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

updates since ECFA-LC workshop @Santander

ILD analysis meeting, 27 July 2016

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Motivation

Higgs mass eigenstate may not be CP eigenstate

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

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

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

coupling of Higgs to fermions may violate CP

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

CP conserving coupling $\psi_{CP}=0$

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

CP of fermion pair reflected in correlation between spins

- fermion with significant BR from Higgs
- how to observe fermion spin?
  - look at decay product distribution
  - → unstable fermion
- final state affected by QCD will probably have spin
  - correlations largely washed out
- that leaves tau leptons
  - or top quarks → decay too fast for QCD to act

This analysis: taus

spin information from tau decays

tau spin **s** can be partially reconstructed from
decay product distribution

$$d\Gamma(\tau \to X) \sim (1 + a\,\mathbf{h}(X) \cdot \mathbf{s})$$

h (X) is the polarimeter vector

encodes spin-dependent part of tau decay

depends on momenta of final state particles X

easy to calculate for $\tau^\pm \to \pi^\pm \nu$ (~11% of taus)

$\pi^\pm \pi^0 \nu$ (~26%)

to do this completely,

need to reconstruct tau lepton momenta

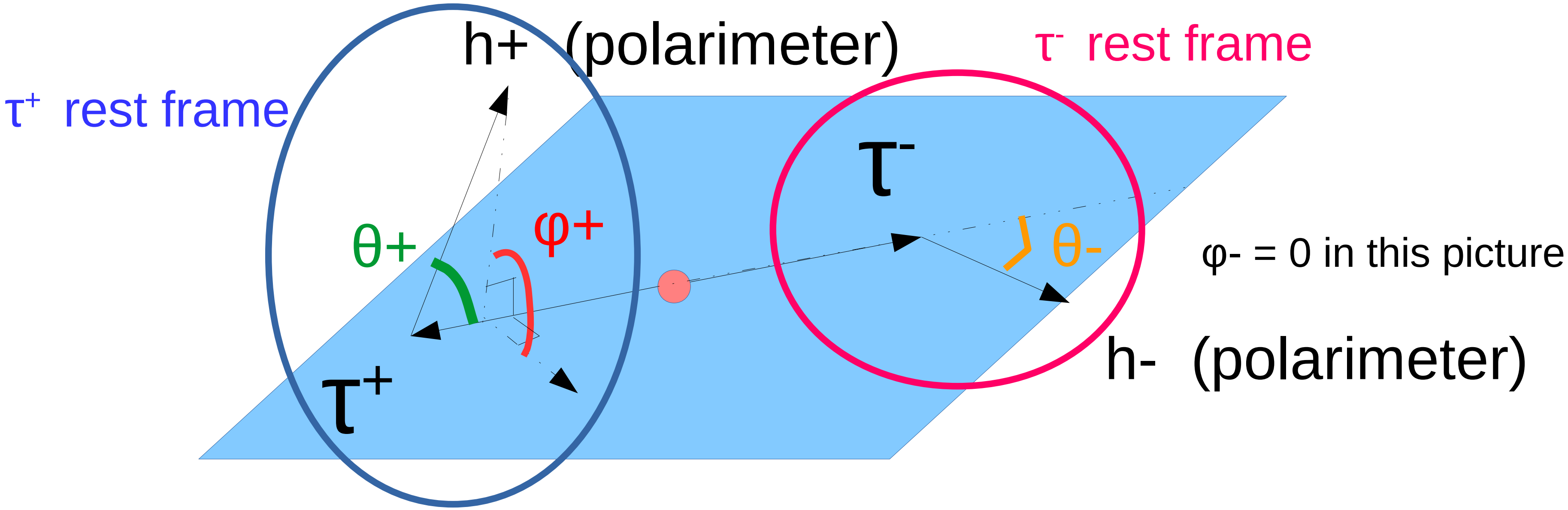
use my "impact parameter" method arXiv:1507.01700

works in Higgs-strahlung events, with $Z \to$ visible

6 unknowns: two neutrino 3-momenta

6 constraints: 2 impact parameter, 2 tau mass, 2 from event pT

CP from polarimeters : taus from spin 0 parent



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

θ, φ are direction of polarimeter w.r.t. tau- momentum in tau rest frames

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

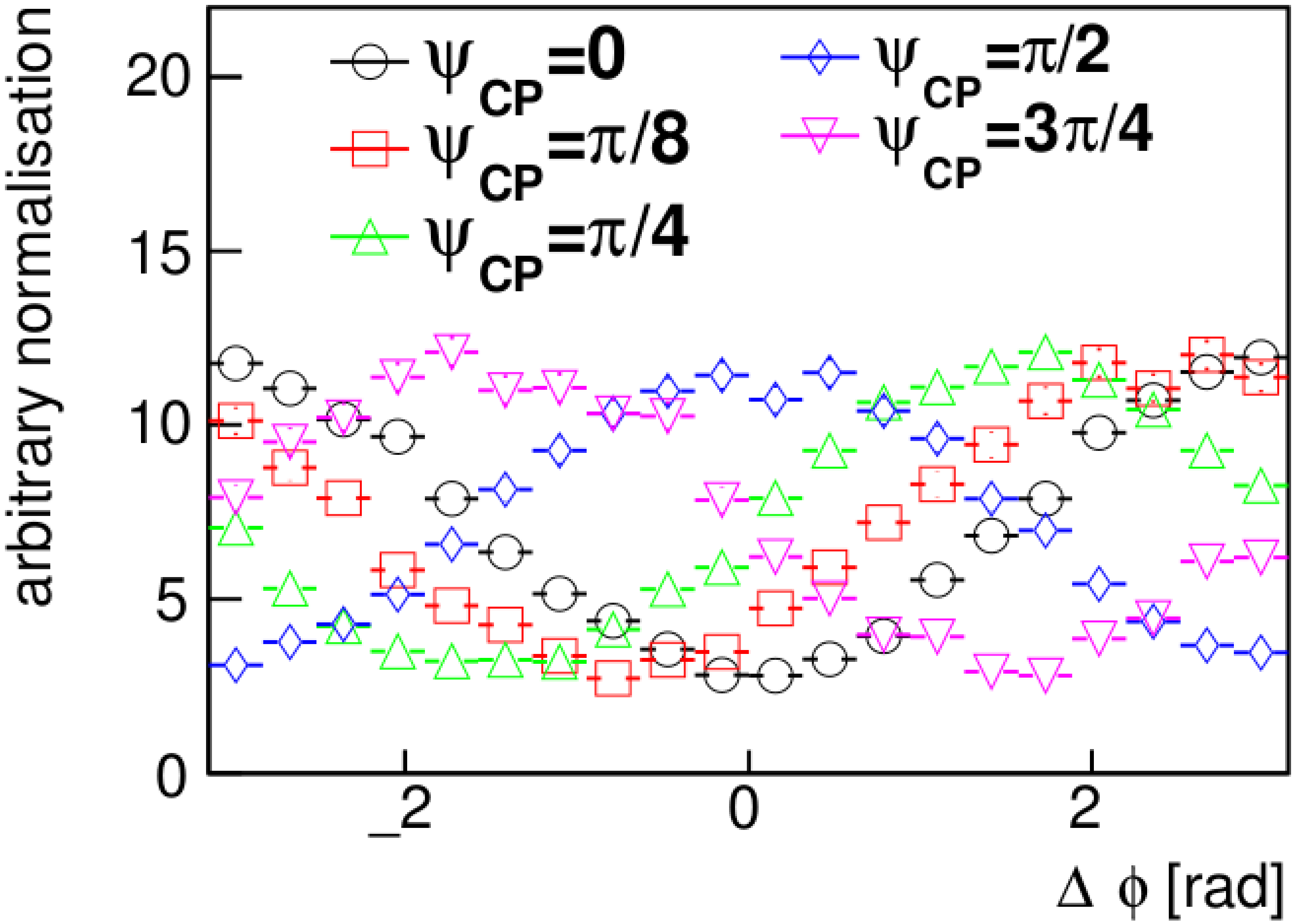
ψ_{CP} is the CP mixing angle we want to measure

Δφ distribution sensitive to ψ_{CP}

events with large ($\sin\theta^+ \sin\theta^-$) are more strongly affected by ψ_{CP}

distributions of Δφ at different ψ_{CP}

signal only, MC level



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

Full simulation & reconstruction

Whizard 2.2.8

- 250 GeV, polarised beams, CIRCE2 beam-strahlung, ISR
- e+ e- → f+f-τ+τ-   (τ+τ- from 125 GeV Higgs)
- e+ e- → f+f-τ+τ-   (τ+τ- not from Higgs)
  - f = e, μ, u, d, s, c, b   (some generator level cuts, particularly for e+e-τ+τ-)

Pythia v8.212 for hadronisation, FSR, tau decays

Mokka simulation: ILD model ILD_o1_v05

standard Marlin/ILDConfig reconstruction [ilcsoft v01-17-09]

- background overlay
- standard Pandora steering (with recent photon reco)

scale everything to H20:

- 2 ab^{-1} @ 250 GeV in various polarisation combinations

Update since Santander

FSR issues:

previously used PYTHIA for FSR, TAUOLA for tau decays

one of my samples (ZH, Z-> mu mu) had no FSR from taus
→ too optimistic

when FSR *was* applied to taus in the other samples,
problem with my interface between PYTHIA and TAUOLA
any FSR from tau removed spin correlations
(tau no longer tagged as coming from Higgs decay)
→ too pessimistic

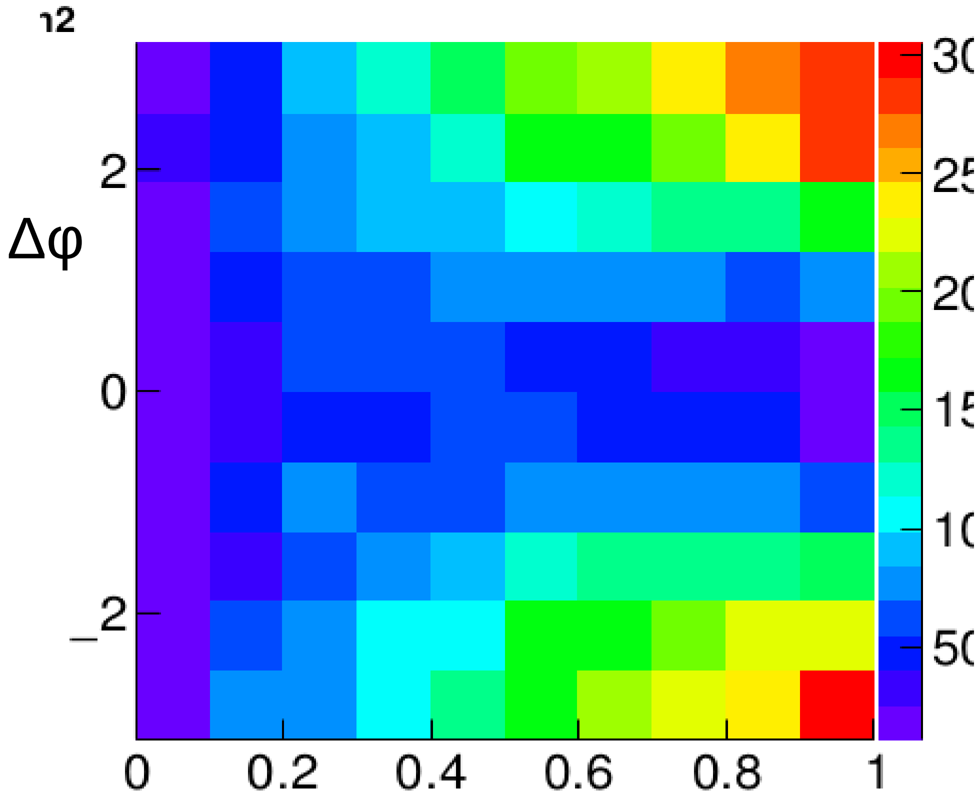
now do everything in PYTHIA
correlated tau decays included in PYTHIA since v8.150

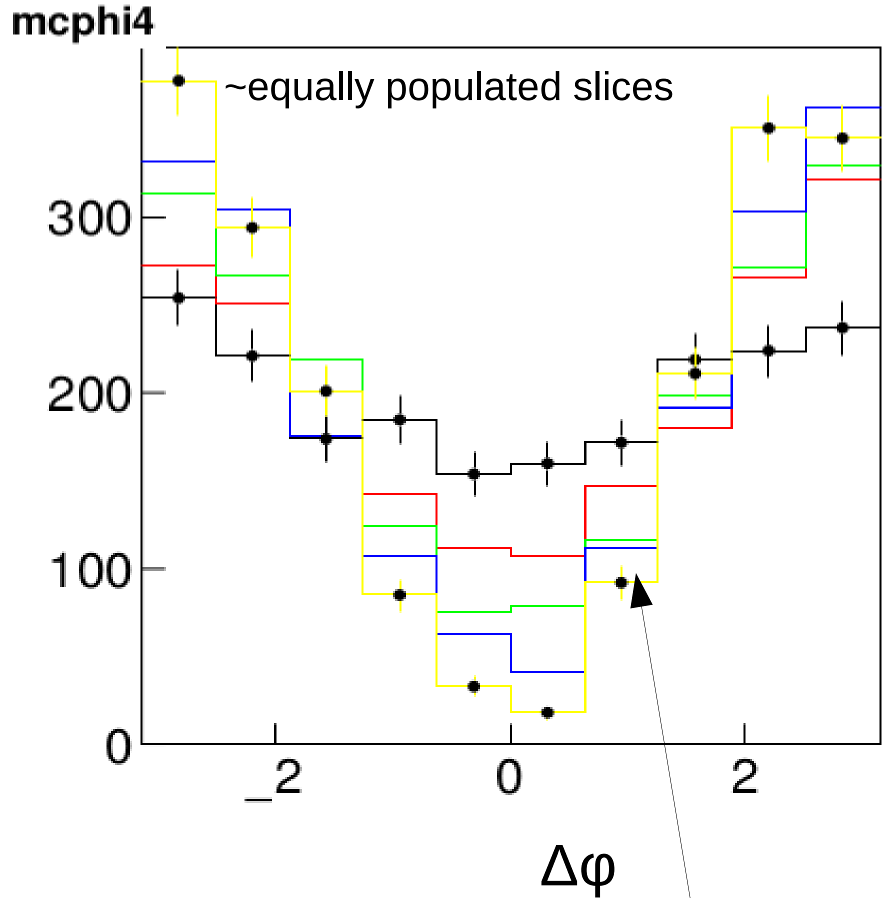
now also include Z decays to cc, bb

$\Delta\varphi$ vs. $\sin\theta^+ \sin\theta^-$

signal only, MC truth

different colours =
different ranges of $\sin\theta^+ \sin\theta^-$





$\sin\theta^+ \sin\theta^-$

one or both polarimeters along tau momentum

both polarimeters perpendicular to tau momentum

we want to measure phase of this modulation

Update since Santander

previously integrated over sin θ^+ sin θ^-

now slice events according to sin θ^+ sin θ^-

→ improves statistical precision

previously quoted error on phase of $\Delta\varphi$ distribution

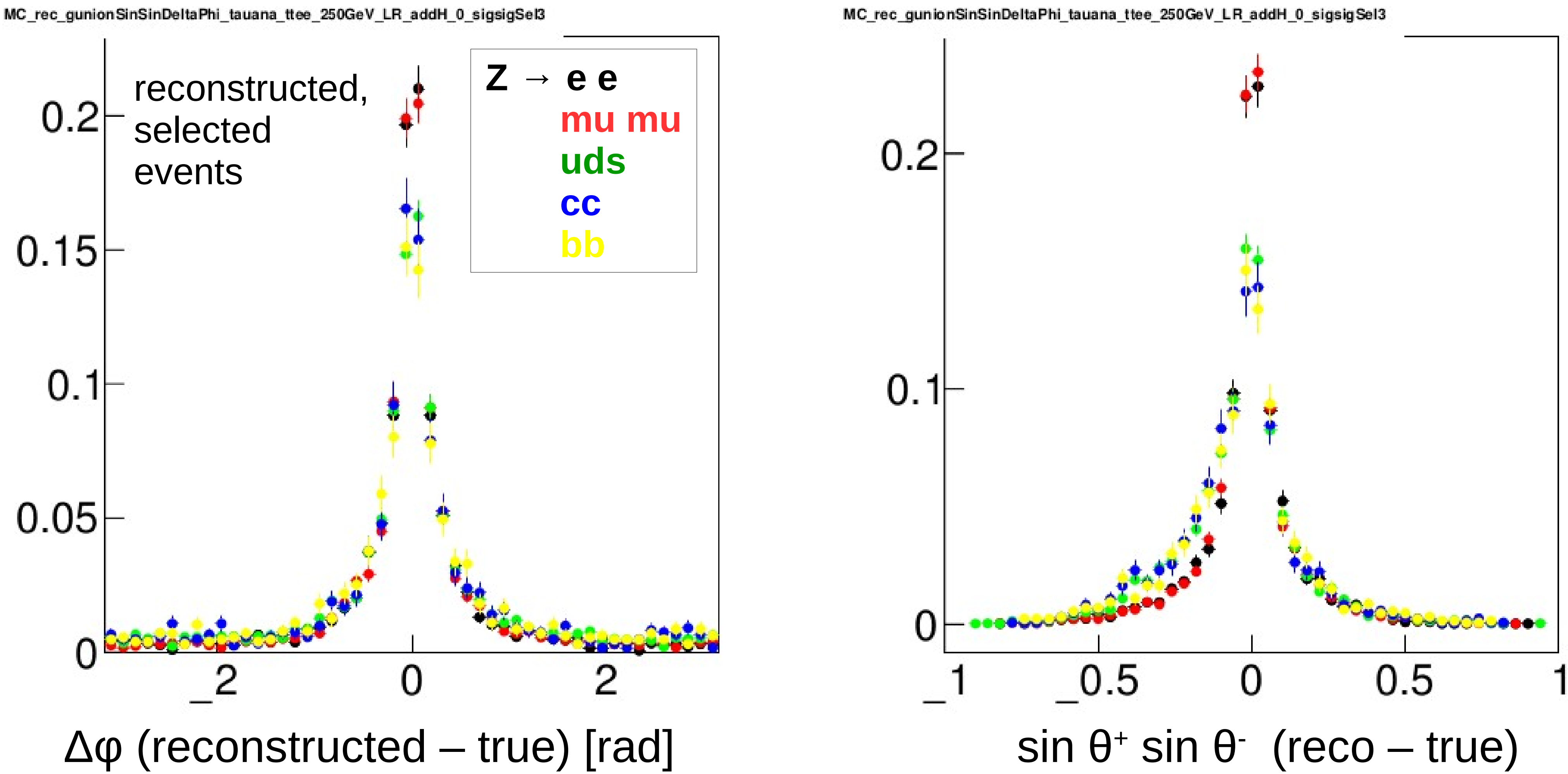
→ this corresponds to $2\psi_{CP}$

now quote error on ψ_{CP}

→ "gain" a factor 2

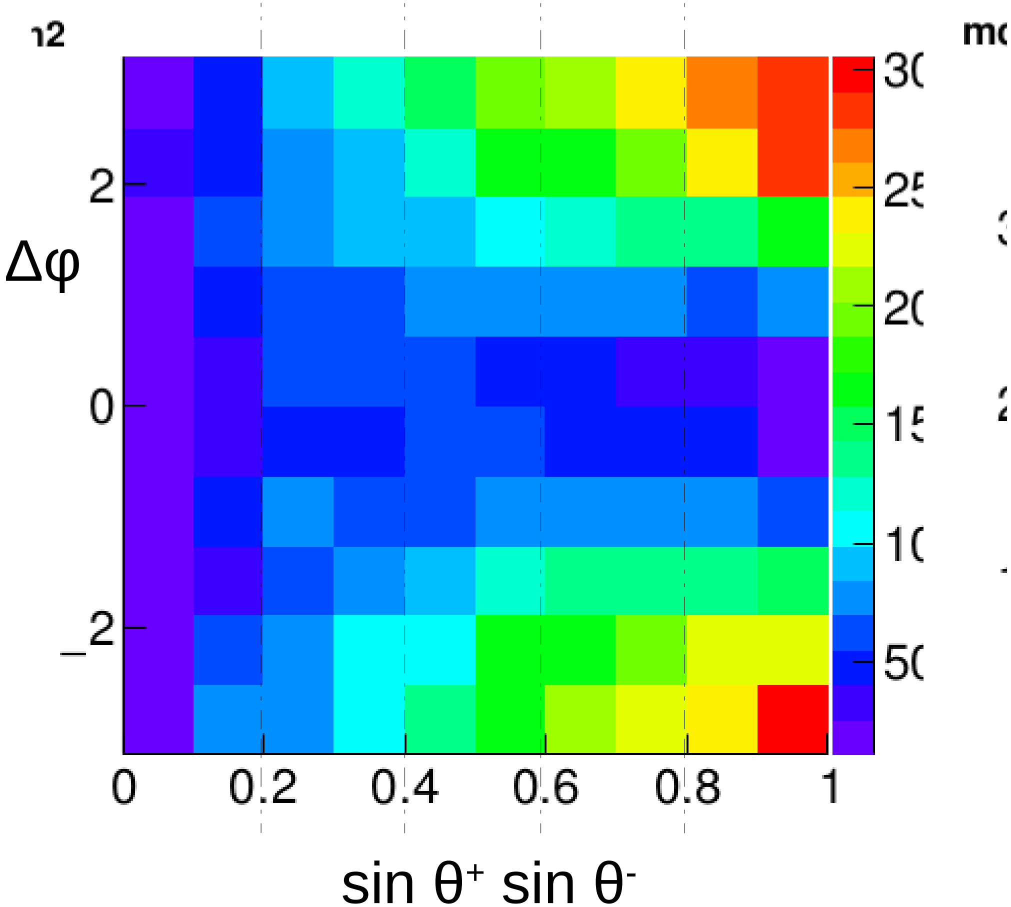
→ consistent with other studies

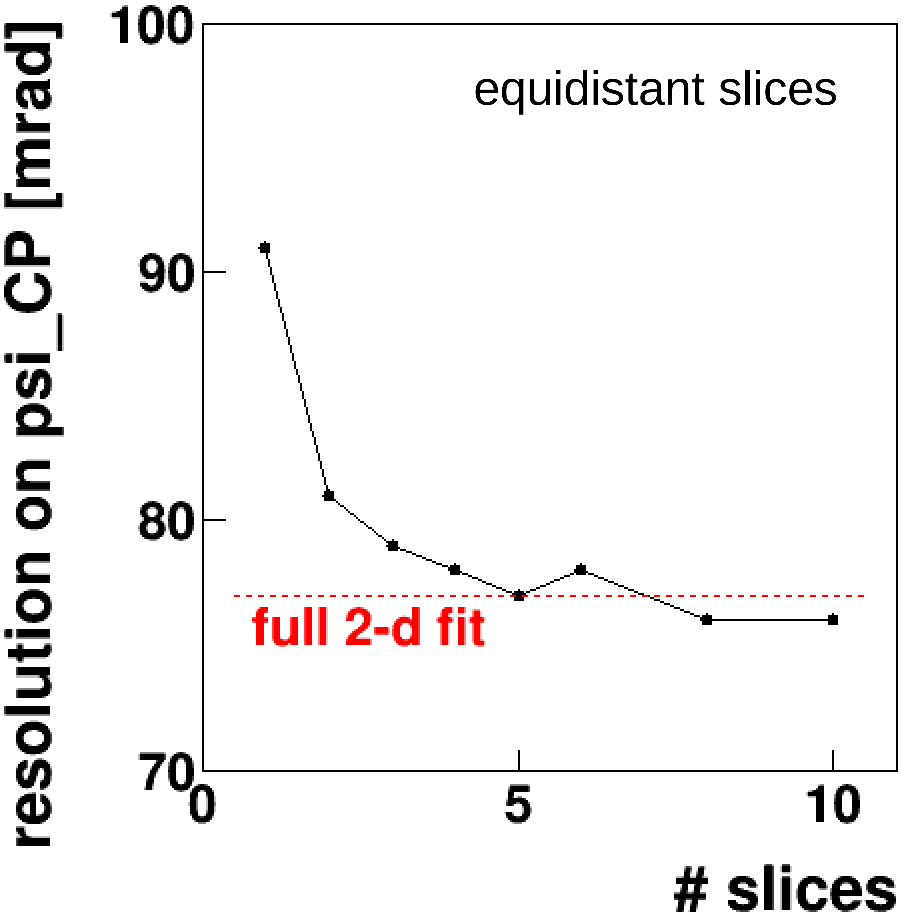
resolution on the two important observables



resolution slightly better for leptonic Z decays
no bias in $\Delta\varphi$
for hadronic Z decays, small bias in $\sin\theta^+ \sin\theta^-$
not so important, used only for binning of events

how finely do we have to slice in sin θ⁺ sin θ⁻ ?





5 slices looks sufficient:

- no significant gain from slicing more finely
- gives ~ same result as full 2-d fit.

Event selection

done in 3 channels according to Z decay:
ee, μμ, jets

simple cut-based selection

Update since Santander

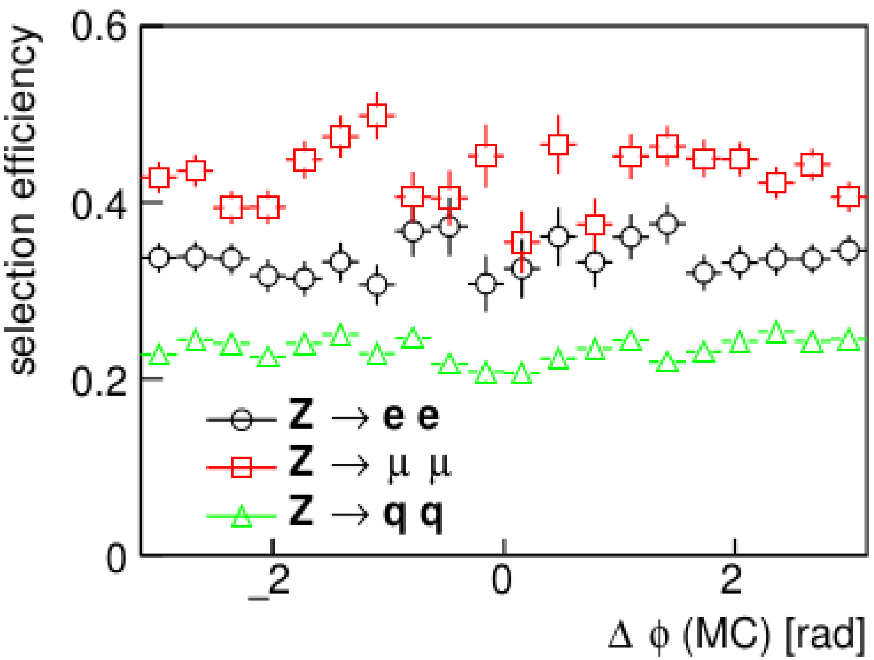
several tweaks to event reconstruction & selection

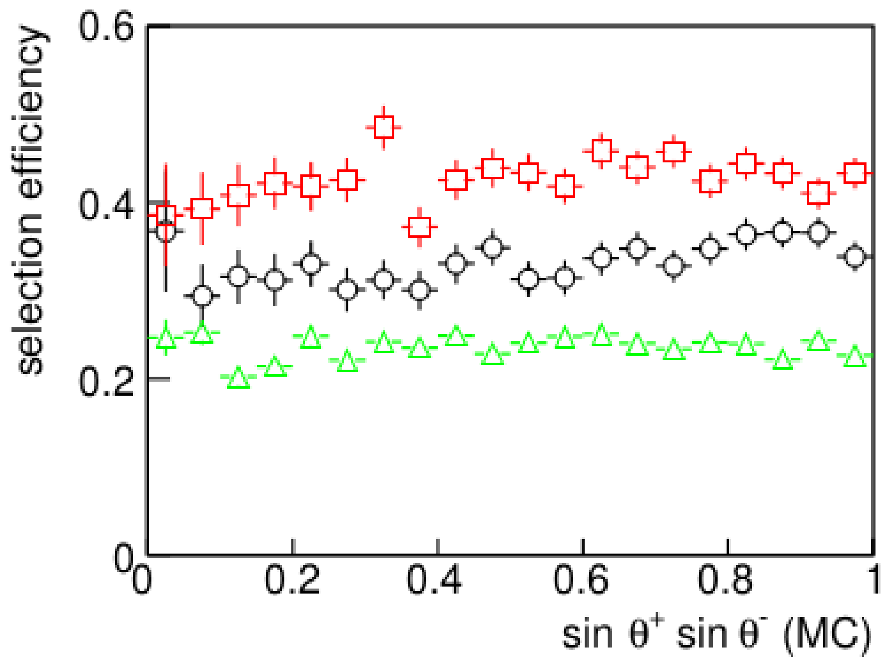
latest results:

H20: 2 ab^{-1} @ 250 GeV	$Z \rightarrow e^+e^-$	$Z \rightarrow \mu^+\mu^-$	$Z \rightarrow qq$
signal selection efficiency	33 %	43 %	22 %
selected signal events	51	63	651
selected Higgs background events	17	25	198
selected non–Higgs background events	25	22	442
reconstructed signal contrast	0.47	0.46	0.37

reconstruction and selection efficiency

dependence on true value of our two observables

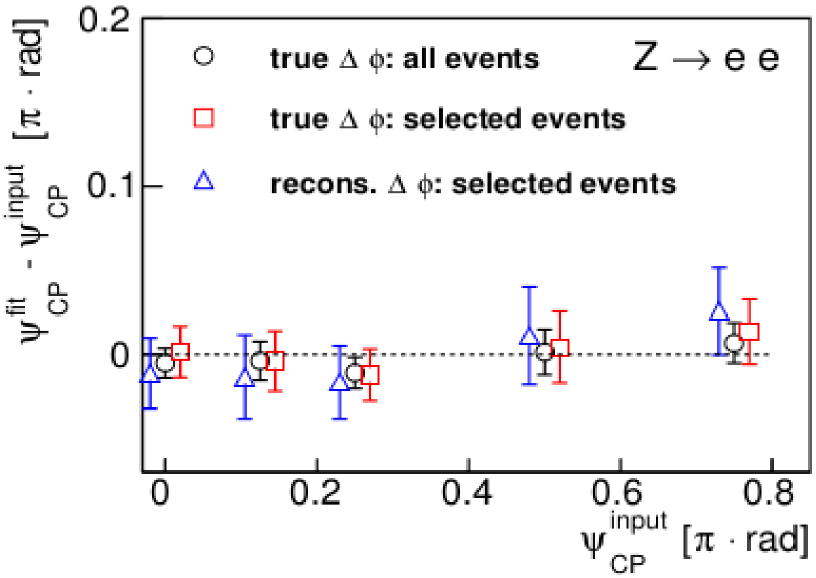


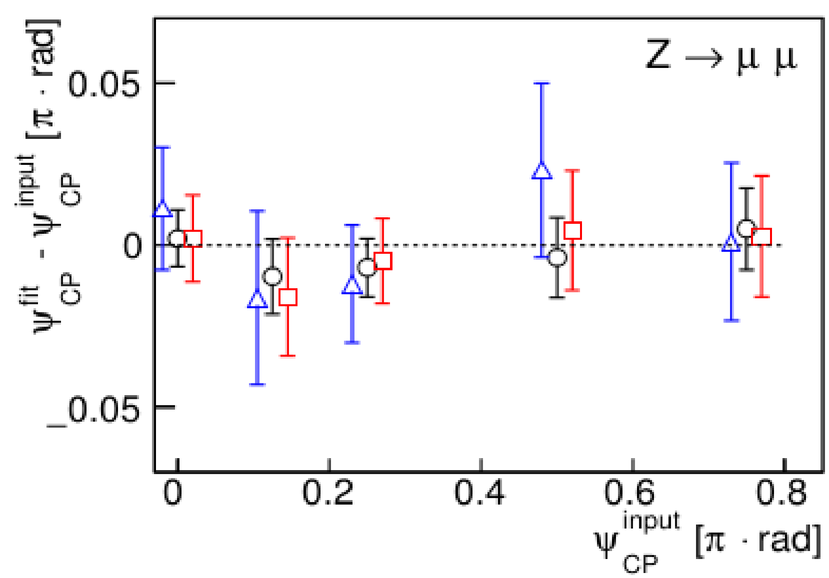


basically flat → unbiased selection

Fitting procedure: bias check

Fit large MC signal samples generated with different ψ_{CP}
compare input and extracted ψ_{CP}

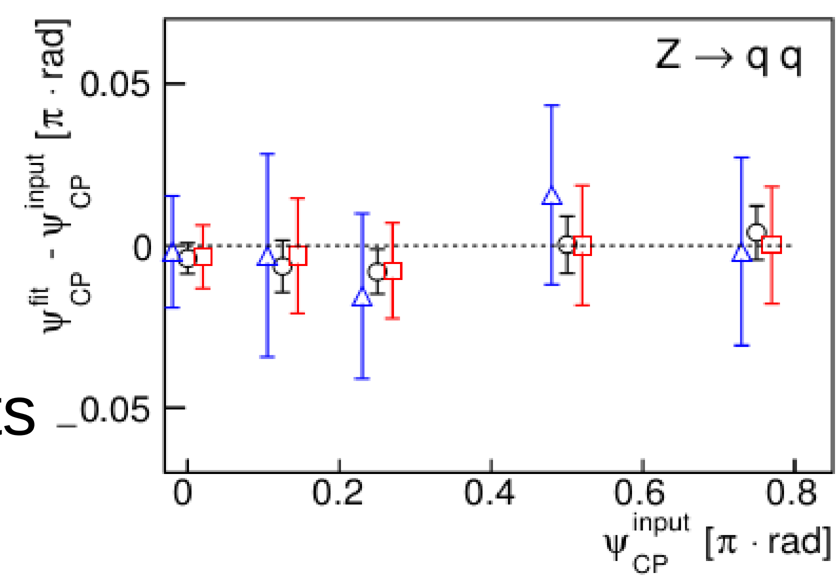




fit Δφ distributions:

- MC / full reco

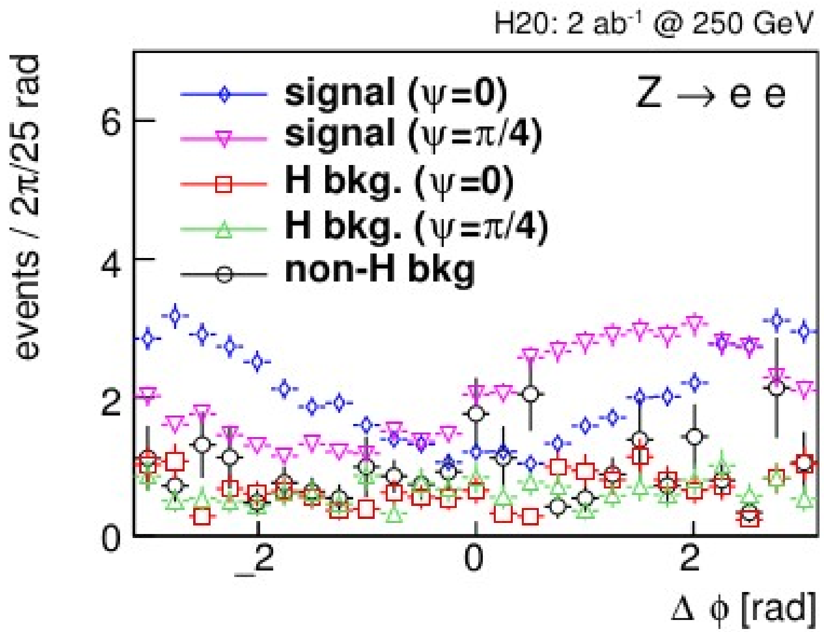
- all / selected events

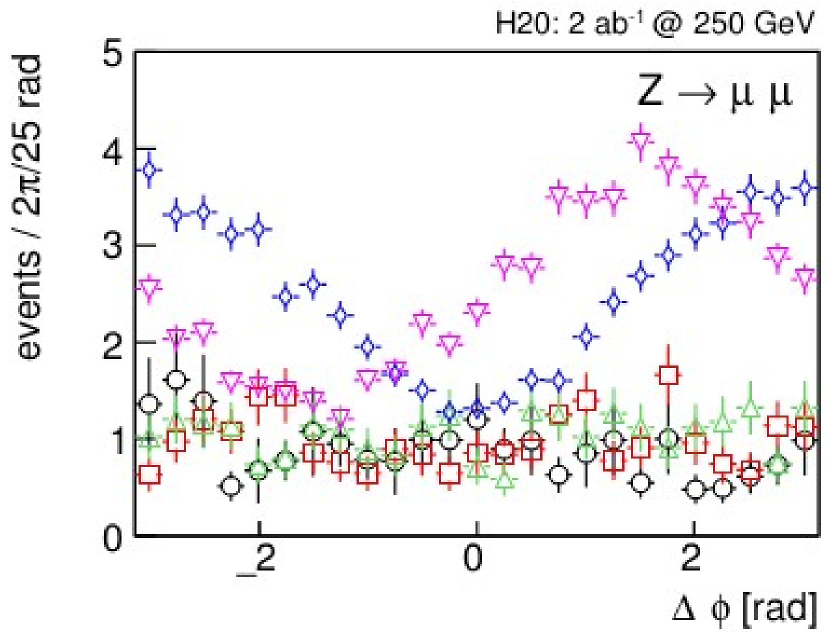


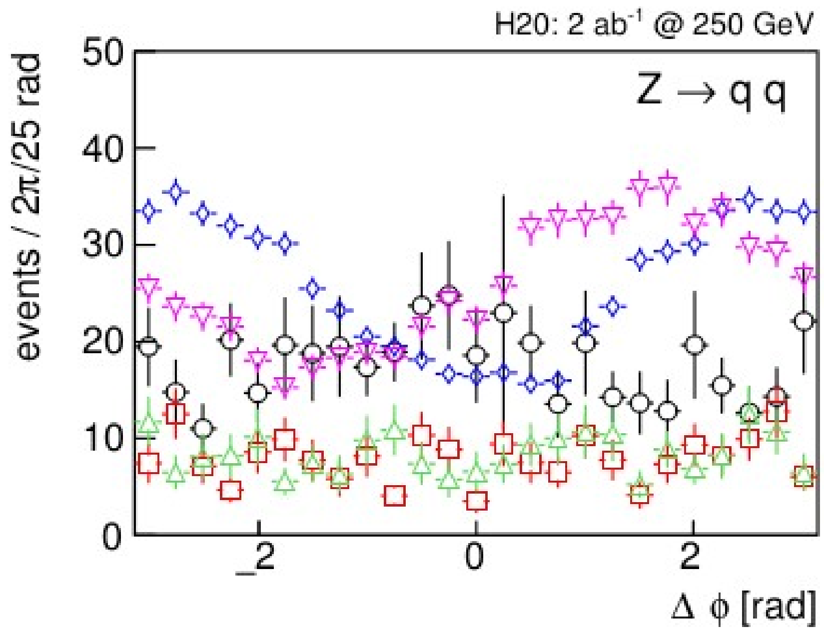
always consistent with input value:

no bias in fitting method

Signal + background, scaled to 2/ab (H20 scenario)



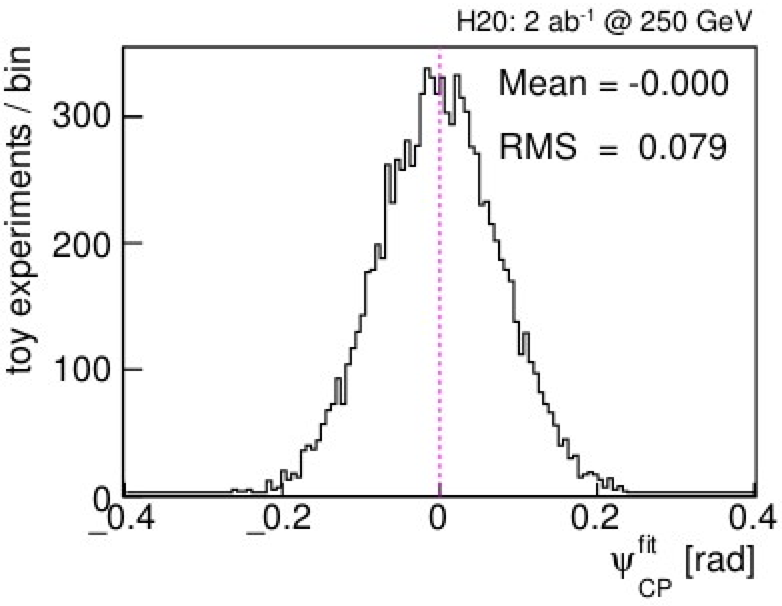


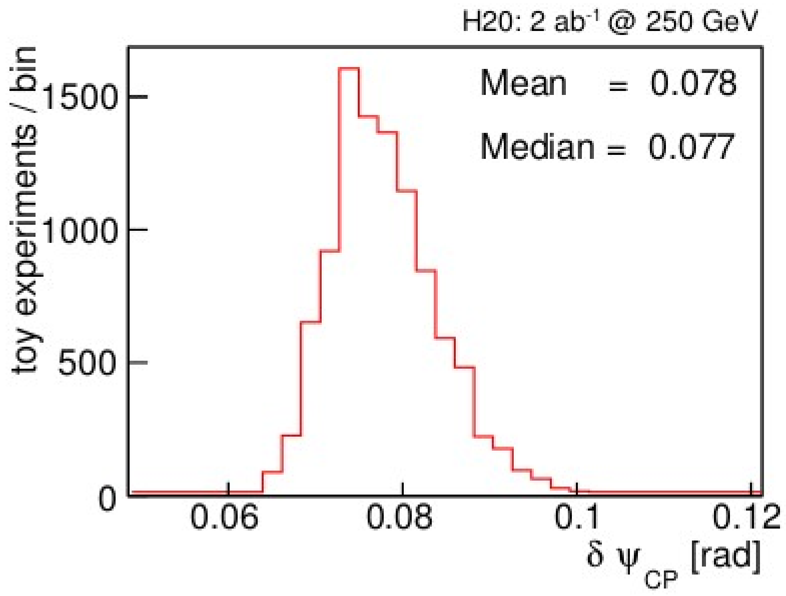


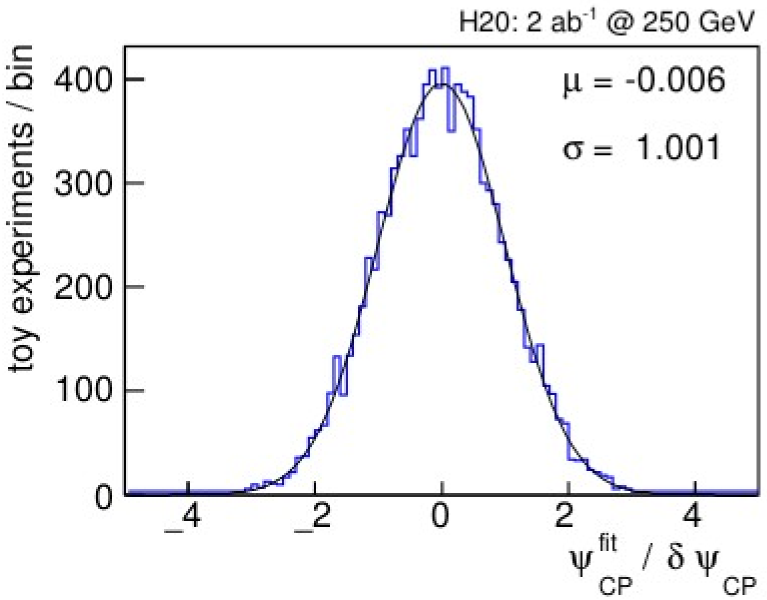
fits to these distributions used as inputs to toy MC

Results of 10k toy MC experiments

simultaneous fit to all channels and sub-samples







everything looks fine

Pull distribution perfect

median uncertainty on ψ_{CP} = 77 mrad (4.4 degrees)

Sensitivity on ψ_{CP}

after full H20 @ 250 GeV (2 / ab) (~20 years)

→ 77 mrad (4.4 degrees) assuming SM Higgs-strahlung xsec (σ_{ZH})

before lumi upgrade (after ~8 years running)

0.5 / ab @ 250 GeV → 152 mrad

non-SM CP properties may reduce σ_{ZH}

σ_{ZH} (SM) → 77 mrad full H20

σ_{ZH} - 10% → 83 mrad

σ_{ZH} - 25% → 93 mrad

σ_{ZH} - 50% → 124 mrad

full H20, 100% selection efficiency,

perfect reconstruction, no background → 17 mrad

Summary

since Santander:

a few bugs fixed (most important: FSR)

quote error on ψ_{CP} (not 2 ψ_{CP})

several tweaks to reconstruction selection

include Z → cc, bb decays

improvement to fitting procedure
slicing into sub-samples according to sensitivity
simultaneous likelihood fit over all sub-samples

paper: first draft completed

ILD review procedure?

backup

selection: leptonic Z decay

electron or muon
charged hadron
photon

>=1 leptonic Z decay candidate
→ **particle ID**

>=2 additional charged hadrons
→ tau seeds

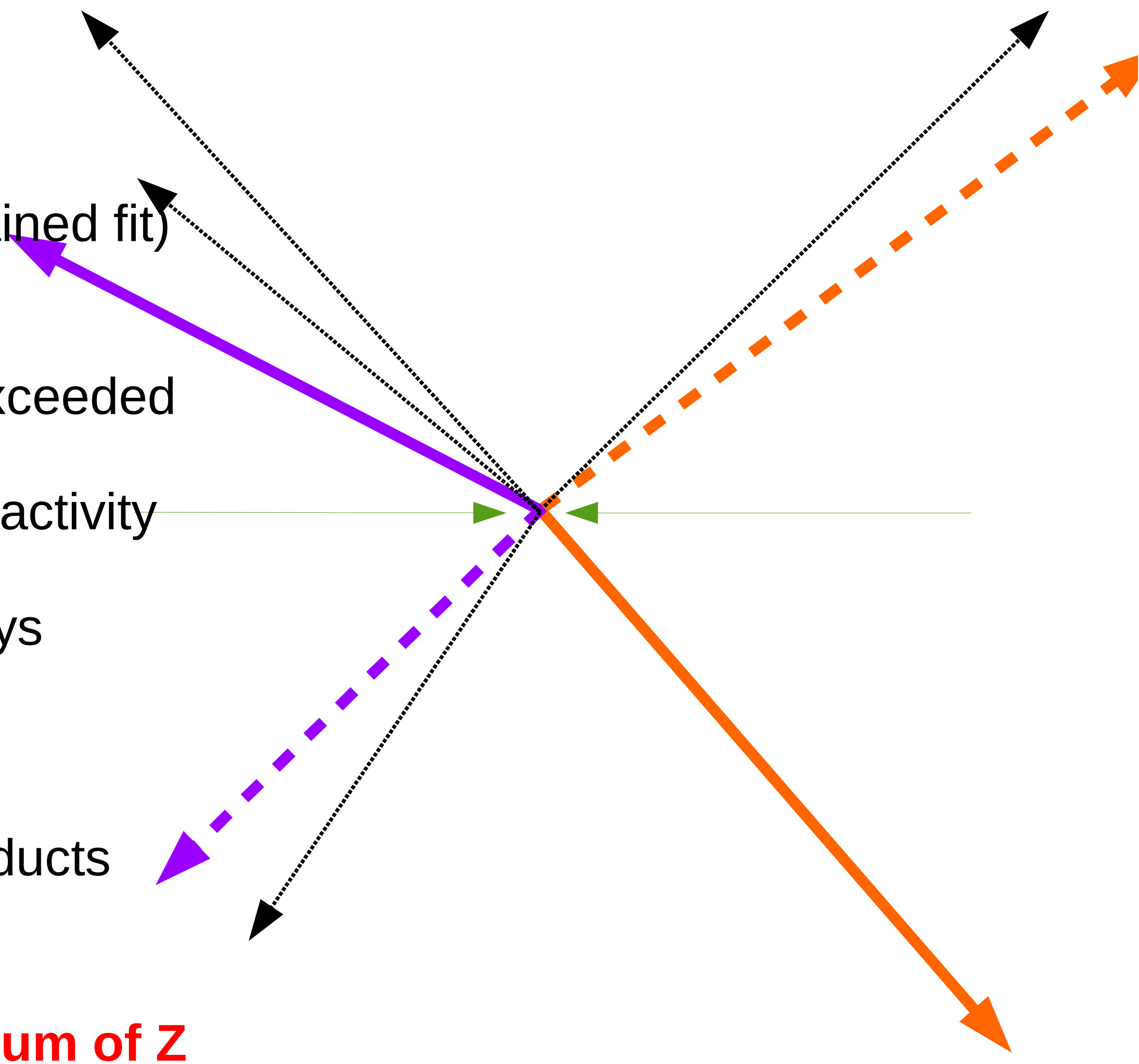
associate photons → pi0 (use constrained fit)
→ tau jets, if m_tau not exceeded
associate unpaired photons
to nearest tau jets, if m_tau not exceeded

veto events with significant additional activity

select $\tau^{\pm} \rightarrow \pi^{\pm} \nu$ and $\tau^{\pm} \rightarrow \pi^{\pm} \pi^{0} \nu$ decays
→ **photon reconstruction**

fully reconstruct tau momenta
use impact parameters of tau products
balance event p_T
impose tau mass
→ **impact parameters ; momentum of Z**

cut on tau-tau mass, recoil mass, tau energy



selection: hadronic Z decay

highest energy pair of oppositely charged, isolated-from-other-charged, PFOs

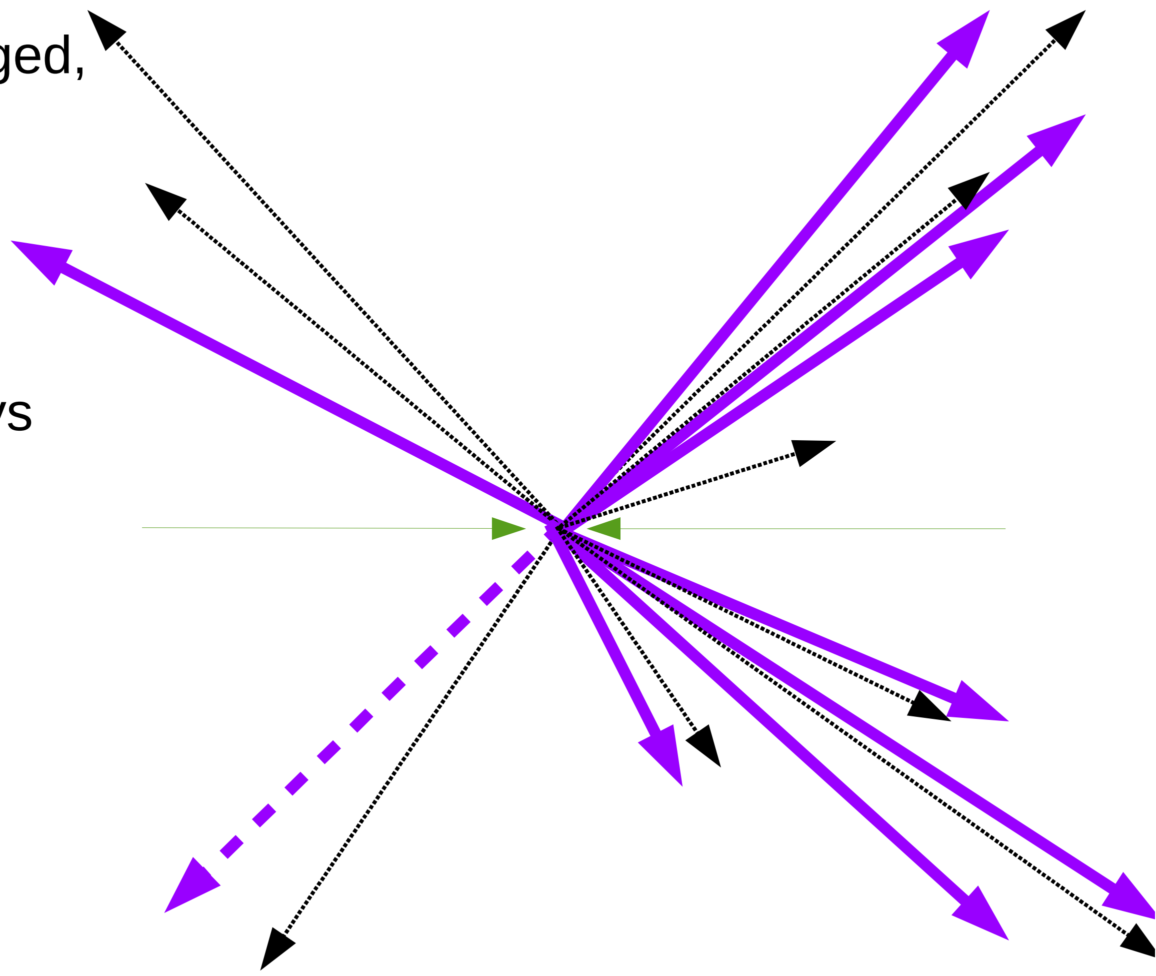
add nearby photons (→ pi0) → tau
if m_tau not exceeded

select $\tau^{\pm} \rightarrow \pi^{\pm} \nu$ and $\tau^{\pm} \rightarrow \pi^{\pm} \pi^{0} \nu$ decays
→ **photon reconstruction**

rest of event → "Z"
require mass consistent with mZ

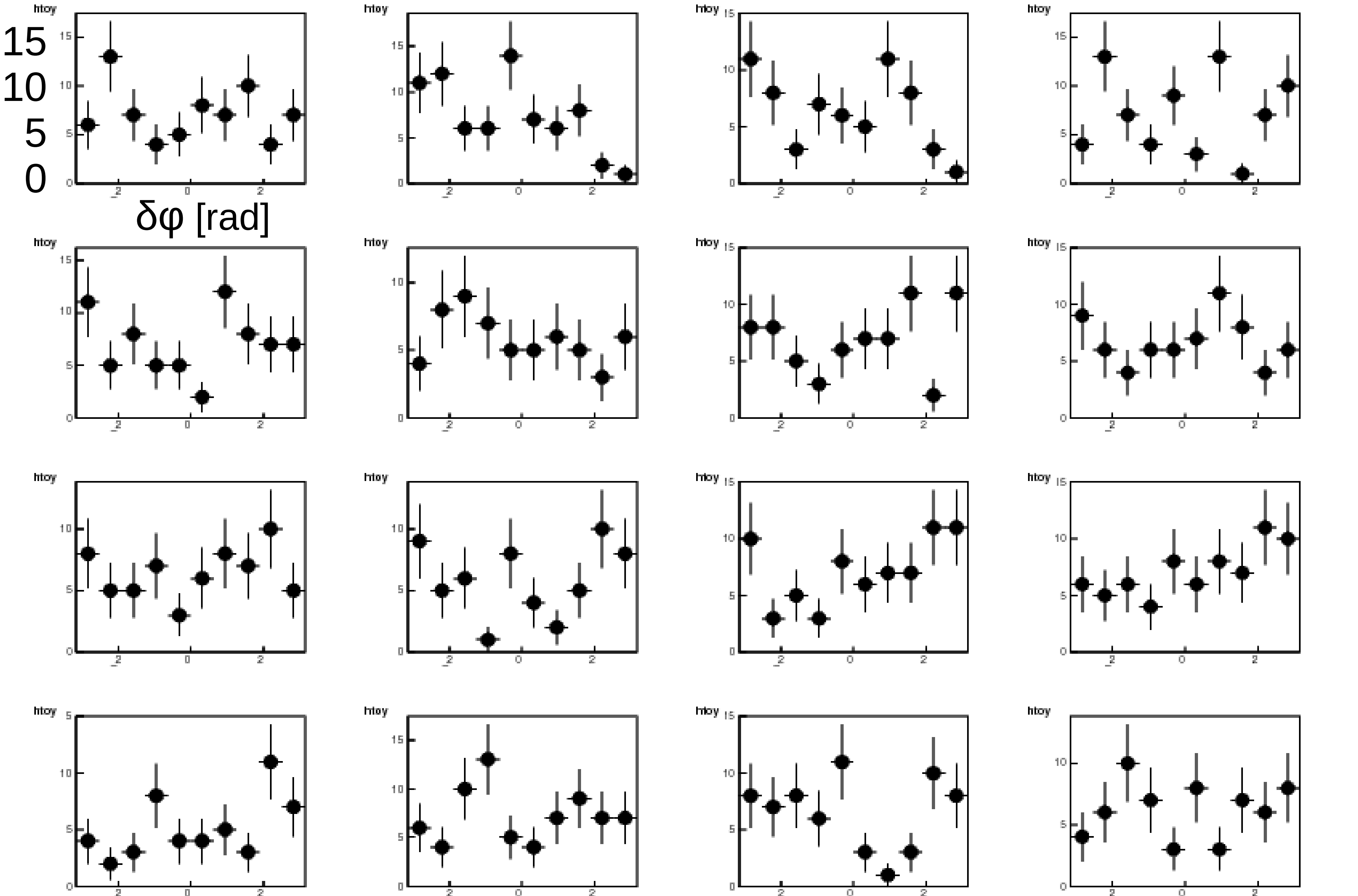
fully reconstruct tau momenta
→ **IP reconstruction**
→ **impact parameters**
→ **momentum of Z → JER**

cut on tau energy, tau-tau mass, recoil mass



μμττ channel some toy MC experiments **illustrative**

P(e-,e+) = (-0.8, +0.3), 1350 fb-1



(prelim results@Santander)

expected statistical uncertainties on CP mixing angle 2ψ *[ψ = 0 : CP even, 2ψ = pi : CP odd]*

channel	e e τ τ		μ μ τ τ		q q τ τ	
polarisation	(-0.8, +0.3) 1350 fb-1	(+0.8, -0.3) 450 fb-1	(-0.8, +0.3) 1350 fb-1	(+0.8, -0.3) 450 fb-1	(-0.8, +0.3) 1350 fb-1	(+0.8, -0.3) 450 fb-1
signal efficiency	31%	30%	50%	51%	16%	15%
# selected signal events	36.3	7.9	56.7	12.9	221	48
signal contrast	0.28	0.28	0.48	0.50	0.28	0.25
Signal / Background	1.0	1.2	2.0	2.2	0.74	0.92
mean err on *2ψ* [rad]	0.9	1.4	0.5	0.9	0.4	0.8
mean error on *2ψ* [rad]	0.8		0.5		0.4	
mean error on *2ψ*	0.3 rad ~ π/10 rad ~ 17 degrees					

[n.b. people usually quote error on ψ] event reconstruction depends largely on:

tau decay mode identification
→ pattern recognition in ECAL

impact parameter resolution
→ vertex detector

jet energy resolution

example cut table: LR signal in Z → ee channel

sample tauana_ttee_250GeV_LR_addH_0_sigsig : xsec 0.00014418
tree entries : 9863

selection variable	EVENT COUNT	EFFICIENCY
ALL	9863	100 %
GENERATORCUT	9863	100
>=4 chg PFOs	9167	92.9433
>=1 Z candidate	8105	82.1758
no forward electron in Z	7425	75.2814
no muon PID in tau decay	7320	74.2168
no elec PID in tau decay	6532	66.2273
opposite charge taus	6388	64.7673
FINALPRESEL	6388	64.7673
ZMASS	6090	61.7459
EXTRA ACTIVITY	5586	56.6359
TAUJETS – tau → $\pi\nu$ or $\rho\nu$	4463	45.2499
TAUTAUFIT – successful fit	3991	40.4644
TAU ENERGY	3707	37.5849
TAUTAU MASS	3356	34.0262
RECOIL MASS	3315	33.6105