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

a progress report

→ all results preliminary

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projection of spin on some axis: ↑, ↓

spin state of pair of spin ½ particles
produced by spin-0 parent:

$(1/\sqrt{2})\ (\ |\uparrow\downarrow> + e^{i\xi}\ |\downarrow\uparrow>\ )$

$\xi = 0$: CP even eigenstate
$\xi = \pi$: CP odd eigenstate
otherwise a mixture

General coupling of Higgs to fermions

$$L = g \bar{f} (\cos \psi + i \gamma^5 \sin \psi) f H$$

if CP conserving coupling: $\psi=0$

If Higgs is CP even, then

$2\psi = \xi$ (from previous page)

distribution of spins (s) of fermions (f) from spin-zero parent

spin components parallel / perpendicular to flight direction

$$s_z \quad / \quad s_\perp$$

$$\Gamma(H \text{ (CP even)}, A \text{ (CP odd)} \rightarrow f^+ f^-) \sim 1 - s^+_z s^-_z \pm s^+_\perp s^-_\perp$$

CP state affects **tranverse** spin correlations

tau decay; polarimeter vector

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

Polarimeter vector **h** couples to spin **s**
depends on momenta of τ decay products

factor *a* depends on decay mode:
maximal for hadronic decays,
smaller for leptonic decays

h can be easily calculated for
$\tau^{\pm} \rightarrow \pi^{\pm} \nu$ and $\tau^{\pm} \rightarrow \pi^{\pm} \pi^{0} \nu$
if τ momentum is fully reconstructed
(BR ~ 11% and 25% respectively)

General strategy

Higgs-strahlung events

Fully reconstruct tau momenta

I know how to do for Higgs-strahlung & hadronic taus decays

Reconstruct polarimeter vectors

look at correlation between

transverse components of

reconstructed polarimeter vectors in

$H \rightarrow \tau^+ \tau^-$

in $\tau^\pm \rightarrow \pi^\pm \nu$ and $\tau^\pm \rightarrow \pi^\pm \pi^0 \nu$ decay modes

Extract CP-violating angle ψ

simulation, reconstruction

whizard 2.2.8, CIRCE2 beams, ISR

e+ e- → μ+μ-τ+τ- (τ+τ- from 125 GeV Higgs)

e+ e- → μ+μ-τ+τ- (τ+τ- not from Higgs)

pythia v8.212

tauola c++ v1.1.4

restrict to $\tau^{\pm} \rightarrow \pi^{\pm} \nu$ and $\tau^{\pm} \rightarrow \pi^{\pm} \pi^{0} \nu$ "rho / ρ"

add spin correlations (H_{SM}, $H_{\not CP}(\psi=\pi/4)$, non-H)

Mokka simulation ILD_o1_v05

(more or less) standard Marlin/ILDConfig reconstruction

leptonic Z channel

look for $Z \rightarrow \mu^+\mu^-$, e^+e^-

require exactly 2 additional charged PFOs (no underlying event)
- not muon-like or electron-like
- opposite charge
- treat as tau jet seeds

starting with highest energy photon candidates,
- try to make pi0 consistent with tau mass
- apply mass constraint to pi0s: keep if good probability

add remaining “orphan” photons to tau jet
- if they don't take it over the tau mass

if no leptonic Z found, apply **“hadronic” selection**

use TauFinder (T. Suehara) to look for tau jets

require exactly two
    single prong tau jets of
        opposite charge

assume all other PFOs are in recoiling system

Then apply my **tau fitting** procedure NIM A810 (2016) 51-58
arXiv:1507.01700

6 unknowns per tau pair: two neutrino 3-momenta

6 constraints:
- tau invariant mass (2)
- tau impact parameter plane (2) ← requires good knowledge of IP
- event transverse momentum (x,y = 2) ← little effect from ISR

[method minimizes pT, other constraints applied exactly]

typically get several solutions:
- choose only those with positive tau decay lenths and pT < 1 GeV
- of those, choose one with tau-tau mass closest to 125 GeV

calculate polarimeter vector: [probably too simple, could be improved]
- treat as rho decay if >0 photons
- treat as pi decay if 0 photons

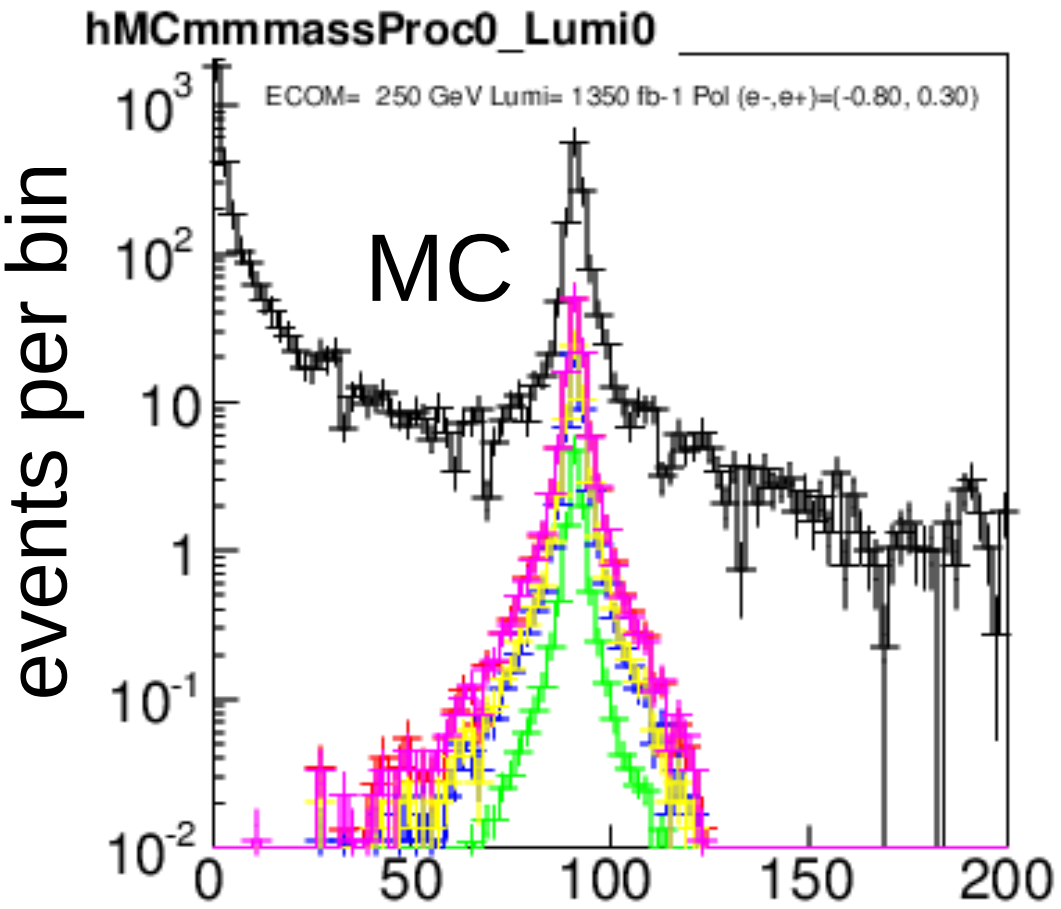
only 250 GeV for now [pessimistic]

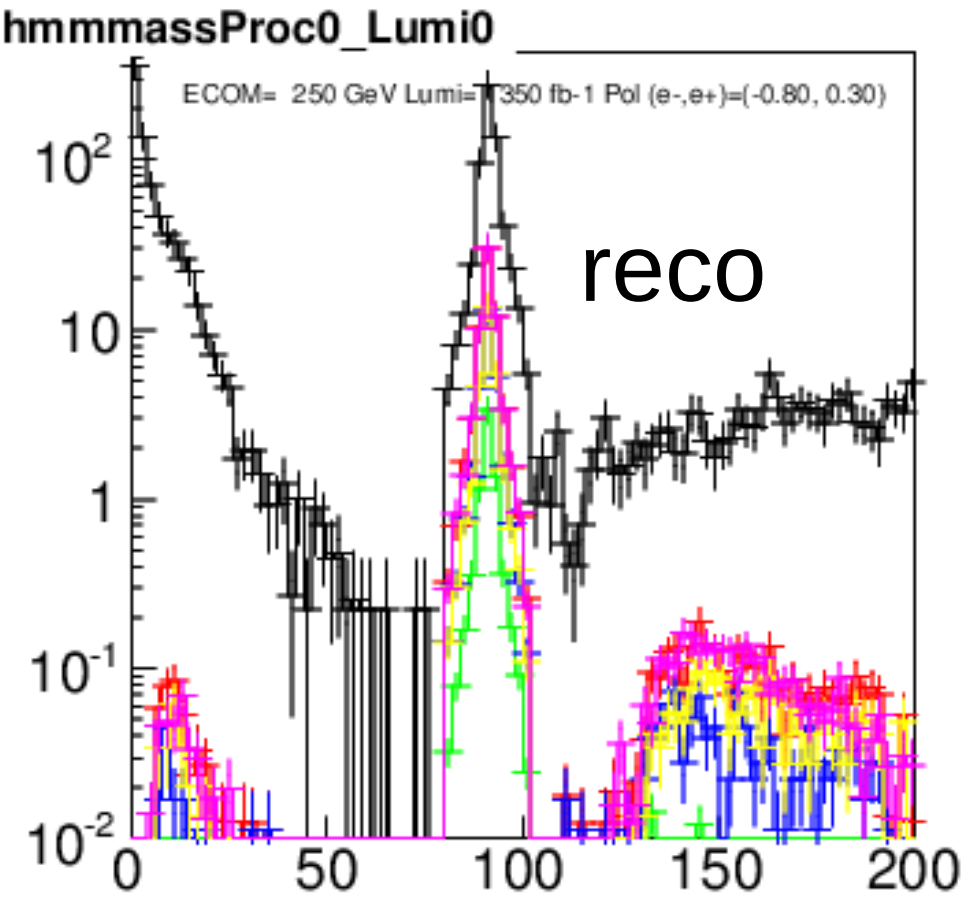
only Z → mu+ mu- for now [pessimistic]

Scale data to full H20 program
1350 fb-1 @ polarisation -80, +30
450 fb-1 @ polarisation +80, -30

only tau decays to π± & (π± π0)
[a little over-optimistic,
there may be some cross-talk from other modes]

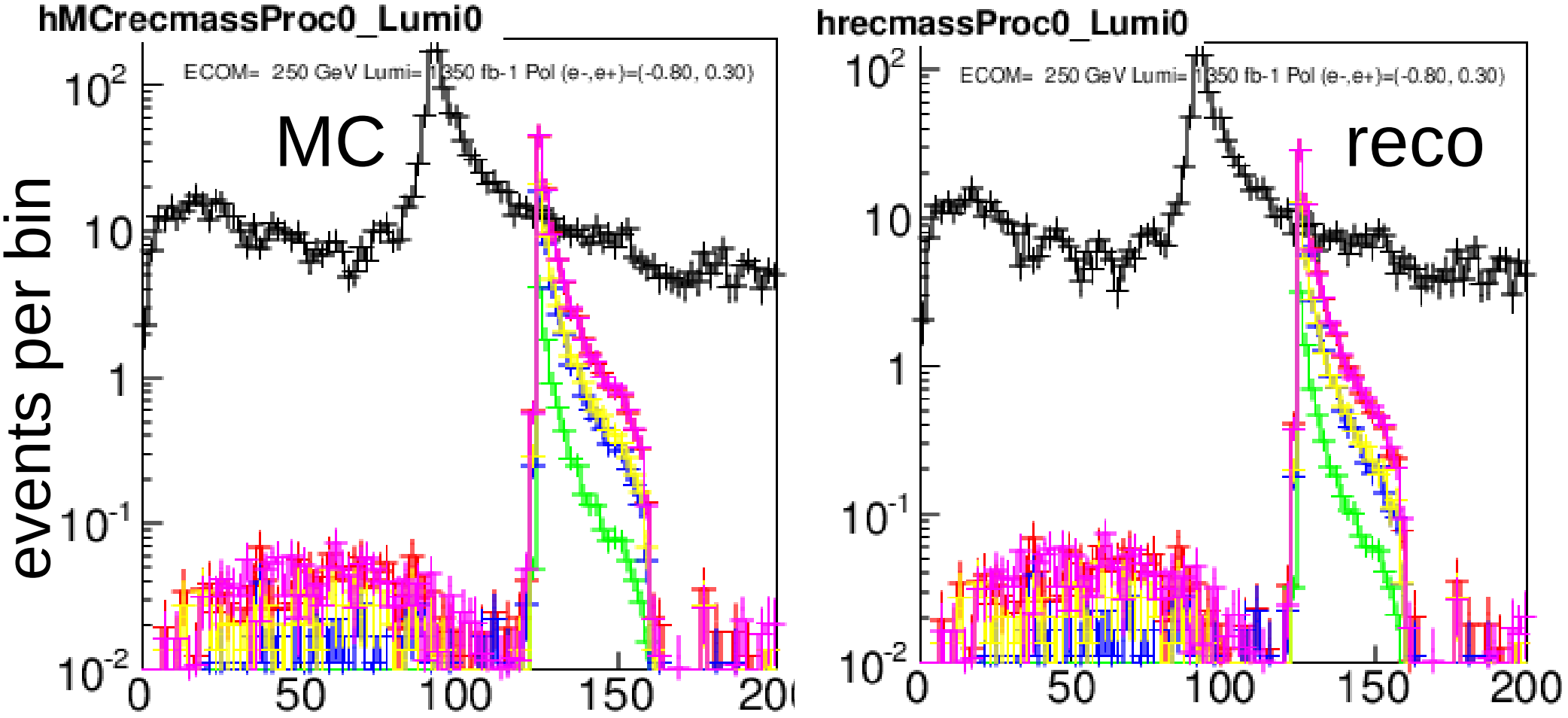
non-Higgs, $H_{SM} = \pi\pi + \pi\rho + \rho\rho$, $H_{\not CP}$



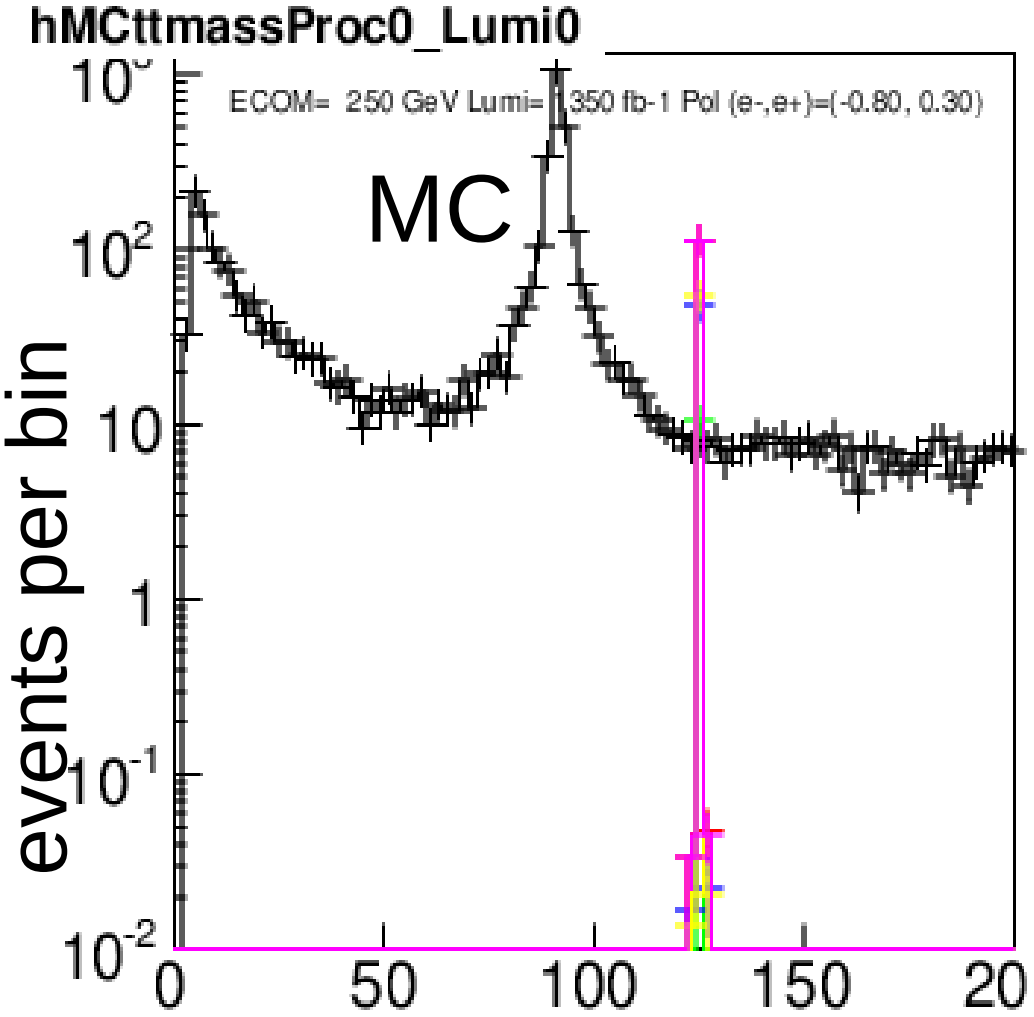


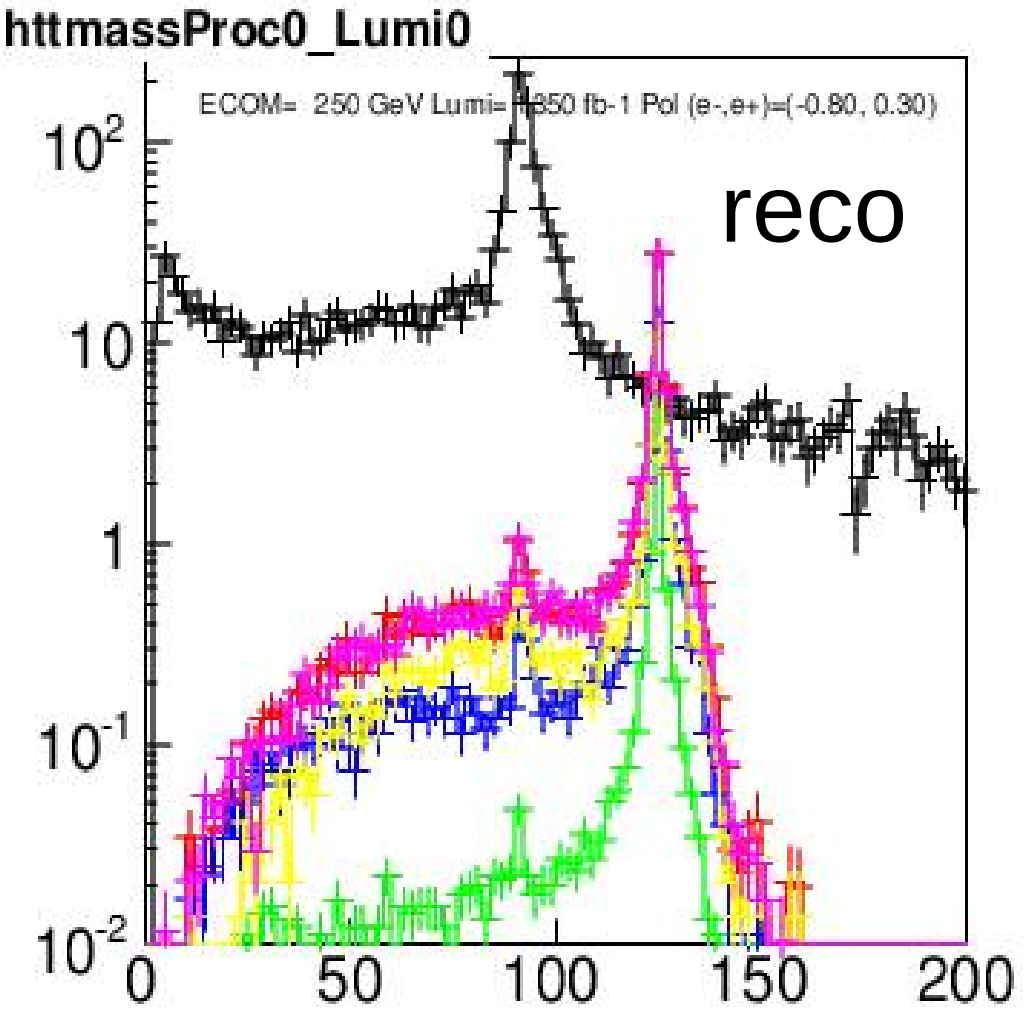
mu-mu invariant mass [GeV]

non-Higgs, H_{SM} = ππ + πρ + ρρ, $H_{\not CP}$



non-Higgs, $H_{SM} = \pi\pi + \pi\rho + \rho\rho$, $H_{\not CP}$





tau-tau mass [GeV]

Use these 3 observables

mu-mu mass,

mass recoiling against mu-mu

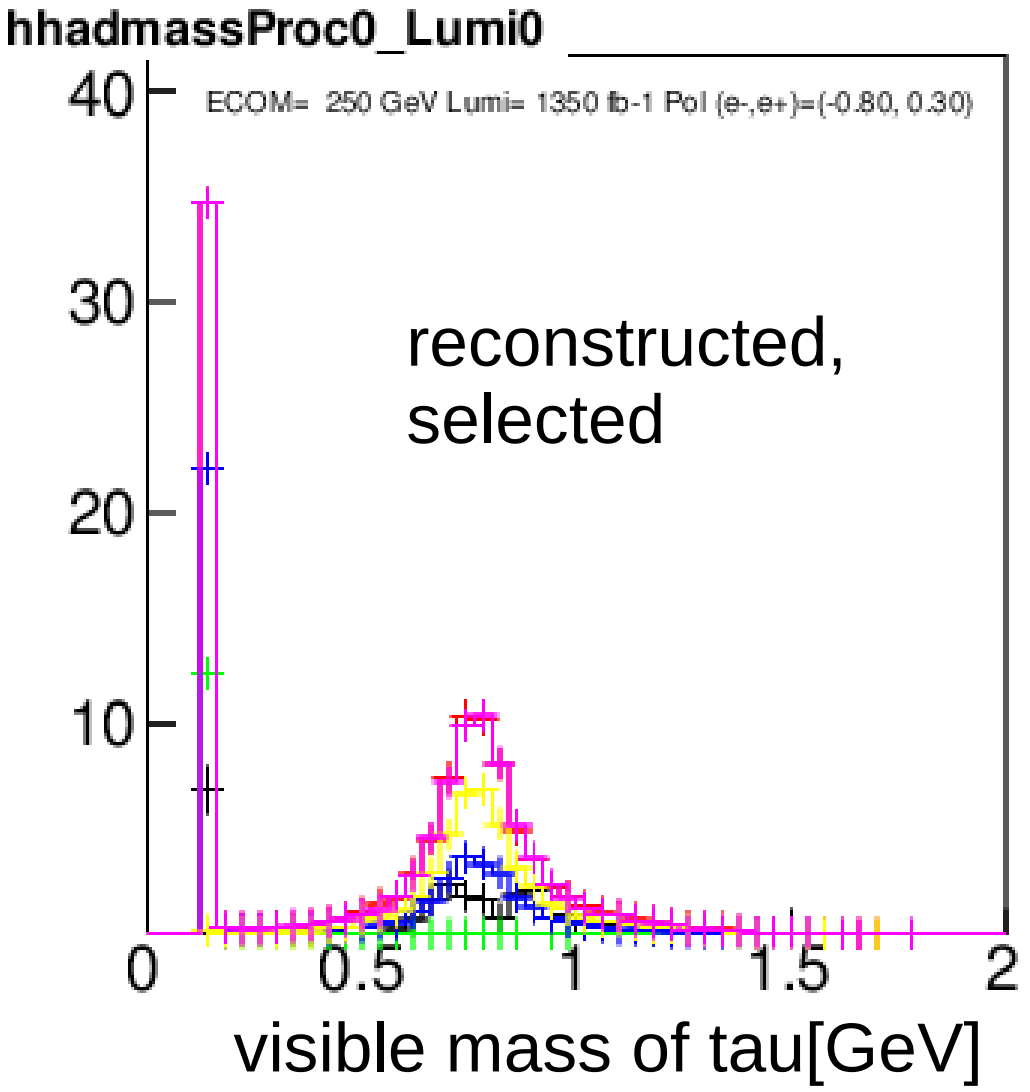
tau-tau mass

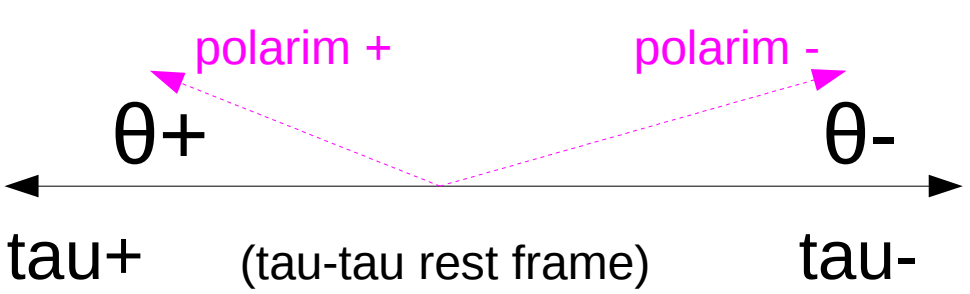
to reject non-H background

non-Higgs,

$H_{SM} = \pi\pi + \pi\rho + \rho\rho$,

H_{CP}





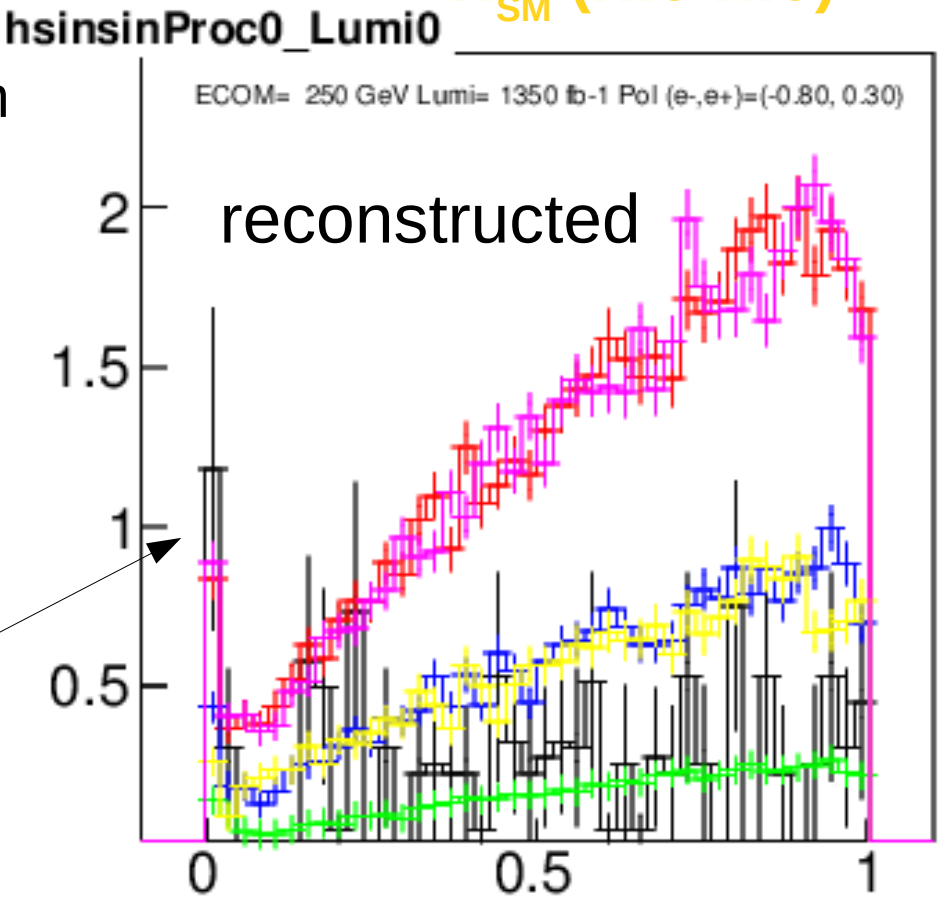
non-H
H_{SM} (CP even)
H (CP mix)
H_{SM} (pi pi)
H_{SM} (pi rho)
H_{SM} (rho rho)

Longitudinal polarimeter components

angle between polarimeter and momentum (in tau-tau rest frame)

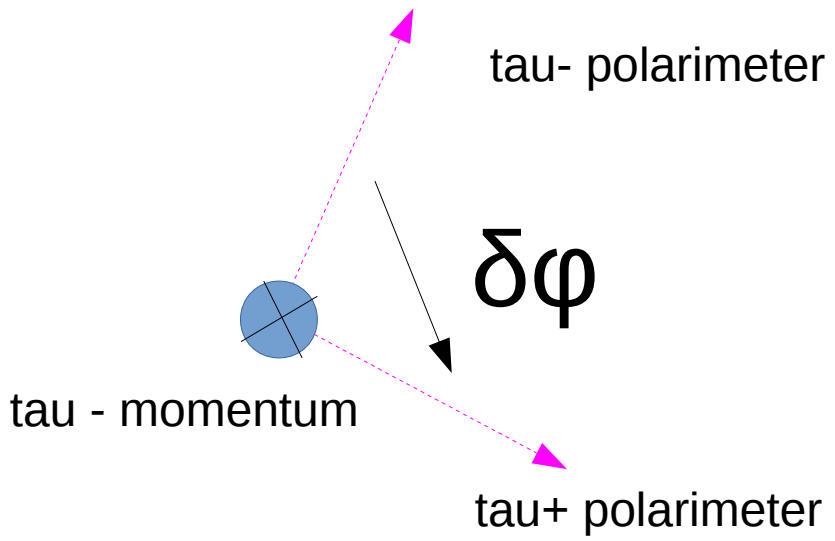
remember:

$$\Gamma(H, A \rightarrow f^+ f^-) \sim 1 - s^+_z s^-_z \pm s^+_\perp s^-_\perp$$



remove these badly reconstructed events

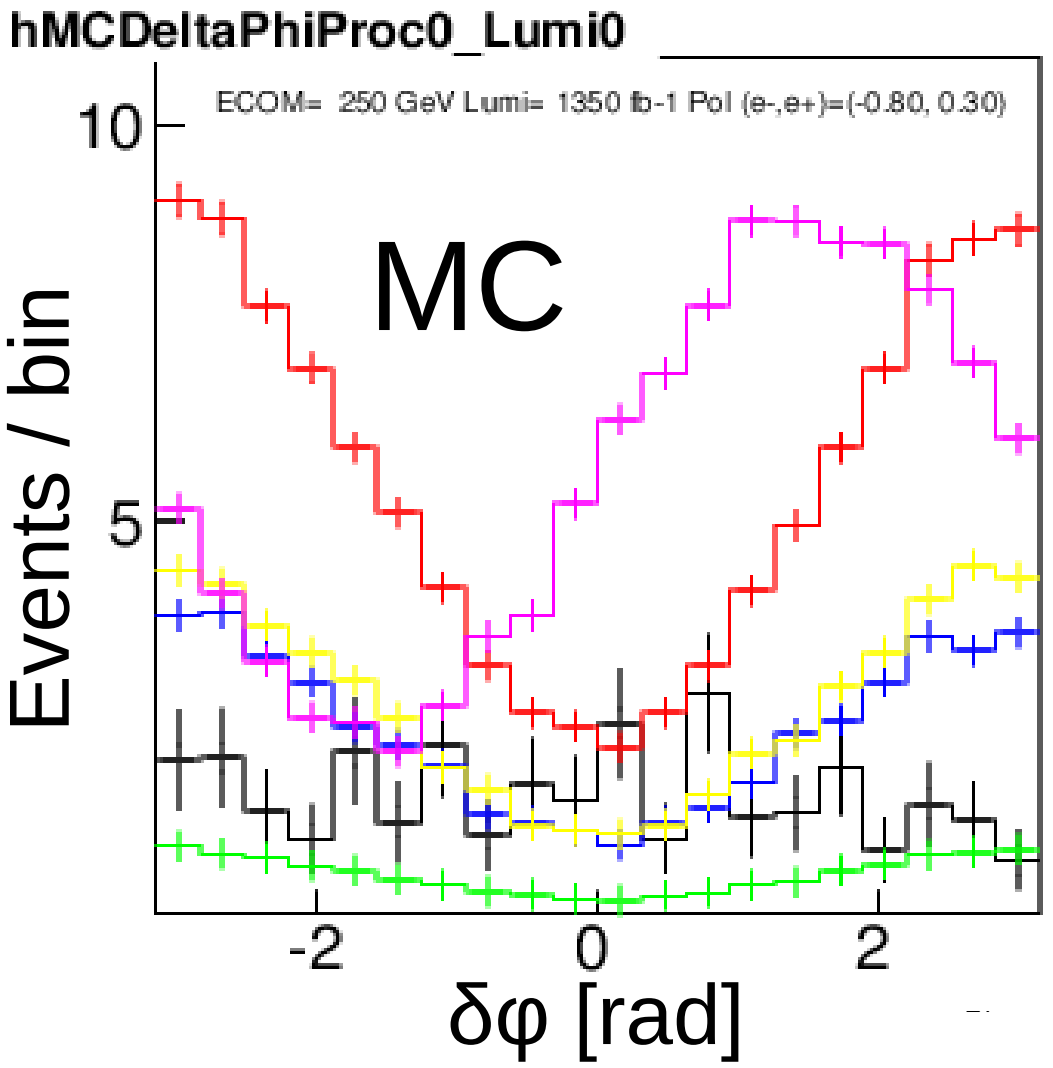
transverse spin correlations



non-H

H_{SM} (CP even)

H (CP mix)



$L = g \bar{f} (\cos \psi + i \gamma^5 \sin \psi) f H$

H_{SM} (CP even) has $\psi = 0$

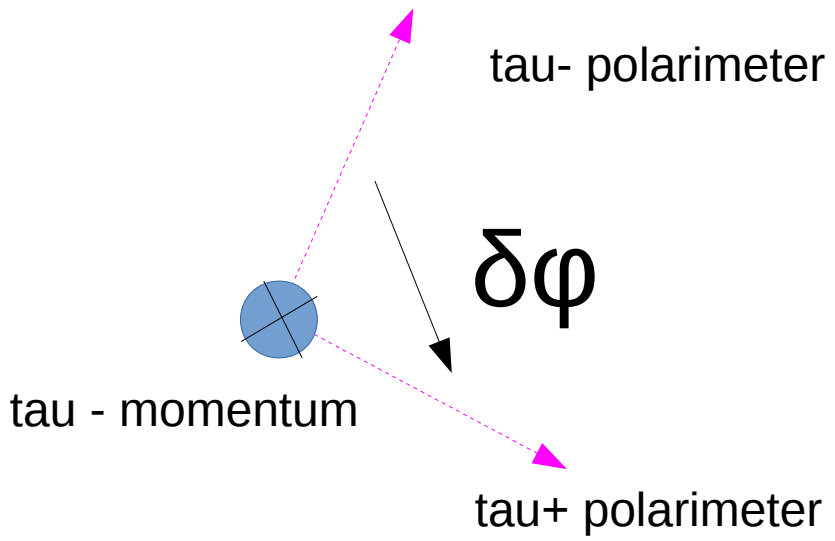
H (CP mix) has $\psi = \pi/4$

clear modulation, depends on ψ

expect $f(\delta\varphi) \sim 1 - A (\delta\varphi - 2\psi)$

non-H background ~flat

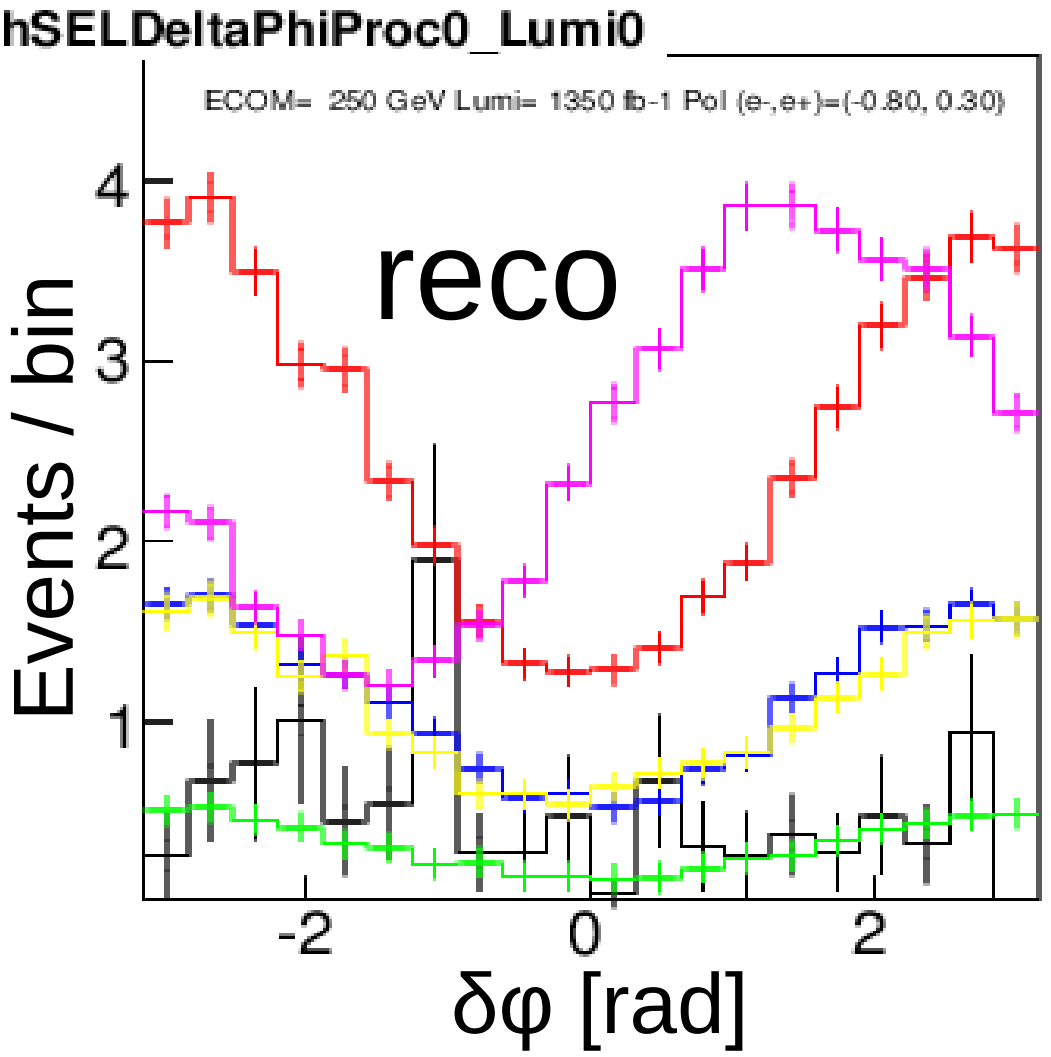
transverse spin correlations



non-H

H_{SM} (CP even)

H (CP mix)



$L = g \bar{f} (\cos \psi + i \gamma^5 \sin \psi) f H$

H_{SM} (CP even) has $\psi = 0$

H (CP mix) has $\psi = pi/4$

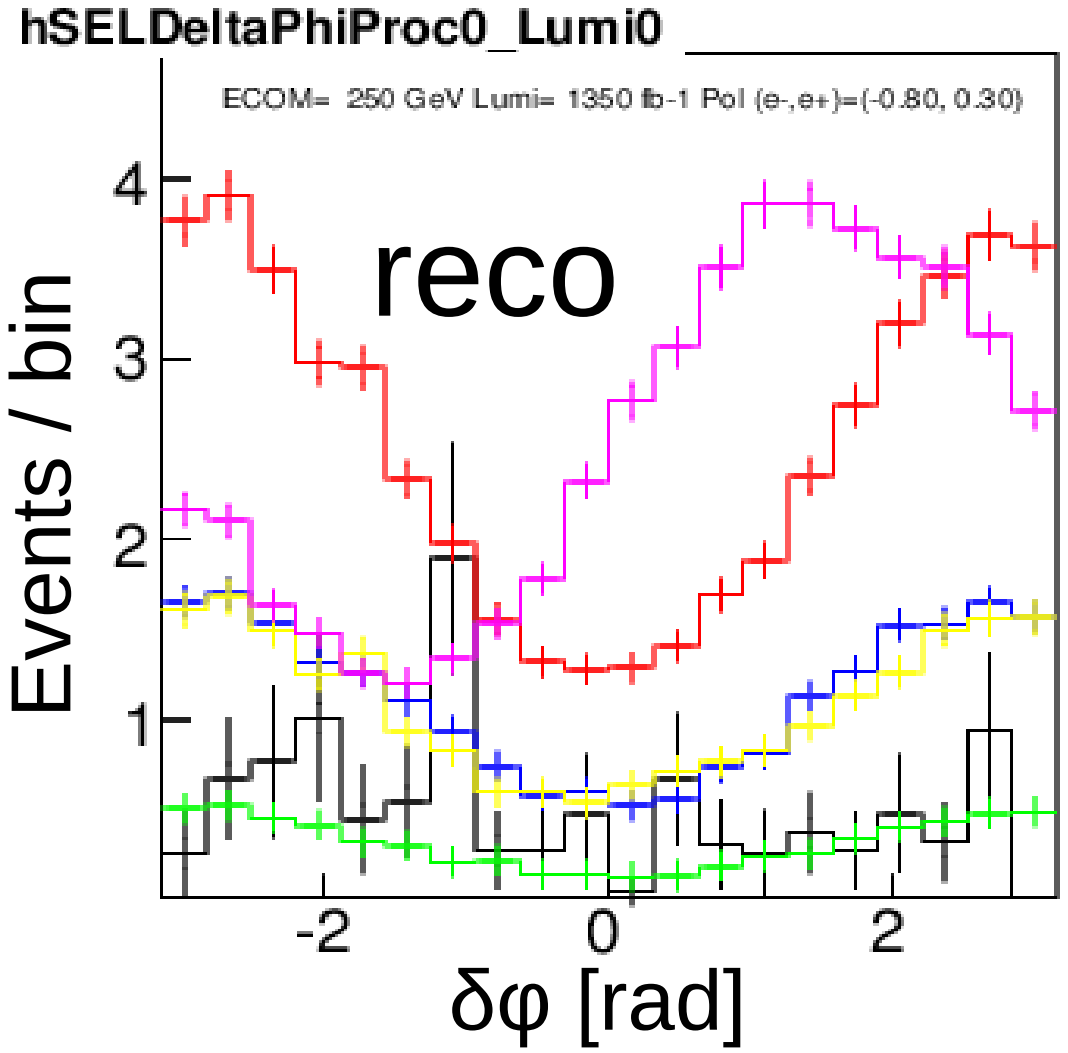
reconstruction:

- loses statistics
- loses contrast
  - but still looks OK

efficiencies, numbers of events after H20

250 GeV only, Z → mu mu only

process	final efficiency	final events (-0.80, +0.30)	final events (+0.80, -0.30)
H_{SM} (pi pi)	60 %	6	1
H_{SM} (pi rho)	48 %	23	5
H_{SM} (rho rho)	40 %	22	5
H_{SM} (sum)	51 %	51	11
non-H	0.2 %	10	2



Sensitivity

Fit red curve with
a * (1 – b * cos (dPhi))

Assume BG is flat

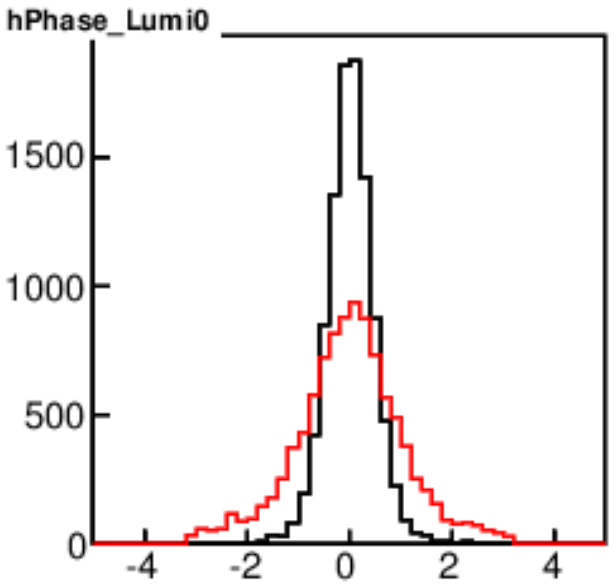
estimate expected number of signal, BG events

run toy MC experiments using these inputs

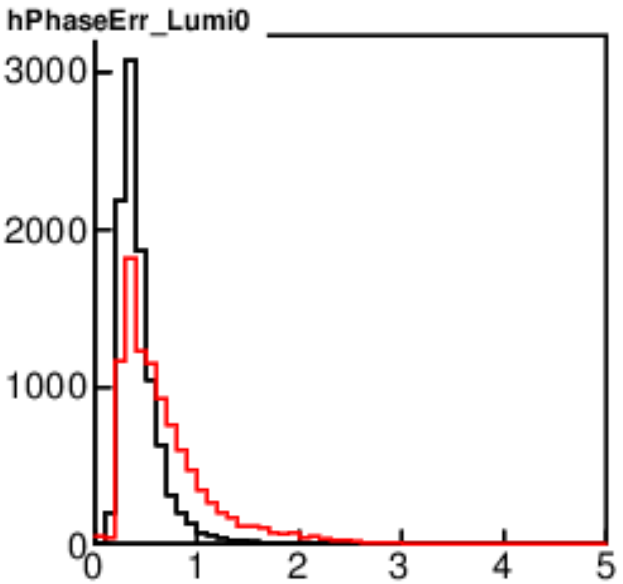
Unbinned maximum likelihood fit to resulting dPhi values

toy MC results

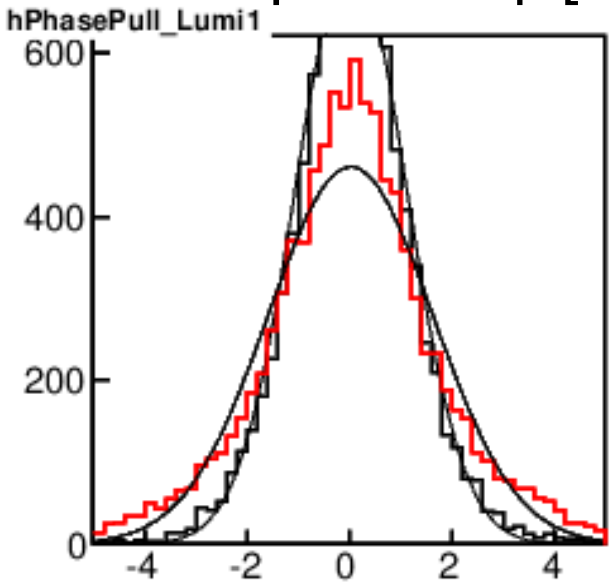
preliminary



extracted phase 2ψ [rad]



error on phase [rad]



pull

Full H20 @ 250 GeV, Z → mu mu

Pe-, e+ = -0.80, +0.30

+0.80, -0.30

mean error on

2ψ ~ 0.45 (0.69) radians

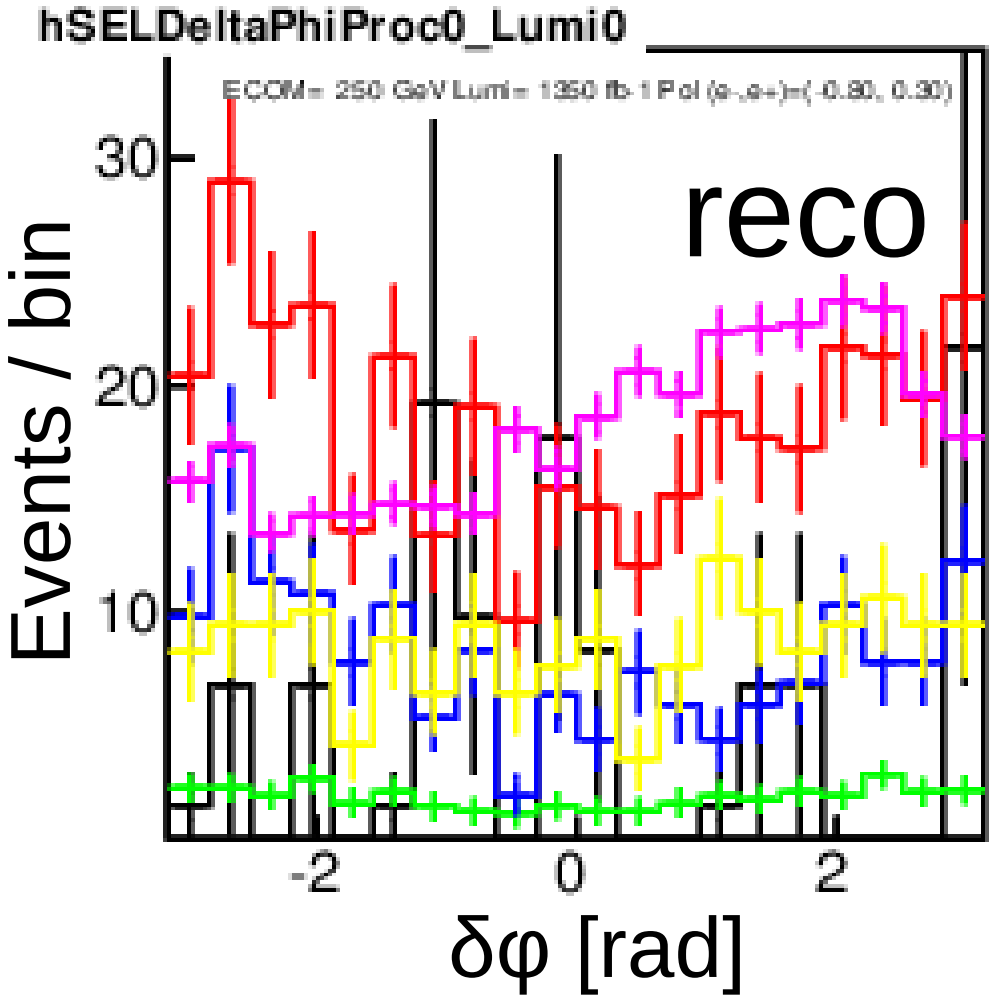
ψ ~ 0.23 (0.35) radians

~ 13 (20) degrees

Pull looks a little strange...

very prelim

First look at hadronic Z decays (uds only)



more events

less strong modulation

non-H

H_{SM} (CP even)

H (CP mix)

H_{SM} (pi pi)

H_{SM} (pi rho)

H_{SM} (rho rho)

very prelim

First look at hadronic Z decays (uds only)

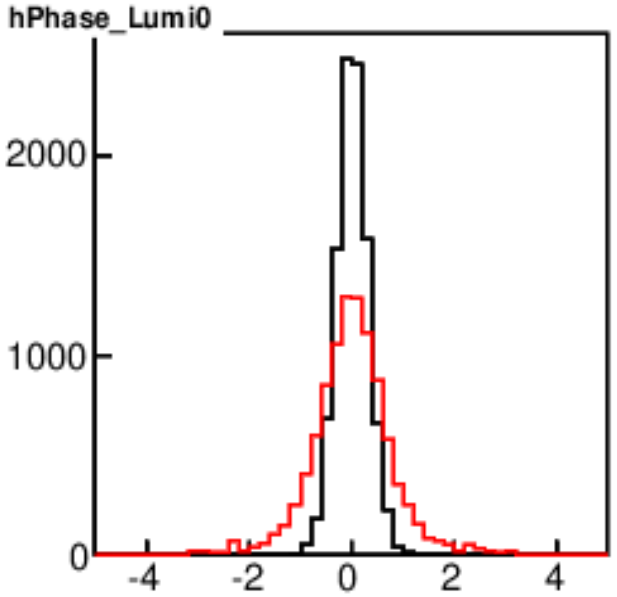
efficiencies, numbers of events after H20

250 GeV only, Z → uds only

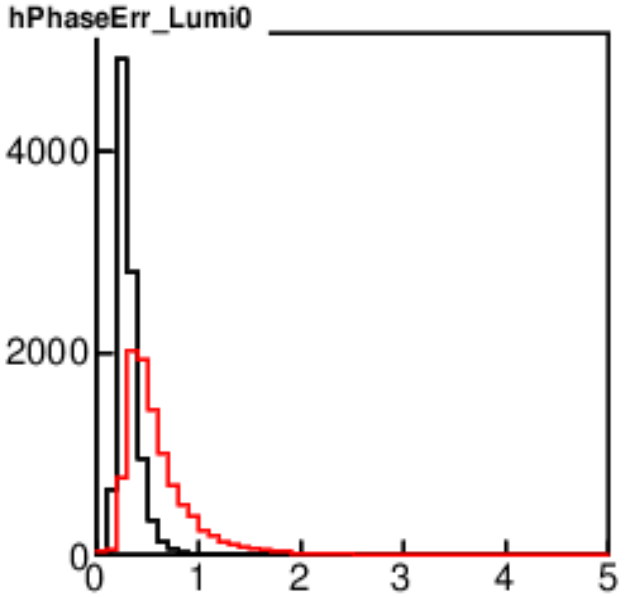
process	final efficiency	final events (-0.80, +0.30)	final events (+0.80, -0.30)
H_{SM} (pi pi)	29 %	37	8
H_{SM} (pi rho)	28 %	163	37
H_{SM} (rho rho)	25 %	170	38
H_{SM} (sum)	27 %	370	83
non-H	0.6 %	109	21

very prelim

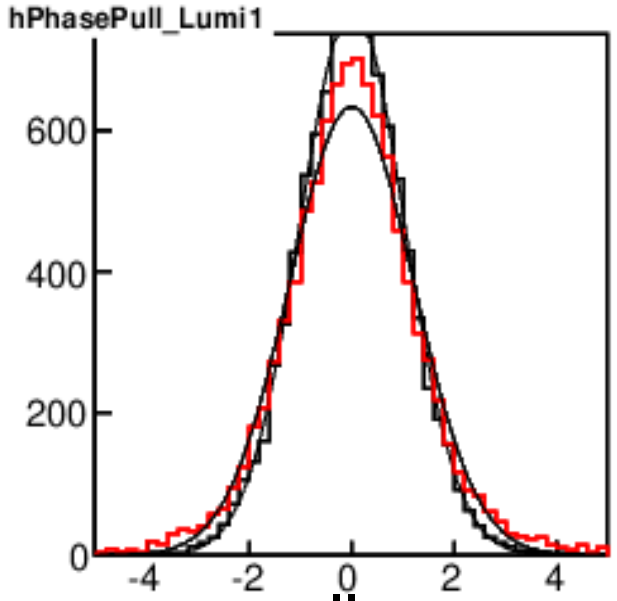
First look at hadronic Z decays (uds only)



extracted phase 2ψ [rad]



error on phase [rad]



pull

Toy MC results

Full H20 @ 250 GeV, Z → uds

Pe-, e+ = -0.80, +0.30

+0.80, -0.30

mean error on

2ψ ~ 0.32 (0.61) radians

ψ ~ 0.16 (0.31) radians

~ 9 (18) degrees

Pull looks not perfect...

CP nature of tau pairs from Higgs(-strahlung) decays

fully reconstruct tau momenta and polarimeter vectors
in $\tau^{\pm} \rightarrow \pi^{\pm} \nu$ and $\tau^{\pm} \rightarrow \pi^{\pm} \pi^{0} \nu$ decay modes
(total BR ~ 36%/tau ~ 13%/Higgs)

correlation between transverse components sensitive to CP

some effects ignored for now:
beam backgrounds
cross-talk from other tau decay modes
other backgrounds (not μμττ final state: expect to be small)

H20 $Z \rightarrow$ mu mu @ 250 GeV
gives precision on CP violating angle ~ 13 deg ← preliminary

expect $Z \rightarrow$ electron mode to have similar power

hadronic Z decay less clean, but more statistics.
seems to have slightly better sensitivity (~9 deg ← very preliminary)

Plans:

refine analysis (esp. hadronic Z decays)

use Z → electrons

Higgs-strahlung @ 500 GeV