arXiv:1912.08403

arXiv:2203.07668

Measuring the tau polarisation at the ILC

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KEK, SOKENDAI

Motivation

The aim of this study

The reconstruction of tau spin orientation ("**Polarimeter**")
in order to measure polarisation to investigate new physics.

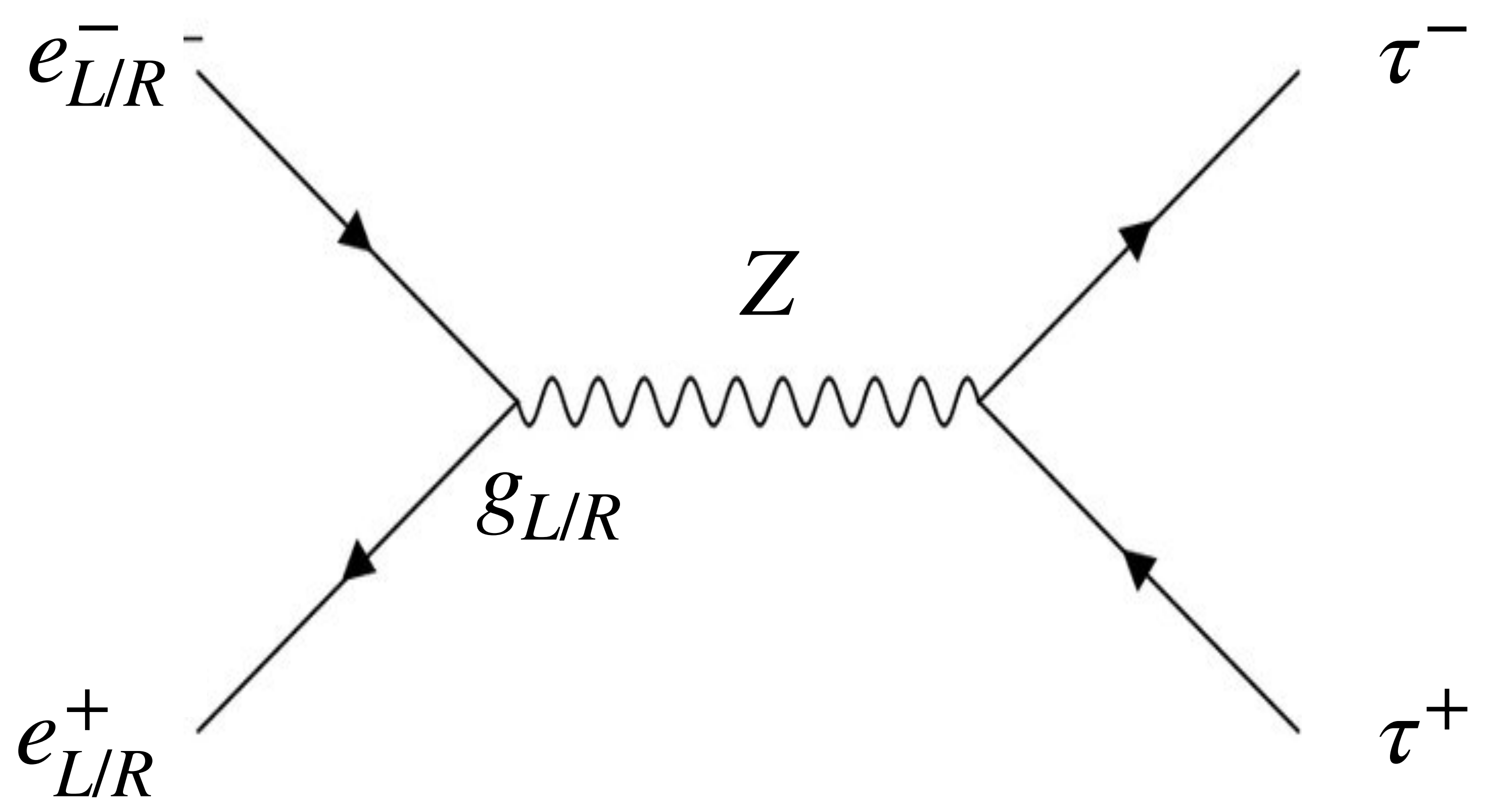
<u>Two tools are available at ILC to measure the chirality of such new interactions.</u>

- At the ILC, forward-backward asymmetry $A_{FB} = \frac{3}{4} A_e \cdot A_f$ can be measured

  Thanks to ILC's polarised beams, A_e can be measured $\Rightarrow$ A_f can be extracted from A_{FB}

- We can also directly measure A_τ by using tau polarisation $P(\tau)$

$$\frac{dP(\tau)}{d\cos\theta} = \frac{3}{8} A_\tau (1 + \cos^2\theta) + \frac{3}{4}\left(\frac{A_e - P_e}{1 - A_e P_e}\right)\cos\theta$$



Polarimeter

Reconstruction of tau polarisation $P(\tau)$ depends on tau decay mode.

only look at $\tau \to \pi\nu$ (BR $\sim 10\,\%$)

$\tau \to \rho\nu$ (BR $\sim 26\,\%$)

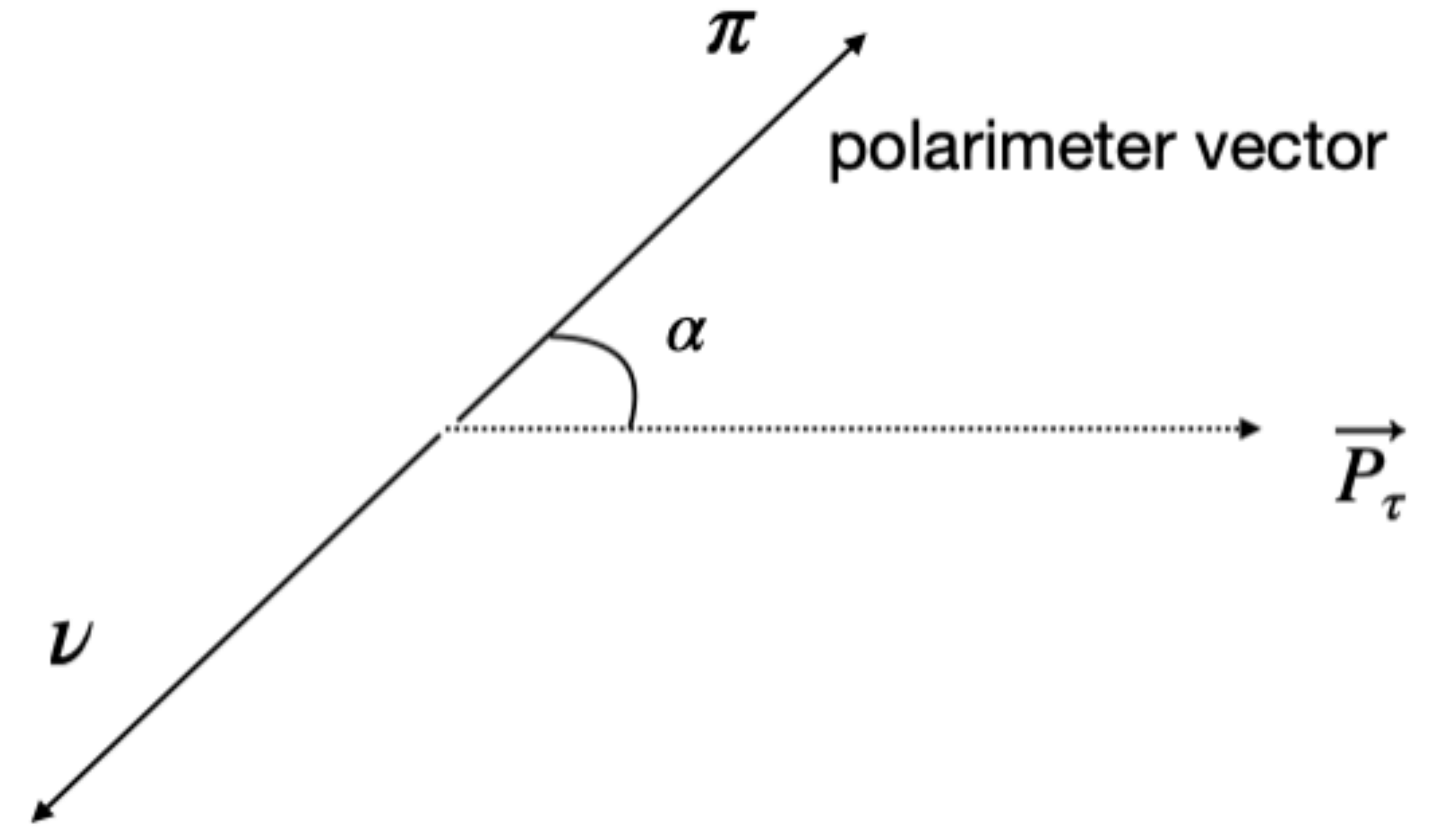
in this talk

Polarimeter vectors of $\tau \to \pi\nu$ in τ rest frame

$$h(\tau^{\pm} \to \pi^{\pm}\nu) = \frac{p_{\nu}}{|p_{\nu}|}$$

Polarimeter vectors of $\tau \to \rho\nu$ in τ rest frame

$$h(\tau^{\pm} \to \pi^{\pm}\pi^{0}\nu) = 2\left(q \cdot p_{\nu}\right) q - m_q^2 p_{\nu}$$



Where $q = p_{\pi^{\pm}} - p_{\pi^{0}}$

$p_{\nu}, p_{\pi^{\pm}}, p_{\pi^{0}}$ the 3-momenta of the neutrinos, charged pions, neutral pions

"Polarimeter"

The cosine of the angle this polarimeter vector makes to the tau flight direction

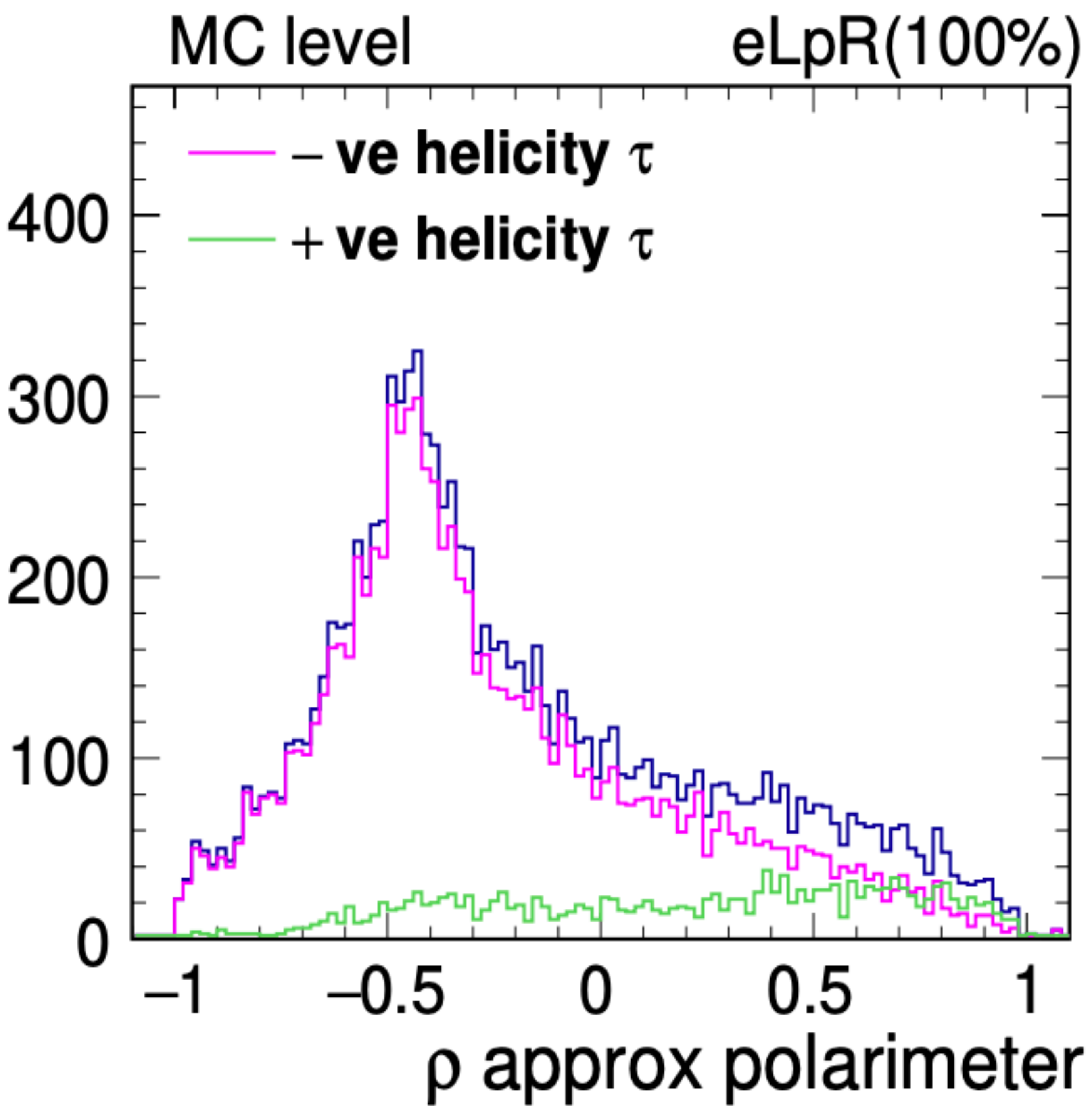
Previous study

Extract polarimeter without using neutrino information

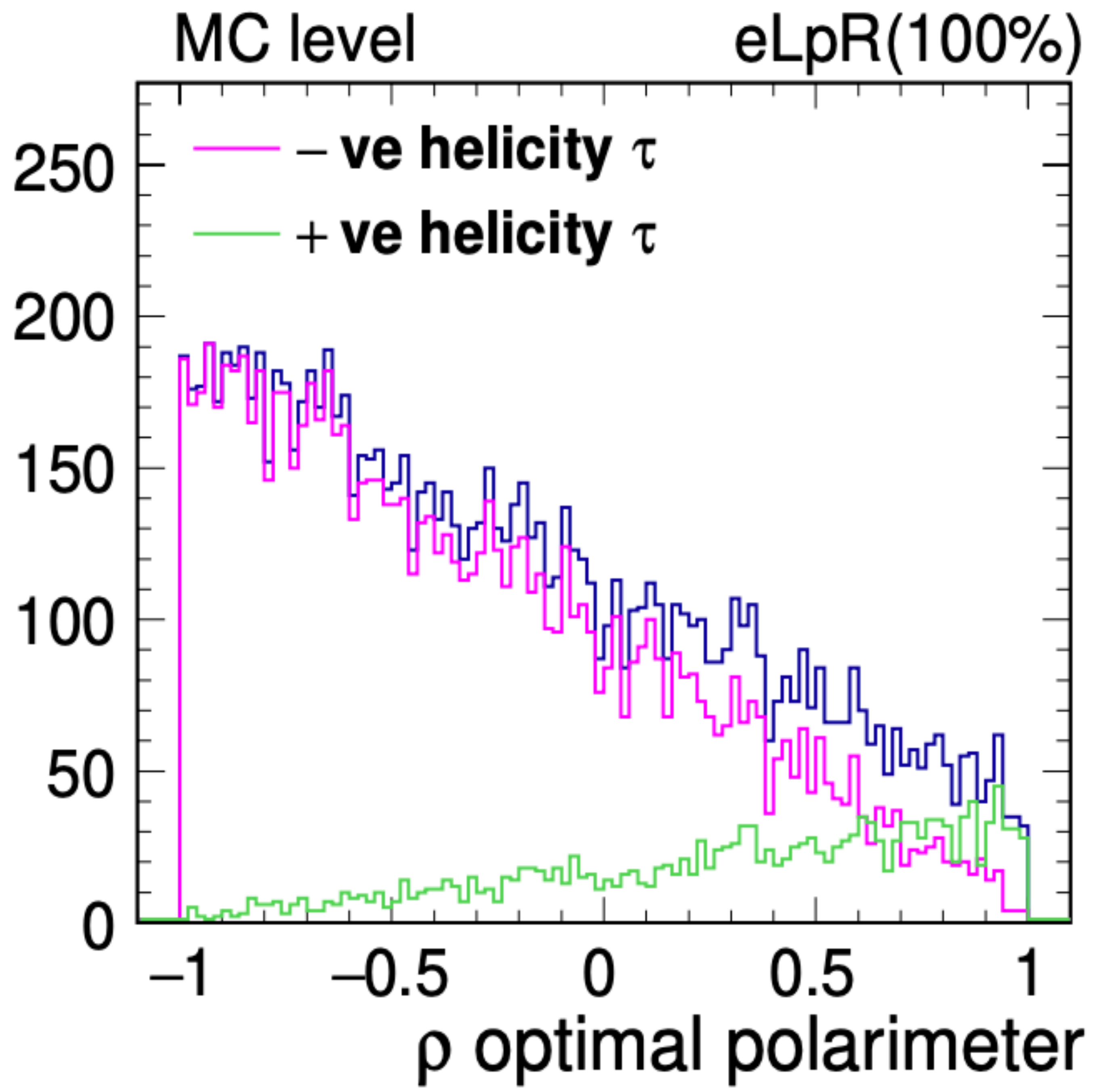
"Approximate" polarimeters based only on the momenta of visible tau decay products

"Optimal" polarimeters including the neutrino component

Do not Use neutrino



Use neutrino



mean statistical error on tau polarisation

($E_{CM} = 500$ GeV, $\mathscr{L} = 1.6$ ab^{-1})

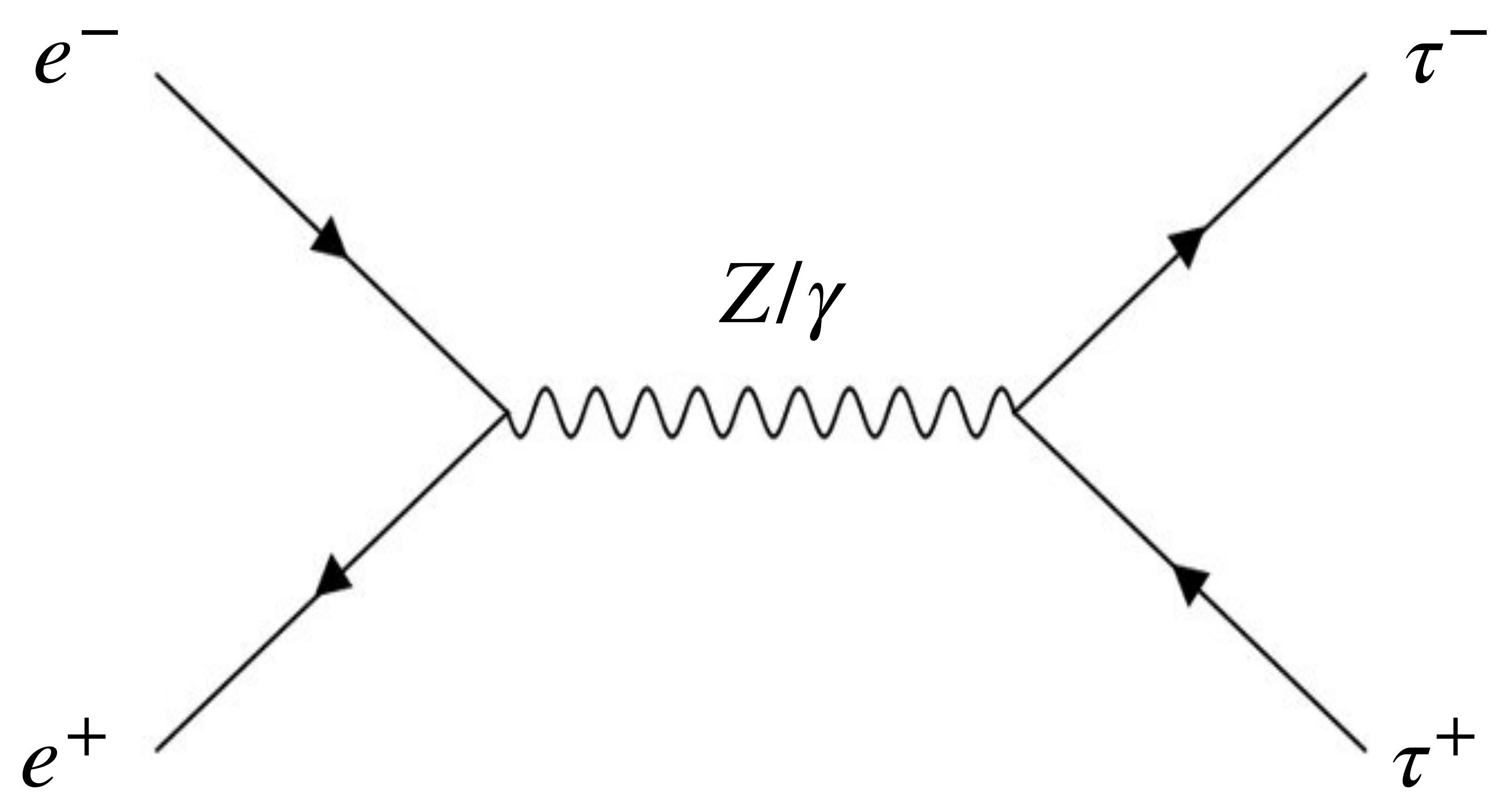
0.40 %

0.30 %

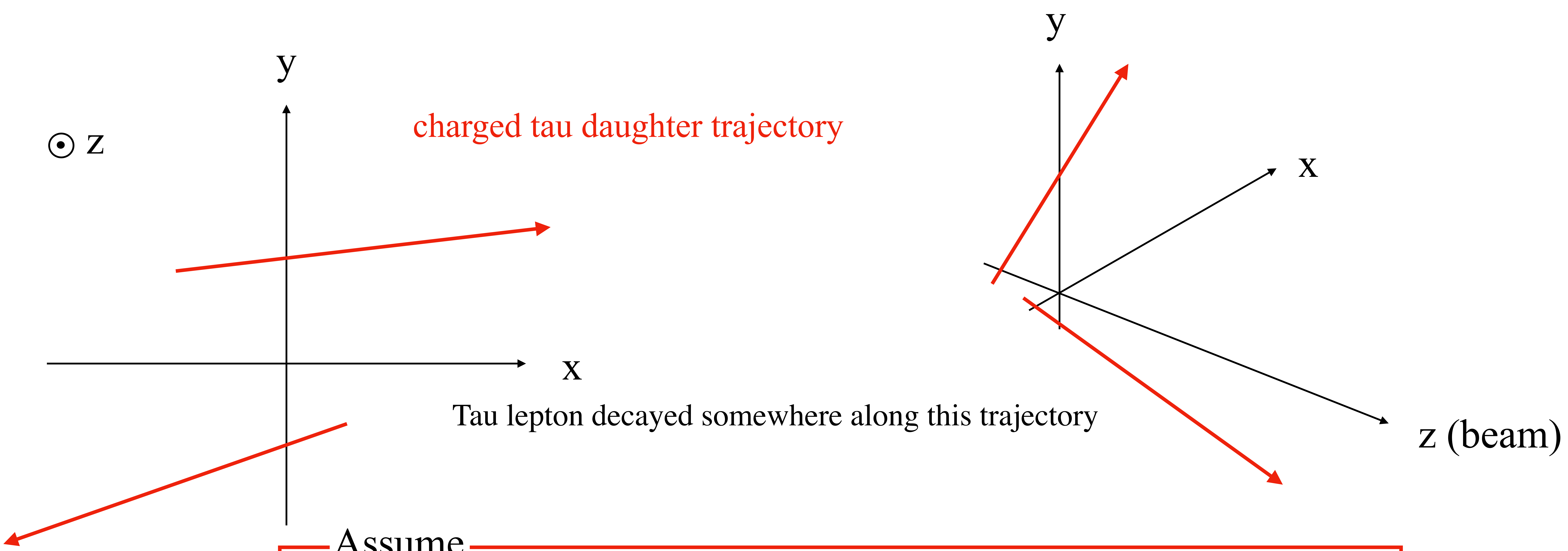
In this talk: reconstruct neutrino momentum → optimal polarimeters

Simulation setup

- ILD mc-2020 $e^+e^- \rightarrow \tau^+\tau^-$ signal event sample with $100\,\%$ beam polarisations
- The decay of the polarised tau was done using TAUOLA.
- MC truth information was used.



τ reconstruction method

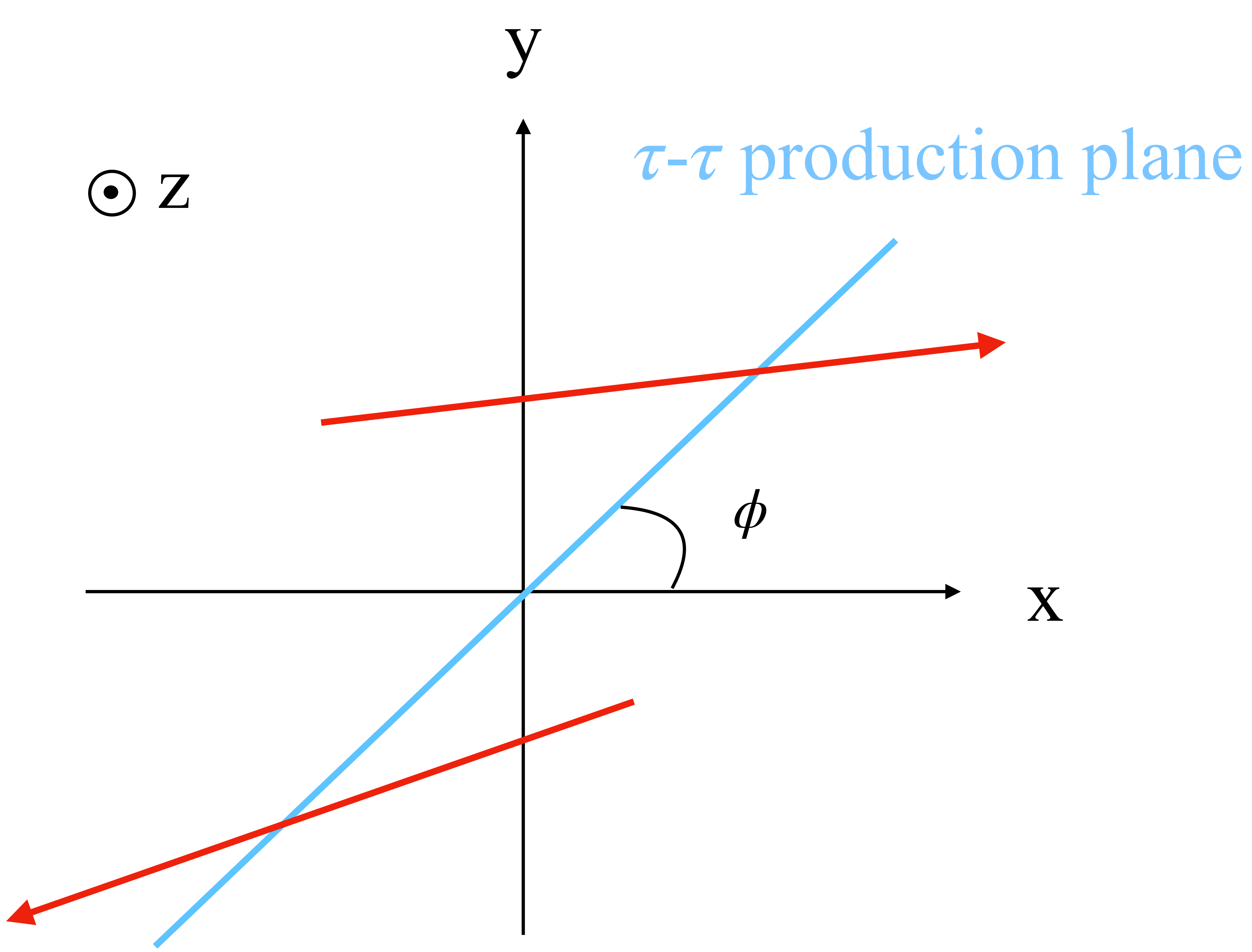


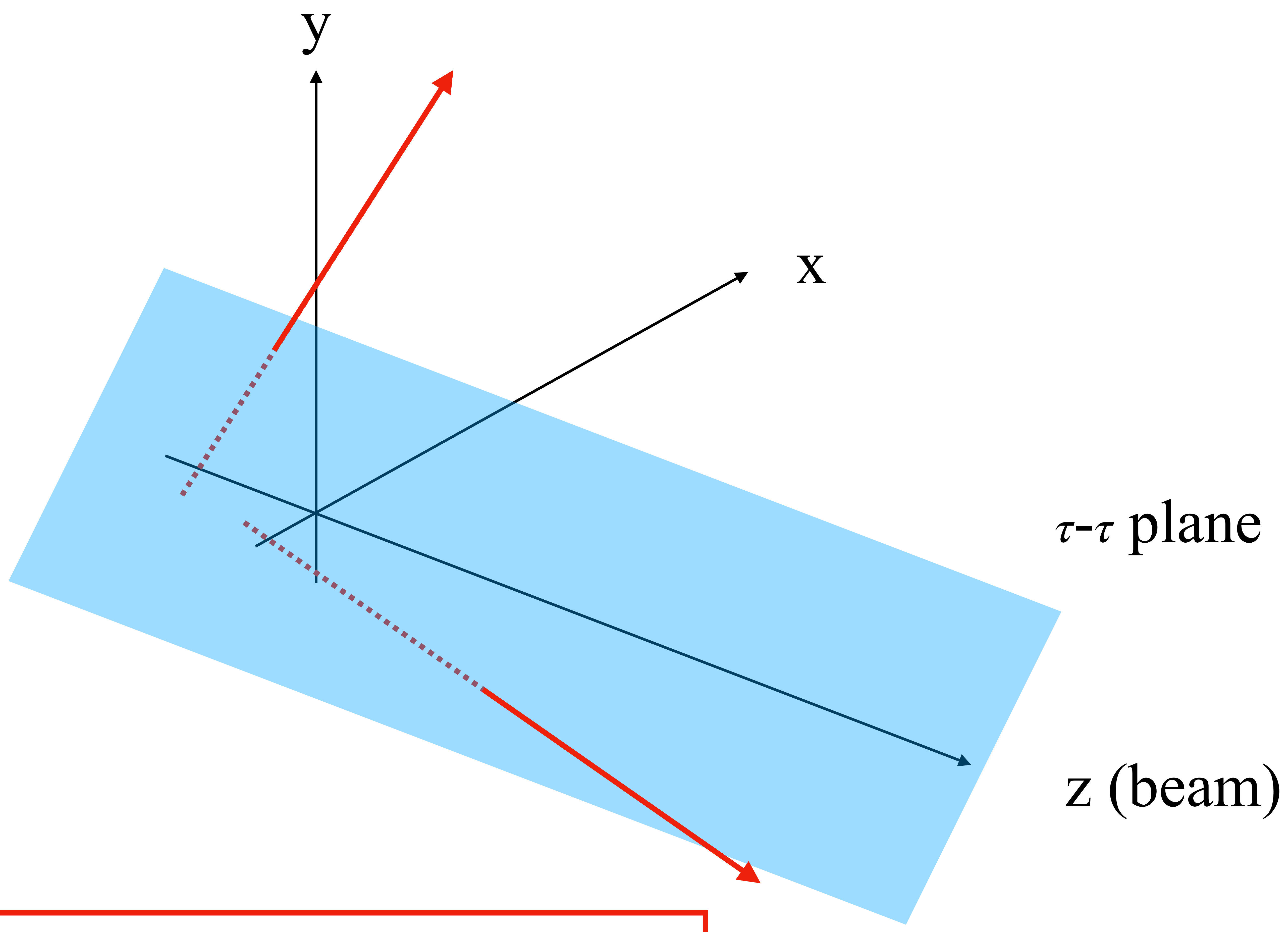
Assume

- Two taus are produced along the beam line(interaction point has $x = y = 0$),
- Two taus are back-to-back in x-y plane,

  — any ISR photons have negligible p_T
- Charged particle travels approximately in a straight line near IP.

τ reconstruction method



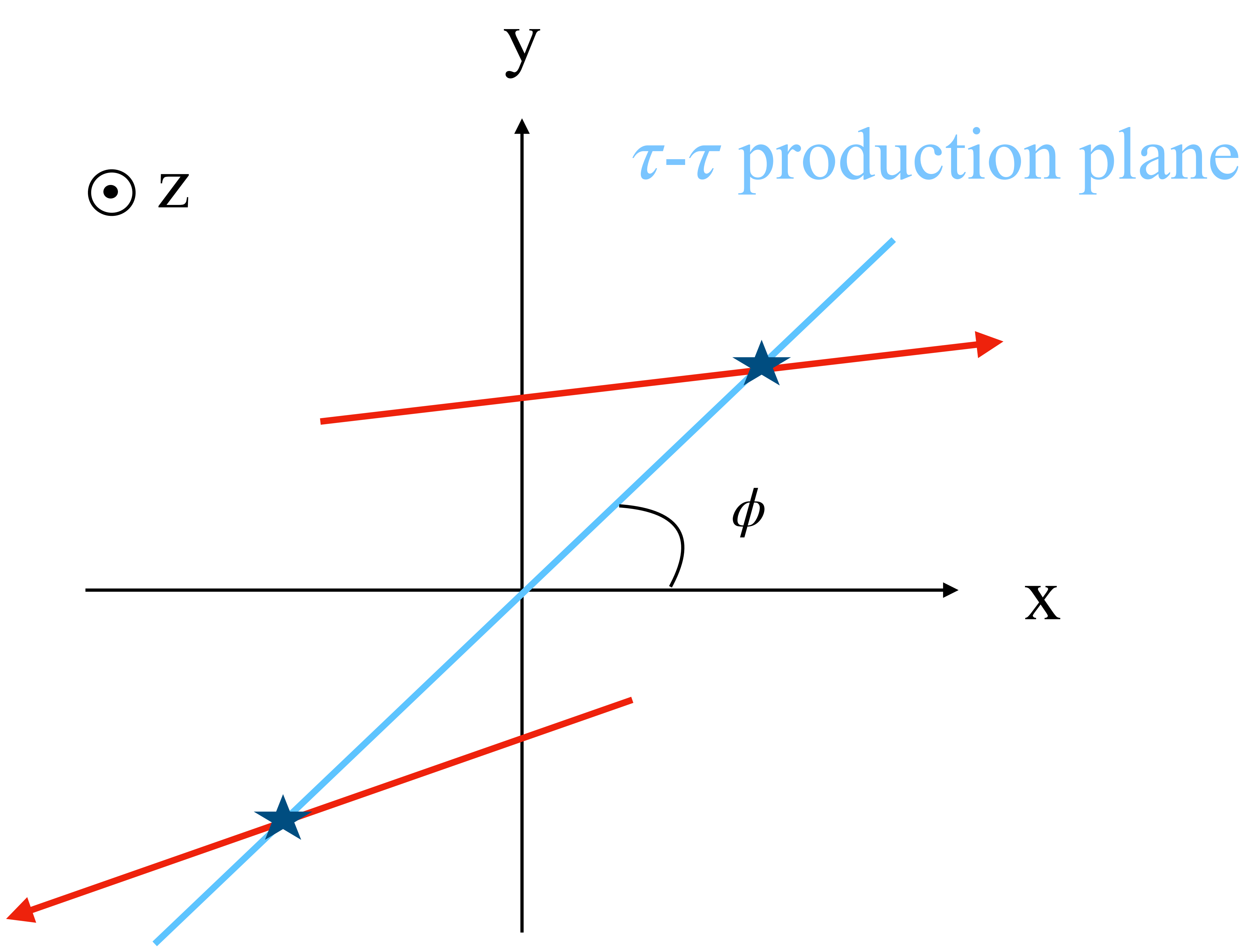


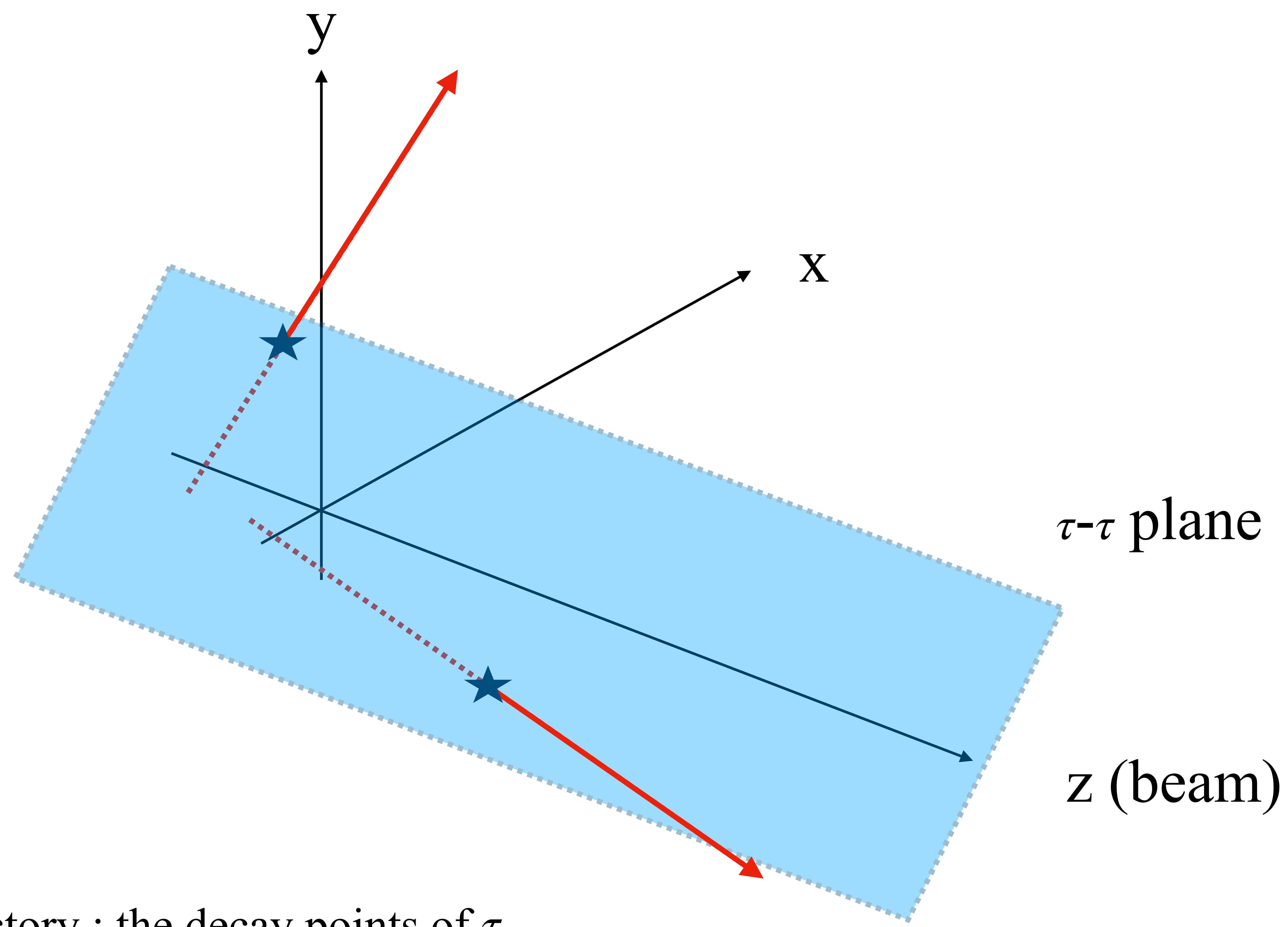
Assume

- Primary interaction occurs along the beam line(interaction point has $x = y = 0$),
- Two taus are back-to-back in x-y plane,
- Charged particle travels approximately in a straight line near IP.

- Two tau momenta lie in a plane containing z-axis, at some azimuthal angle ϕ

τ reconstruction method

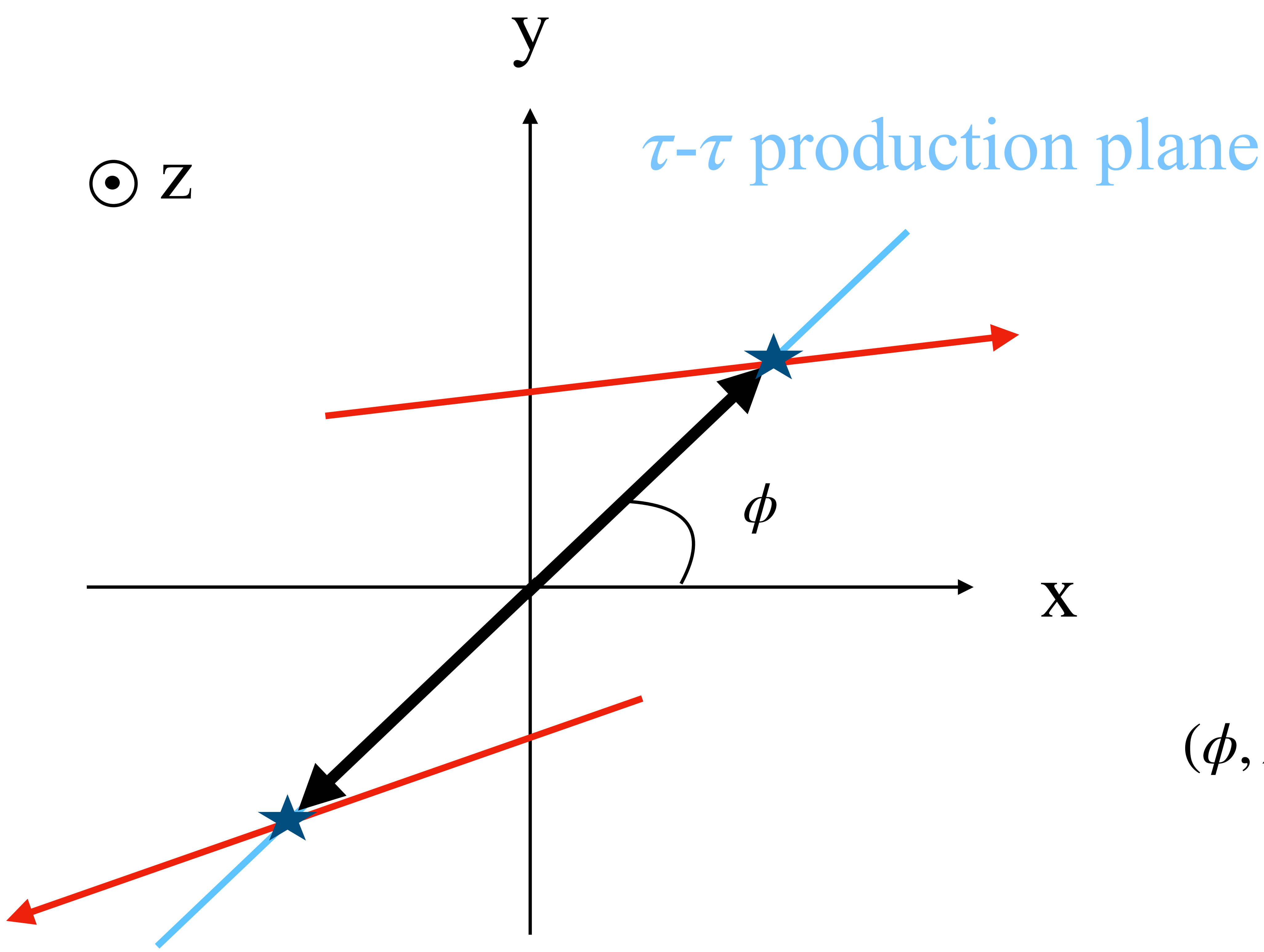




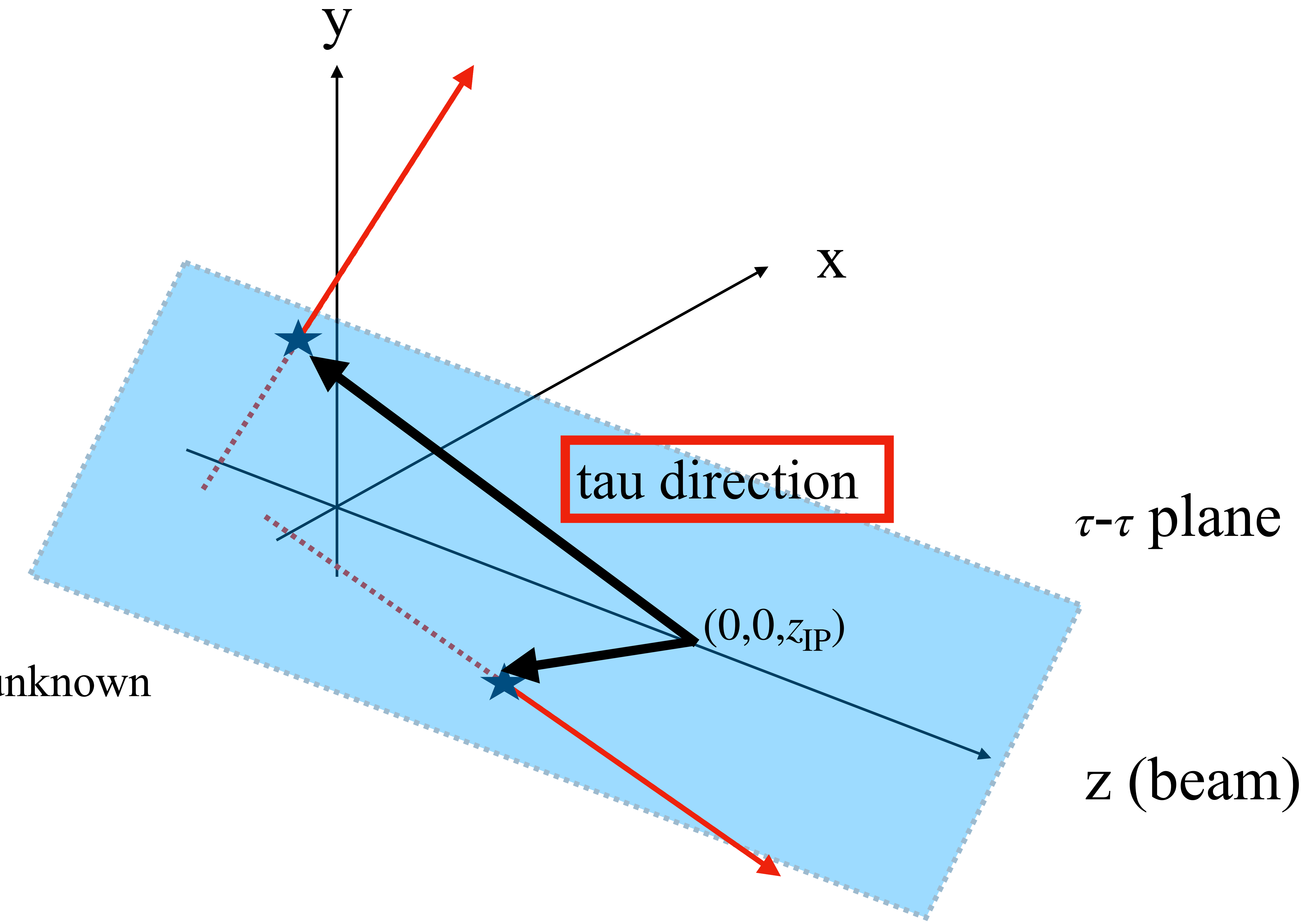
★ The intersection between plane and trajectory : the decay points of τ

For a plane with azimuthal angle ϕ,
the intersection of trajectories with this plane can be calculated.

τ reconstruction method



(ϕ, z_{IP}) : unknown



then choice of z_{IP} gives direction of tau momenta

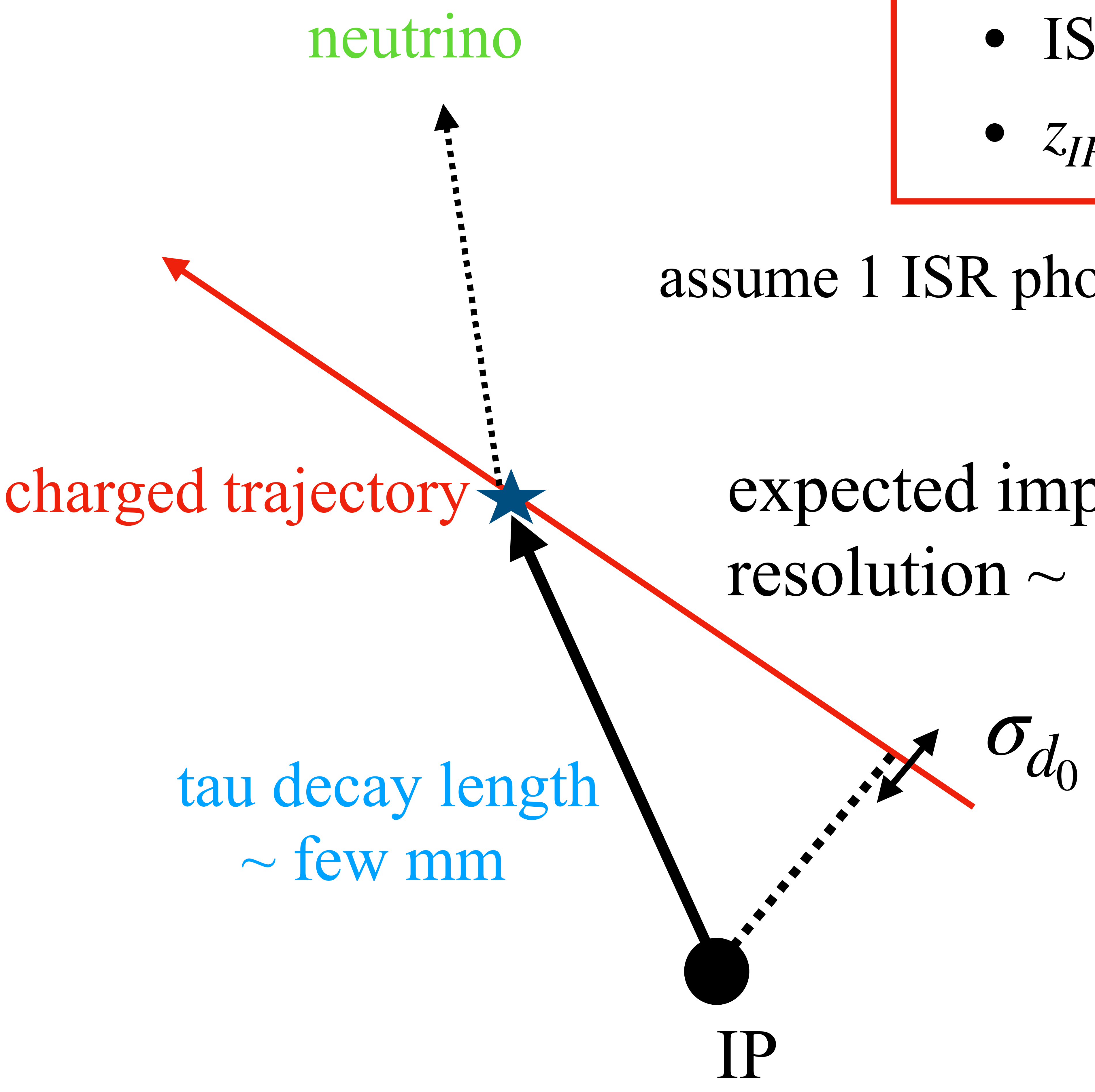
$\Rightarrow$How can we choose ϕ, z_{IP} ?

τ reconstruction method

Unknown
- neutrino 3-momentum $\times 2$
- ISR momentum
- z_{IP}

Constraints
- 4-momentum conservation
- tau mass $\times 2$
- Decay point on trajectory $\times 2$

assume 1 ISR photon collinear with beam



expected impact parameter resolution ~ few μm

For choice of z_{IP}, ϕ

we can calculate tau 4-momenta P_τ

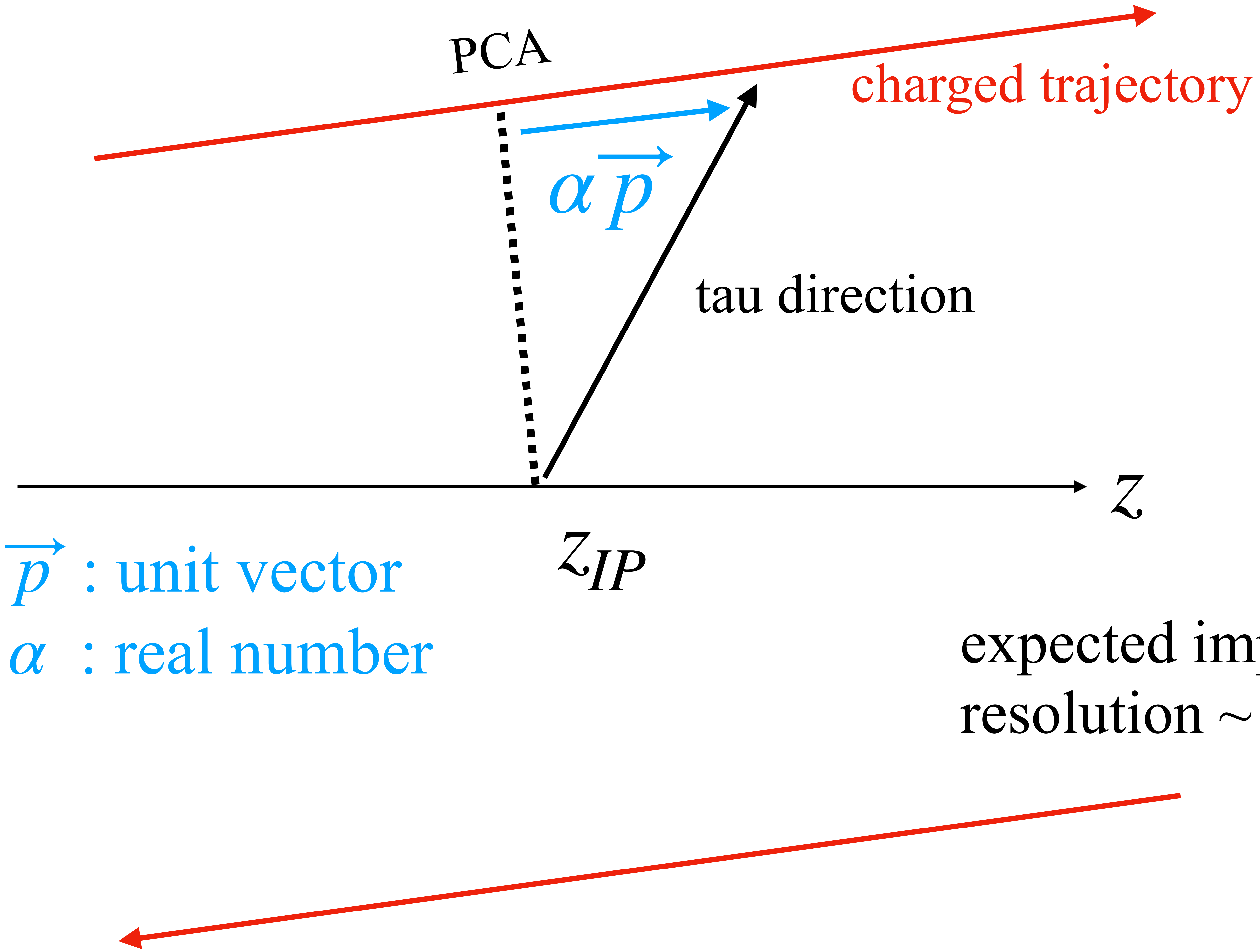
the invariant mass of the missing (neutrino) momentum for each tau can be calculated

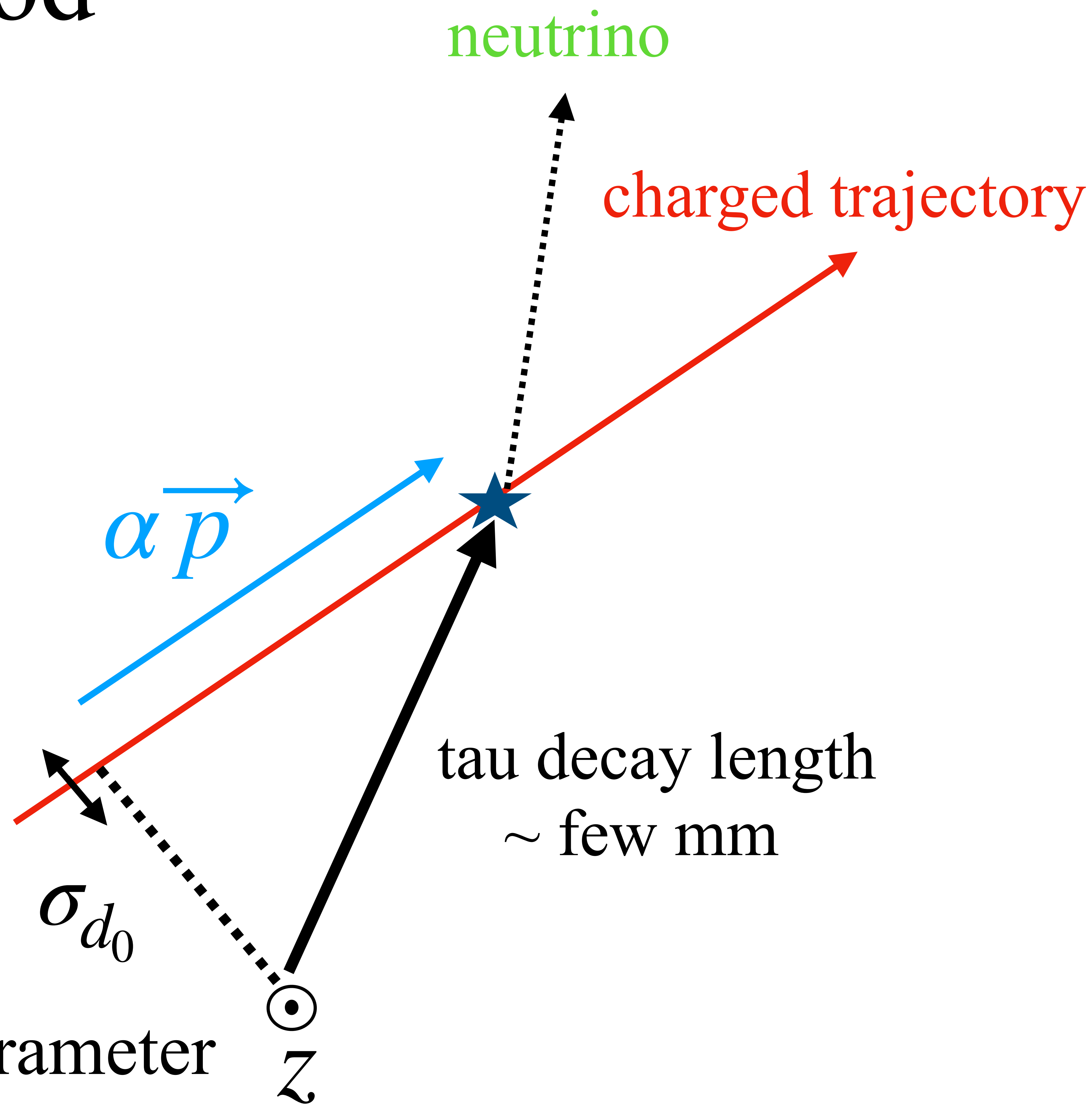
$$P_\nu = P_\tau - P_{vis}$$

We choose the values of z and ϕ which result in neutrino masses closest to zero

τ reconstruction method

We have tried another method

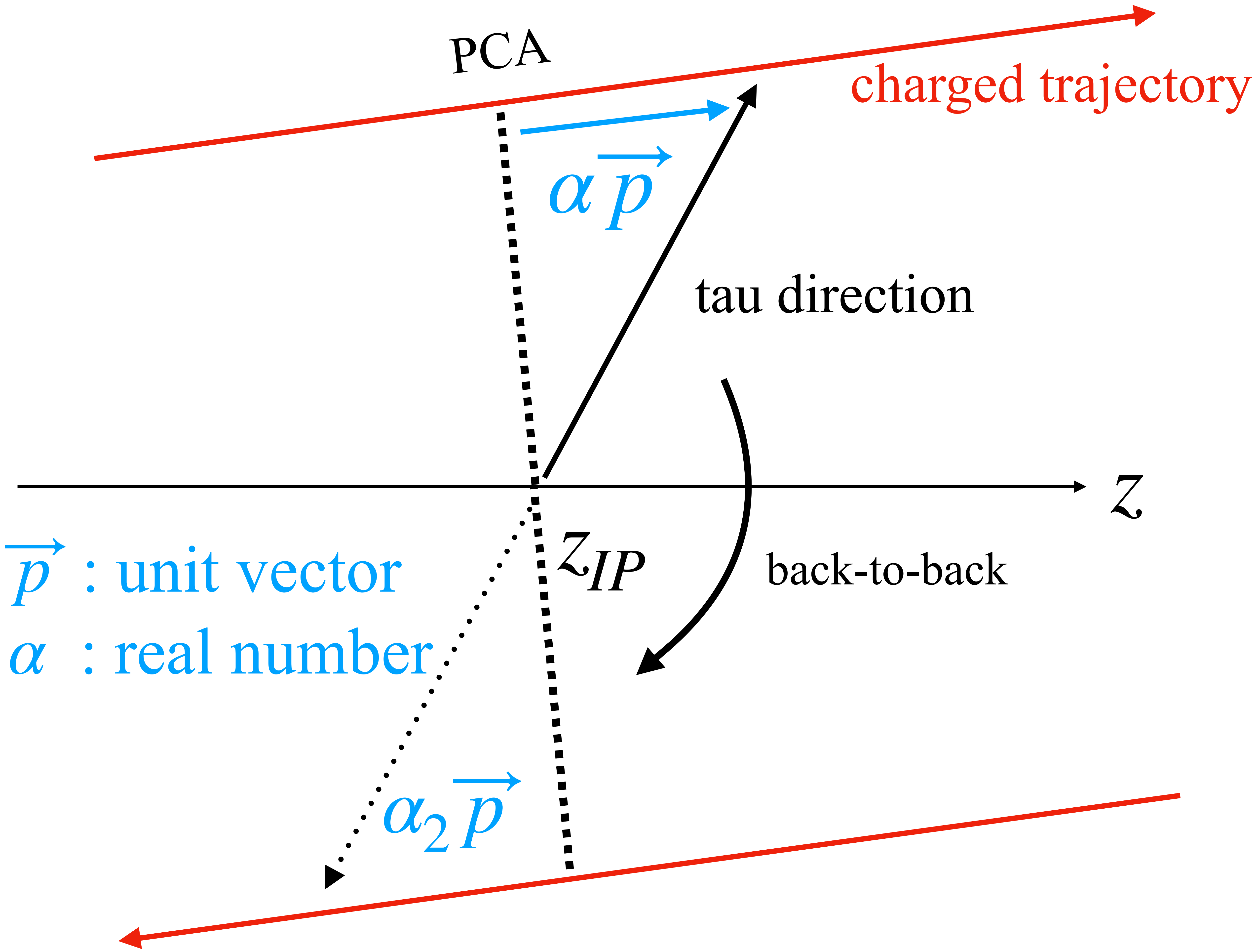




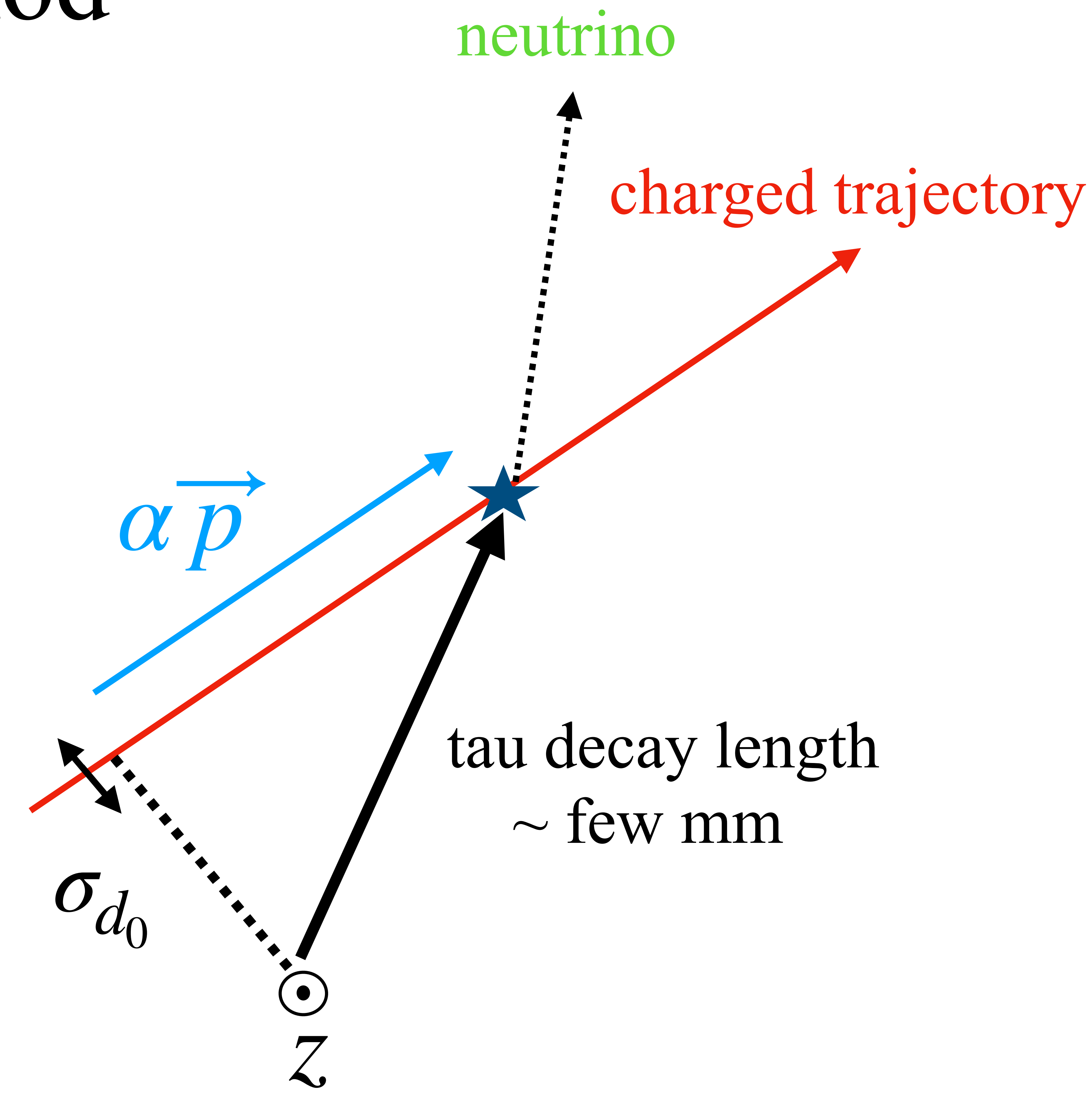
$$(\phi, z_{IP}) \rightarrow (\alpha, z_{IP})$$

τ reconstruction method

We have tried another method



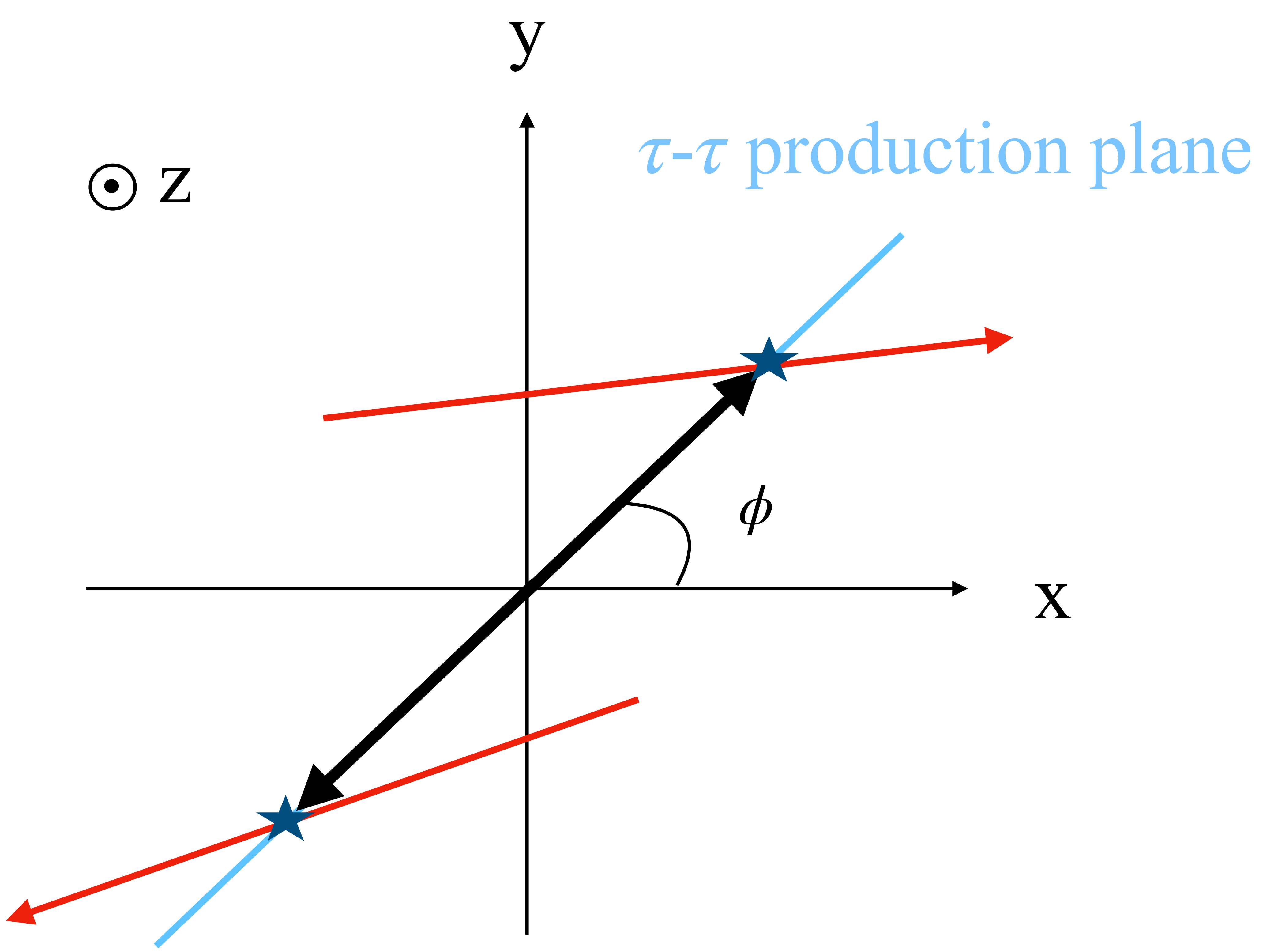
$\vec{p}$: unit vector
α : real number

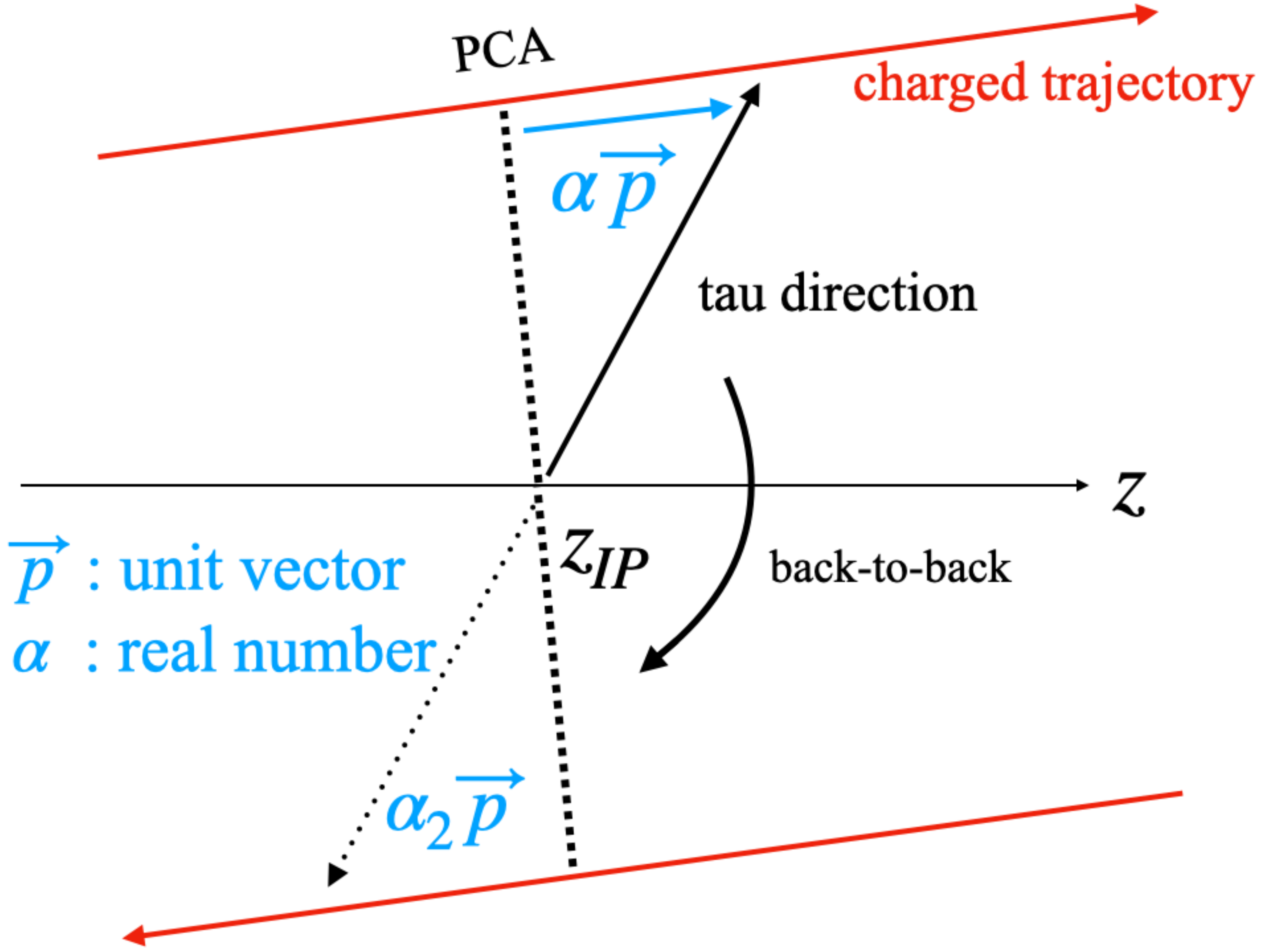


α_2 can be calculated by imposing back-to-back-ness in the x-y projection

τ reconstruction method

Two methods to find solutions





(ϕ, z_{IP}) : unknown

(α, z_{IP}) : unknown

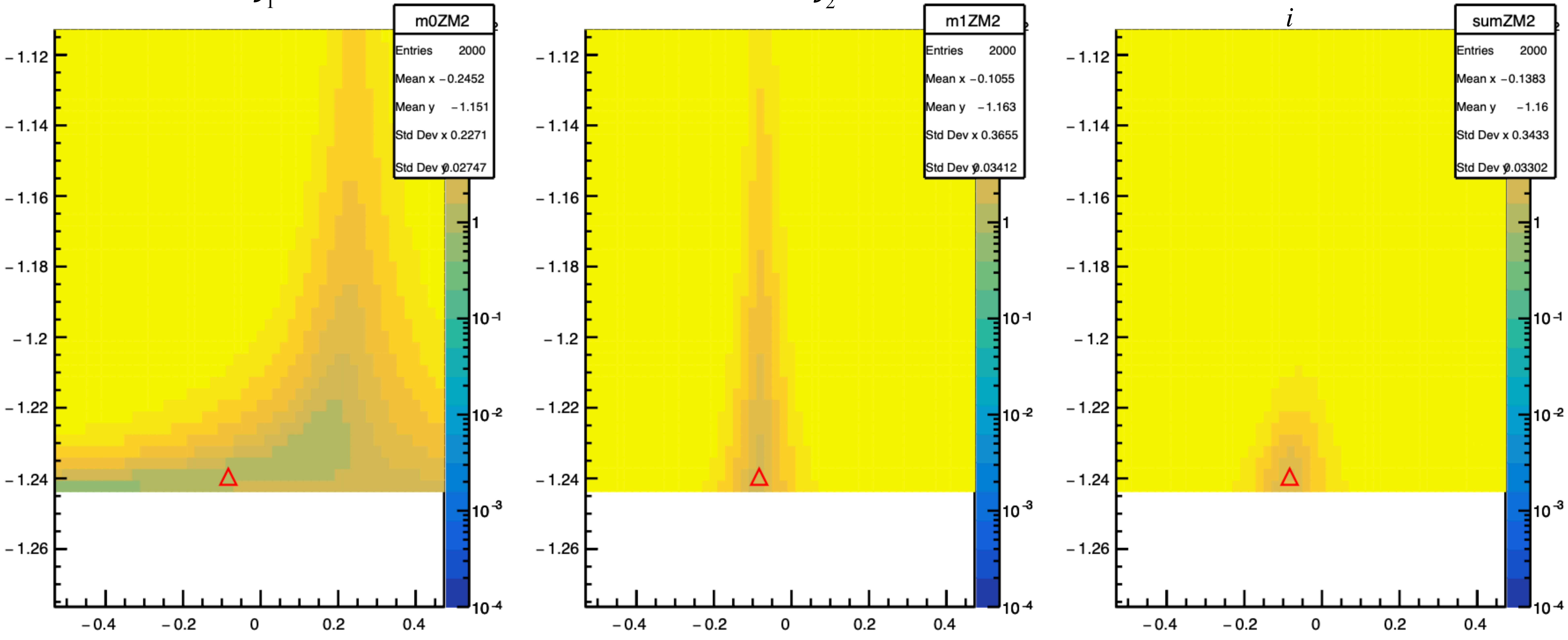
We have combined them

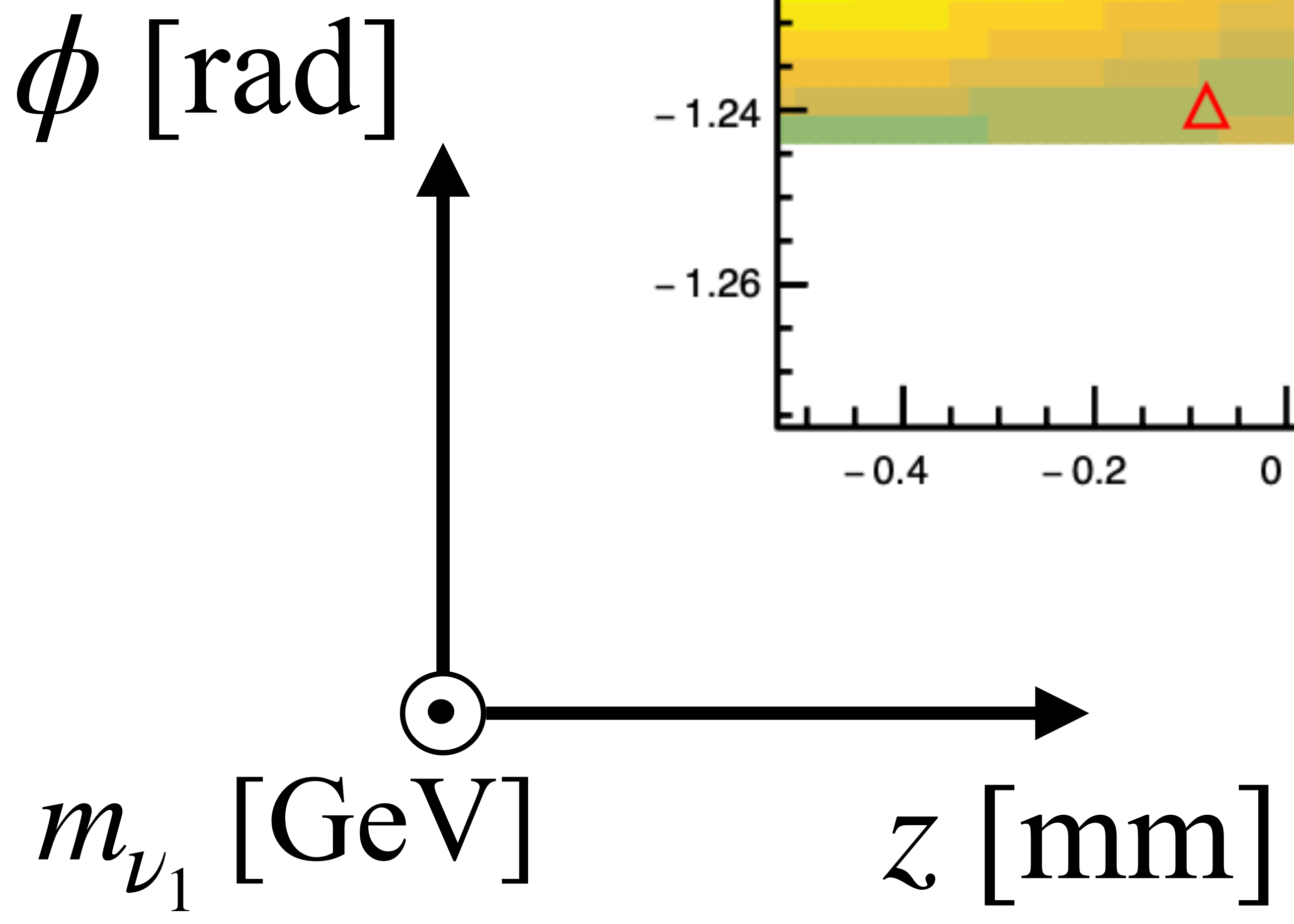
Find solutions

We choose the values of z and ϕ which result in neutrino masses closest to zero

example event with 1 solution

$|m^2_{\nu_1}|$ $\qquad$ $|m^2_{\nu_2}|$ $\qquad$ $\sum_i |m^2_{\nu_i}|$





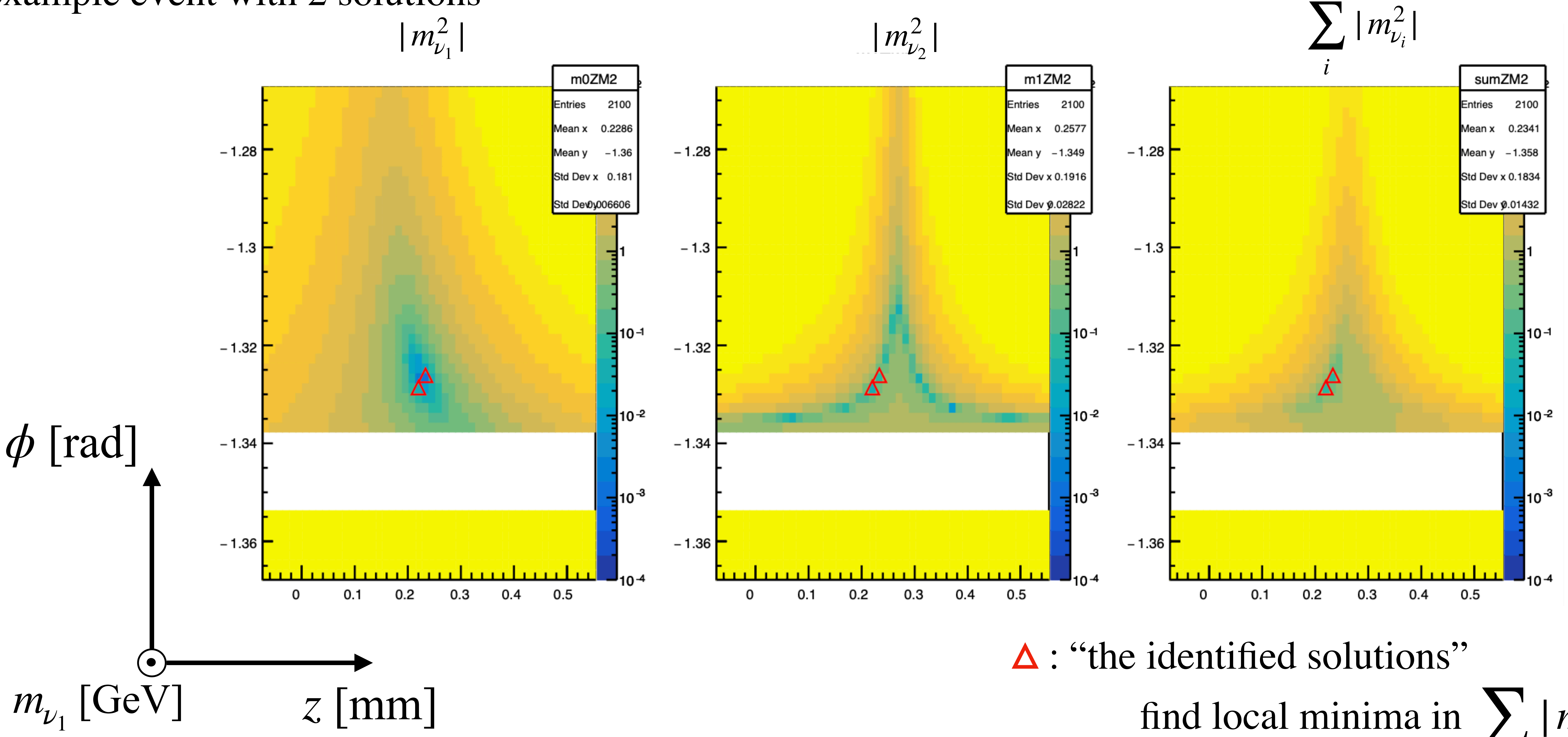
△ : "the identified solutions"

find local minima in $\sum_i |m^2_{\nu_i}|$

Find solutions

We choose the values of z and ϕ which result in neutrino masses closest to zero

example event with 2 solutions



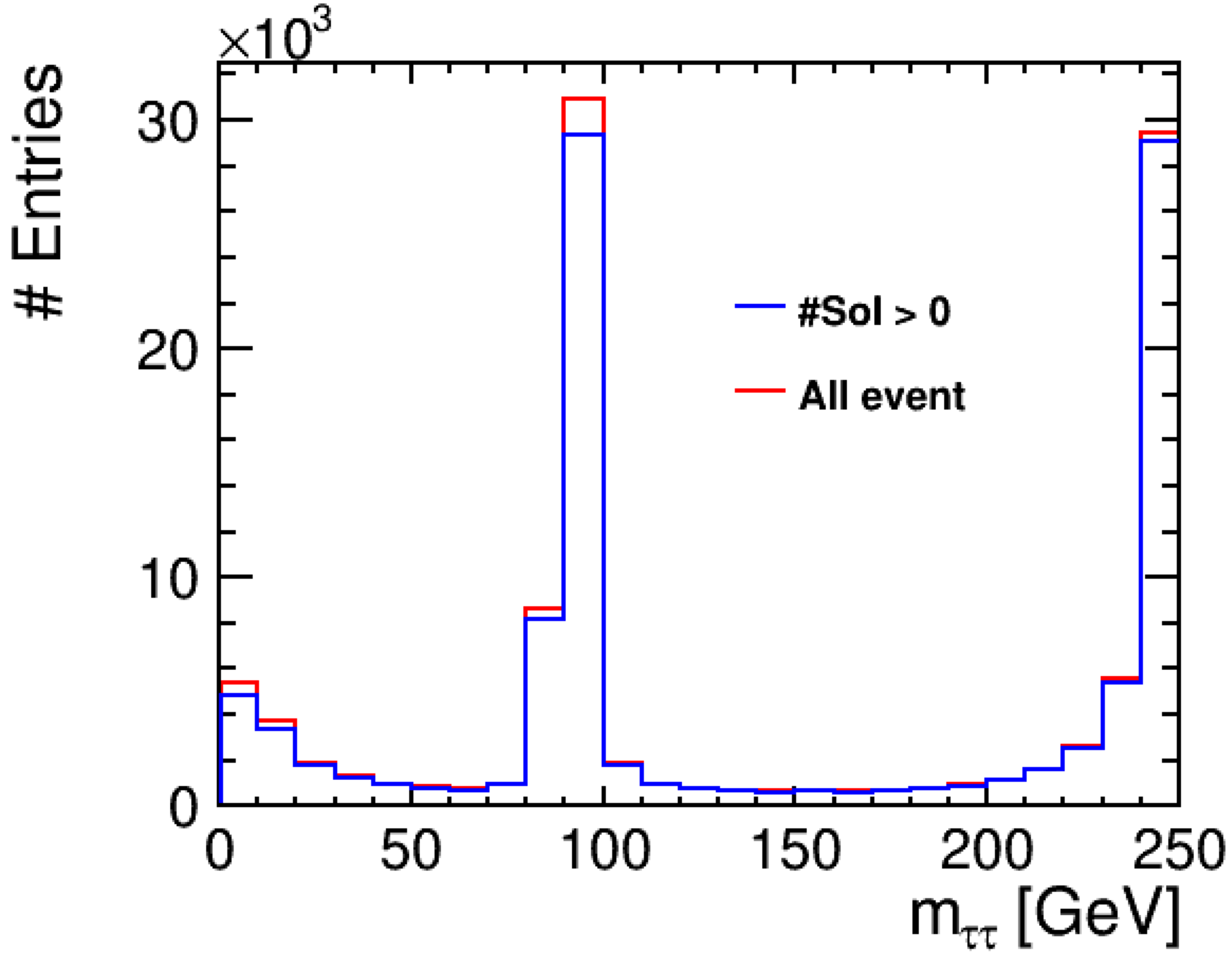
△ : "the identified solutions"

find local minima in $\sum_i |m_{\nu_i}^2|$

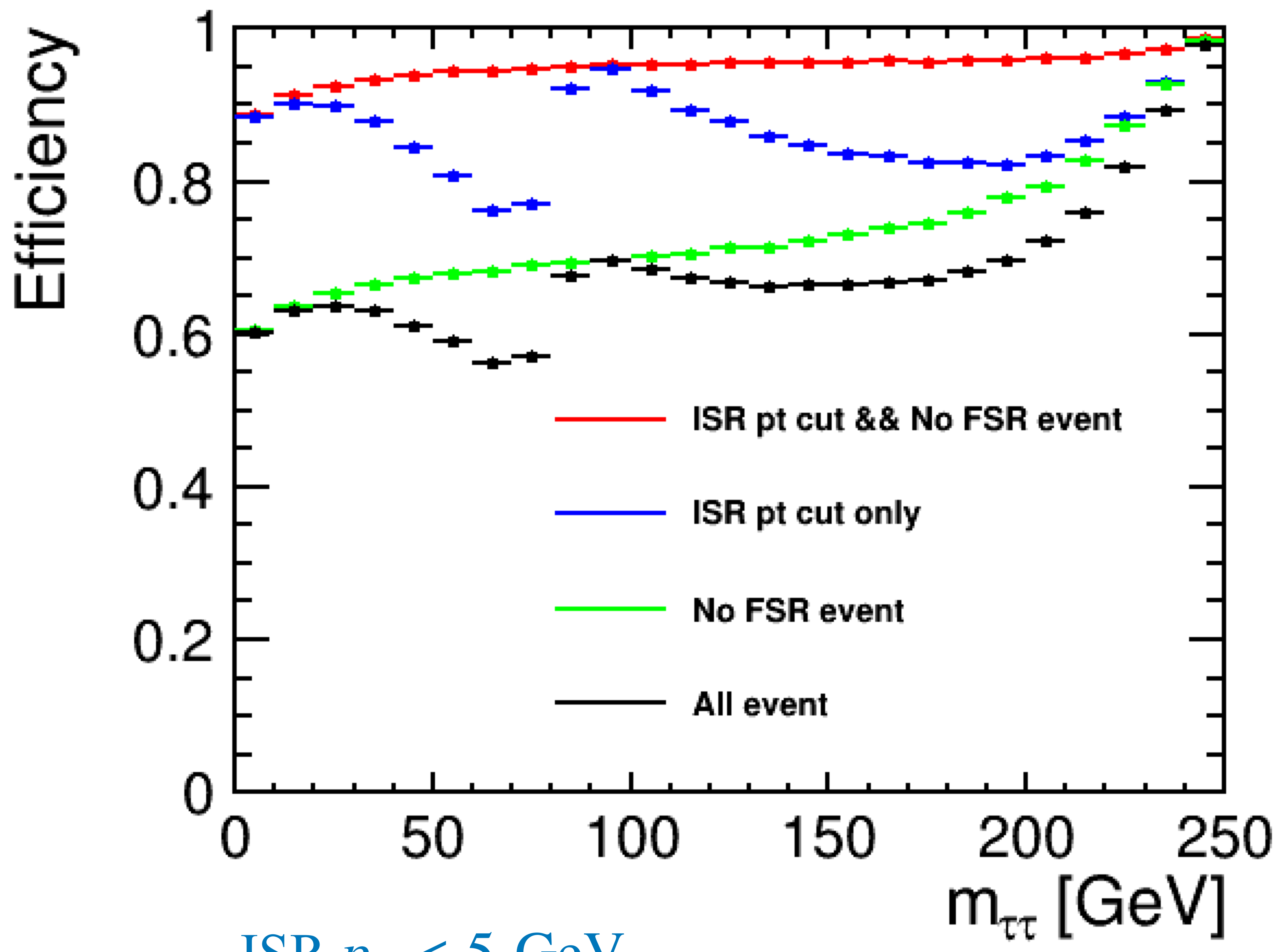
Method efficiency

All
Method worked

At least 1 $\tau \to \pi/\rho$



Impact parameter method efficiency



ISR $p_T < 5$ GeV

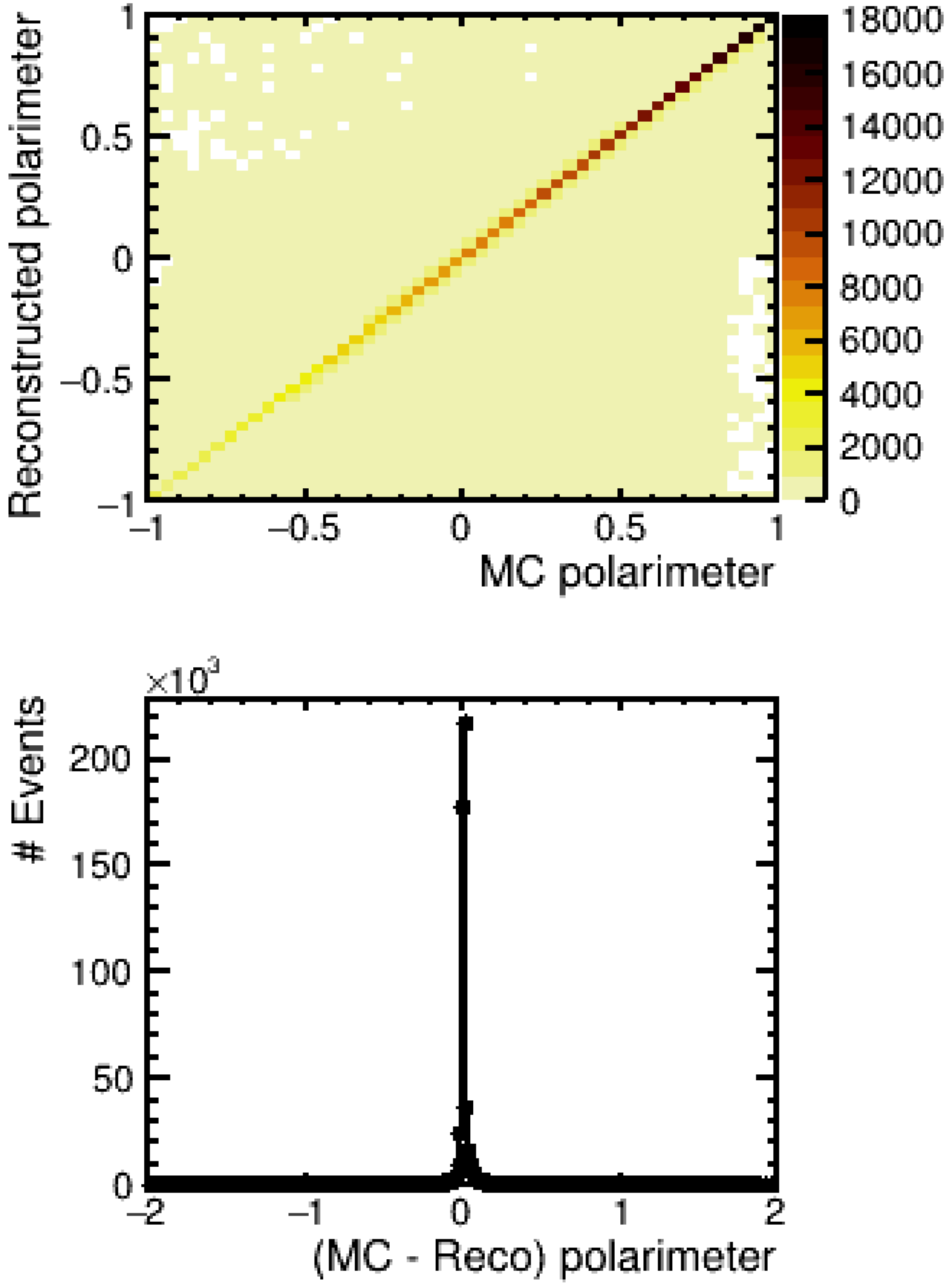
No FSR photon event

Impact parameter method efficiency is $> 90\,\%$ for events with $m_{\tau\tau} \sim 250$ GeV

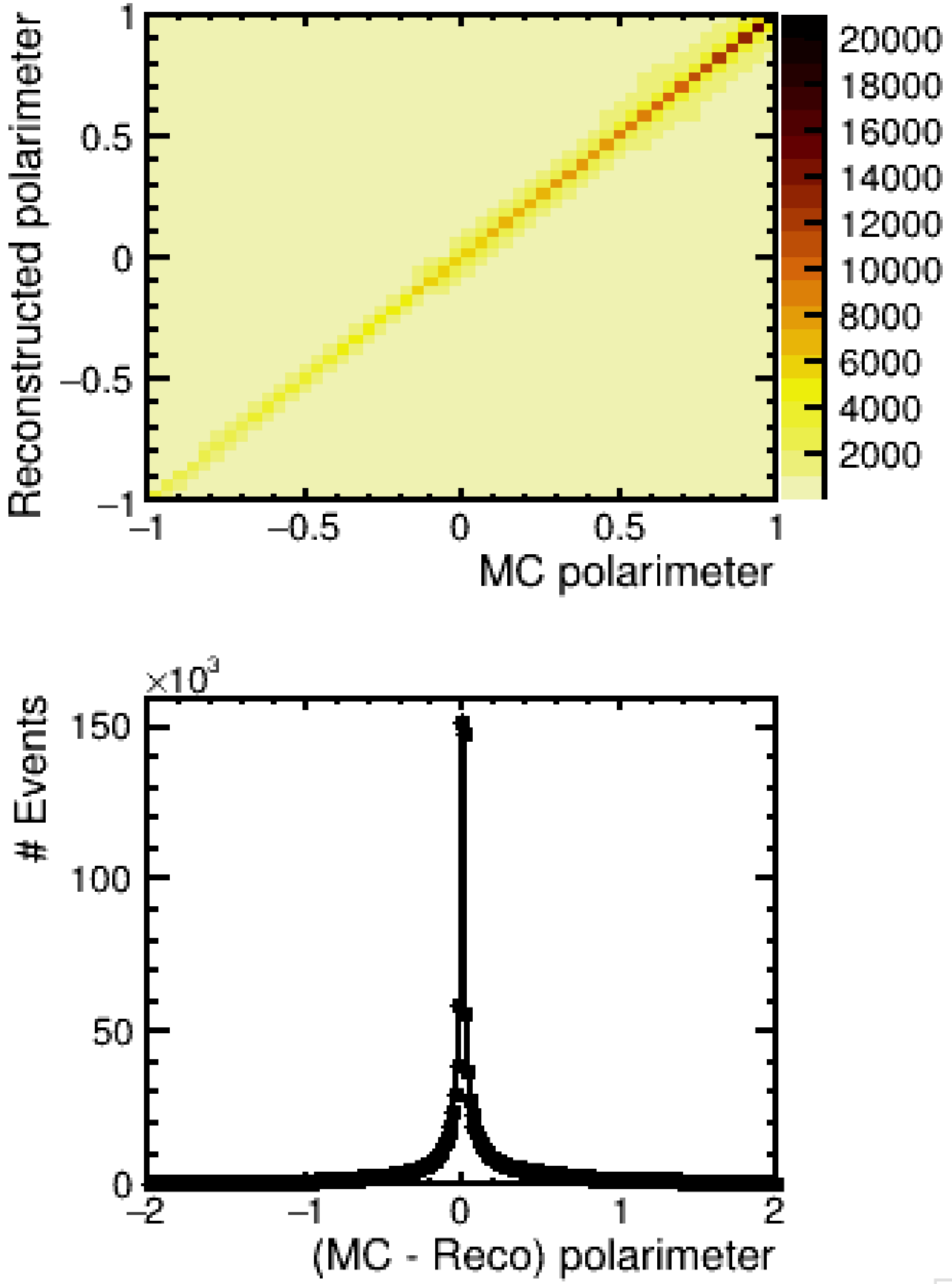
MC

Polarimeter

$\tau \rightarrow \pi\nu$ Impact parameter method vs MC eLpR(100%)

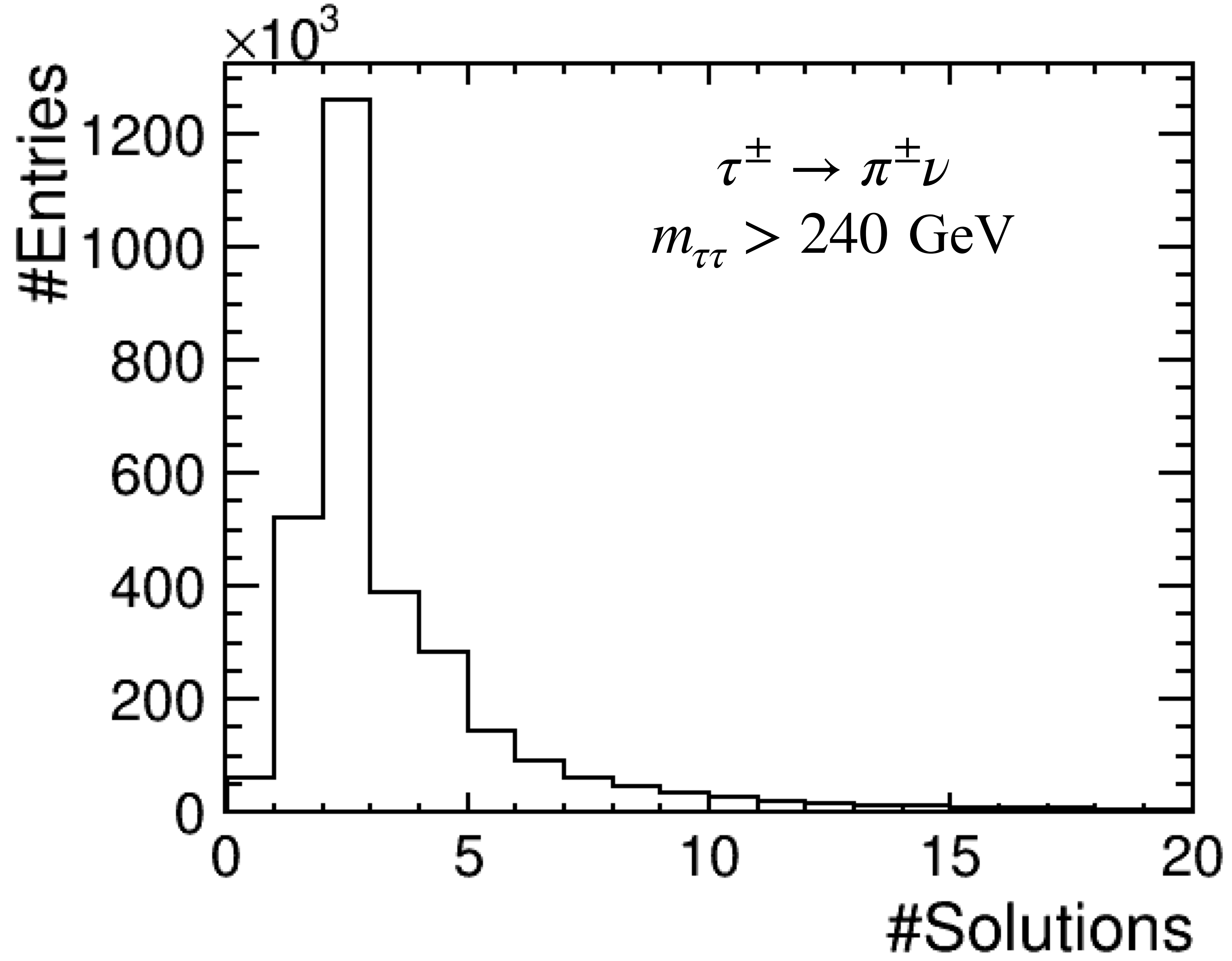


$\tau \rightarrow \rho\nu$ Impact parameter method vs MC eLpR(100%)

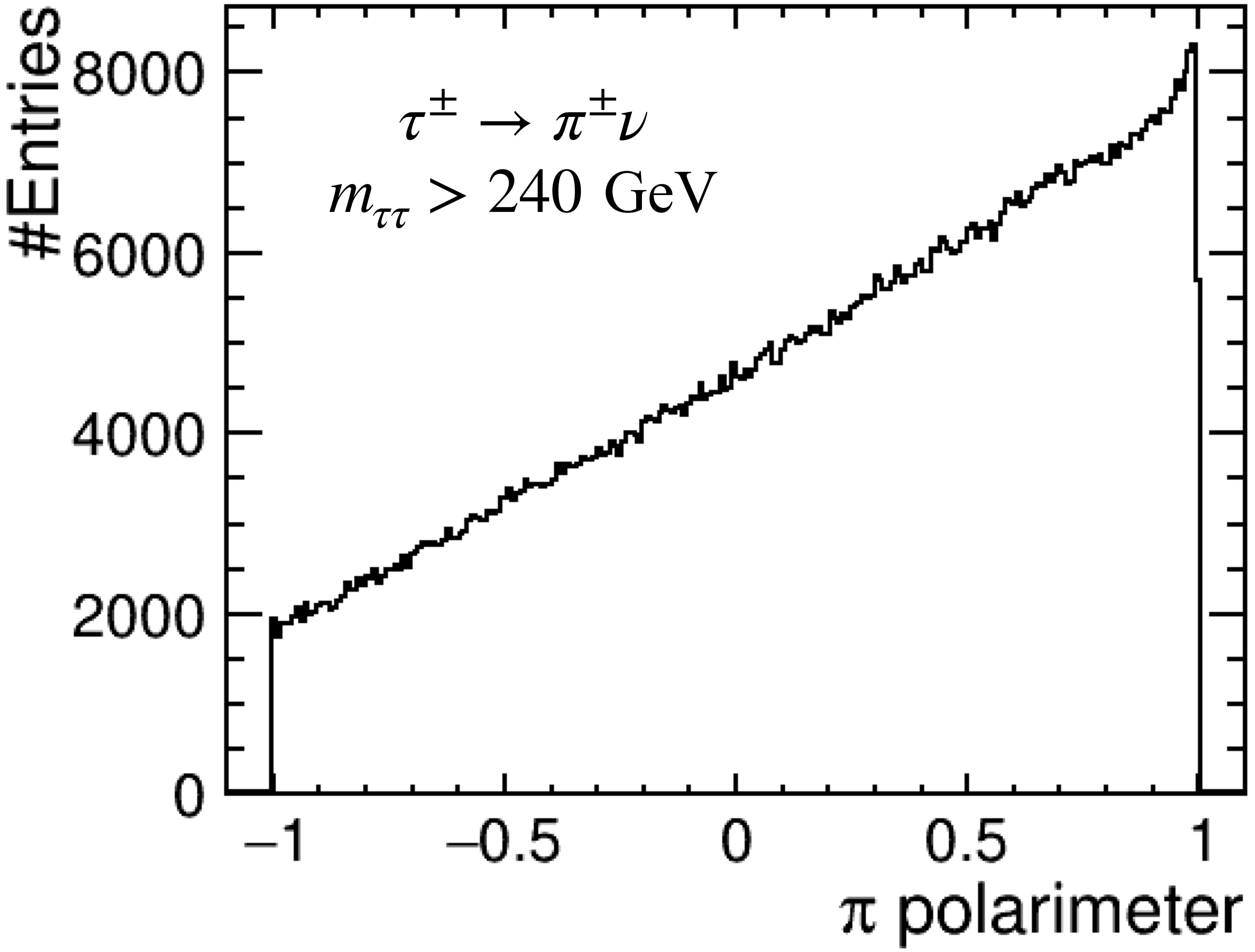


Polarimeter using reconstructed ν is in reasonable agreement with MC one.

Problem



We have up to 20 possible solutions per event



Polarimeter distributions for $\tau^\pm \to \pi^\pm \nu$ decays
in events with $>$ 240 GeV

Some entries per event
=> we cannot trust the statistical errors from simple fit

Use Jackknife method

Jackknife method

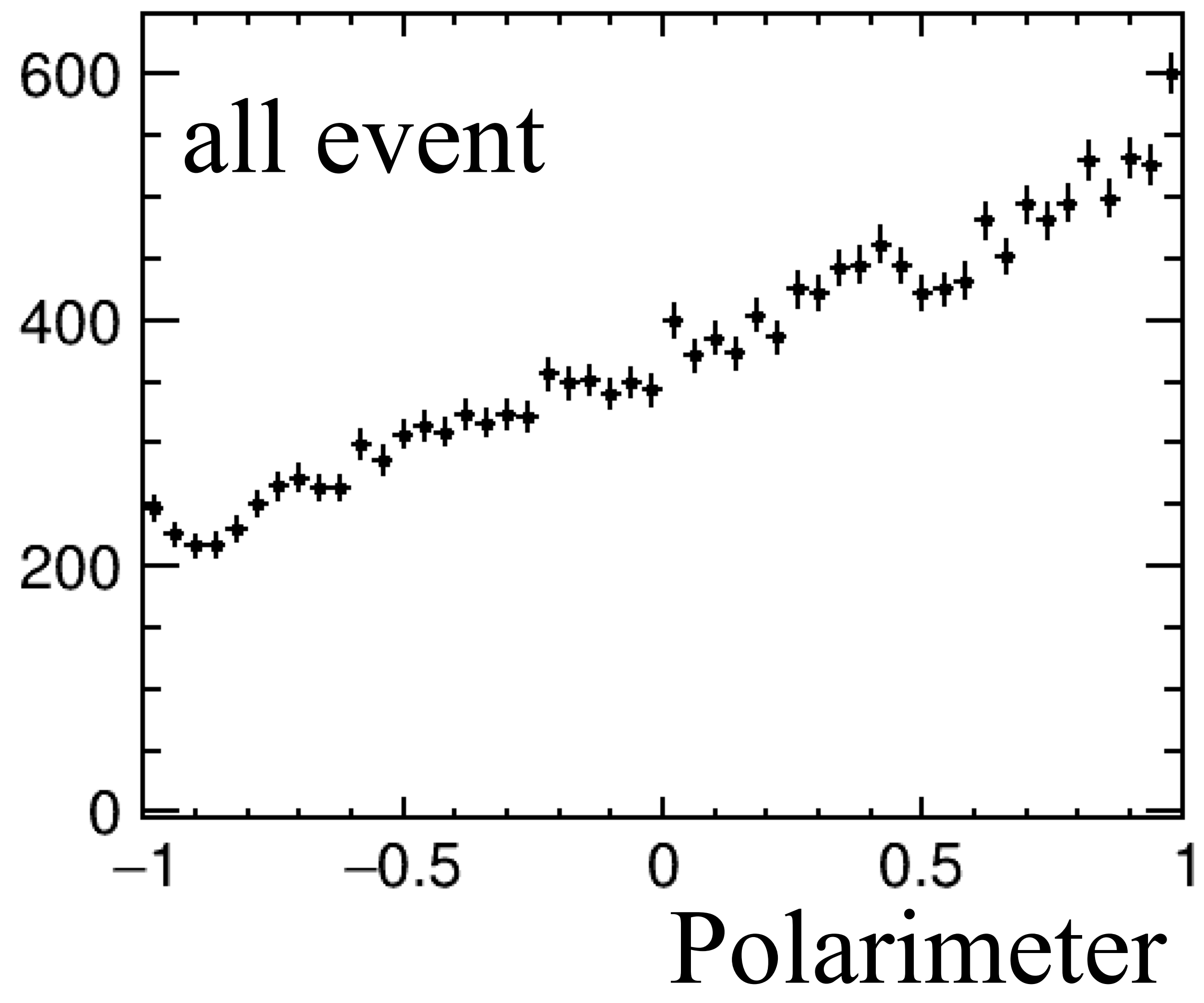
The basic idea is to calculate the estimator (e.g tau polarisation) by sequentially deleting a single event polarimeter from the sample.

The estimator is recomputed until there are *n* estimates for a sample size of *n*.

Variation of n estimates gives

$$\sigma_{jackknife} = \sqrt{\frac{n-1}{n}\sum_{i=1}^{n}(\hat{P}_i - \hat{P})^2}$$

arXiv:1606.00497



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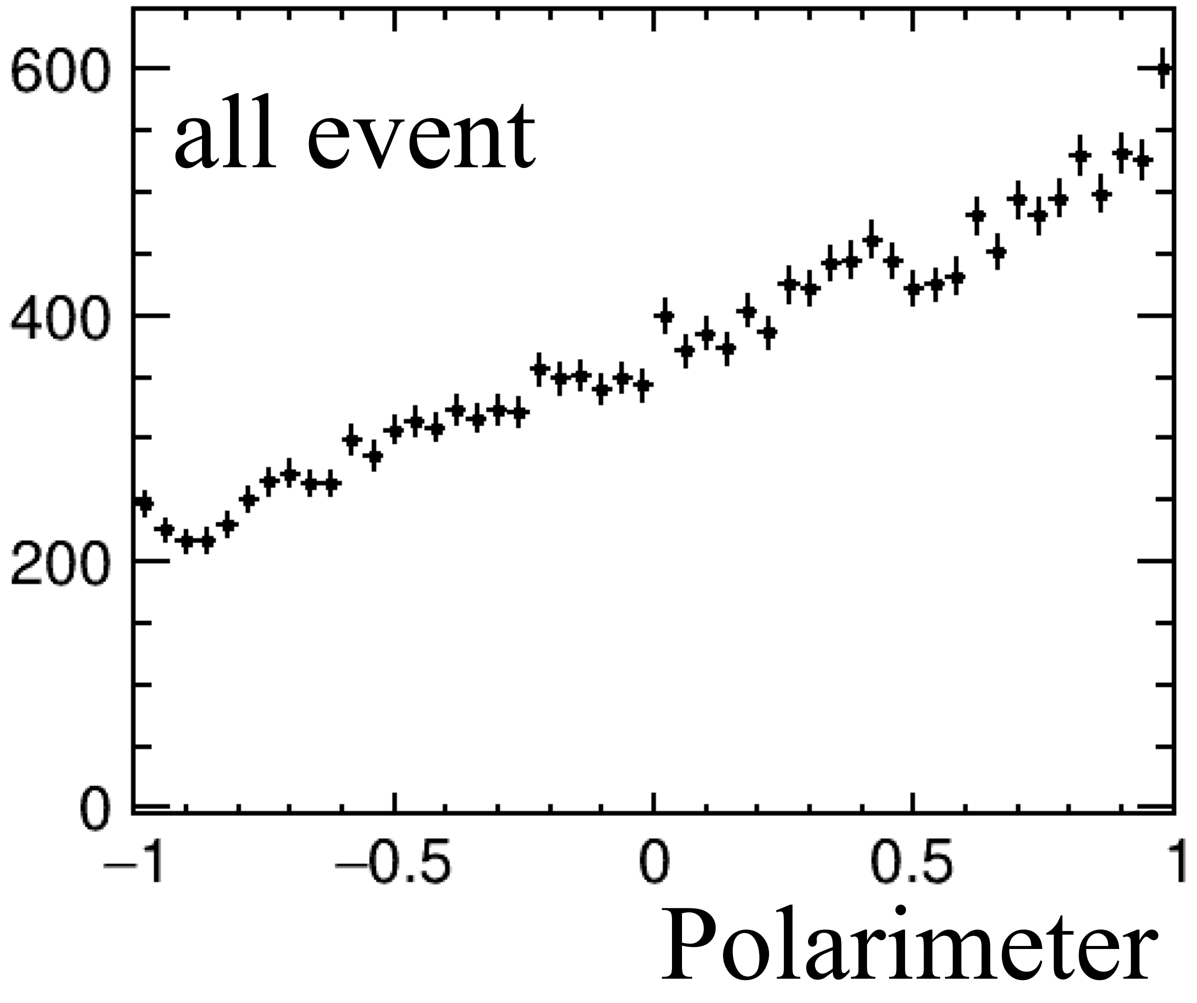
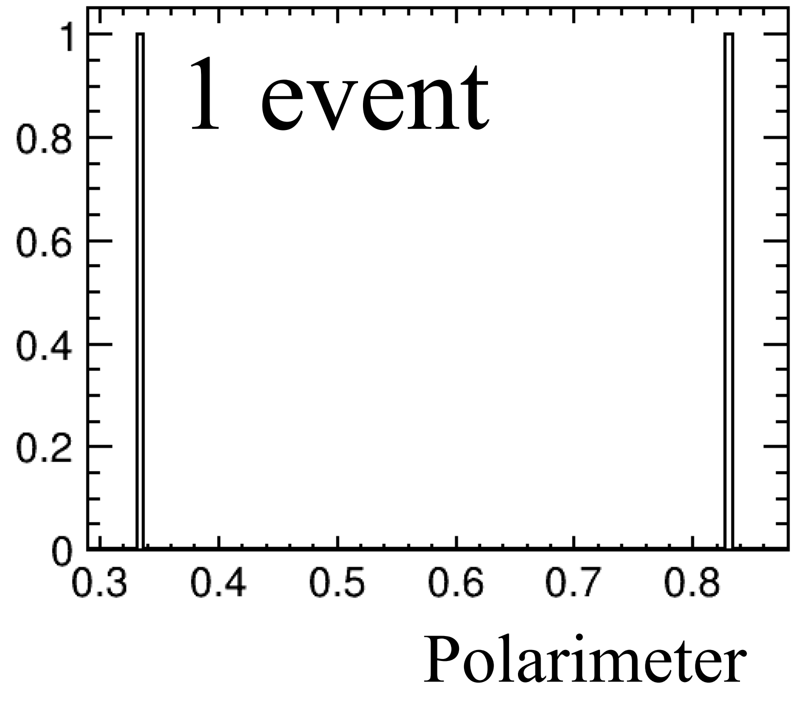
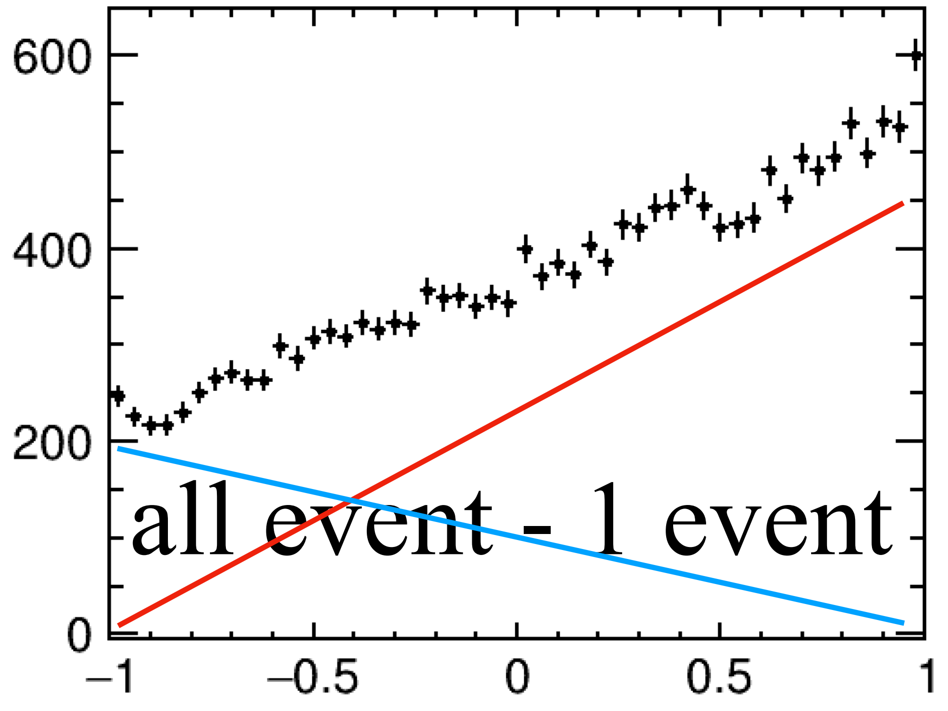


delete 1 event



Extract tau polarisation from log likelihood fit



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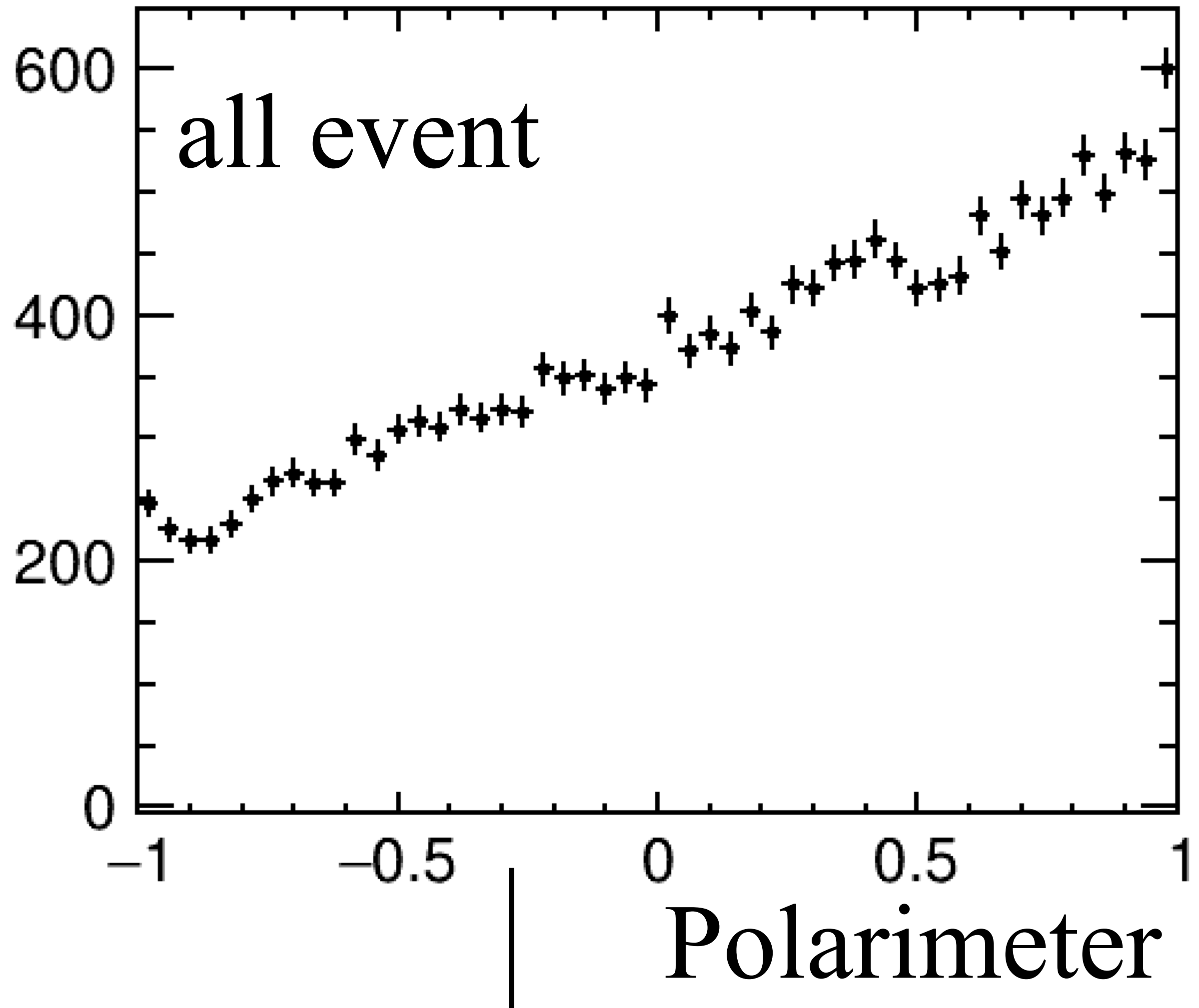
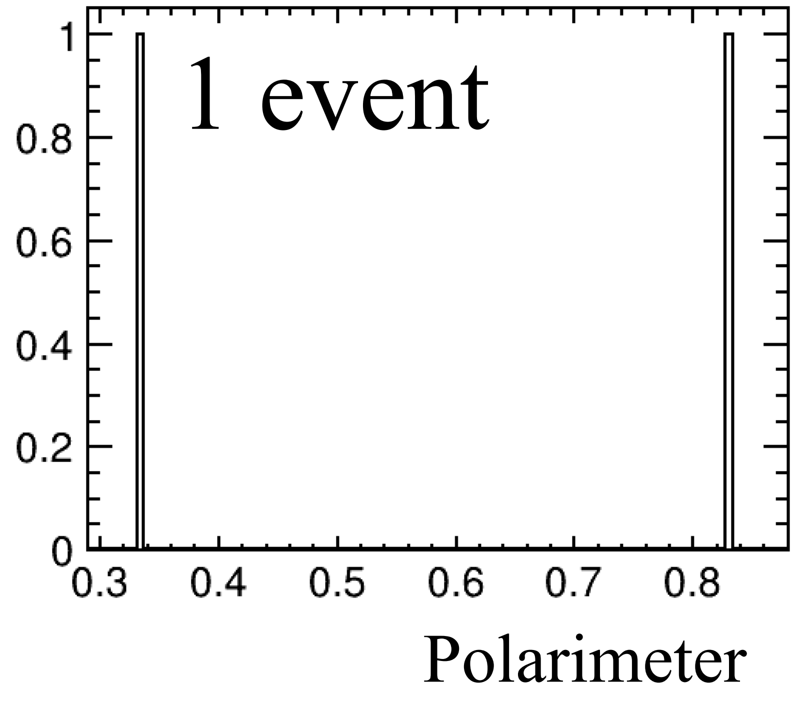
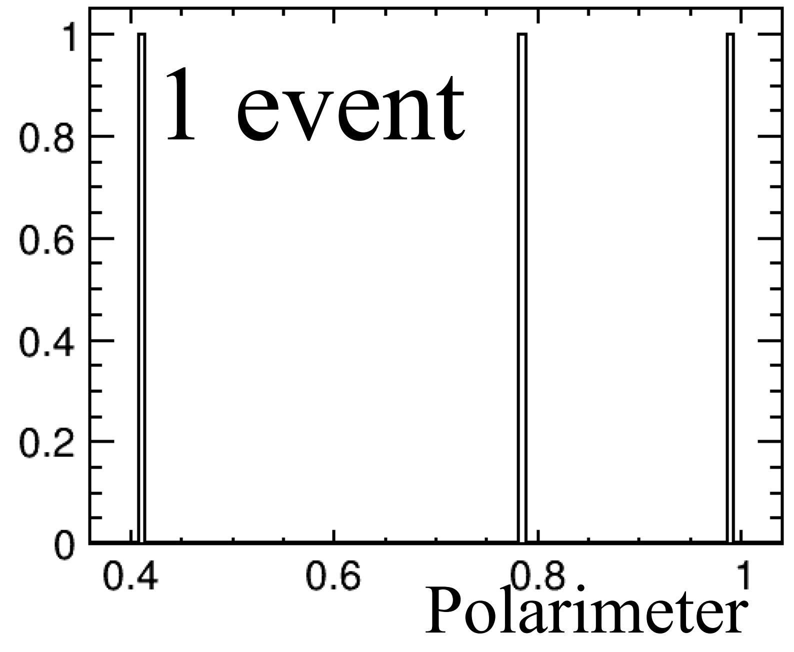


delete 1 event



delete 1 event



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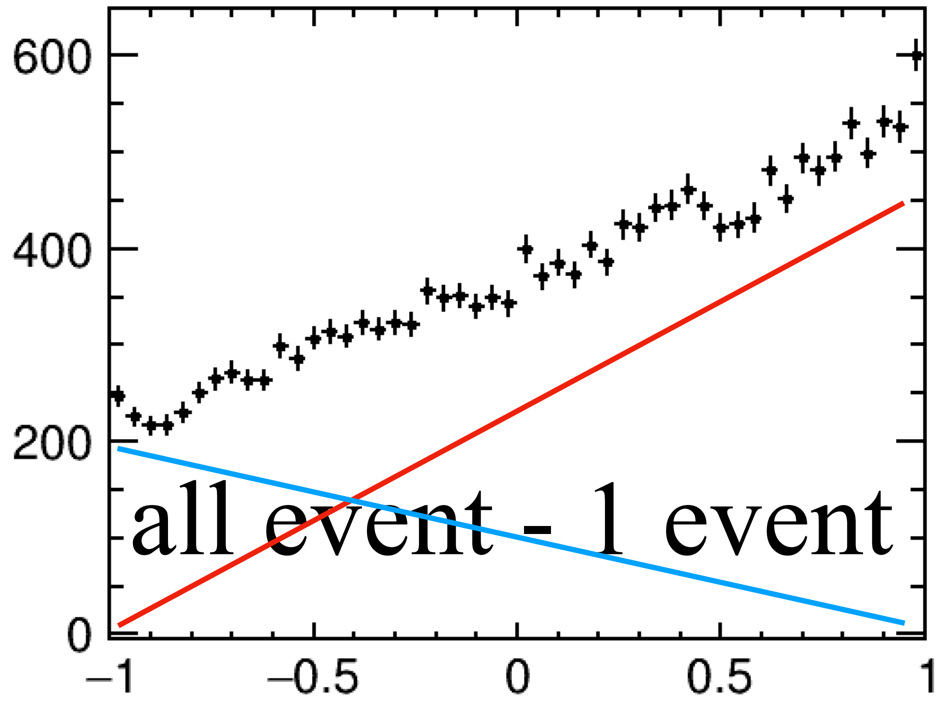

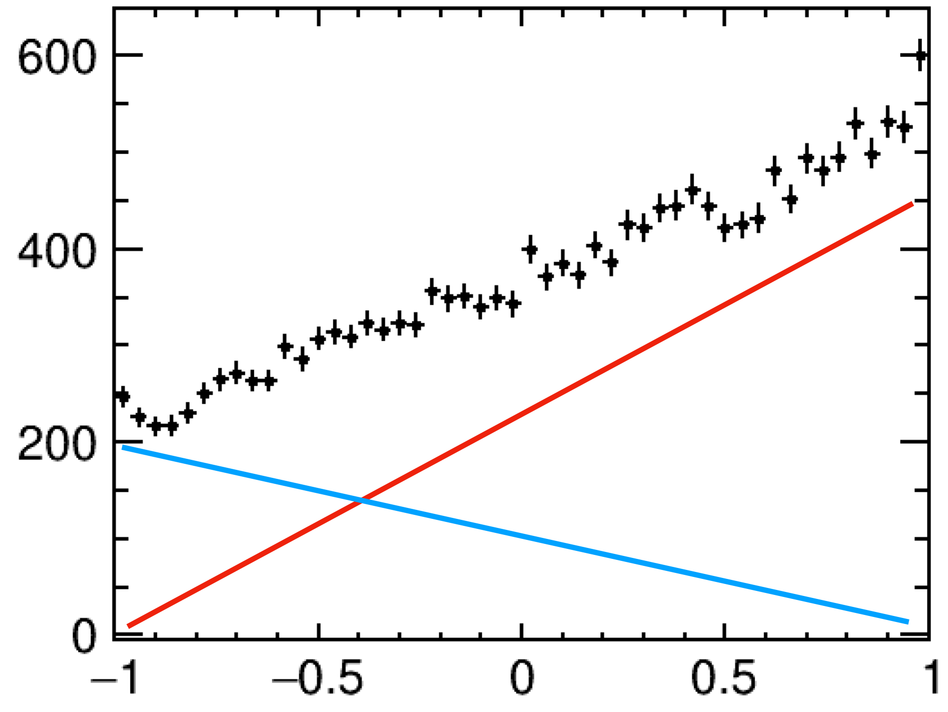

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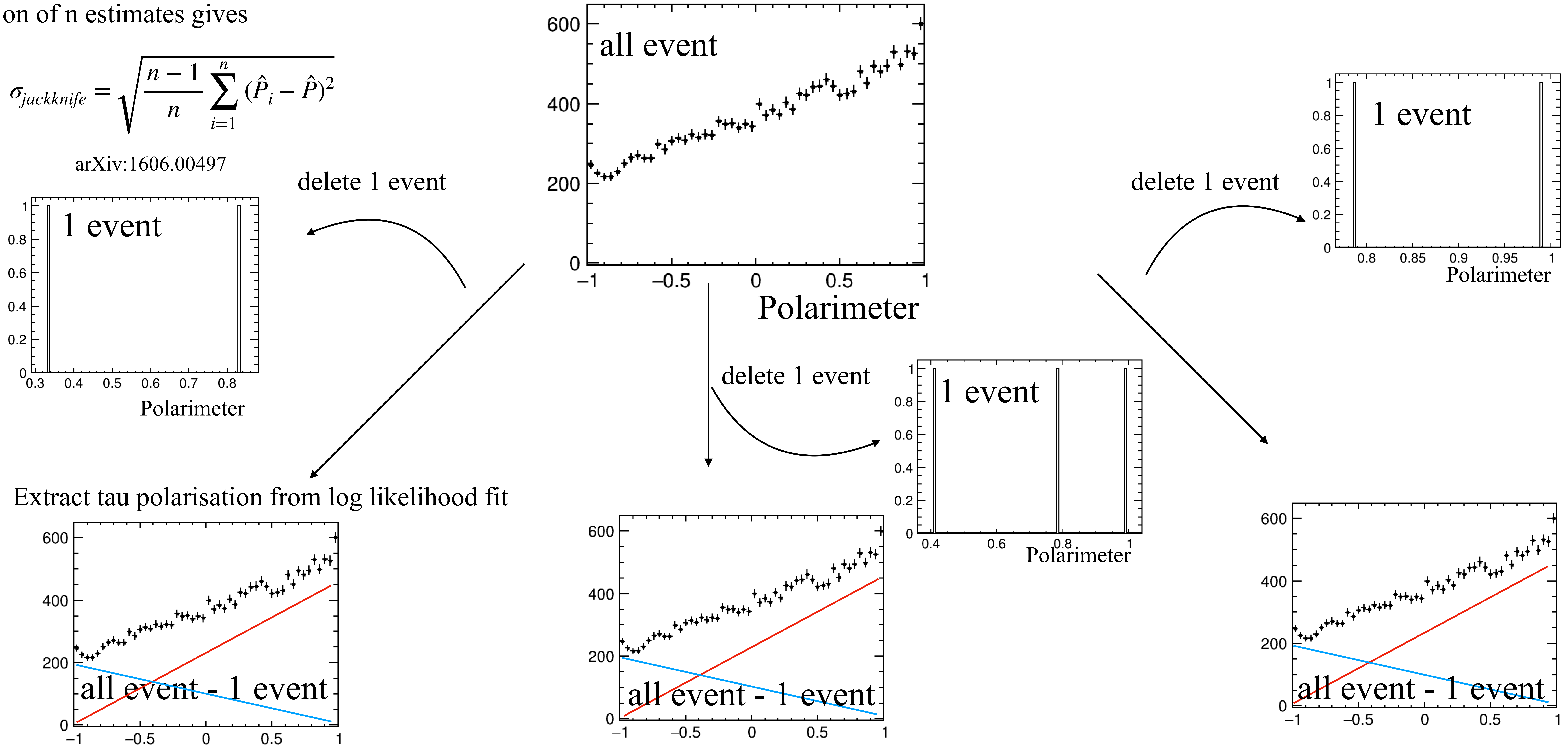
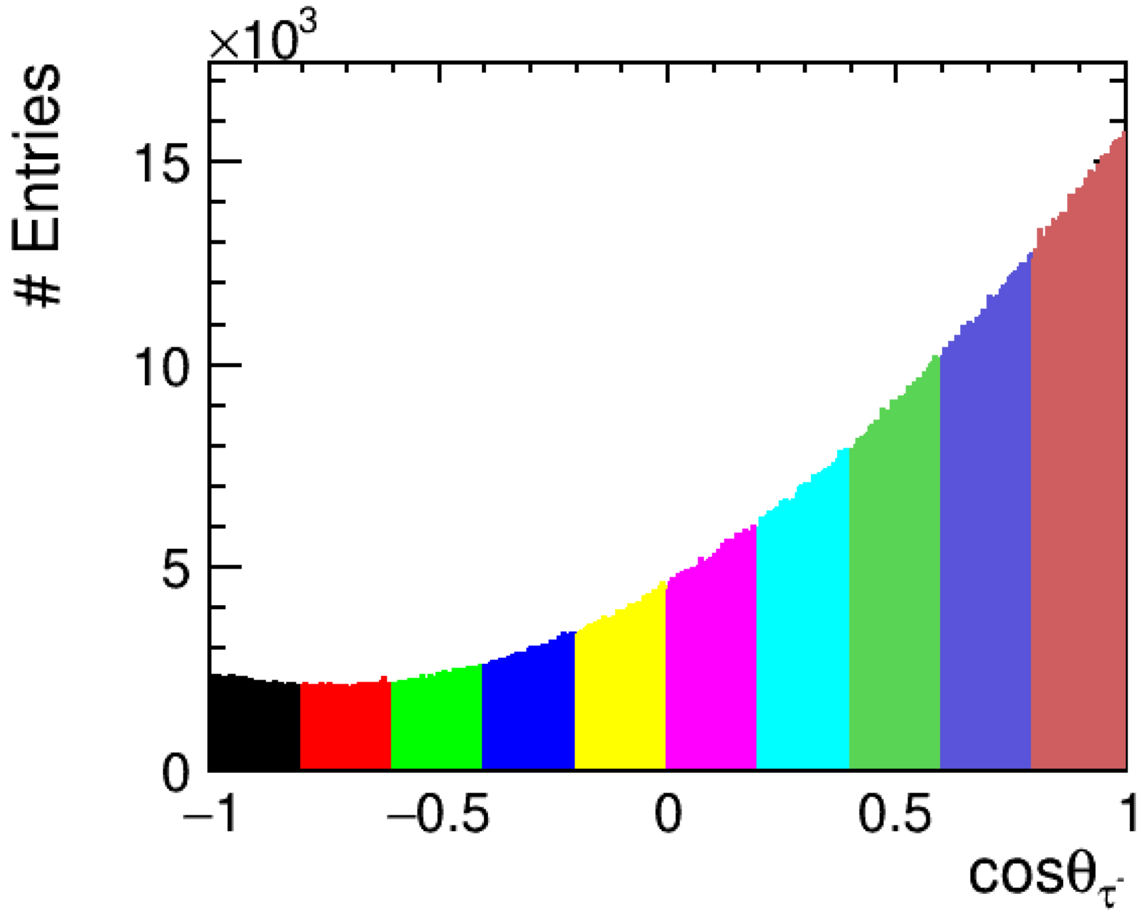


Method Calibration

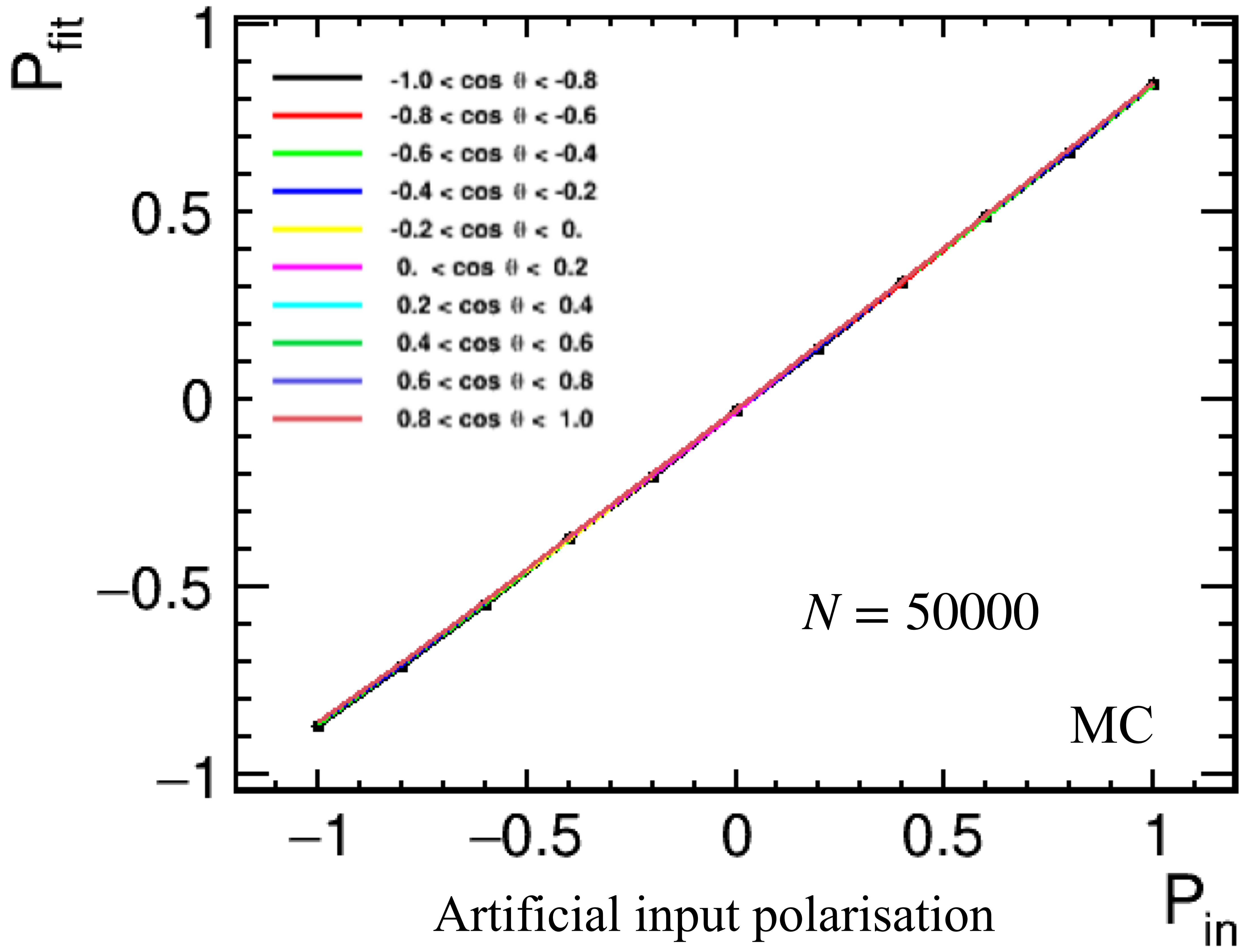
To check the bias, an artificial polarisation was created by changing the ratio of N_R and N_L to calculate P_{fit}



$$P_{in} = \frac{N_R - N_L}{N_R + N_L}$$

N_R: right-handed tau
N_L: left-handed tau

At least 1 tau $\rightarrow \pi/\rho$
$m_{\tau\tau} > 240$ GeV



- Bias due to the presence of wrong solution was found
- There seems have no $\cos\theta_{\tau^-}$ dependence

Summary

- Full reconstruction of $e^+e^- \to \tau^+\tau^-$ using impact parameter was investigated.
- New method to find solutions was implemented and method efficiency was improved

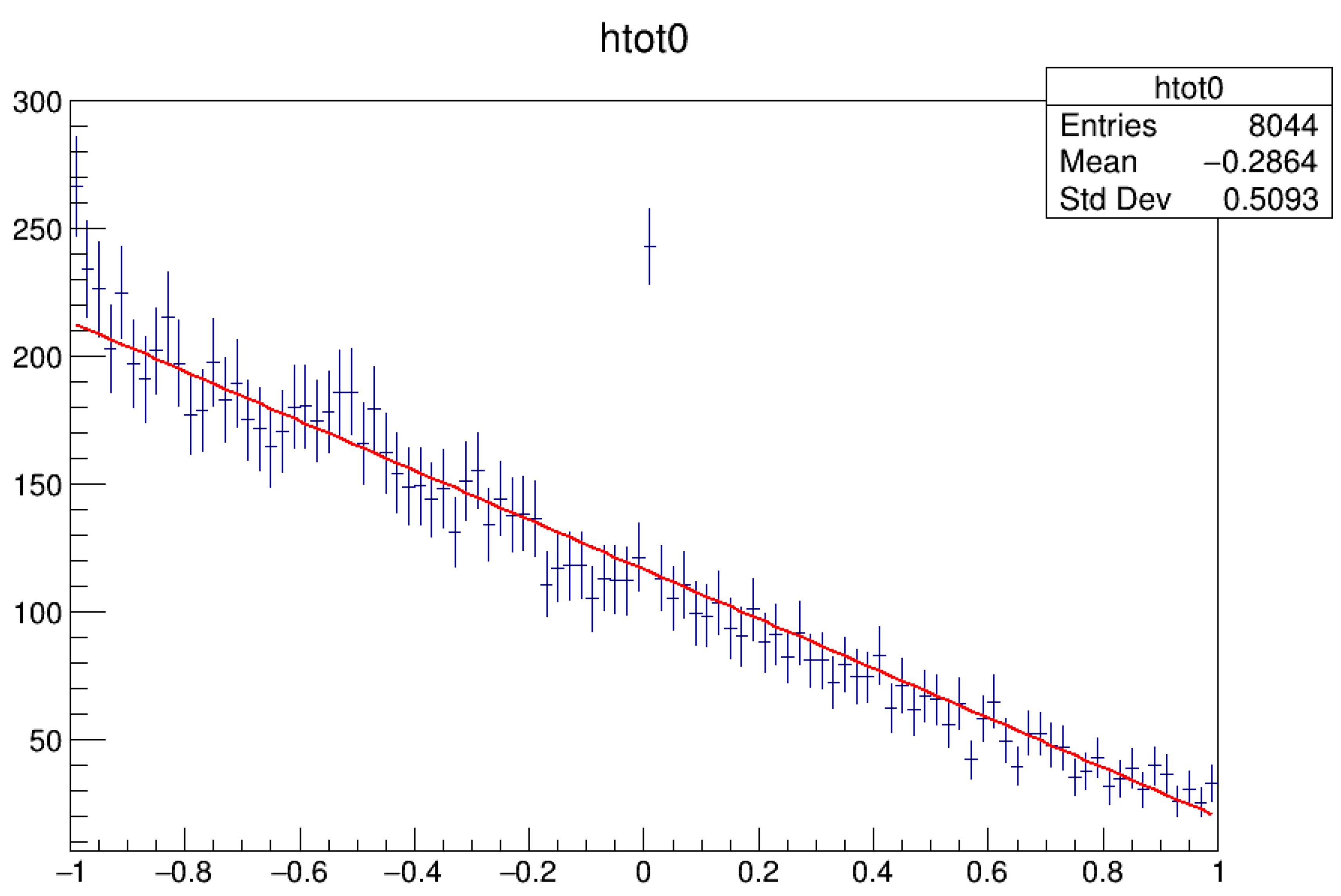
  For events with both $m_{\tau\tau} \sim 91$ GeV and ~ 250 GeV, new method efficiency is $> 90\,\%$

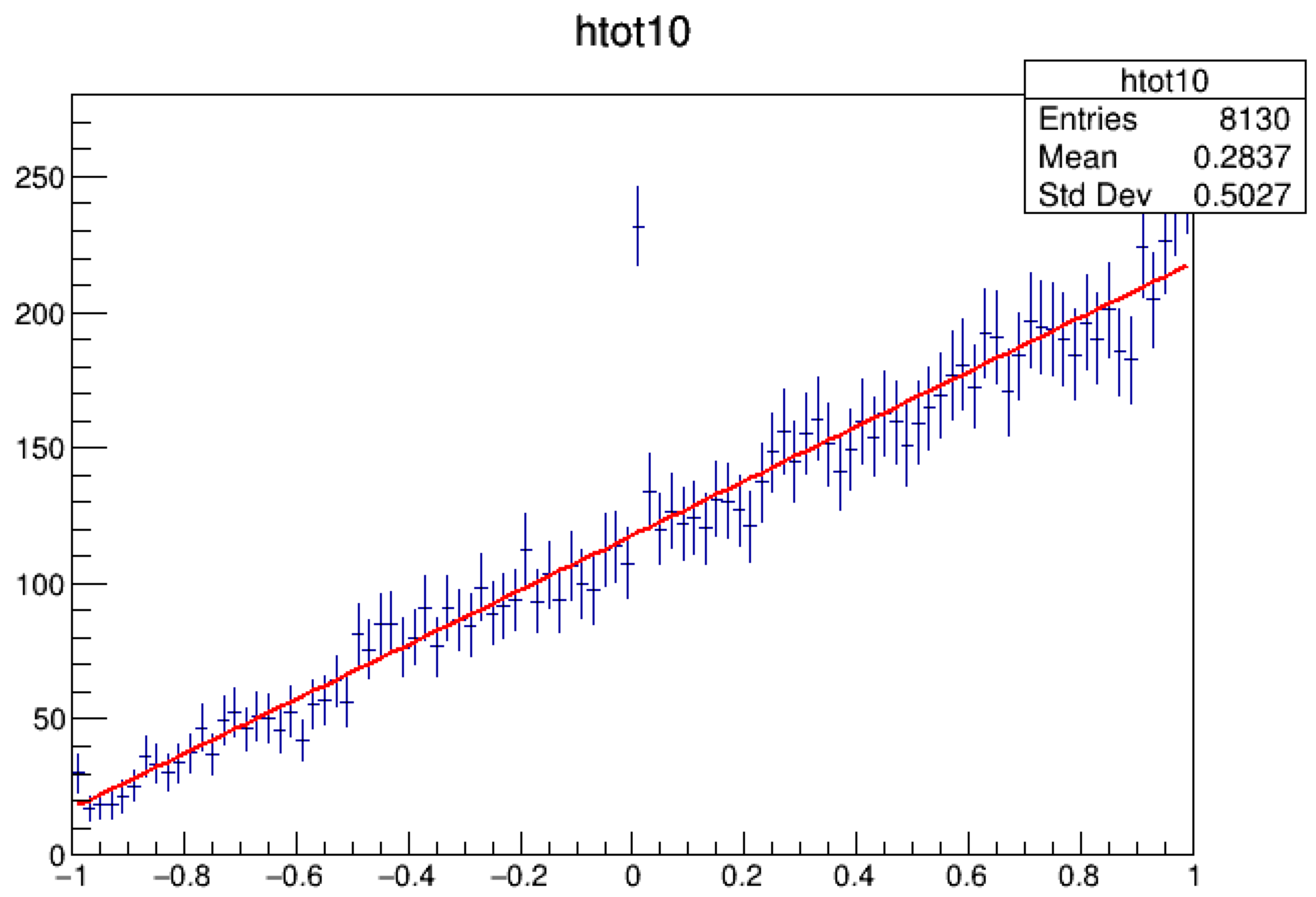
- Polarimeters were reconstructed in the $\tau \to \pi\nu$ and $\tau \to \rho\nu$ decay modes and reasonable agreement between MC truth polarimeter and the one from new method were found.
- Jackknife method was used to estimate tau polarisation errors.

Future plan

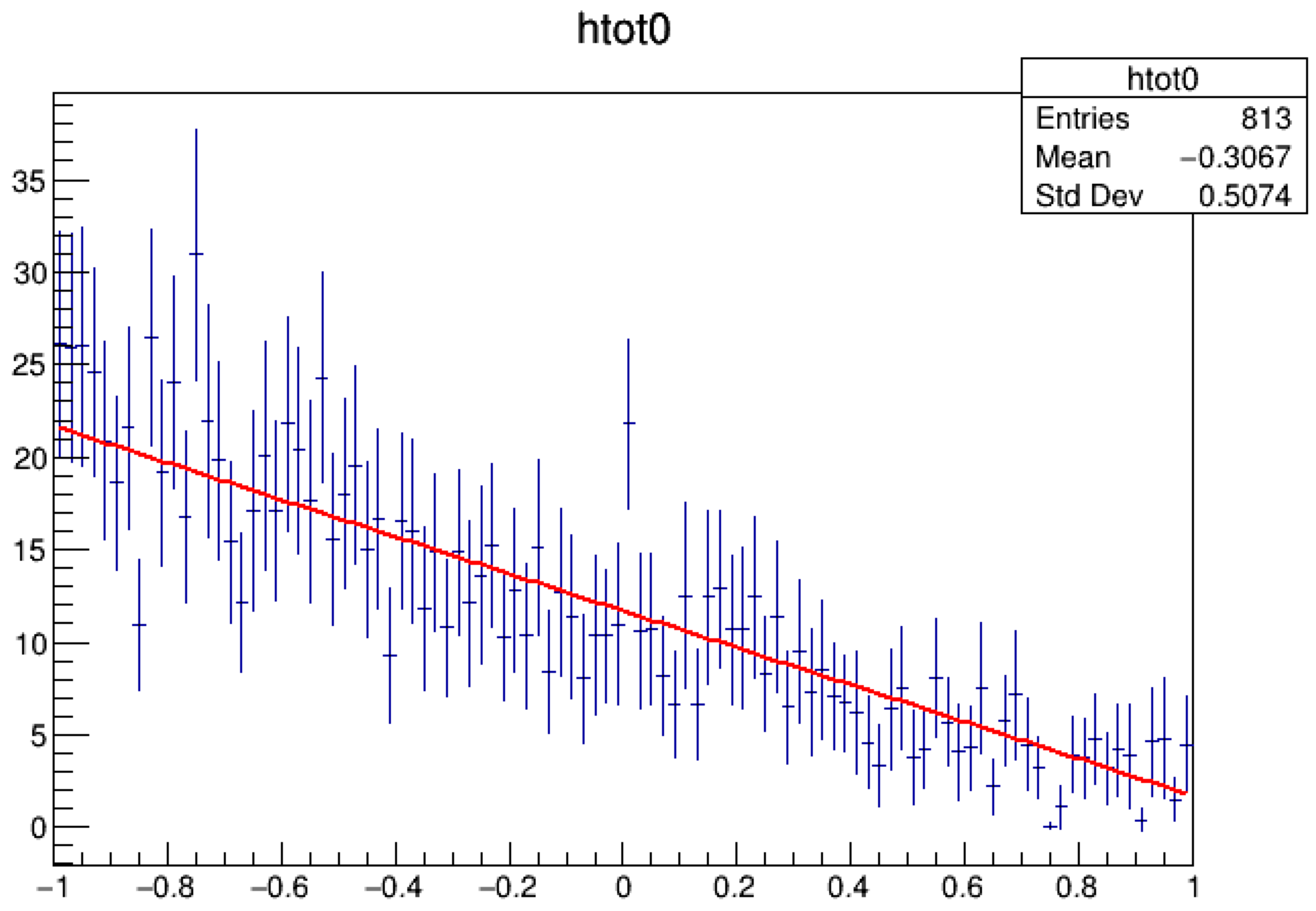
- Investigate search for new physics by using the tau polarisation.

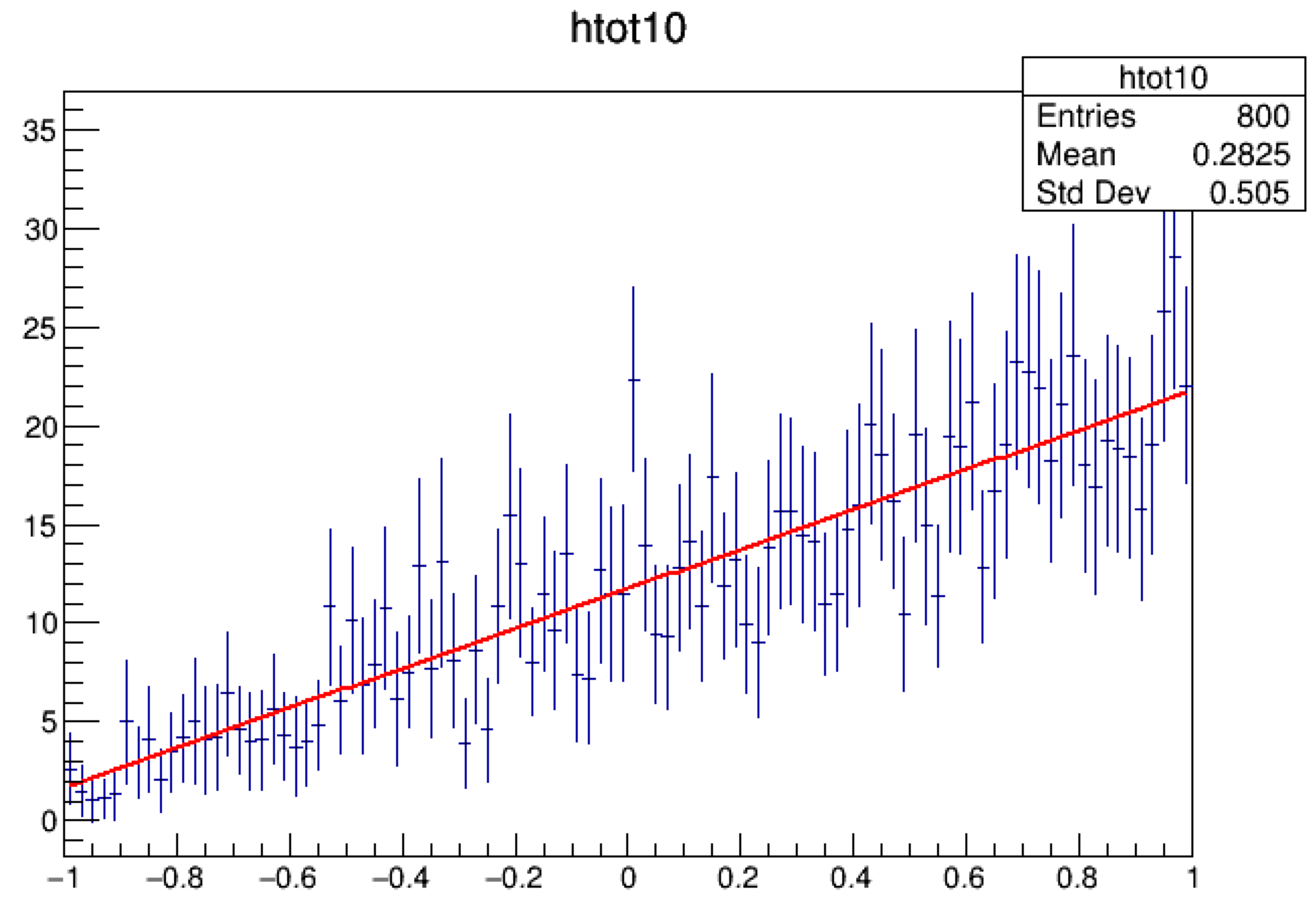
w/o reset





w/reset

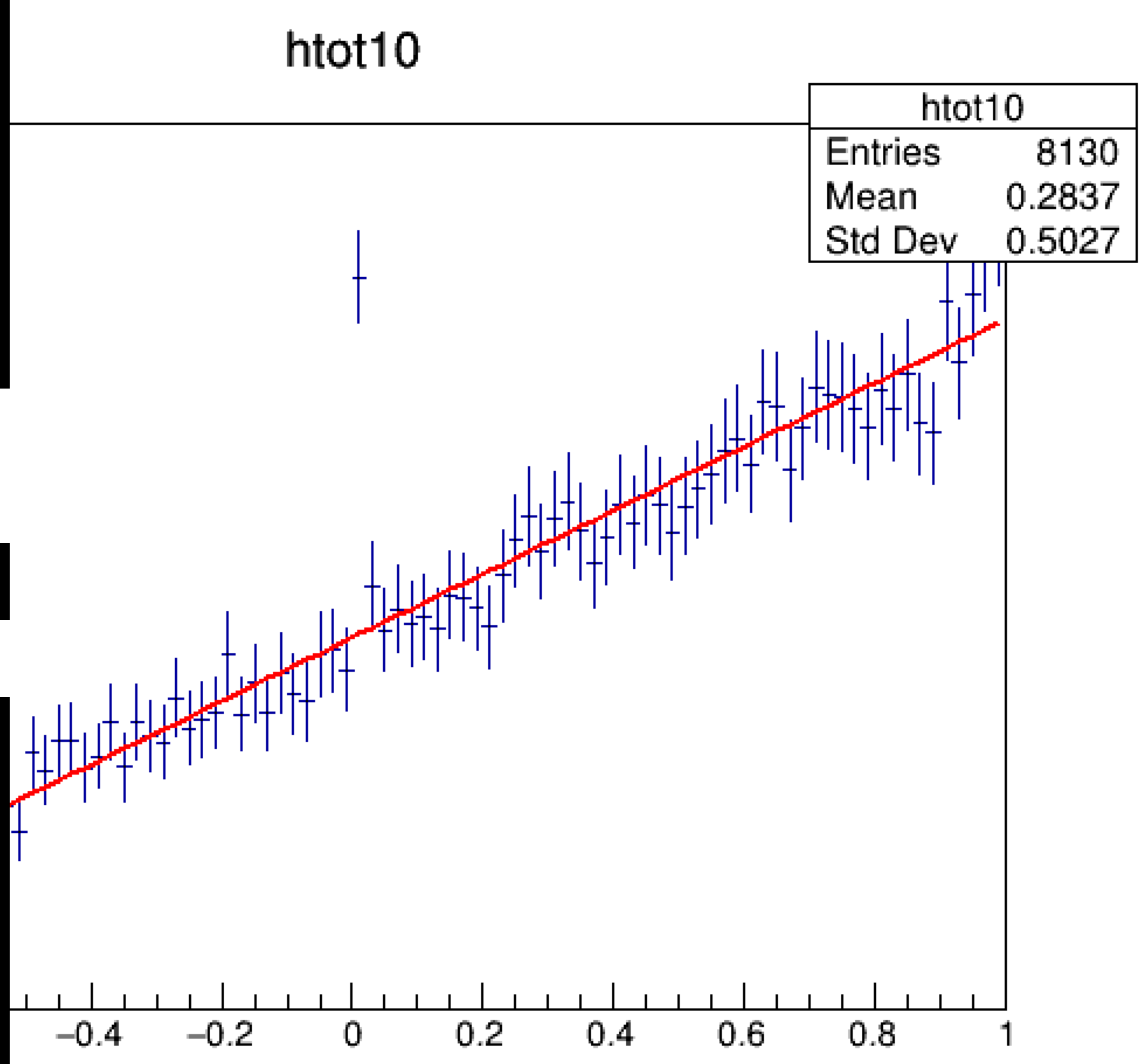


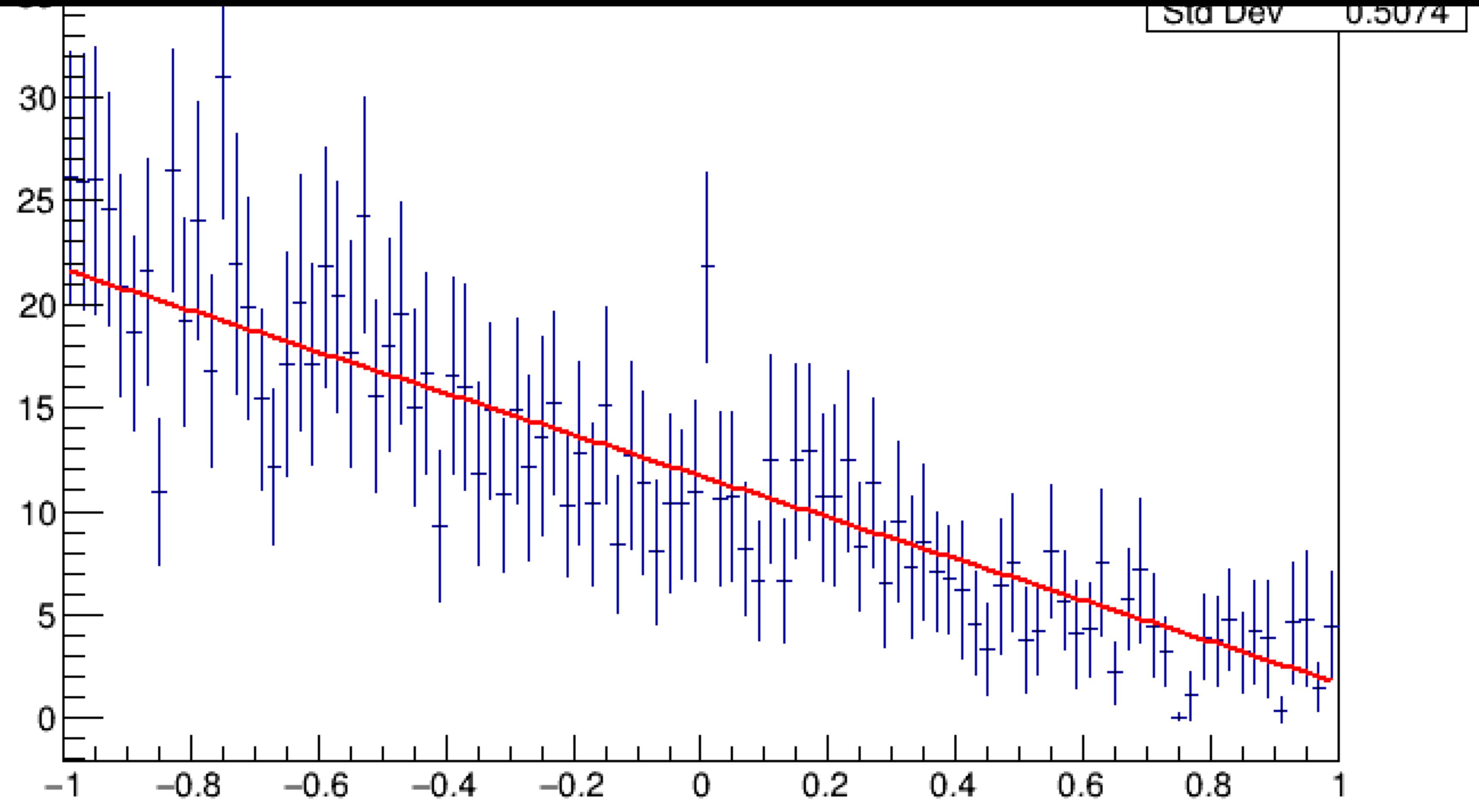


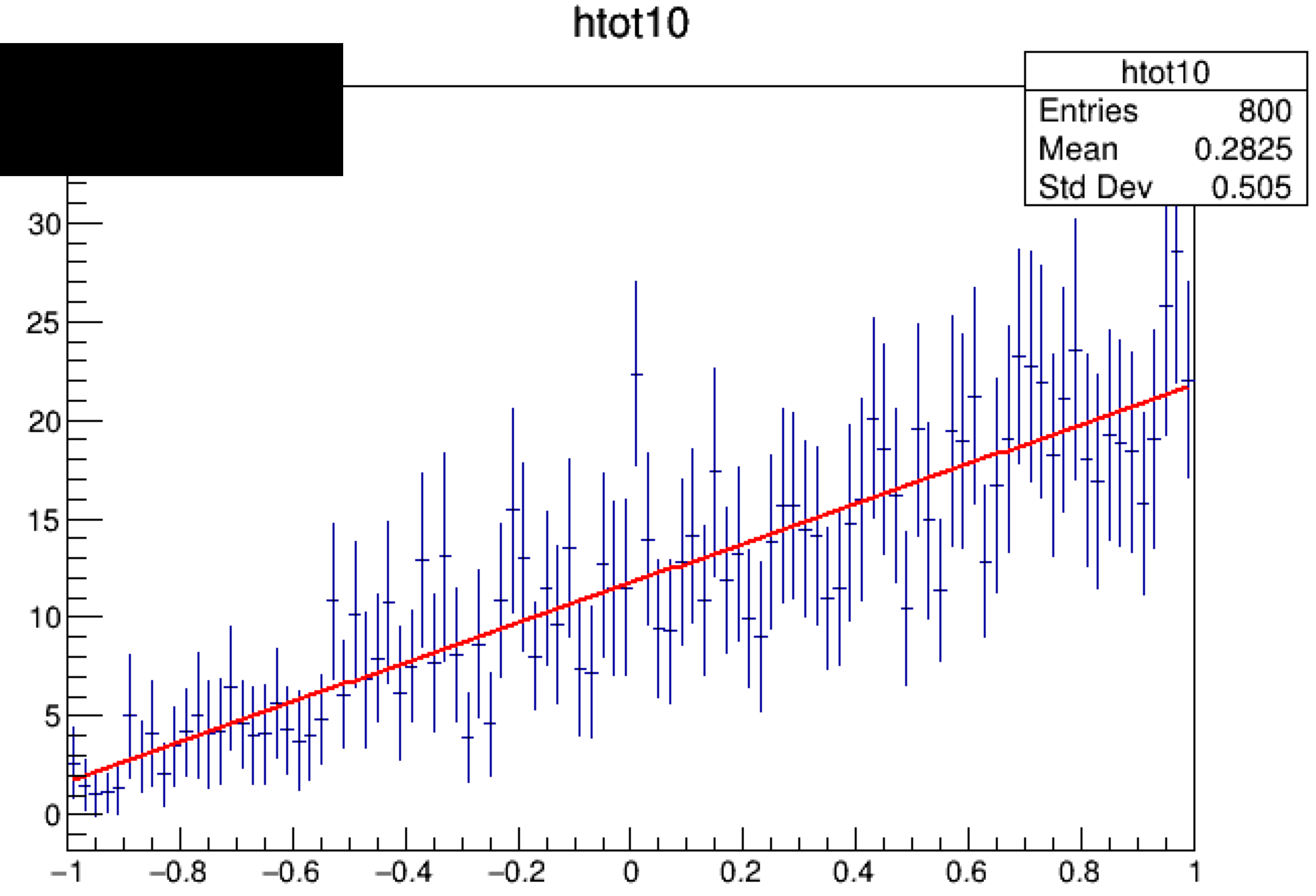
```
const int NN = 11;              // different polarisation

for ( int i = 0; i<NN; i++) {
  TString samp;
  samp+=i;
  _htot[i]     = new TH1F( "htot"     + samp, "htot"     + samp, 100, -1, 1 );
}
```

```
for ( int icos = 0; icos < ncos; icos++ ) {
  for ( int pwant = 0; pwant<NN; pwant++ ) {
      for (int itau=0; itau<2; itau++) {
       if ( newmeth_polarimeter[0][itau]>-999 ) {
          for (int isol=0; isol<newmeth_nsol; isol++) {
            _htot[pwant]->Fill( newmeth_polarimeter[isol][itau], solweight );
          }
        }
     }// end itau loop
  }
}
```





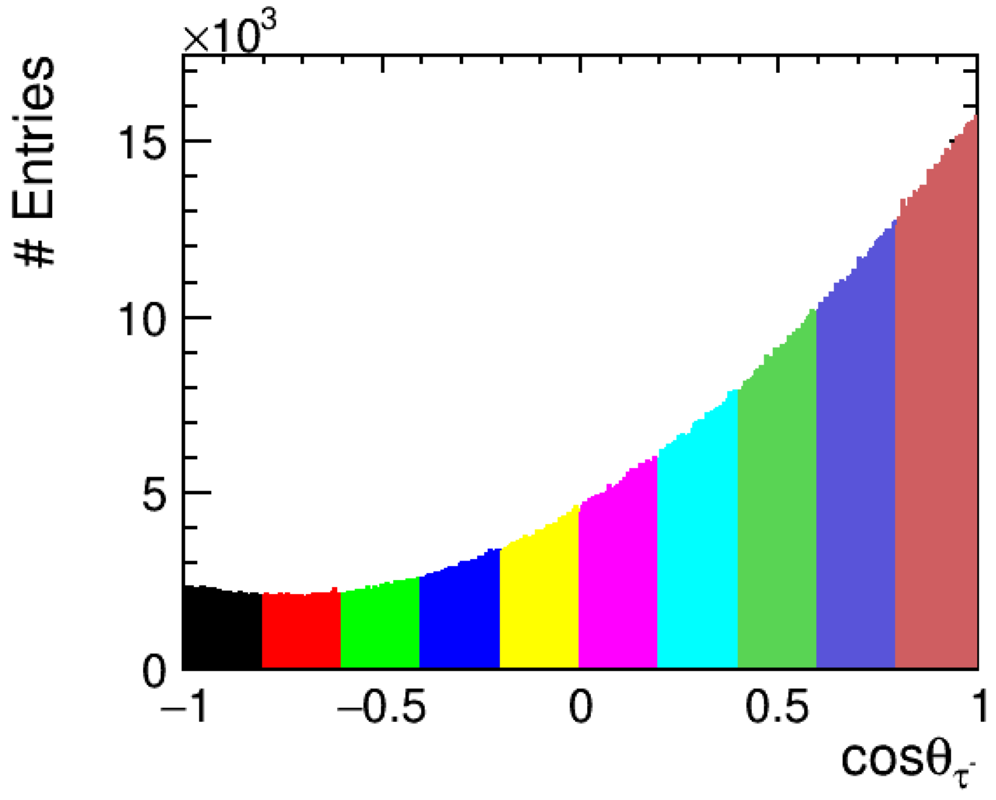


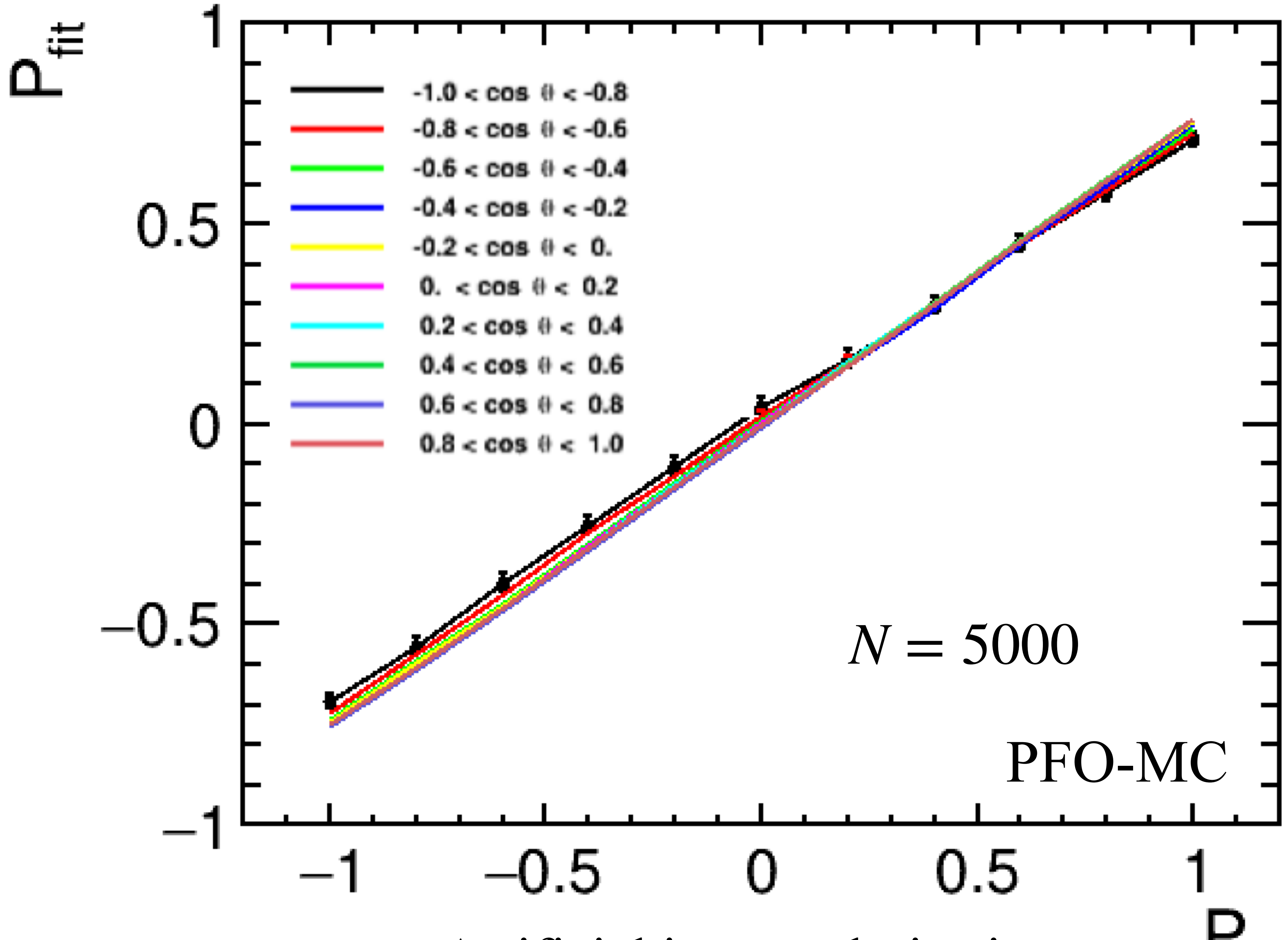
Before FSR
After FSR
p_T
MC $m_{\tau\tau}$ [GeV]
p_T
MC $m_{\tau\tau}$ [GeV]
Before FSR
After FSR
e^-
e^+
τ^-
τ^+
on-shell Z is produced
Significant FSR
$\rightarrow m_{\tau\tau} < m_Z$

Method Calibration

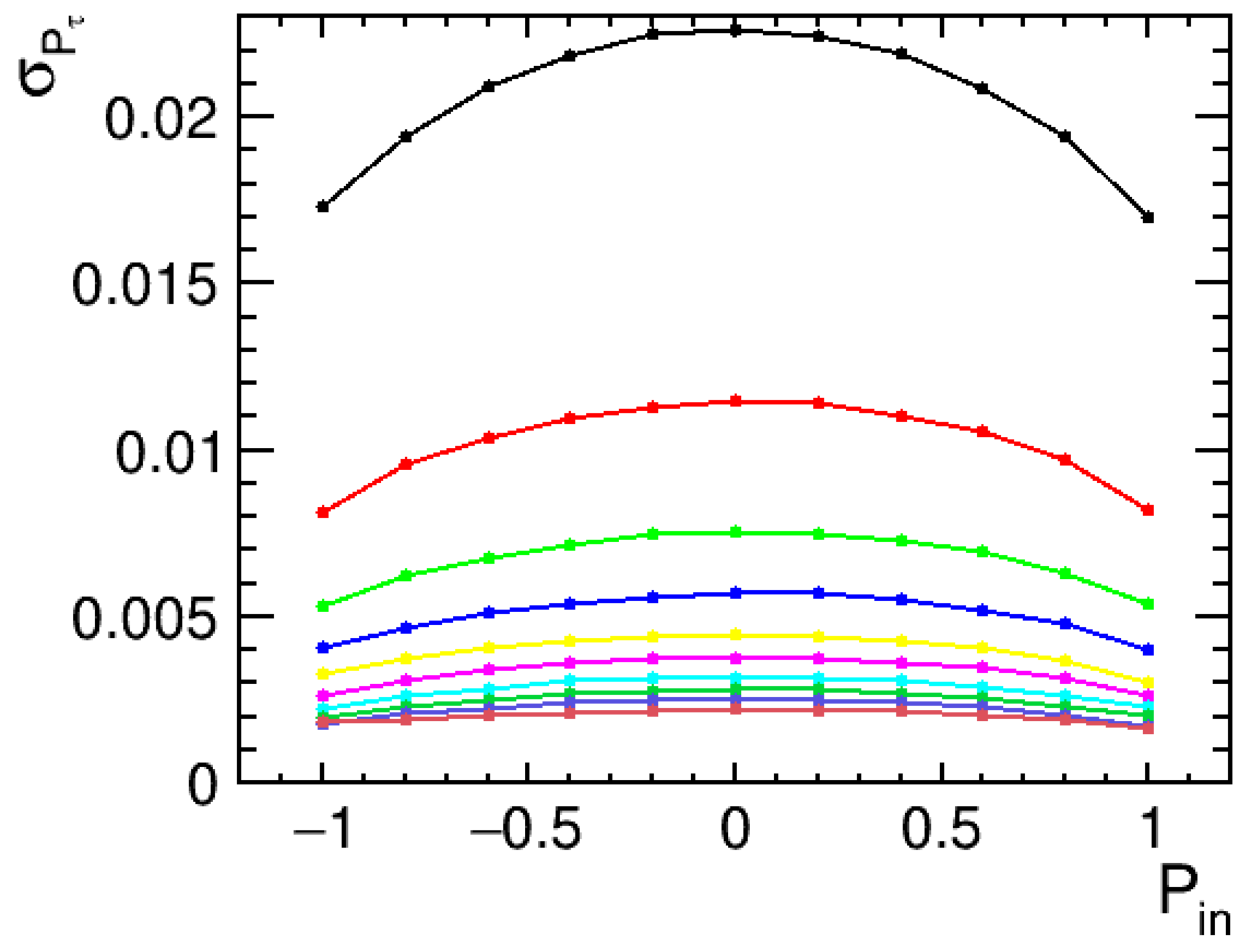
MC linked PFO : which MC particles produced the hits included in this reconstructed particle

At least 1 tau $\rightarrow \pi/\rho$
$m_{\tau\tau} > 240$ GeV

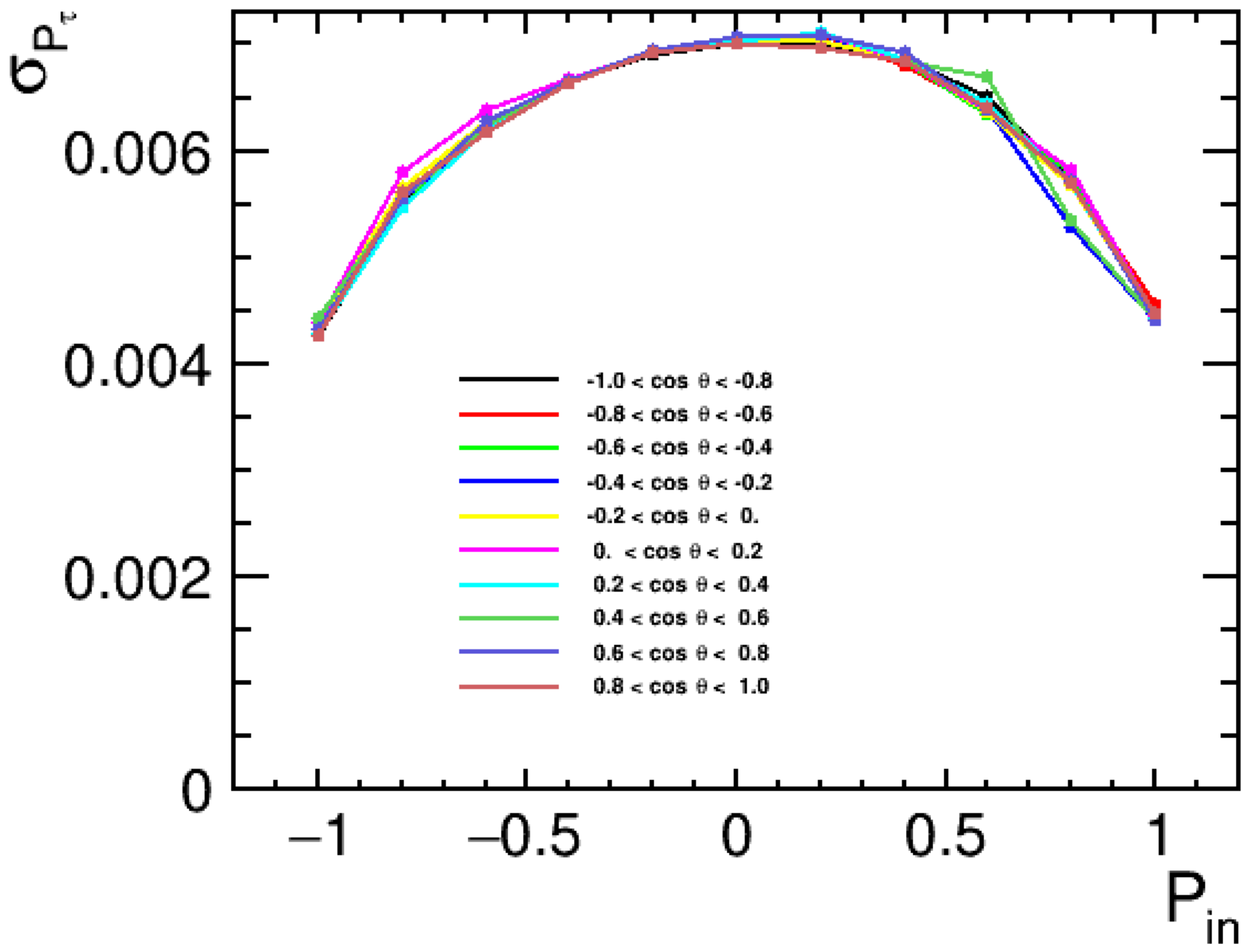




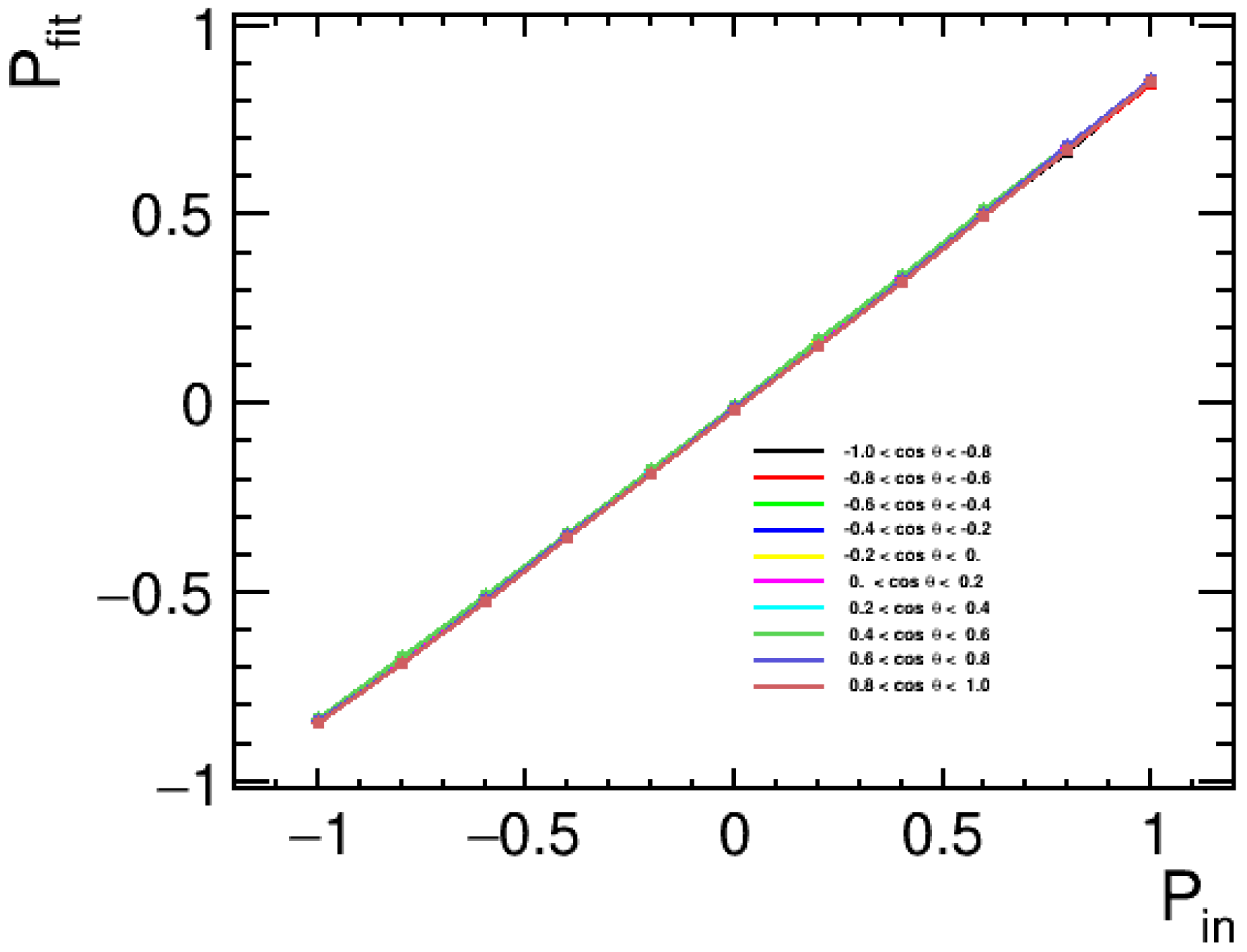
Artificial input polarisation



Errors from Jackknife method



σ_{P_τ}
0.006
0.004
0.002
0
−1
−0.5
0
0.5
1
P_{in}
-1.0 < cos θ < -0.8
-0.8 < cos θ < -0.6
-0.6 < cos θ < -0.4
-0.4 < cos θ < -0.2
-0.2 < cos θ < 0.
0. < cos θ < 0.2
0.2 < cos θ < 0.4
0.4 < cos θ < 0.6
0.6 < cos θ < 0.8
0.8 < cos θ < 1.0



P_{fit}
1
0.5
0
−0.5
−1
−1
−0.5
0
0.5
1
P_{in}
-1.0 < cos θ < -0.8
-0.8 < cos θ < -0.6
-0.6 < cos θ < -0.4
-0.4 < cos θ < -0.2
-0.2 < cos θ < 0.
0. < cos θ < 0.2
0.2 < cos θ < 0.4
0.4 < cos θ < 0.6
0.6 < cos θ < 0.8
0.8 < cos θ < 1.0