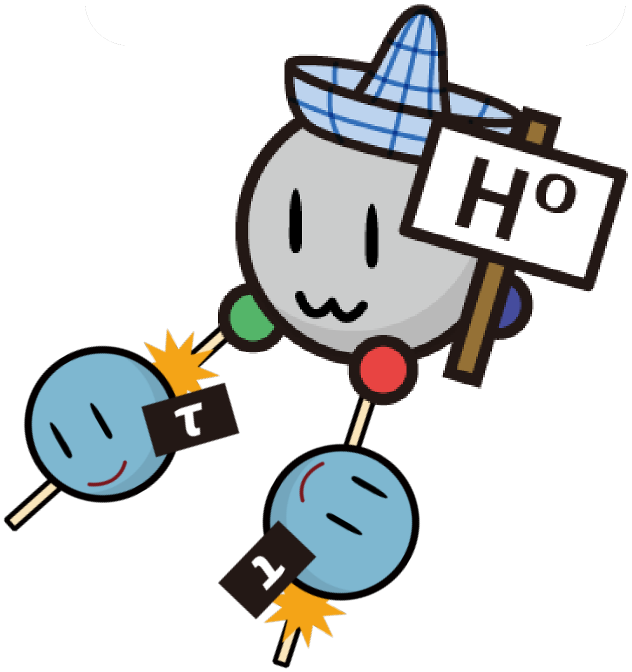
Phys.Rev. D98 (2018) no.1, 013007 / arXiv:1804.01241

Measuring CP properties of Higgs using decay to tau leptons at ILC-250



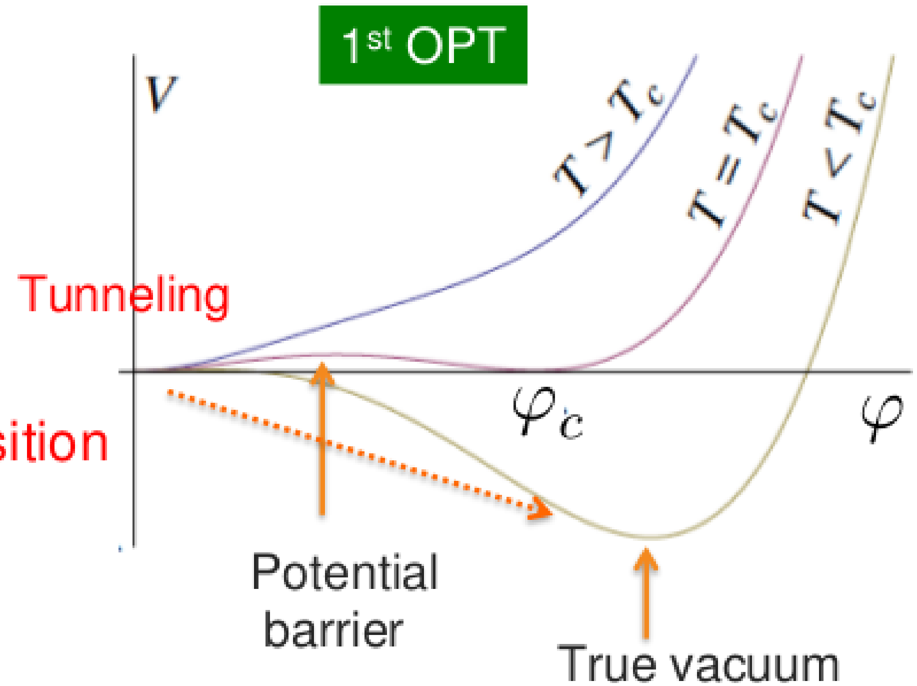
Daniel Jeans
ILC Summer camp 2019

from Kakizaki-san's talk yesterday

Electroweak baryogenesis (EWBG) and Higgs boson couplings

Sakharov's conditions for BAU

1. Baryon number violation
   - Sphaleron process
2. Violation of C and CP
   - Extended Higgs sector
3. Departure from thermal equilibrium
   - Strongly first order phase transition (1st OPT): $\varphi_c/T_c \gtrsim 1$



SM Higgs sector w/ one doublet:

- Electroweak phase transition (EWPT) is NOT of 1st order for $m_h = 125\ \mathrm{GeV}$

EWBG is an important physics case relating the Higgs sector to BSM phenomena

Motivation

a CP-odd Higgs appears in many extensions of Higgs sector

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 some mixture?

Do Higgs couplings conserve CP ?

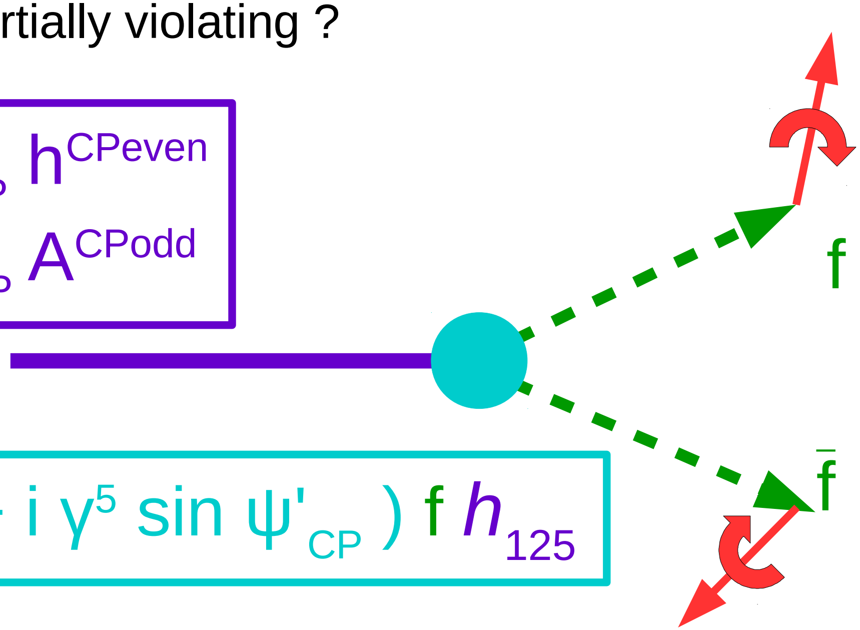
e.g. coupling to fermions: $L \sim g\, \bar{f}\, (\cos \psi_{CP} + i\, \gamma^5 \sin \psi_{CP})\, f\, H$

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

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

or partially violating ?

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



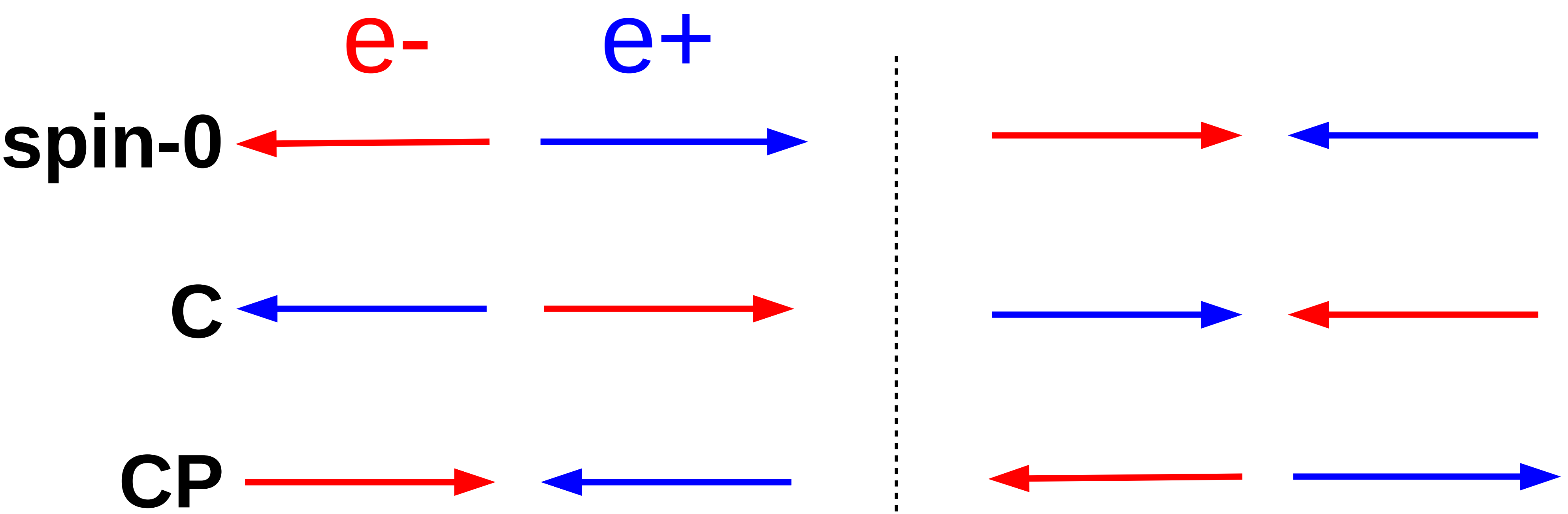
h is a spin 0 state:

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

[ψ = 0 CP even,
$\pi/2$ CP odd]

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

spin-0 state → 2 fermions



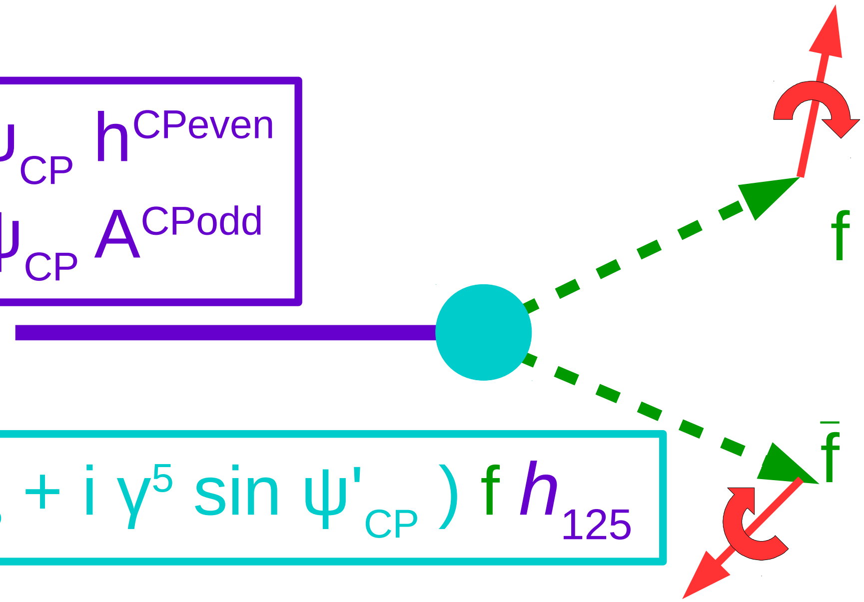
h is a spin 0 state:

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

[ψ = 0 CP even,
$\pi/2$ CP odd]

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

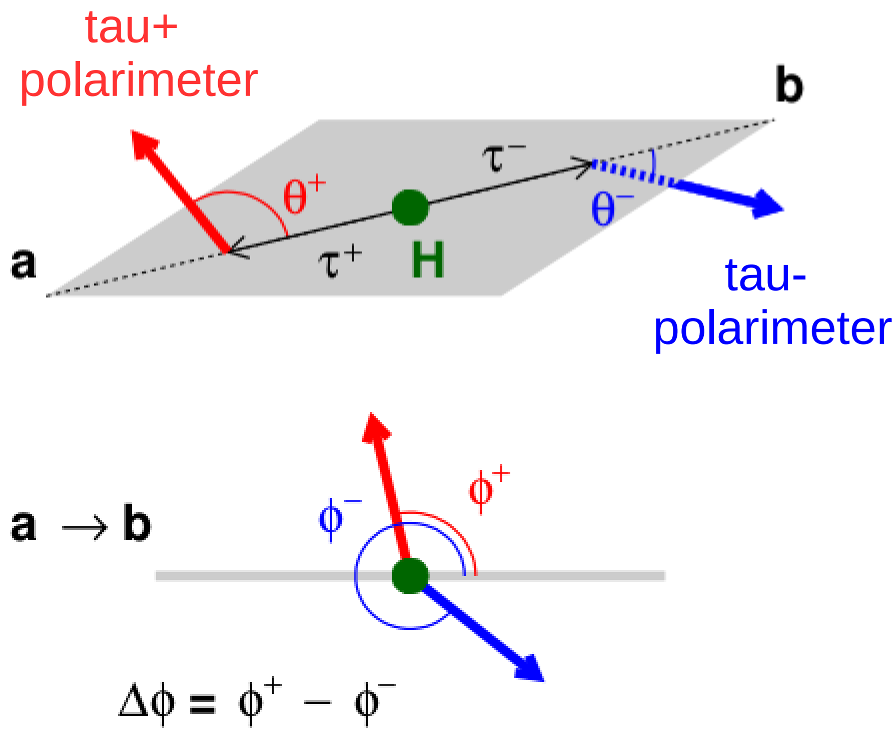
$$h_{125} = \cos\psi_{CP}\, h^{CPeven} + \sin\psi_{CP}\, A^{CPodd}$$

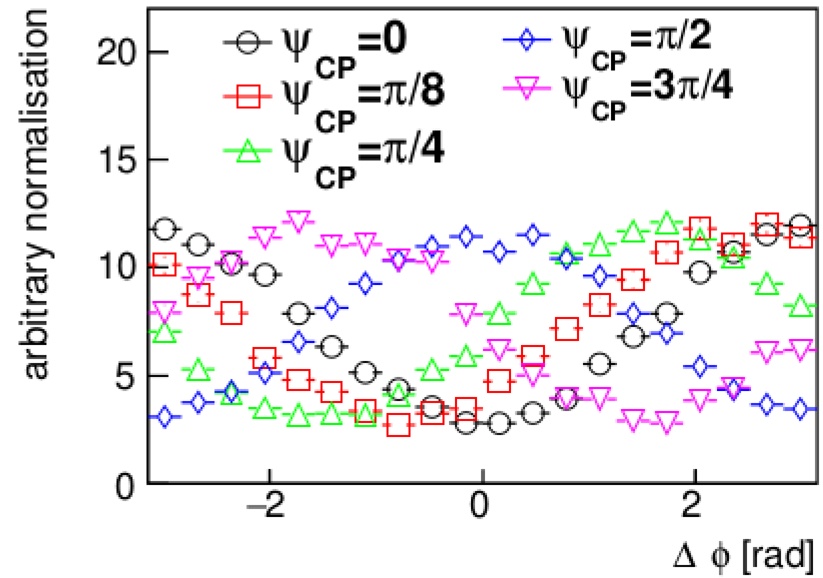


$$g\,\bar{f}\,(\cos\psi'_{CP} + i\,\gamma^5 \sin\psi'_{CP})\, f\, h_{125}$$

why use tau leptons to measure CP in Higgs sector?

- unstable fermion:
  - distribution of tau decay products → tau spin direction
  - optimal estimator = "polarimeter vector"
    - easy to extract for tau+ → pi+ nu and tau+ → (pi+ pi0 nu) decays
- reasonable 6% branching ratio
- clean separation of the two fermion decays
  - (no colour string as in H → bb)





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 contrast function:

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

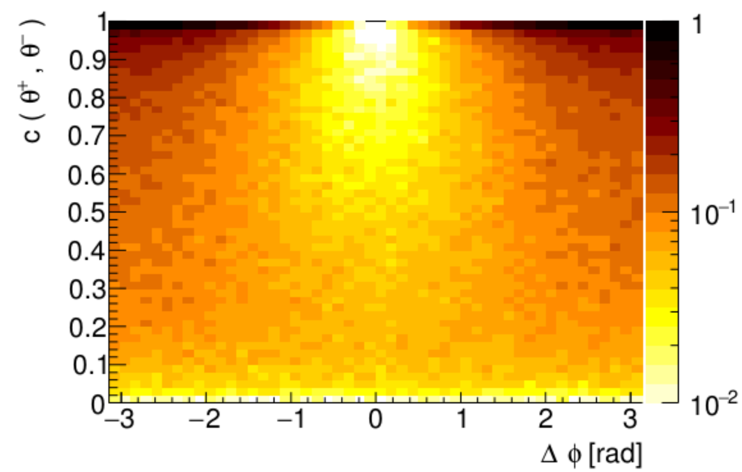
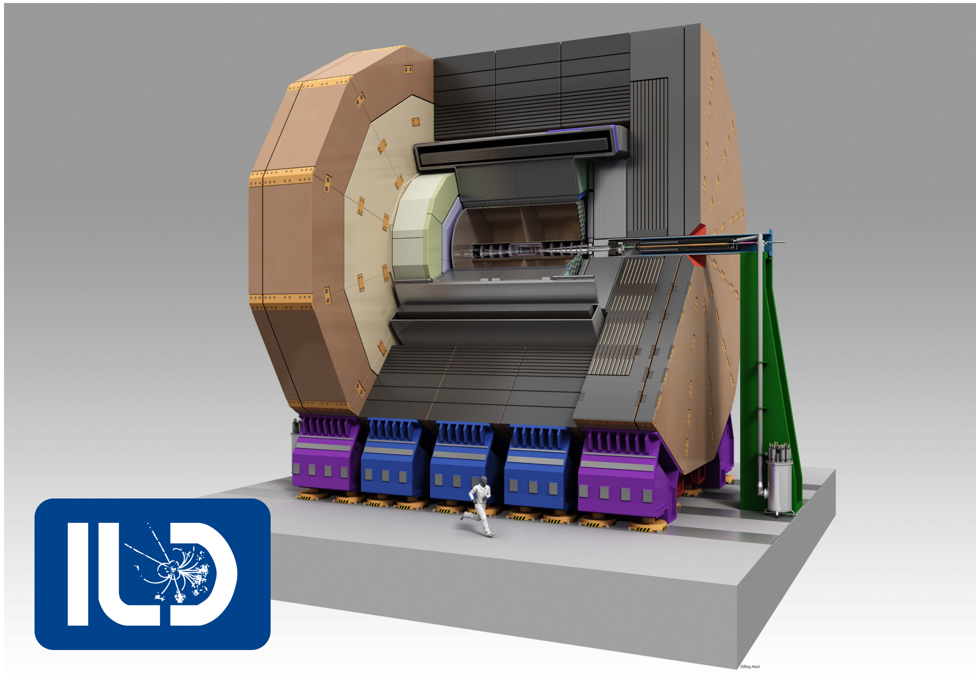


FIG. 3. Two-dimensional distribution of events in $\Delta\phi$ and $c(\theta^+,\theta^-)$ at MC truth level, for the case $\psi_{\rm CP} = 0$.

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

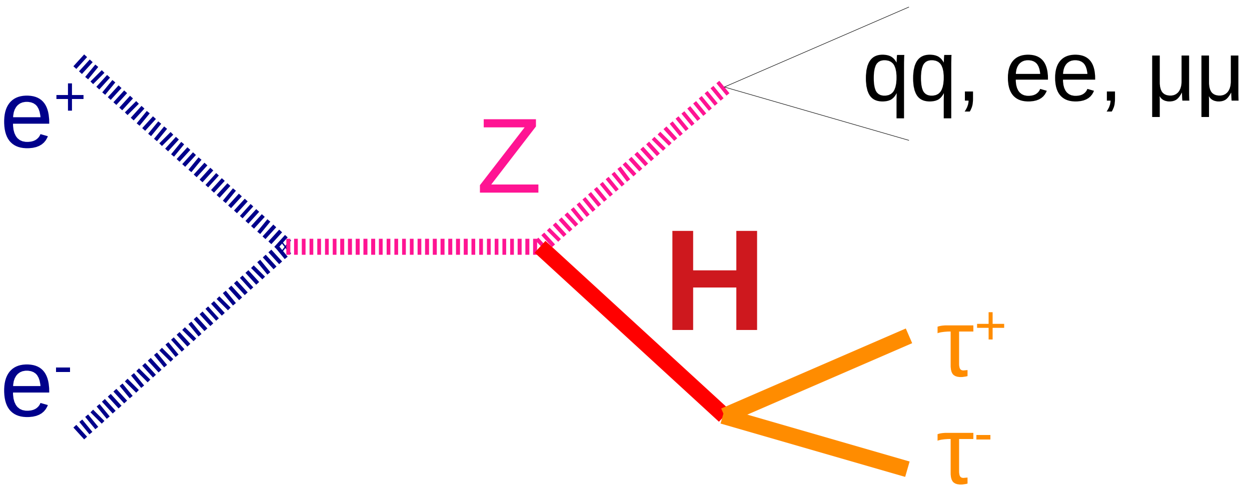


SIGNAL: $e^+ e^- \rightarrow Z\, H$

$Z \rightarrow$ 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

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 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]

vertex detector
tracking
photon reco.
Jet En. Res.

reconstruct Z → e e, μ μ, jets + 2 x (1-prong tau jets)

simple preselection

some distributions after reconstruction and preselection:

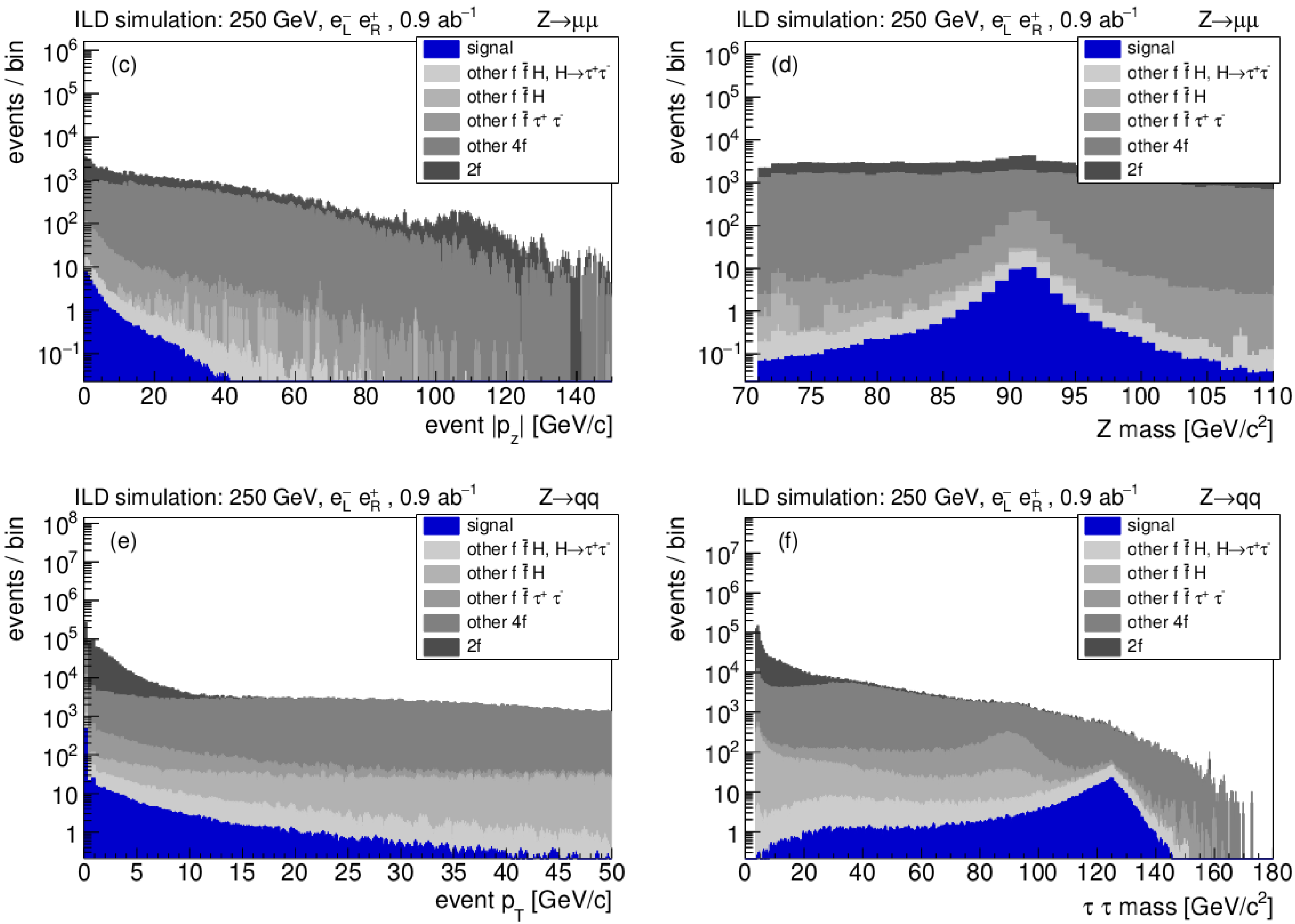


TABLE II. Selection cuts [see text for details; (energies, momenta, and masses) in GeV/c$^{(0,1,2)}$], signal selection efficiencies ϵ (in %), and number of expected background events (BG) at various stages of the selection in the three selection channels e, μ, q. Event numbers are scaled to the 2 ab^{-1}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

	leptonic preselection				hadronic preselection		
event property	requirement	ϵ_e	ϵ_μ	$\mathrm{BG}_{\mathrm{lep}}$	requirement	ϵ_q	$\mathrm{BG}_{\mathrm{had}}$
		100	100	142 M		100	142 M
chg. 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
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					$60 \to 160$	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	

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 %.

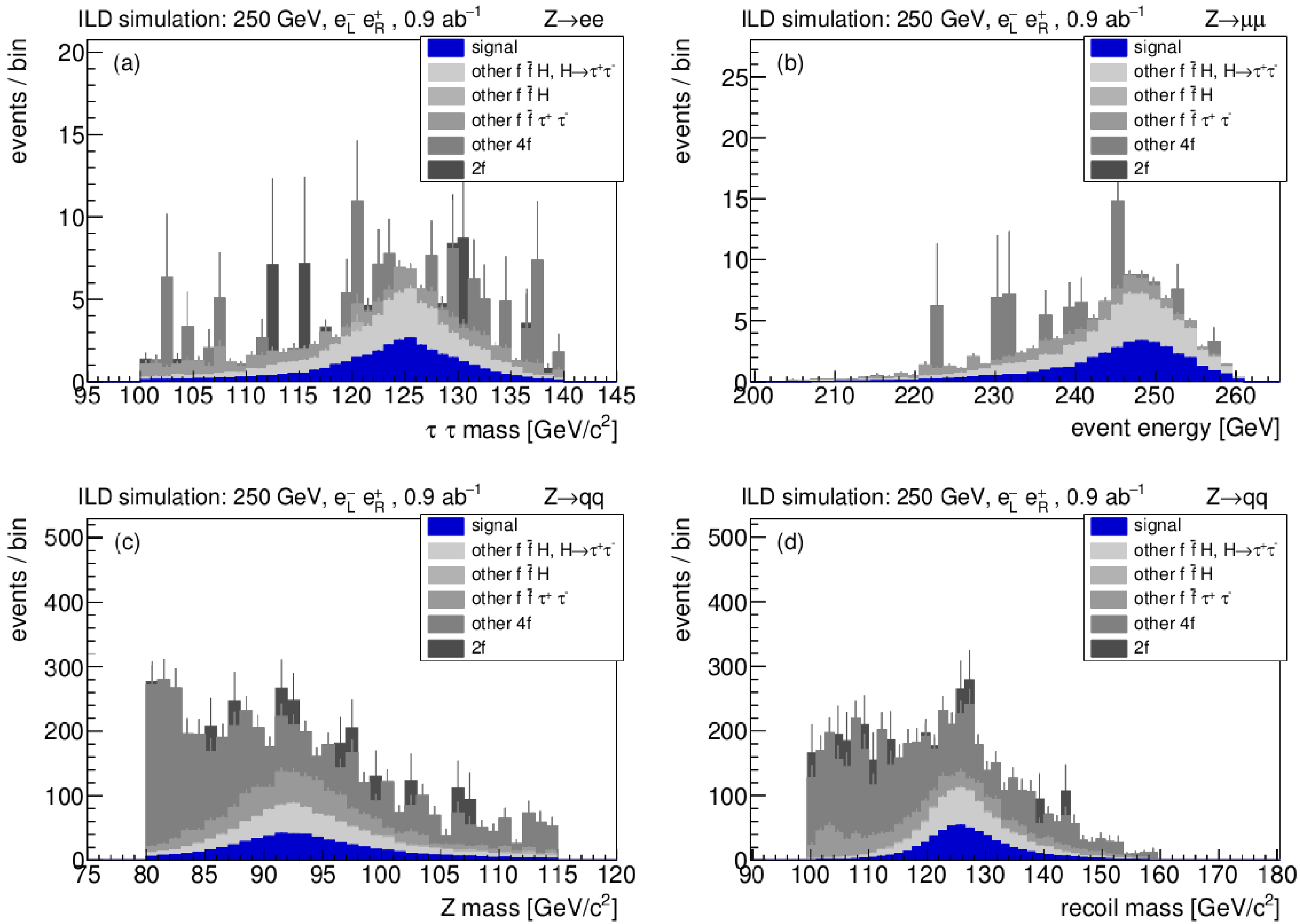
	True decay		
Reco. decay	$(\pi\nu, \pi\nu)$	$(\pi\nu, \rho\nu)$	$(\rho\nu, \rho\nu)$
		$Z \to \mu^+\mu^-$	
$(\pi\nu, \pi\nu)$	93	3	< 1
$(\pi\nu, \rho\nu)$	7	93	6
$(\rho\nu, \rho\nu)$	< 1	4	94
		$Z \to qq(uds)$	
$(\pi\nu, \pi\nu)$	89	6	< 1
$(\pi\nu, \rho\nu)$	11	89	12
$(\rho\nu, \rho\nu)$	< 1	5	87

reconstructing polarimeter vectors: in tau rest frame

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

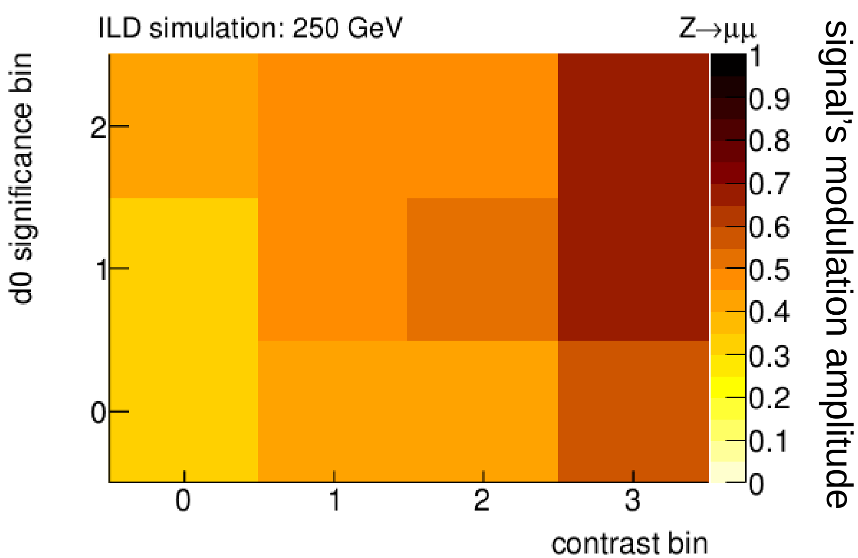
$$\begin{aligned}\mathbf{h}(\tau^\pm \to \pi^\pm\pi^0\nu) \propto\ & m_\tau(E_{\pi^\pm} - E_{\pi^0})(\mathbf{p}_{\pi^\pm} - \mathbf{p}_{\pi^0}) \\ & +2(p_{\pi^\pm} + p_{\pi^0})^2\mathbf{p}_\nu,\end{aligned} \tag{7}$$

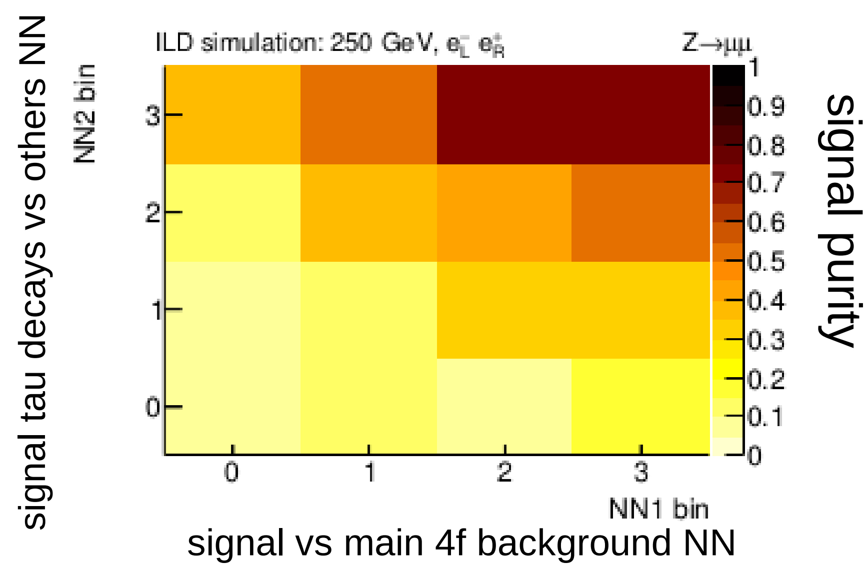
some distributions after selection



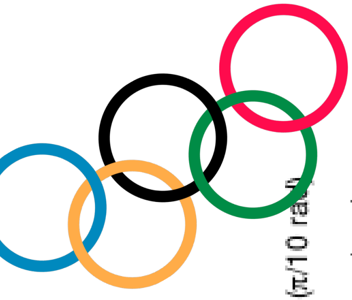
group events according to expected sensitivity, based on:

- 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



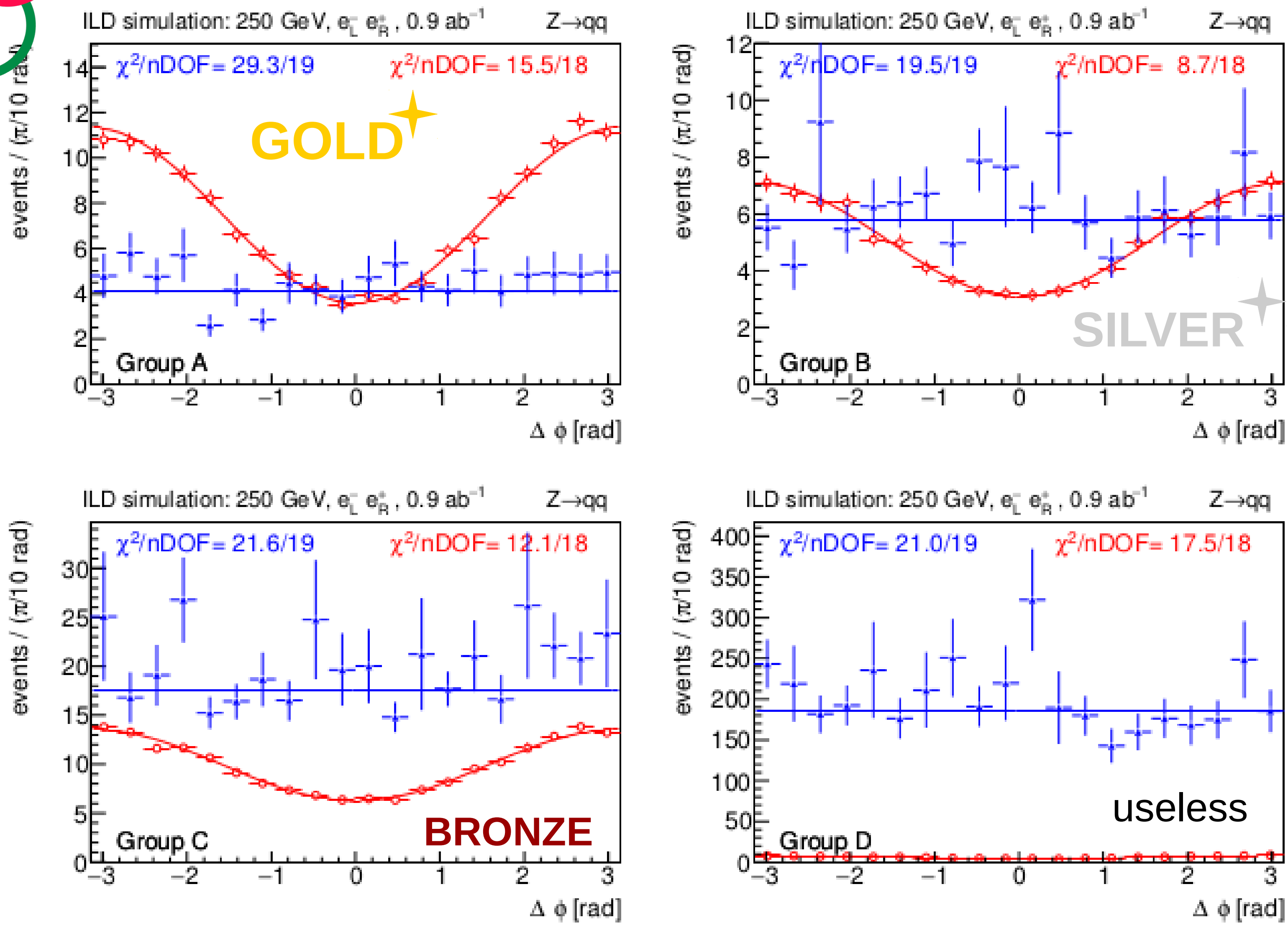


CP sensitive observable Δφ in different event sensitivity bins



error bars:
MC statistics

signal background

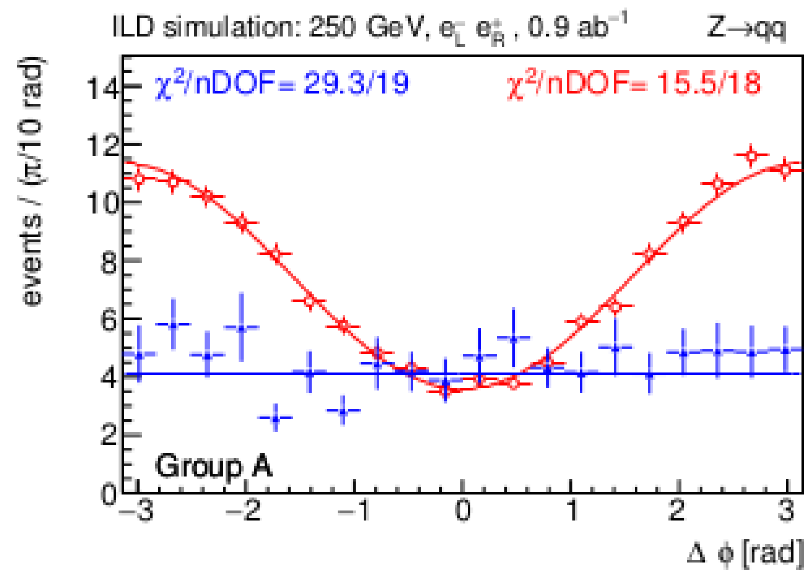


phase of signal distributions is sensitive to CP

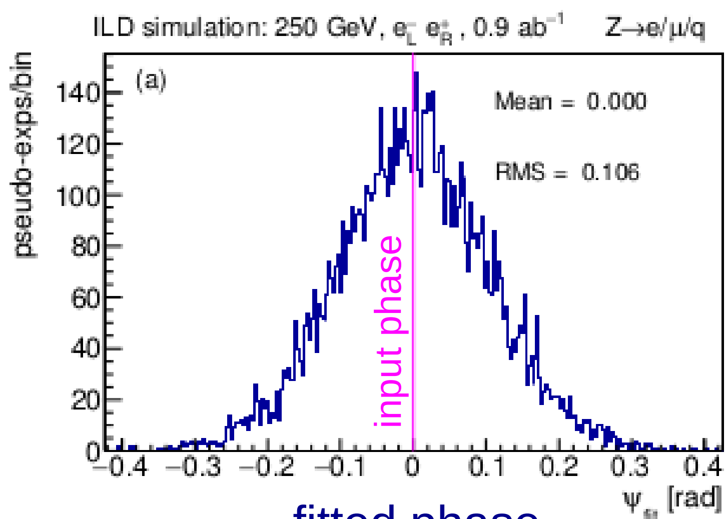
estimating measurement sensitivity

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

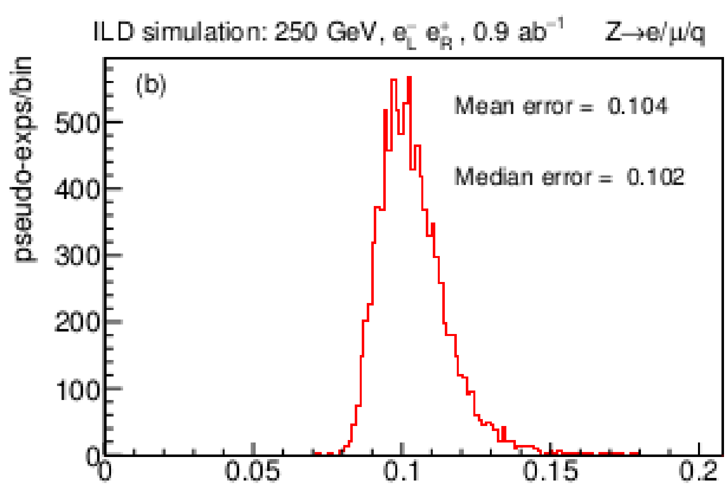
perform series of toy pseudo-experiments using
simulated distributions



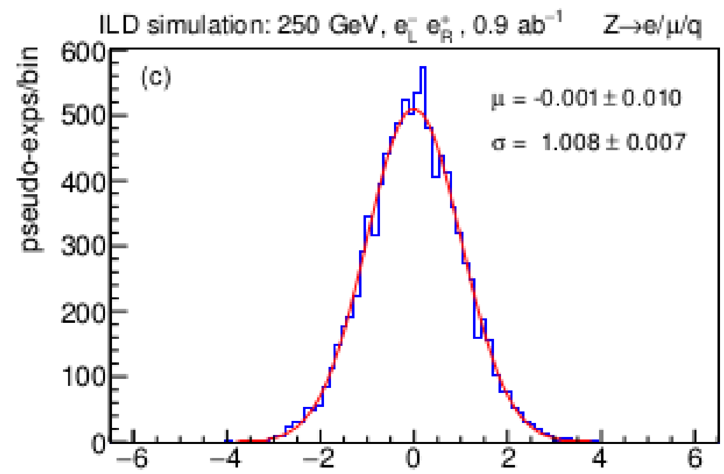
results of 10k pseudo-exps



fitted phase



fitted uncertainty



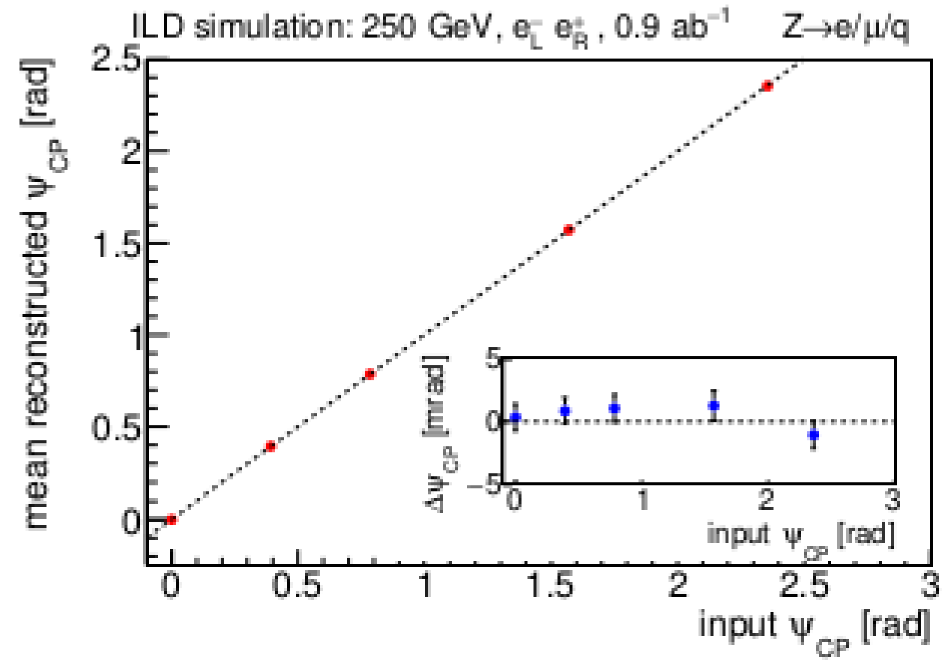
pull distribution

predicted sensitivity on ψ_{CP} under various conditions

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

$\int \mathcal{L}$ [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

sanity check: output = input phase



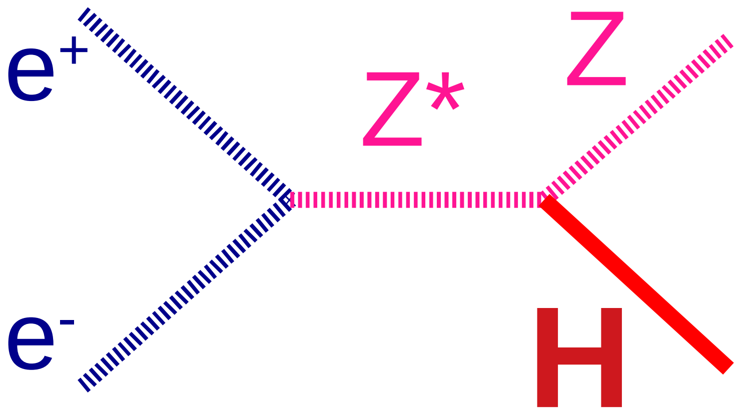
sensitivity on ψ_{CP} :

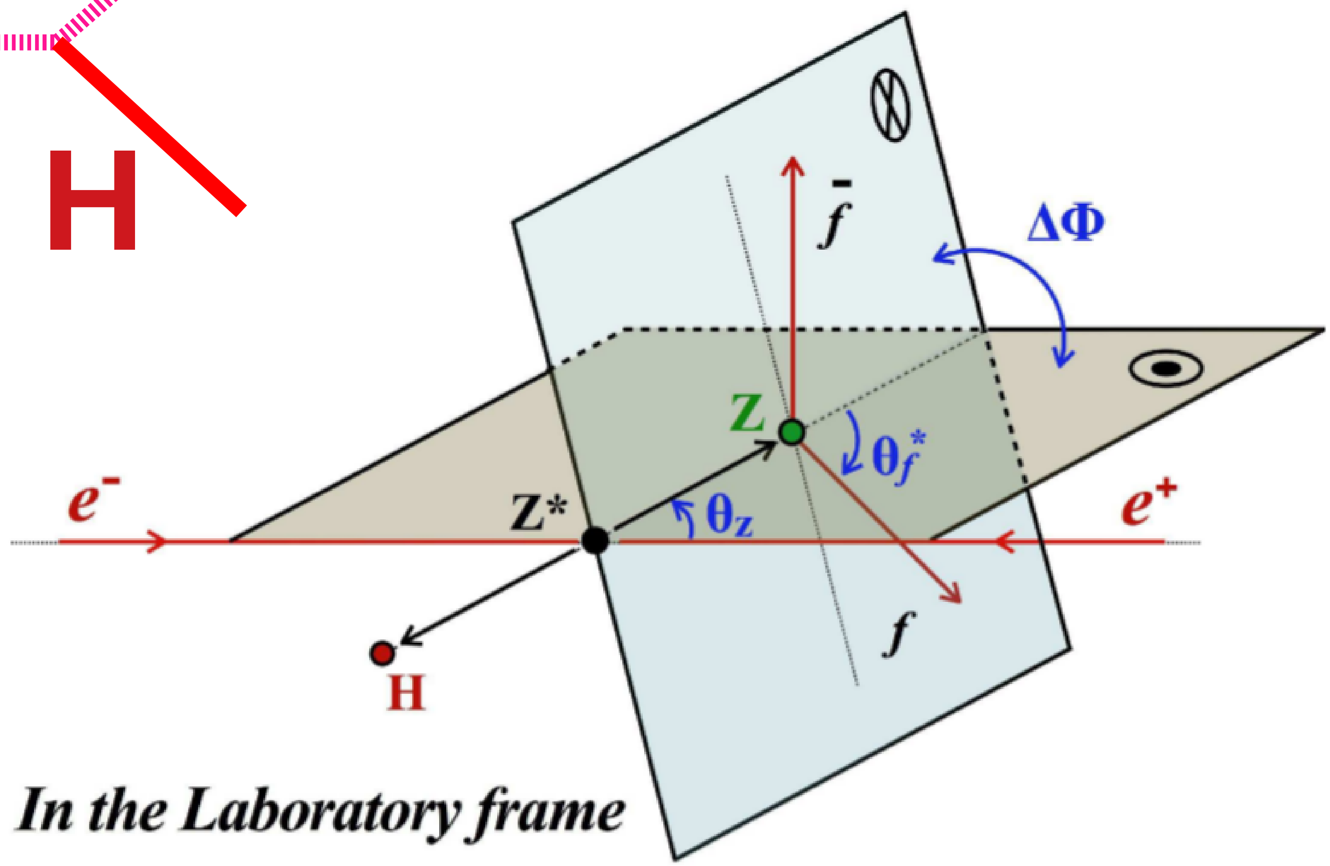
2/ab, all channels: 75 mrad

dominated by events with hadronic Z decay

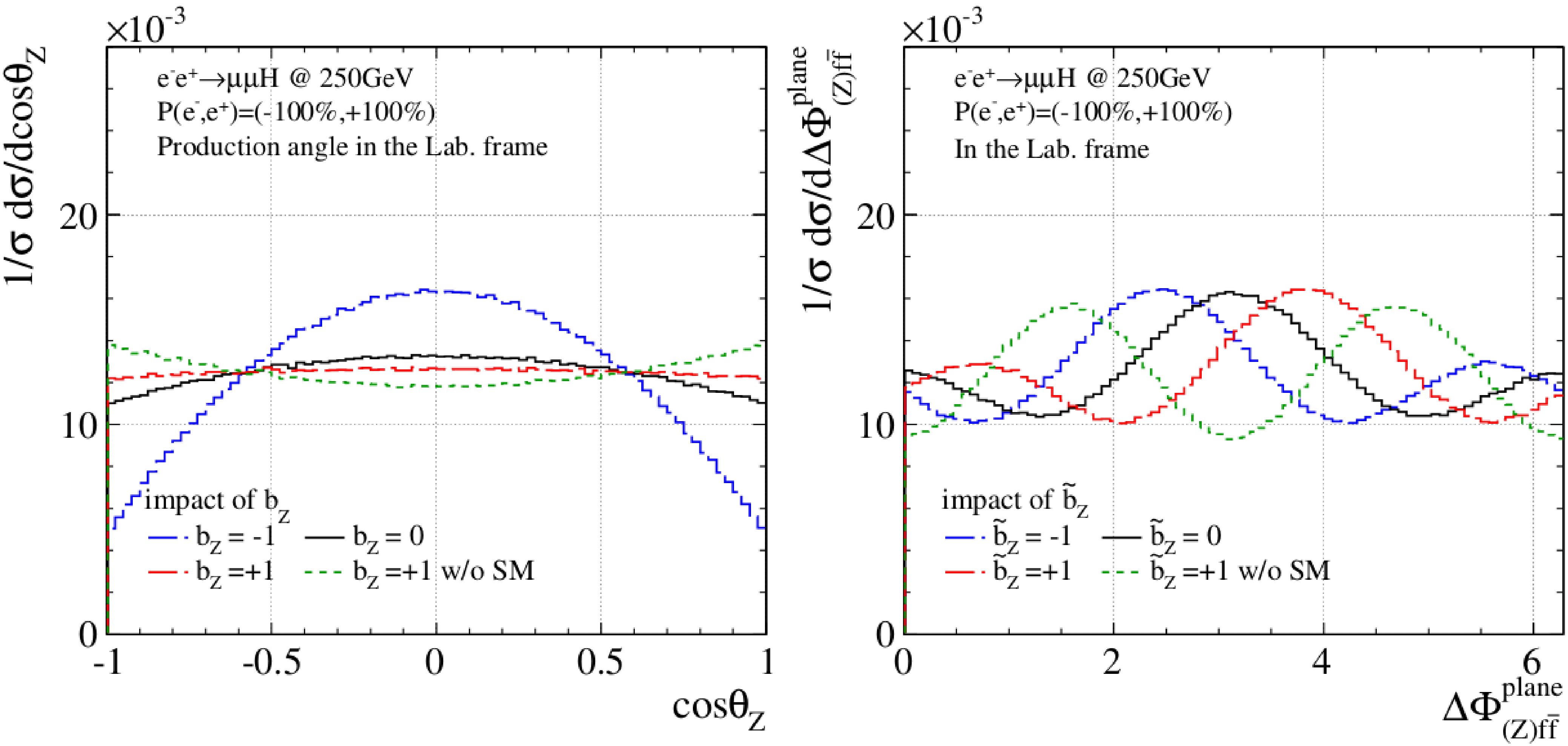
perfect reconstruction, selection: 25 mrad sensitivity

can also access CP in
Higgs coupling to ZZ,WW @ ILC





CP in Higgs coupling to W, Z @ ILC



through HZZ/HWW

$$L_{HVV} = 2C_V M_V^2 (\frac{1}{v} + \frac{a}{\Lambda}) H V_\mu V^\mu + C_V \frac{b}{\Lambda} H V_{\mu\nu} V^{\mu\nu} + C_V \frac{\tilde{b}}{\Lambda} H V_{\mu\nu} \tilde{V}_{\mu\nu}$$

(CP-odd)

$\Delta\tilde{b} \sim 0.016$ (for Λ=1TeV)

Ogawa, 1712.09772

summary

CP effects in Higgs sector are
important ingredient in EW Baryogenesis

Higgs decay to tau leptons is a nice system in which to study this

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

potential for improved analysis methods
to significantly improve results [ultimately → 25 mrad]

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

backup

International Linear Collider

electron-positron collisions

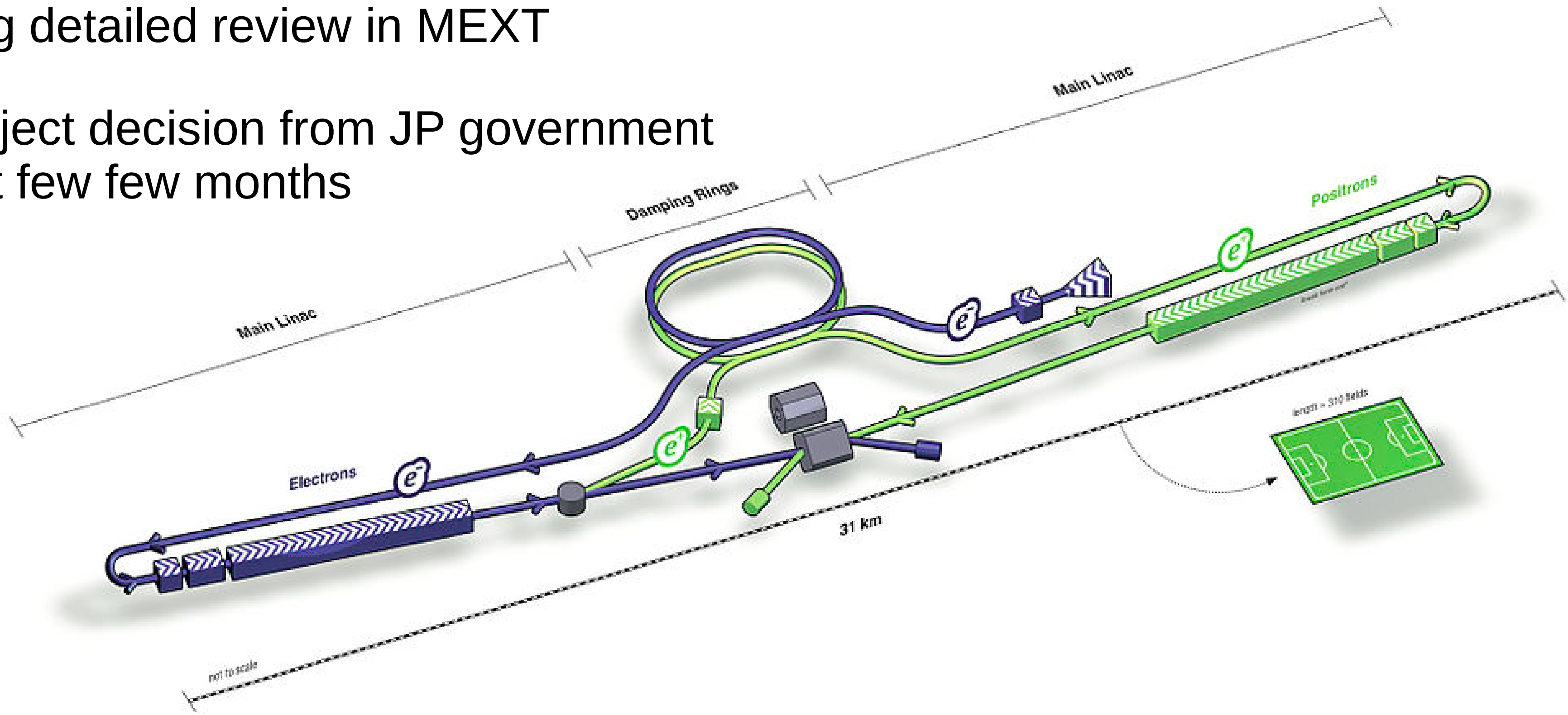
initial collision energy 250 GeV → Higgs factory
linear design allows relatively simple energy upgrade in the future

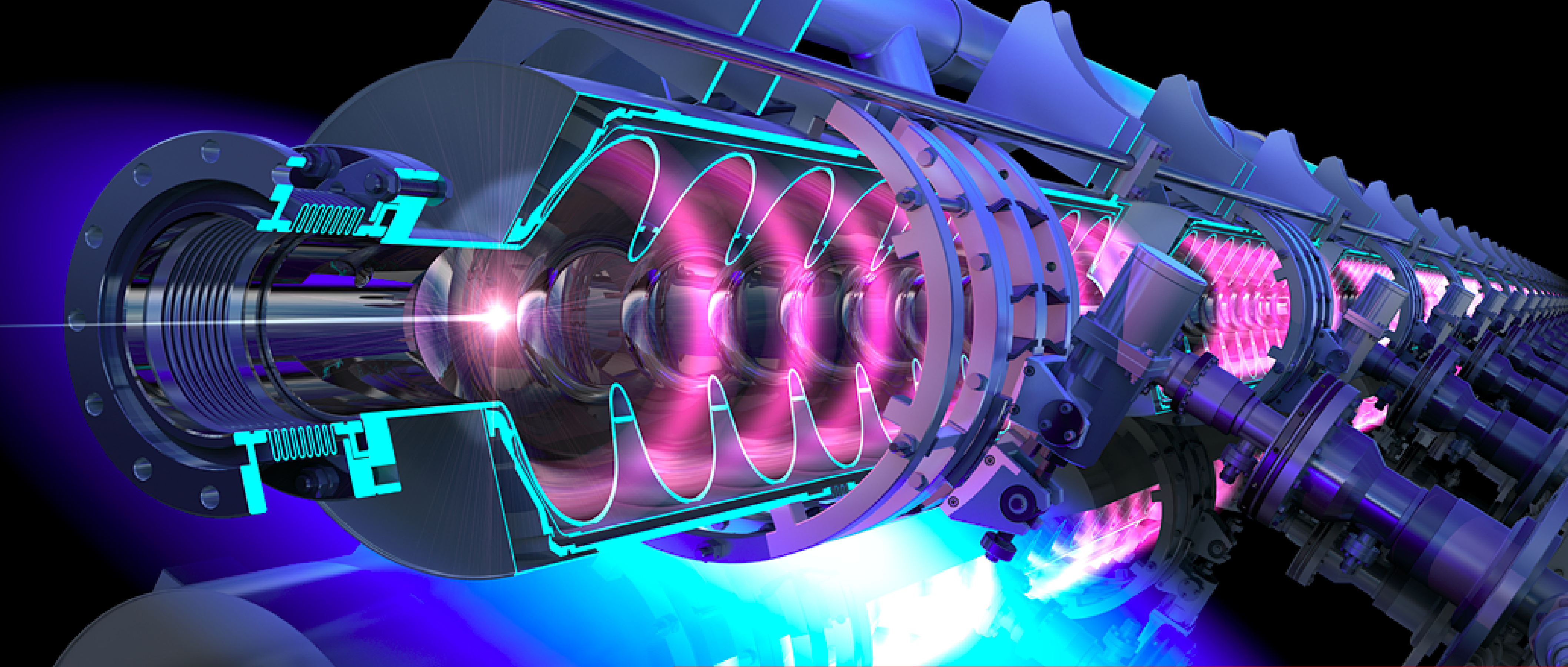
longitudinally polarised beams

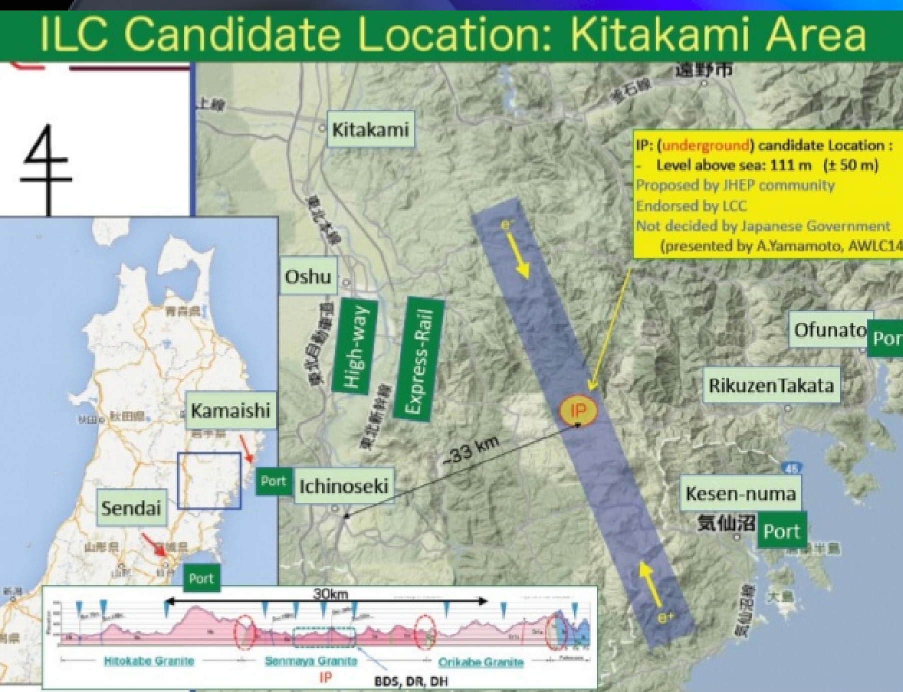
Technical Design Report published 2012

undergoing detailed review in MEXT

expect project decision from JP government
in next few few months







Kaname Kodashima

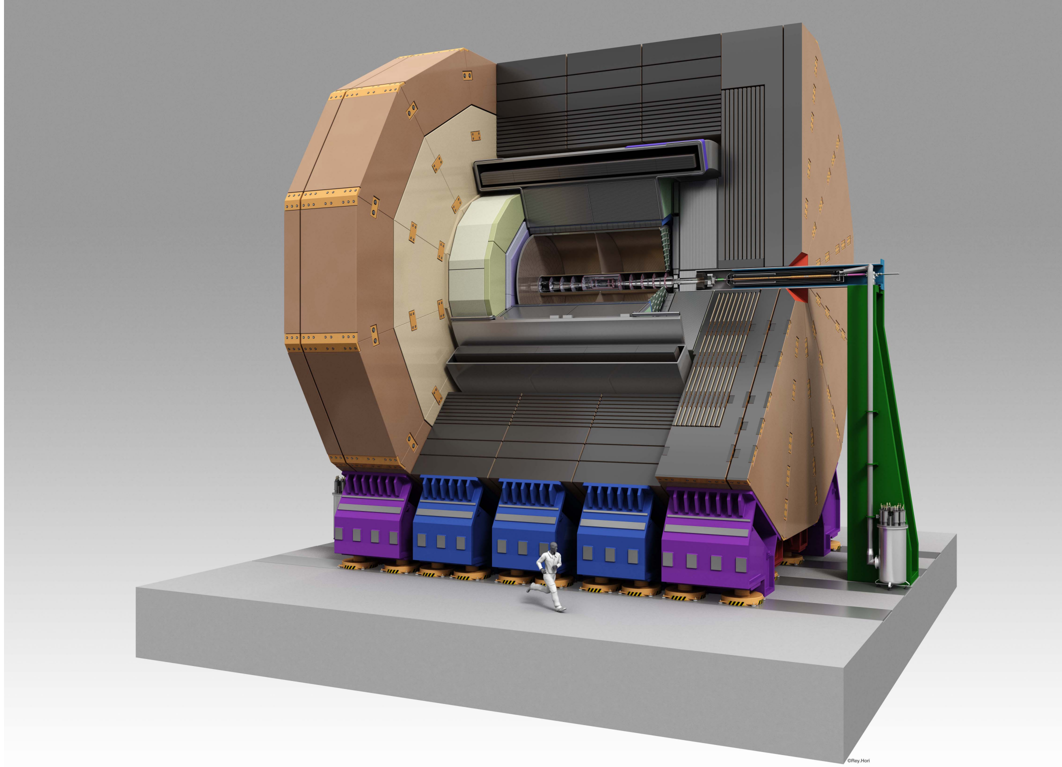
“Lots of encounters through the ILC”

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
(1^{st}~3^{rd} grade entries)

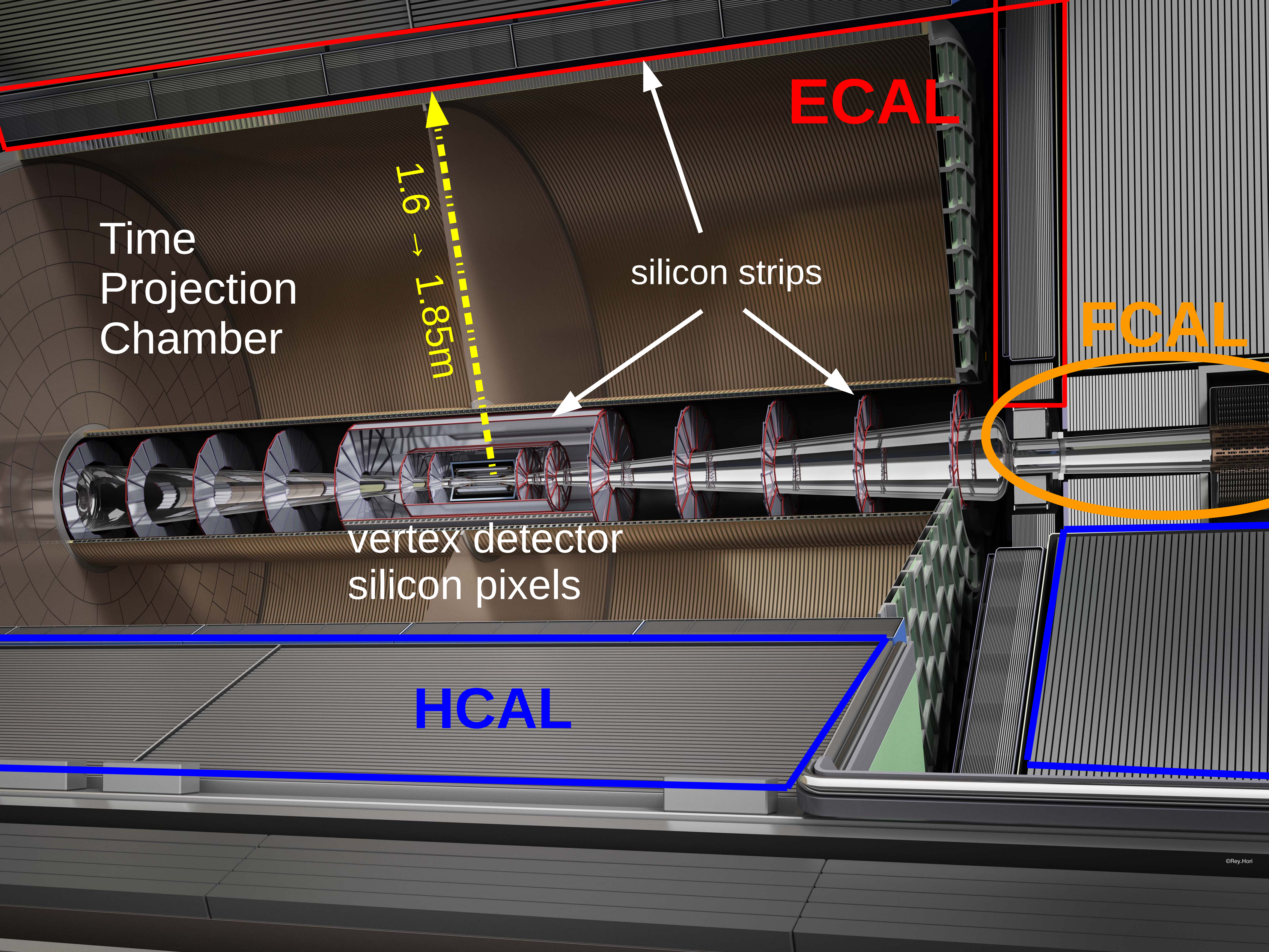
International Large Detector



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
©Rey.Hori

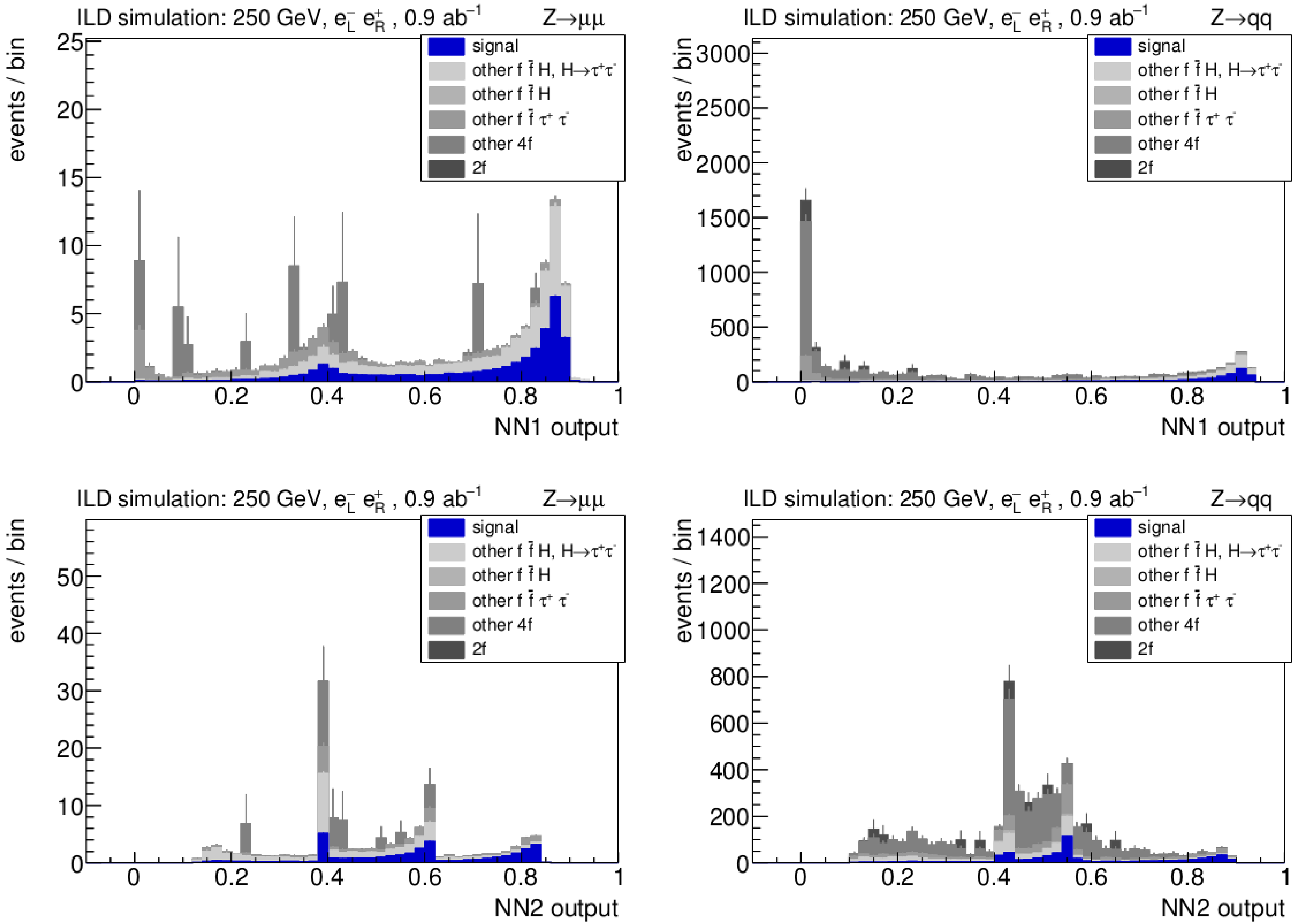


FIG. 7. Distributions of the two Neural Network outputs in the muon and hadronic selection channels. The structure in the output of NN2 is due to the three different combinations of τ lepton decay modes. Distributions are normalized to 0.9 ab^{-1} of data in the $e^-_L e^+_R$ beam polarization.