topical paper:
final ILD presentation
before submission

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

drafts/reviewing process: https://agenda.linearcollider.org/event/7841/
(see my mail from March 8 for the access key)

Dec 6, 2017:	ILD sw/ana phone meeting	https://agenda.linearcollider.org/event/7823/
Dec 2016:	LCWS/Morioka	
July 27, 2016:	ILD sw/ana phone meeting	https://agenda.linearcollider.org/event/7329/
June 2016:	ECFA-LC/Santander	
May 25, 2016:	ILD sw/ana phone meeting	https://agenda.linearcollider.org/event/7104/

Daniel Jeans, KEK
3rd April 2018

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

or a mixture of even/odd?

Do Higgs couplings conserve CP ?

e.g. coupling to fermions:

$$\mathcal{L} \sim g\ \bar{f}\ (\cos \psi_{CP} + i\ \gamma^5 \sin \psi_{CP}\ )\ f\ H$$

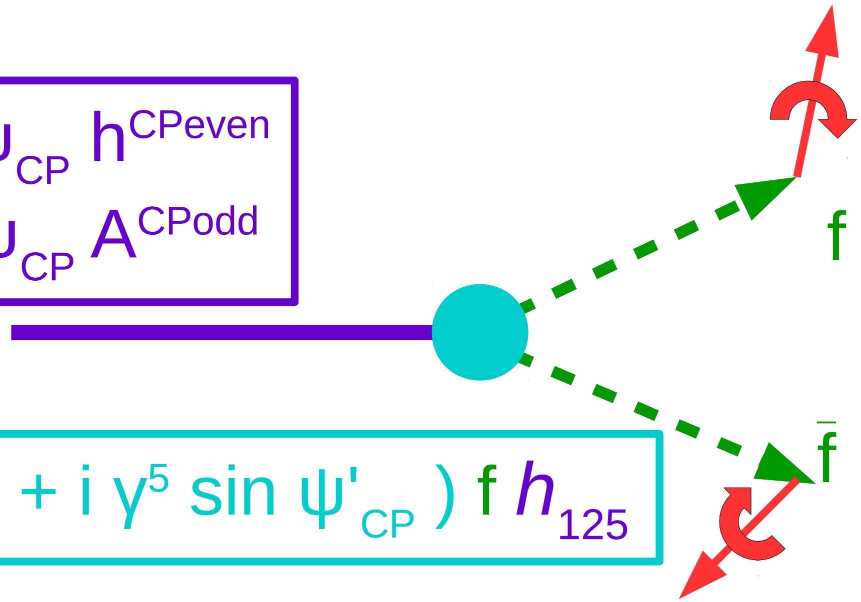
CP conserving coupling $\psi_{CP} = 0$ [Standard Model]

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

or partially violating ?

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

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



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

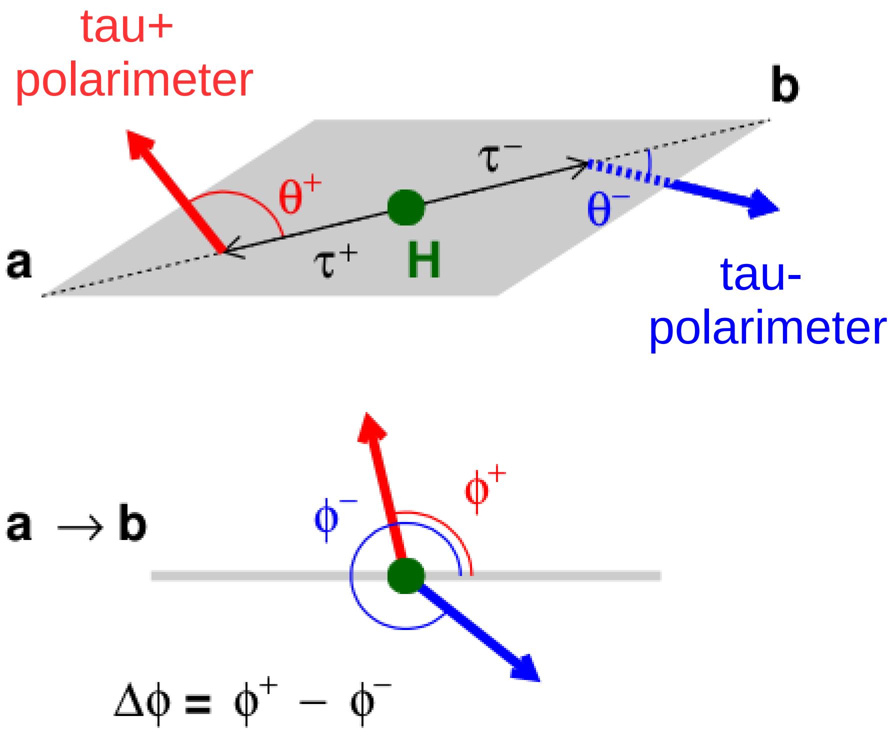
h is a spin 0 state:

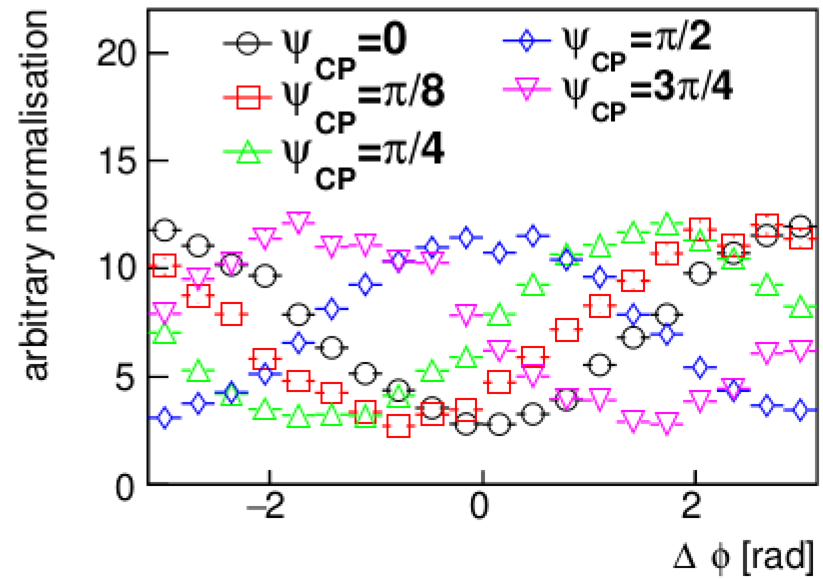
$| f\ \bar{f} \rangle = |\uparrow\downarrow\rangle + e^{2i\psi}\,|\downarrow\uparrow\rangle$

[ψ = 0 CP even,
$\pi/2$ CP odd]

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+ → (pi+ nu) and tau+ → (pi+ pi0 nu) decay modes
- 6% branching ratio
- clean separation of two fermions
  (no colour string as in H→bb)





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

In this analysis, we measure ψ_{CP} of the tau pair from Higgs decay
in a model-independent way

we don't try to understand which mechanism creates the mixing:
explicitly CP violating coupling, mixed CP mass eigenstate, …
→ would require global analysis of several measurements,
+ model assumptions

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 **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]

analysis uses events fully simulated in ILD

- DBD era software version v01-16-02
- privately produced tau-tau-f-f samples (WHIZARD)
  - signal: with tau-tau from H
  - backgrounds: tau-tau not from H [H mass set very high]
    - with full spin correlations in tau-pair decays (PYTHIA)
- other backgrounds: centrally produced DBD samples

SIGNAL: e+ e- → Z H

- Z → electrons, muons, quarks
- H → tau tau
- tau → (pi+ nu) or (pi+ pi0 nu)

SM backgrounds:

- all ffH, 4f, 2f

assume 2 ab^{-1} of 250 GeV data: H20-staged reconstruct Z → [e e, mu mu, jets] + 2 x (1-prong tau jets)

simple preselection

some distributions after reco/presel:

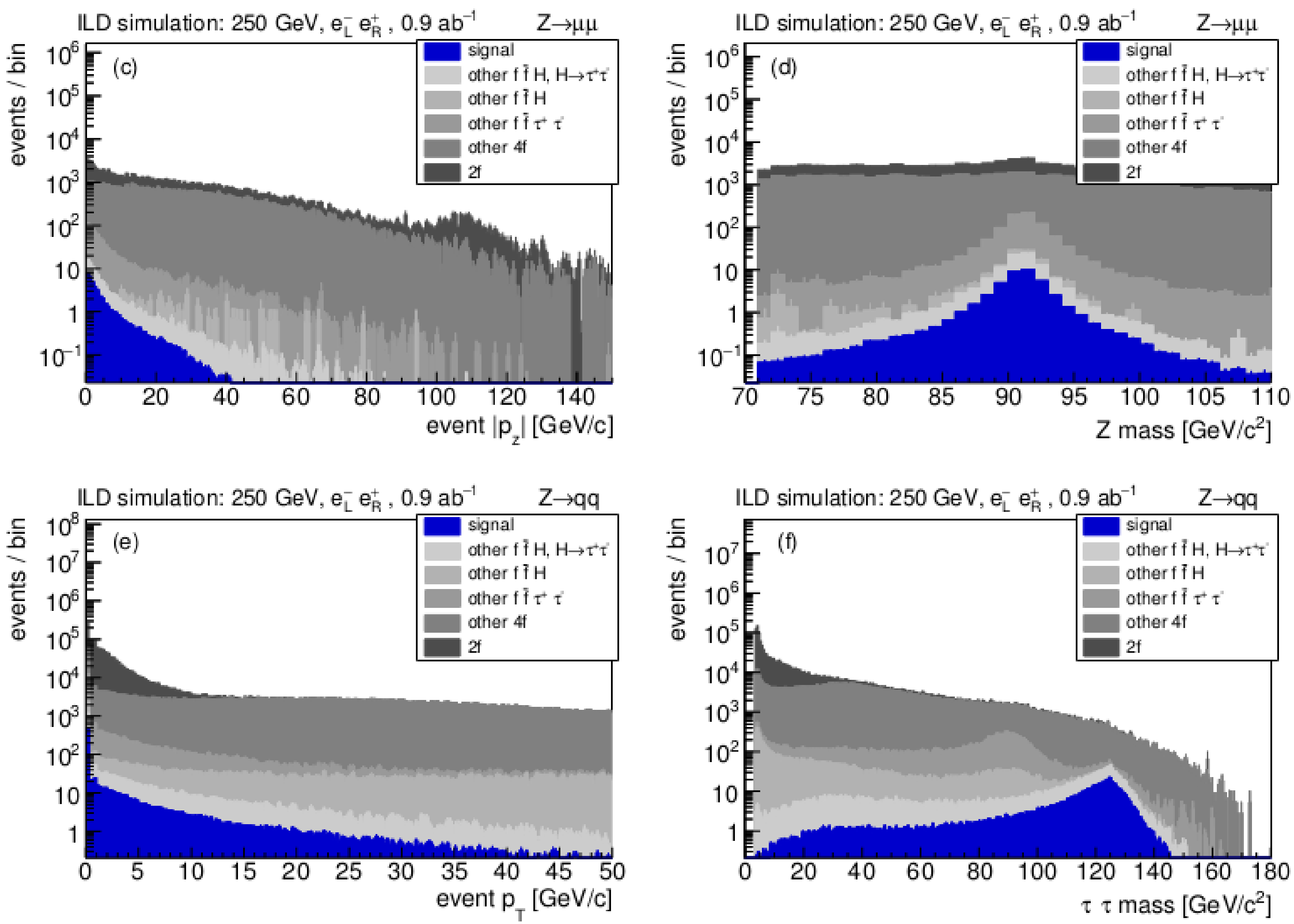


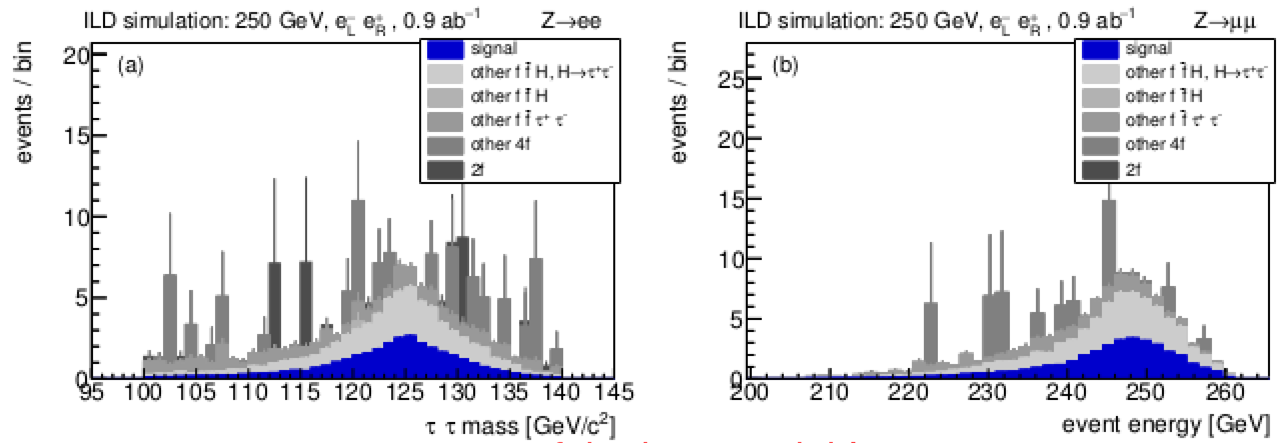
TABLE II. Selection cuts [see text for details; (energies, momenta, and masses) in GeV/c$^{(0,1,2)}$], signal selection efficiencies ϵ (in %), and number of expected background events (BG) at various stages of the selection in the three selection channels e, μ, q. Event numbers are scaled to the 2 ab^{-1} 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	$4 \rightarrow 7$	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

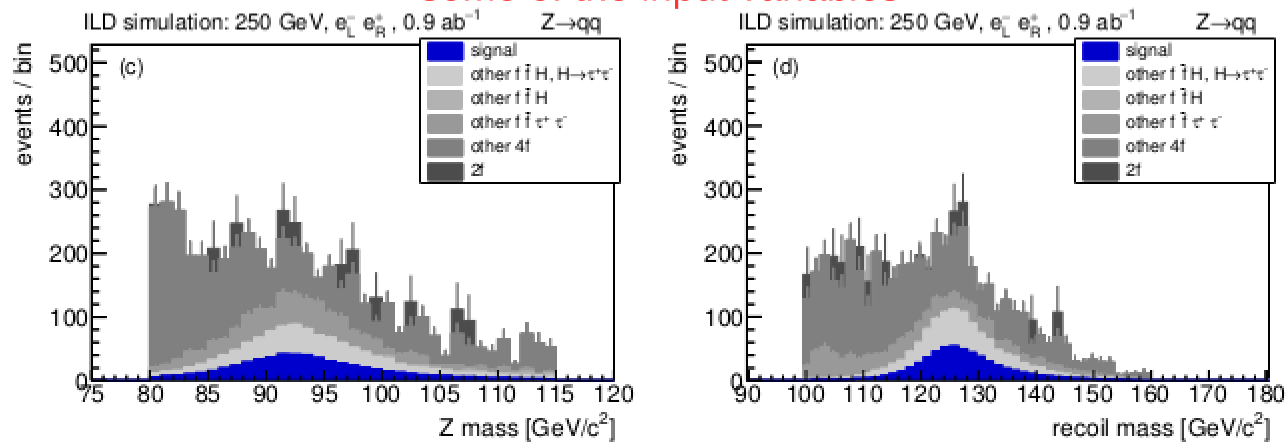
full selection		$Z \rightarrow ee$		$Z \rightarrow \mu\mu$			$Z \rightarrow qq$	
event property	requirement	ϵ_e	BG_e	ϵ_μ	BG_μ	requirement	ϵ_q	BG_q
good $\tau^+\tau^-$ fit		57	112 k	59	99.5 k		58	1.64 M
$m_{\tau\tau}$	$100 \rightarrow 140$	46	618	52	366	$100 \rightarrow 140$	42	43.5 k
event p_T	< 5	43	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
$\lvert\cos\theta_Z\rvert$	< 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	

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



some of the input variables



group events according
to expected sensitivity, based on:

- tau decay prongs:
  - d0 measurement significance
  - → reconstruction quality
- longitudinal comp. of polarimeters
  - → intrinsic sensitivity
- output of simple NN [6 inputs]
  - (signal vs. main 4f bgs)
  - → bg. contamination
- output of simple NN [4 inputs]
  - (signal tau decays vs. others)
  - → tau mis-id

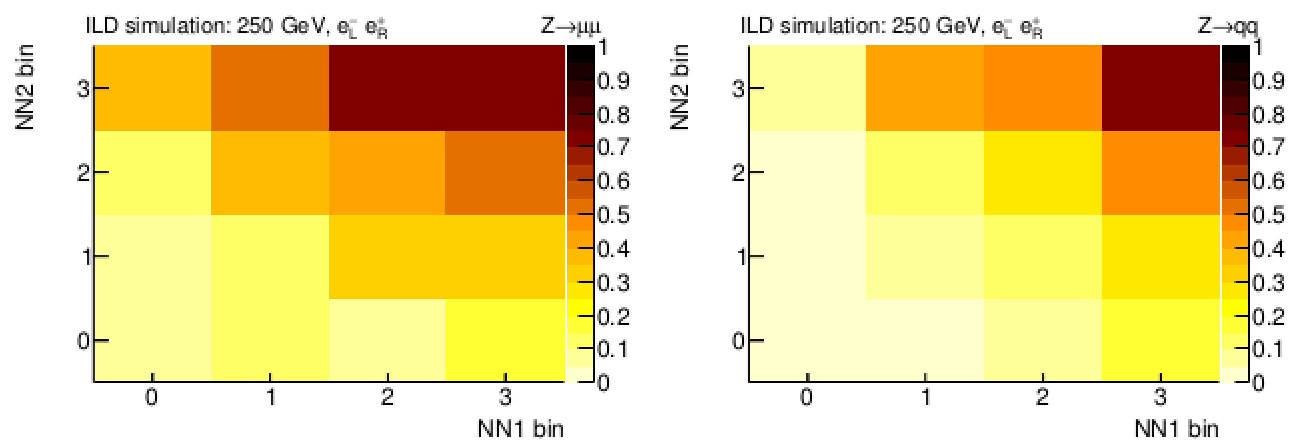
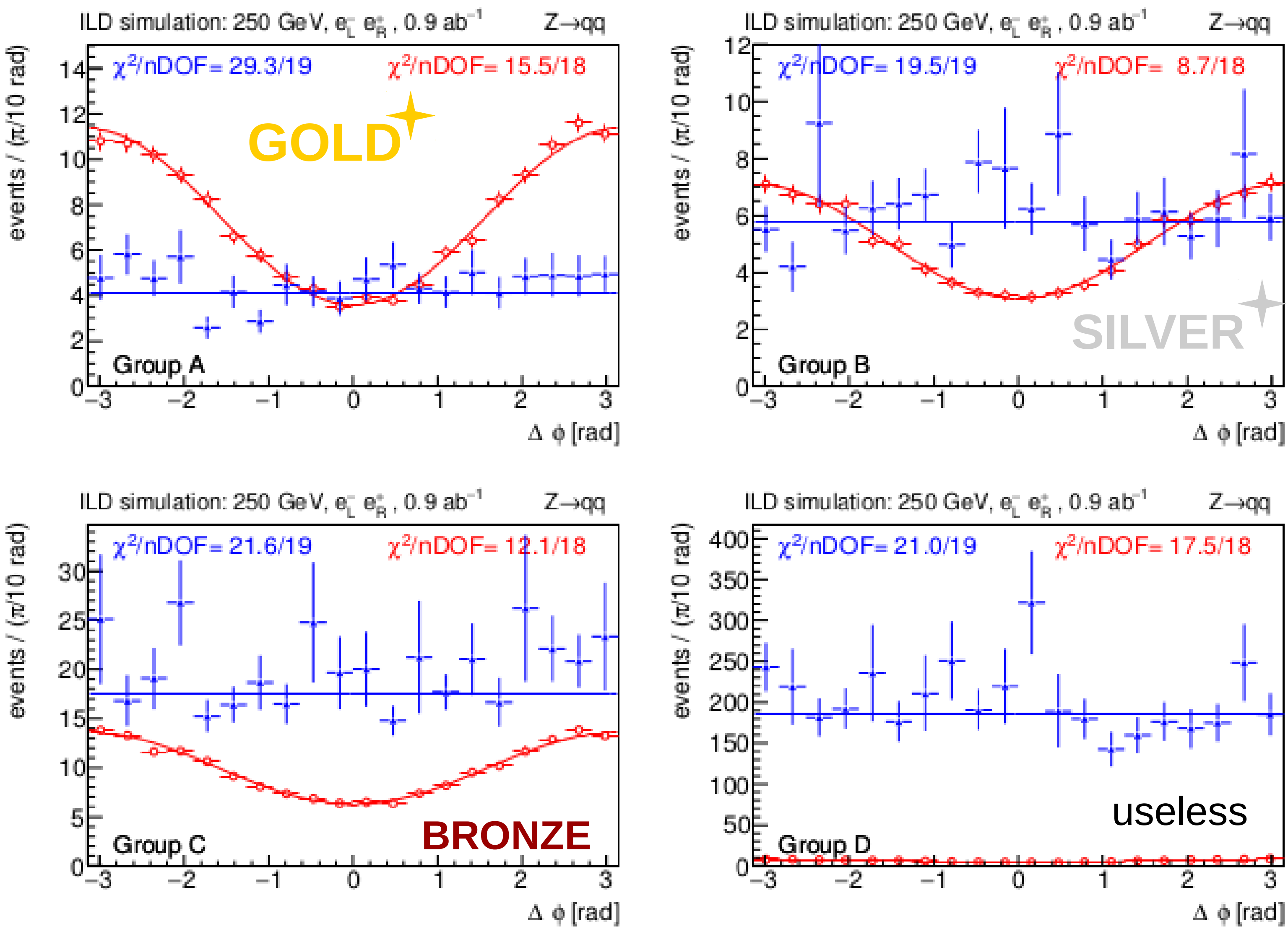


FIG. 8. The color scale shows the signal purity in 4×4 bins of Neural Network outputs, in the muon and hadronic selection channels.

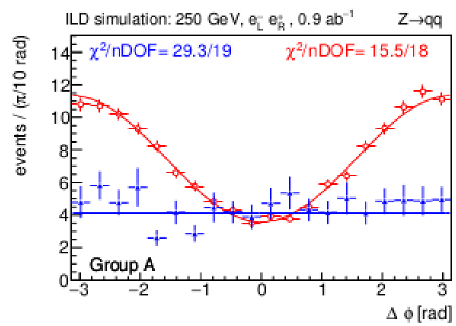
CP sensitive observable Δφ in different event sensitivity bins

signal background

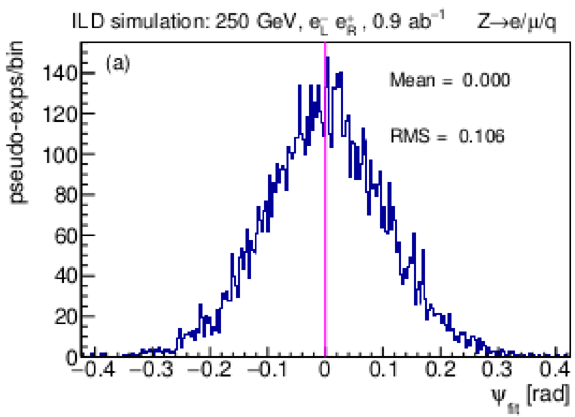


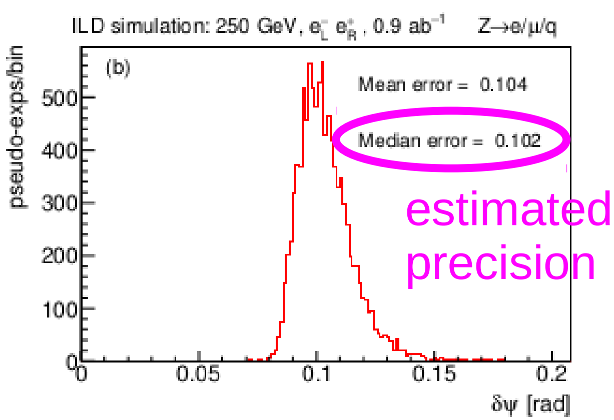
use fitted functions to run pseudo-experiments unbinned maximum likelihood fit simultaneously in all purity bins and selection channels

extract single parameter, the phase of Δφ distribution



results of 10k pseudo-exps





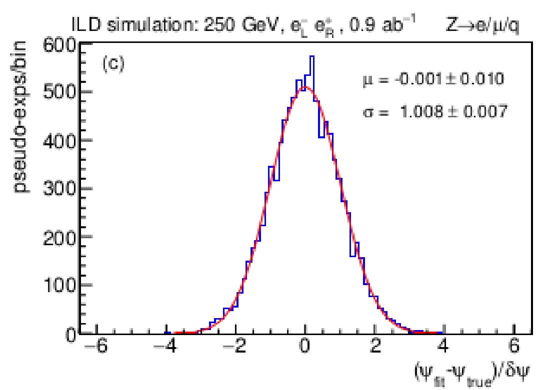
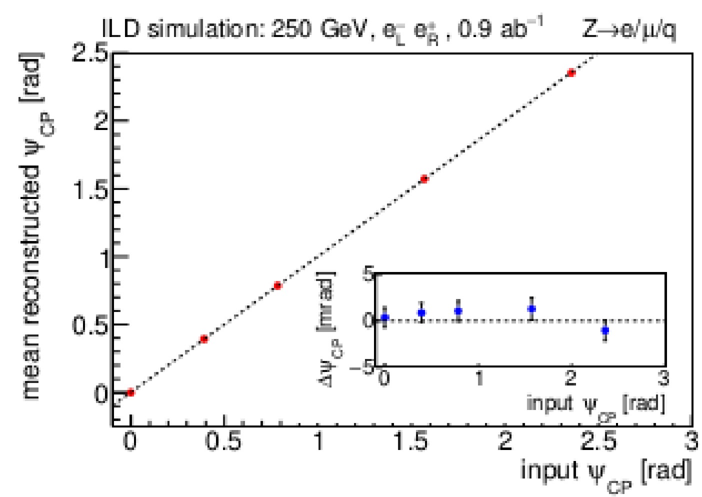


TABLE IV. Estimated experimental precision $\delta\psi_{CP}$ on the CP phase in different scenarios.

$\int\mathcal{L}$ [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	σ_{ZH} + 20%	104
1.0	0	0	σ_{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



timeline

~ 2011 started thinking about it

2014 ~ 2015 working on tau-pair reconstruction method
using impact parameters; published Feb 2016 (NIM)

Aug 2016: first paper draft to ILD refs (v1.21)
(Klaus Desch, Graham Wilson)

Sep 2016: reviewers' comments received
many on presentation
a few which prompted significant analysis improvements
(particularly from Graham)

Dec **2017**: updated version (v2.0)
significant changes to analysis
significant rewrite of several sections

Jan/Mar 2018: comments received from ILD reviewers
mostly regarding presentation

Mar 2018: updated version (v2.1)
ILD-wide review 8→23 March)

Comments from Aharon Levy, Jan Timmermans
regarding presentation → updated draft (v2.2a)

2 April: author opt-in period ends

I hope this keeps the record for longest
ILD paper-writing process for many years!

Authorship

no requests to opt-in to author list

due to the analysis improvements which his comments prompted, I asked Graham to be a co-author: he accepted.

I plan to submit to PRD

Thanks to:
- those who followed and commented on
  the analysis at various stages
- those who read the circulated draft,
- internal reviewers Graham and Klaus.