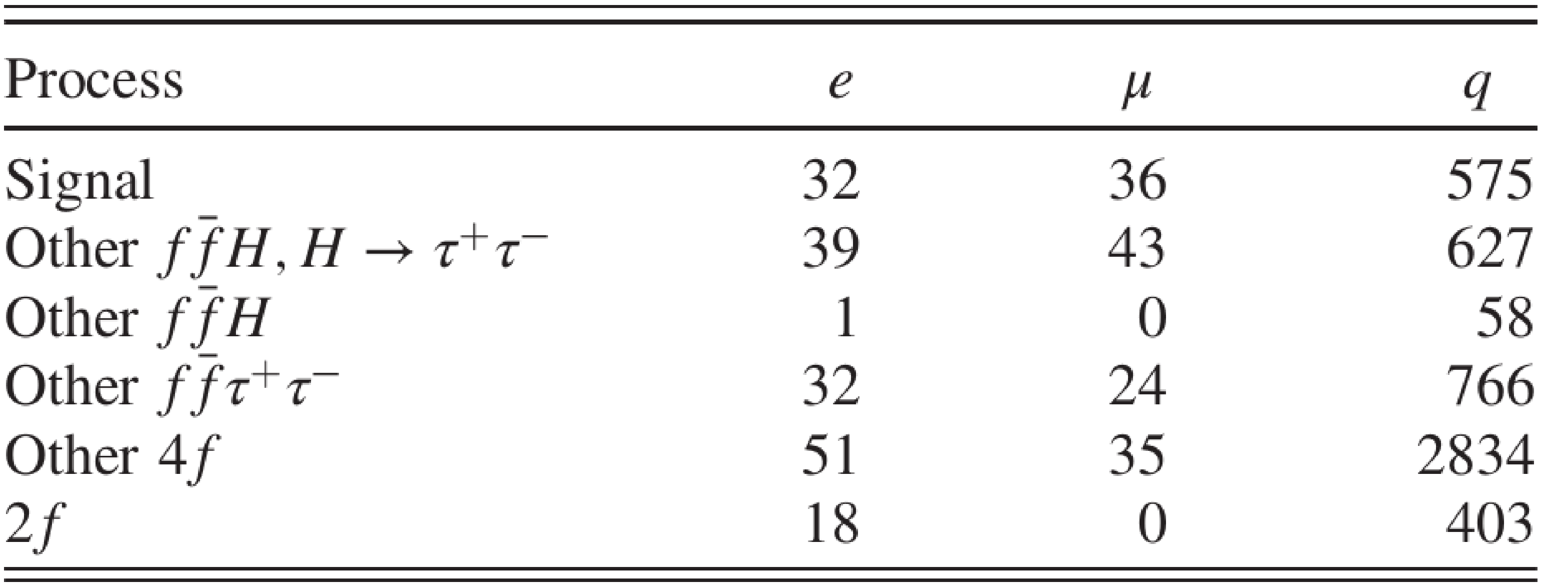


use these and other observables to select signal events

After relatively simple cut-based event selection

expected numbers of signal and background events

(2 ab^{-1} integrated luminosity at 250 GeV)



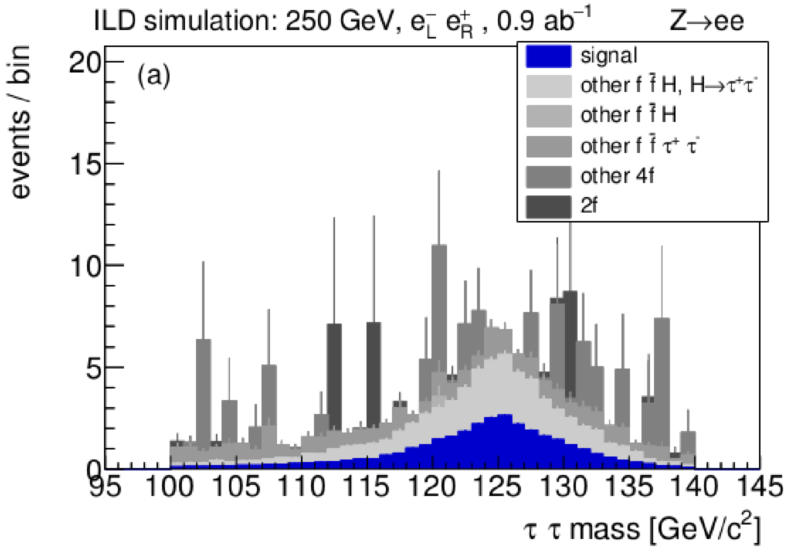
Z →	e^+e^-	$\mu^+\mu^-$	qq
Process	e	μ	q
Signal	32	36	575
Other $f\bar{f}H, H \to \tau^+\tau^-$	39	43	627
Other $f\bar{f}H$	1	0	58
Other $f\bar{f}\tau^+\tau^-$	32	24	766
Other $4f$	51	35	2834
$2f$	18	0	403

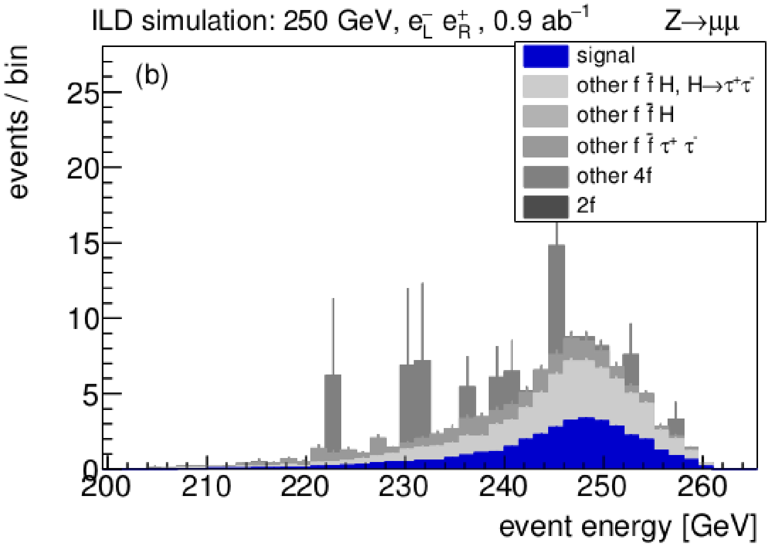
Z decays to leptons: few 10s of signal events; S:B ~ 1:3~4

Z decays to quarks: many more signal events; S:B ~ 1:8

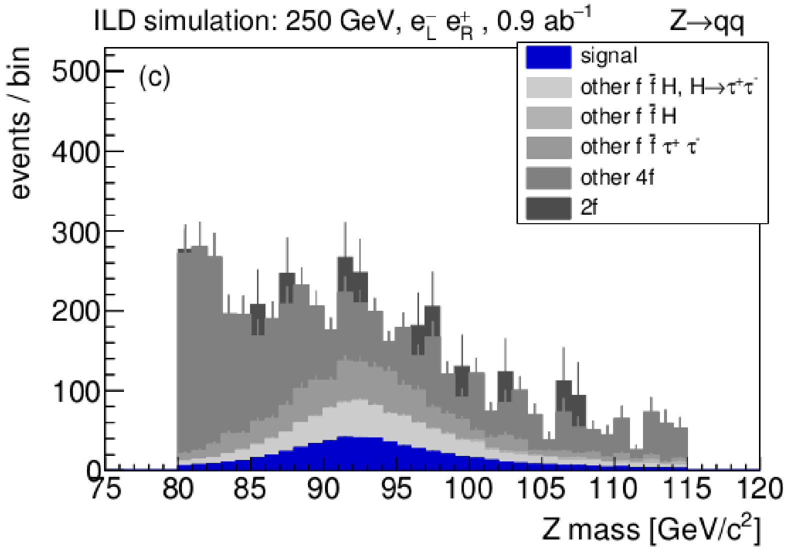
Some distributions after selection

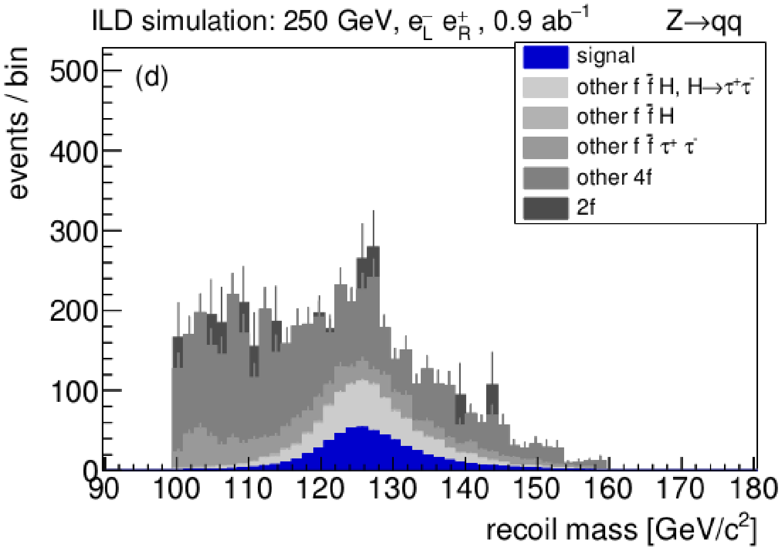
Z → leptons





Z → $q\bar{q}$

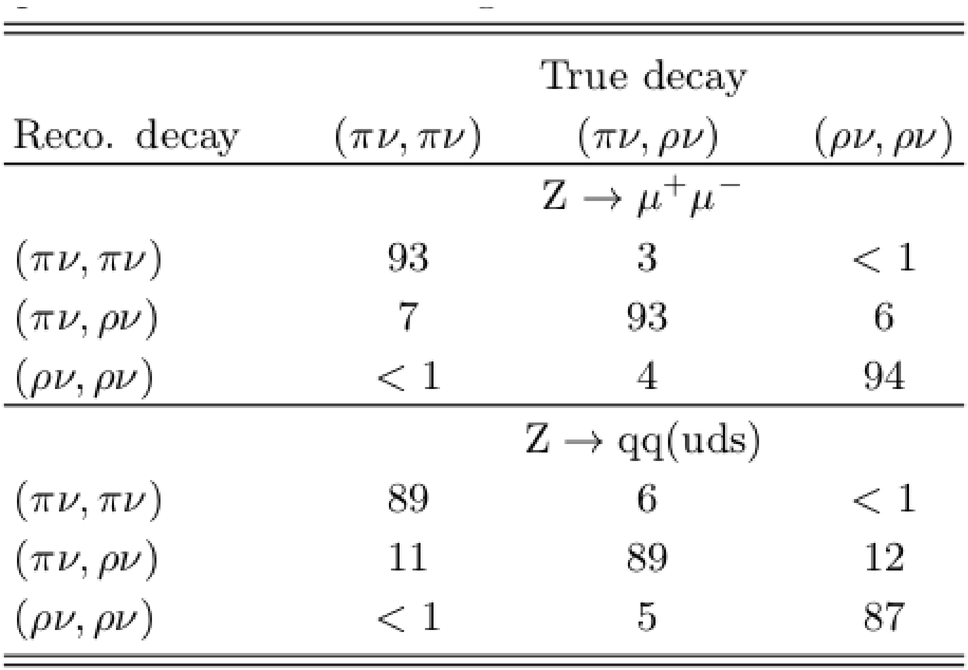




train Neural Networks to further separate signal from backgrounds

to extract tau polarimeter (estimator of spin direction),
must identify tau decay mode

→ consider number of charged particles and photons
reconstructed in the tau jet, and their invariant mass
simple cut-based classification

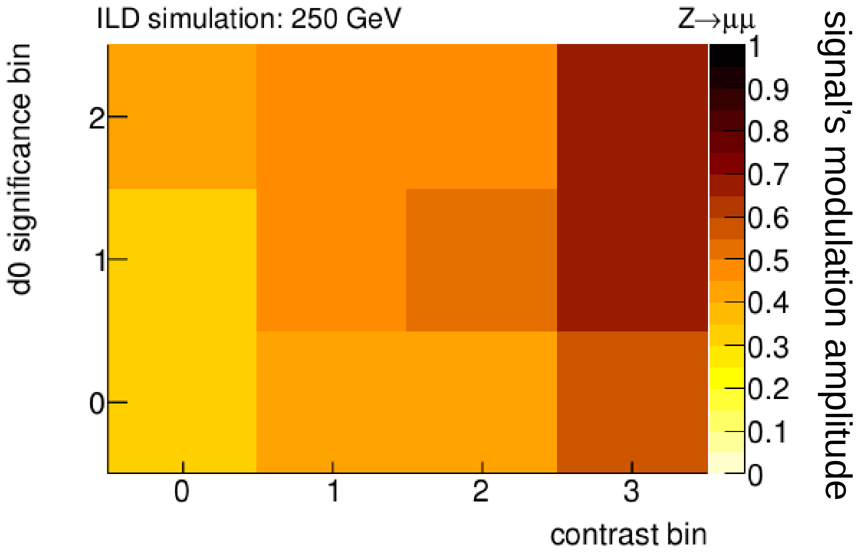


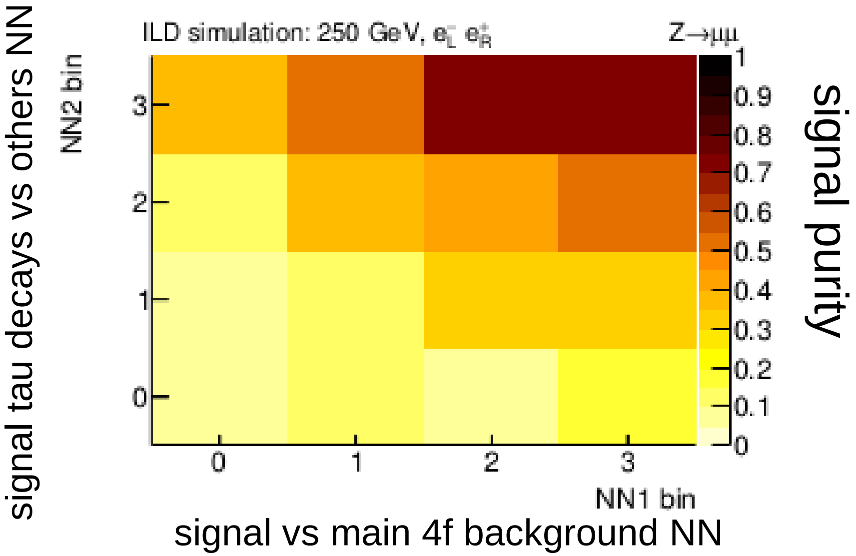
	True decay		
Reco. decay	$(\pi\nu, \pi\nu)$	$(\pi\nu, \rho\nu)$	$(\rho\nu, \rho\nu)$
	$Z \to \mu^+\mu^-$		
$(\pi\nu, \pi\nu)$	93	3	< 1
$(\pi\nu, \rho\nu)$	7	93	6
$(\rho\nu, \rho\nu)$	< 1	4	94
	$Z \to qq(uds)$		
$(\pi\nu, \pi\nu)$	89	6	< 1
$(\pi\nu, \rho\nu)$	11	89	12
$(\rho\nu, \rho\nu)$	< 1	5	87

87% ~ 94% efficiency to correctly identify tau decay modes,
better in events with little hadronic activity

Group events according to expected CP sensitivity, based on:

intrinsic:
orientation of polarimeters (“contrast” function)
reconstruction quality and tau flight distance:
tau decay prongs’ impact parameter measurement significance
background contamination:
output of simple NN [6 inputs] (signal vs. main 4f bkgs)
wrong tau decay mode contamination:
output of simple NN [4 inputs] (signal tau decays vs. others)

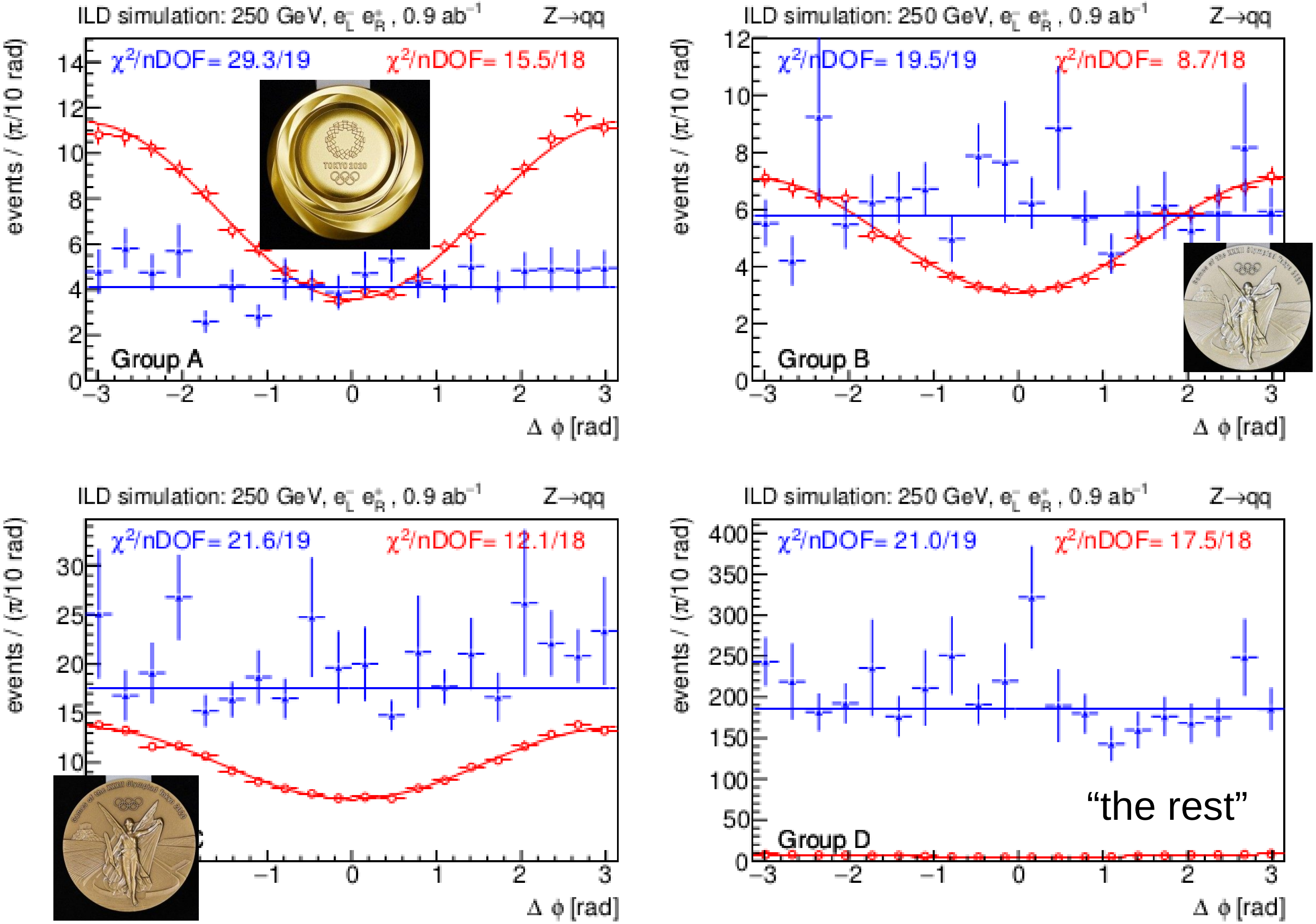




CP sensitive observable Δφ in different event sensitivity bins

signal background

error bars:
MC statistics

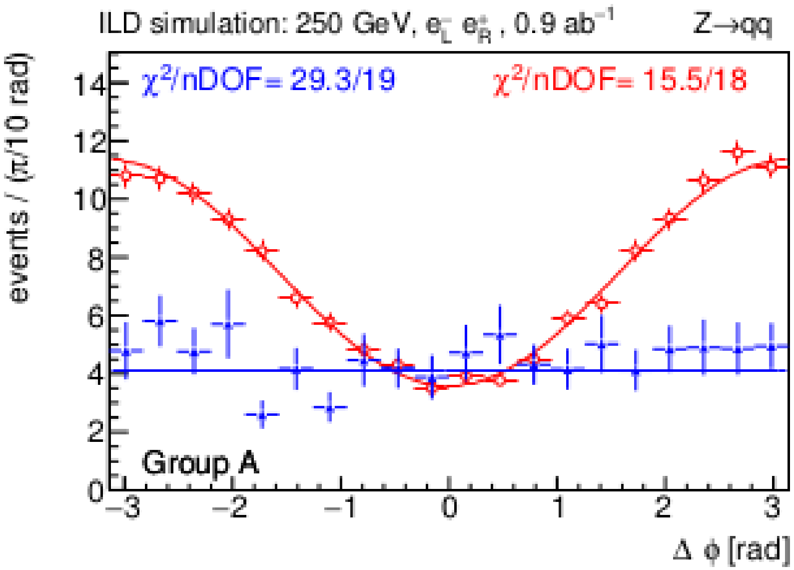


phase of signal distribution is sensitive to CP

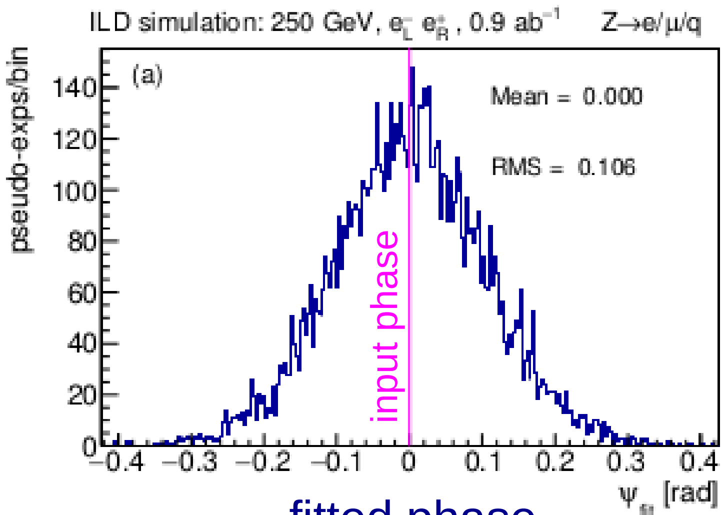
Estimating measurement sensitivity

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

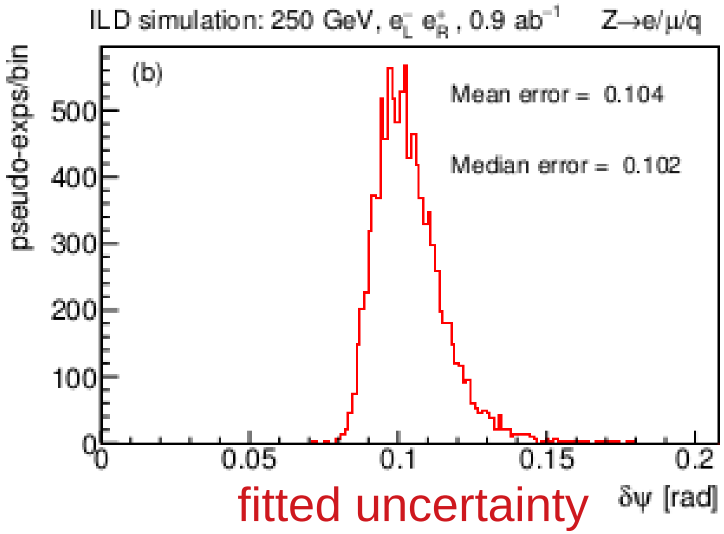
perform series of toy pseudo-experiments using
- simulated distributions



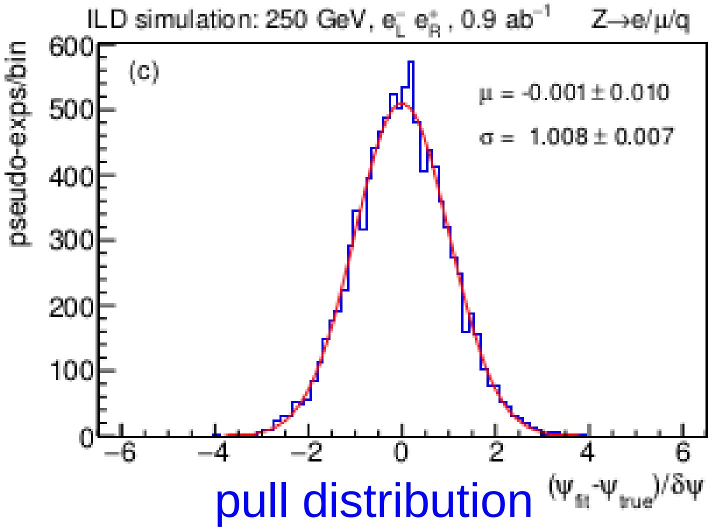
results of 10k pseudo-exps



fitted phase



fitted uncertainty



pull distribution

sensitivity on ψ_{CP} under various conditions

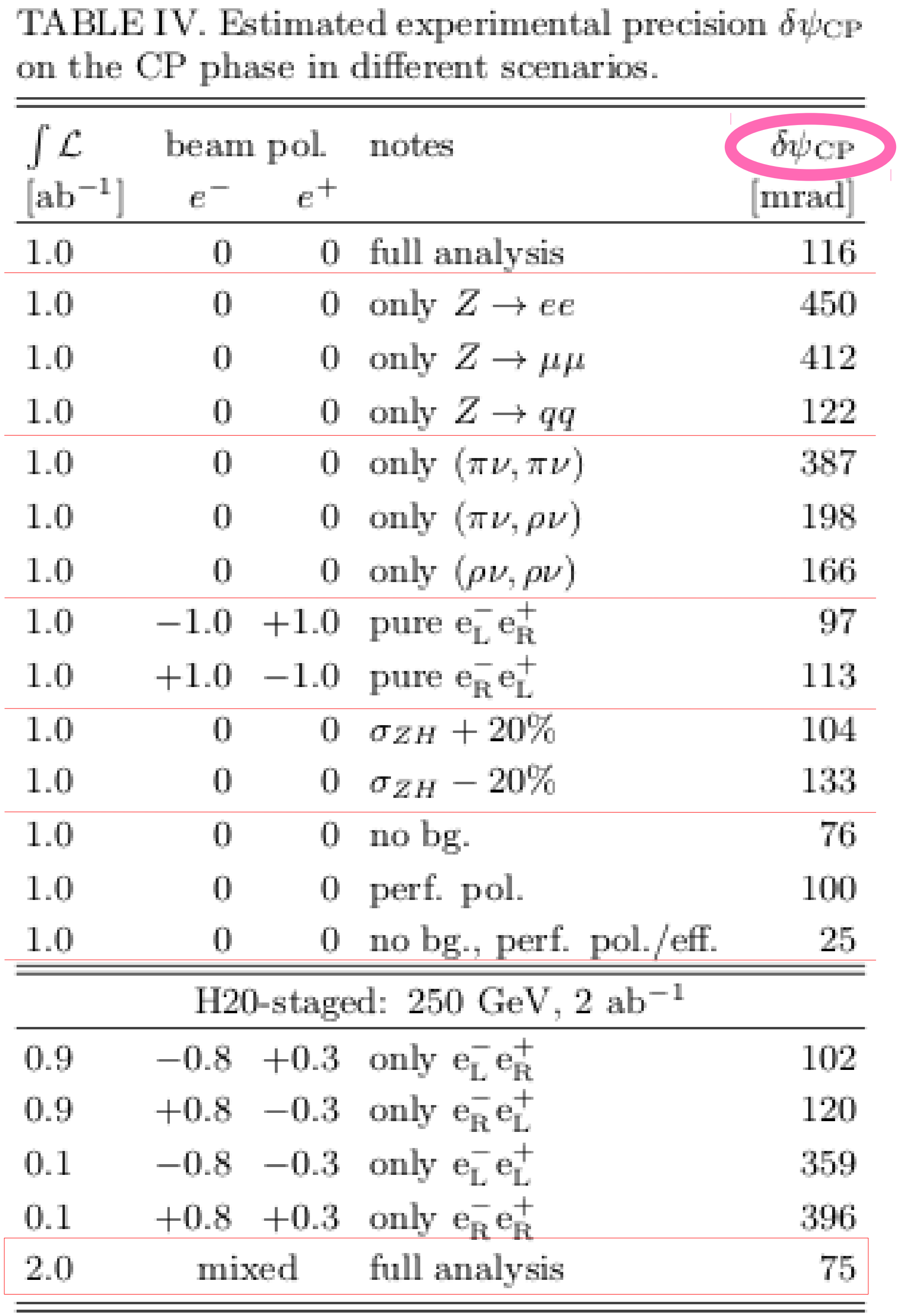


TABLE IV. Estimated experimental precision $\delta\psi_{CP}$ on the CP phase in different scenarios.

$\int \mathcal{L}$ [ab^{-1}]	beam pol. 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

dominated by events with hadronic Z

1 ab^{-1} (unpolarised):

realistic : 116 mrad

perfect detector/analysis: 25 mrad

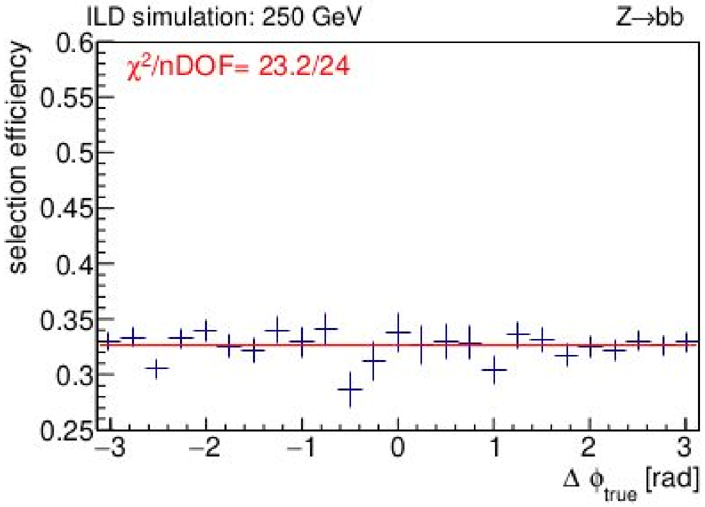
significant instrumental effects

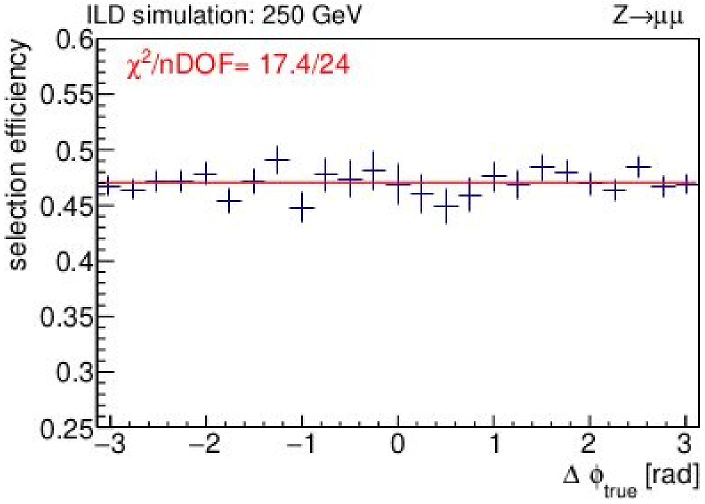
→ full simulation essential

2 ab^{-1} @ ILC-250: 75 mrad ≈ 4.3°

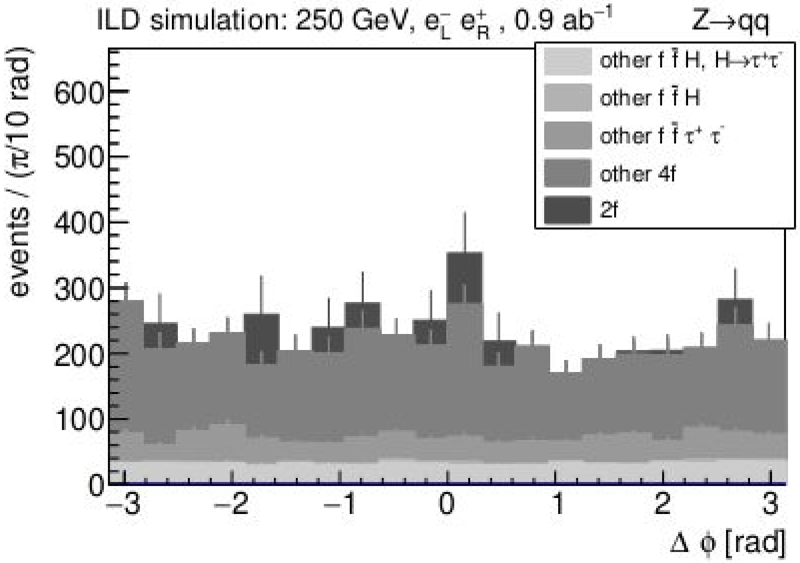
thoughts on systematics

signal acceptance vs. CP-sensitive angle is rather flat





as is the selected background



data-driven: e+ e- → Z (→ tau tau) Z (→ e, mu, q)

larger xsec, similar kinematics

expected to be flat in Δφ

→ verify @ Z-pole

Summary

Precision studies of the Higgs sector are of great interest
→ point the way to physics beyond SM
CP properties are one aspect of such precision Higgs studies

studied prospects for measurement of CP in Yukawa coupling
full simulation of the ILC and the ILD detector
realistic reconstruction algorithms
full SM backgrounds

tau lepton reconstruction
→ precision vertex detector
→ PFA calorimeter

The CP even-odd mixing angle of $\tau^+\tau^-$ from Higgs decay
can be determined to 75 mrad ≈ 4.3° at ILC250

Scope for further improvement:
better tau reconstruction, polarimeter reco., BG suppression,
additional tau decay modes, systematic controls…

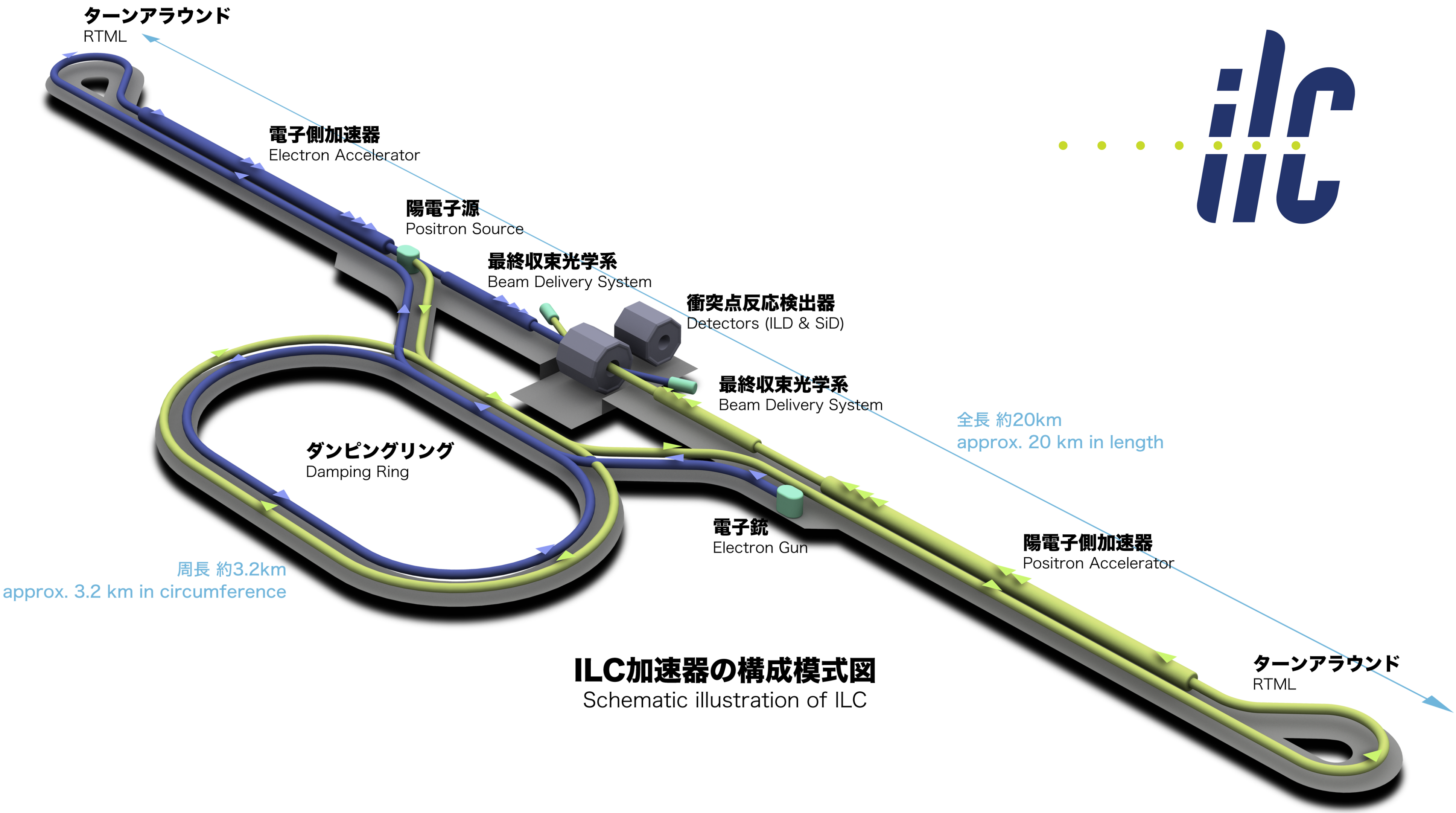
end

backup

The Higgs boson presents us a
once-in-a-generation opportunity to
study properties of a
new type of particle

→ (HL-)LHC
→ electron-positron Higgs factory
→ muon collider, ...

almost all models of new physics at ~TeV scale
leave an imprint on Higgs boson properties
O(few-%) deviations from SM (eg for decay branching ratios)
→ O(%) or better precision desired



ILC加速器の構成模式図
Schematic illustration of ILC

initial centre-of-mass energy	250 GeV : 2/ab in first ~11 years
upgrade energy	>1000 GeV possible
electron (positron) beam polarisation	80% (30%)
political status	under consideration by Japanese govt. as host of an international project

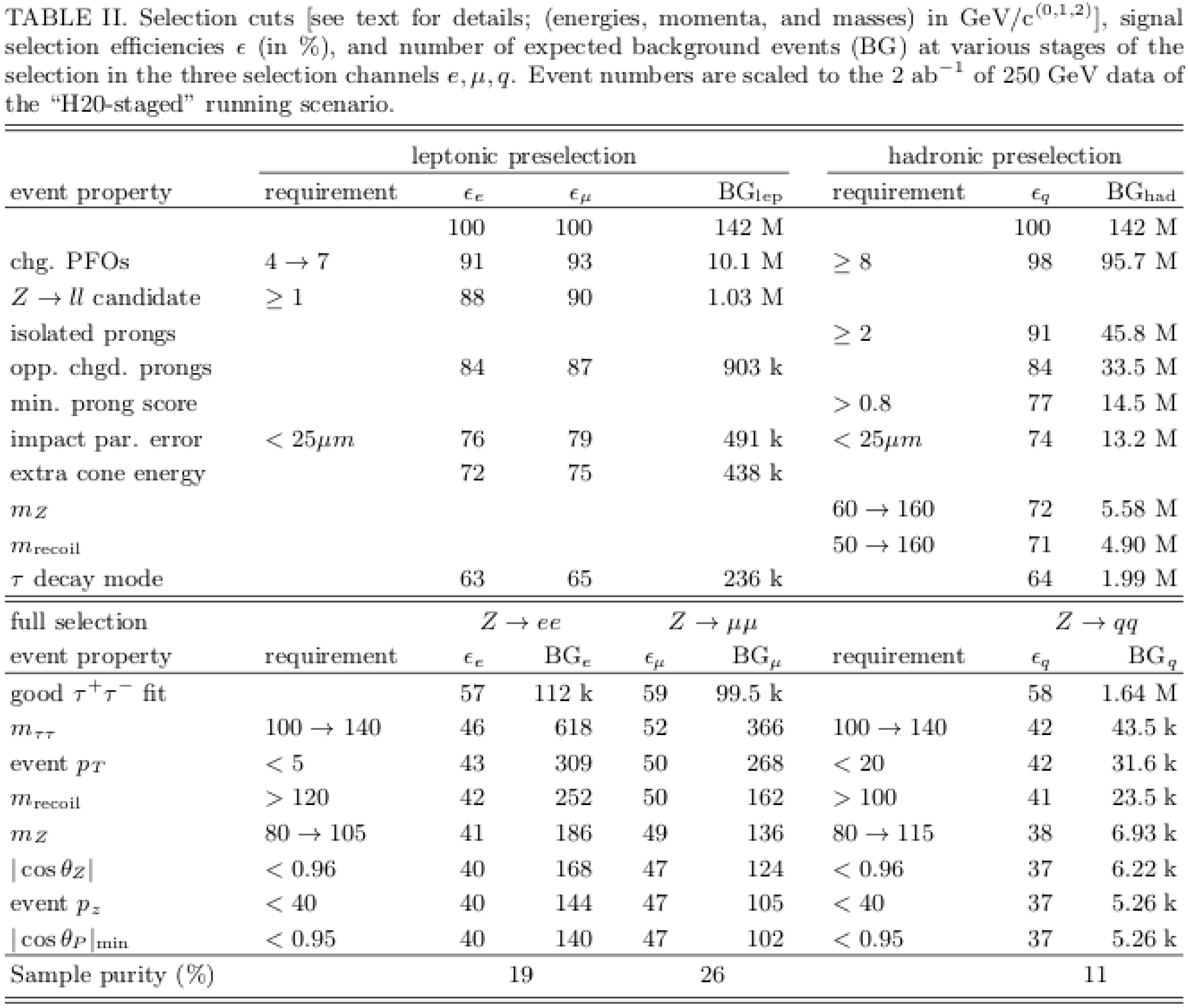


TABLE II. Selection cuts [see text for details; (energies, momenta, and masses) in GeV/c$^{(0,1,2)}$], signal selection efficiencies ϵ (in %), and number of expected background events (BG) at various stages of the selection in the three selection channels e, μ, q. Event numbers are scaled to the 2 ab^{-1}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

	leptonic preselection				hadronic preselection		
event property	requirement	ϵ_e	ϵ_μ	BG$_{\text{lep}}$	requirement	ϵ_q	BG$_{\text{had}}$
		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$_\mu$	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
$\lvert \cos \theta_Z \rvert$	< 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
$\lvert \cos \theta_P \rvert_{\min}$	< 0.95	40	140	47	102	< 0.95	37	5.26 k
Sample purity (%)		19		26			11	

amplitude of modulation in Δφ varies from event to event, depending on θ±, according to the contrast function:

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

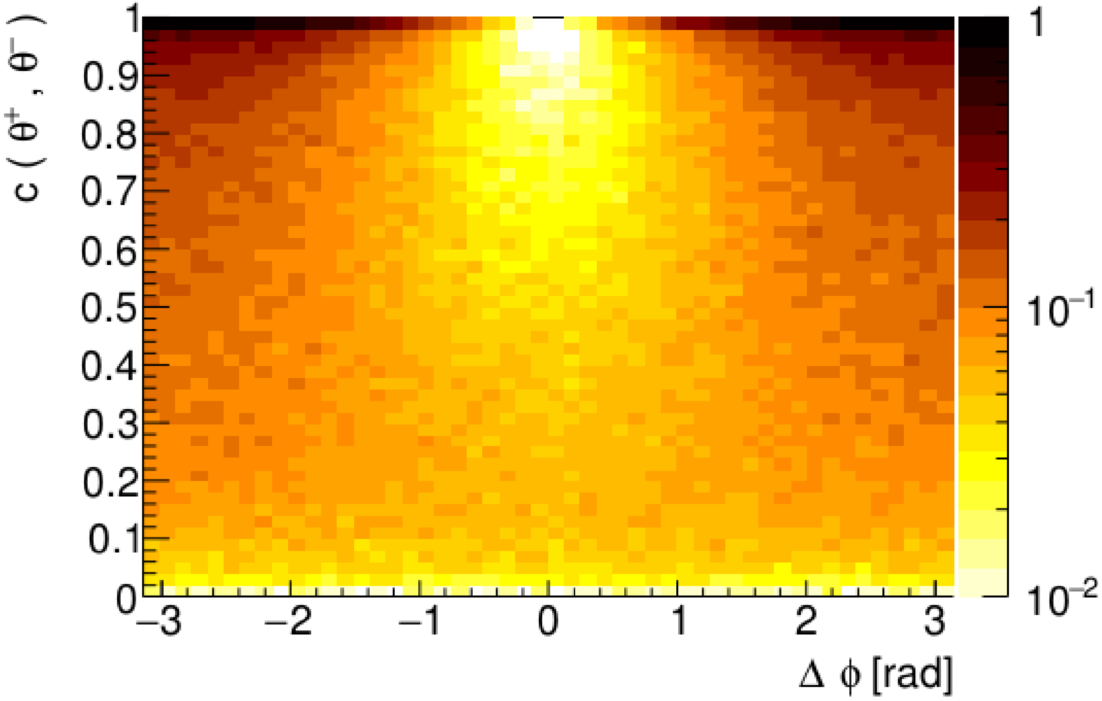
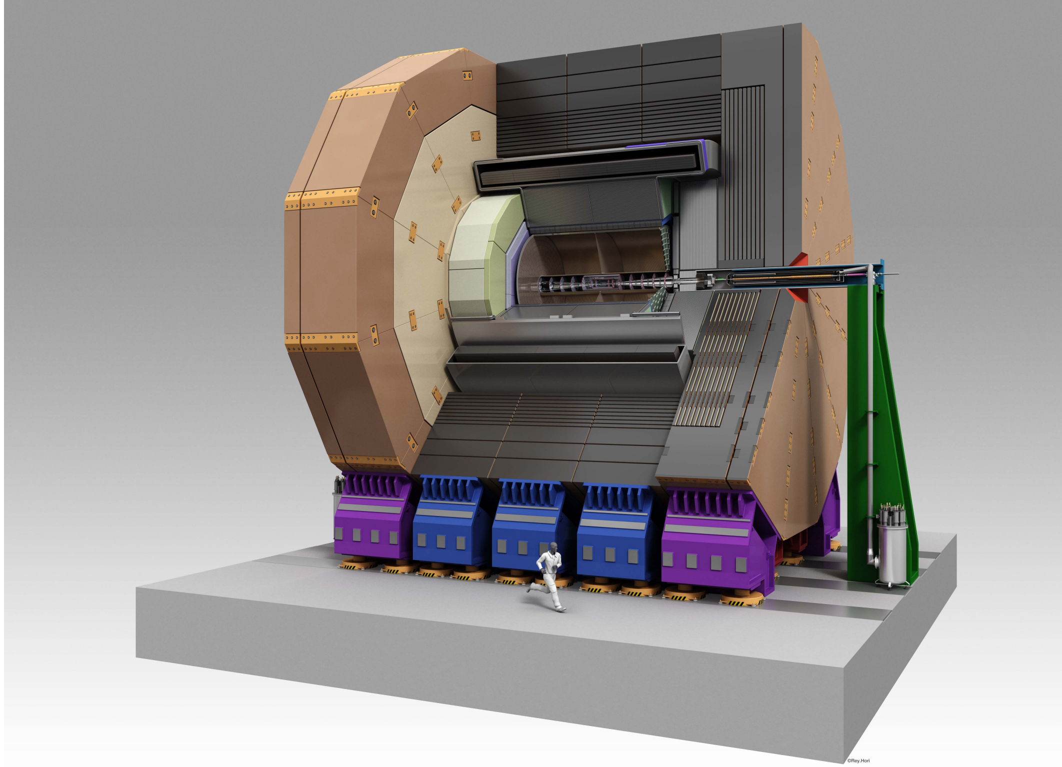


FIG. 3. Two-dimensional distribution of events in $\Delta\phi$ and $c(\theta^+,\theta^-)$ at MC truth level, for the case $\psi_{\mathrm{CP}}=0$.

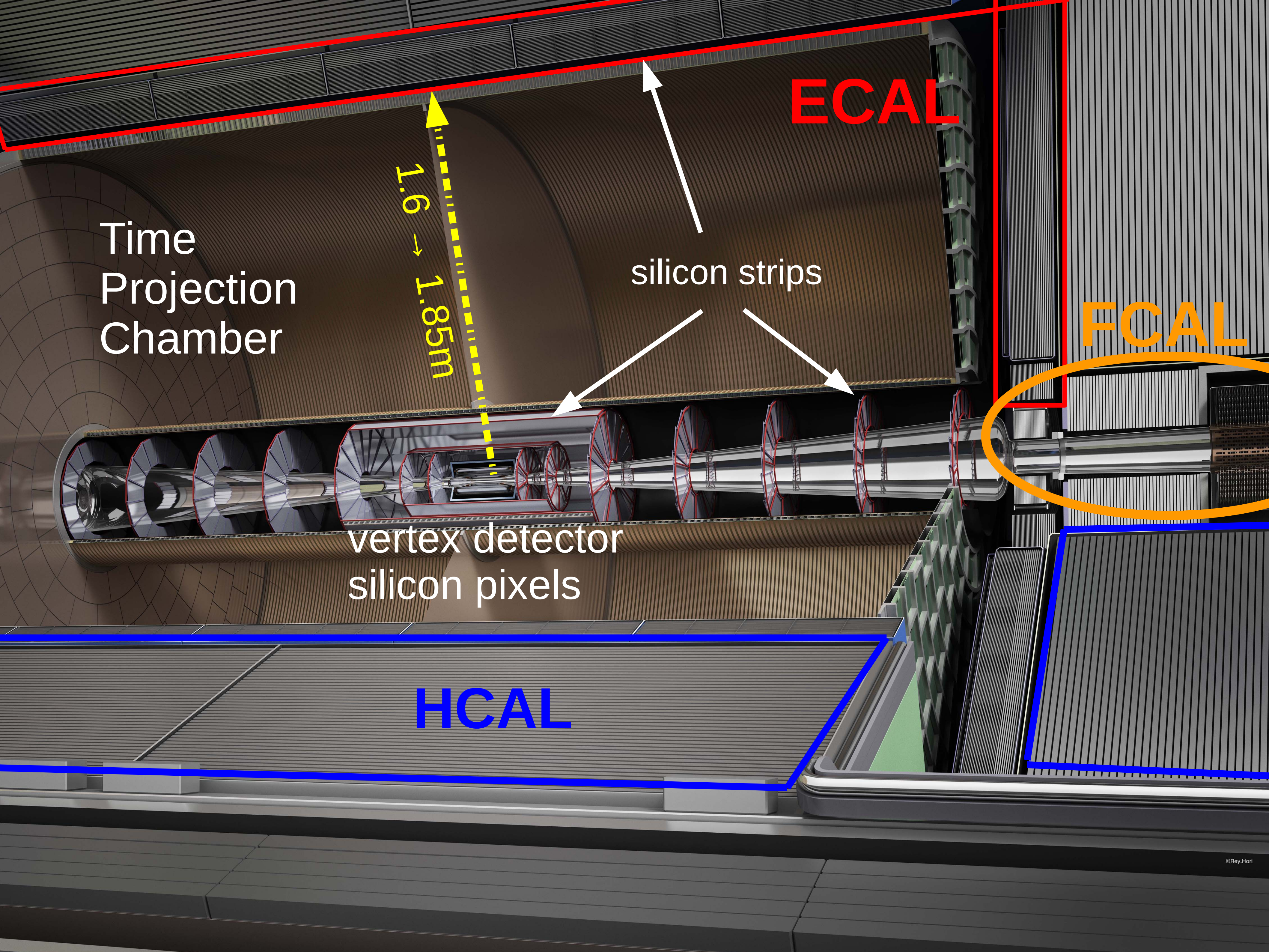
International Large Detector



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

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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

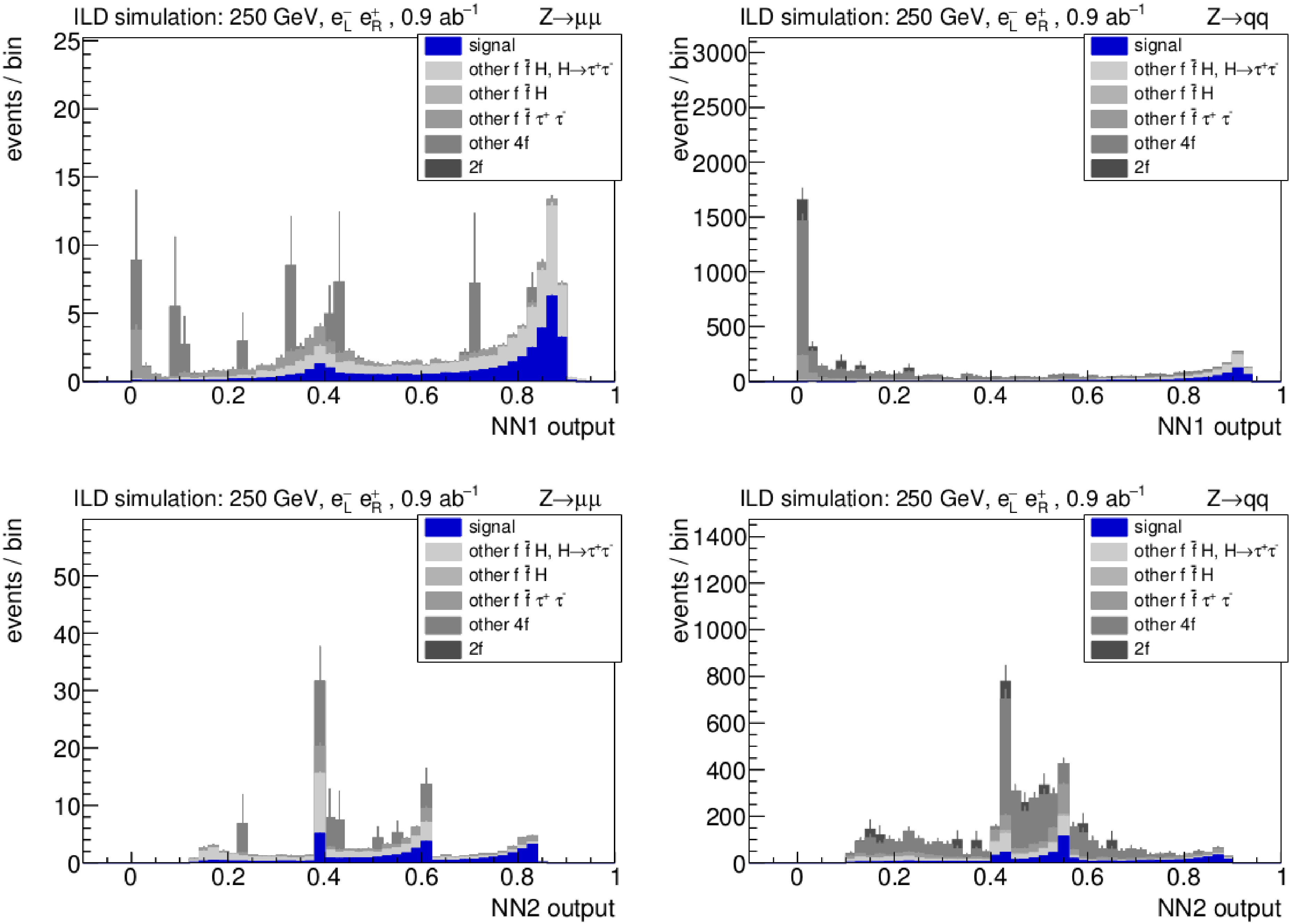

FIG. 7. Distributions of the two Neural Network outputs in the muon and hadronic selection channels. The structure in the output of NN2 is due to the three different combinations of τ lepton decay modes. Distributions are normalized to 0.9 ab^{-1} of data in the $e^-_L e^+_R$ beam polarization.