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

June 2016: first update

15 July 2016: Further update

updates after 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: ↑, ↓

spin state of pair of spin ½ 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

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

h (X) is the polarimeter vector

most likely tau spin direction for a given configuration X of its decay products

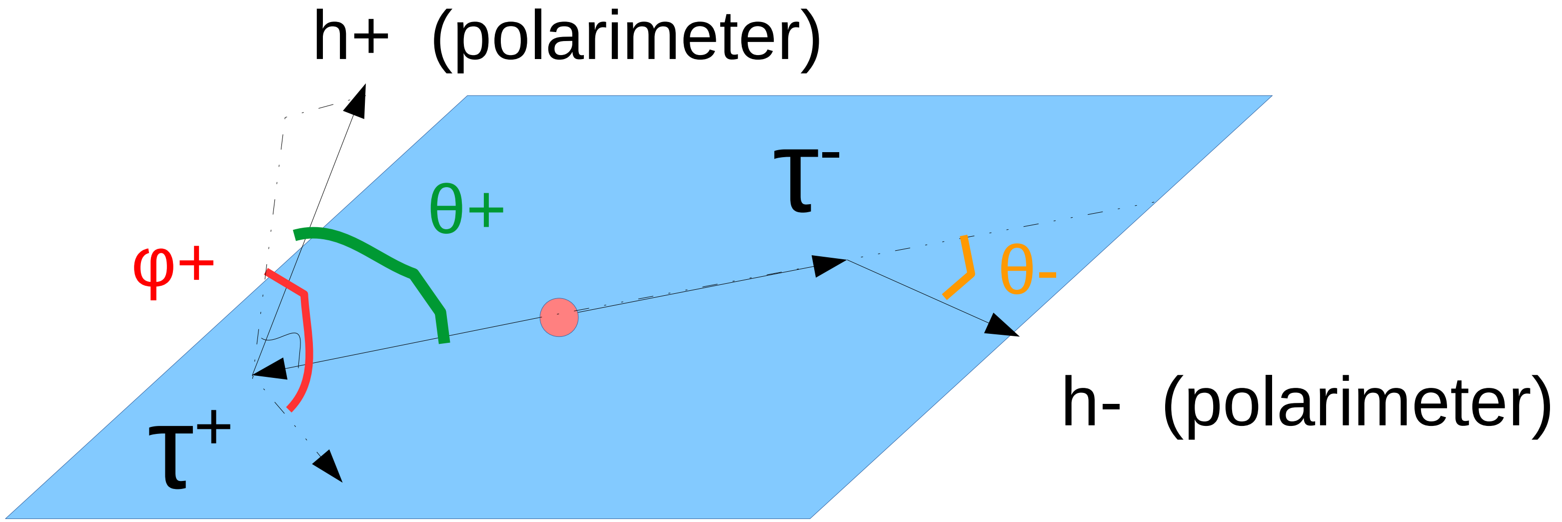
easy to calculate for $\tau^{\pm} \to \pi^{\pm} \nu$ (~11%)

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

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

$$\Gamma(\text{CP even/odd} \to f^{+} f^{-}) \sim 1 - s^{+}_{z}\, s^{-}_{z} \;\mathbf{+/-}\; s^{+}_{\perp}\, s^{-}_{\perp}$$

July update



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

θ, φ are direction of polarimeter wrt tau- momentum in tau rest frames

$\Delta\varphi = \varphi^+ - \varphi^-$; ψ_{CP} is the CP mixing angle we want to measure

$\Delta\varphi$ distribution sensitive to ψ_{CP}

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

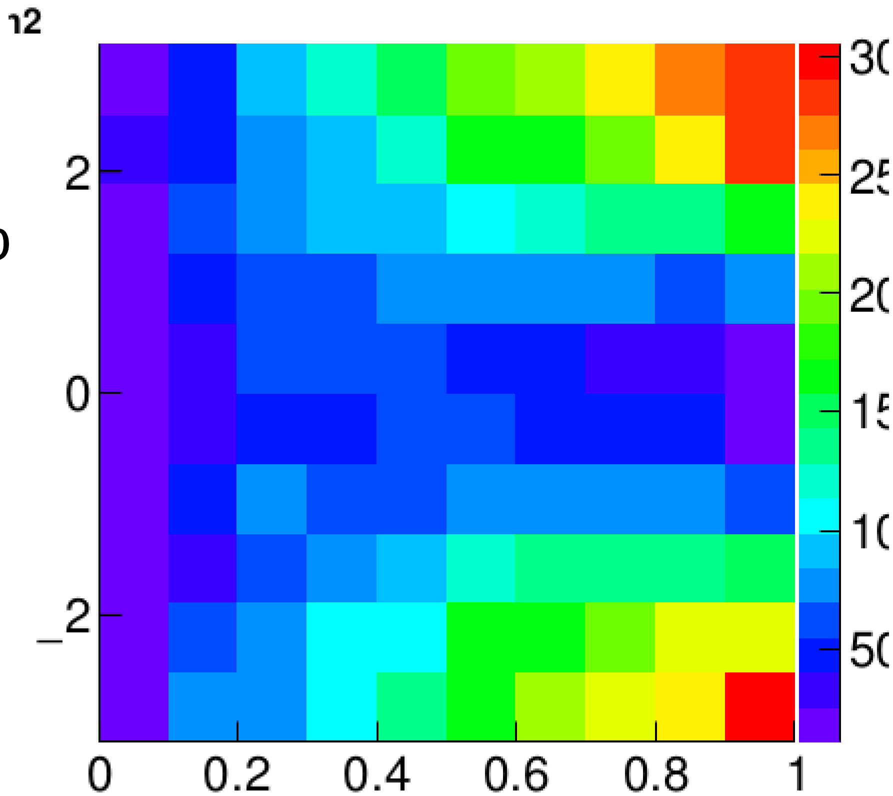
until now I have integrated over $\sin\theta^+ \sin\theta^-$

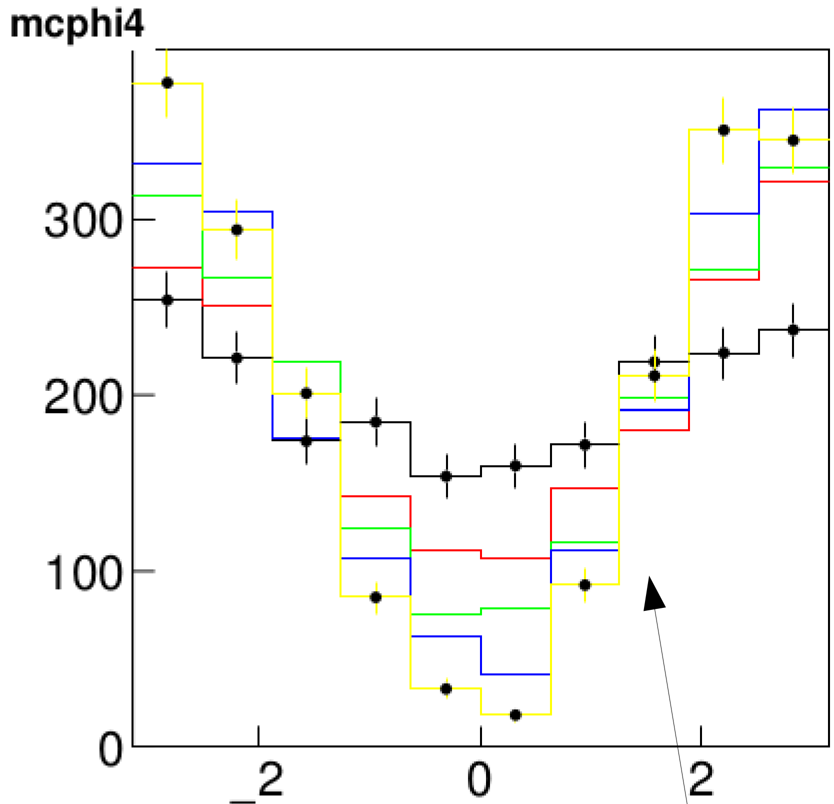
today I will show effect of not doing this integration

July update

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

Δφ





$\sin\theta^{+} \sin\theta^{-}$

Δφ

one polarimeter
along tau direction

both polarimeters
perpendicular to
tau direction

we want to measure phase
of this modulation

signal only, MC truth

July update

split simulated & reconstructed MC data
into 5 bins of sin θ^+ sin θ^-

  in each bin:

    estimate size of modulation and
    number of signal & background events

use this to make templates for toy MC experiments.

for each toy experiment,

  perform **simultaneous** likelihood fit to data in

    5 bins and 3 channels (Z->ee, mm, qq)

      to extract single value of ψ_{CP}

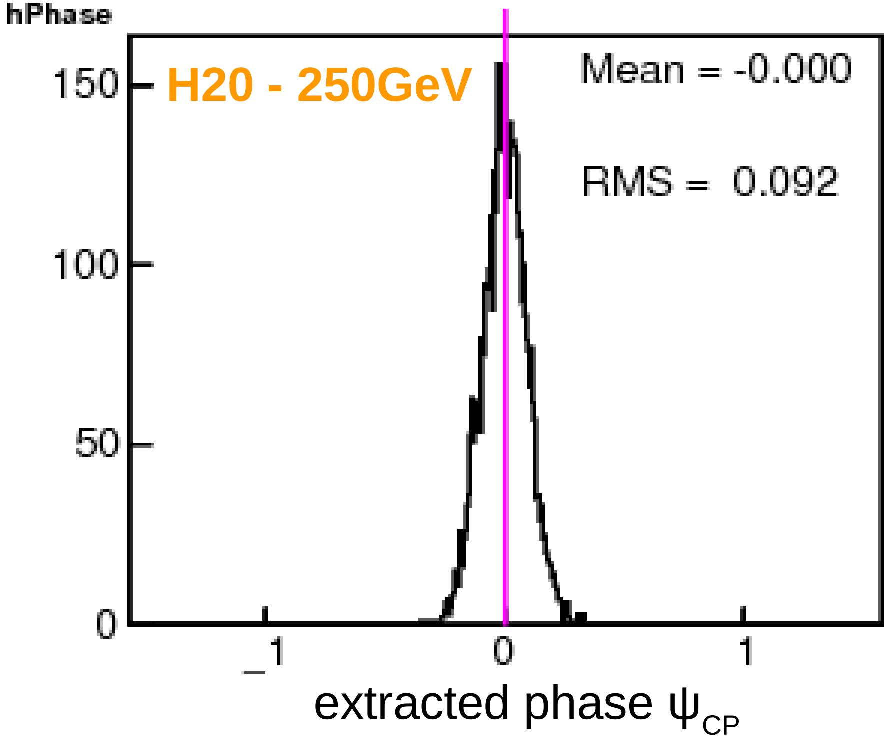
(simultaneous fit is better behaved:

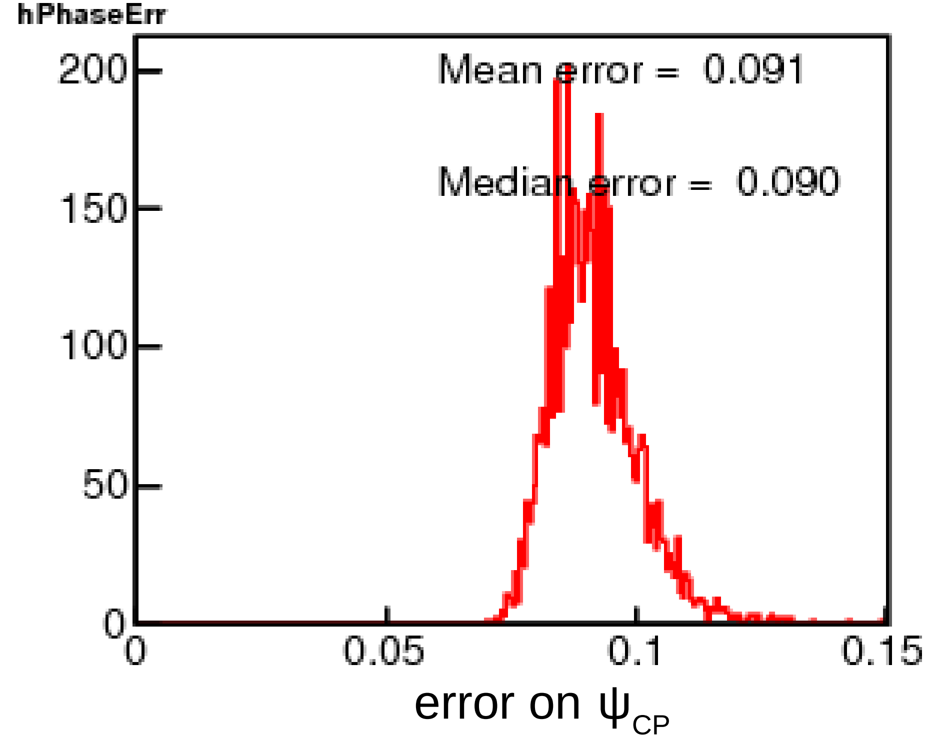
  otherwise rather small number of events per experiment,
  and somewhat non-gaussian errors)

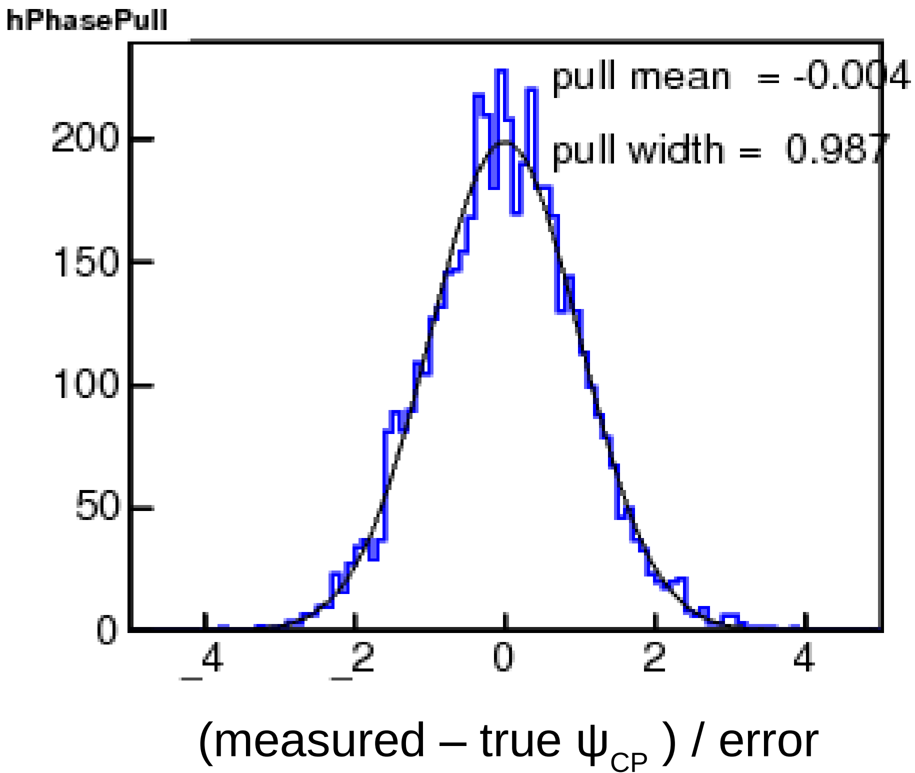
also:

  a few small tweaks to selection cuts
  now include also rather small contribution to H20 luminosity from

    (-0.8, -0.3) and (+0.8, +0.3) polarisations @ 250 GeV







July update

integrating over sin θ^+ sin θ^-

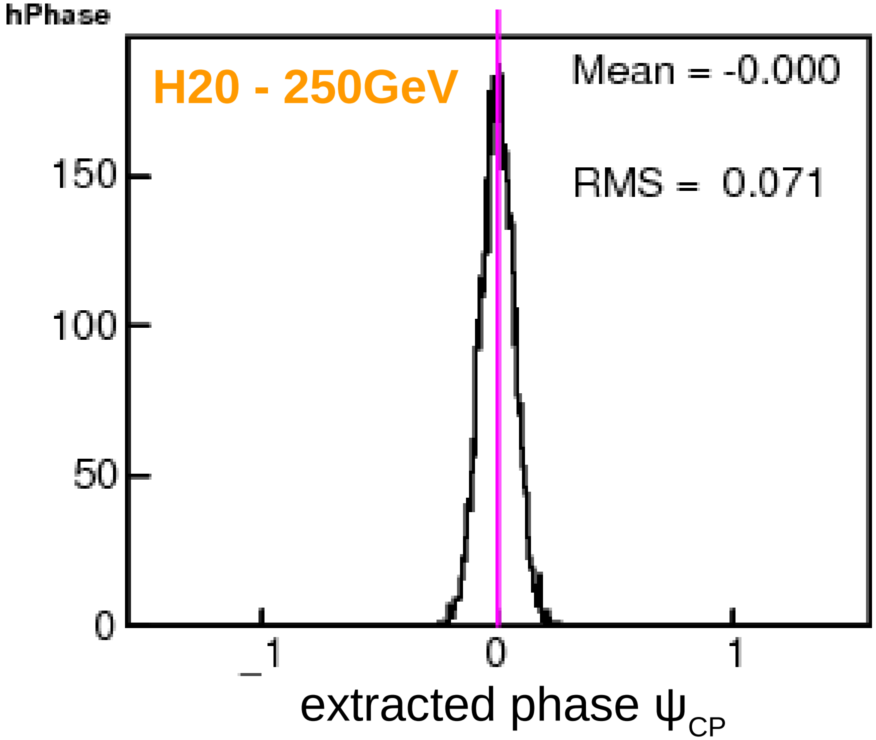
all channels

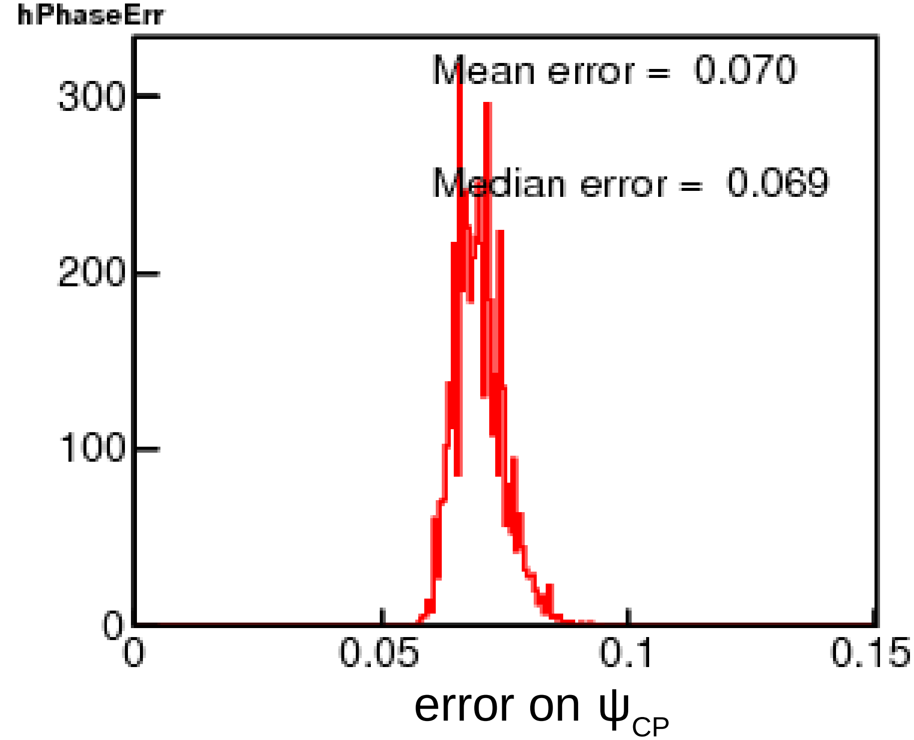
results of 5000 toy mc experiments

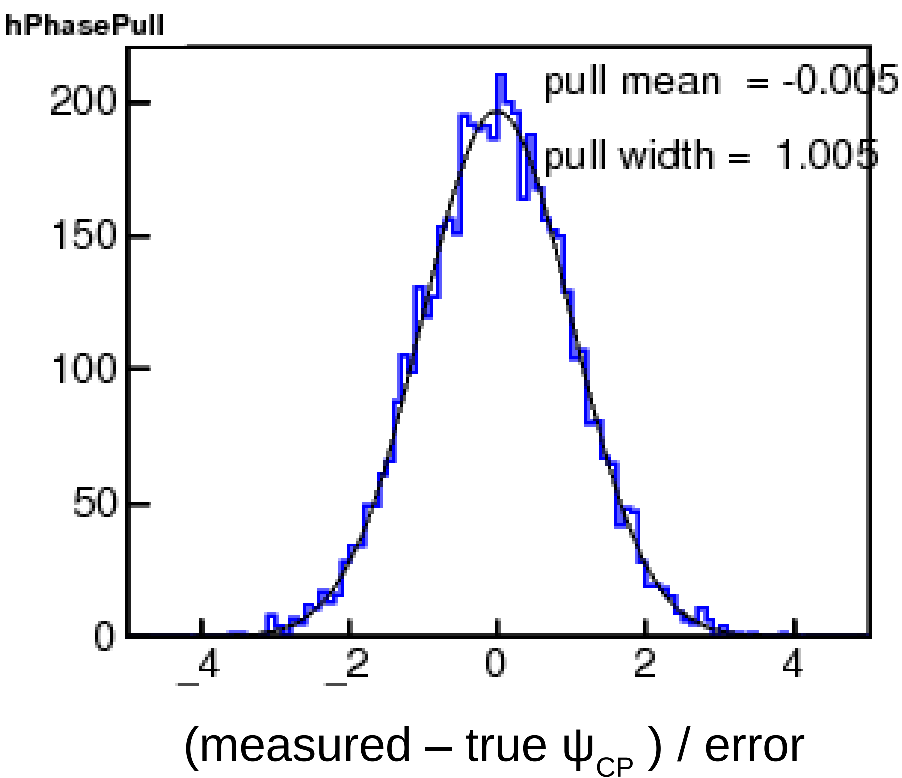
no bias in phase extraction

pull distribution looks good

expected uncertainty: 90 mrad ~ 5.2 deg







July update

5 bins in sin θ^+ sin θ^-

all channels

results of 5000 toy mc experiments

no bias in phase extraction

pull distribution looks good

expected uncertainty: 70 mrad ~ 4.0 deg

Summary (July update)

split data according to how perpendicular
the polarimeters are to the tau momentum

H20 precision on ψ_{CP} improves: 90 → 70 mrad

rather than binning data,
a true 2d approach should improve result further
→ now studying

paper writing is progressing reasonably well old slides

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

Pythia v8.212 for hadronisation & FSR

~~Tauola c++ v1.1.4~~ → UPDATE: tau decays now in Pythia

1. signal decays: $\tau^\pm \rightarrow \pi^\pm \nu$ and/or $\tau^\pm \rightarrow \pi^\pm \pi^0 \nu$ "rho / ρ"
2. all $\tau^\pm$ decays

include spin correlations (H_{SM}, $H_{\not{CP}}(\psi_{CP}=\pi/4)$, 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)

UPDATE

found various FSR-related problems:

I had added FSR to electron and quark channels,
but not to muon channel

I had not applied FSR correctly:
when tau radiates FSR,
tauola did not realise it comes from Higgs →
does not apply spin correlations in tau decay

now perform tau decays within pythia v8.212 instead of Tauola,
"at same time" as doing FSR.
(tau spin correlations can be included from Pythia v8.150)
seems to give consistent results.

UPDATE

now include e+ e- → c c τ+τ- , b b τ+τ- processes

[previously only light uds quarks considered]

General strategy

consider 250 GeV running in H20 scenario

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

Pol(e-,e+) = (+0.8, -0.3), 450 fb-1

select e+e- → (H → τ τ) (Z → ee, μμ, qq) events

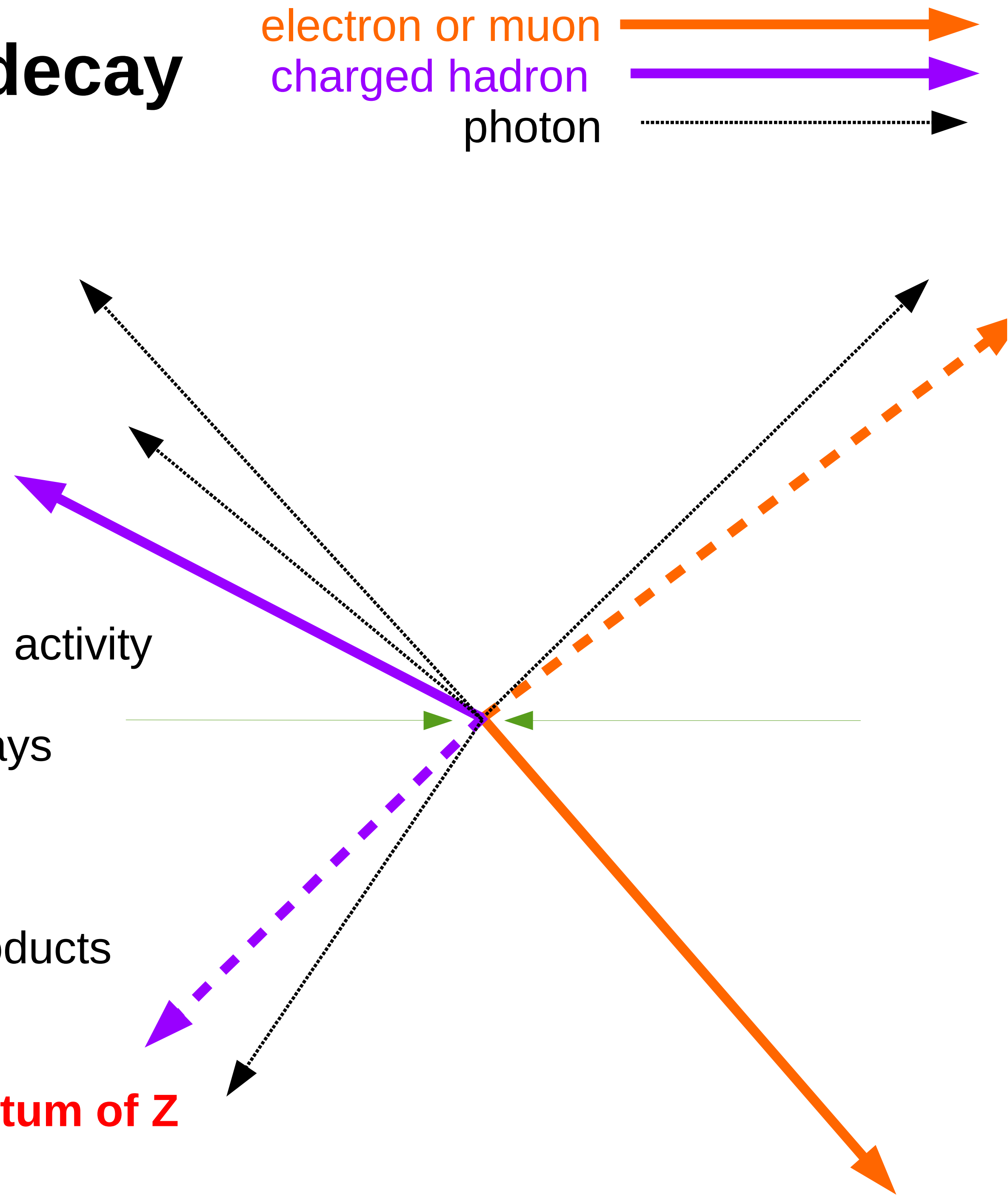
fully reconstruct tau momenta

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 → pi0
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 ~ mH

selection: hadronic Z decay

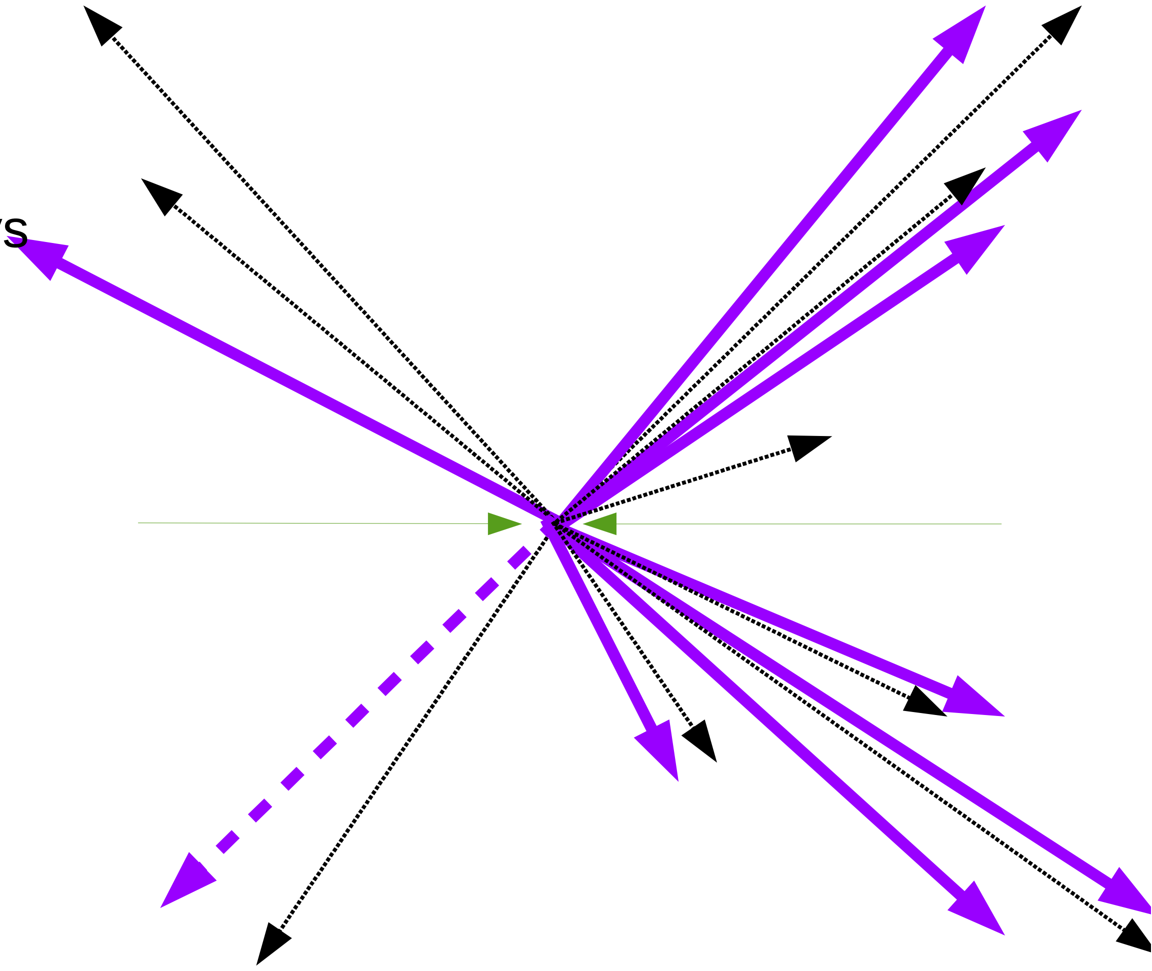
two tau-like jets (TauFinder)
→ **tau identification**

select $\tau^\pm \to \pi^\pm \nu$ and $\tau^\pm \to \pi^\pm \pi^0 \nu$ decays
→ **photon reconstruction**

rest of event → “Z”
require mass consistent with mZ

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

require tau-tau mass ~ mH



UPDATE

various tweaks to reconstruction

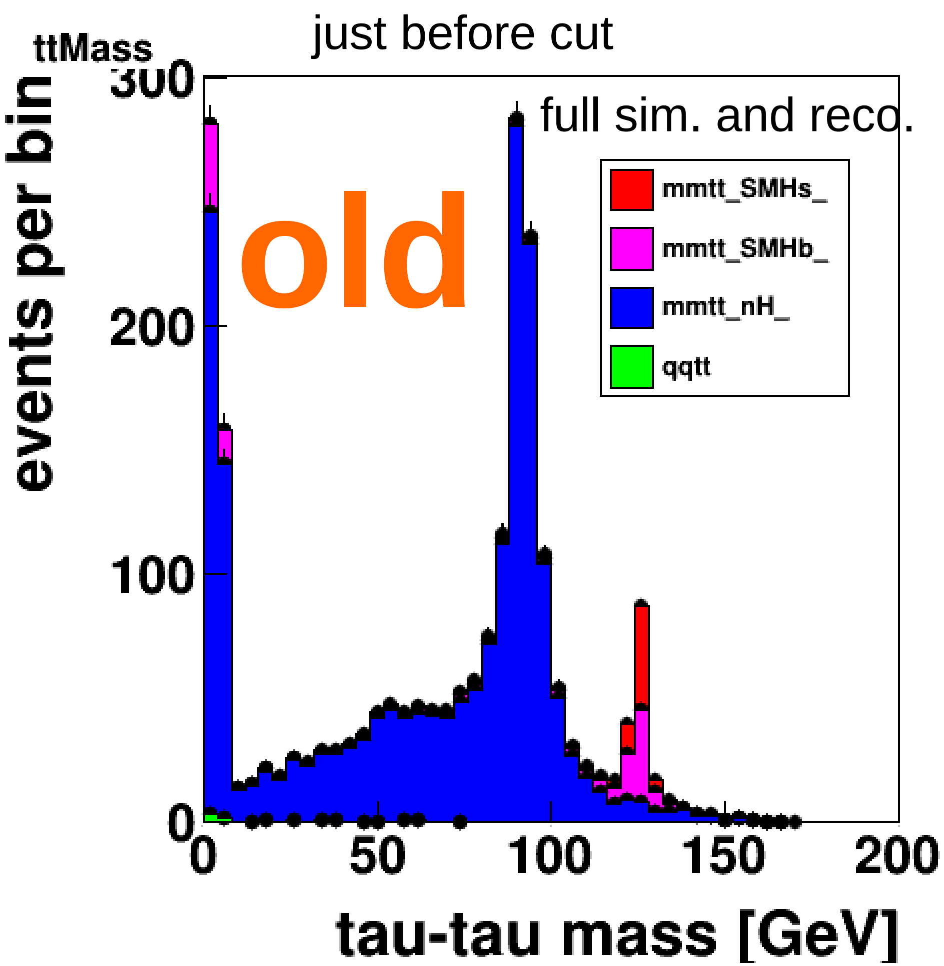
- e.g.
  - lepton ID
  - identification of FSR & bremsstrahlung photons

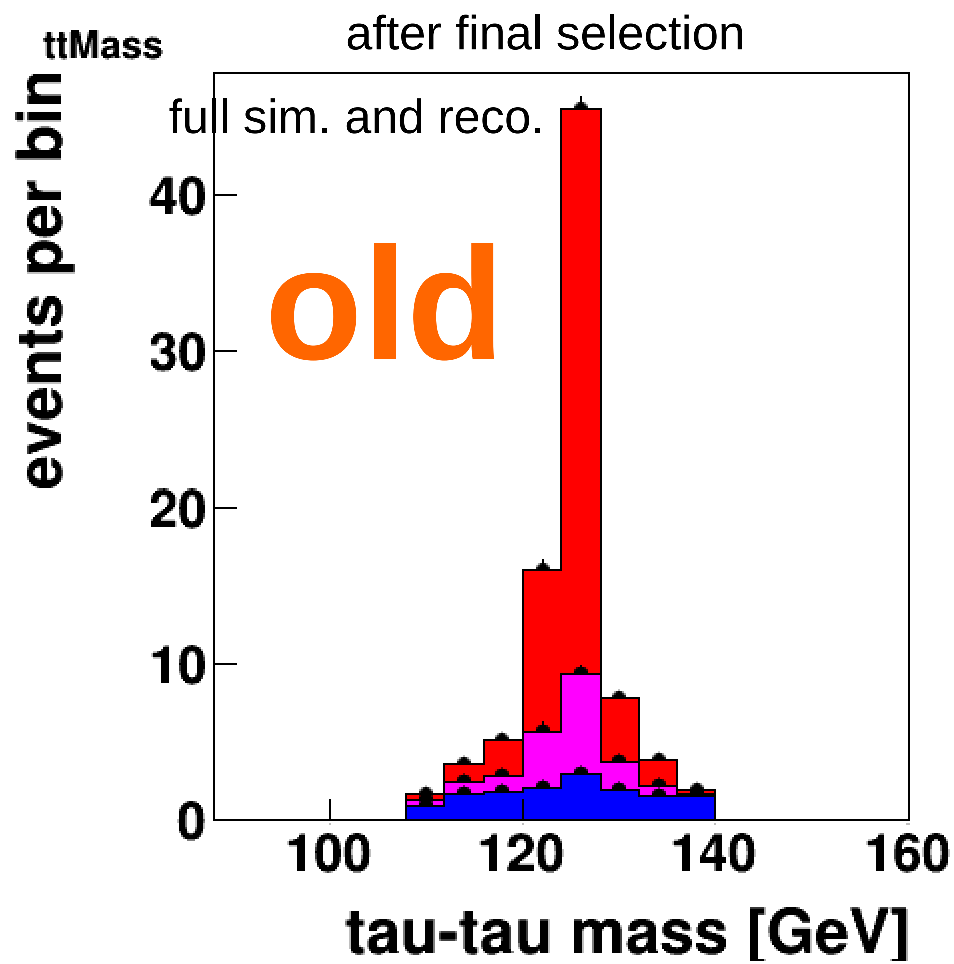
various tweaks to selection cuts

- most to improve signal selection efficiency
- some to improve background rejection

Invariant mass of reconstructed tau-tau system

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



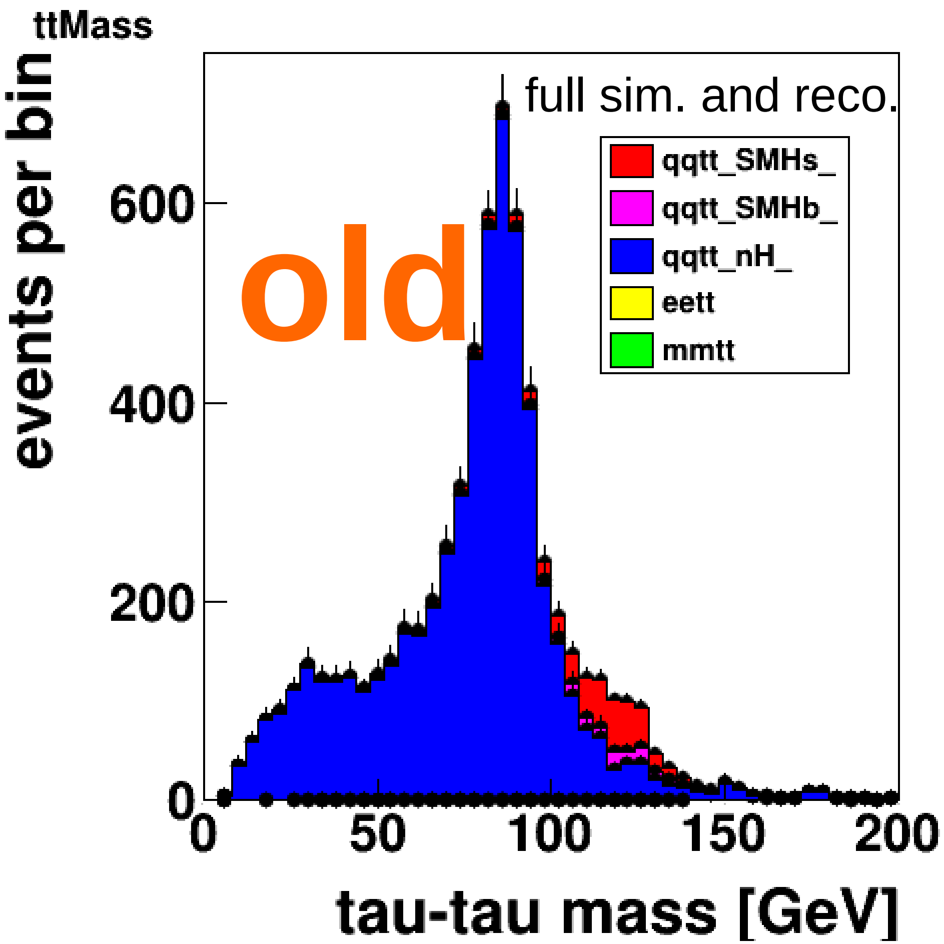


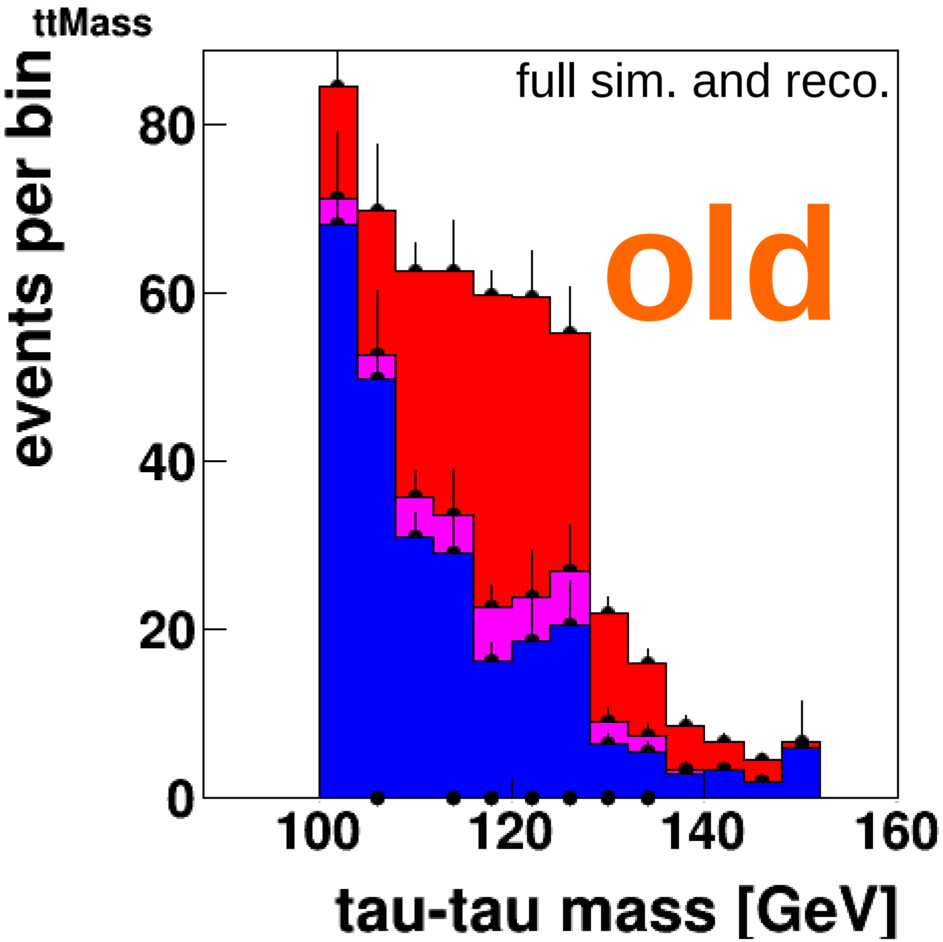
μμ tau tau (SM Higgs, tau → pi or rho) signal
μμ tau tau (SM Higgs, other tau decay channels)
μμ tau tau (non-Higgs) background

pretty good tau momentum reconstruction

Invariant mass of reconstructed tau-tau system

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

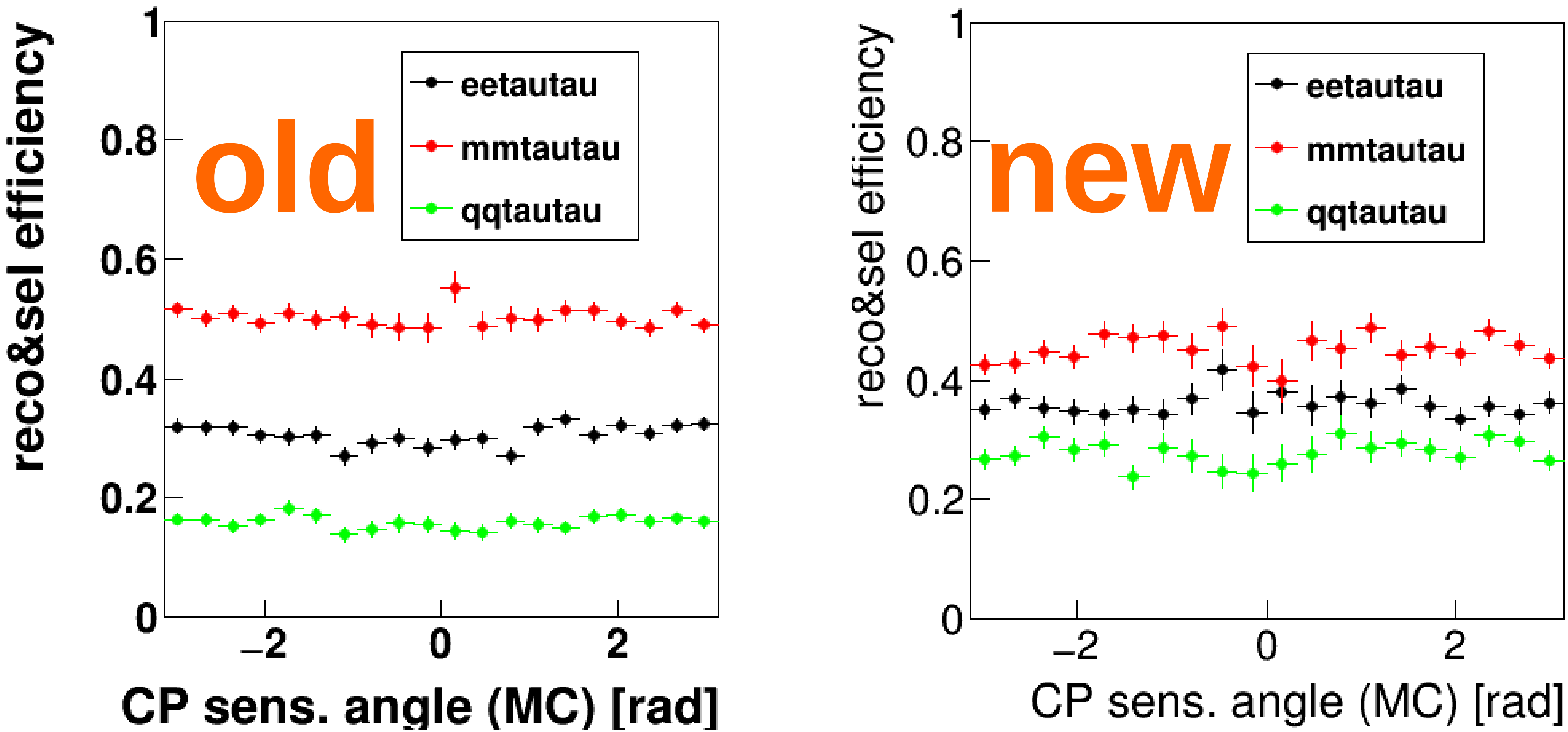




μμ tau tau (SM Higgs, tau → pi or rho) signal
μμ tau tau (SM Higgs, other tau decay channels)
μμ tau tau (non-Higgs) background

tau momentum reconstruction much worse
→ jet energy resolution

Reconstruction and selection efficiency



muon channel efficiency reduced somewhat
(due to now-included FSR?)
others slightly increased
(improved selection cuts?)
remain ~flat wrt CP angle

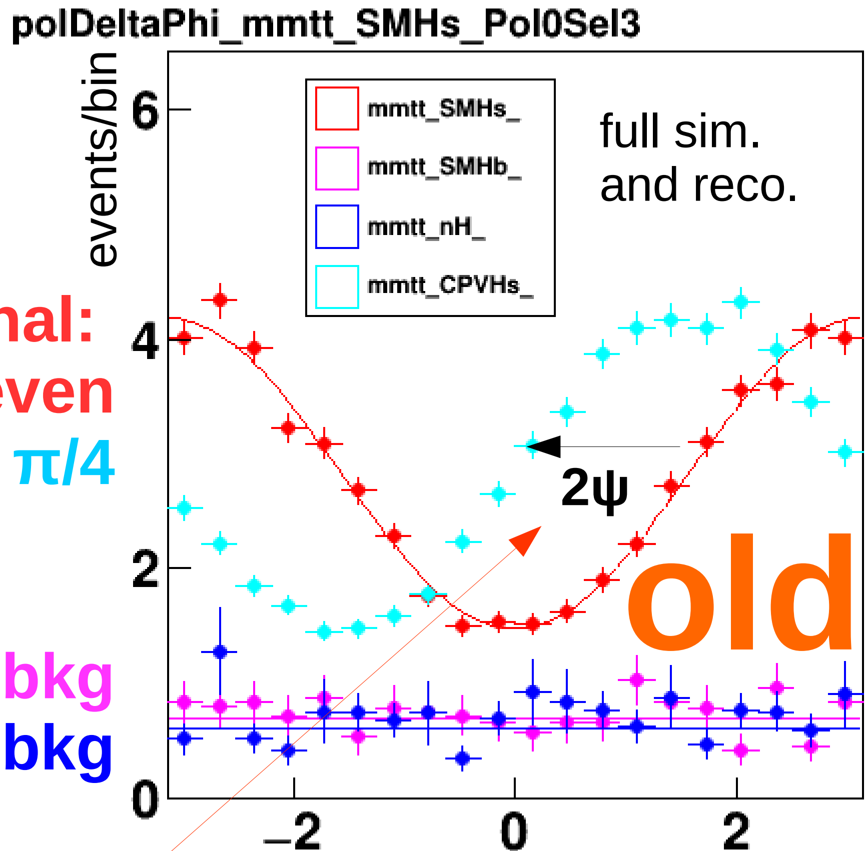
transverse spin correlations: after selection and reconstruction

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

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

Higgs bkg

non-H bkg



UPDATE
definition of angular shift
shift in distr ~ $2\psi_{CP}$

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

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

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

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

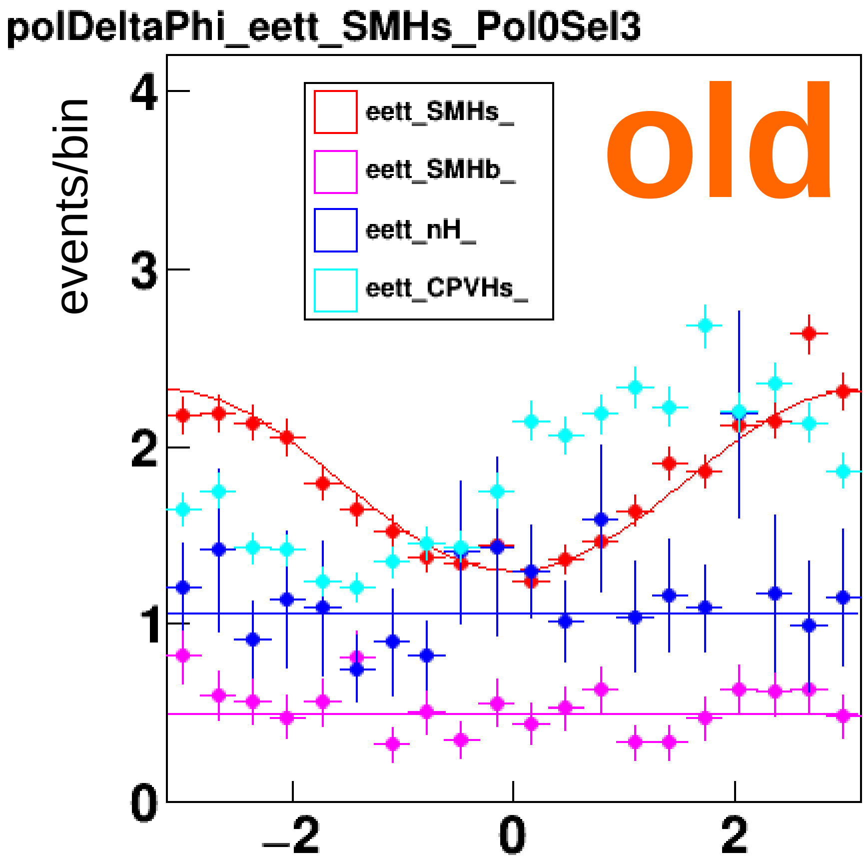
$a_{MC} = \pi^2/16 \sim 0.6$

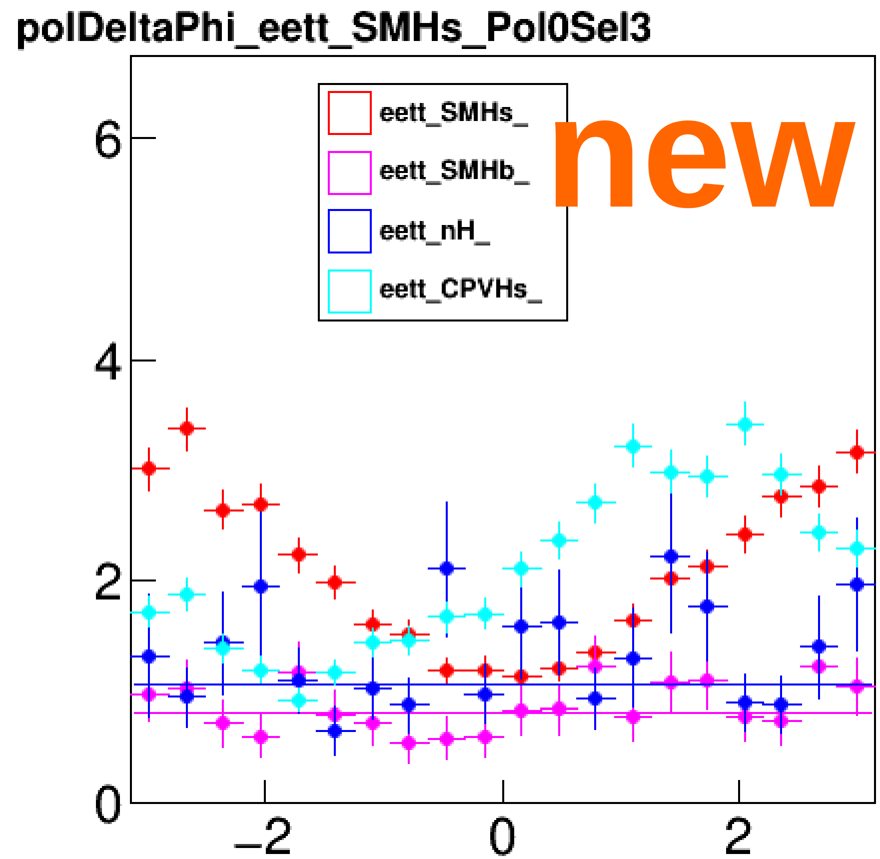
$a_{reco} \sim 0.5$

backgrounds small and flat

transverse spin correlations: electron channel

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





signal:

CP even ψ = 0

ψ = π/4

Higgs bkg

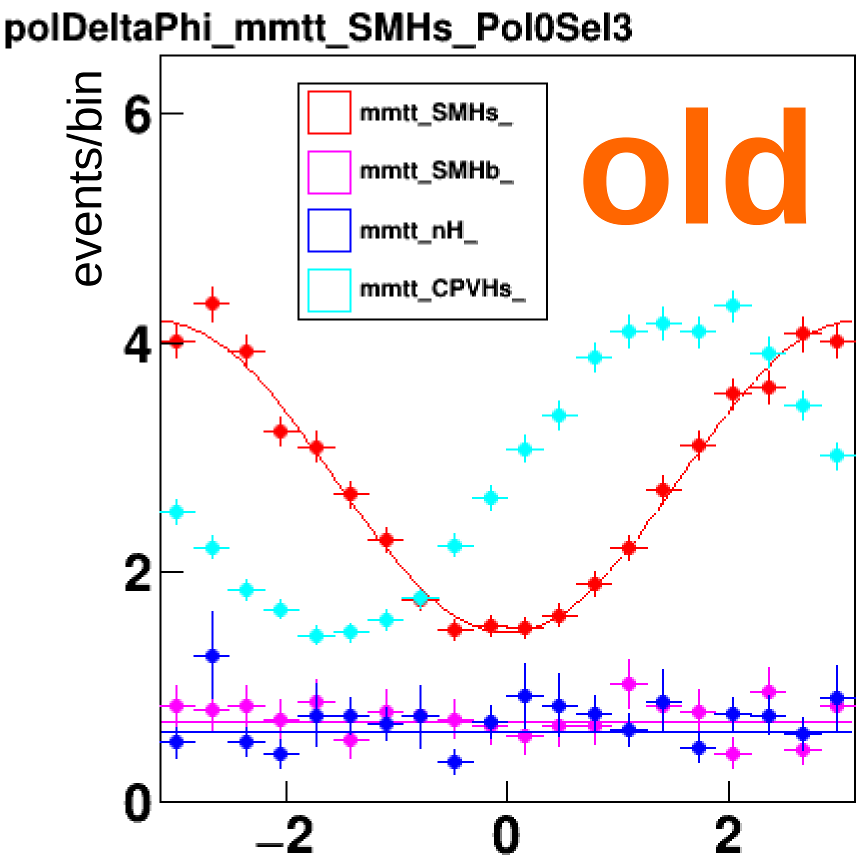
non-H bkg

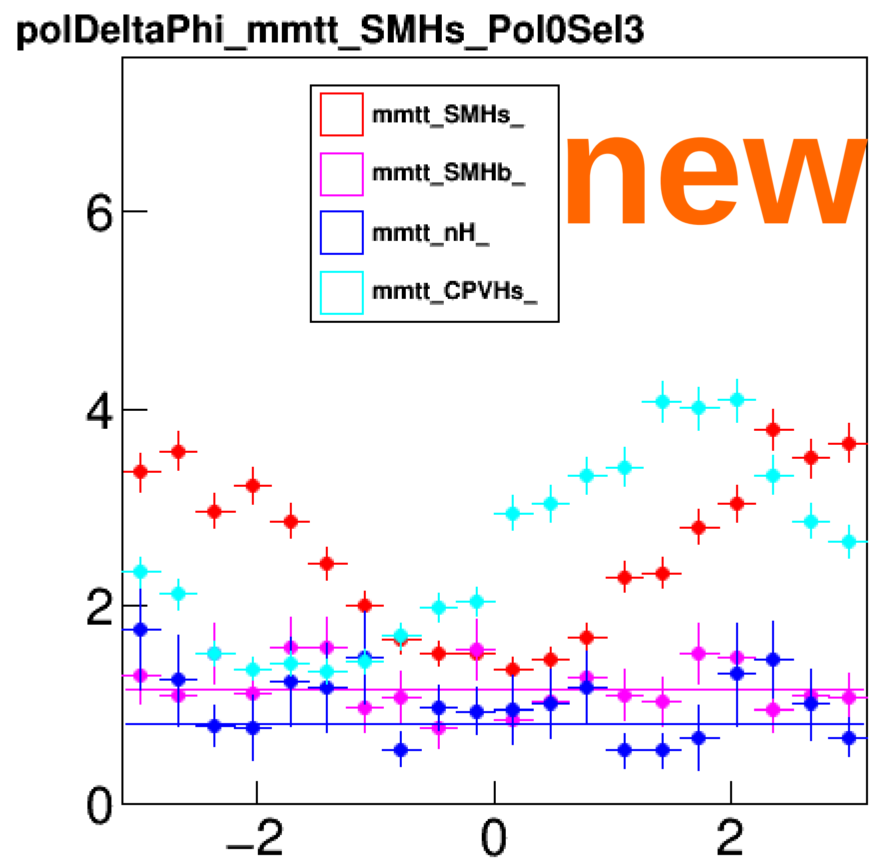
slightly more signal (better selection)

more modulated signal (FSR problem fixed)

transverse spin correlations: muon channel

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





signal:

CP even ψ = 0

ψ = π/4

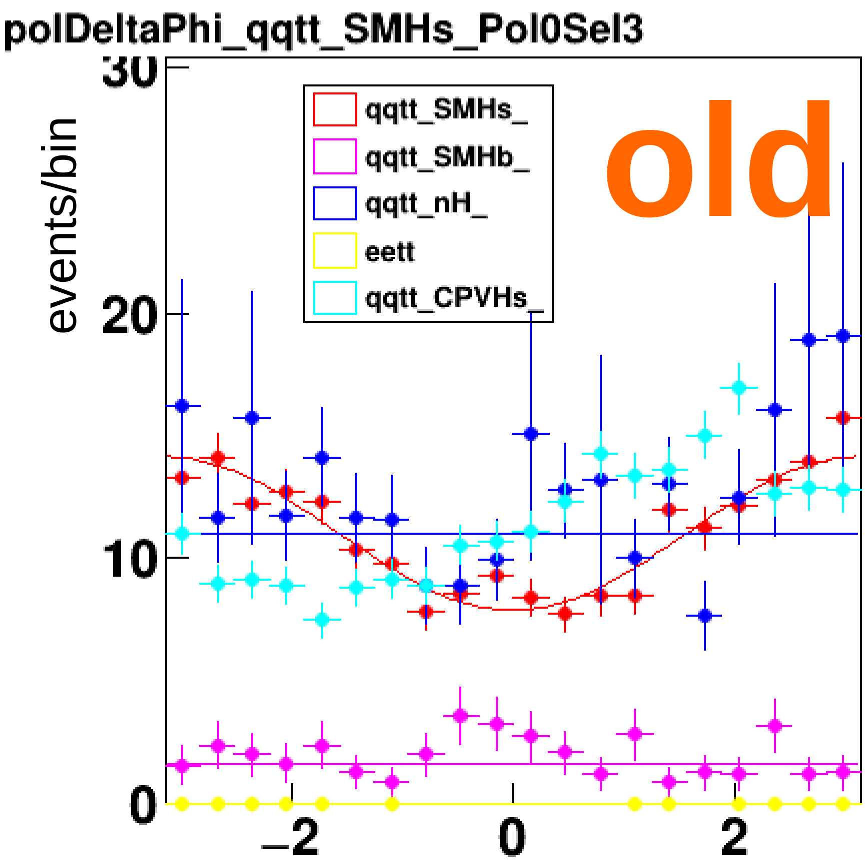
Higgs bkg

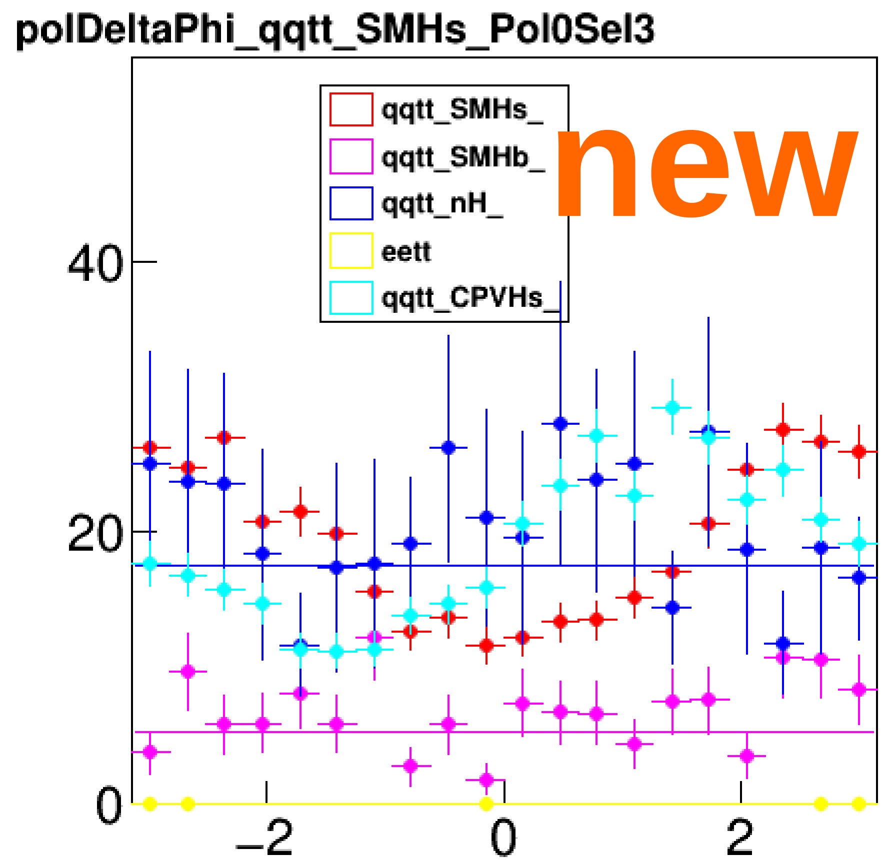
non-H bkg

slightly less signal, and less modulated
(FSR now included)

transverse spin correlations: quark channel

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





signal:
CP even ψ = 0
ψ = π/4
Higgs bkg
non-H bkg

more events (added cctautau, bbtautau)

slightly more modulated (FSR fixed)

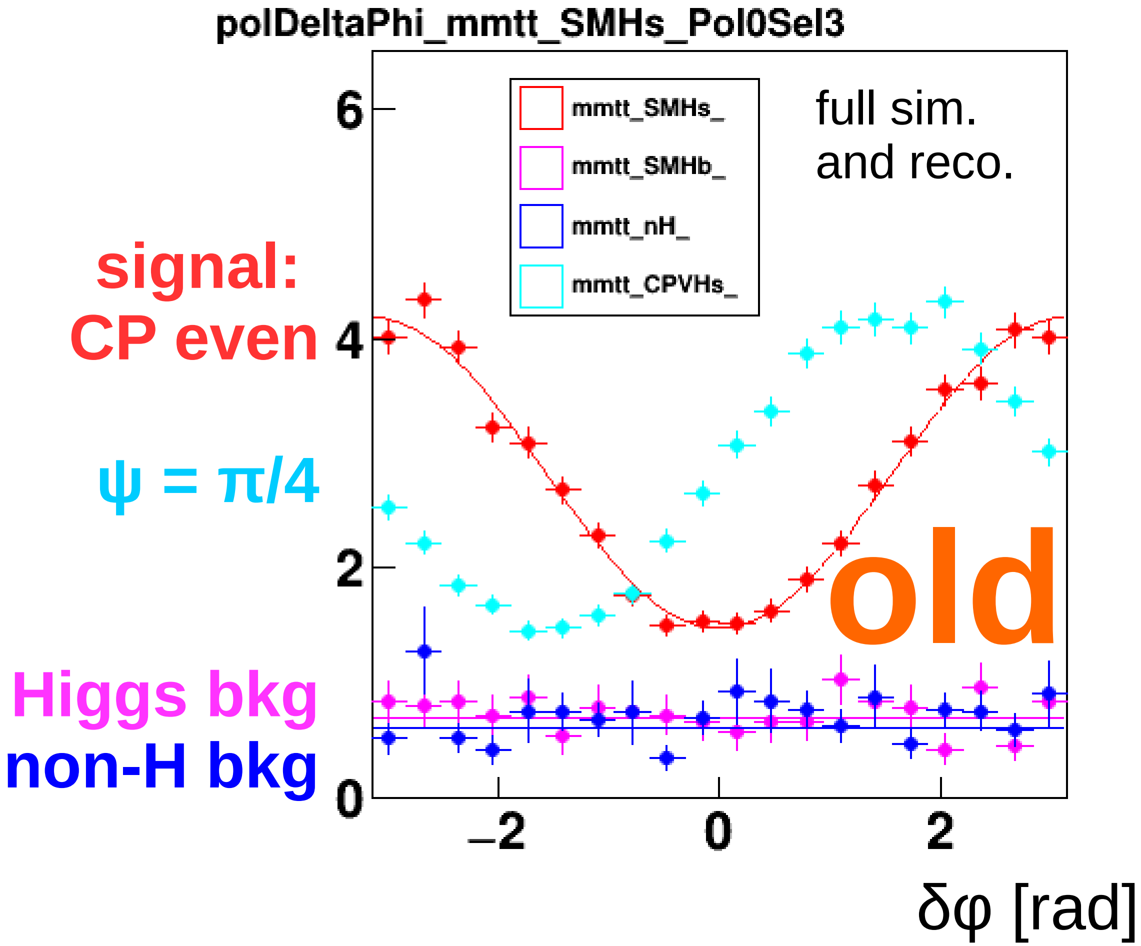
Estimation of sensitivity

Assume: sinusoidal signal
flat background
→ fit parameters

Use fit functions to run
toy MC experiments

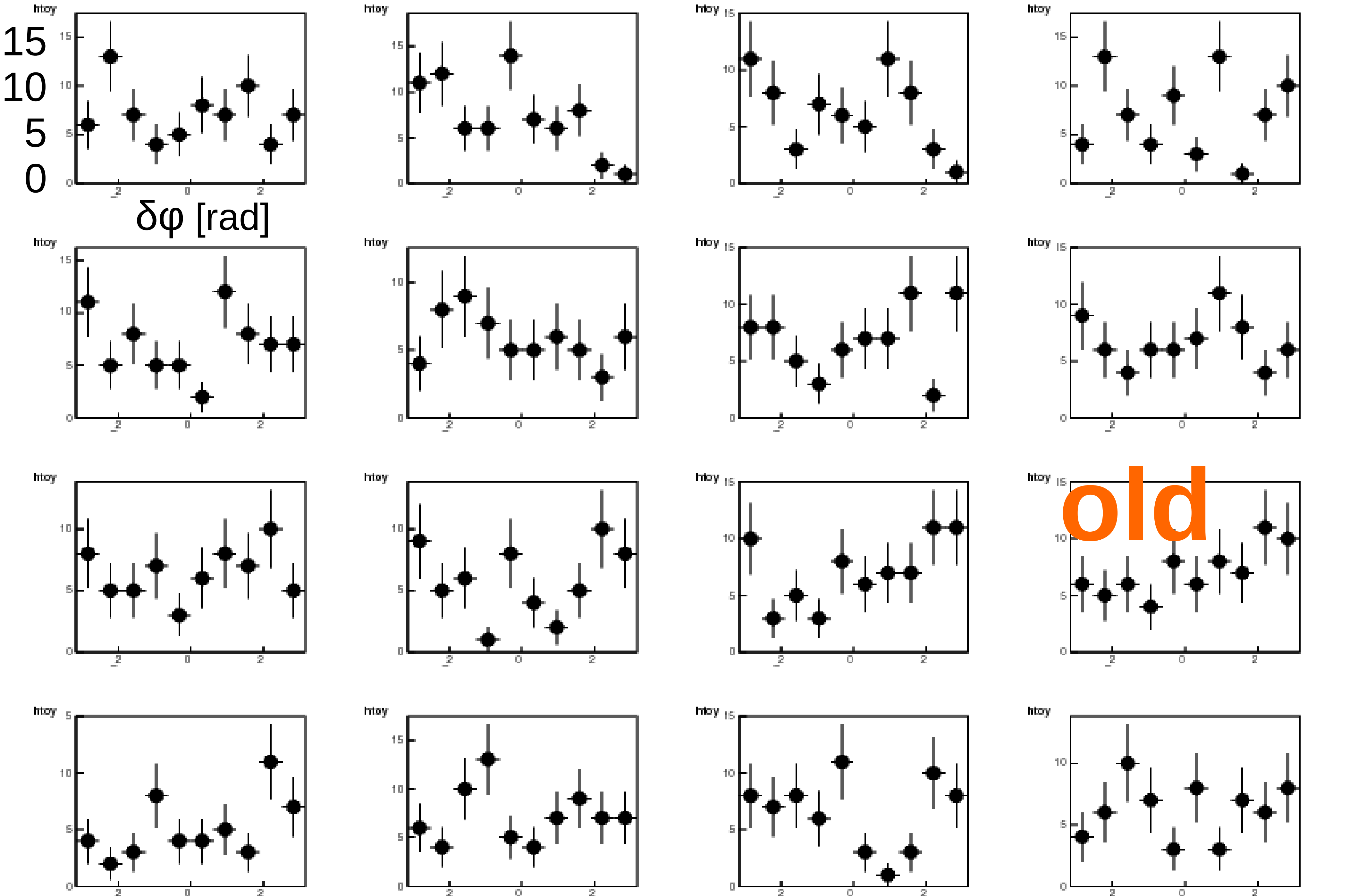
assume total xsec
independent of CP
→ maybe not a valid assumption:
extra information in xsec variation

extract phase of δφ variation
using unbinned maximum
likelihood fit



μμττ channel some toy MC experiments

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



UPDATE

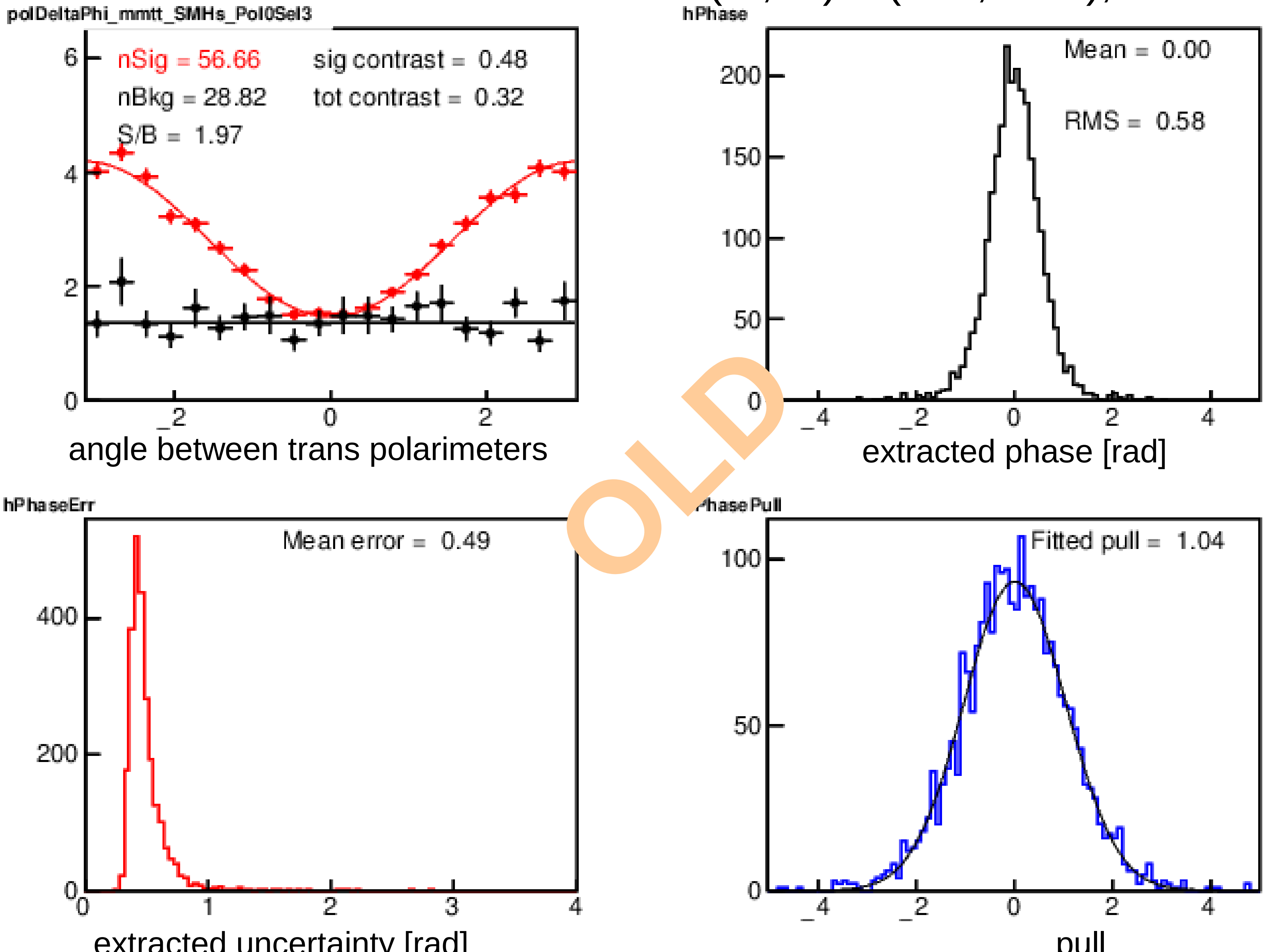
Toy MC exps:

improved **estimation of uncertainty** on extracted phase:
- manual scan to find points where -2*log(like) increases by 1.0
  - [previously directly used MINUIT errors]
- pull distributions now all have width 1.0 +/- 0.1
  - [previously up to ~1.4 in some cases]

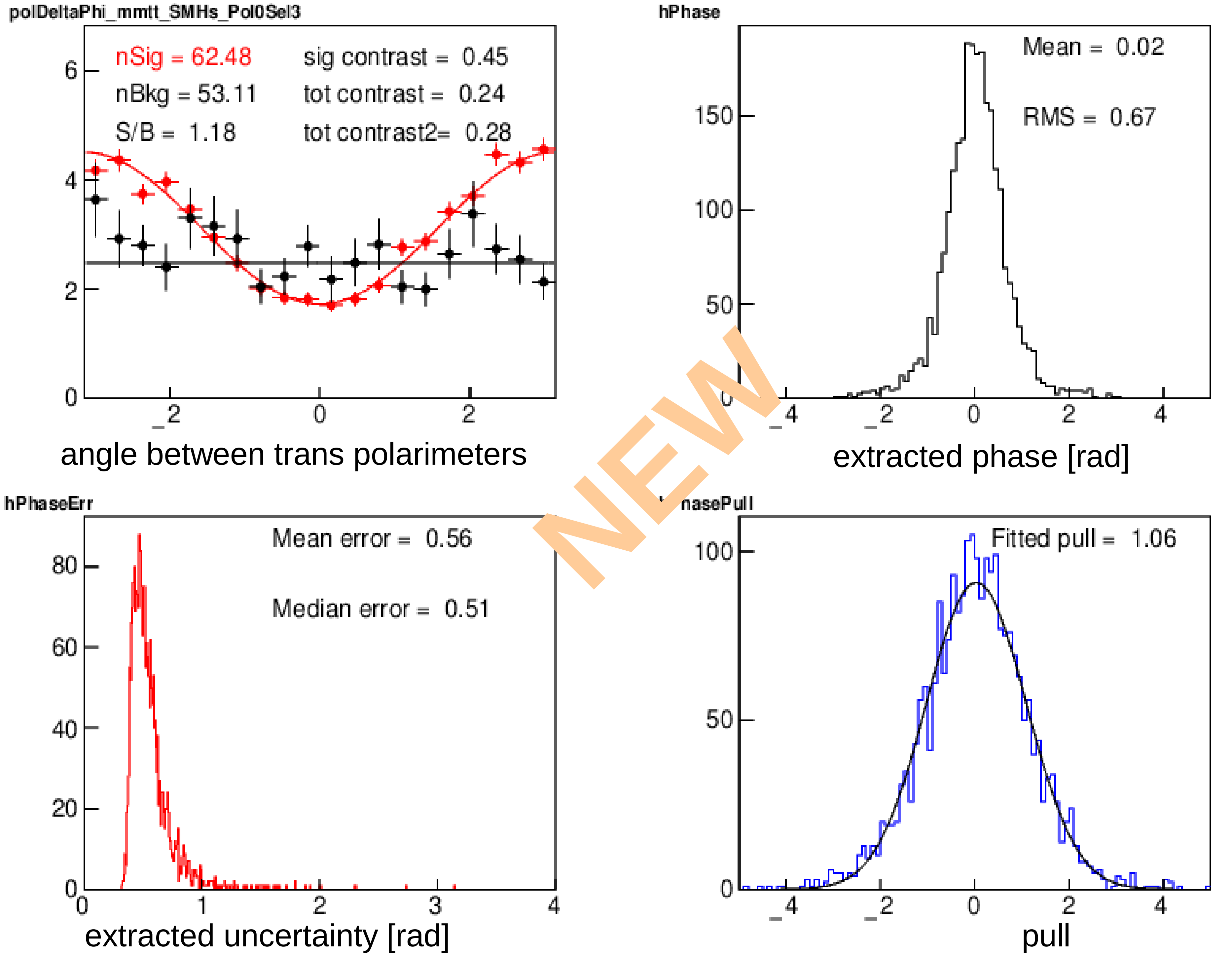
expected error distribution rather non-symmetrical
- → now quote **median** rather than **mean** error [do you agree?]
  - (gives an artificial "improvement")

results of toy MC experiments: μμττ channel

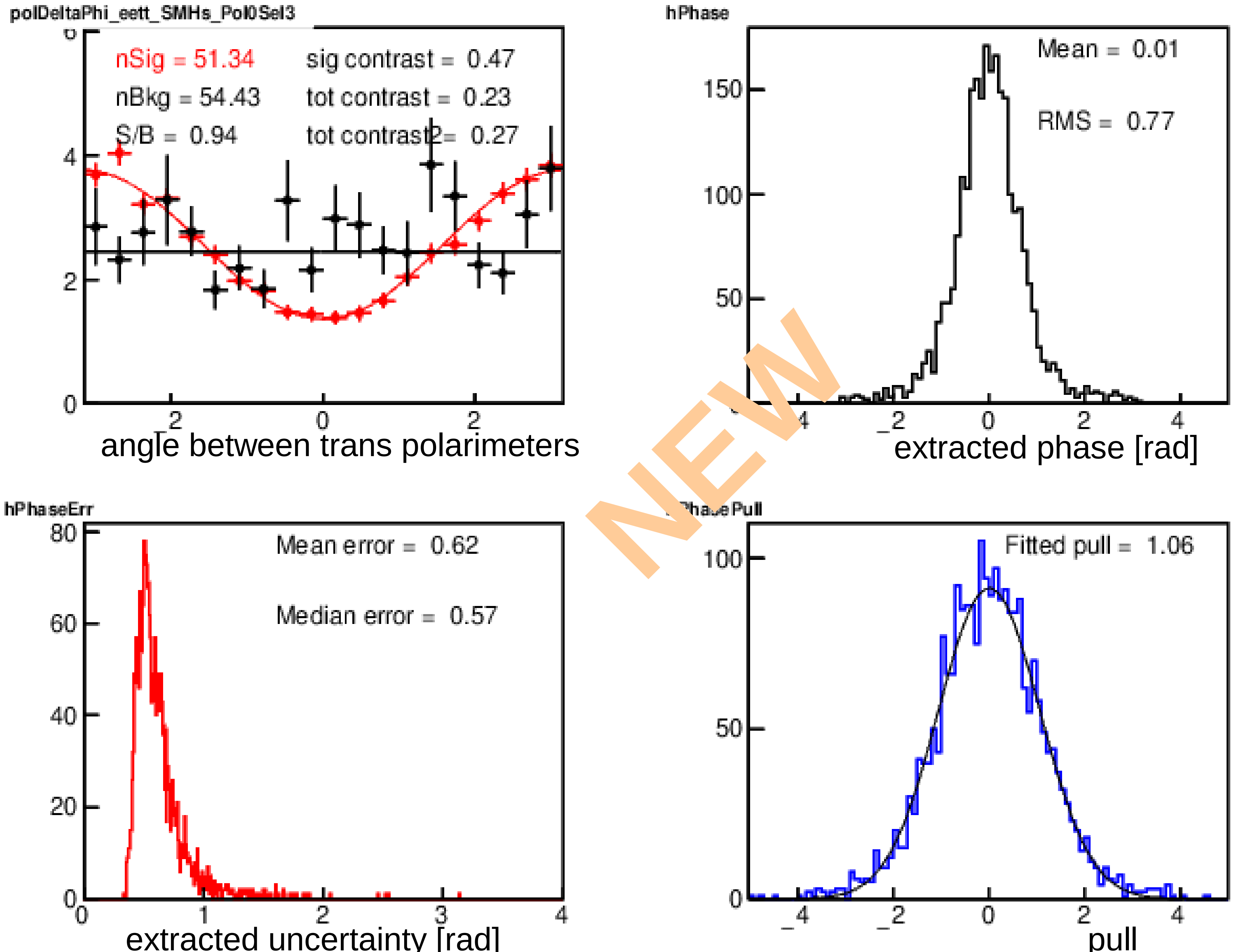
P(e-,e+) = (-0.8, +0.3), 1350 fb-1



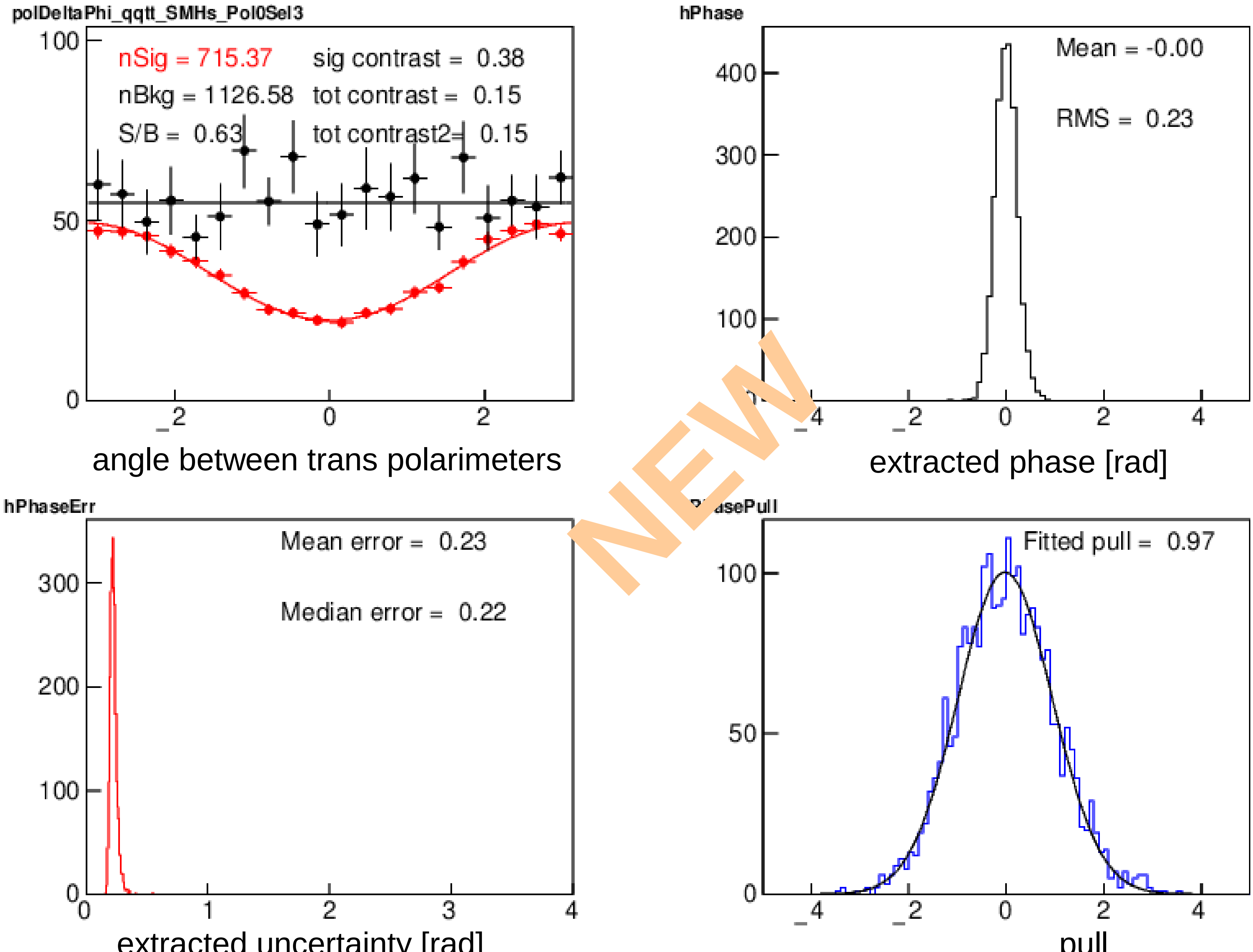
UPDATED: muon channel, full H20 (sum of both polarisations)



UPDATED: electron channel, full H20 (sum of both polarisations)



UPDATED: quark channel, full H20 (sum of both polarisations)



(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] *updated results*

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 (uds/cc/bb)	
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	36%	35%	45%	45%	28/25/19%	28/25/19%
# selected signal events	42.1	9.2	51.0	11.4	584	131
signal contrast	0.47	0.47	0.44	0.46	0.38	0.38
Signal / Background	0.95	0.92	1.2	1.3	0.62	0.73
median error on 2ψ [rad]	0.61	1.1	0.57	0.97	0.25	0.47
median error on 2ψ [rad]	0.57		0.51		0.22	
median error on 2ψ	0.190 rad ~ π/16.5 rad ~ 10.9 degrees					
median error on ψ	5.45 degrees					

summary

various updates to analysis:

- fixed treatment of FSR
- improvements to lepton and event selection
- error estimation in toy MC experiments
- definition of final CP mixing angle

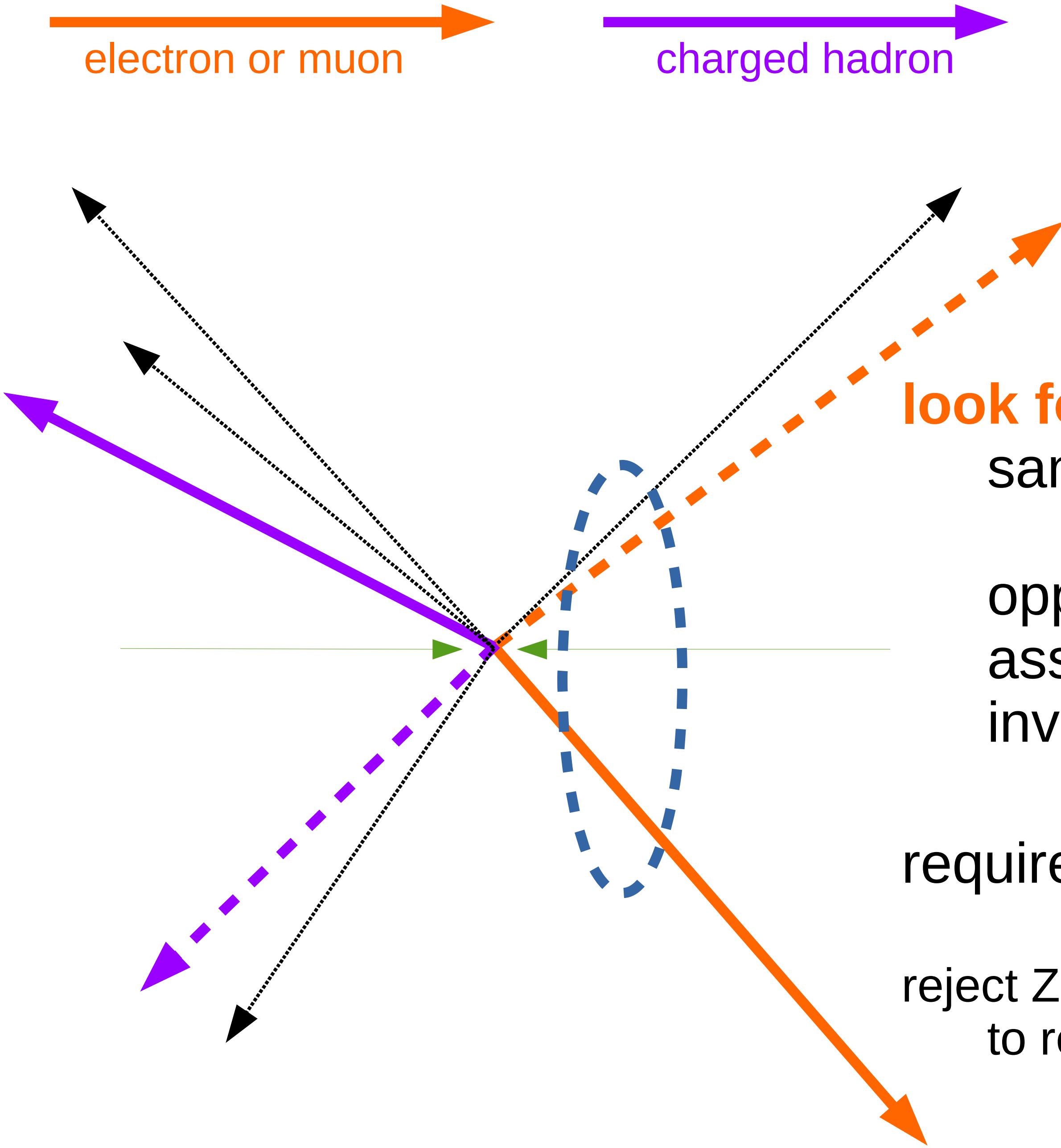
updated estimate of sensitivity ~ 5.5 degrees on ψ_{CP}

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

writing a paper on 250 GeV

then move to 500 GeV.

backup slides



look for Z → 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 → ee with very forward electrons
to reduce non-H backgrounds

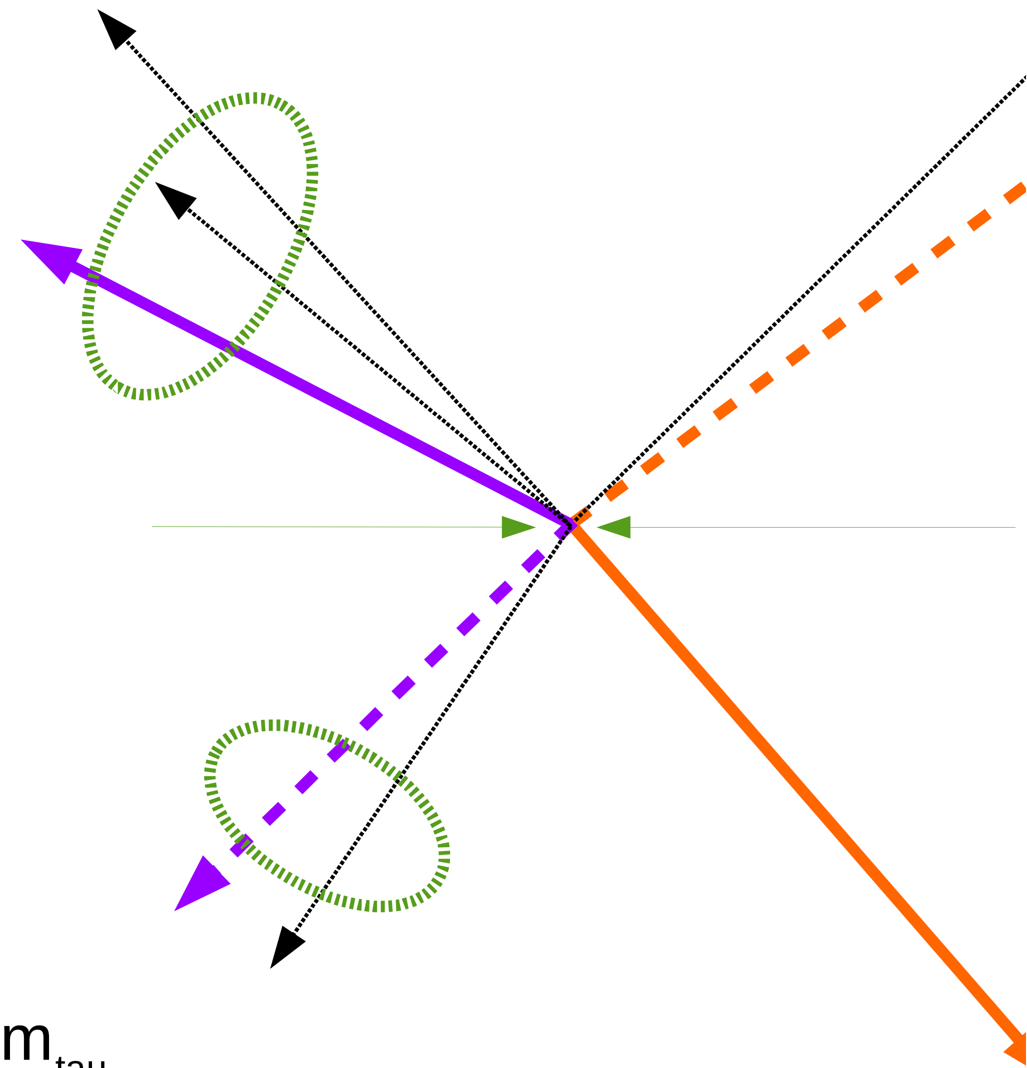
Identify hadronic tau candidates

>=2 additional charged PFOs
    2 most energetic → tau seeds

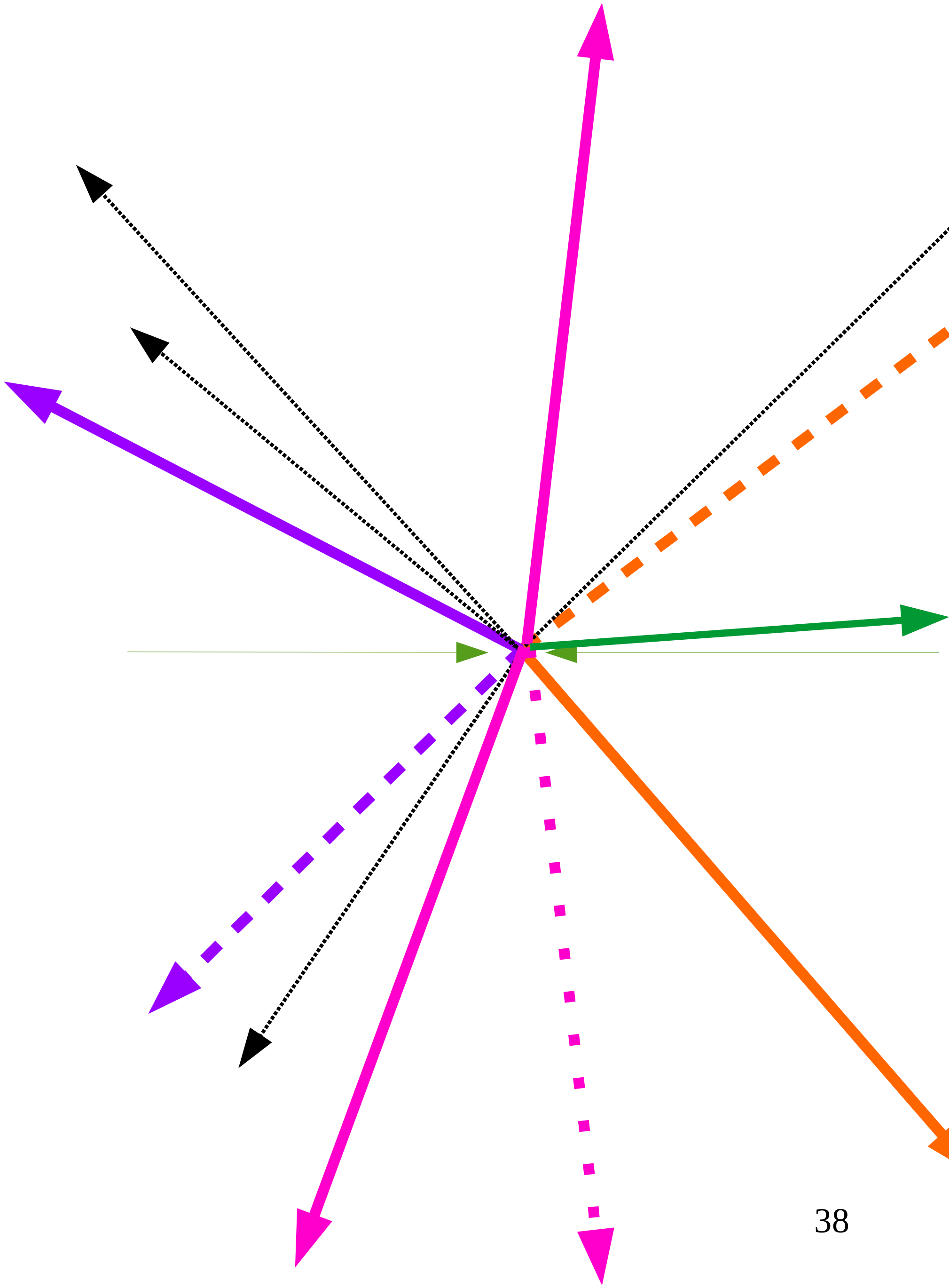
require oppositely charged seeds
    not identified as e/mu

group remaining photons into pi0s
    if $m < m_{tau}$ with a tau seed
    use mass constrained kinematic pi0 fit

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



electron or muon charged hadron photon

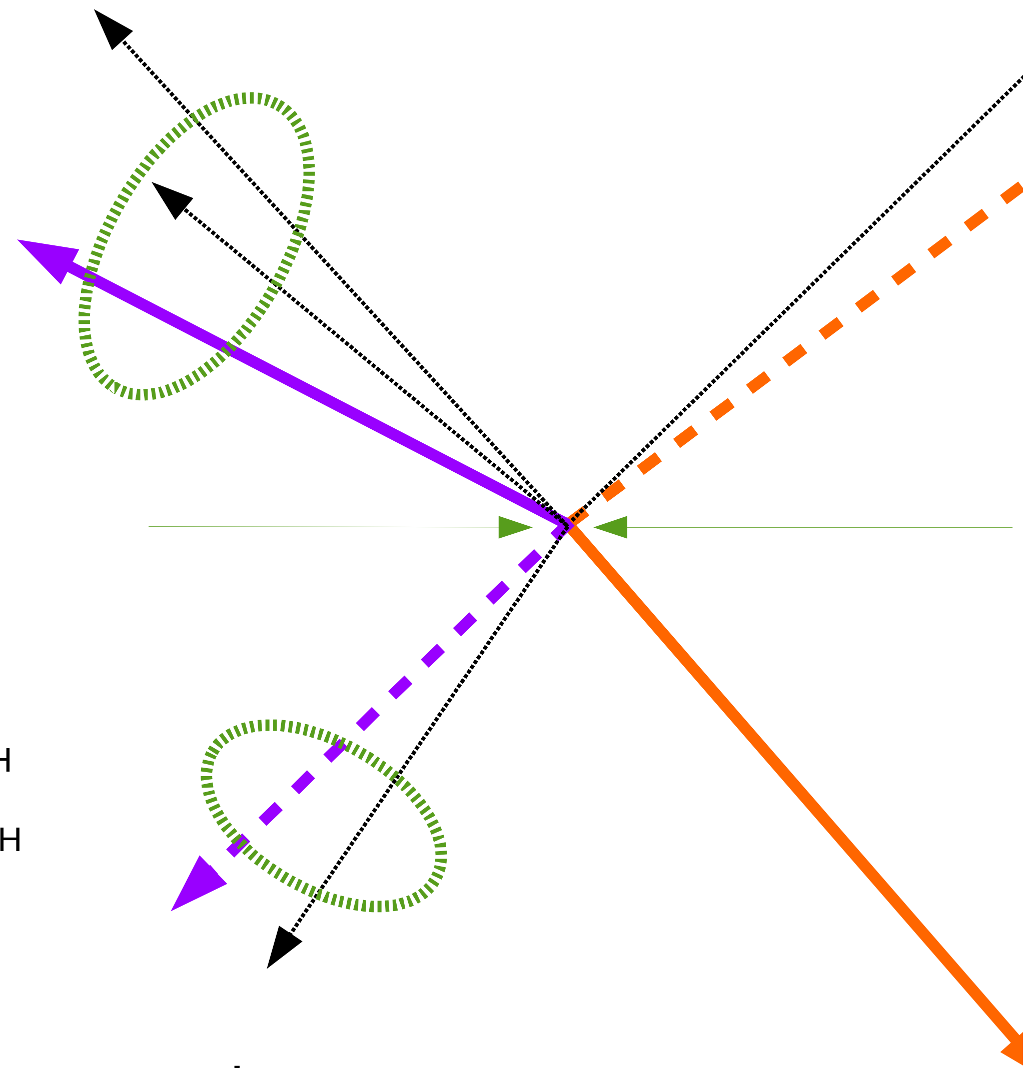


veto events with > 10 GeV
charged or neutral hadron
energy or pT
in addition to
Z and tau candidates

(some from underlying event allowed)

select tau → pi, tau → 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 → 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 → CP

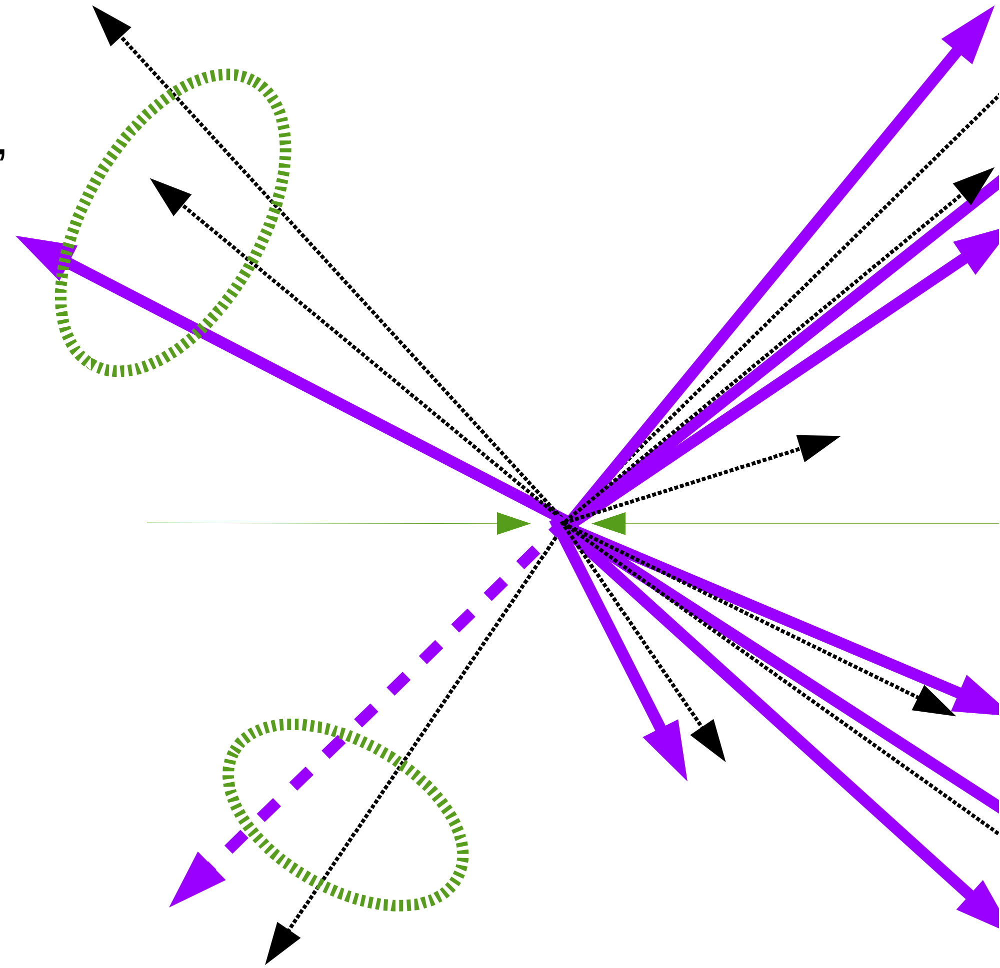
Hadronic Z decay channels

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

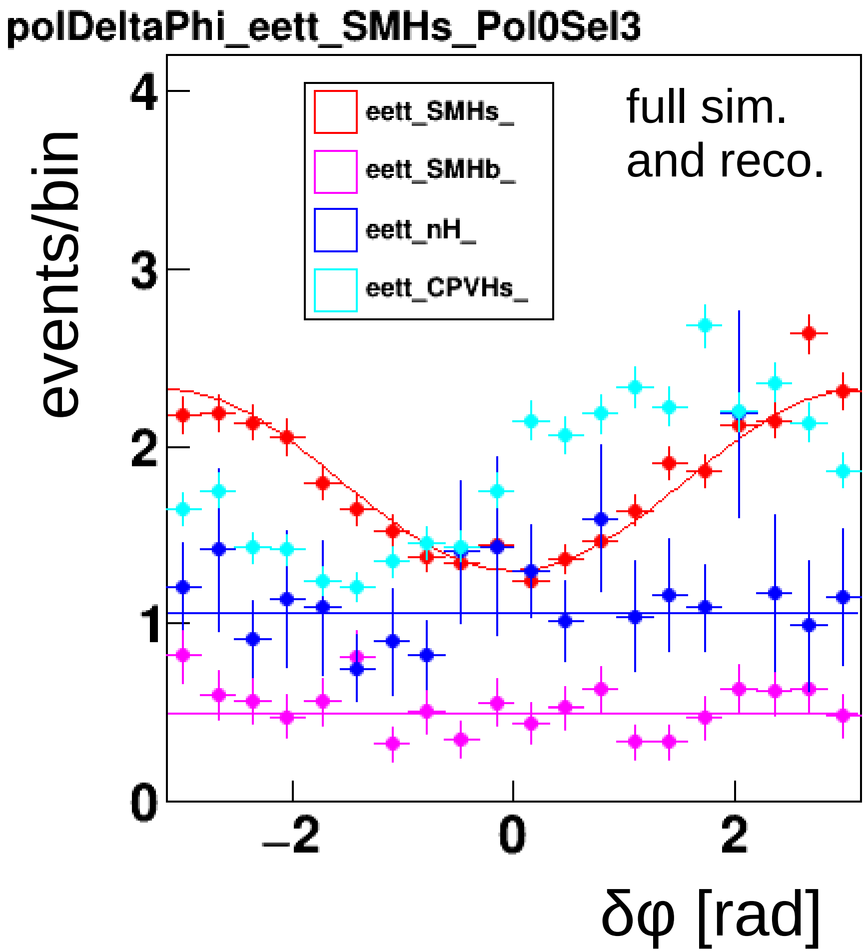


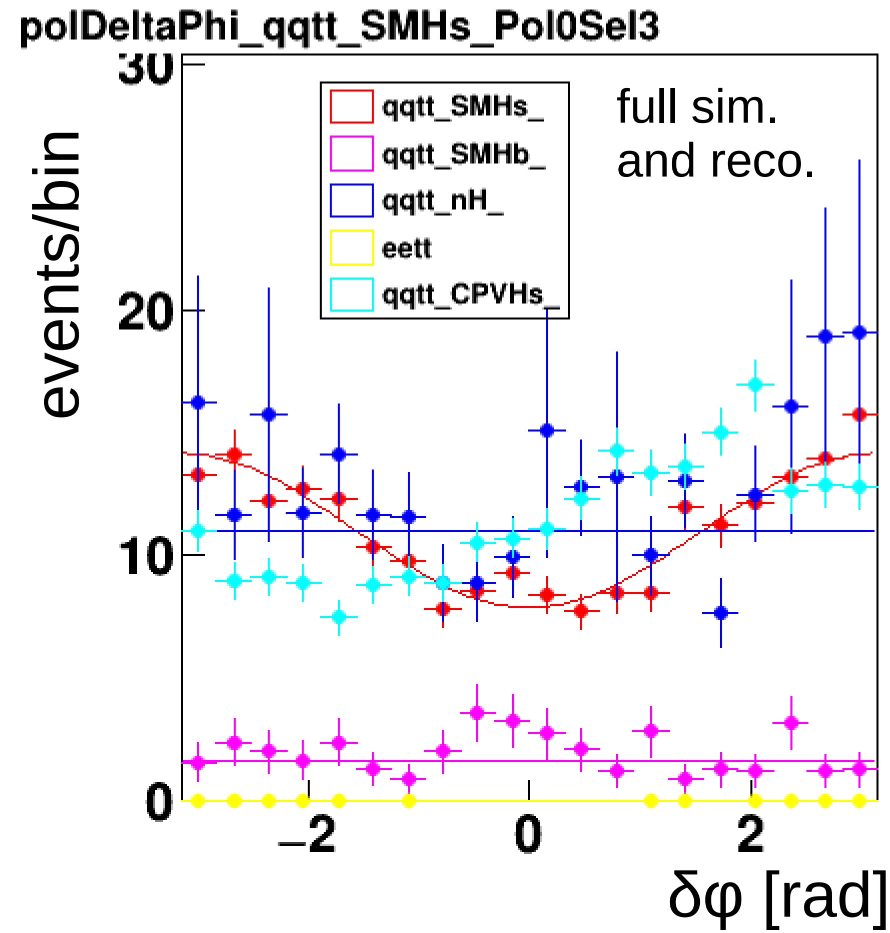
event reconstruction depends largely on:

- tau decay mode identification
  - → pattern recognition in ECAL
- impact parameter resolution
  - → vertex detector
- jet energy resolution

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

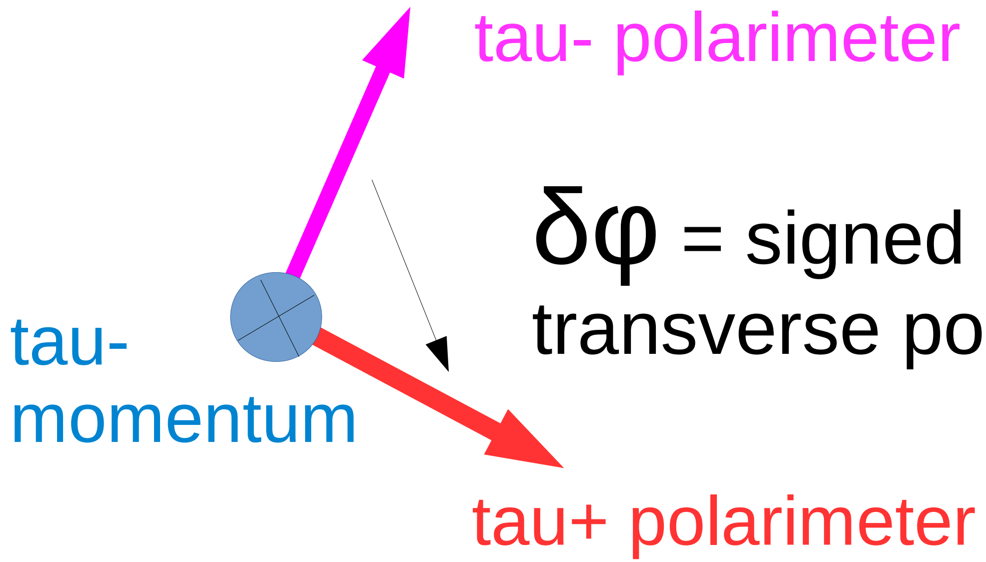
old plots

typical selection efficiencies

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

PRELIMINARY

transverse spin correlations



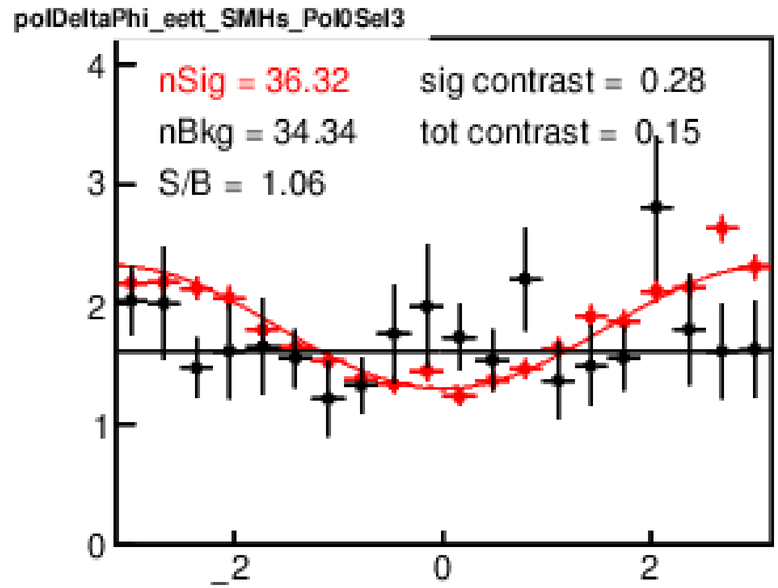
$\delta\varphi$ = signed angle between transverse polarimeter components

If everything is known perfectly, this is distributed as

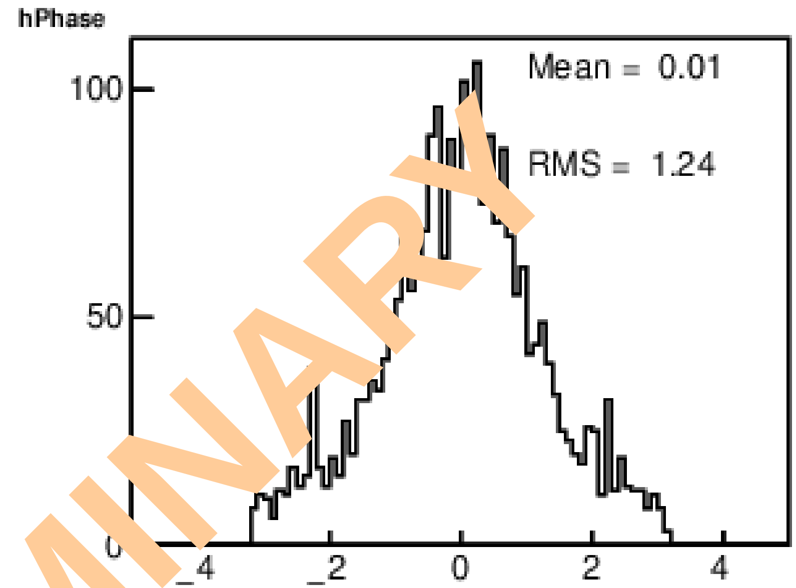
$$f\,(\,\delta\varphi\,) \sim 1 + (\pi^2/16)\cos(\,\delta\varphi + \psi\,)$$

results of toy MC experiments: eeττ channel

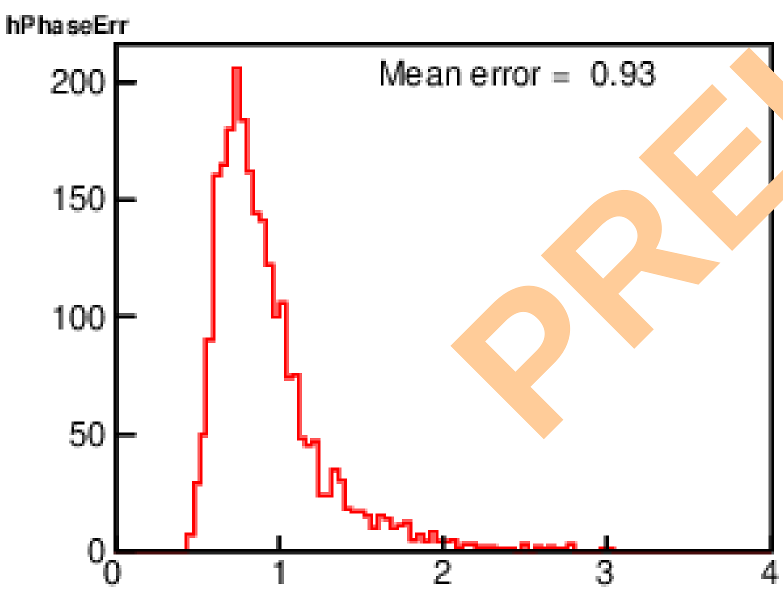
P(e-,e+) = (-0.8, +0.3), 1350 fb-1



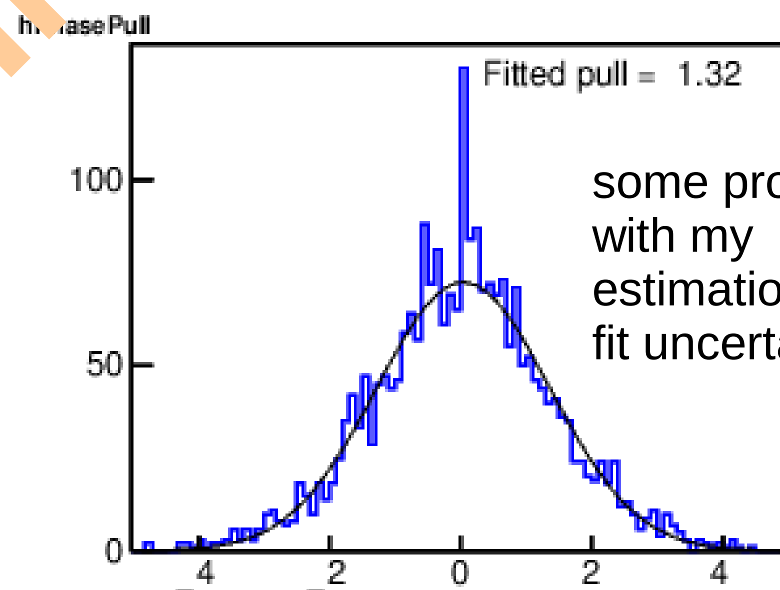
angle between trans polarimeters



extracted phase [rad]



extracted uncertainty [rad]

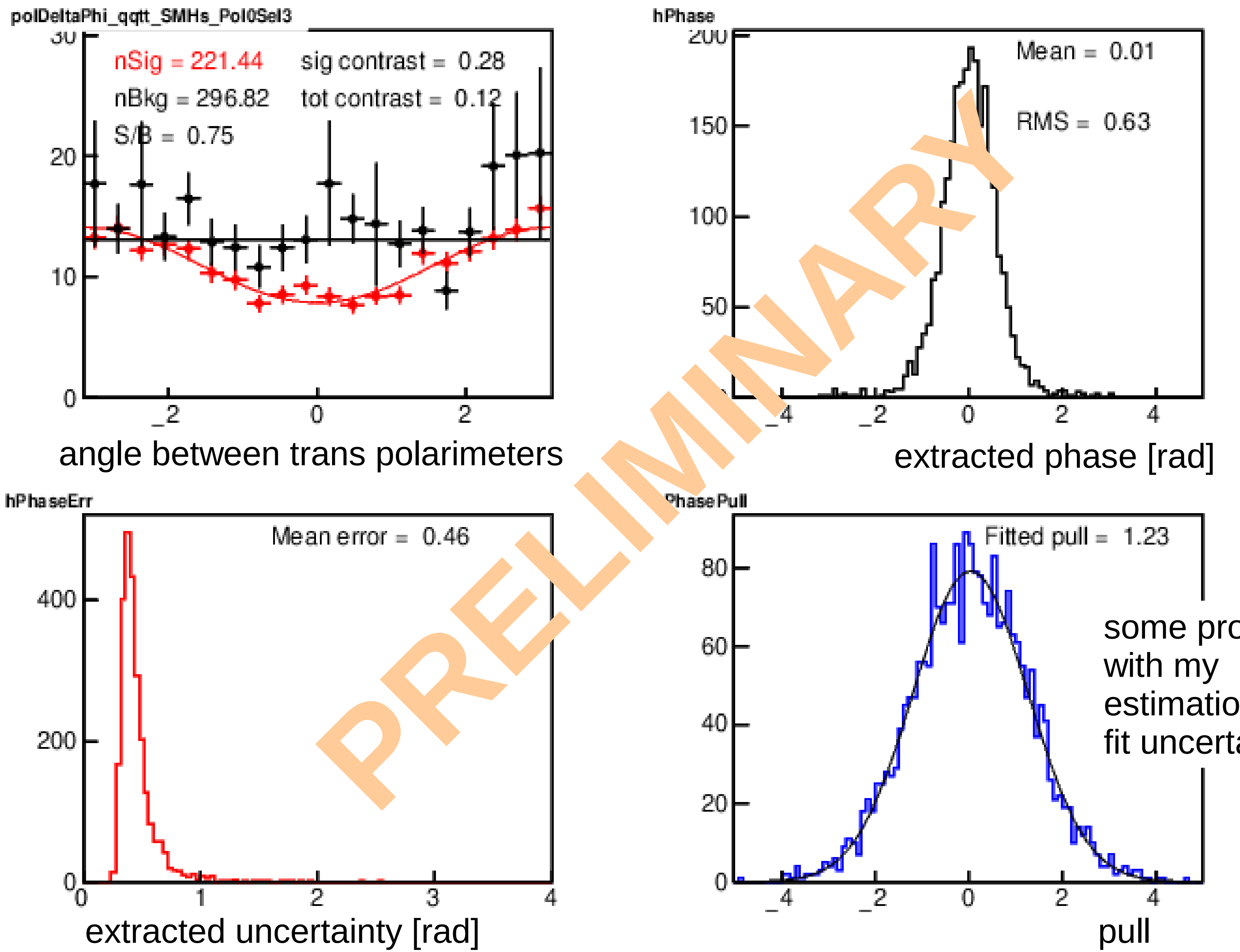


pull

some problem with my estimation of fit uncertainties?

results of toy MC experiments: qqττ channel

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



some problem with my estimation of fit uncertainties?

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 ~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 cosTheta>0.99 of lepton
  - (m – m_Z) < 10 (15) GeV for mumu (ee)

reject if Z → ee & | costh(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 pi0 candidates which match a tau seed
- [reasonable probability in constrained mass pi0 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 pi0 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

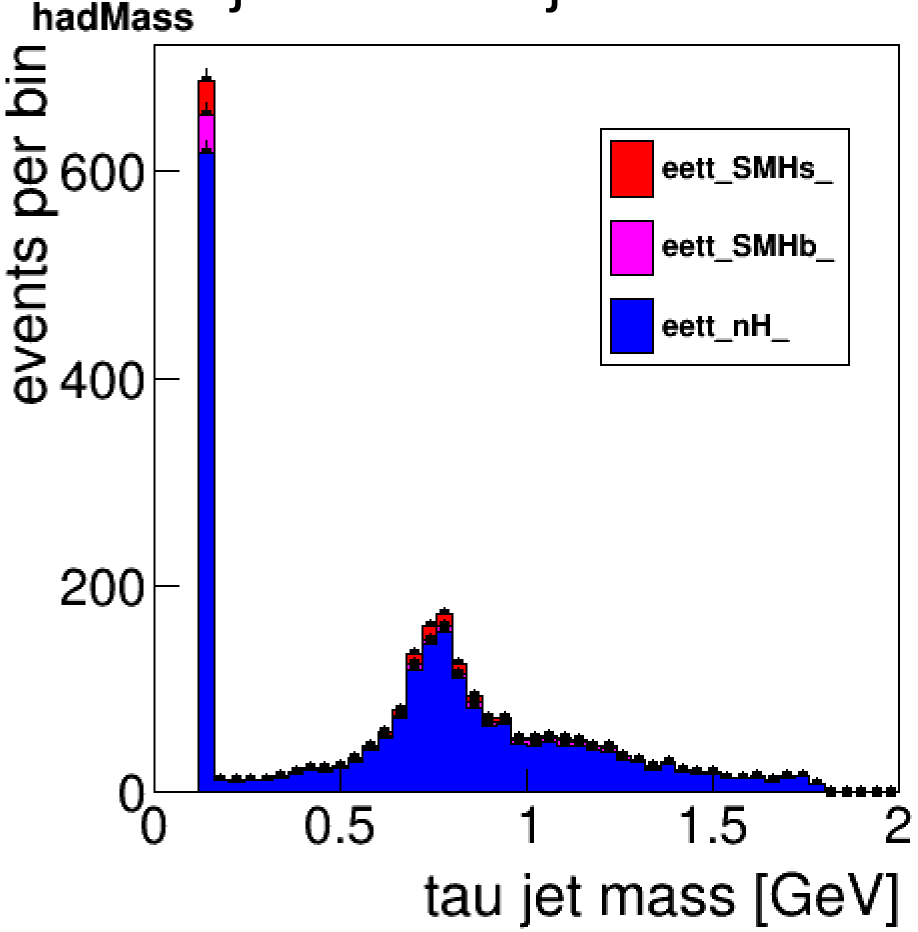
hadronic selection

- invariant mass of remainder of event 70 → 110 GeV
- successful reconstruction of tau momenta
- 100 GeV < tau-tau mass < 150 GeV
- recoil mass > 110 GeV

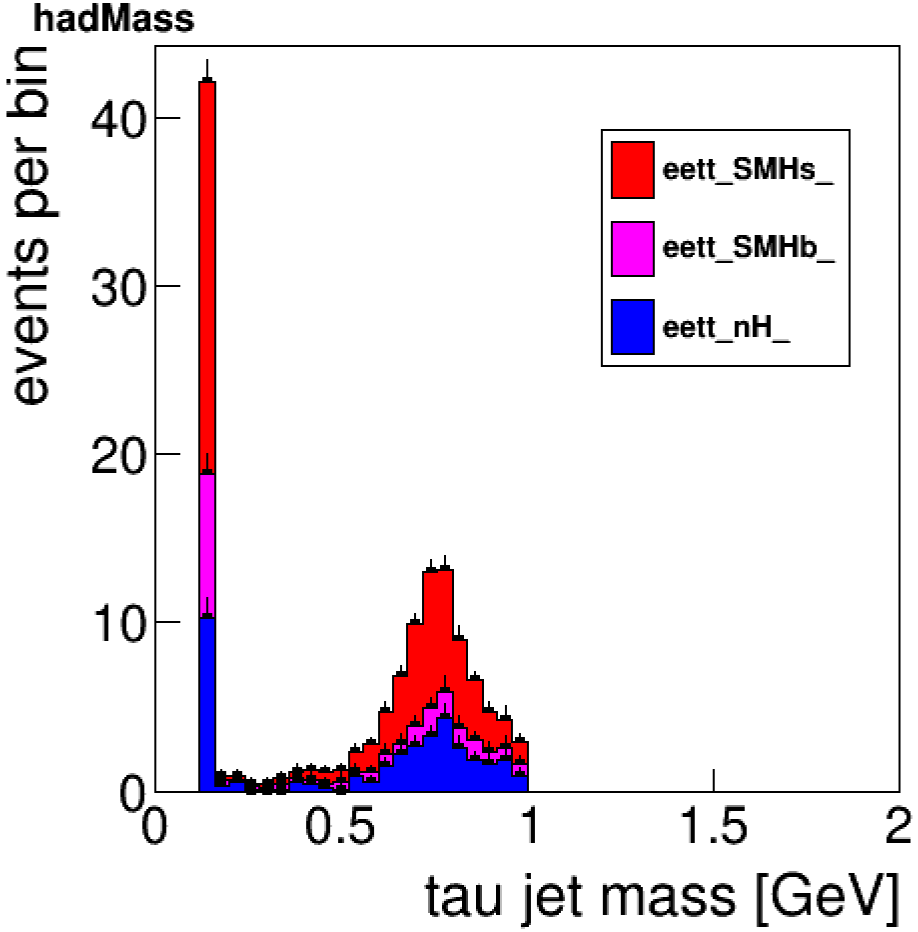
Tau jet mass (e e τ τ selection)

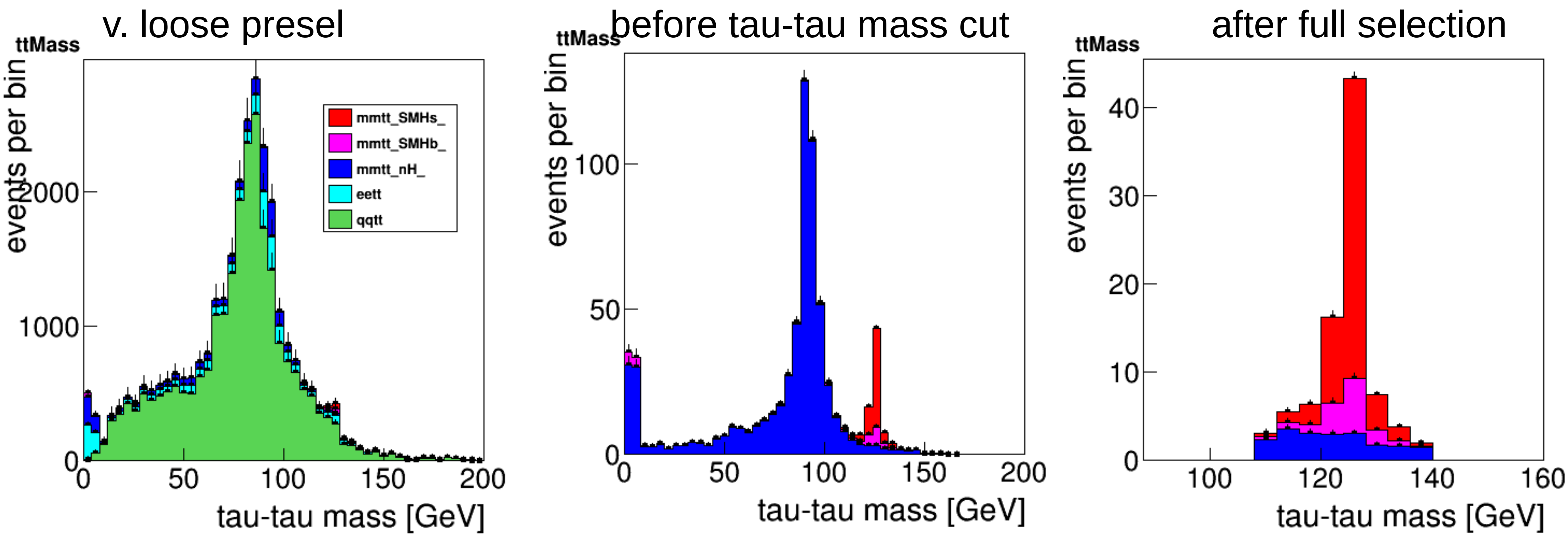
P(e-,e+) = (-0.8, +0.3), 1350 fb-1

just before jet mass sel



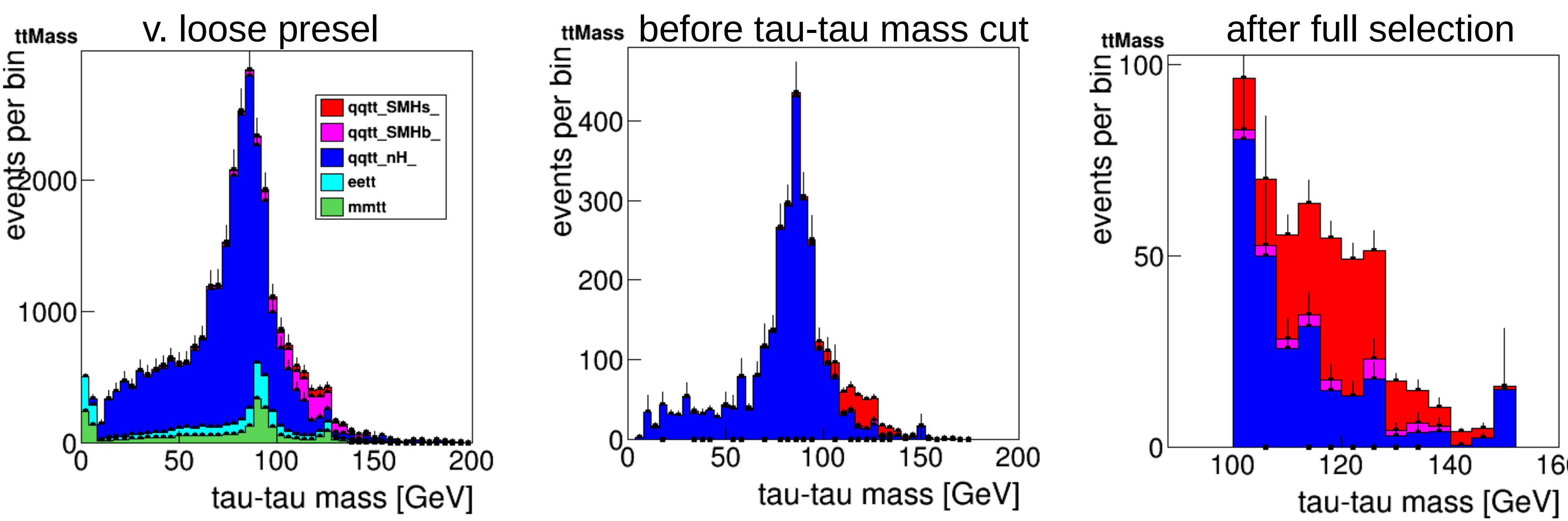
final selection





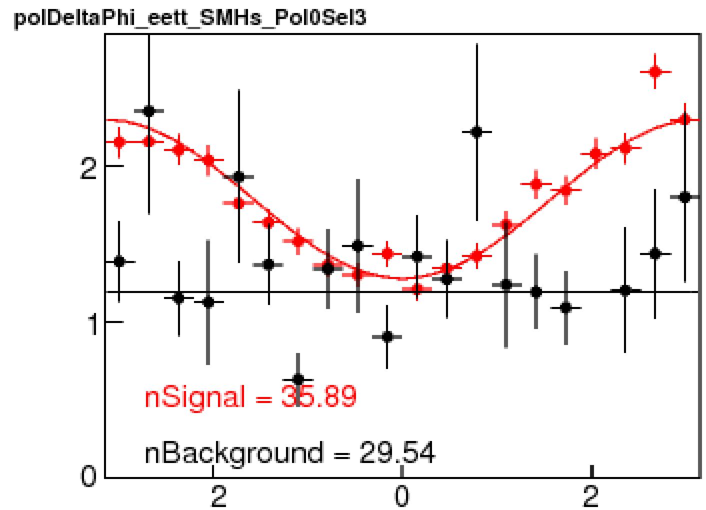
reconstructed tau-tau invariant mass μ μ τ τ ↑

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

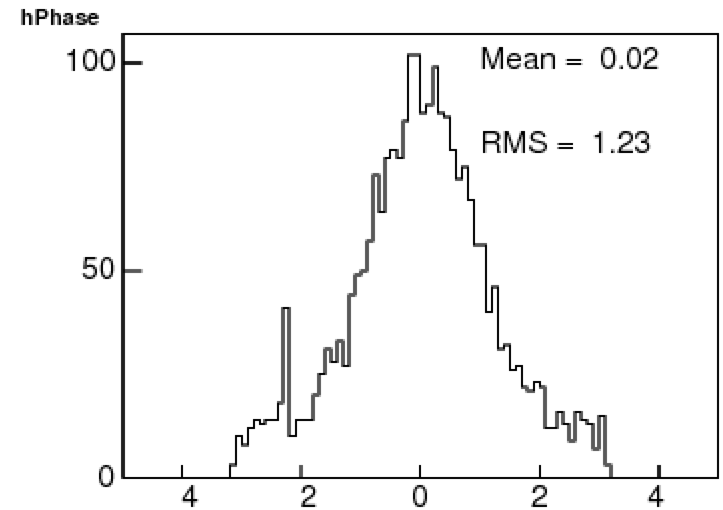


eeττ channel results of toy MC experiments

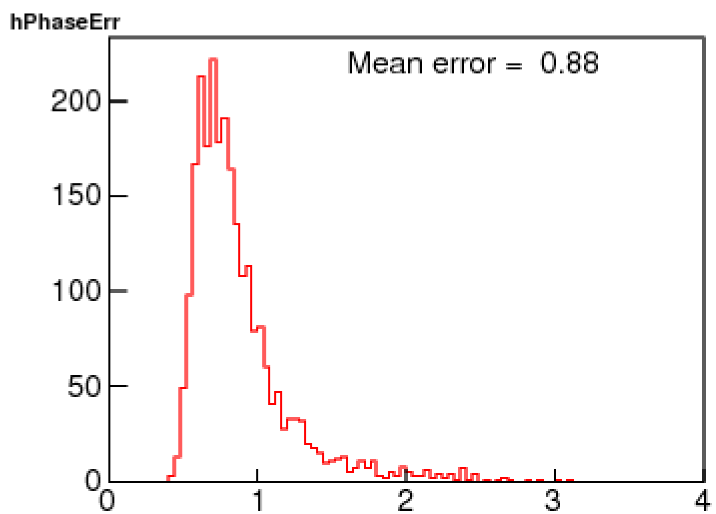
P(e-,e+) = (-0.8, +0.3), 1350 fb-1



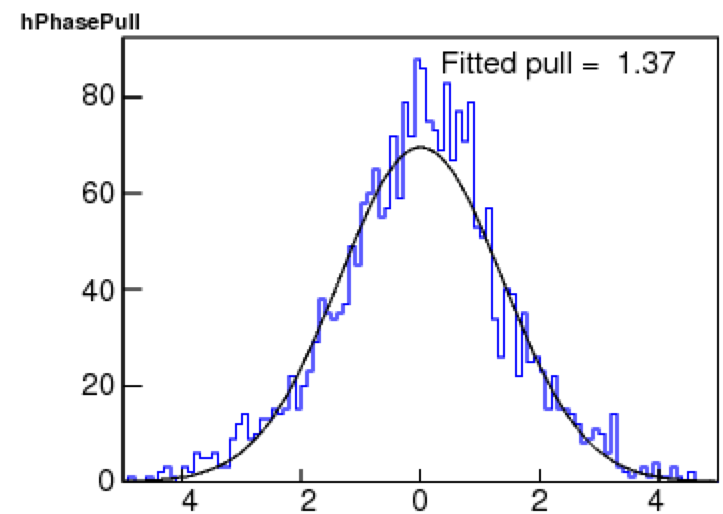
angle between trans polarimeters



extracted phase [rad]



extracted uncertainty [rad]



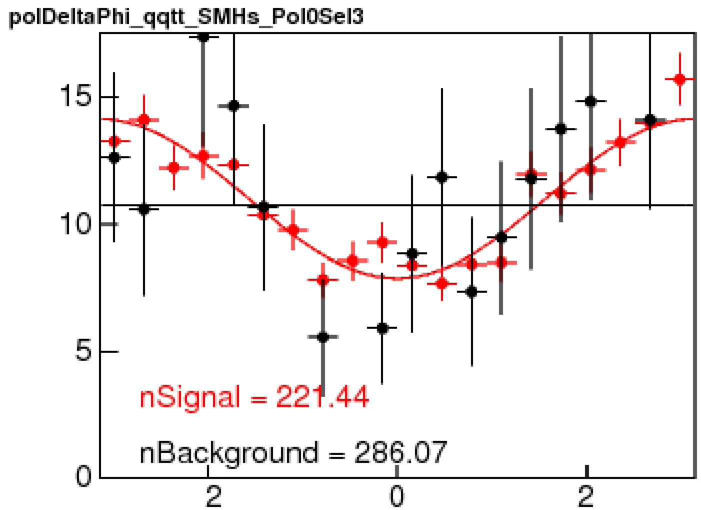
pull

pull distribution suspiciously large

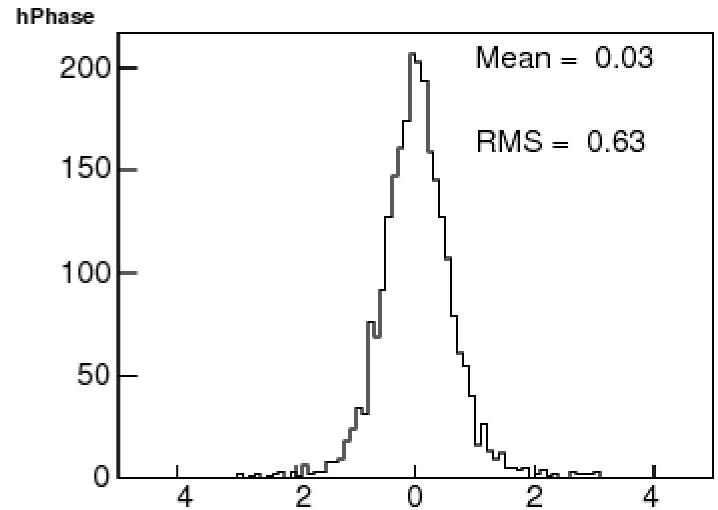
qqττ channel

results of toy MC experiments

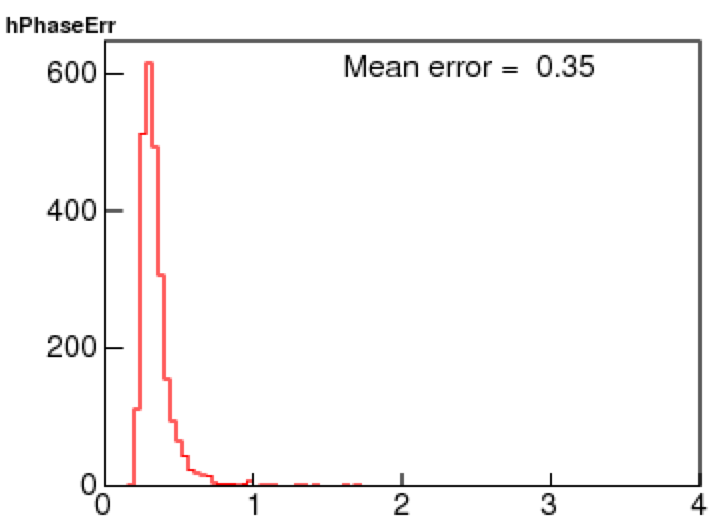
P(e-,e+) = (-0.8, +0.3), 1350 fb-1



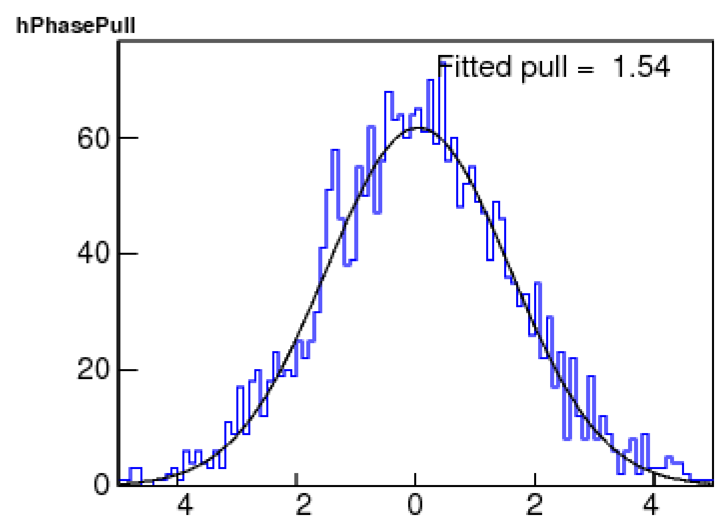
angle between trans polarimeters



extracted phase [rad]



extracted uncertainty [rad]

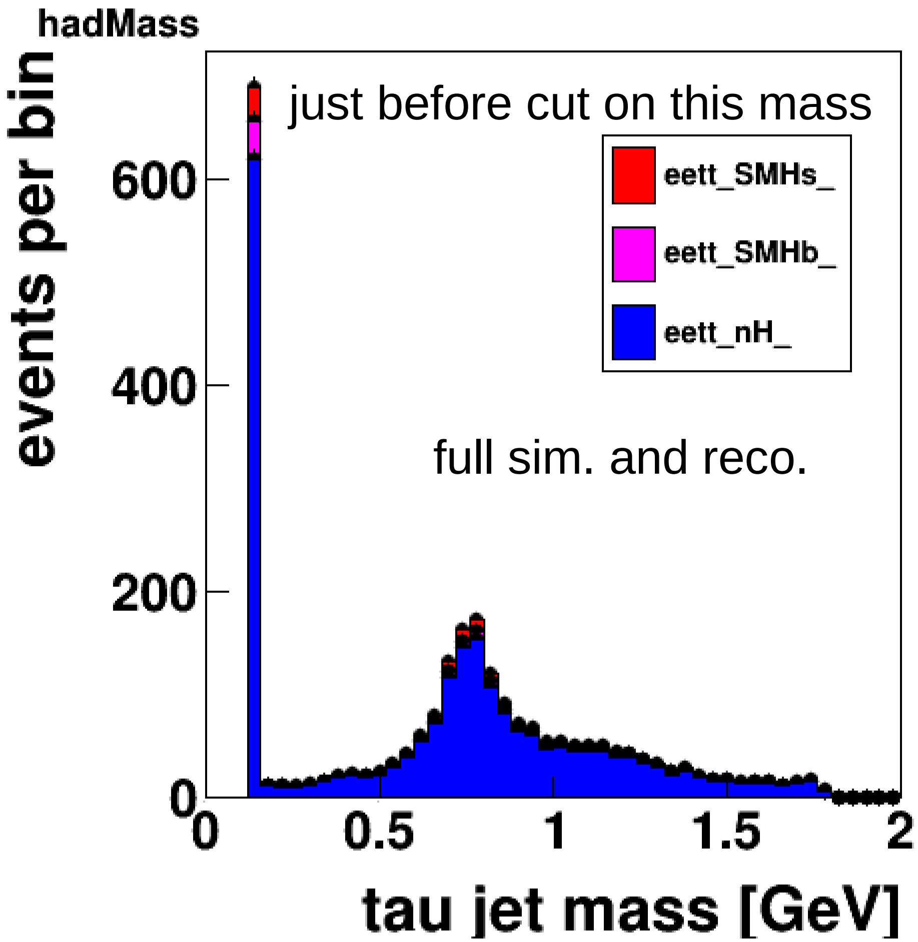


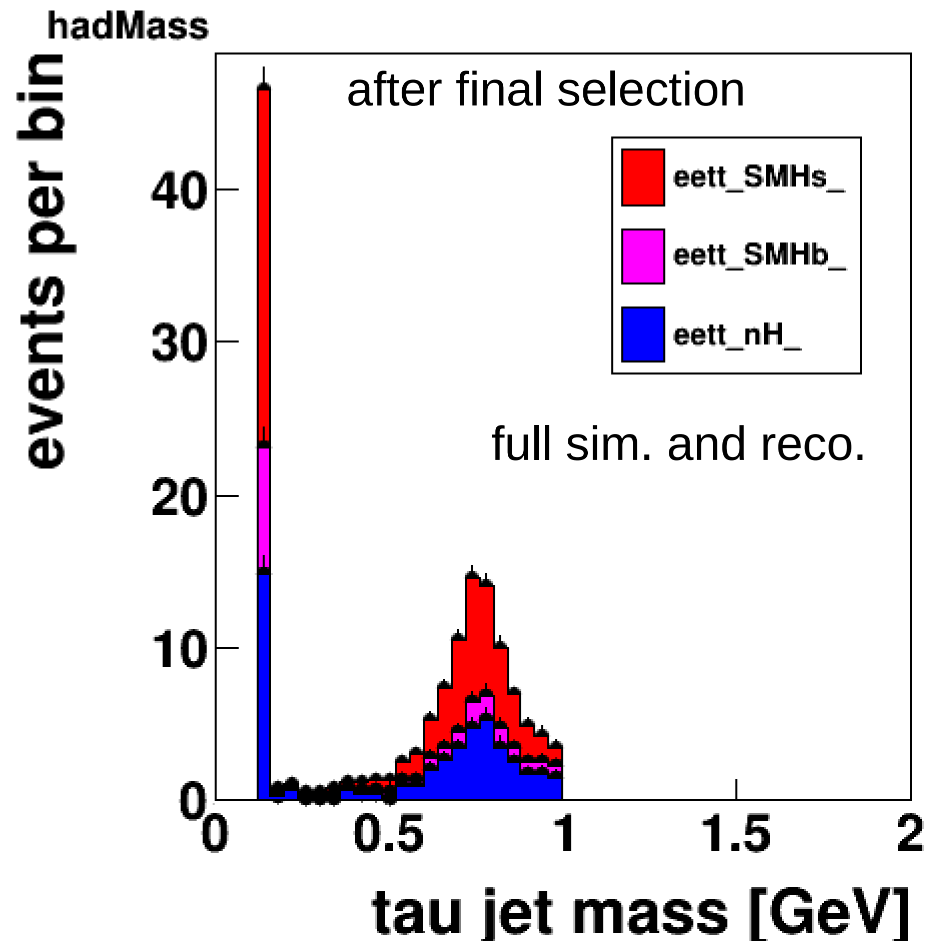
pull

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 → pi or rho) signal

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

e e tau tau (non-Higgs) background