

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

all results preliminary

ECFA-LC workshop @Santander

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CP-violating coupling of Higgs to fermions possible at tree level

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

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

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

consider projection of spin on some axis: \uparrow, \downarrow

spin state of pair of spin $1/2$ particles

produced by spin-0 parent: $\sim (|\uparrow\downarrow\rangle + e^{2i\psi} |\downarrow\uparrow\rangle)$

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

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

otherwise a mixture

decays of Higgs to tau pairs allows this to be probed

H decay to taus has significant BR

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

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

h(X) is the polarimeter vector
most likely tau spin direction for a
given configuration X of its decay products

easy to calculate for $\tau^\pm \rightarrow \pi^\pm \nu$ (~11%)
 $\pi^\pm \pi^0 \nu$ (~26%)

CP effects best seen in correlation of
spin components transverse to tau momentum:

$$\Gamma(\text{CP even/odd} \rightarrow f^+ f^-) \sim 1 - s_z^+ s_z^- \text{ +/- } s_\perp^+ s_\perp^-$$

Full simulation & reconstruction

Whizard 2.2.8, CIRCE2 beam-strahlung, ISR

$e^+ e^- \rightarrow f+f-\tau^+\tau^-$ ($\tau^+\tau^-$ from 125 GeV Higgs)

$e^+ e^- \rightarrow f+f-\tau^+\tau^-$ ($\tau^+\tau^-$ not from Higgs)

$f = e, \mu, (uds)$ (some generator level cuts, particularly for $e^+e^-\tau^+\tau^-$)

Pythia v8.212 for hadronisation & FSR

Tauola c++ v1.1.4

1. signal decays: $\tau^\pm \rightarrow \pi^\pm \nu$ and/or $\tau^\pm \rightarrow \pi^\pm \pi^0 \nu$ “rho / ρ ”

2. all τ^\pm decays

include spin correlations (H_{SM} , $H_{CP}(\psi_{CP}=\pi/4)$, non-H)

Mokka simulation: ILD model ILD_o1_v05

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

background overlay

standard Pandora steering (with recent photon reco)

General strategy

consider 250 GeV running in H20 scenario

$$\text{Pol}(e^-,e^+) = (-0.8, +0.3), 1350 \text{ fb}^{-1}$$

$$\text{Pol}(e^-,e^+) = (+0.8, -0.3), 450 \text{ fb}^{-1}$$

select $e^+e^- \rightarrow (H \rightarrow \tau \tau) (Z \rightarrow ee, \mu\mu, qq)$ events

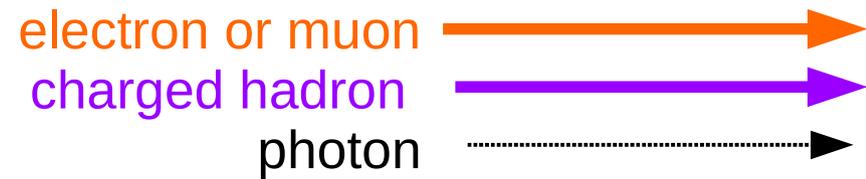
fully reconstruct tau momenta

reconstruct tau polarimeter vectors

look at angle between transverse components of polarimeters

use toy MC experiments to extract sensitivity to CP mixing angle

selection: leptonic Z decay



one leptonic Z decay candidate

→ **particle ID**

≥ 2 additional charged hadrons

→ tau seeds

associate photons → π^0

with tau seeds

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

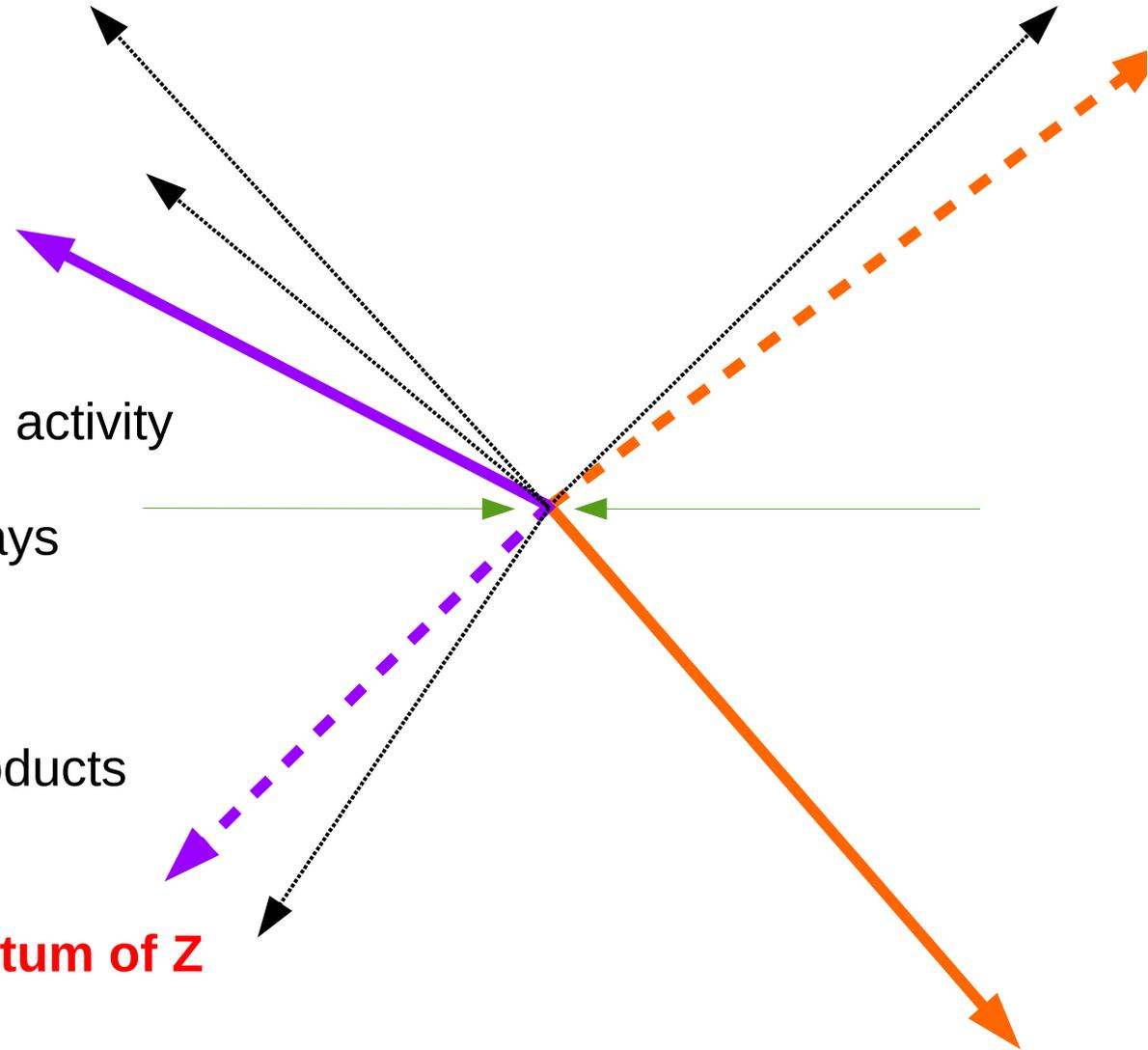
use impact parameters of tau products

balance event p_T

impose tau mass

→ **impact parameters ; momentum of Z**

require tau-tau mass $\sim m_H$



selection: hadronic Z decay

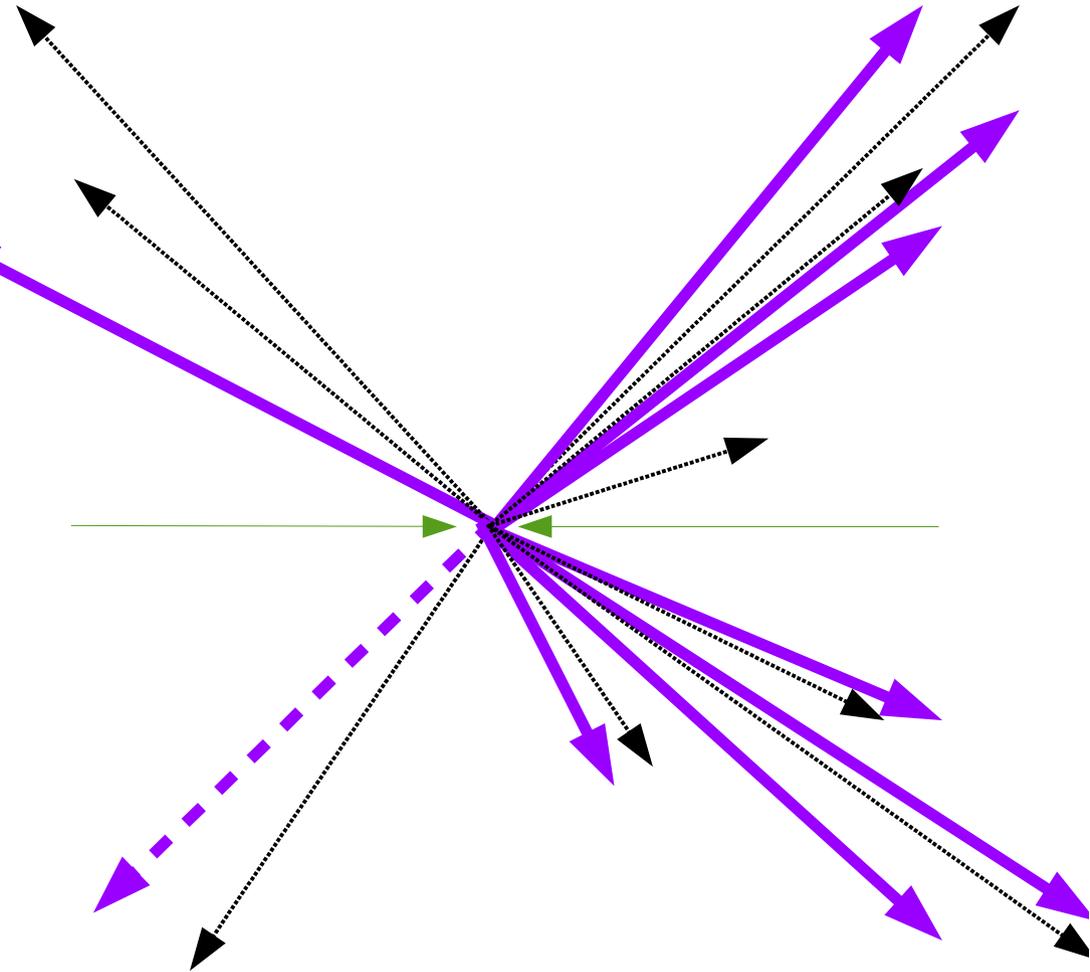
two tau-like jets (TauFinder)
→ **tau identification**

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 m_Z

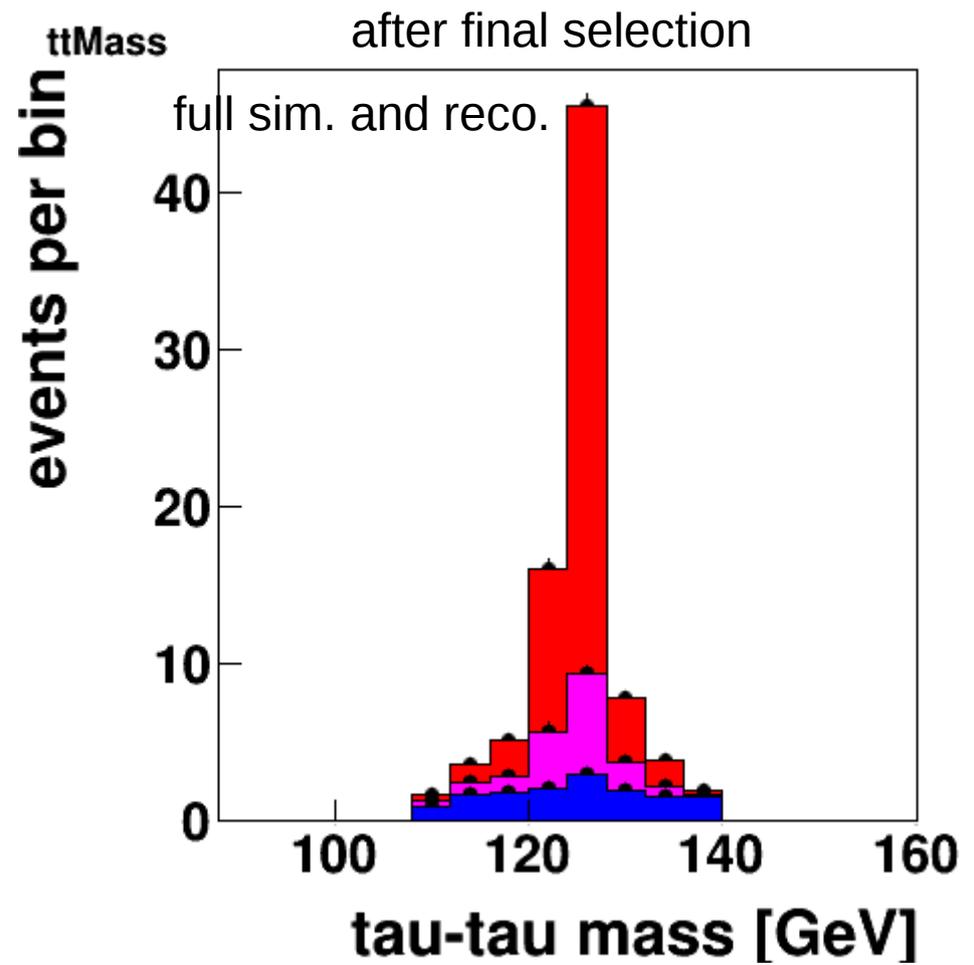
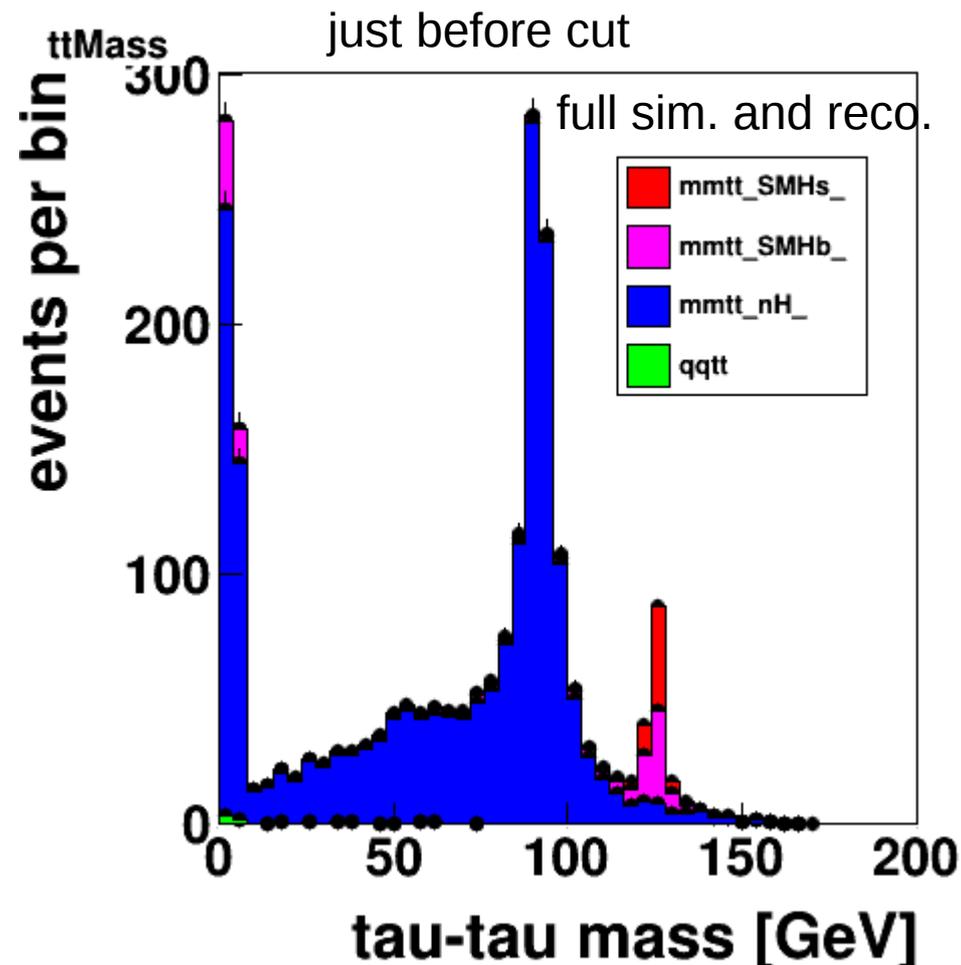
fully reconstruct tau momenta
→ **impact parameters ;**
→ **momentum of Z → JER**

require tau-tau mass $\sim m_H$



Invariant mass of reconstructed tau-tau system

muon channel, 1350 fb⁻¹ @ P(e⁻,e⁺) = (-0.8, +0.3)

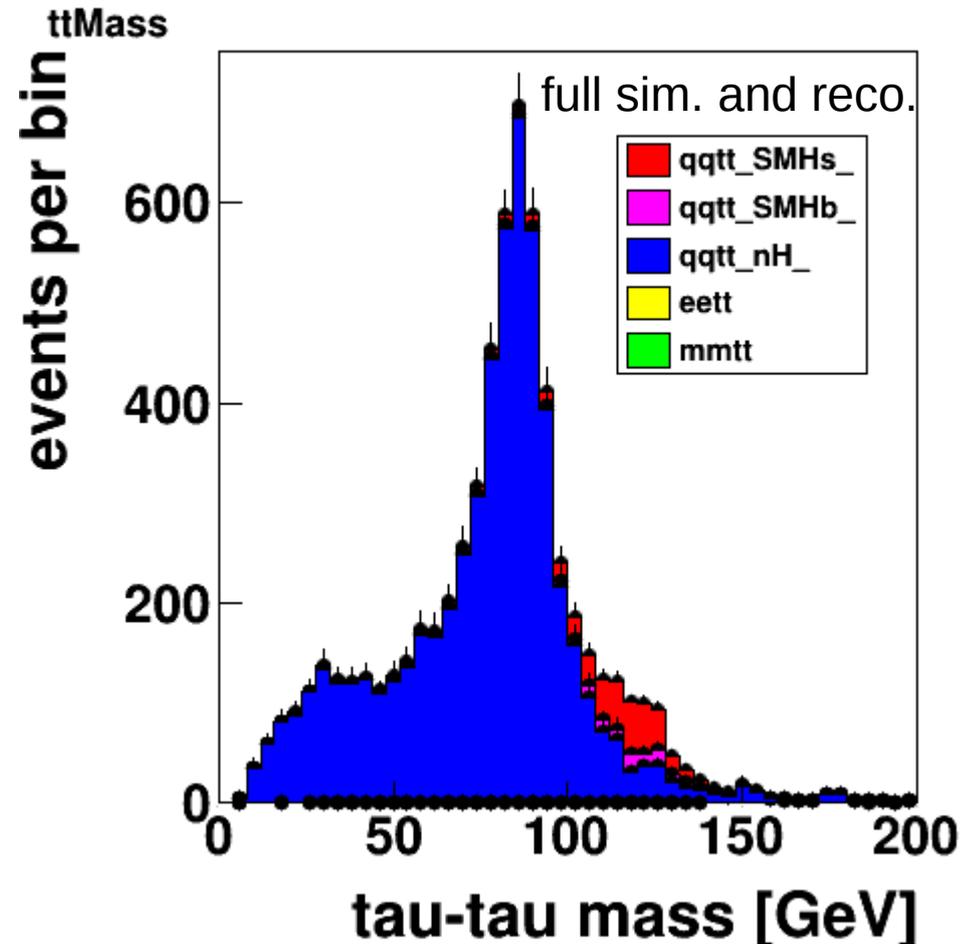


μμ tau tau (SM Higgs, tau → pi or rho) signal
μμ tau tau (SM Higgs, other tau decay channels)
μμ tau tau (non-Higgs) background

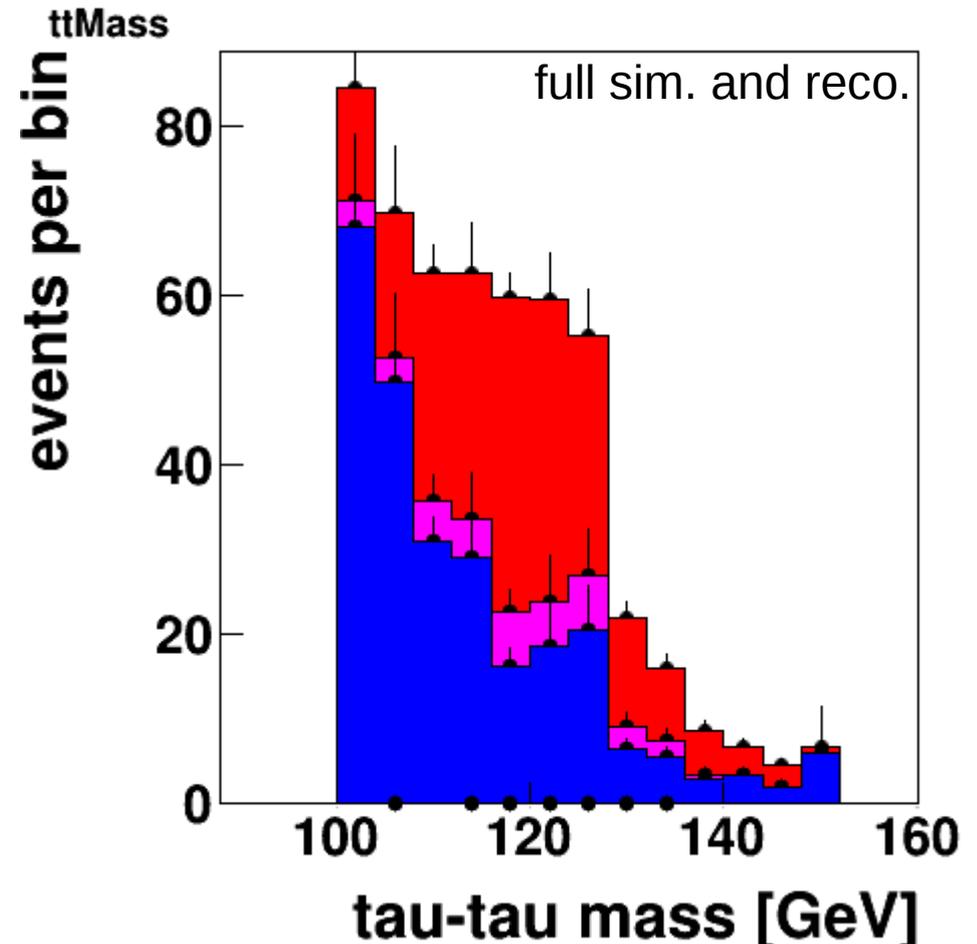
pretty good tau
momentum
reconstruction

Invariant mass of reconstructed tau-tau system

hadronic channel, 1350 fb⁻¹ @ $P(e^-, e^+) = (-0.8, +0.3)$



$\mu\mu$ tau tau (SM Higgs, tau \rightarrow pi or rho) signal
 $\mu\mu$ tau tau (SM Higgs, other tau decay channels)
 $\mu\mu$ tau tau (non-Higgs) background



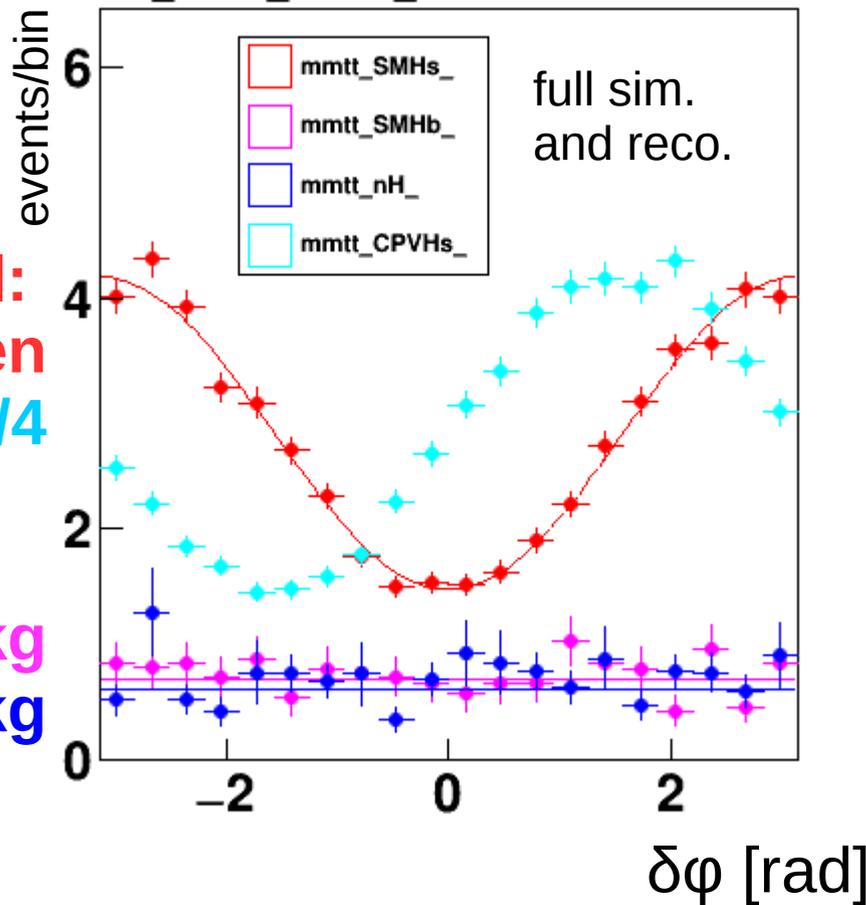
tau momentum
reconstruction much worse
 \rightarrow jet energy resolution

transverse spin correlations: after selection and reconstruction

muon channel

1350 fb⁻¹ @ P(e⁻,e⁺) = (-0.8, +0.3)

polDeltaPhi_mmtt_SMHs_Pol0Sel3



signal:
CP even
 $\psi = \pi/4$

Higgs bkg
non-H bkg

$$\sim 1 + a (\delta\phi + \psi_{CP})$$

clear phase shift for $\psi_{CP} = \pi/4$

statistics and the contrast “a”
determines how well we can
measure ψ_{CP}

$$a_{MC} = \pi^2/16 \sim 0.6$$

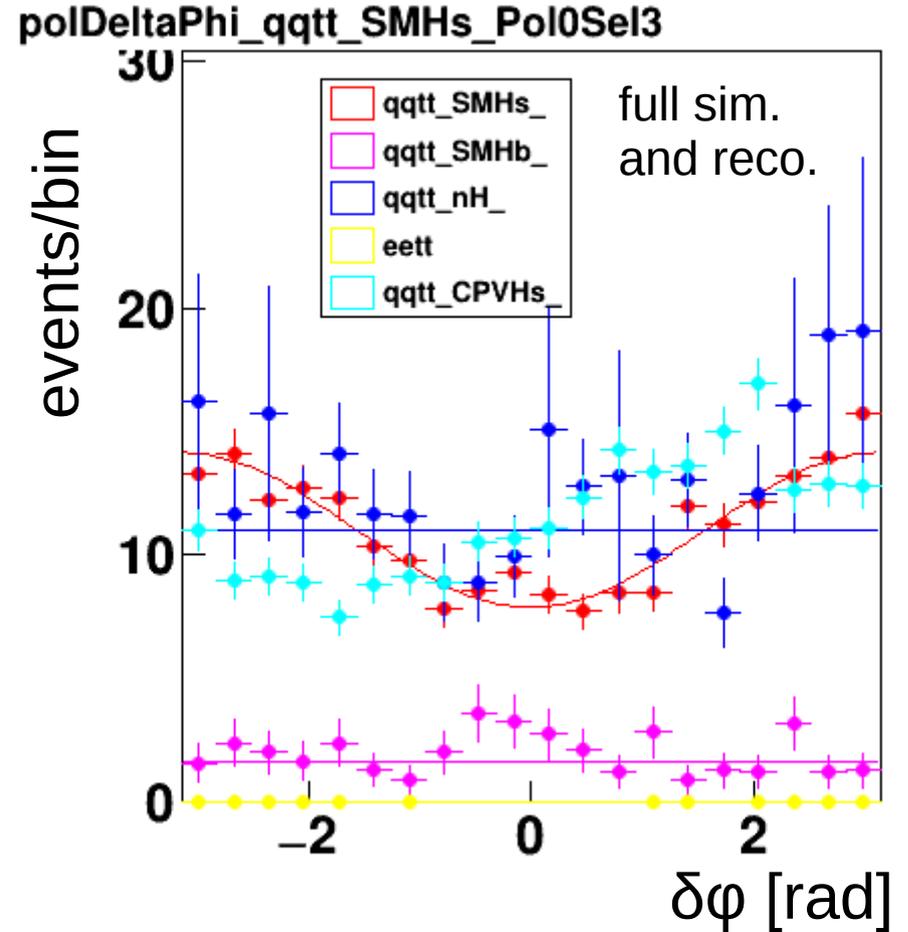
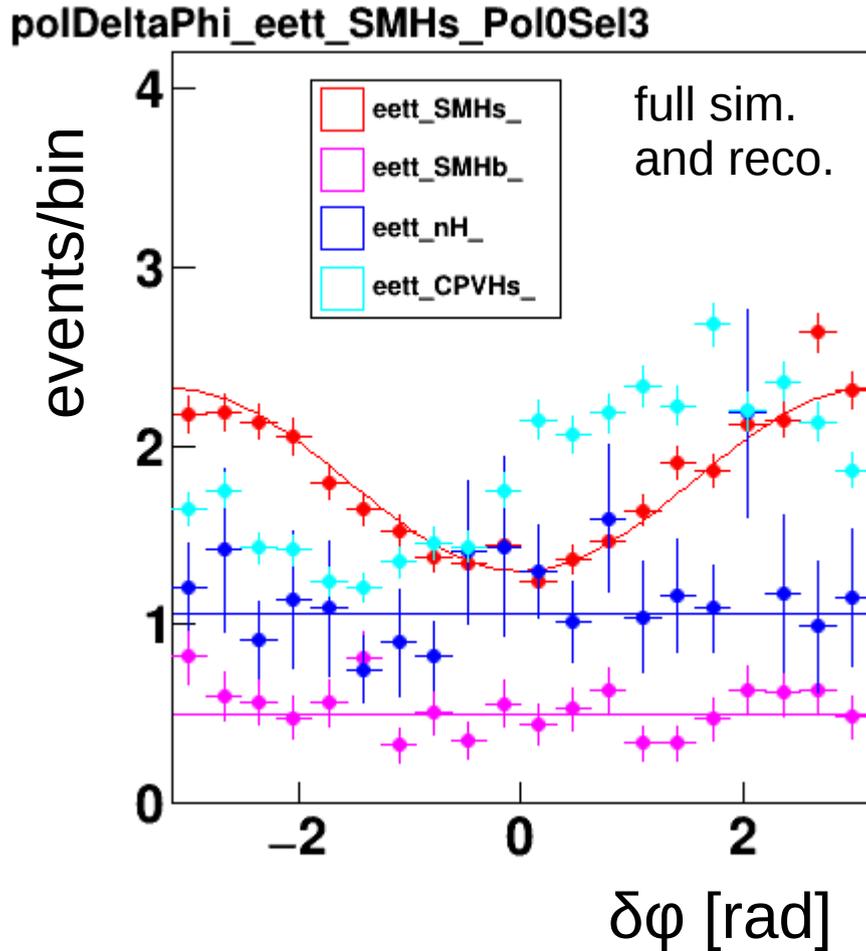
$$a_{reco} \sim 0.5$$

backgrounds small and flat

electron channel

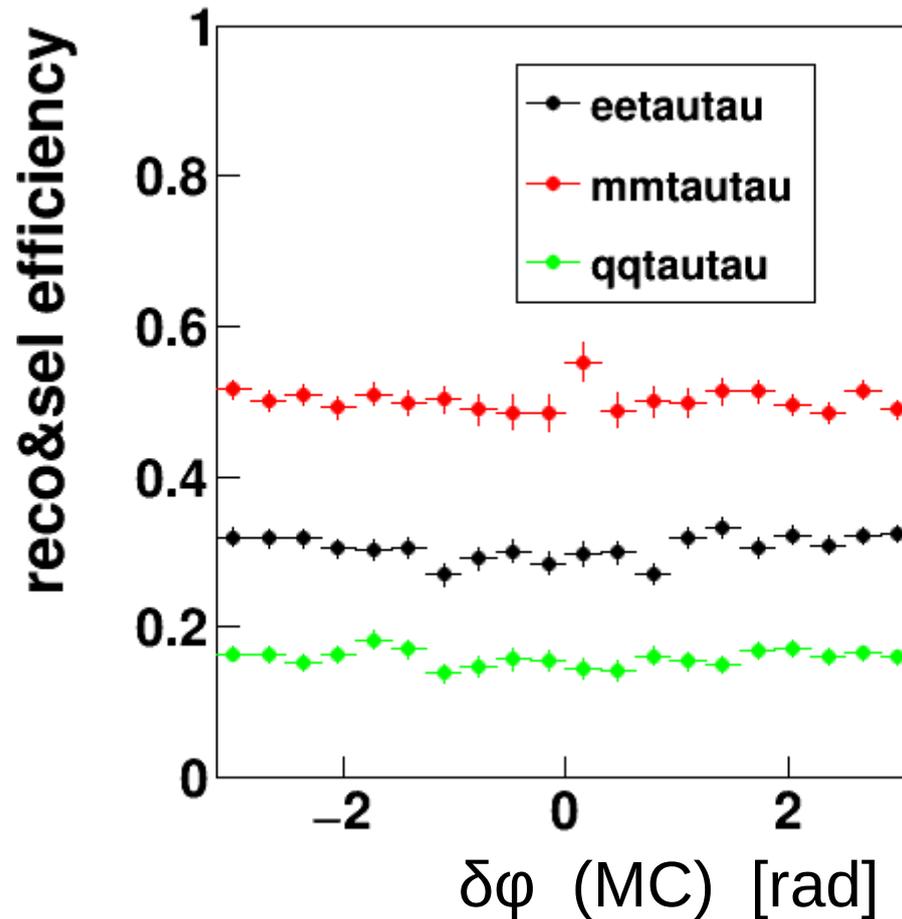
hadronic channel

1350 fb⁻¹ @ P(e⁻,e⁺) = (-0.8, +0.3)



significantly less signal contrast
significantly larger backgrounds
higher statistics in hadronic channel

Reconstruction and selection efficiency



- modest reco & selection efficiency
- does not depend on spin correlation
 - unbiased measurement
 - limited systematic effects (probably)

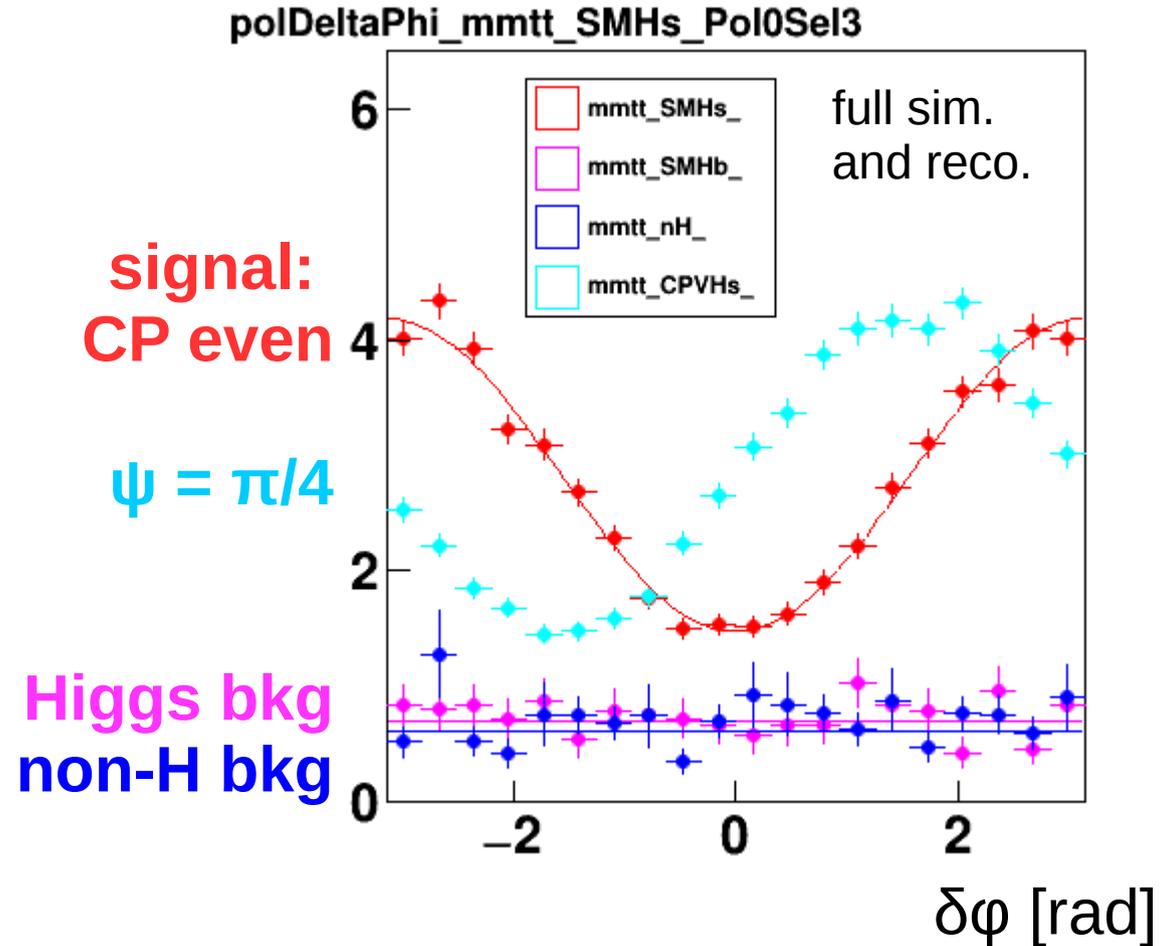
Estimation of sensitivity

Assume: sinusoidal signal
flat background
→ fit parameters

Use fit functions to run
toy MC experiments

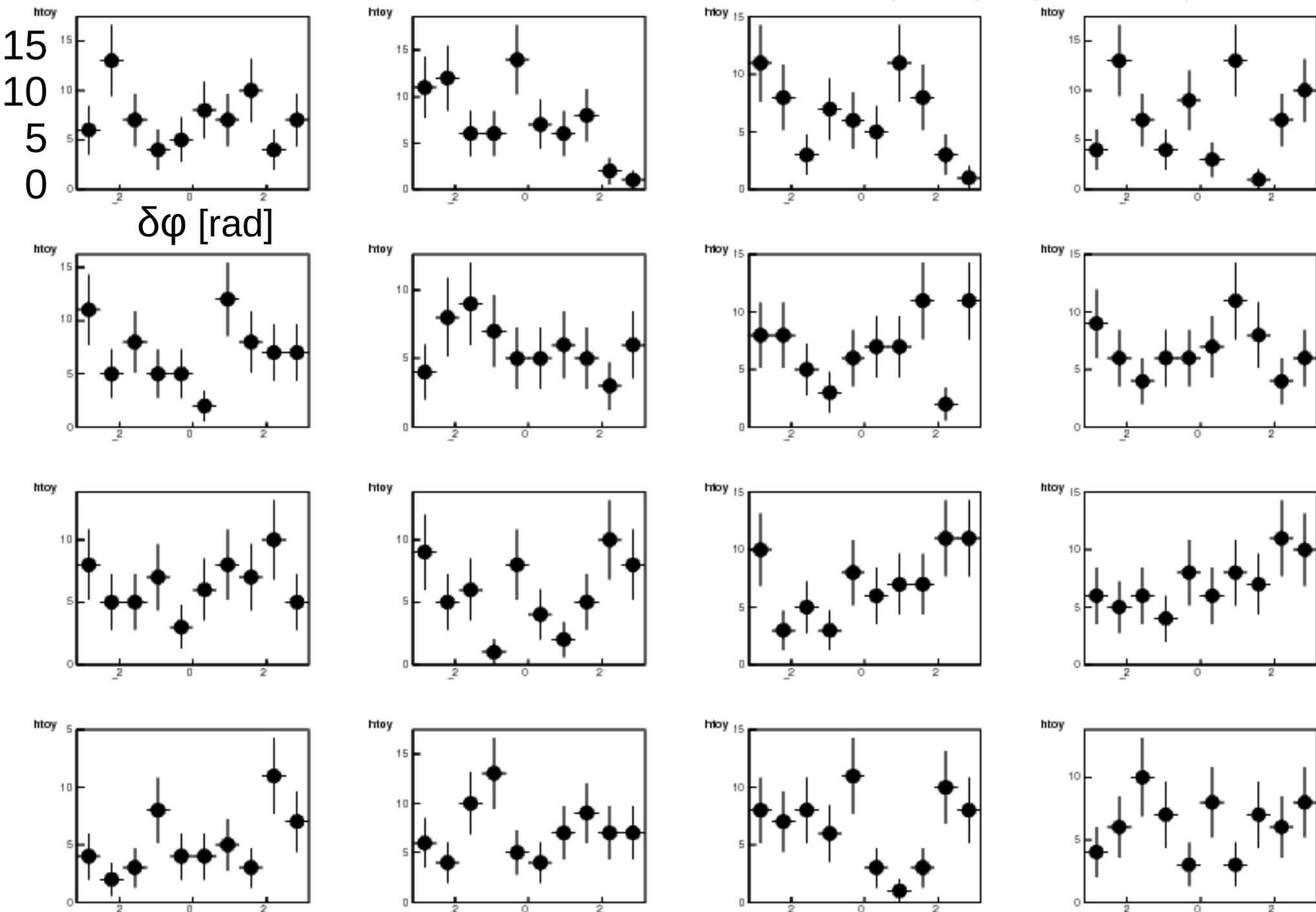
assume total xsec
independent of CP
→ maybe not a valid assumption:
extra information in xsec variation

extract phase of $\delta\phi$ variation
using unbinned maximum
likelihood fit



$\mu\tau$ channel some toy MC experiments

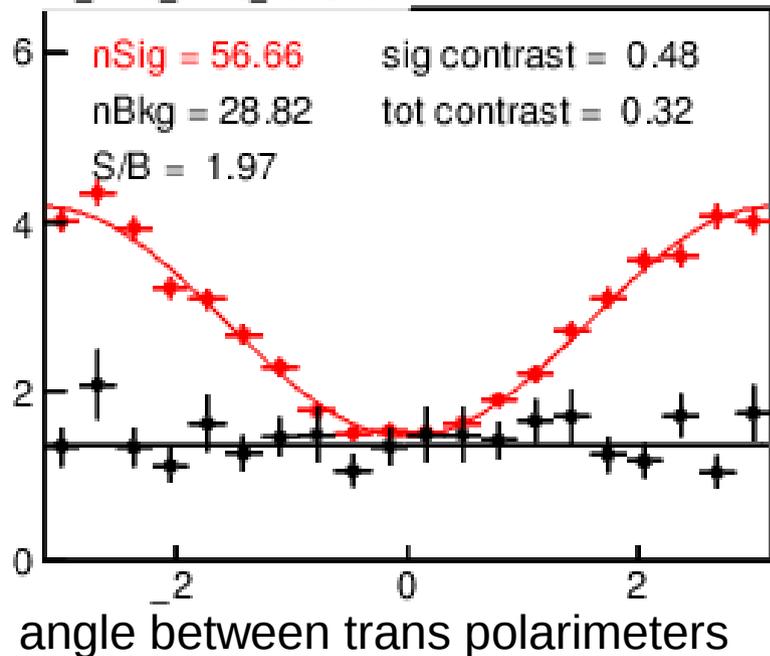
$P(e^-,e^+) = (-0.8, +0.3), 1350 \text{ fb}^{-1}$



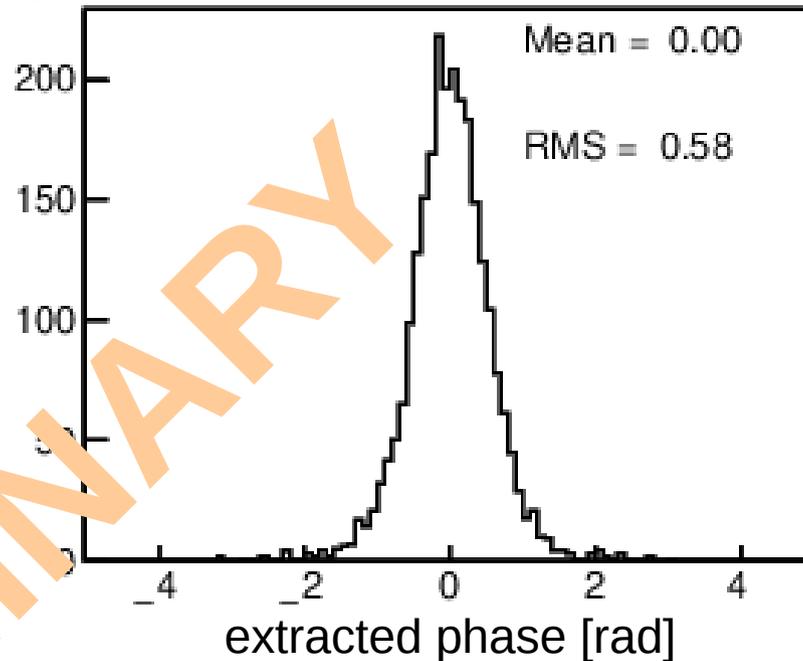
results of toy MC experiments: $\mu\mu\tau$ channel

$P(e^-, e^+) = (-0.8, +0.3)$, 1350 fb $^{-1}$

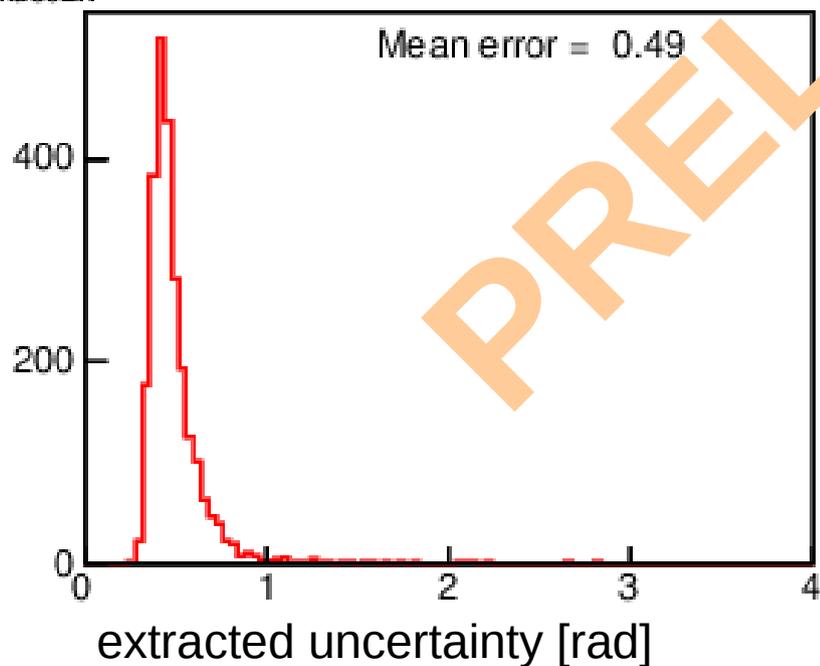
polDeltaPhi_mmtt_SMHs_Pol0Sel3



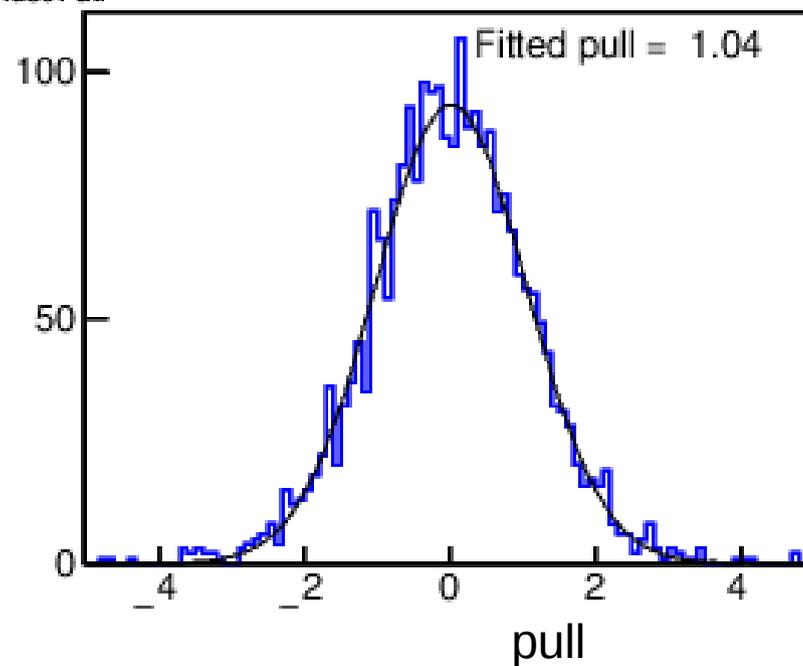
hPhase



hPhaseErr



hPhasePull



PRELIMINARY

expected statistical uncertainties on CP mixing angle

preliminary results

channel	$e e \tau \tau$		$\mu \mu \tau \tau$		$q q \tau \tau$	
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
expected error [rad]	0.9	1.4	0.5	0.9	0.4	0.8
averaged [rad]	0.8		0.5		0.4	
all averaged	0.3 rad \sim $\pi/10$ rad \sim 17 degrees					

summary

a non-standard CP nature of the Higgs and its couplings
can be probed in its decays to taus

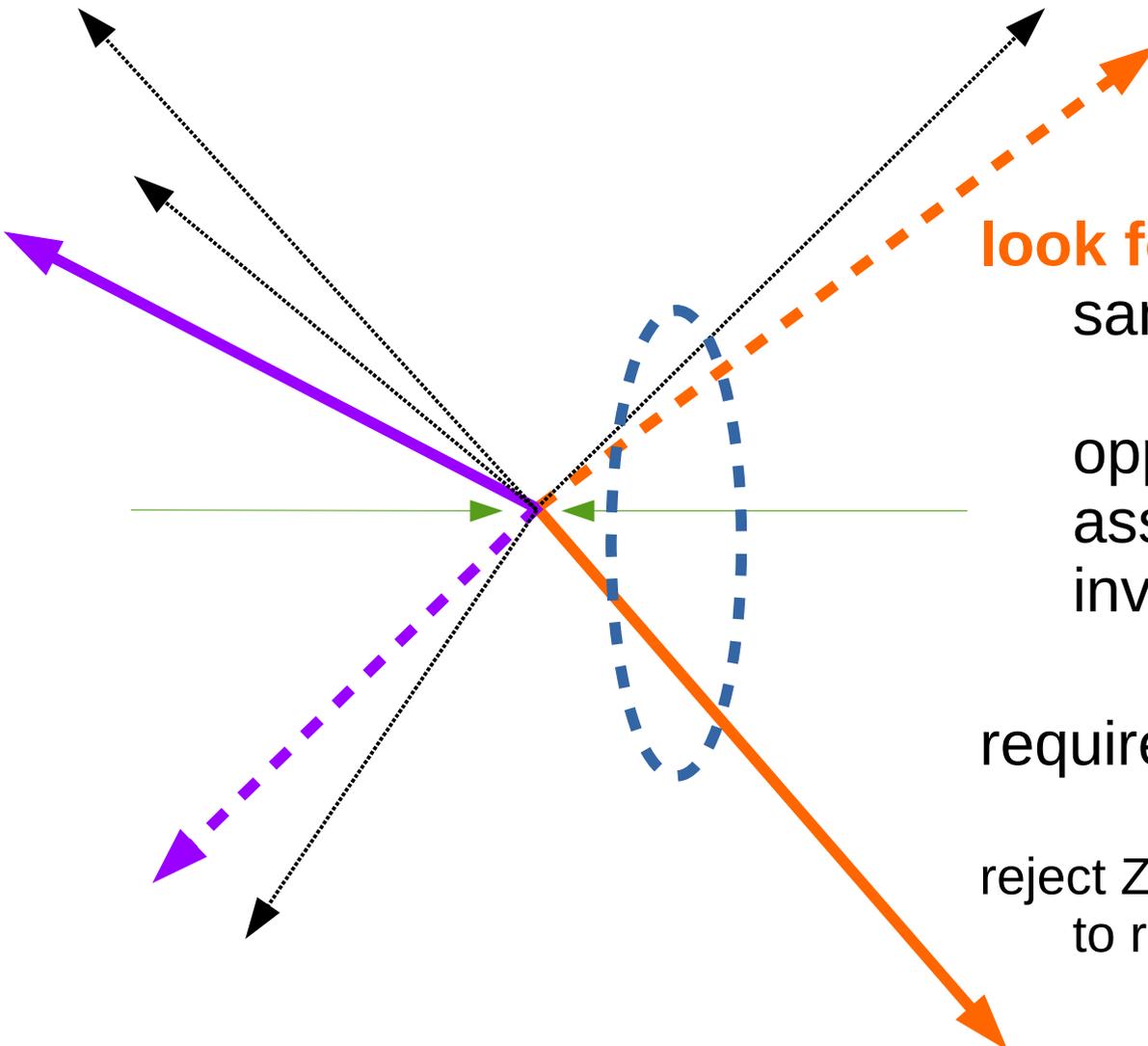
first iteration of such an analysis has been developed,
and its performance characterised
using full simulation and reconstruction at ILC250
Higgs-strahlung, with $Z \rightarrow e e, \mu \mu$ and $q q$

analysis relies on several aspects of detector performance
impact parameter resolution
charged particle identification
photon and π^0 reconstruction
tau jet finding
particle flow performance / hadronic jet energy resolution

this analysis suggests that the 250GeV portion
of the ILC run scenario (H20) will be able to
measure CP mixing in the Higgs sector at a level of $\sim 20^\circ$

scope for optimisation, refinement and expansion of analysis
addition of 500 & 350 GeV data, $Z \rightarrow c c, b b$ channels

backup slides



look for $Z \rightarrow e^+e^-, \mu^+\mu^-$
same flavour leptons
(PandoraPFA PID)
opposite charge
associate FSR
invariant mass not too far from m_Z

require exactly 1 Z candidate

reject $Z \rightarrow ee$ with very forward electrons
to reduce non-H backgrounds

electron or muon

charged hadron

photon

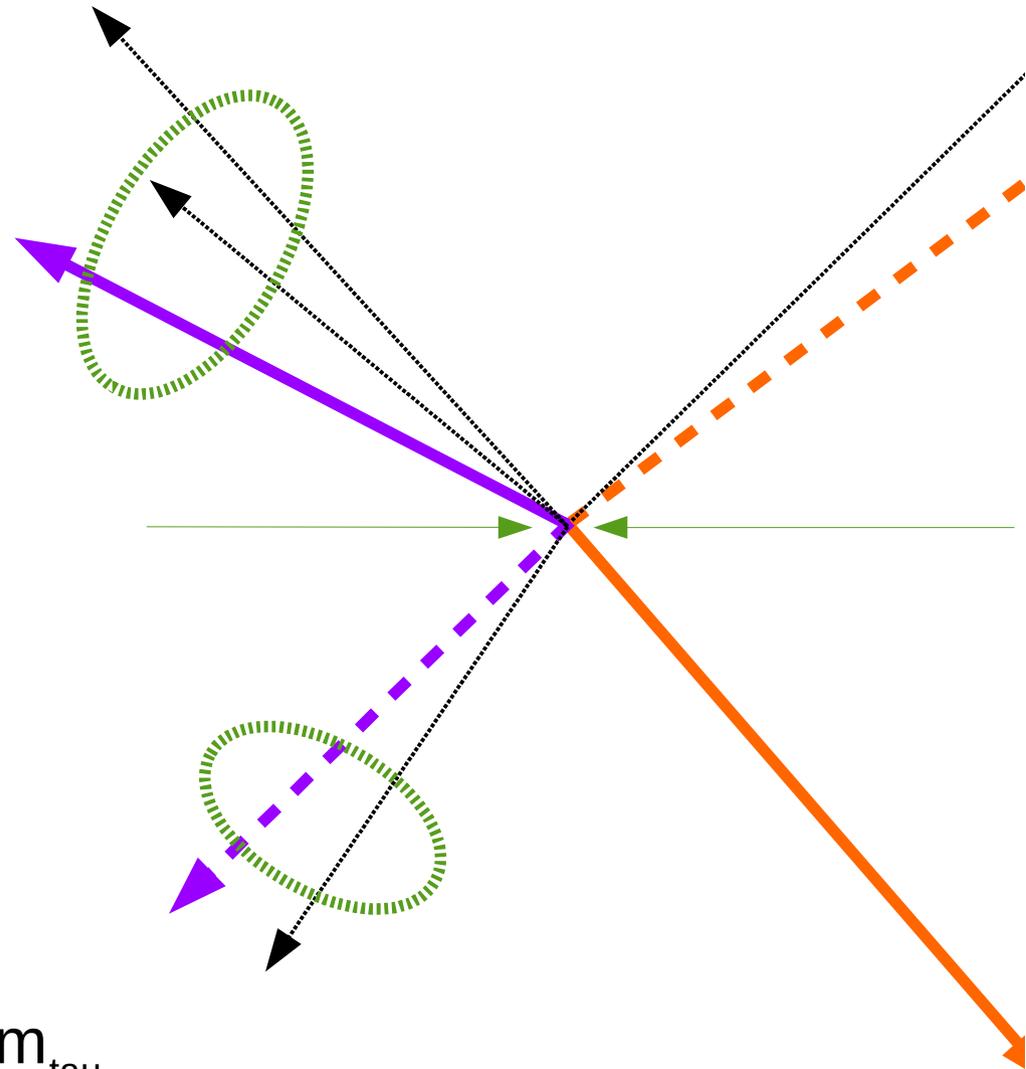
Identify hadronic tau candidates

≥ 2 additional charged PFOs
2 most energetic \rightarrow tau seeds

require oppositely charged seeds
not identified as e/mu

group remaining photons into π^0 s
if $m < m_{\text{tau}}$ with a tau seed
use mass constrained kinematic π^0 fit

add unpaired photons to nearest
tau candidate if resulting mass $< m_{\text{tau}}$



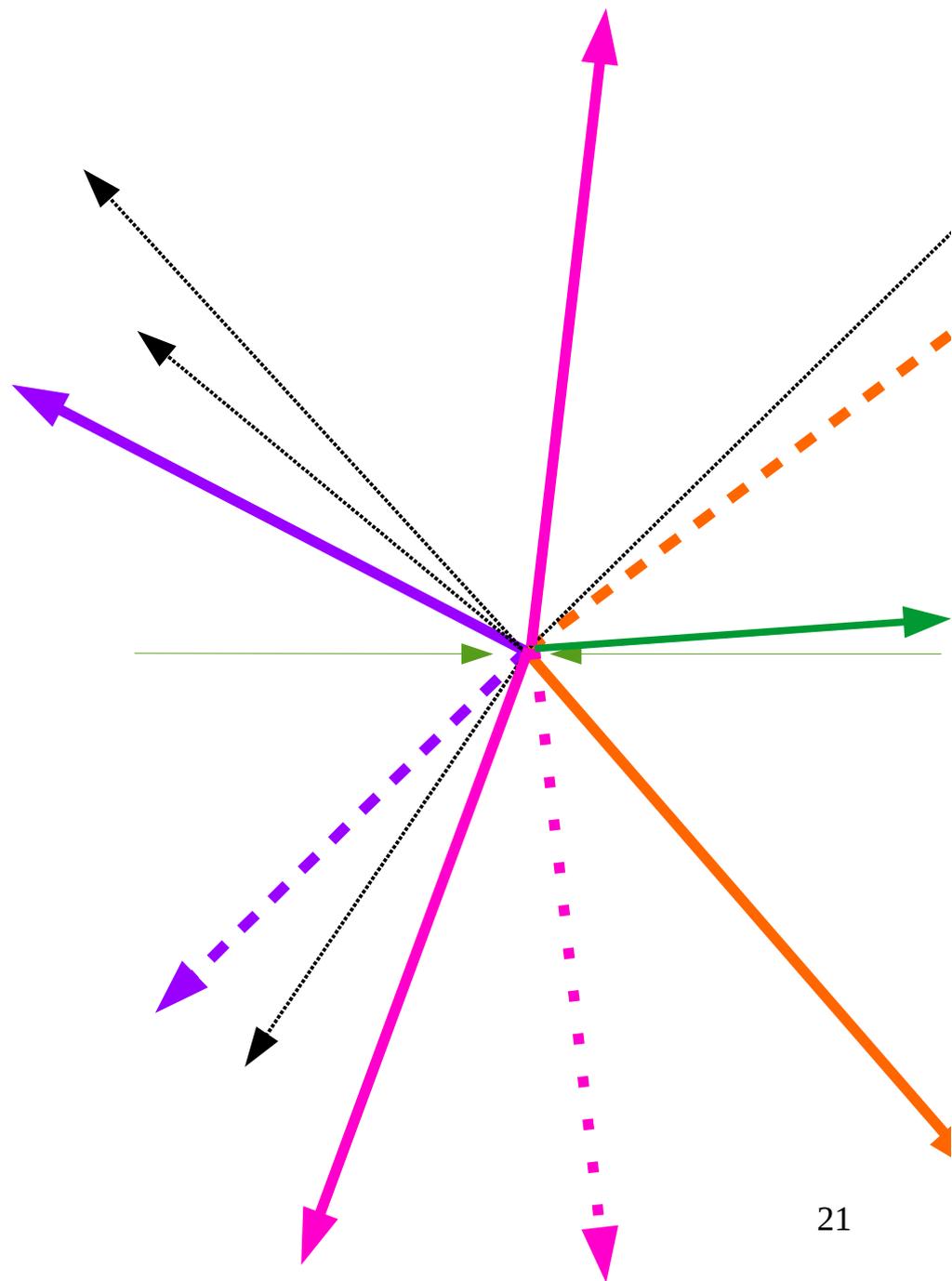
electron or muon

charged hadron

photon

veto events with > 10 GeV
charged or neutral hadron
energy or p_T
in addition to
Z and tau candidates

(some from underlying event allowed)



electron or muon

charged hadron

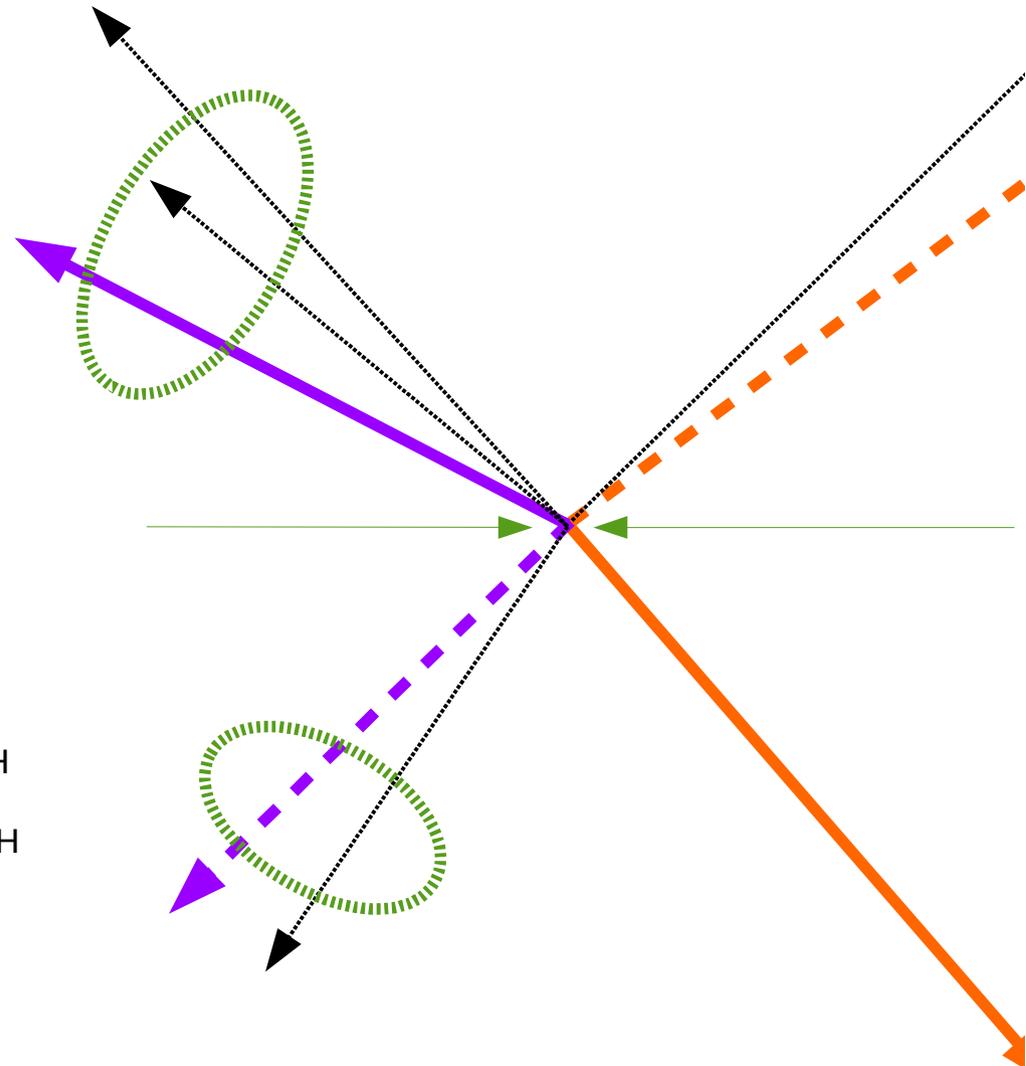
photon

select tau \rightarrow pi, tau \rightarrow rho decays
based on number of photons/pi0 and
visible mass of tau jet

reconstruct tau momenta
using impact parameters,
measured momenta
imposing tau mass, pT balance
(details in NIM A 810 p51)
require successful reconstruction

select H \rightarrow tau tau
require tau-tau mass consistent with m_H
require Z recoil mass consistent with m_H

measure CP properties
reconstruct tau polarimeters
using measured momenta and reconstructed p_{tau}
correlation of transverse components of polarimeters \rightarrow CP





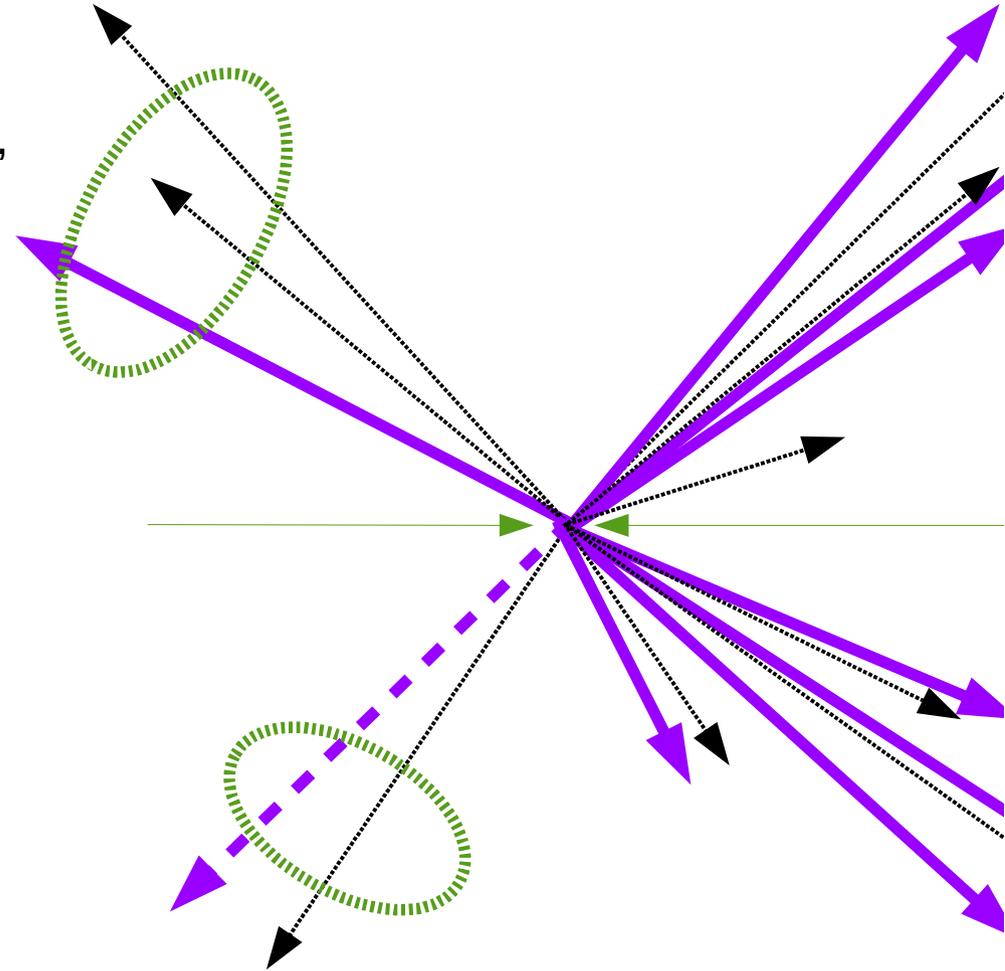
Hadronic Z decay channels

use TauJetFinder (T. Suehara) to look for narrow, isolated, low mass tau jet candidates

require exactly 2 tau jet candidates, each with a single charged particle oppositely charged

Assign remainder of event to the Z:
require a certain range of invariant mass and recoil mass for this system

The proceed as for leptonic channels



event reconstruction depends largely on:

tau decay mode identification

→ pattern recognition in ECAL

impact parameter resolution

→ vertex detector

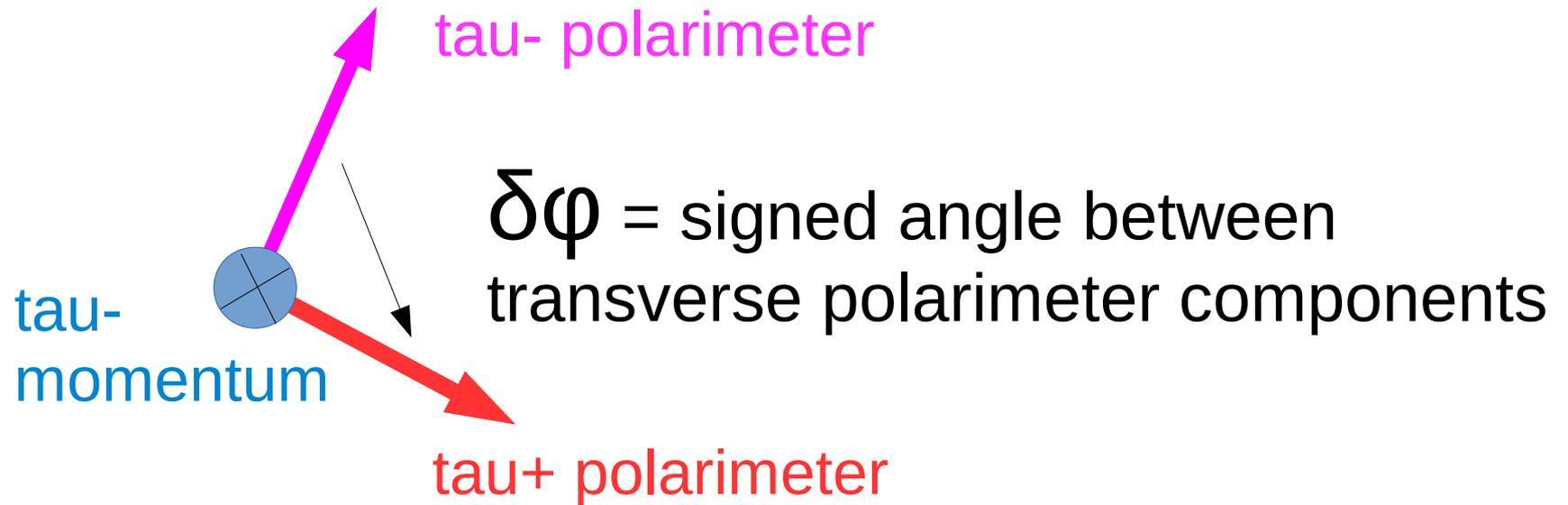
jet energy resolution

typical selection efficiencies

selection chan. → (tau decays) ↓	$e e \tau \tau$	$\mu \mu \tau \tau$	$q q \tau \tau$
signal (pi, pi)	~39 %	~68 %	~20 %
signal (pi, rho)	~33 %	~53 %	~17 %
signal (rho rho)	~27 %	~44 %	~14 %

PRELIMINARY

transverse spin correlations

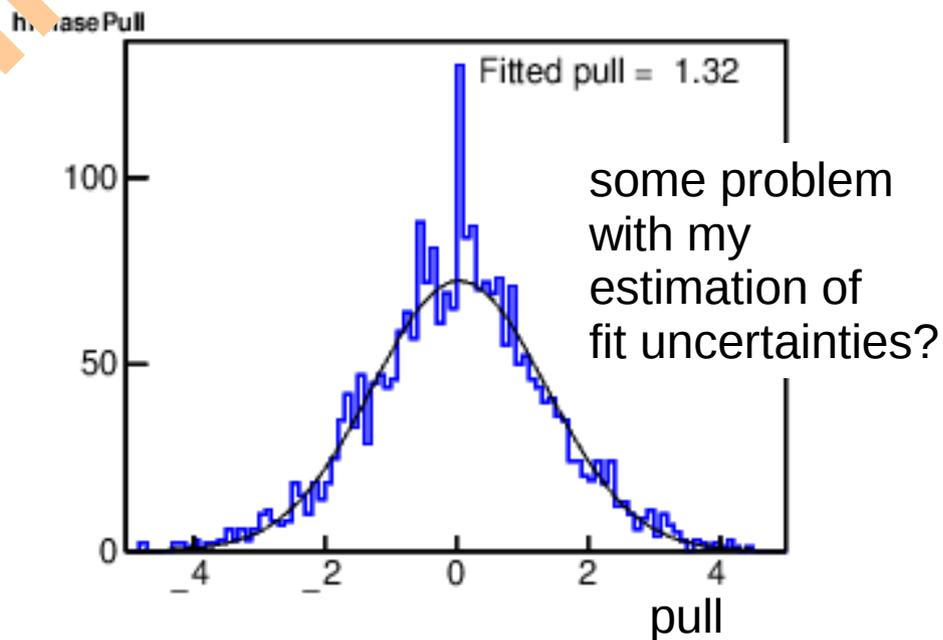
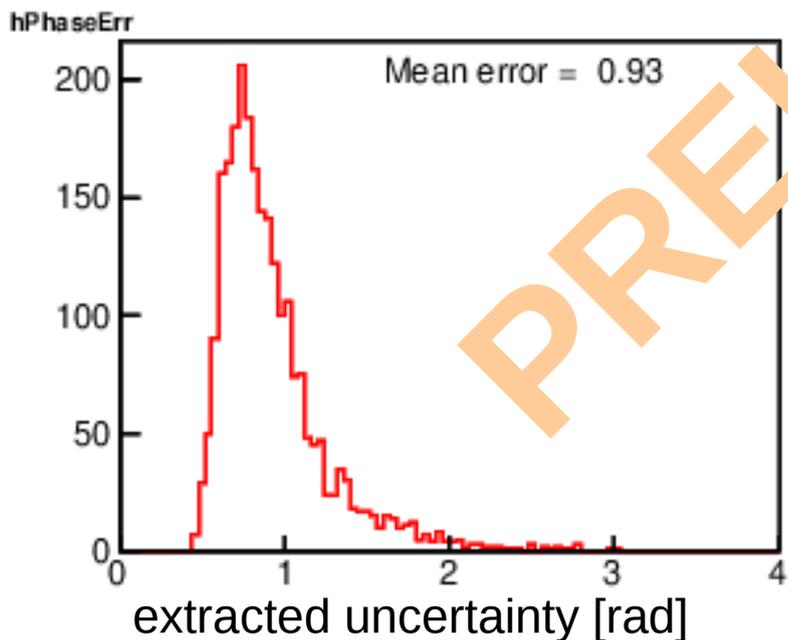
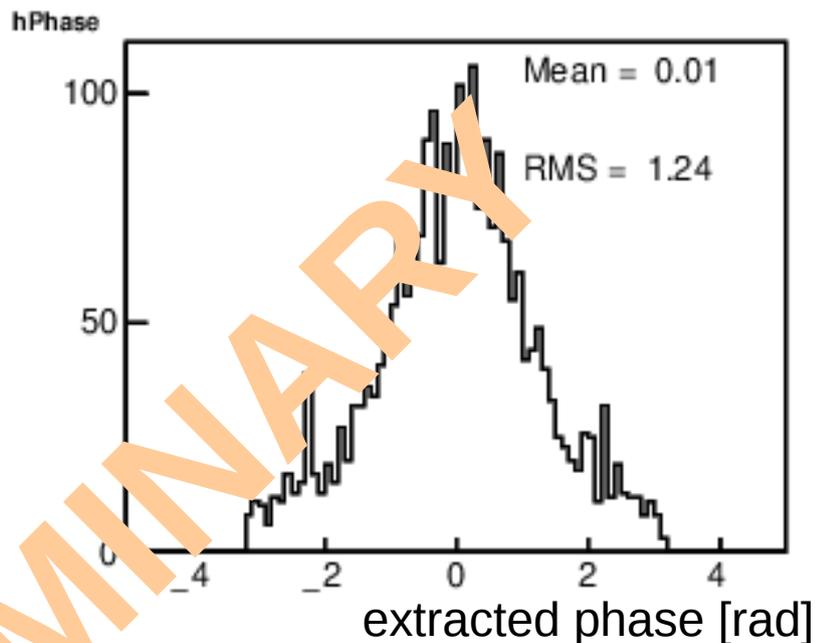
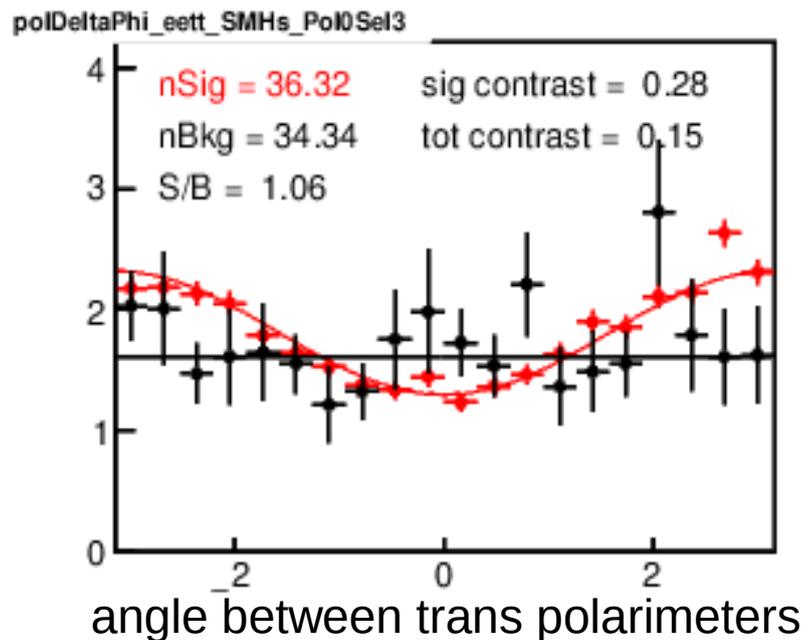


If everything is known perfectly, this is distributed as

$$f(\delta\varphi) \sim 1 + (\pi^2/16) \cos(\delta\varphi + \psi)$$

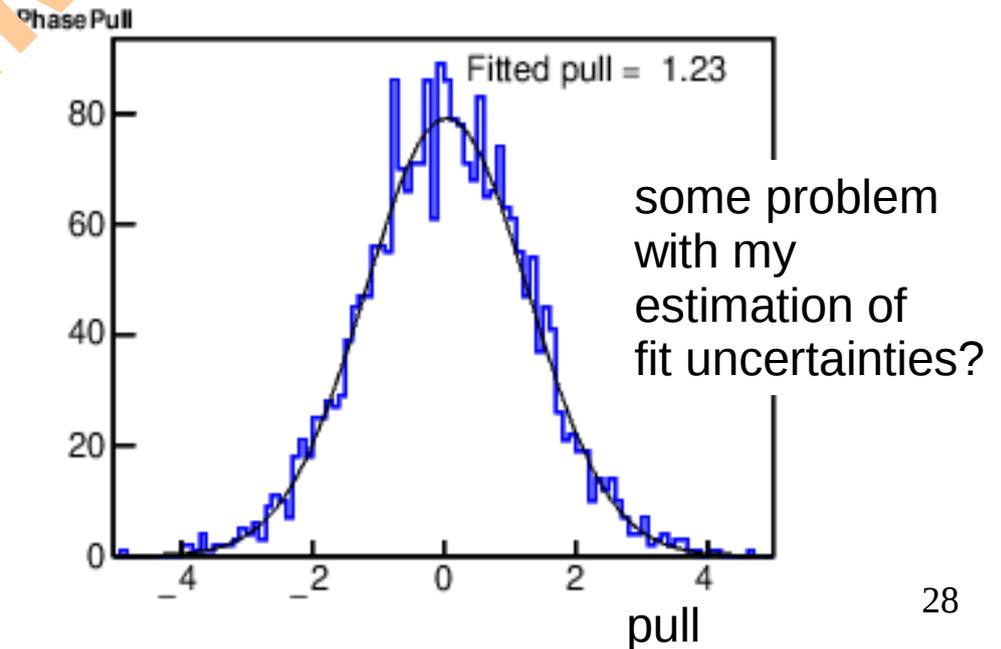
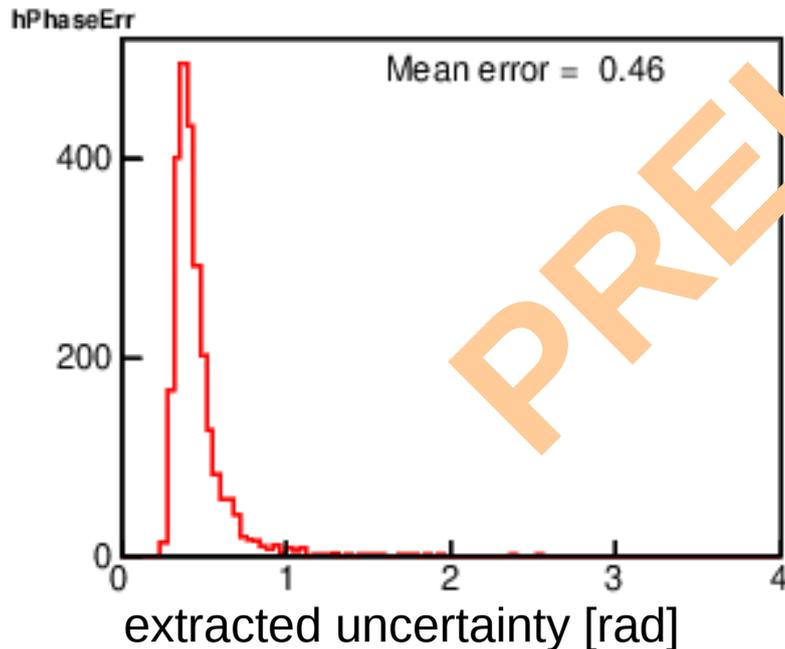
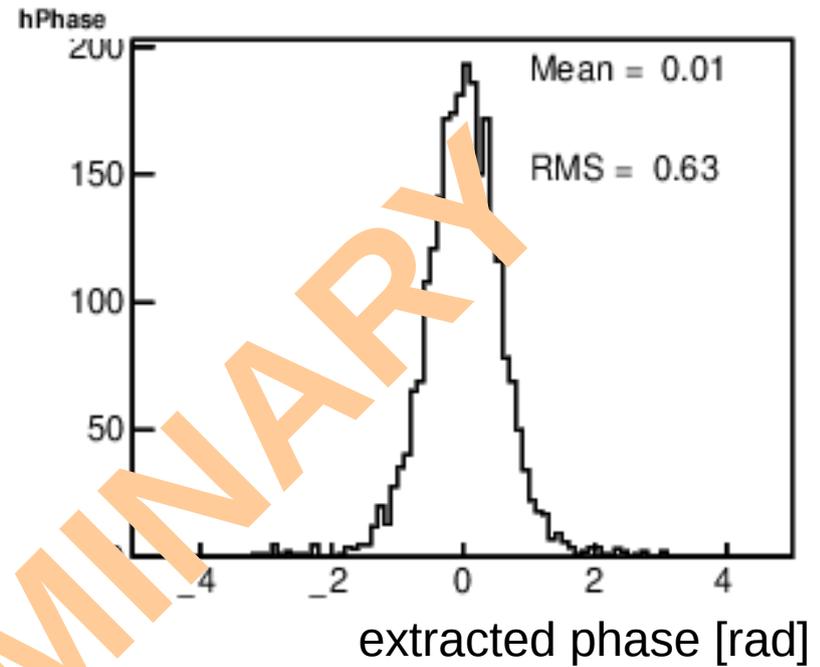
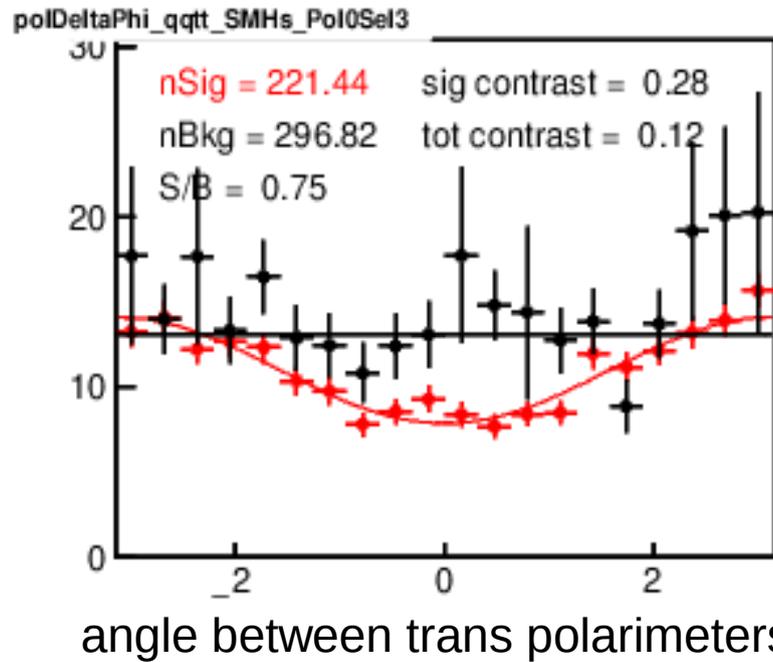
results of toy MC experiments: $e\bar{e}\tau$ channel

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



results of toy MC experiments: qq τ channel

$P(e^-, e^+) = (-0.8, +0.3)$, 1350 fb $^{-1}$



Results *all preliminary*

several caveats:

- selections not carefully optimised
- included major, but not all, backgrounds
- increased MC statistics required in places
- pull distributions not perfect:
probable underestimation of uncertainties

CP Violation needed to explain baryon asymmetry of universe

currently known sources of CPV not sufficient

Higgs of the minimal SM is CP even eigenstate,
with CP conserving couplings

more complex models often also have CP odd states
(H_{125} being pure CP odd is \sim ruled out by LHC)

in the case of CP violation in the Higgs sector,
H and/or its decay products may not be an eigenstate of CP

could the Higgs sector be an additional source of CPV?

leptonic preselection:

exactly 1 Z candidate:

pair of opposite sign, same MarlinPandora PID leptons

$E_{lep} > 20$ GeV

add photons within $\cos\Theta > 0.99$ of lepton

$(m - m_Z) < 10$ (15) GeV for $mumu$ (ee)

reject if $Z \rightarrow ee$ & $|\cos\theta(\text{electron})| > 0.95$

require ≥ 2 additional charged PFOs

highest energy pair considered as tau seeds

require than tau seeds not identified as electron or muon
and that seeds have opposite charge

starting with highest energy photons,

look for π^0 candidates which match a tau seed

[reasonable probability in constrained mass π^0 fit,
total mass with seed $< m_{\tau}$]

unpaired photons: attach to nearest tau if mass $< m_{\tau}$

leptonic selection

tighter lepton-lepton mass cut, within 10 GeV of m_Z for electrons

total pT and energy of remaining charged PFOs < 10 GeV

total pT and energy of neutral hadron PFOs < 10 GeV

visible mass of each tau jet < 1 GeV

no more than 1 π^0 candidate attached to each tau jet

<4 photon PFOs attached to each tau jet

successful reconstruction of tau momenta

110 GeV < tau-tau mass < 140 GeV

recoil mass > 110 (120) GeV for ee (mm)

hadronic preselection

exactly 2 tau jets from TauFinder

each tau jet contains 1 charged particle, not identified as electron or muon

each tau jet contains 0 neutral hadrons

each tau jet contains ≤ 3 photons

oppositely charged tau jets

hadronic selection

invariant mass of remainder of event $70 \rightarrow 110$ GeV

successful reconstruction of tau momenta

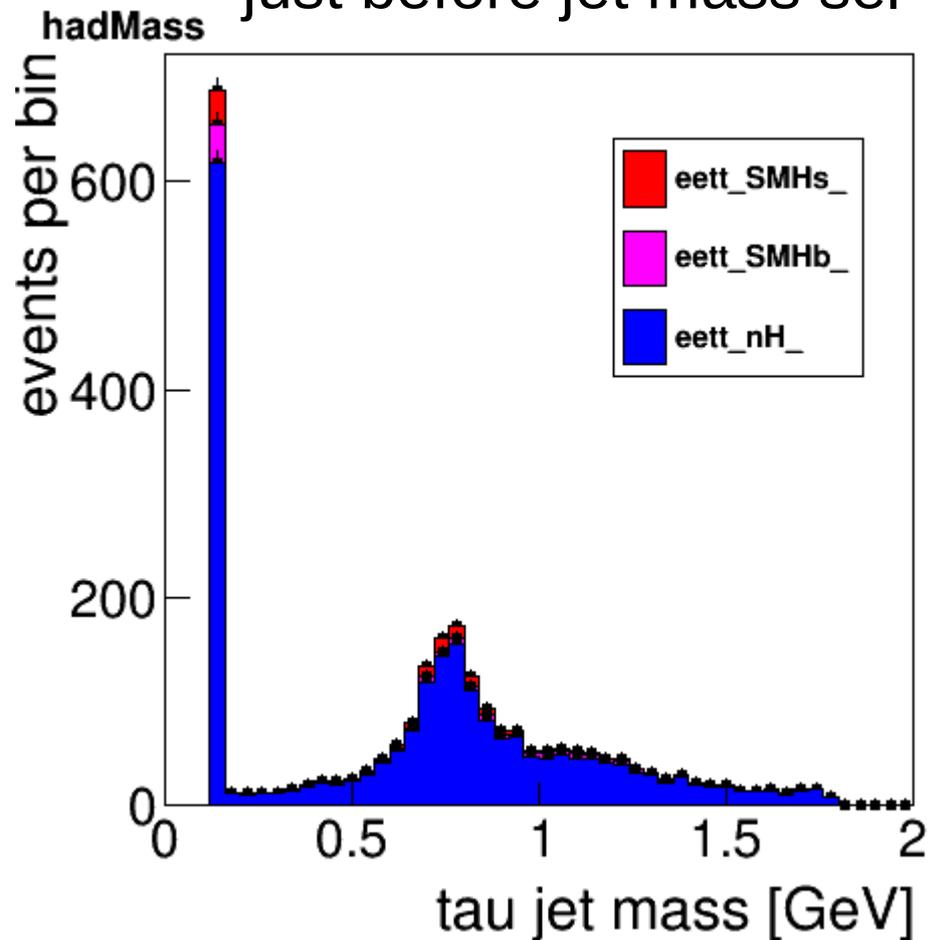
$100 \text{ GeV} < \text{tau-tau mass} < 150 \text{ GeV}$

recoil mass > 110 GeV

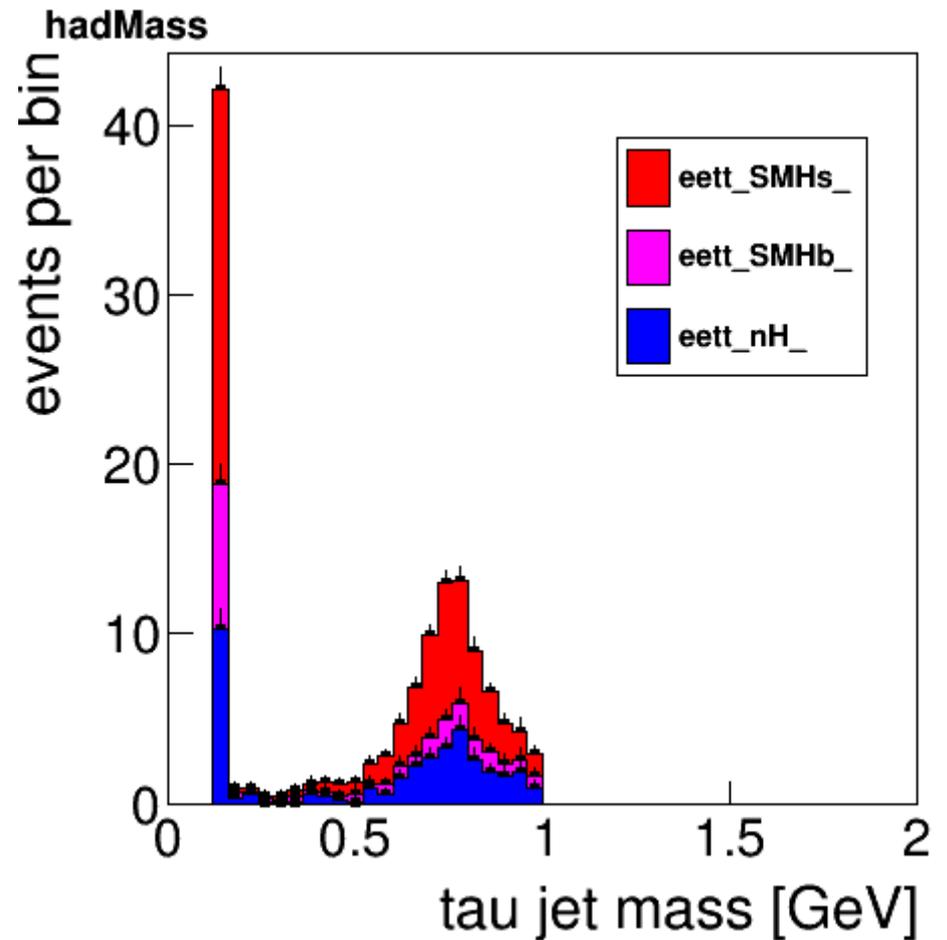
Tau jet mass (e e $\tau \tau$ selection)

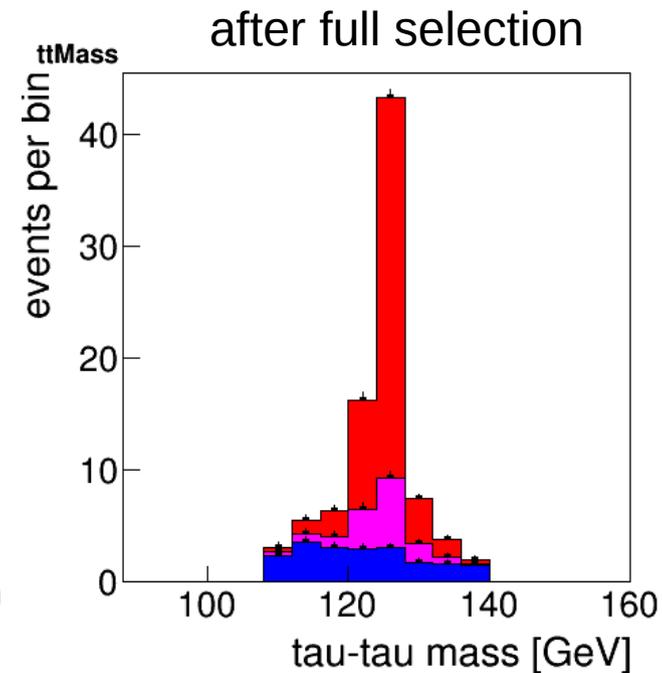
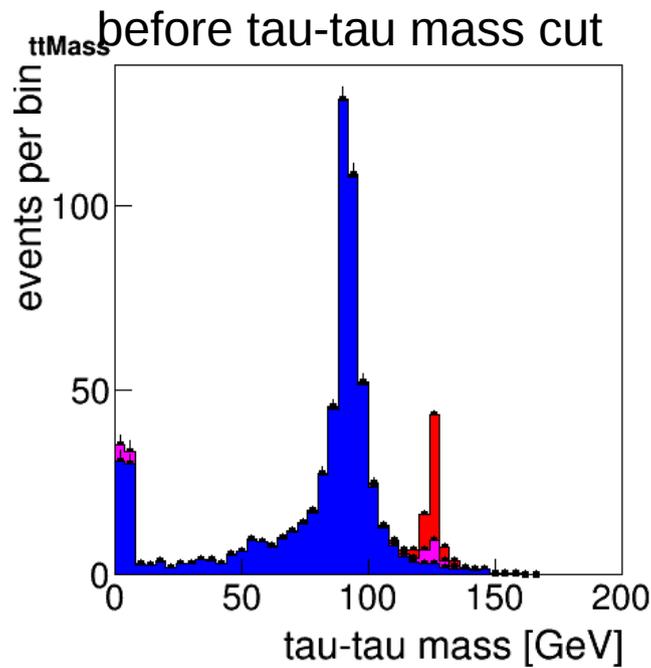
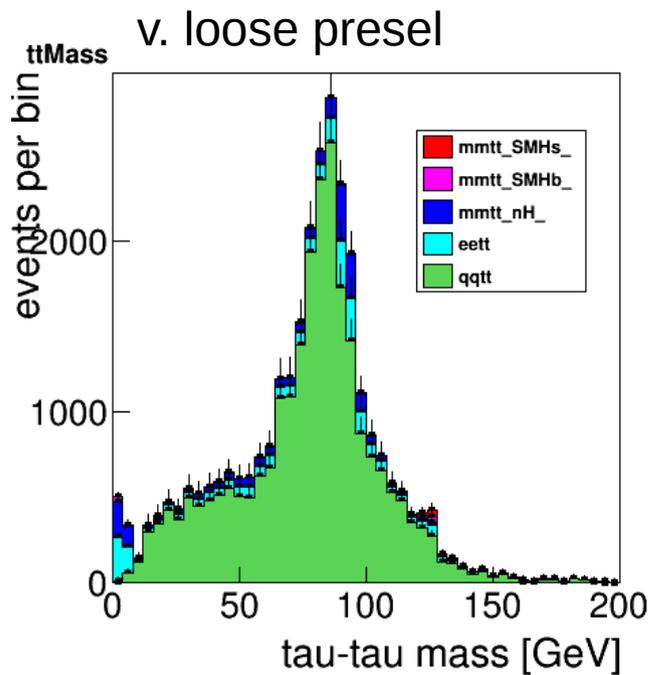
$P(e^-, e^+) = (-0.8, +0.3)$, 1350 fb⁻¹

just before jet mass sel



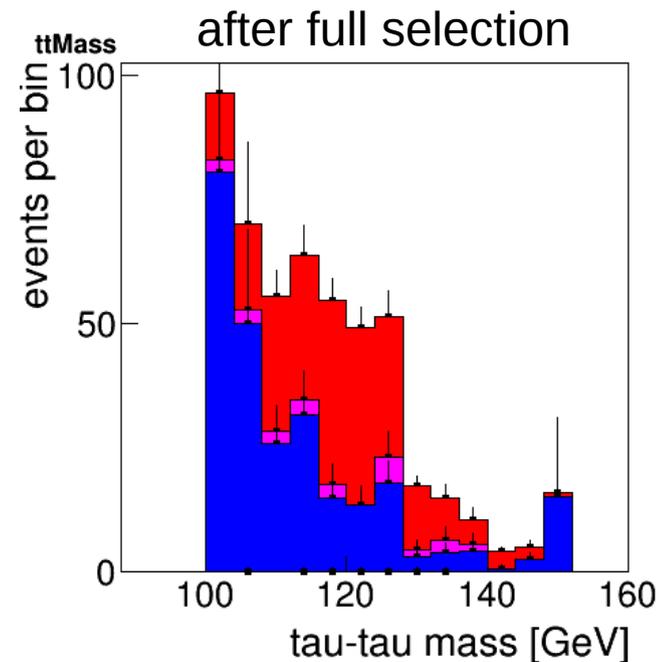
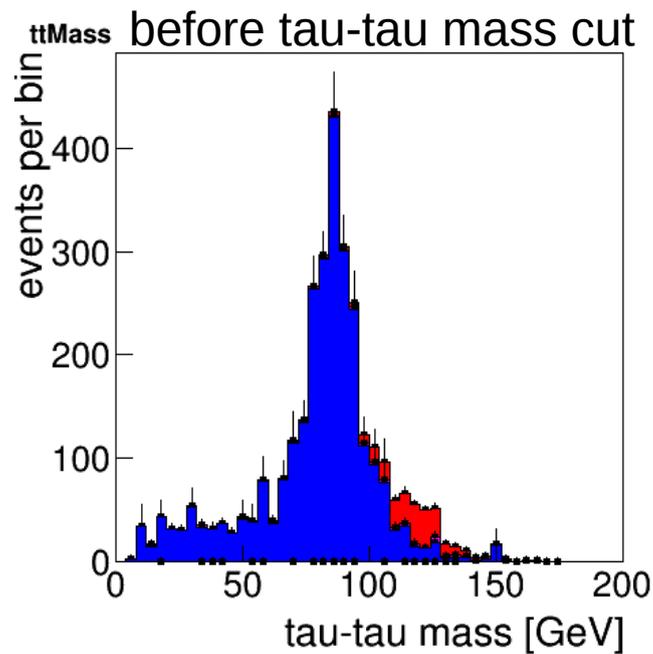
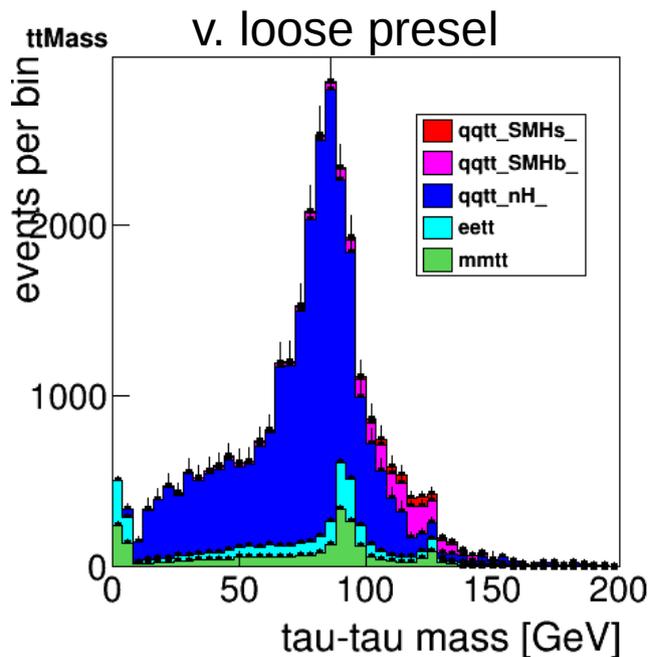
final selection





reconstructed tau-tau invariant mass
 $P(e^-, e^+) = (-0.8, +0.3), 1350 \text{ fb}^{-1}$

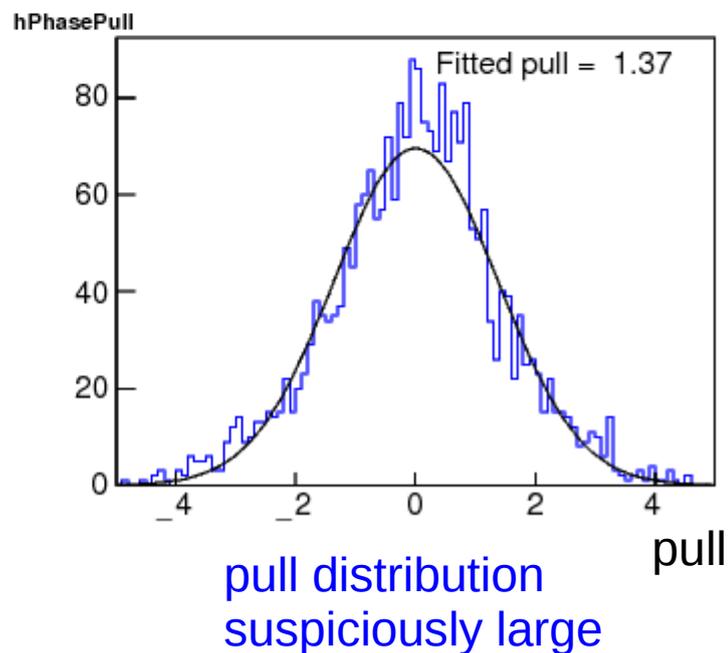
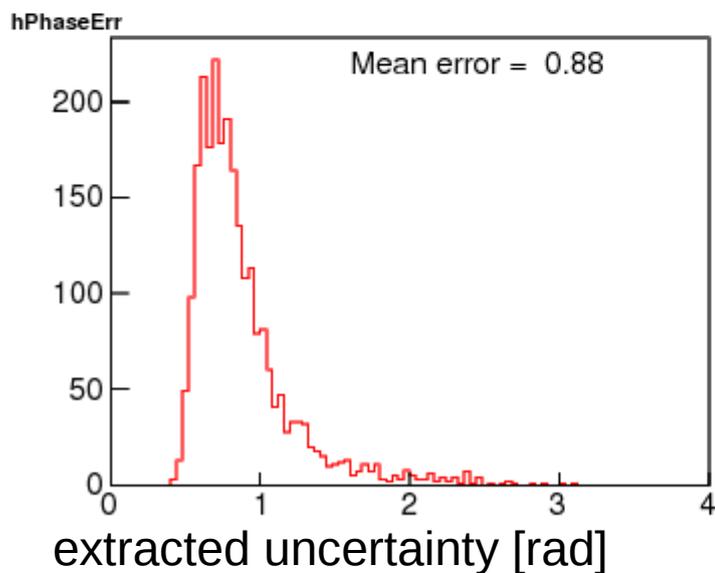
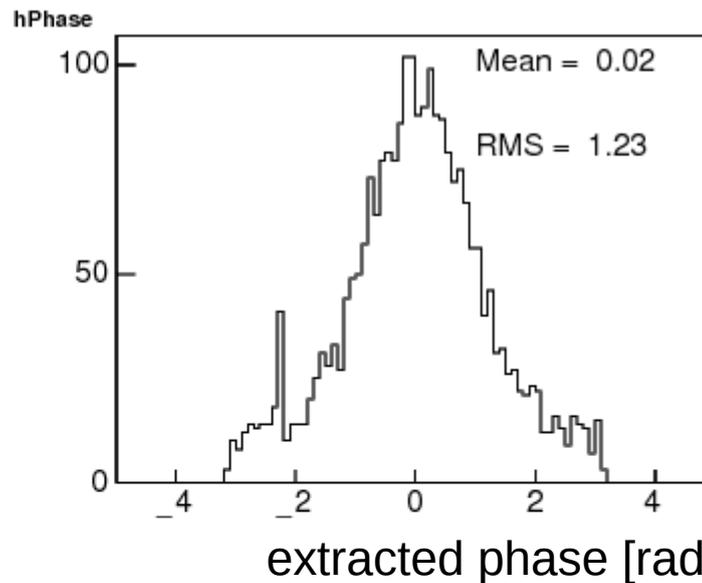
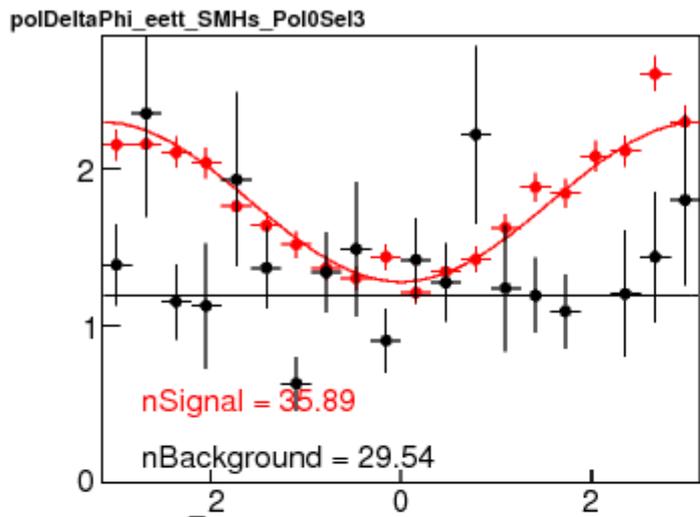
$\mu \mu \tau \tau \uparrow$
 $q q \tau \tau \downarrow$



e $\pi\pi$ channel

results of toy MC experiments

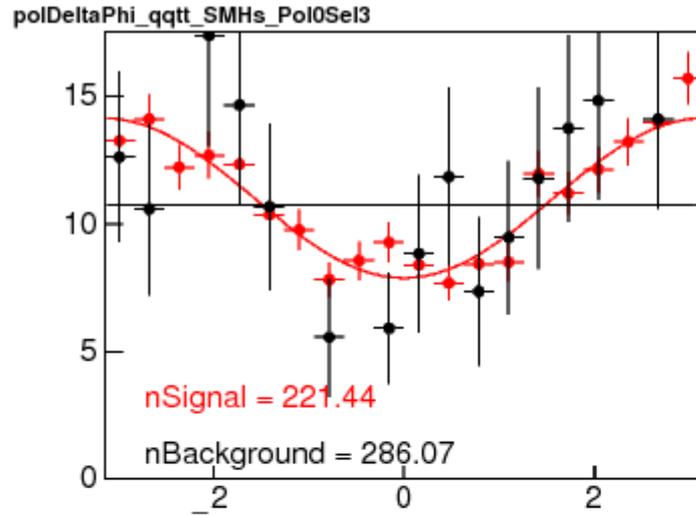
$P(e^-, e^+) = (-0.8, +0.3)$, 1350 fb $^{-1}$



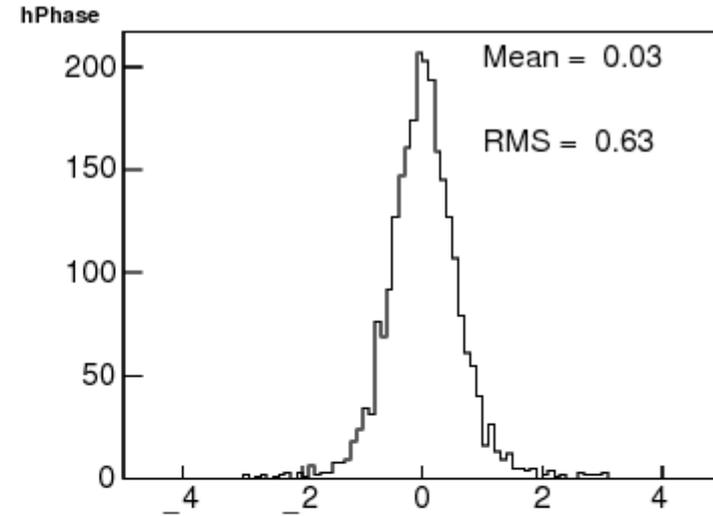
qq π channel

results of toy MC experiments

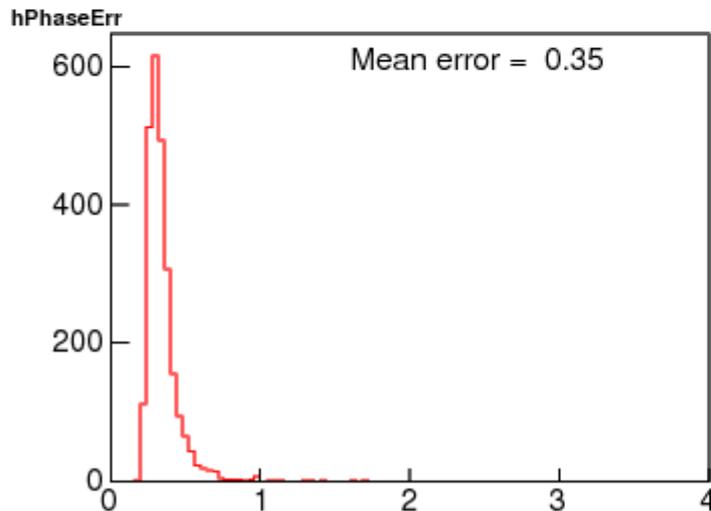
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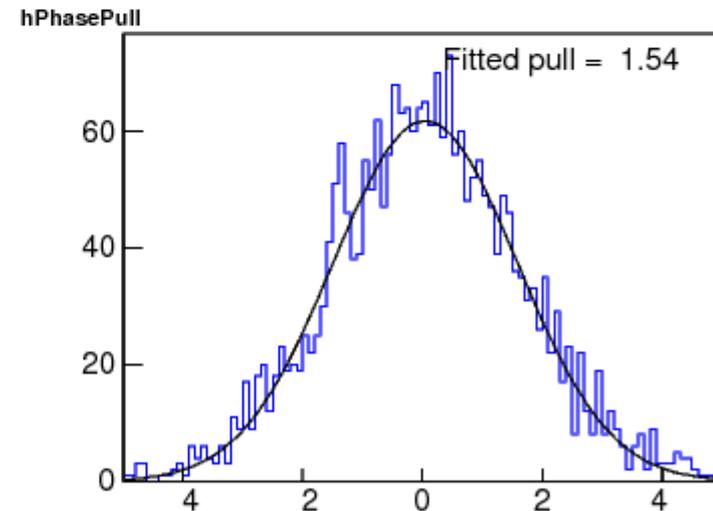
angle between trans polarimeters



extracted phase [rad]



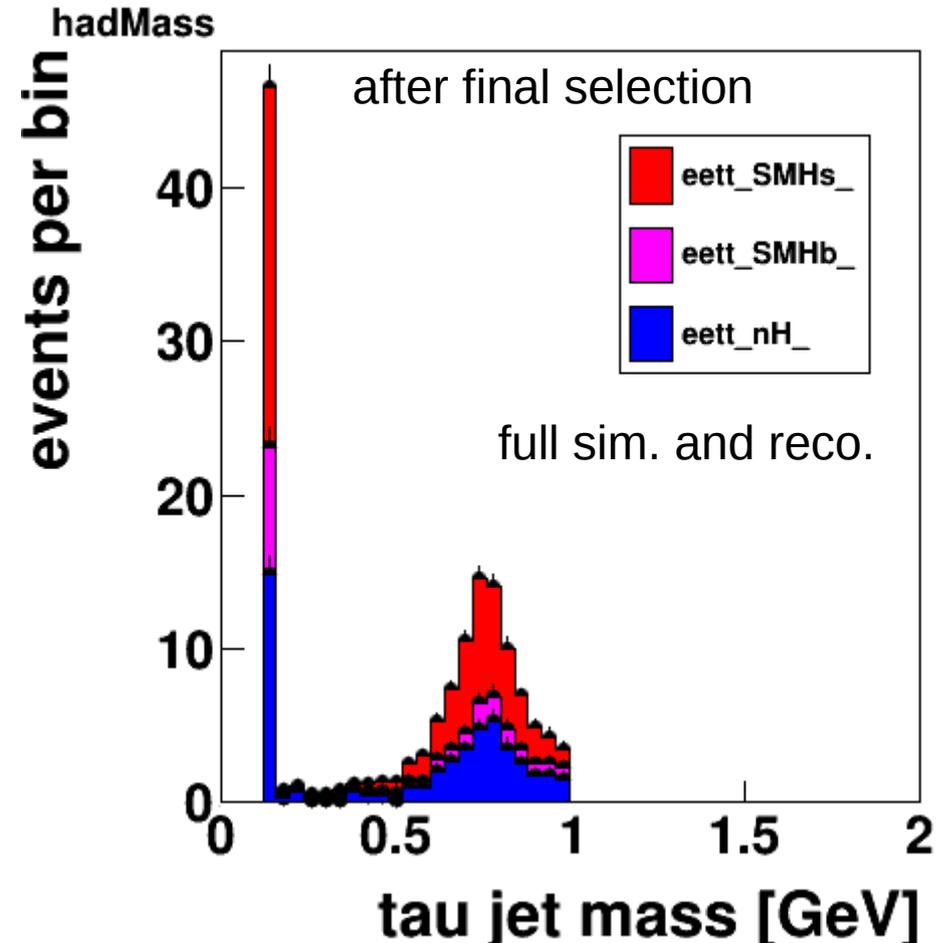
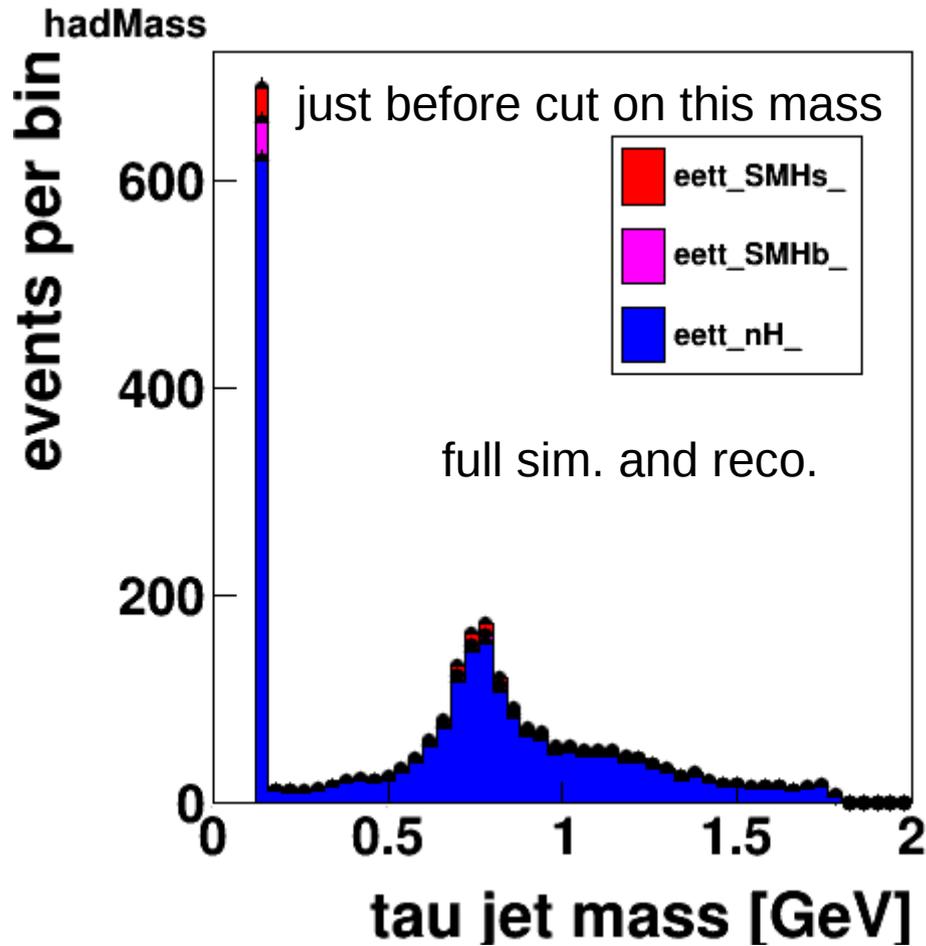
extracted uncertainty [rad]



pull distribution
suspiciously large

Visible mass of tau candidate jets

electron channel, 1350 fb⁻¹ @ $P(e^-, e^+) = (-0.8, +0.3)$



e e tau tau (SM Higgs, tau \rightarrow pi or rho) signal

e e tau tau (SM Higgs, other tau decay channels)

e e tau tau (non-Higgs) background