Measuring CP in H → $\tau^+\tau^-$ at ILC

status update: all results preliminary

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Motivation

Is the 125 GeV Higgs a CP eigenstate ?

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

pure CP even: $\psi_{CP} = 0$

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

Does the Higgs sector provide the additional CP violation needed to explain our universe's baryon – anti-baryon asymmetry ?

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 $\psi_{CP} = 0$

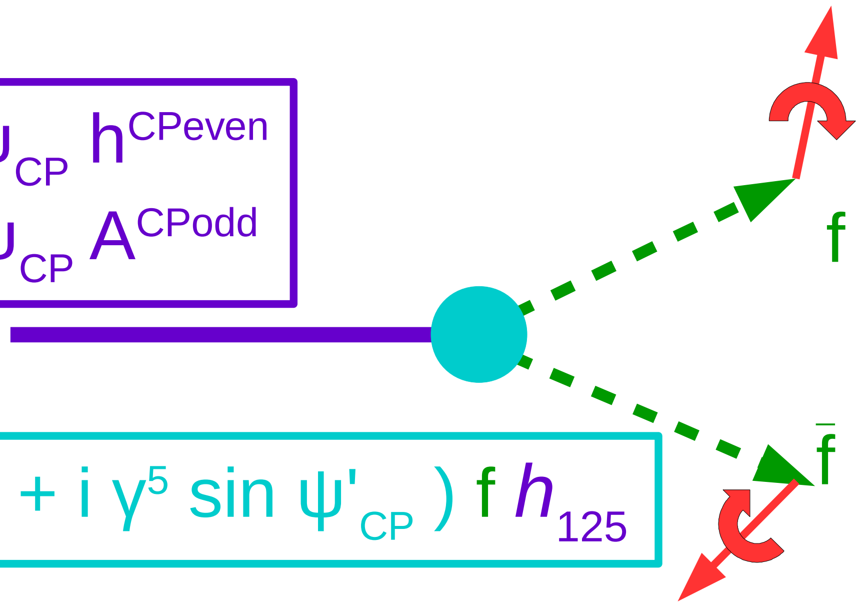
maximally violating $\psi_{CP} = \pi/2$

How to measure CP

for h → fermions

CP affects correlations between polarisation of *h* daughters

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



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

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]

To reconstruct spins of *h* daughters, they must be unstable

kinematics of of *h* grand-daughters →
polarisation of *h* daughters →
CP of *higgs* and couplings

h → bosons a bit more complicated
CP violating coupling only via loops

Higgs branching ratios (predicted @ m_H = 125 GeV)

b b	58 %
W W	21 %
g g	8.2 %
τ τ	6.3 %
c c	2.9 %
Z Z	2.6 %

final state QCD interactions:
diluted spin correlations

best for bosons

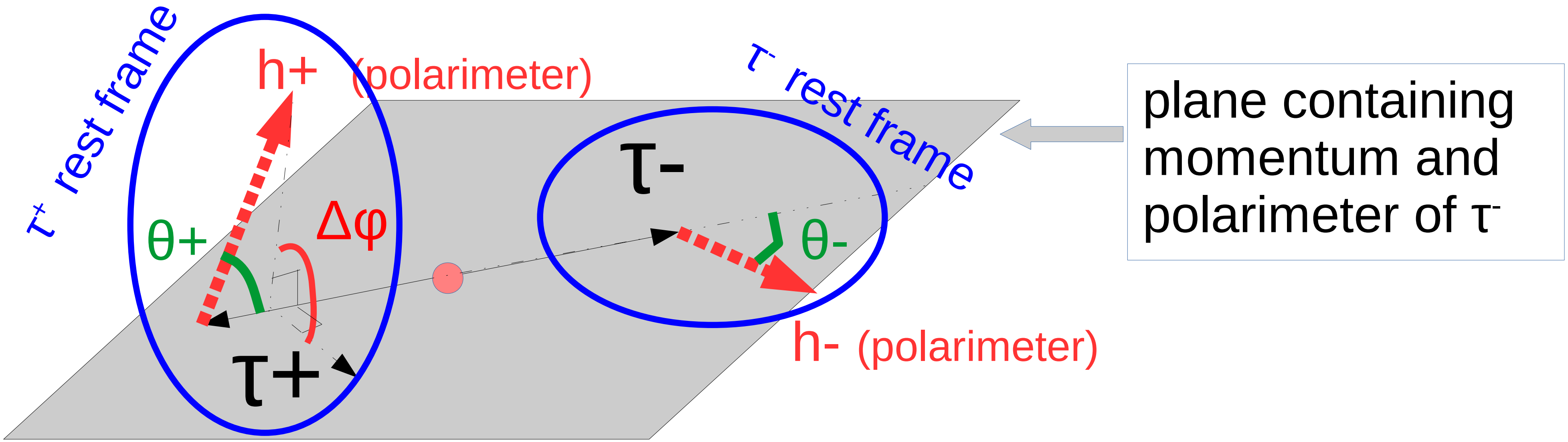
best for fermions
- decays in detector
- no QCD between taus

Measurement of tau polarisation

tau polarisation affects distribution of final state particles
optimal estimator is **polarimeter** vector
straight forward to calculate for $\tau \rightarrow \rho\nu$ [26%]
and $\tau \rightarrow \pi\nu$ [11%]

→ can (easily) get full polarisation information in
$(37\%)^2$ ~14% of H → τ τ decays

CP from polarimeters : taus from spin 0 parent



θ±, φ±	direction of h± with respect to τ- boost in τ± rest frame
Δφ	angle between polarimeter planes
ψ_{CP}	CP mixing angle we want to measure

distribution of events in polarimeter space:

$$dN/(d\cos\theta^+ d\cos\theta^- d\phi^+ d\phi^-) \propto (1+\cos\theta^+\cos\theta^-) - \sin\theta^+\sin\theta^- \cos(\Delta\phi - 2\psi_{\mathrm{CP}}).$$

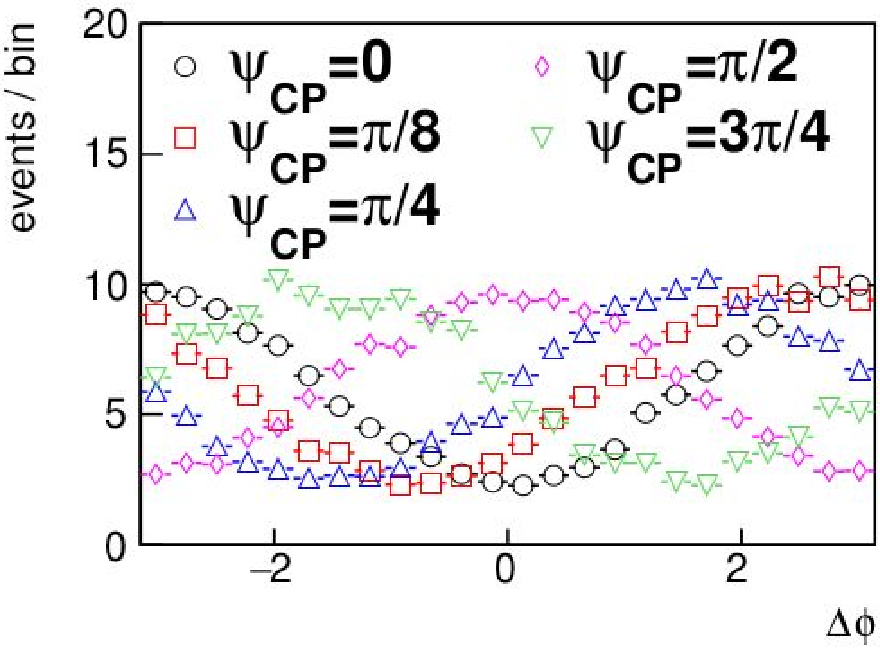
→ Δφ distribution sensitive to ψ_{CP} → **transverse spin components**

→ events with large contrast c = $\sin\theta^+ \sin\theta^- /(1 + \cos\theta^+ \cos\theta^-)$
event sensitivity depends on longitudinal spin components

Event distribution in Δφ and contrast

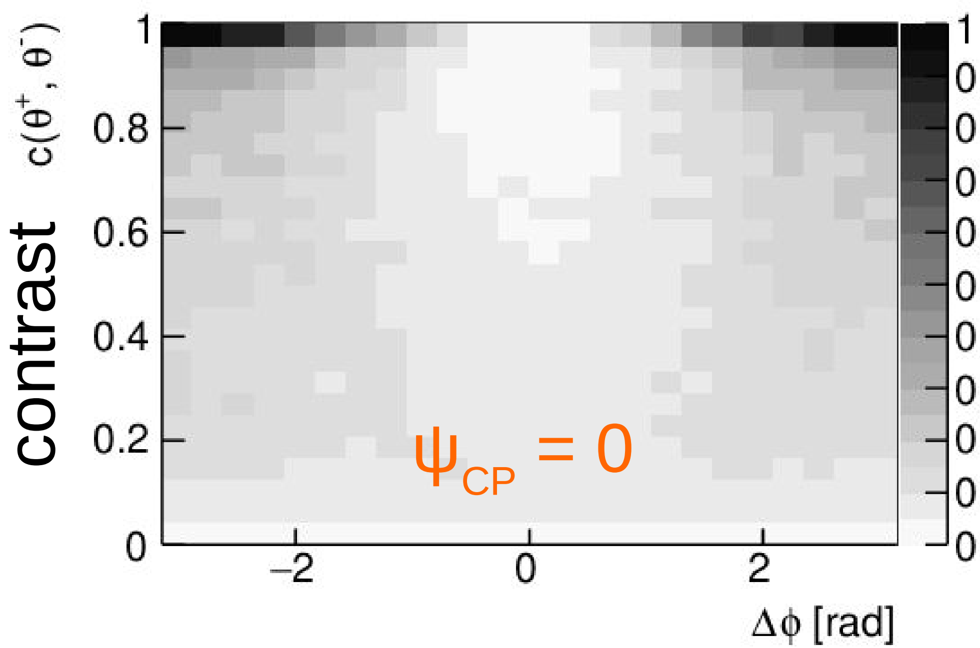
H(125) signal only, MC level

Δφ at different ψ_{CP}



Δφ distribution shifts by $2\psi_{CP}$

Δφ vs. contrast



variation stronger at large c

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

to extract ψ_{CP} , measure phase of Δφ distribution

Full tau reconstruction

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

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[+ solve two-fold ambiguities from quadratic constraints using tau lifetime]

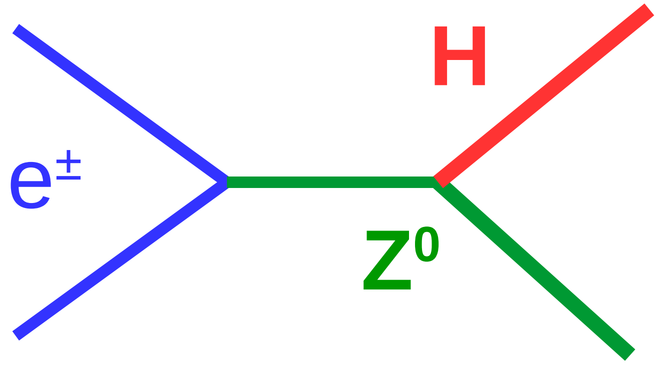
Higgs production at ILC

electron-positron collisions 250 → 500 GeV

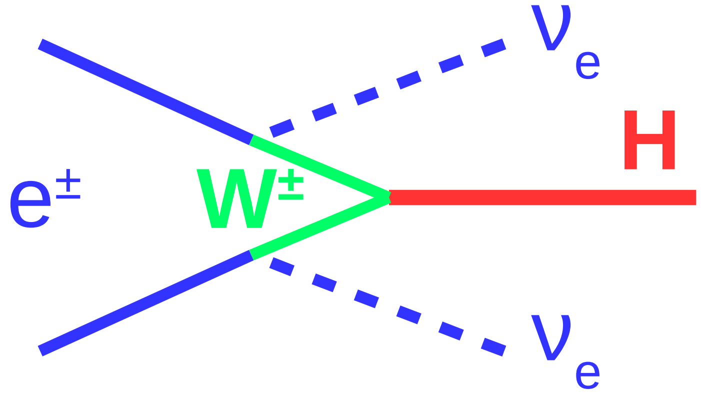
with beam polarisation

major Higgs production processes at ILC

“Higgs-strahlung”



“WW fusion”



dominant at

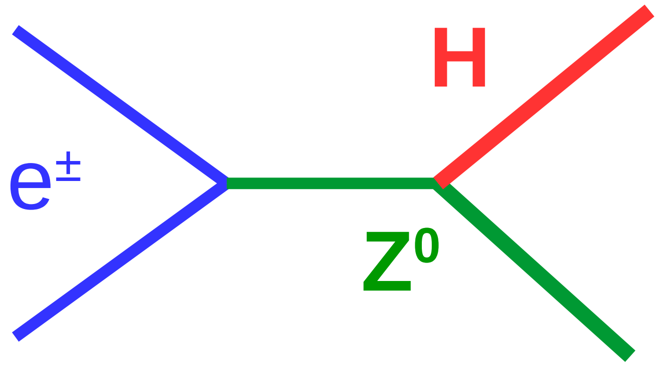
250 GeV

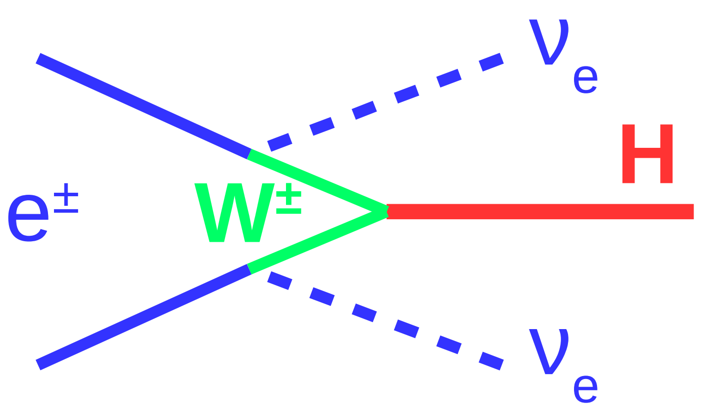
500 GeV

Full tau reconstruction

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

in hadronic tau decays (# neutrino = 1), if we precisely know
the tau **production vertex**,
the **impact parameters** of charged tau decay products,
the **p_T** of the tau-tau system,





use visible Z decay products to estimate
- **τ production vertex**
- **p_T of τ-τ system**

cannot estimate
p_T or production vertex
(some information from
small ILC interaction region)

Implementation of analysis

using full **simulation** and **reconstruction** of events

in the International Large Detector

at the International Linear Collider

assume 2 ab^{-1} of 250 GeV collision data,

shared among various beam polarisation scenarios "H20"

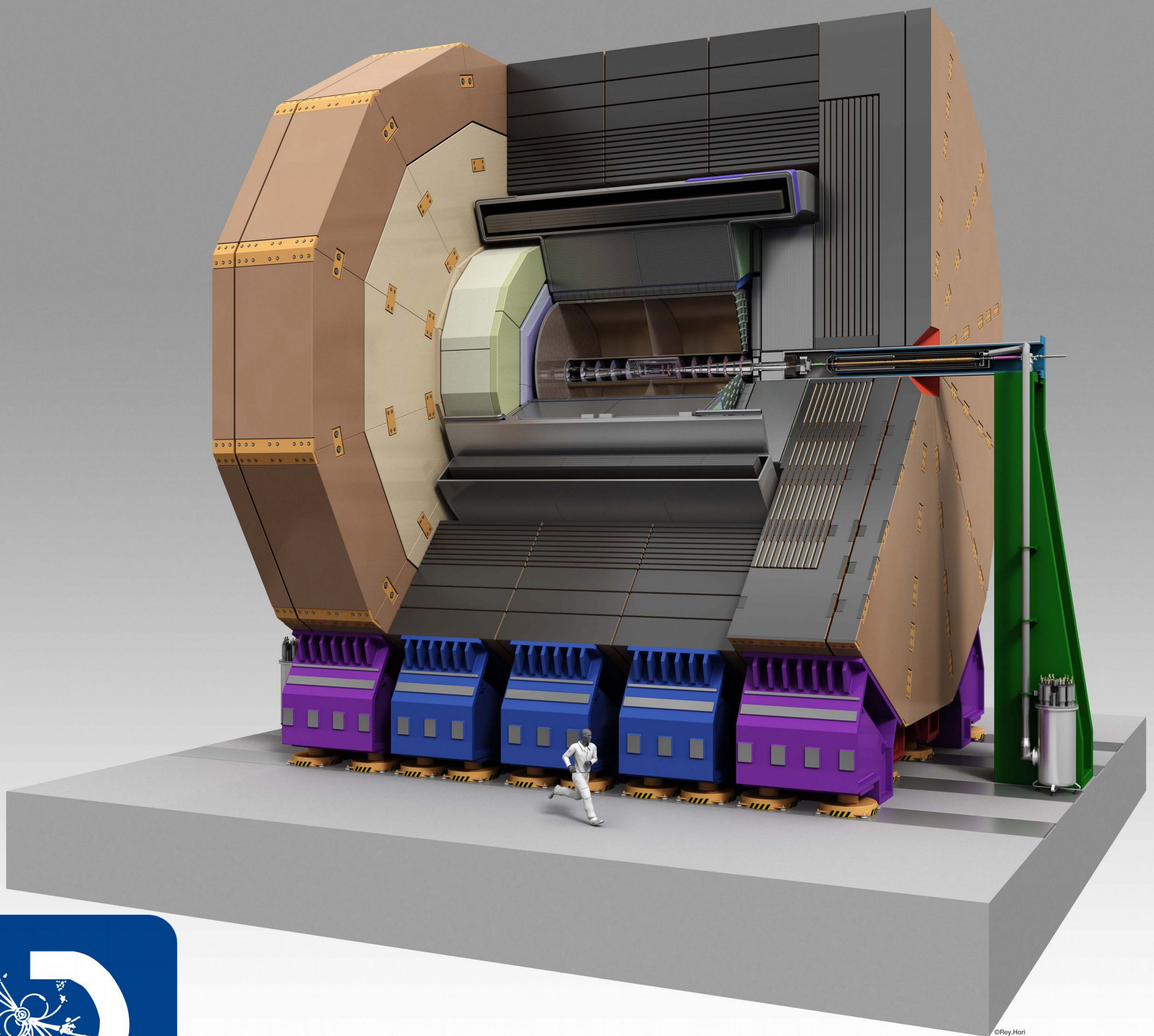
consider irreducible backgrounds,

some (but not all) irreducible backgrounds

Technical details

event generation	Whizard 2.2.8
hadronisation, FSR, tau decays	Pythia v8.212
simulation and reconstruction	ilcsoft v01-17-04
detector model	ILD_o1_v05 (DBD model)

preliminary results



ILD

Event selection

rather simple to avoid biases

Z → electrons, muons

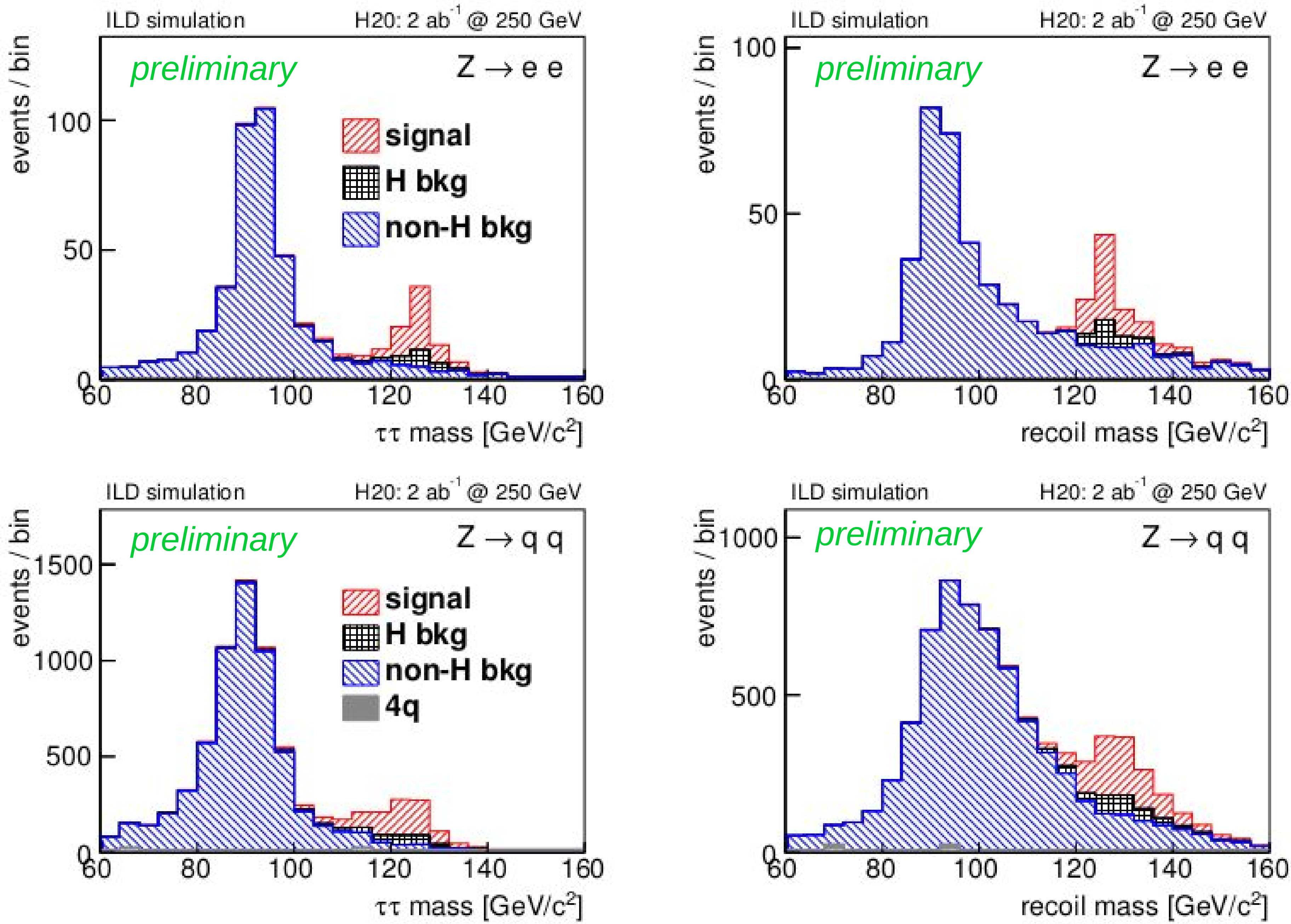
1. identify leptonic Z decay candidates
2. search for single prong tau jets
   - hadron tracks isolated from other charged tracks
   - add nearby photons
3. require that tau jets consistent with $\tau \to \rho\nu$ or $\tau \to \pi\nu$

Z → hadrons

1. identify single prong tau jets
   - hadron tracks isolated from other charged tracks
   - add nearby photons
2. require that tau jets consistent with $\tau \to \rho\nu$ or $\tau \to \pi\nu$
3. assign remainder of event to Z decay

4. use Z decay products to measure **primary vertex**
5. reconstruct **tau momenta** using impact parameter, p_T constraints
6. reject backgrounds → cut on tau energies, di-tau invariant mass, mass recoiling against the Z
7. reconstruct **polarimeter** vectors, **CP-sensitive observables**

Some reconstructed quantities



Selection efficiencies, expected events

H20: 2 ab^{-1} @ 250 GeV	$Z \to e^+e^-$	$Z \to \mu^+\mu^-$	$Z \to q\bar{q}$
signal selection efficiency	33 %	42 %	25 %
selected signal events	50	62	747
selected Higgs background events	16	24	224
selected non–Higgs background events	22	21	362
reconstructed signal contrast	0.45	0.45	0.42

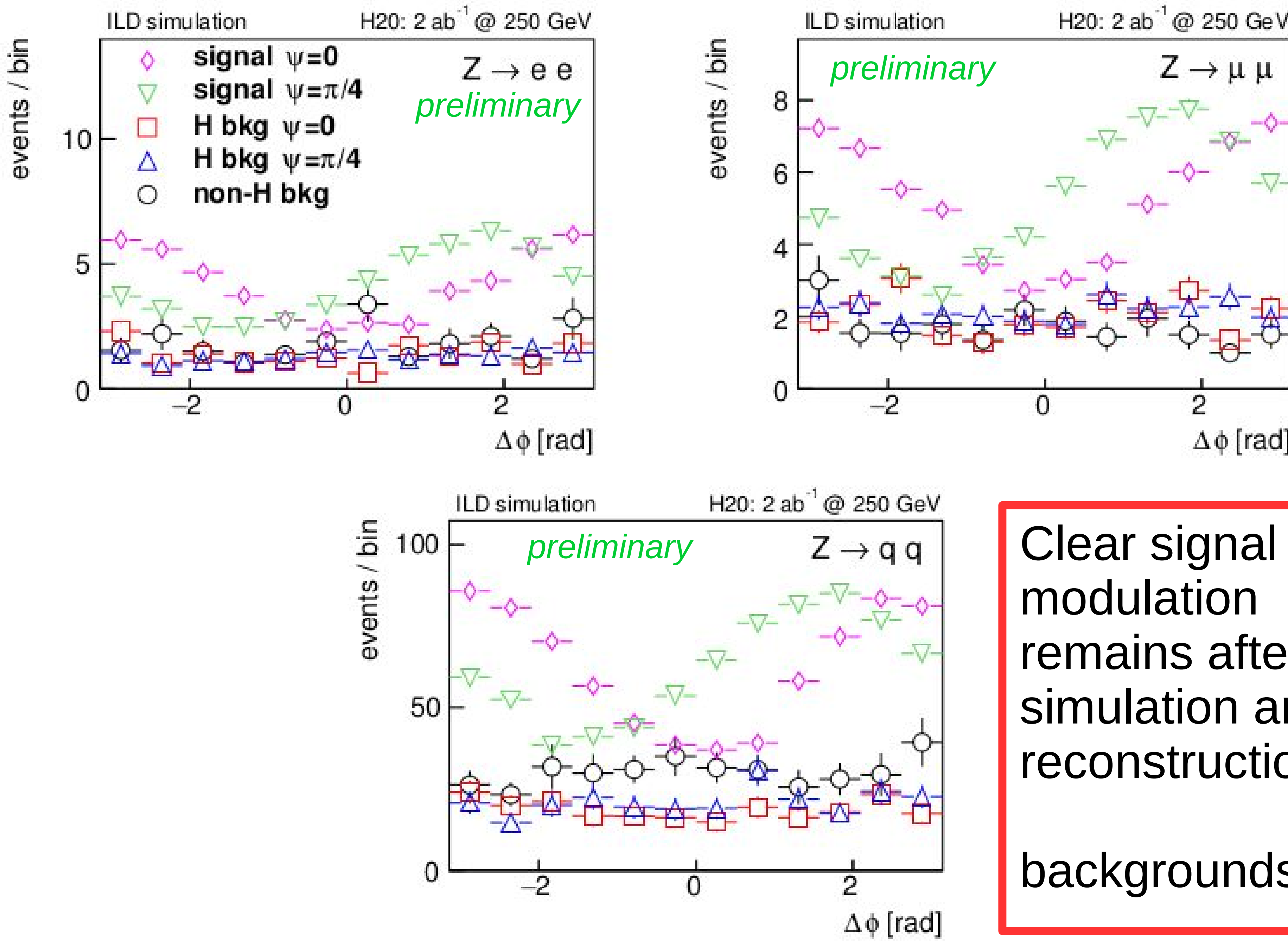
preliminary

simple cut-based selection:
avoid bias on CP-sensitive observables

modest efficiencies:
keep only cleanest events

potential for future improvements via more efficient
lepton / hadron identification
tau jet finding and decay mode identification

Reconstructed Δφ distributions



Clear signal modulation remains after simulation and reconstruction

backgrounds ~flat

Extraction of ψ_{CP}

split selected events into 3x5 categories of similar sensitivity to ψ_{CP}

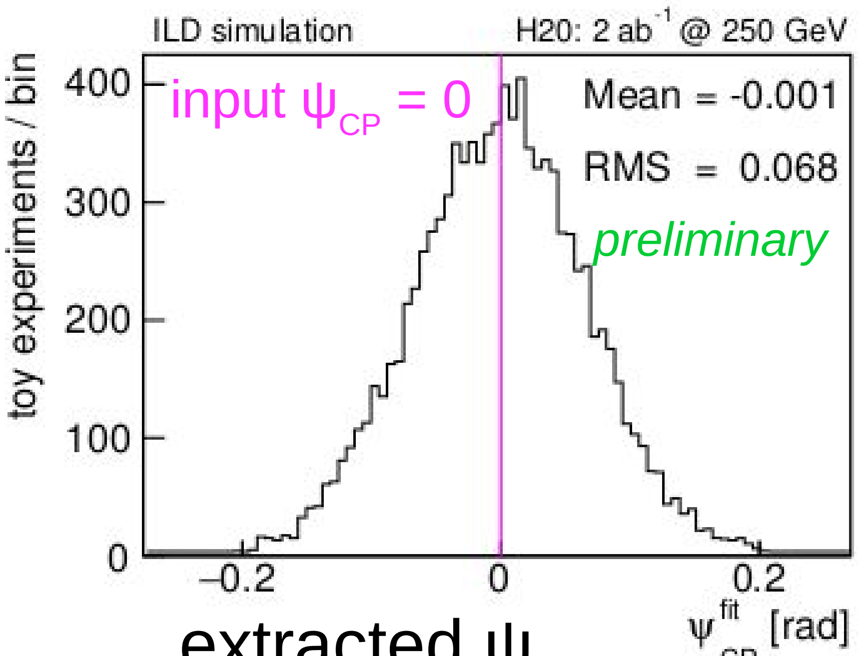
(3 – Z decay channels: electron, muon, hadrons)
X
(5 – ranges of reconstructed contrast function)

consider $\Delta\varphi$ distribution in each category
– expected reconstructed contrast for sum of signal & background

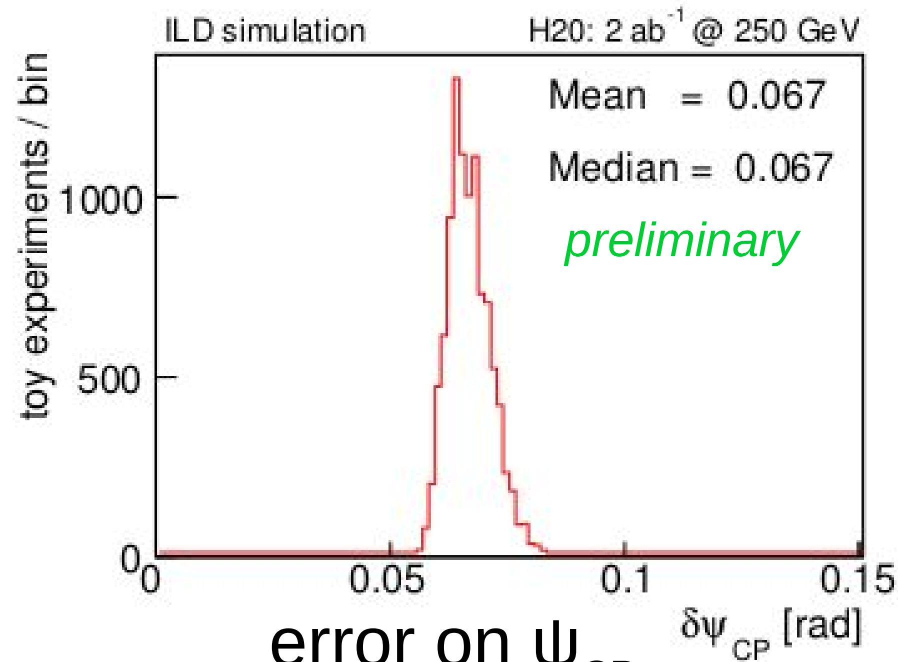
simultaneous maximum likelihood fit of
$\Delta\varphi$ distribution in all categories
– fix expected contrast in each category
– single free parameter ψ_{CP}

estimate ILC sensitivity using pseudo-experiments

Results of 10k pseudo-experiments

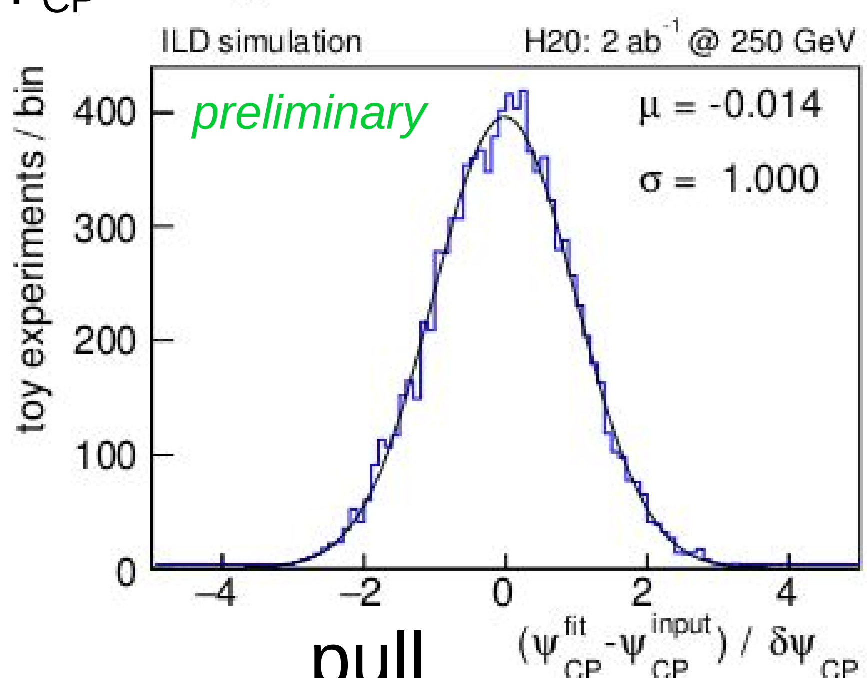


extracted ψ_{CP}



error on ψ_{CP}

preliminary



pull

2 ab^{-1} @ 250 GeV

no sign of bias

pull width = 1
→ errors reasonable

$< \delta\psi_{CP} >$ = 67 mrad
= 3.8°

preliminary

Results extrapolated to different scenarios

preliminary

full ILC: 2/ab @ 250 GeV [after 20 years]

$Z \to \mu\mu$: 220 mrad
$Z \to ee$: 246 mrad
$Z \to$ hadrons : 72 mrad ← dominates (thanks to statistics)
combined : 67 mrad

first 8 years: 0.5/ab @ 250 GeV

combined : 132 mrad

perfect [2/ab]

100 % signal efficiency, no background,
perfect $\tau \to \rho\nu$, $\pi\nu$ polarimeters: 17 mrad

Future prospects

improved reconstruction and selection:

67 mrad should get closer to 17 mrad [perfect]

include other hadronic tau decay modes

[in principle their polarimeters should have same sensitivity]

useful fraction of $H \rightarrow \tau\,\tau$ events increases 14 → 42 %

leptonic τ decay modes probably less useful

include ZH events from 500 GeV collisions

cross-section ~ 3 times smaller, $\int \mathcal{L}$ ~ 2 times larger

→ 2/3 the number of ZH events @ 250 GeV

WW-fusion process

~ same number of

WW-fusion $H \rightarrow \tau\,\tau$ events @ 500 GeV as

ZH events @ 250 GeV

needs approximate CP-sensitive observables

[which would also be applicable to HZ, $Z \rightarrow \nu\nu$]

Summary

CP of Higgs and its couplings are key properties of (B)SM

H → τ τ provides a nice system in which to probe CP

full reconstruction of tau momenta possible in $e^+e^- \rightarrow Z\,H$

developing analysis using full simulation and reconstruction
of ILD at the ILC, assuming expected data at 250 GeV
not all reducible backgrounds included so far

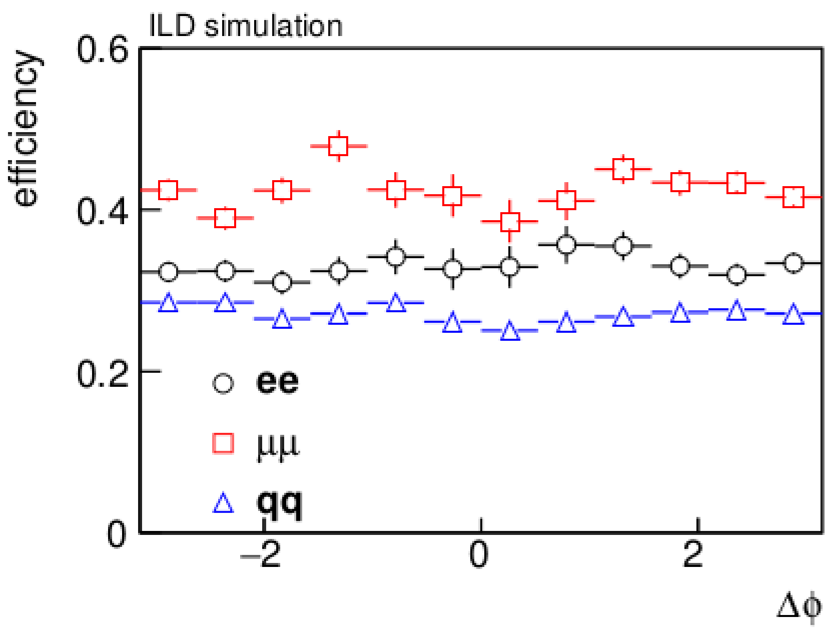
can measure mixing between odd and even CP components
of the τ τ system from Higgs with a precision of <4 degrees

this precision will be improved by:
better reconstruction of detector data; large 500 GeV dataset

similar analysis can be applied to any spin 0 → τ τ state

Backup

Efficiency vs. polarimeter properties



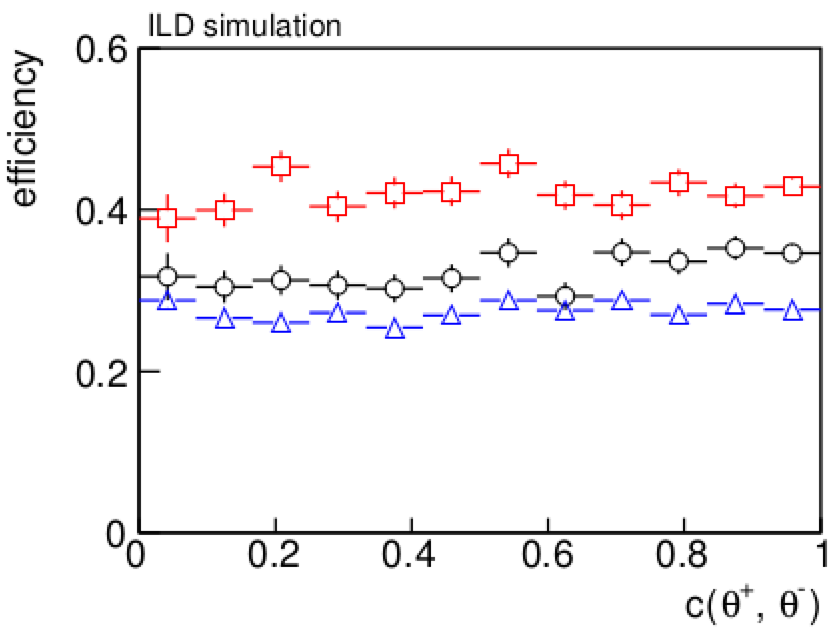


Table 2 Selection efficiencies: illustration using LR signal samples only.

	$Z \to ee$	$Z \to \mu\mu$	$Z \to uds$
preselection			
≥ 4 chg PFOs	92.9	94.1	
≥ 1 lept Z cand.	82.2	83.6	
no forward elec in Z	75.3		
≥ 8 chg PFOs			99.7
≥ 2 isol chg PFOs			96.7
≥ 1 pair opp. chg isol PFOs			90.5
no muon in tau	74.2	82.3	89.5
no elec in tau	66.2	73.9	71.8
opp chg taus	64.8	72.8	
FINAL PRESEL	64.8	72.8	71.8
full selection			
Z MASS	61.7	72.6	45.6
EXTRA ACTIVITY	56.5	70.2	
TAU DECAYS (pi or rho)	45.2	57.1	41.5
TAU-TAU FIT	40.4	50.9	37.6
<35 chg PFOS in Z			37.4
TAU ENERGY	37.4	47.6	30.2
TAU-TAU MASS	33.8	43.2	28.2
RECOIL MASS	32.9	42.4	27.4

Bias check: fit different CP samples