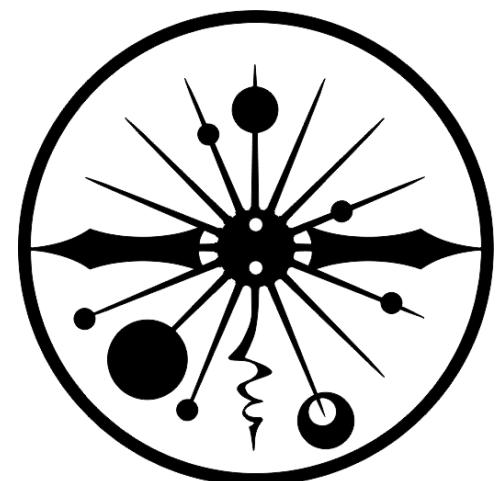


[arXiv:1912.08403](https://arxiv.org/abs/1912.08403)

[arXiv:2203.07668](https://arxiv.org/abs/2203.07668)

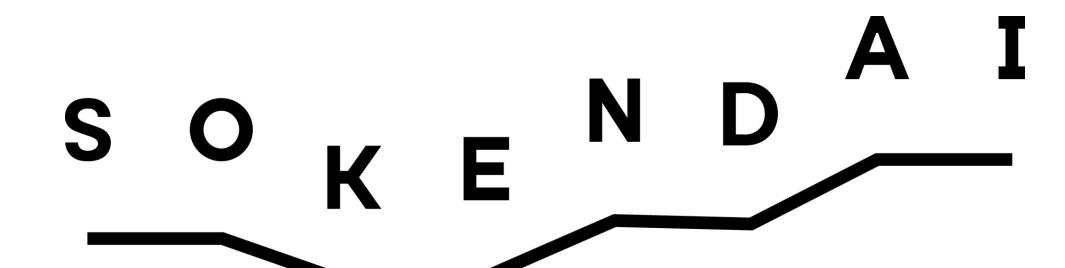
# Measuring the tau polarisation at the ILC



Keita Yumino, Daniel Jeans



KEK, SOKENDAI



# Motivation

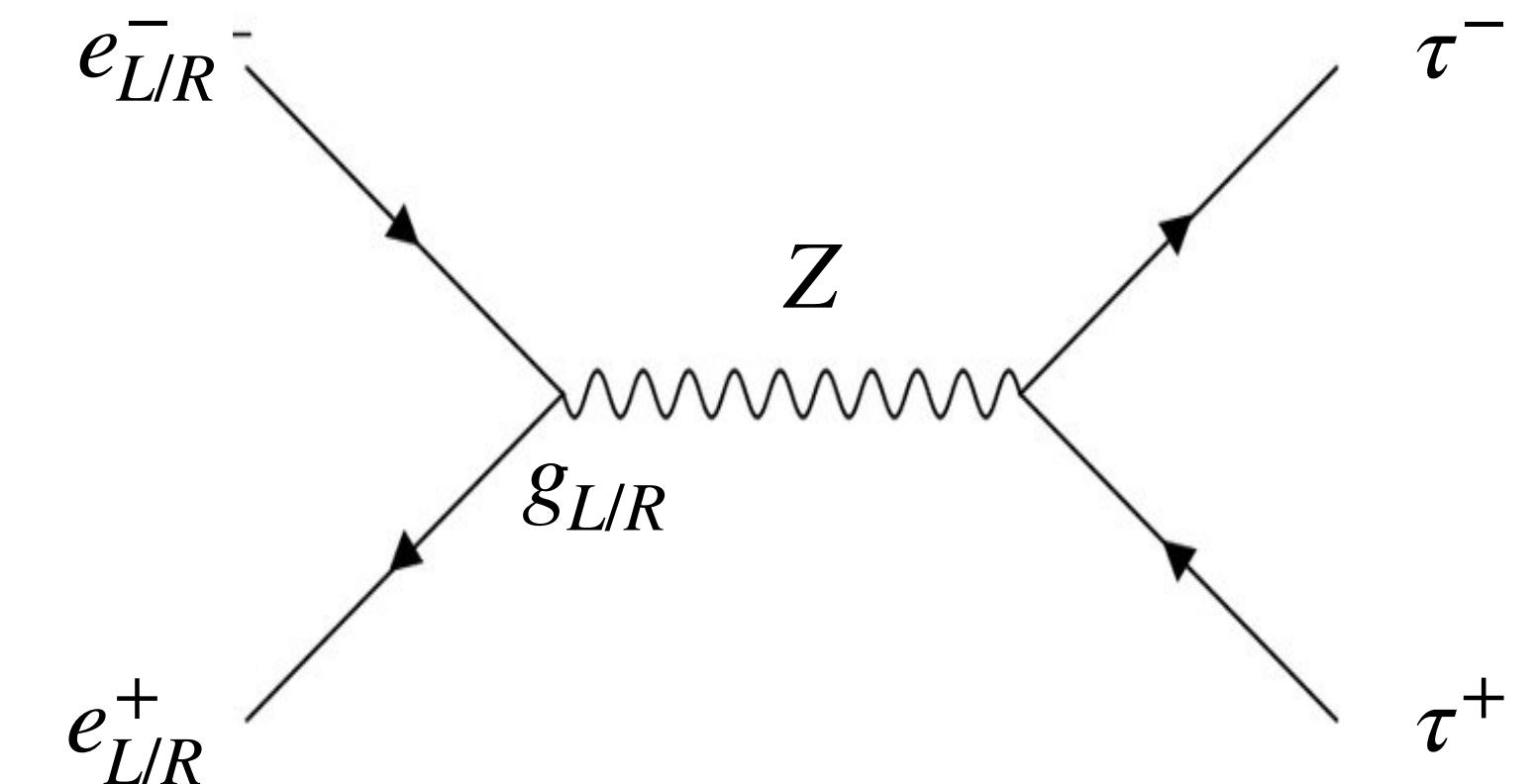
At the ILC, forward-backward asymmetry  $A_{FB} = \frac{3}{4} A_e \cdot A_f$  can be measured

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

By measuring  $A_{FB}$  precisely and looking for deviations from SM predictions, it is possible to search for new physics, such as heavy gauge boson  $Z'$

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

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



The aim of this study

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

# Polarimeter

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

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

$\tau \rightarrow \rho\nu$  (BR  $\sim 26\%$ )

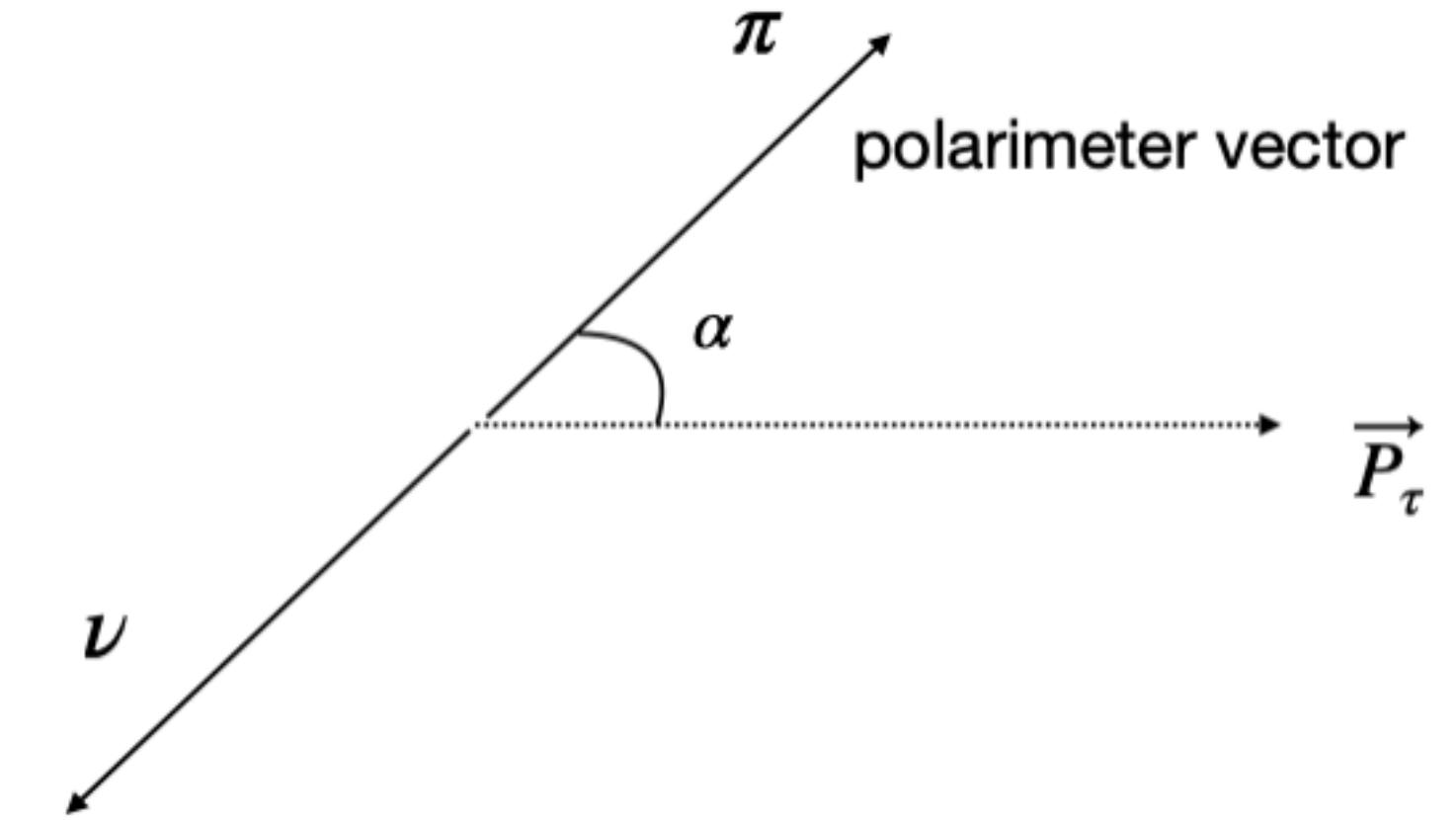
in this talk

Polarimeter vectors of  $\tau \rightarrow \pi\nu$  in  $\tau$  rest frame

$$h(\tau^\pm \rightarrow \pi^\pm \nu) \propto p_{\pi^\pm}$$

Polarimeter vectors of  $\tau \rightarrow \rho\nu$  in  $\tau$  rest frame

$$h(\tau^\pm \rightarrow \pi^\pm \pi^0 \nu) \propto m_\tau (E_{\pi^\pm} - E_{\pi^0}) (p_{\pi^\pm} - p_{\pi^0}) + \frac{1}{2} (p_{\pi^\pm} + p_{\pi^0})^2 p_\nu$$



“Polarimeter”

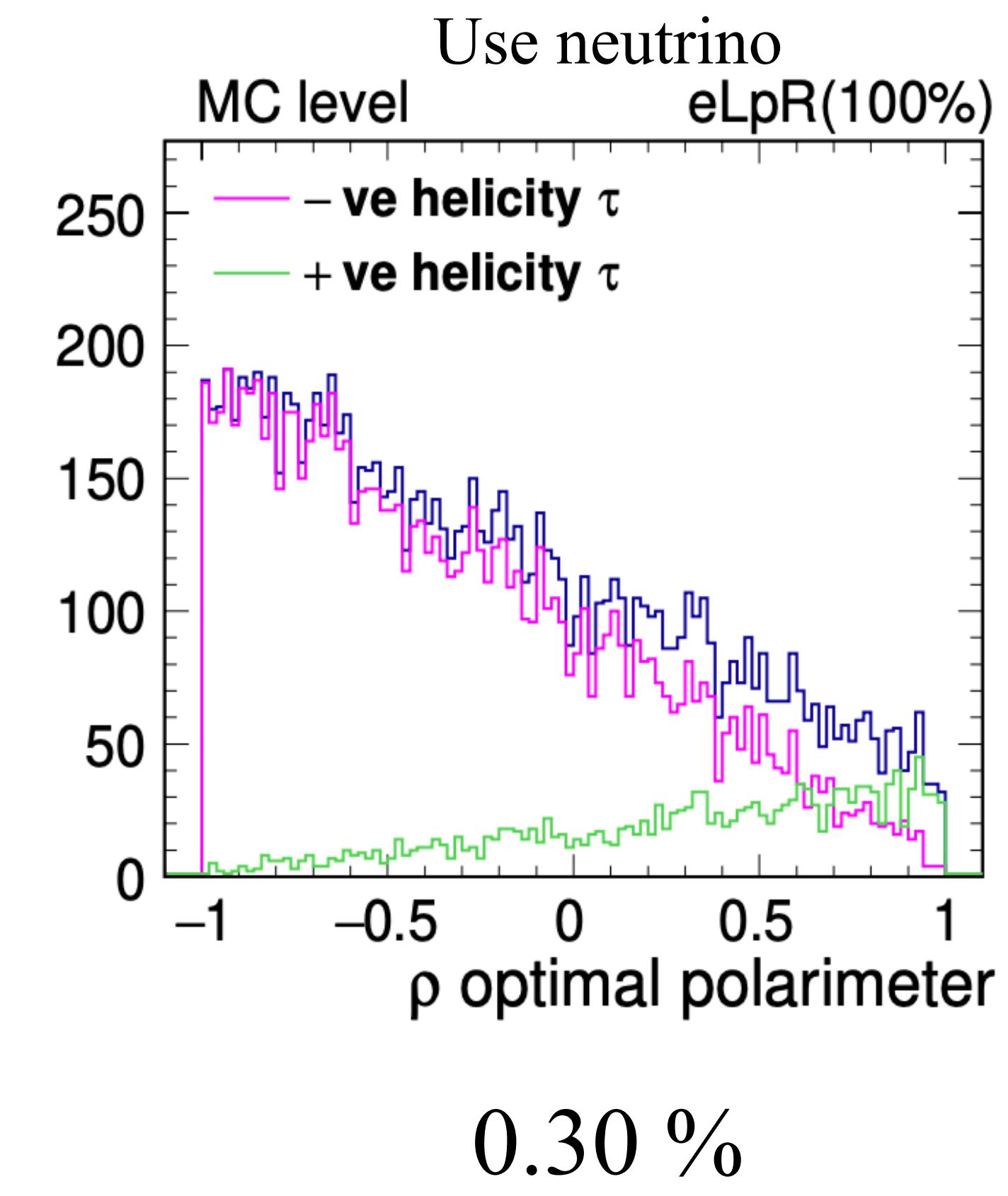
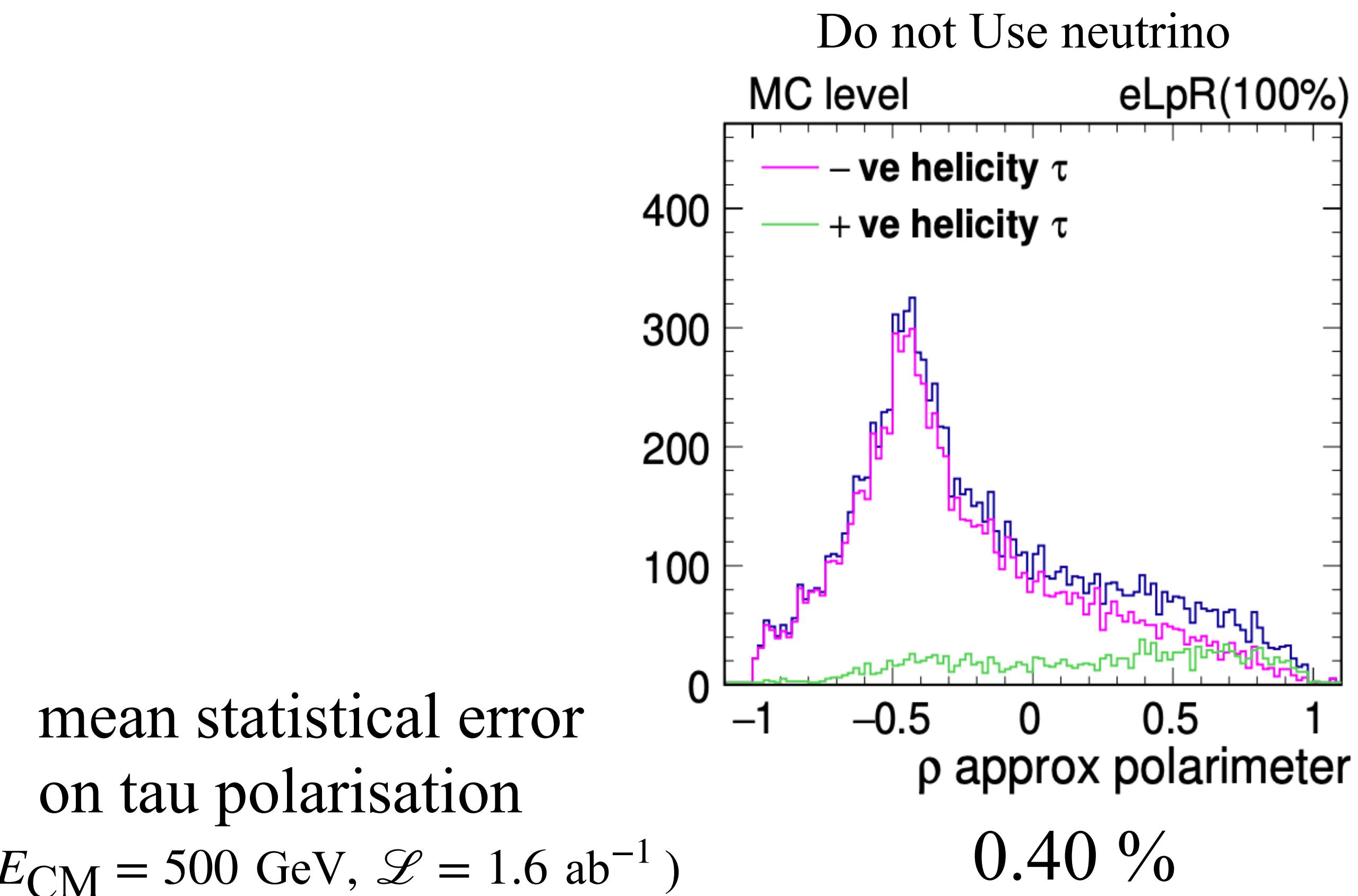
The cosine of the angle this polarimeter vector makes to the tau flight direction

# Previous study

Extract polarimeter without using neutrino information

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

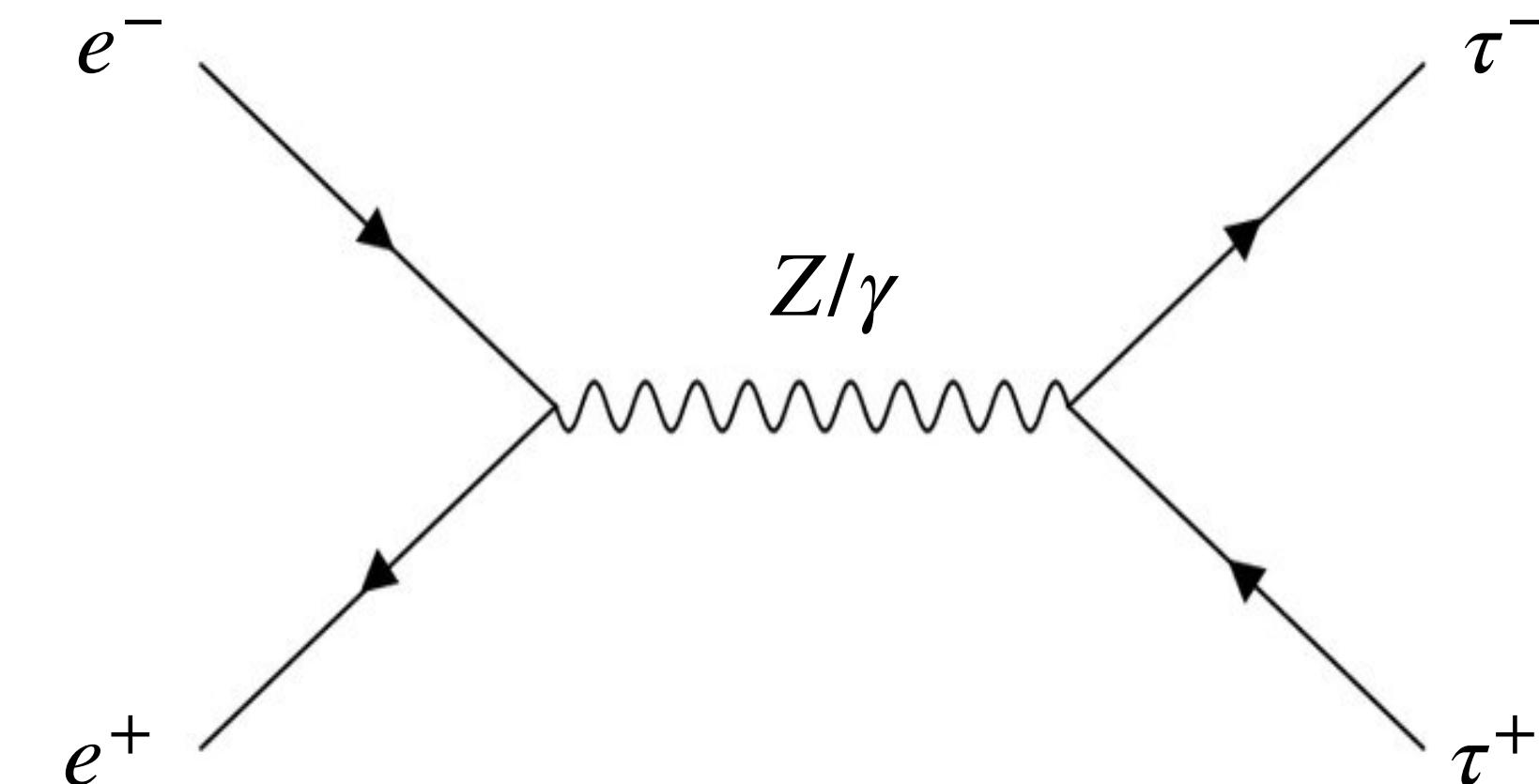
"Optimal" polarimeters including the neutrino component



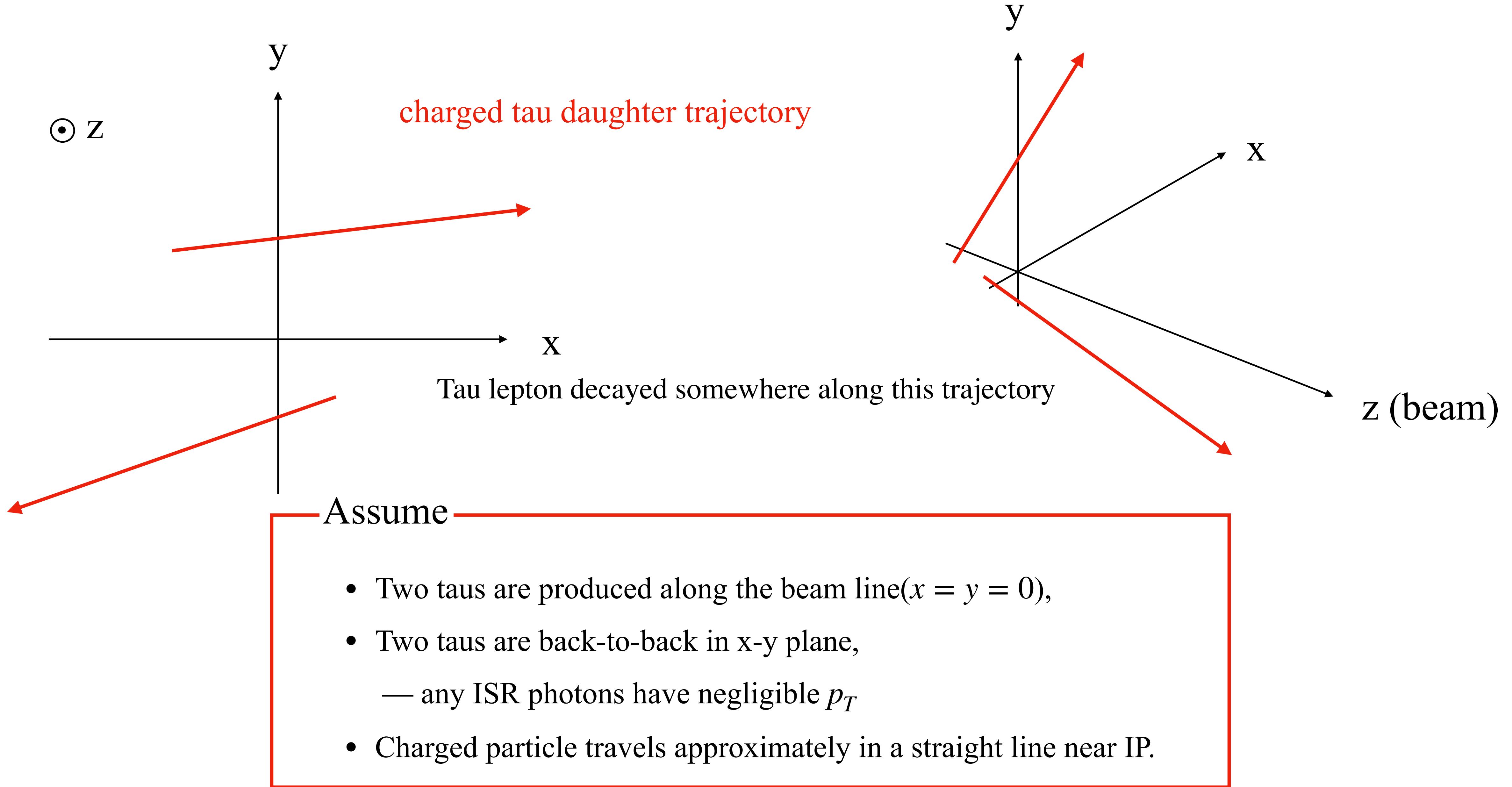
In this talk: reconstruct neutrino momentum  $\rightarrow$  optimal polarimeters

# Simulation setup

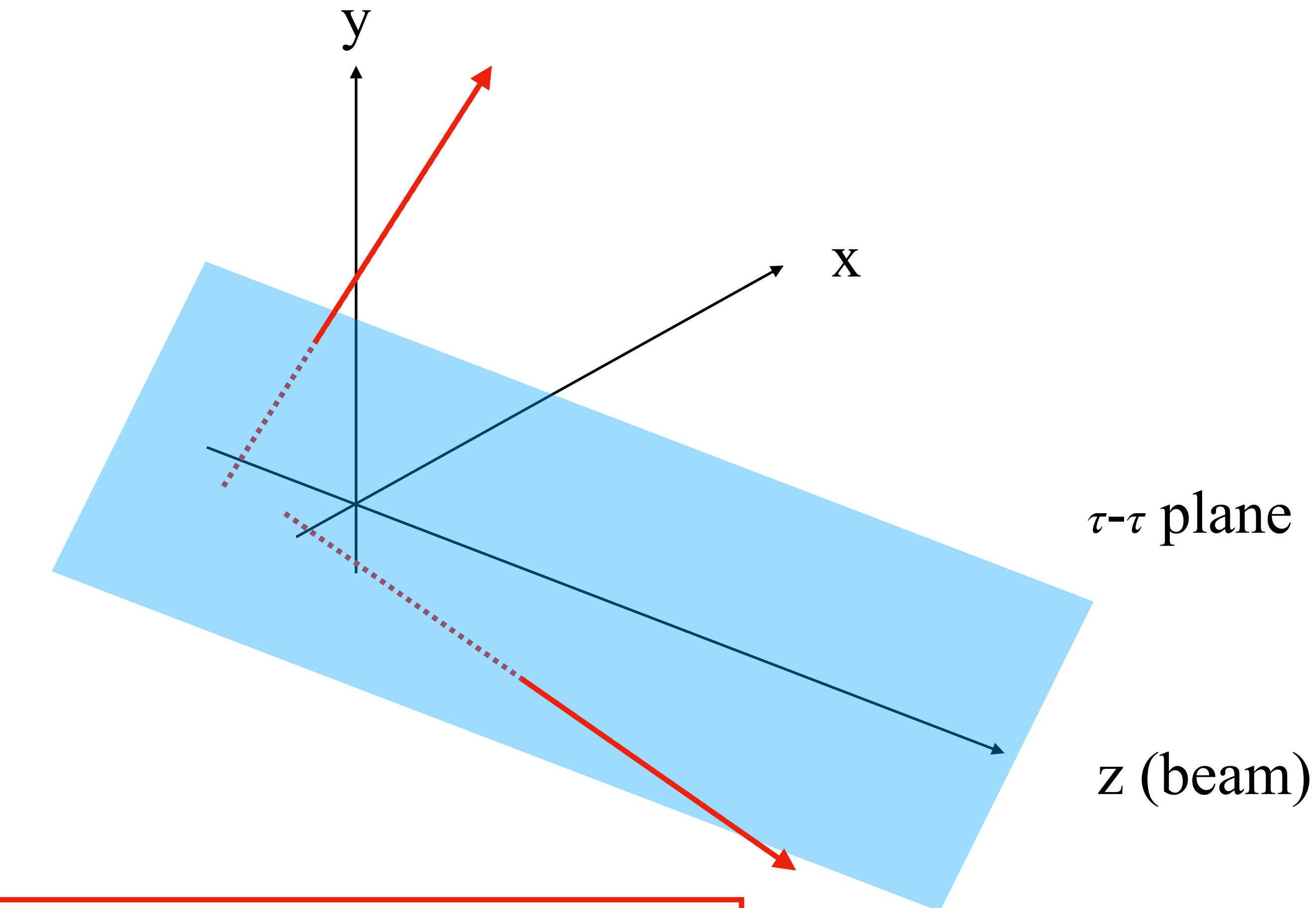
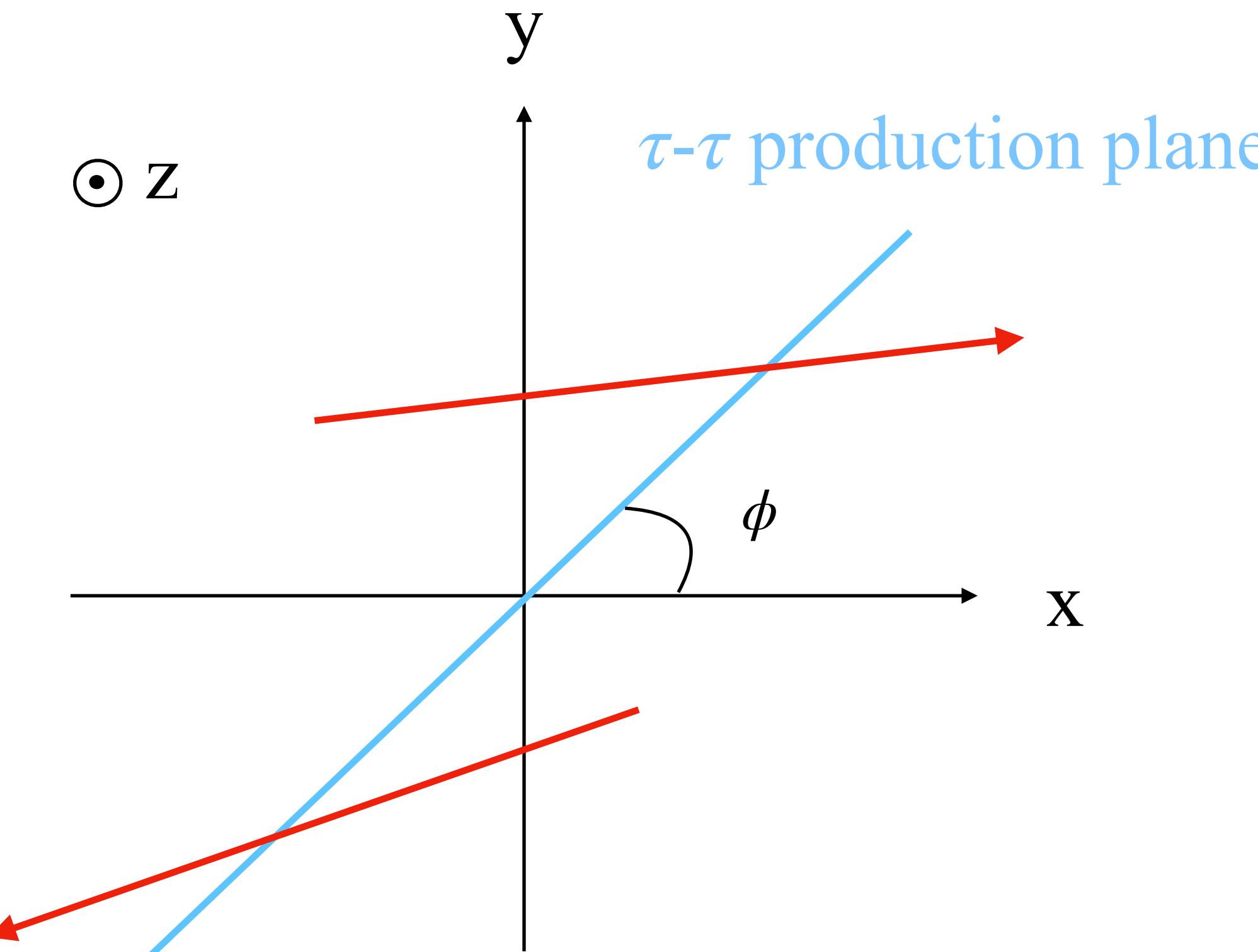
- ILD mc-2020  $e^+e^- \rightarrow \tau^+\tau^-$  signal event sample with 100 % beam polarisations
- The decay of the polarised tau was done using TAUOLA.
- MC truth information was used.



# $\tau$ reconstruction method



# $\tau$ reconstruction method

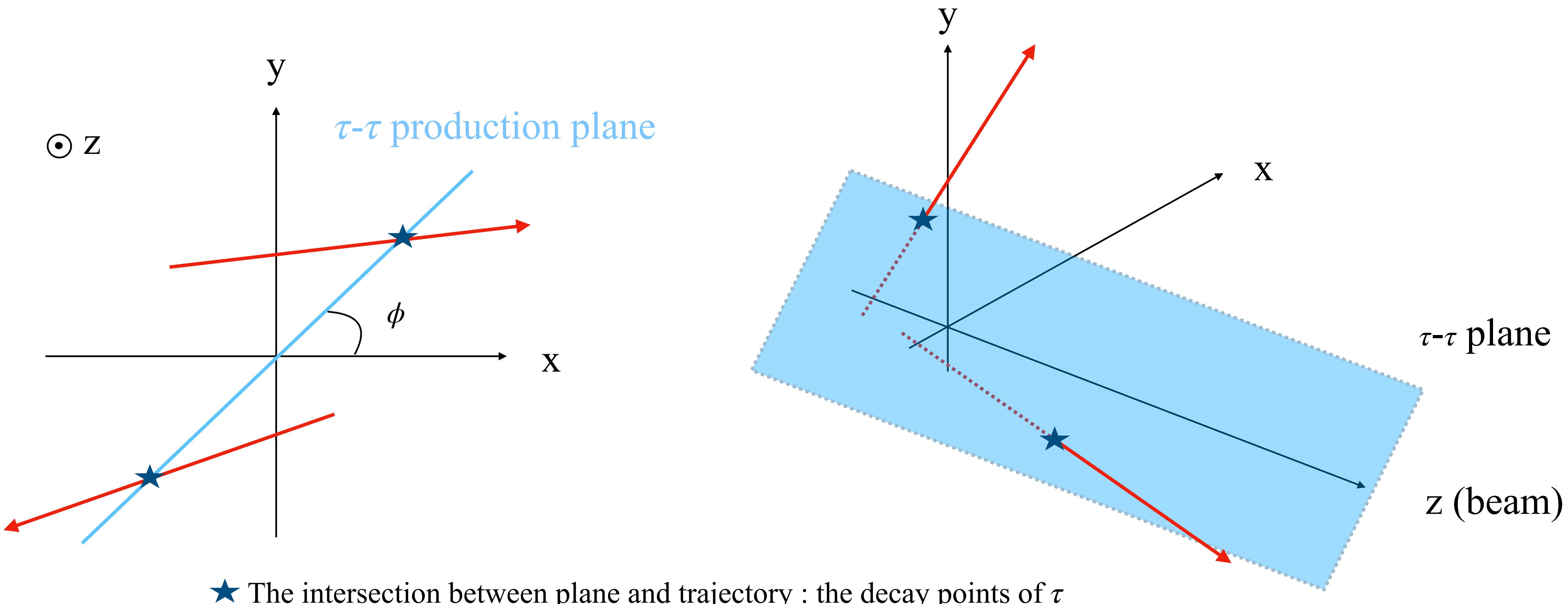


Assume

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

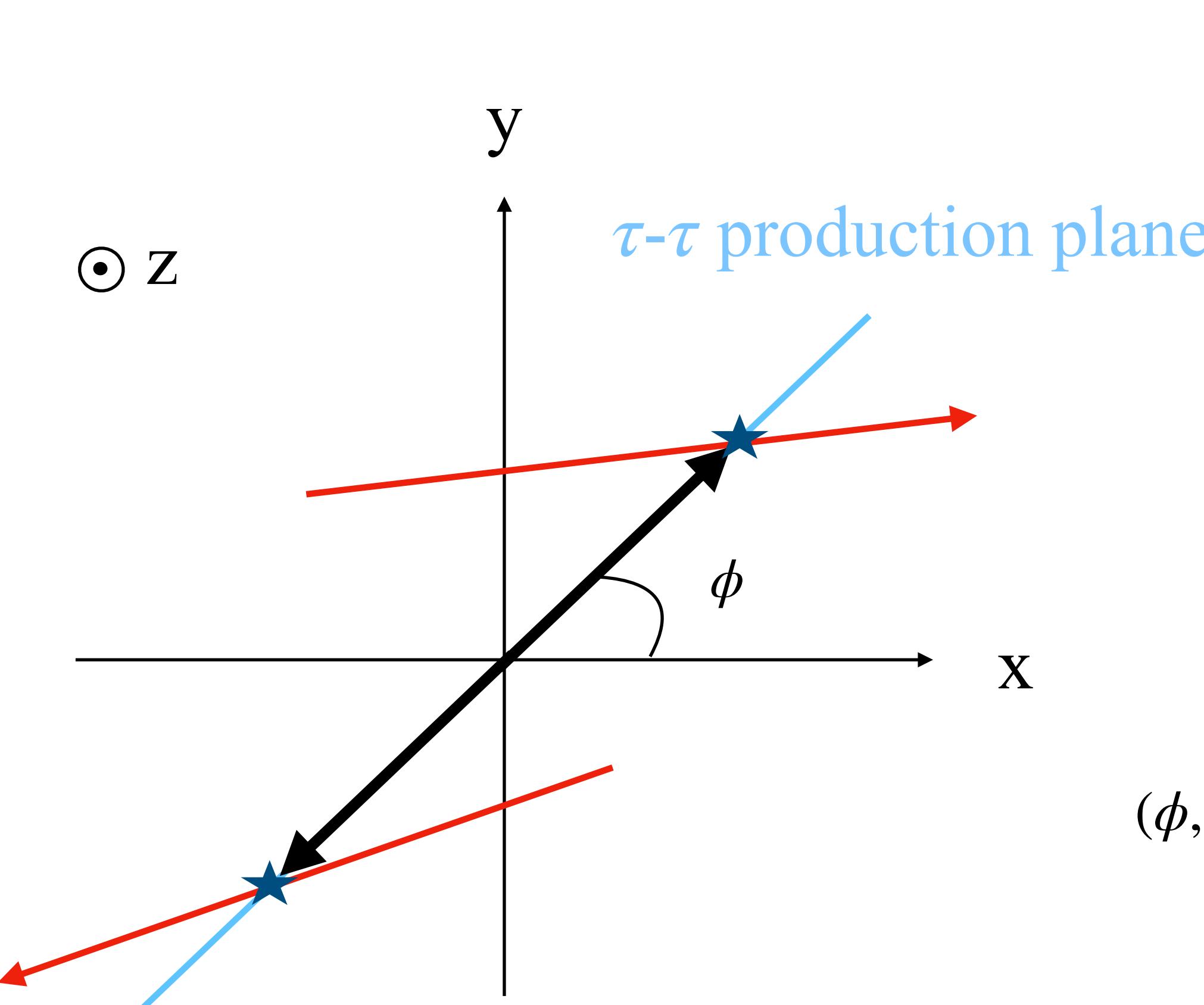
- Two tau momenta lie in a plane containing z-axis, at some azimuthal angle  $\phi$

# $\tau$ reconstruction method

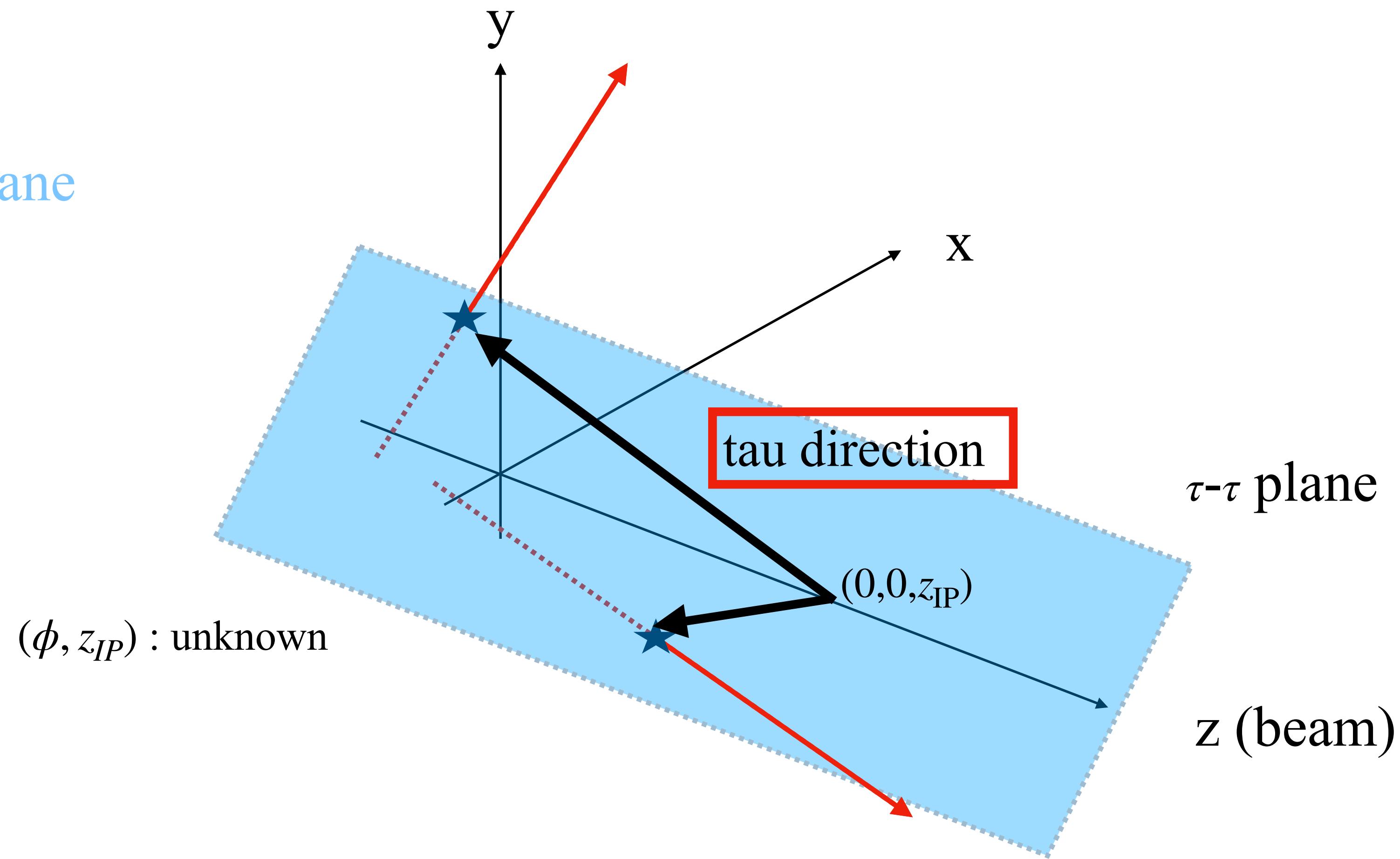


For a plane with azimuthal angle  $\phi$ ,  
the intersection of trajectories with this plane can be calculated.

# $\tau$ reconstruction method



$\tau\text{-}\tau$  production plane



$(\phi, z_{IP})$  : unknown

tau direction

$(0,0,z_{IP})$

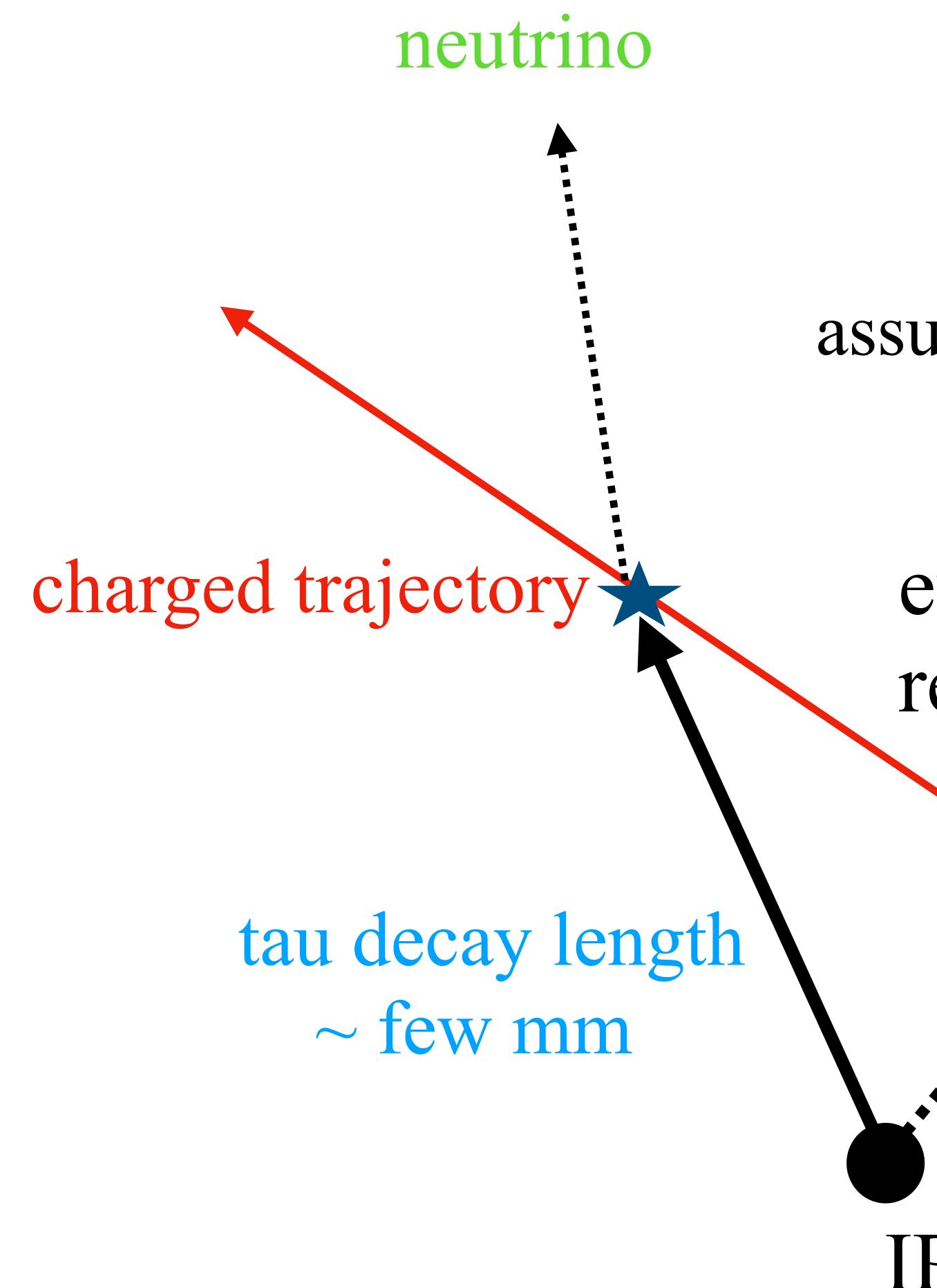
$\tau\text{-}\tau$  plane

z (beam)

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

→ How can we choose  $\phi, z_{IP}$  ?

# $\tau$ reconstruction method



## Unknown

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

assume 1 ISR photon collinear with beam

expected impact parameter  
resolution  $\sim$  few um

## Constraints

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

For choice of  $z_{IP}, \phi$   
we can calculate tau 4-momenta  $P_\tau$

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

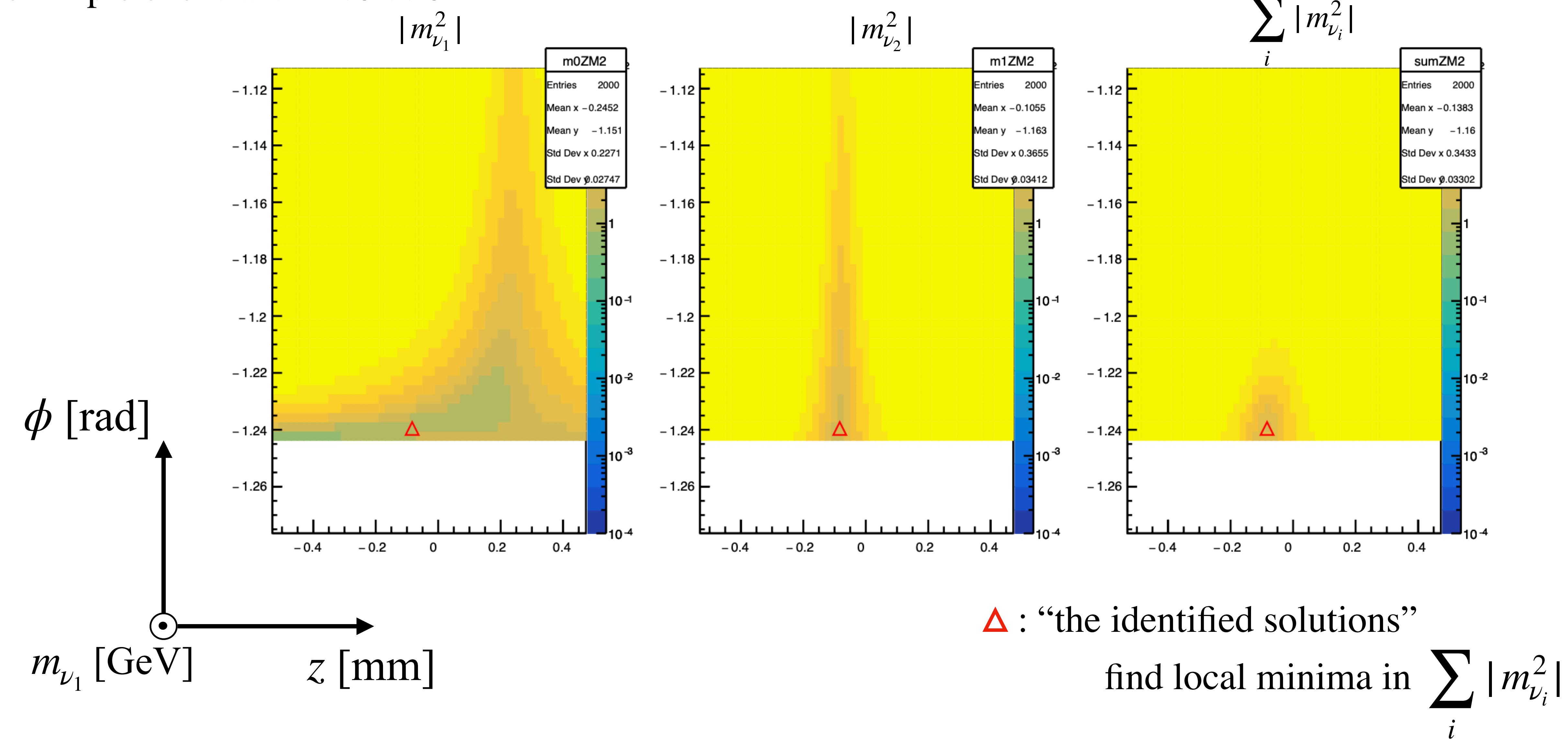
$$P_\nu = P_\tau - P_{vis}$$

We choose the values of  $z$  and  $\phi$  which result in neutrino masses closest to zero

# Find solutions

We choose the values of  $z$  and  $\phi$  which result in neutrino masses closest to zero

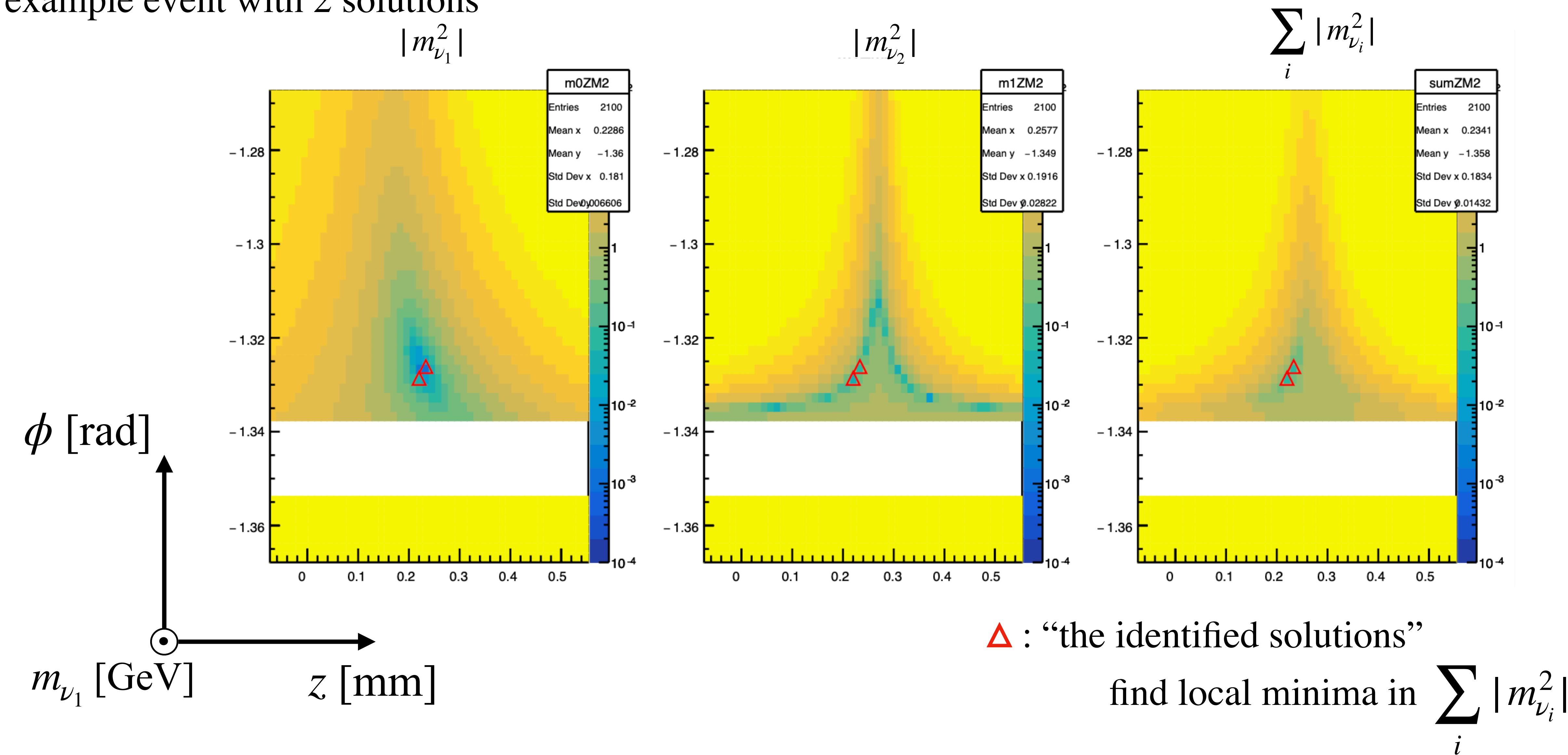
example event with 1 solution



# Find solutions

We choose the values of  $z$  and  $\phi$  which result in neutrino masses closest to zero

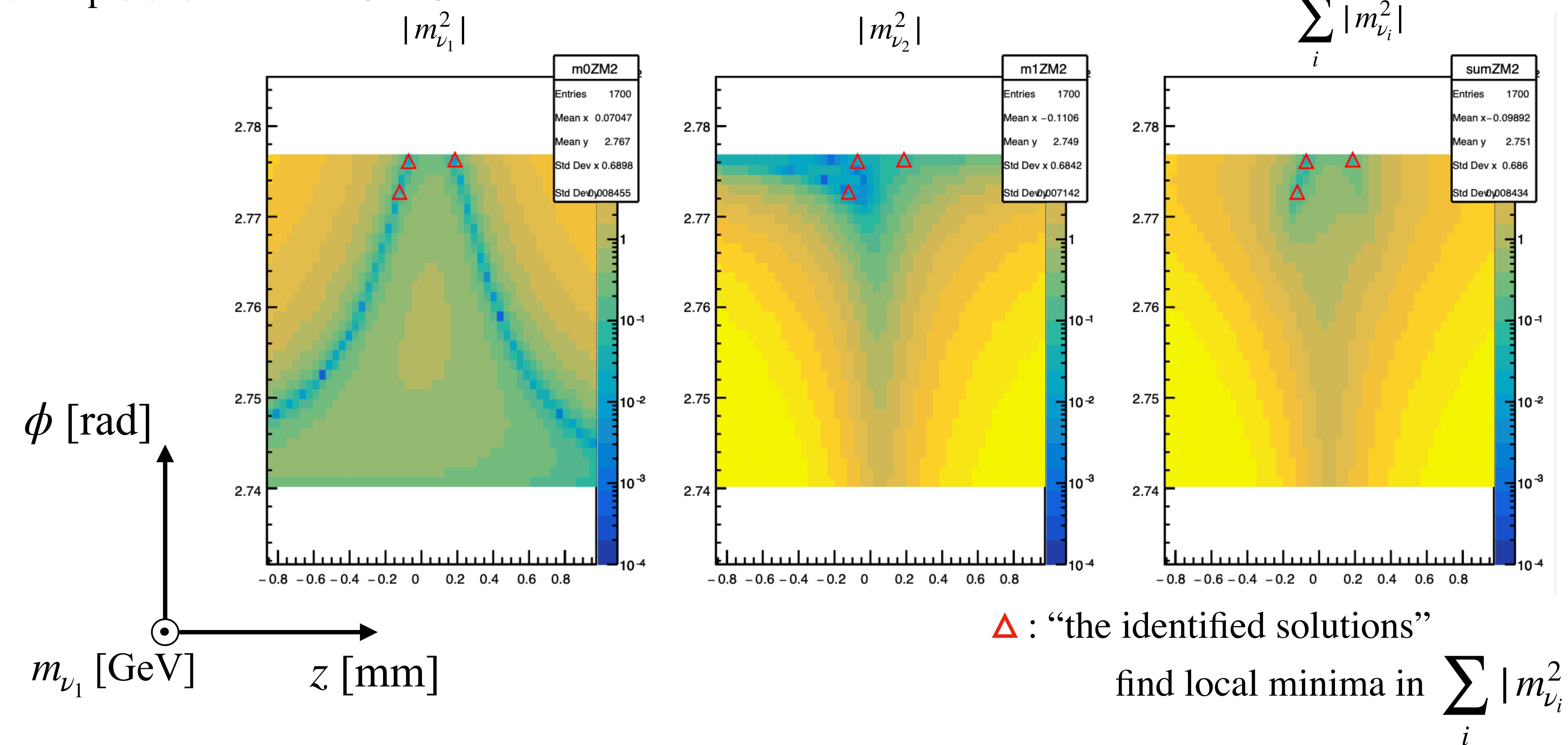
example event with 2 solutions



# Find solutions

We choose the values of  $z$  and  $\phi$  which result in neutrino masses closest to zero

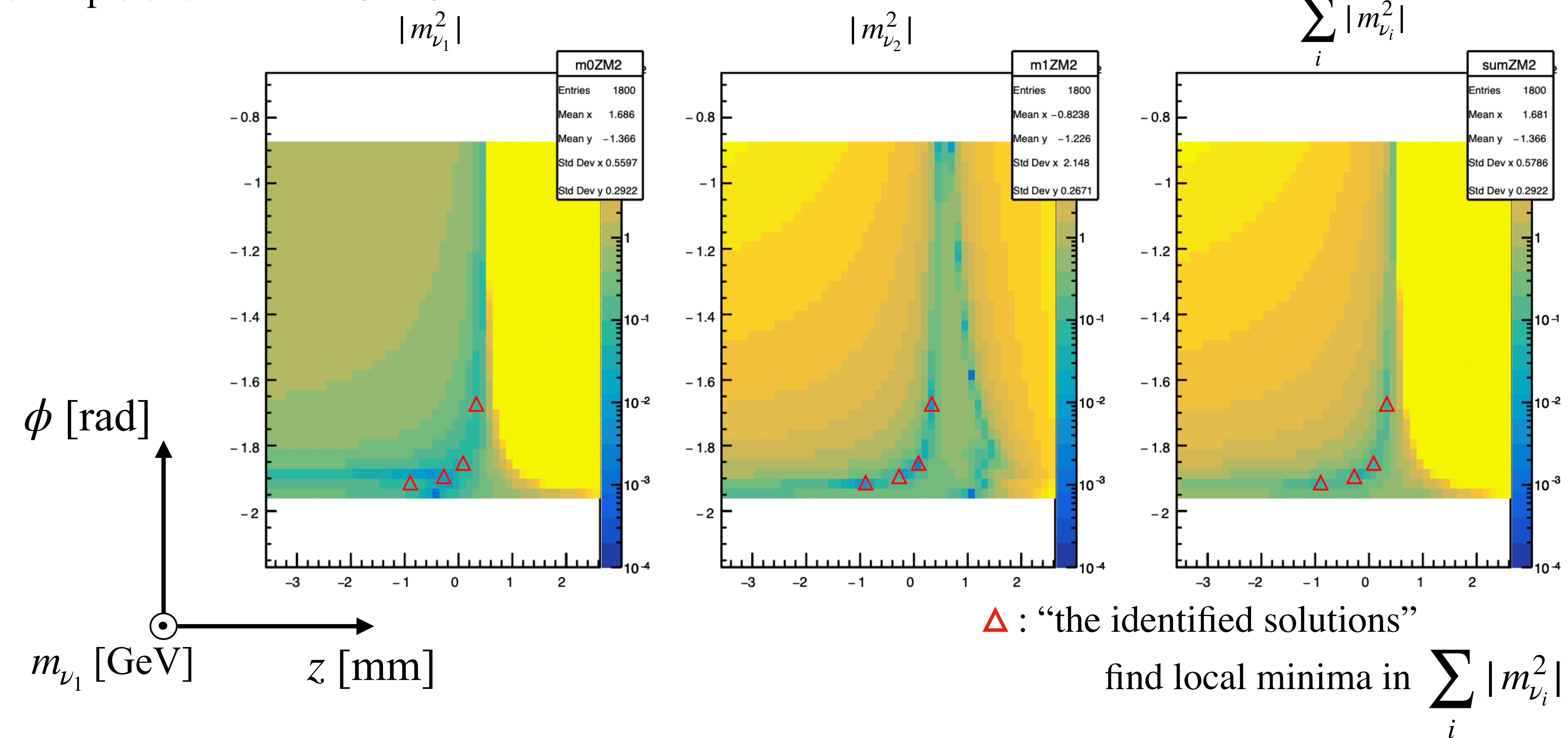
example event with 3 solutions



# Find solutions

We choose the values of  $z$  and  $\phi$  which result in neutrino masses closest to zero

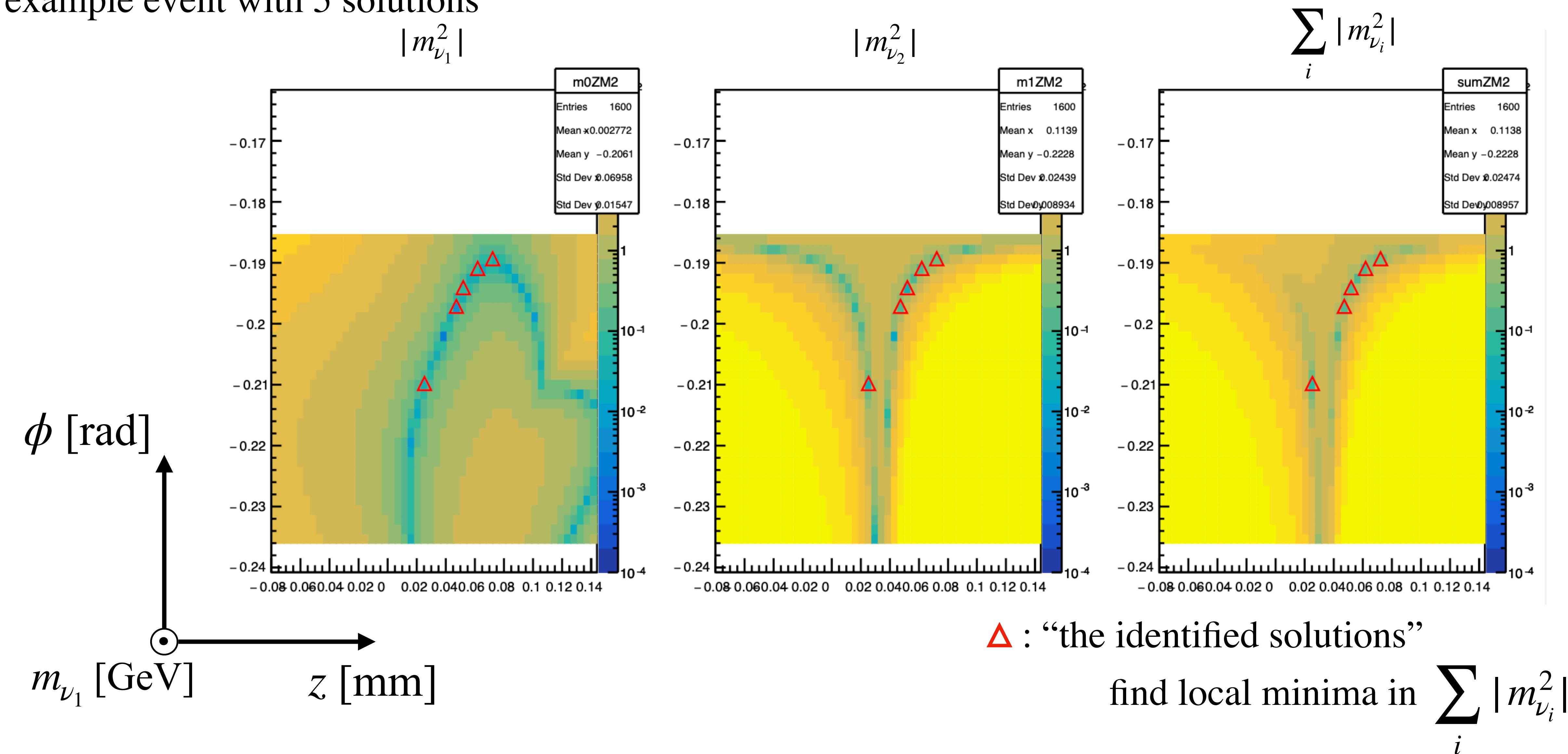
example event with 4 solutions



# Find solutions

We choose the values of  $z$  and  $\phi$  which result in neutrino masses closest to zero

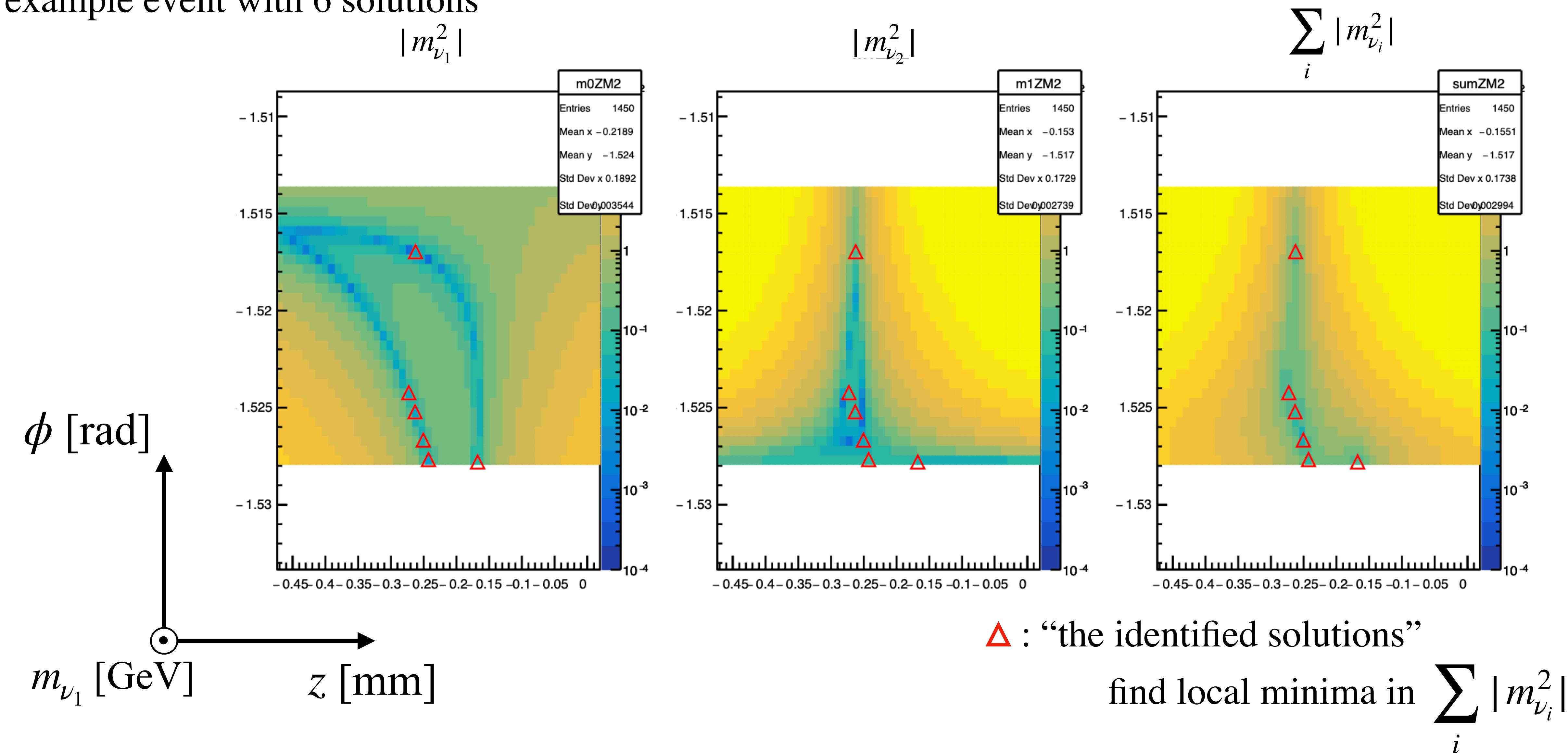
example event with 5 solutions



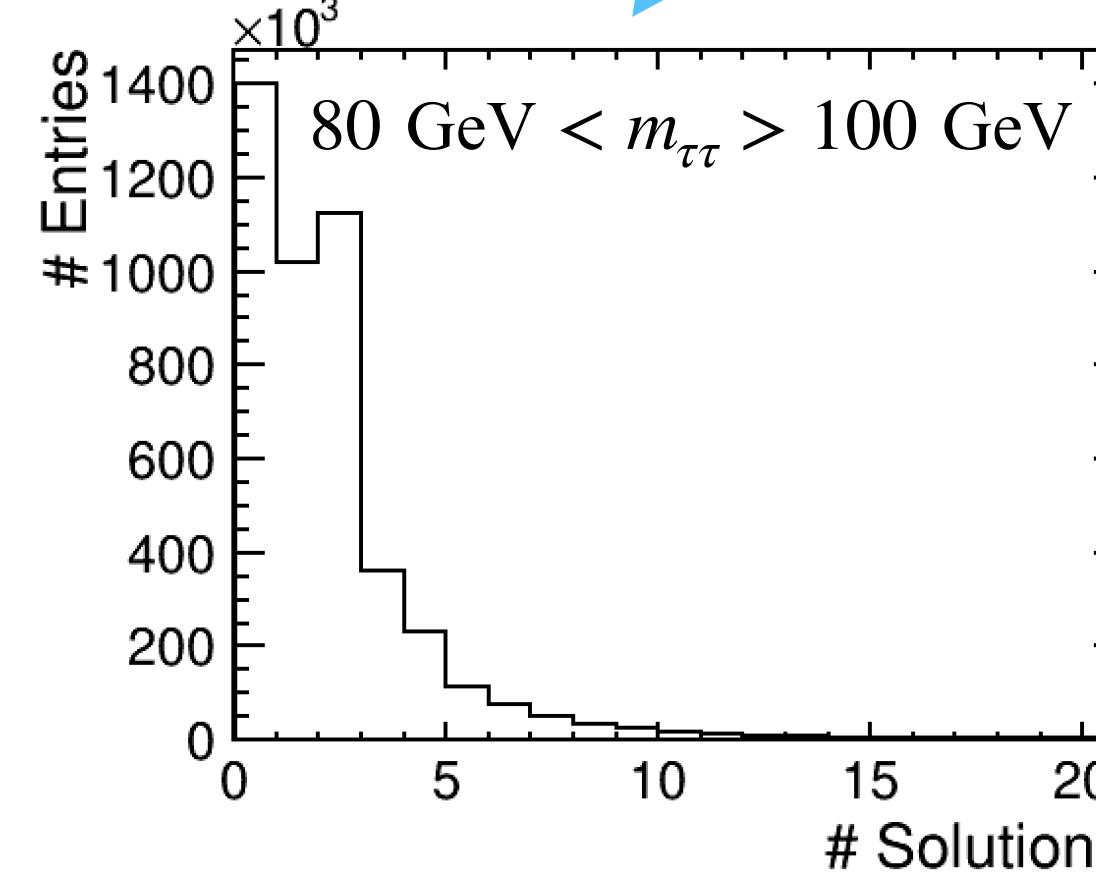
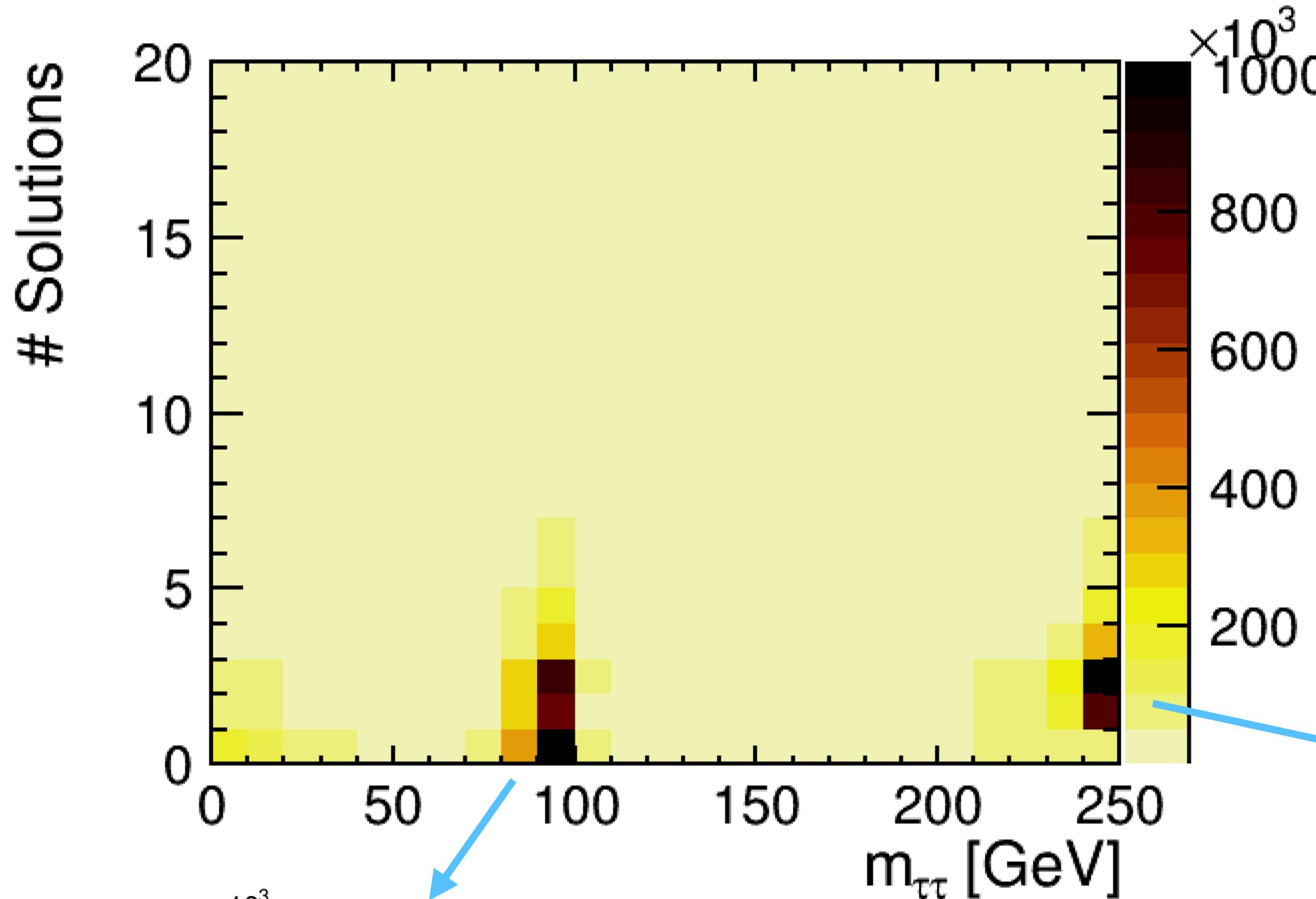
# Find solutions

We choose the values of  $z$  and  $\phi$  which result in neutrino masses closest to zero

example event with 6 solutions

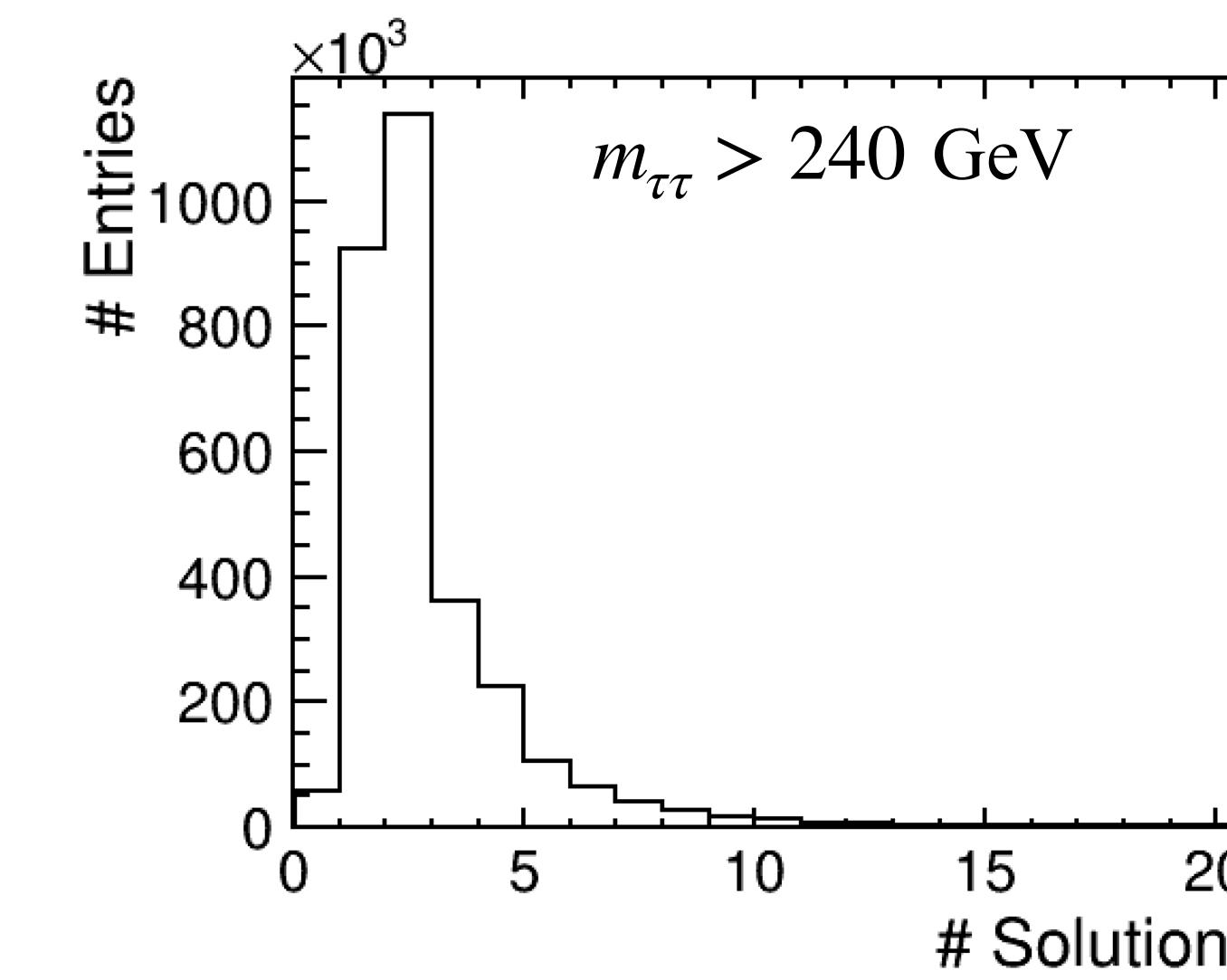


# Number of Solutions



## Assumptions

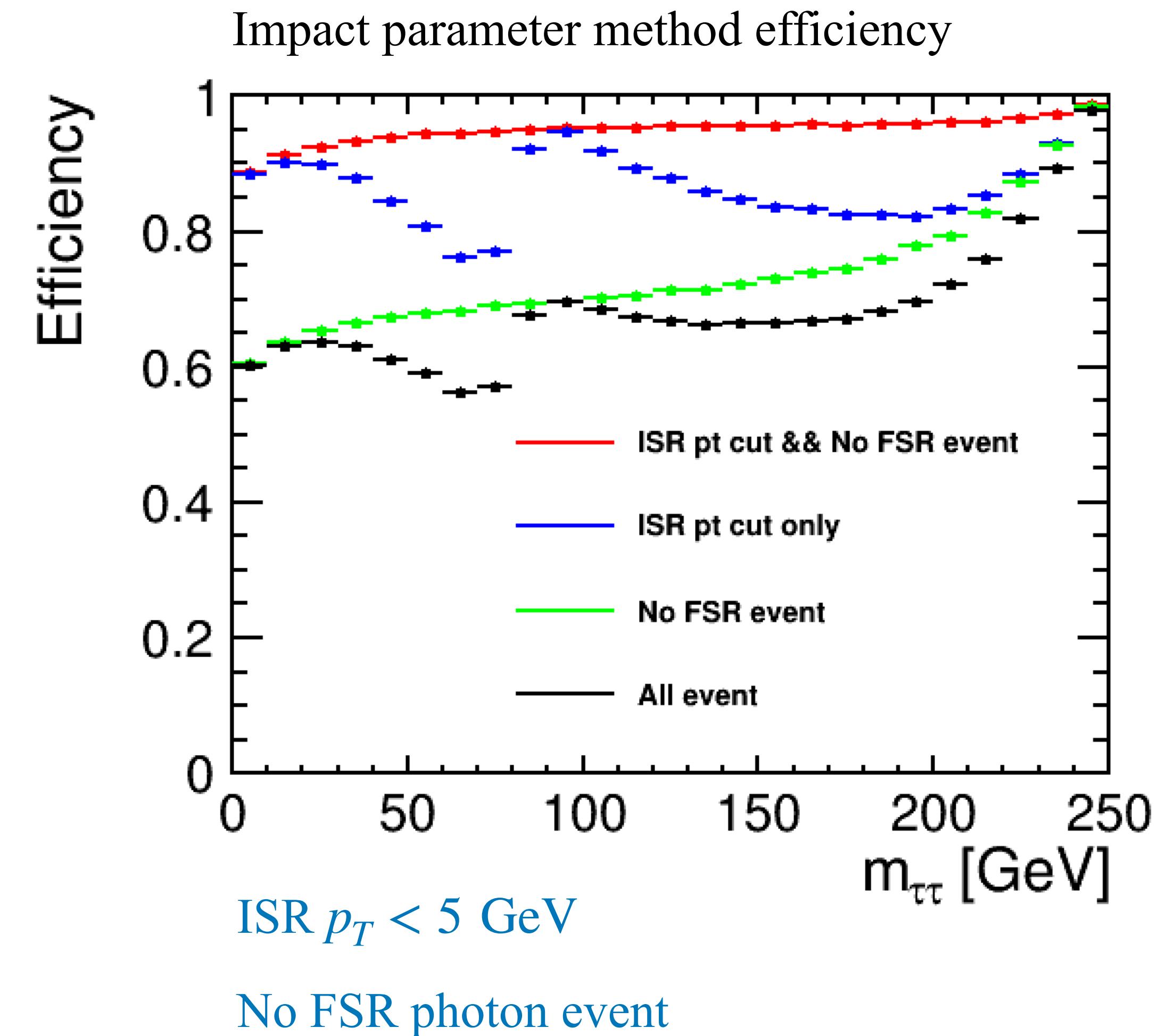
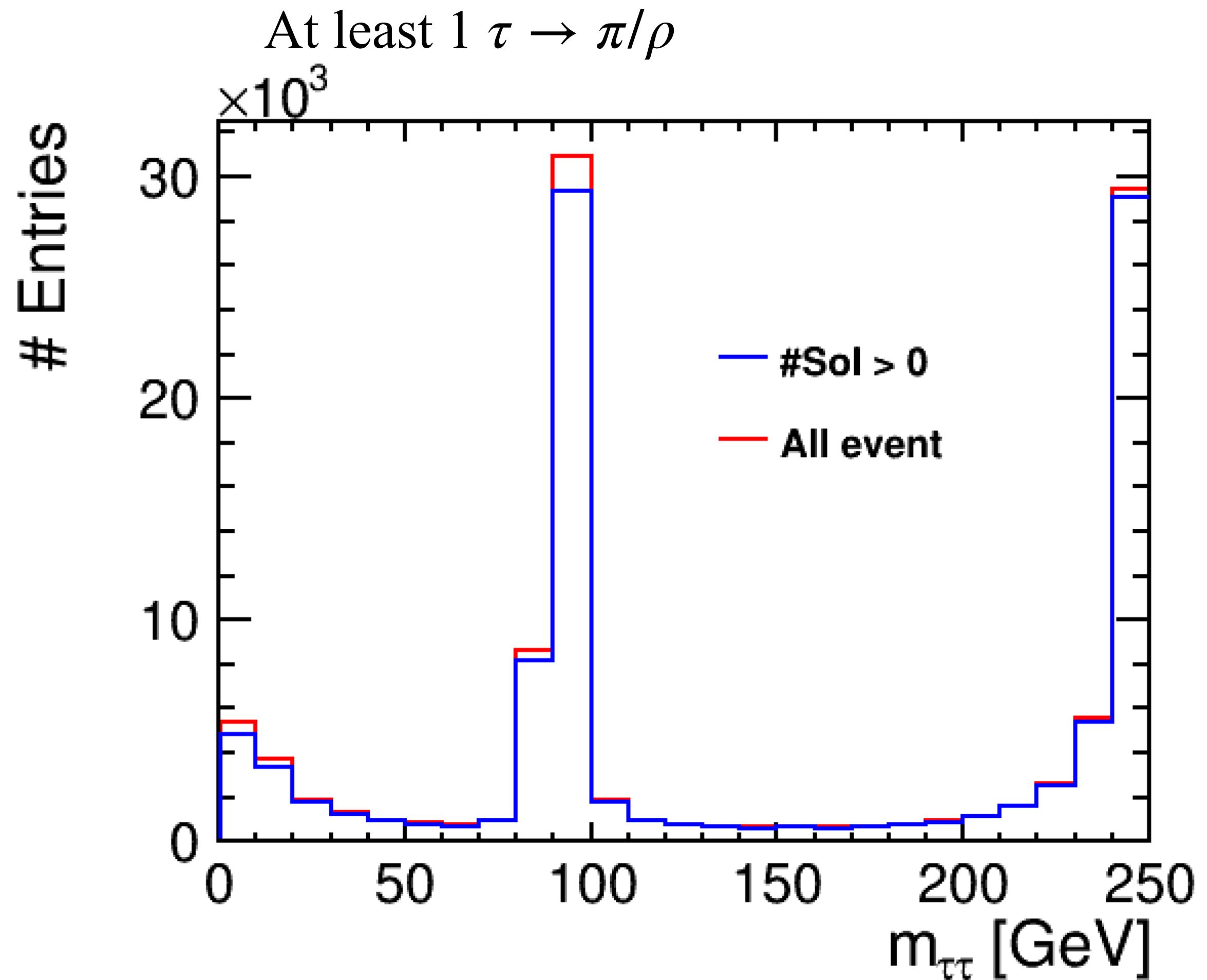
- Two taus are produced along the beam line ( $x = y = 0$ ),
- Two taus are back-to-back in x-y plane,  
— any ISR photons have negligible  $p_T$
- Charged particle travels approximately in a straight line near IP.



2~3 solutions are found in most cases

# Method efficiency

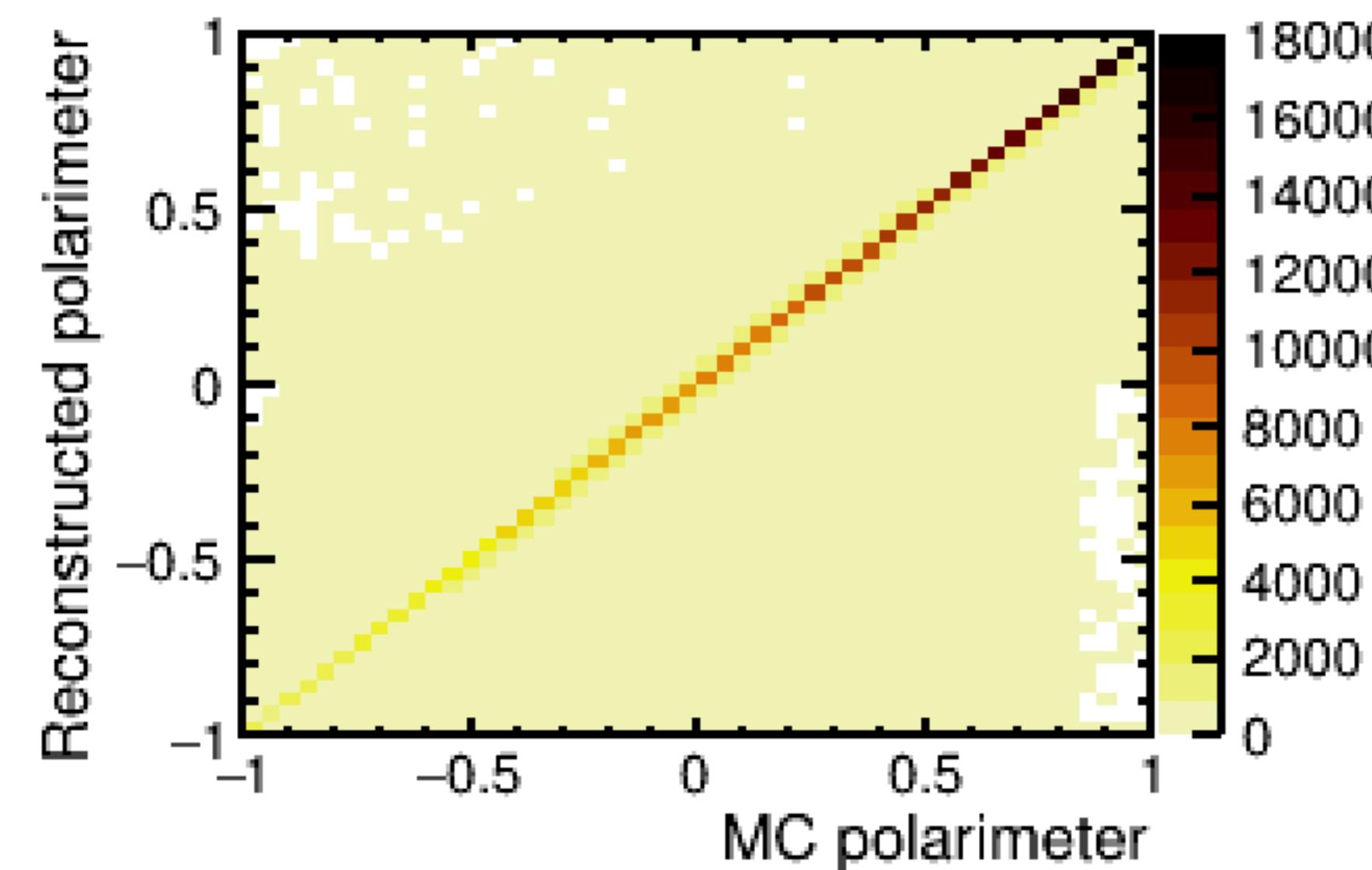
— All  
— Method worked



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

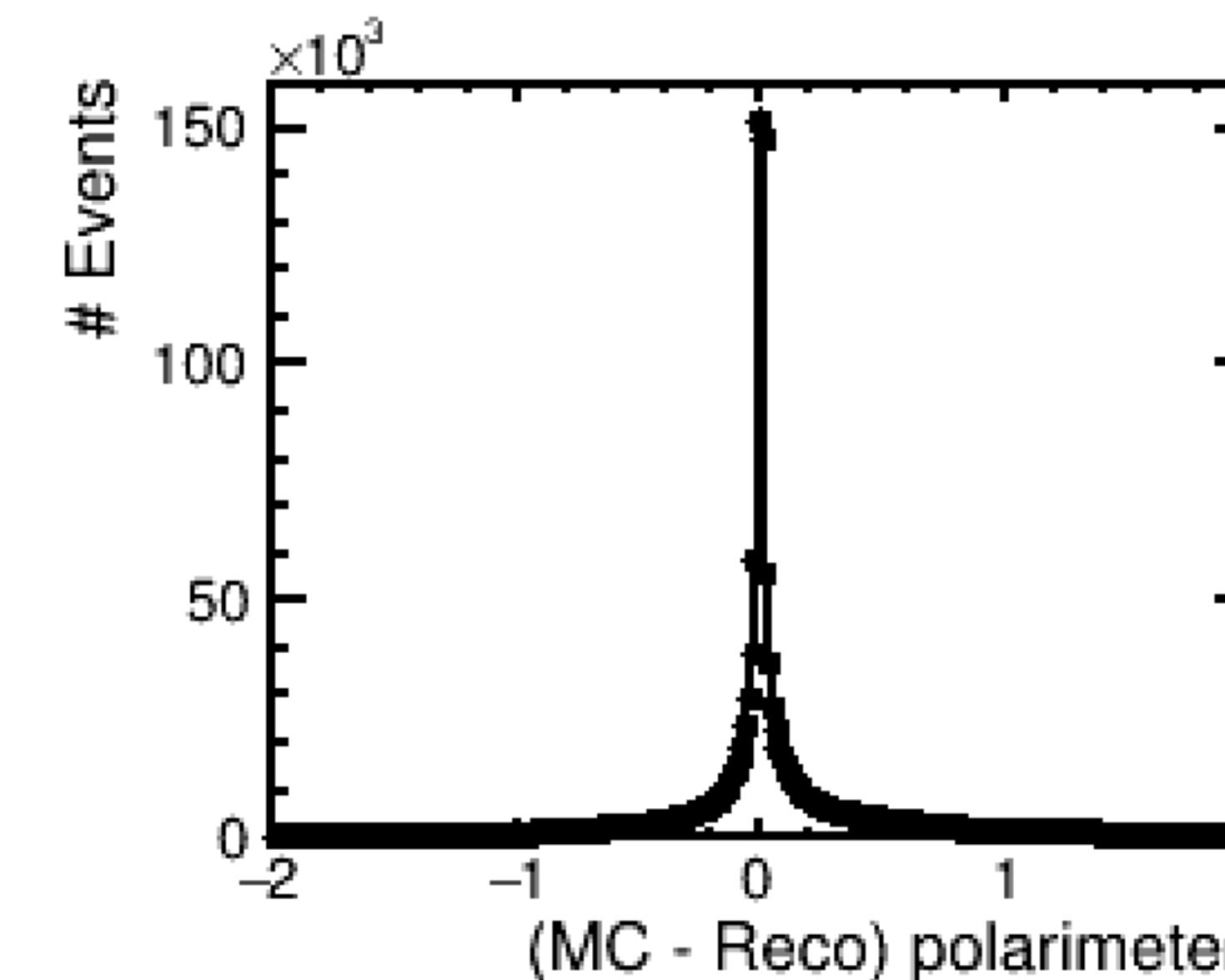
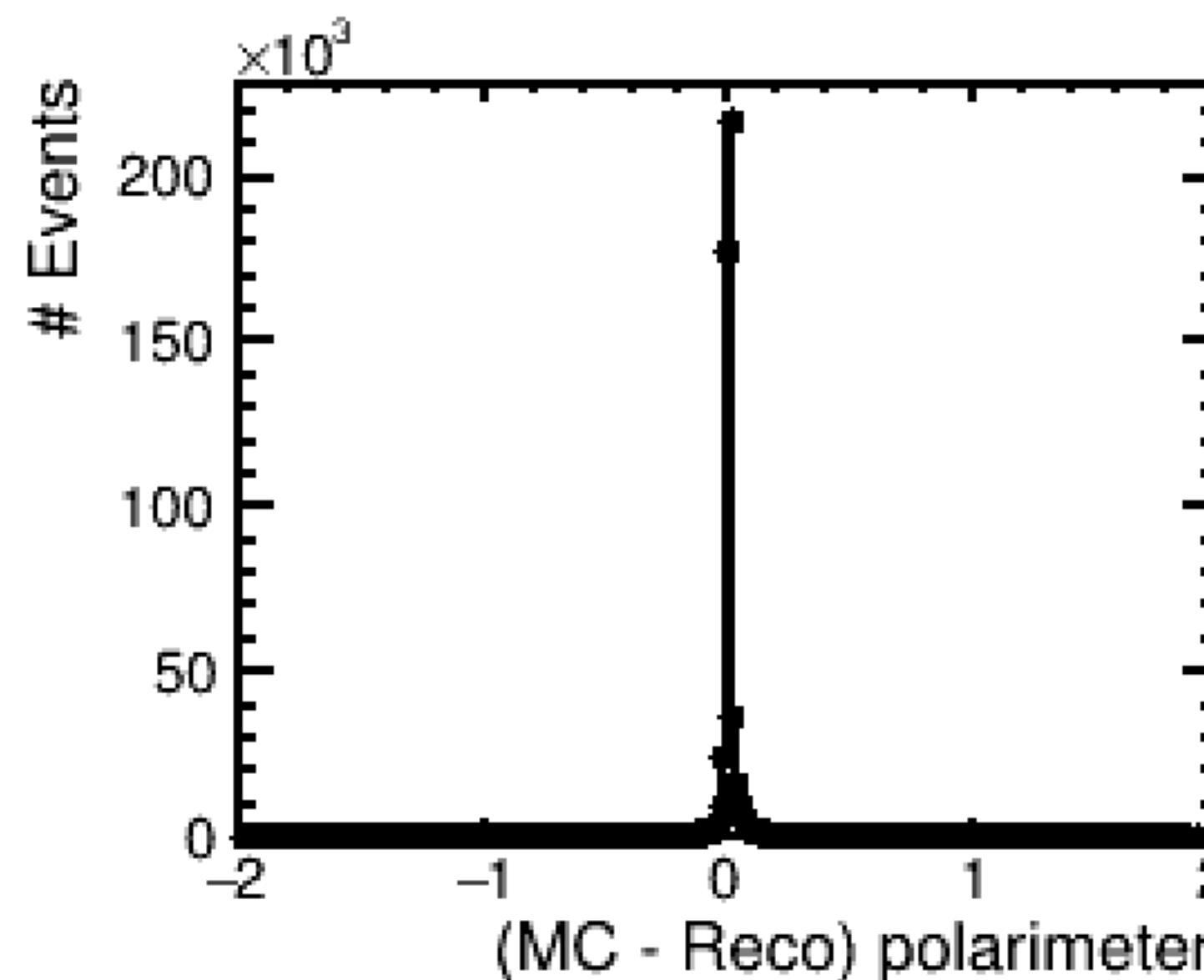
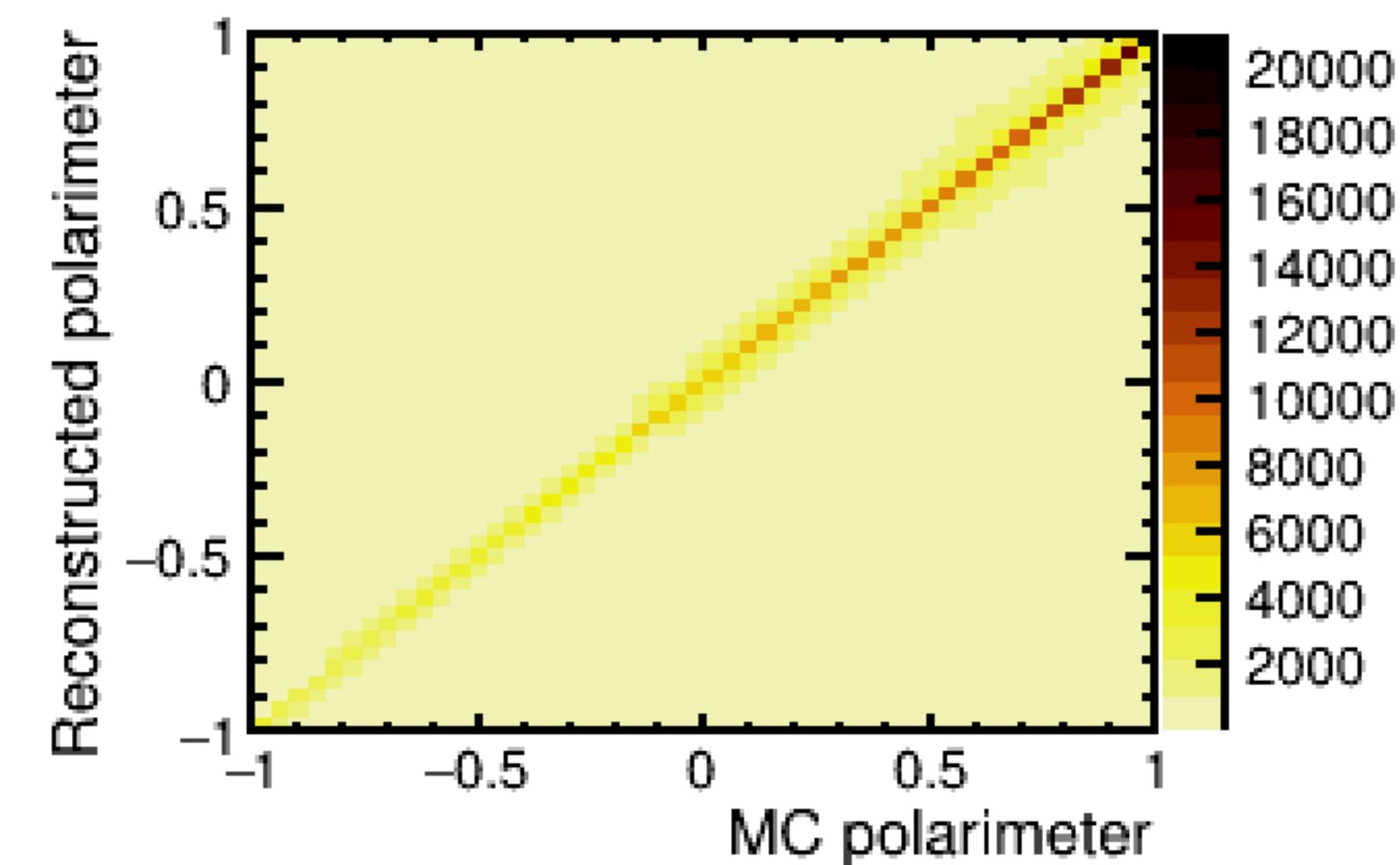
MC

$\tau \rightarrow \pi\nu$  Impact parameter method vs MC



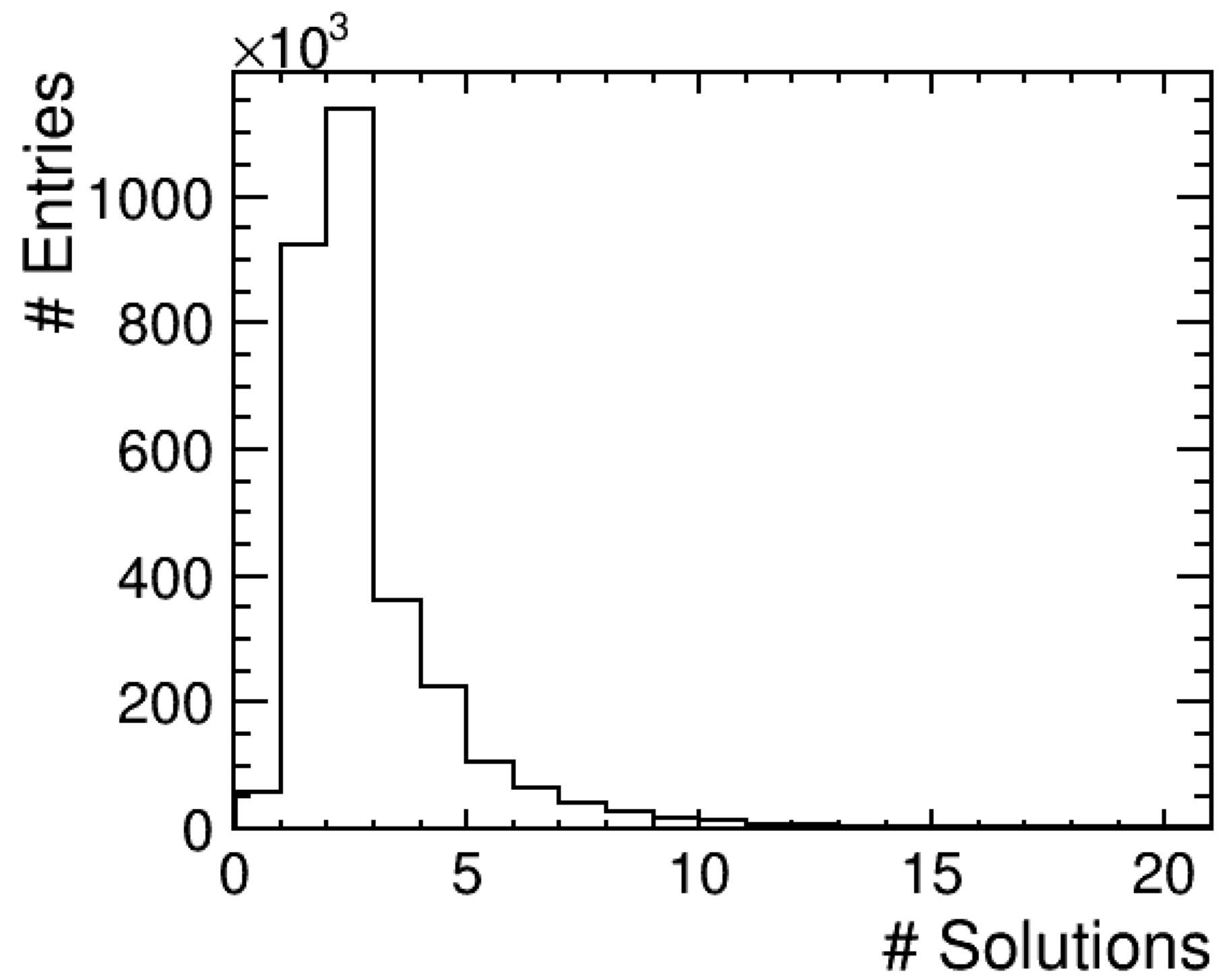
Polarimeter

$\tau \rightarrow \rho\nu$  Impact parameter method vs MC

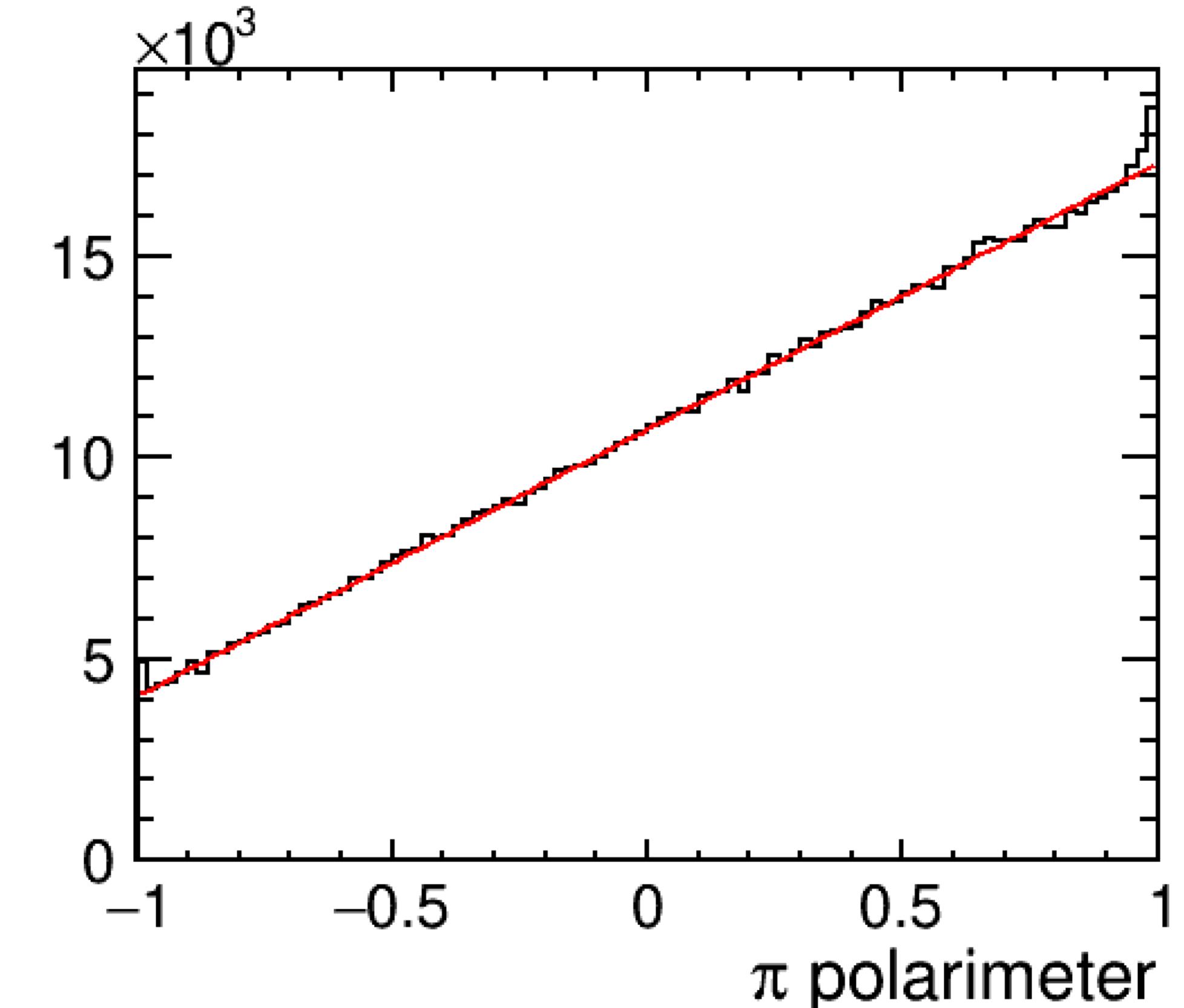


Polarimeter using reconstructed  $\nu$  is in reasonable agreement with MC one.

## Problem



We have up to 20 possible solutions per event



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

Use Jackknife method

# Jackknife method

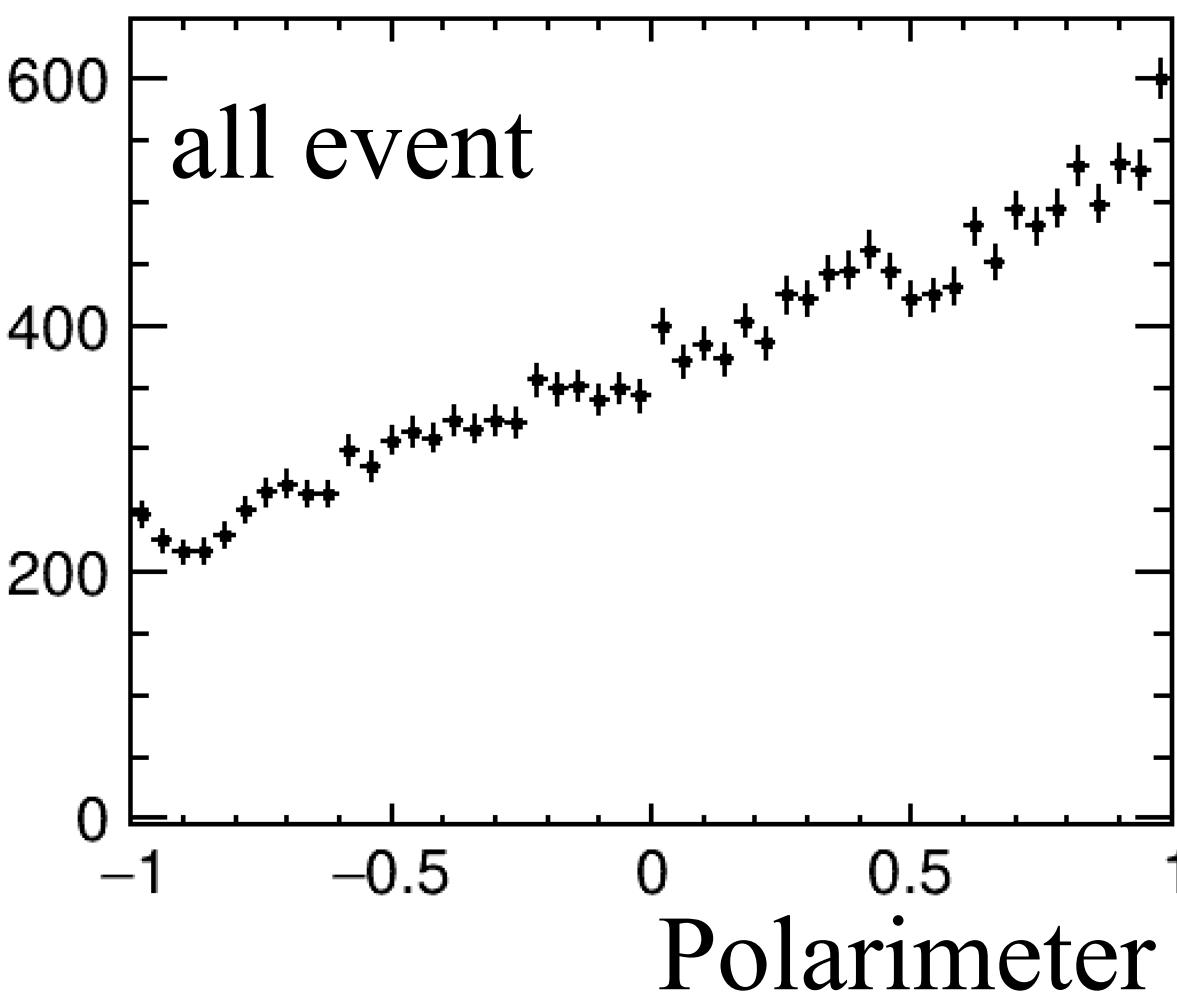
The basic idea is to calculate the estimator (e.g tau polarisation) by sequentially deleting a single event polarimeter from the sample.

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

Variation of  $n$  estimates gives

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

arXiv:1606.00497



# Jackknife method

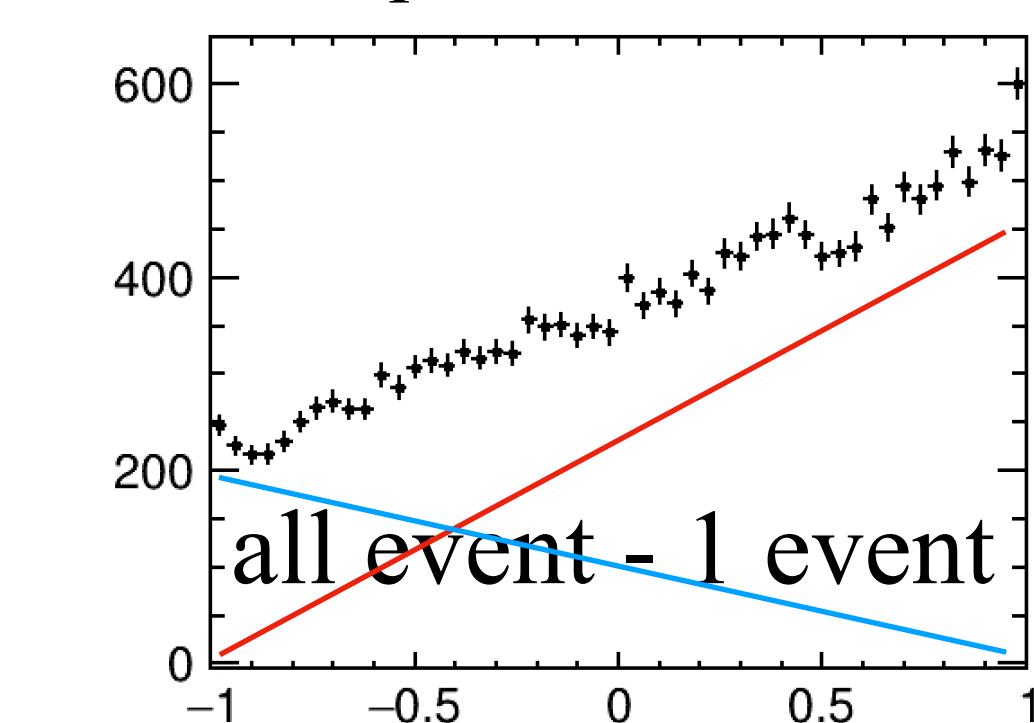
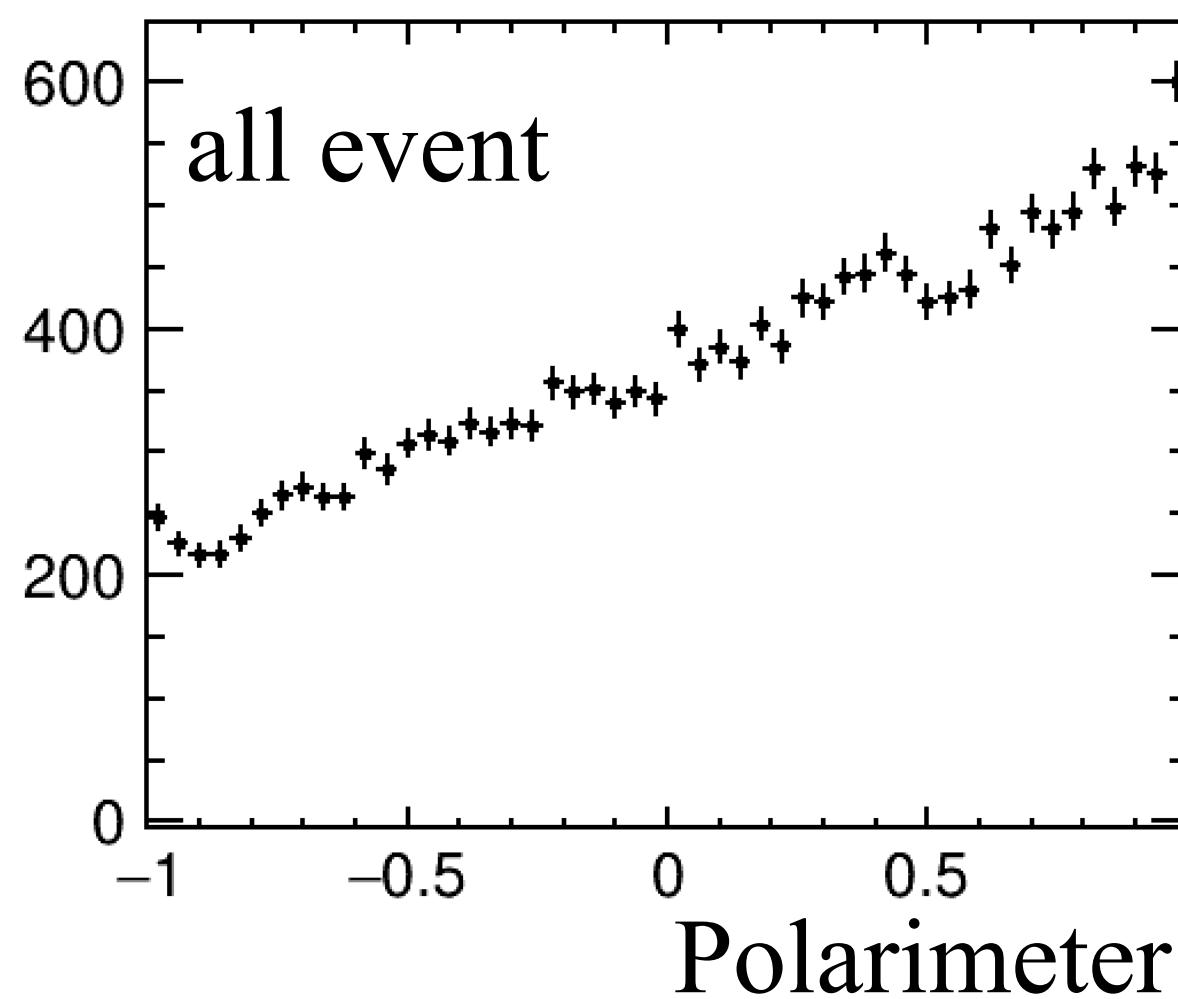
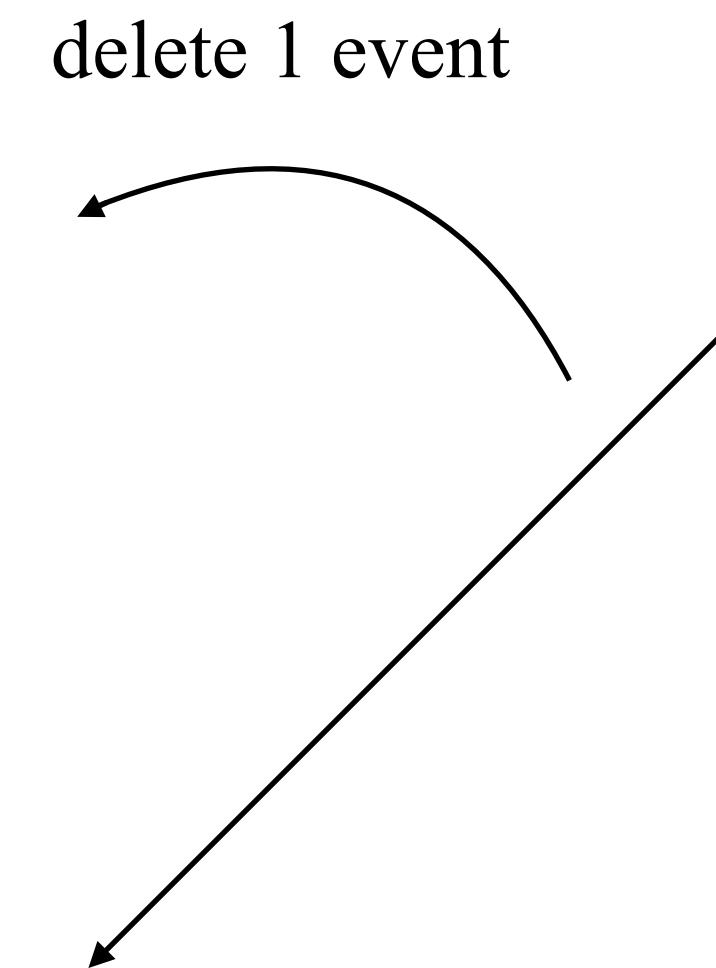
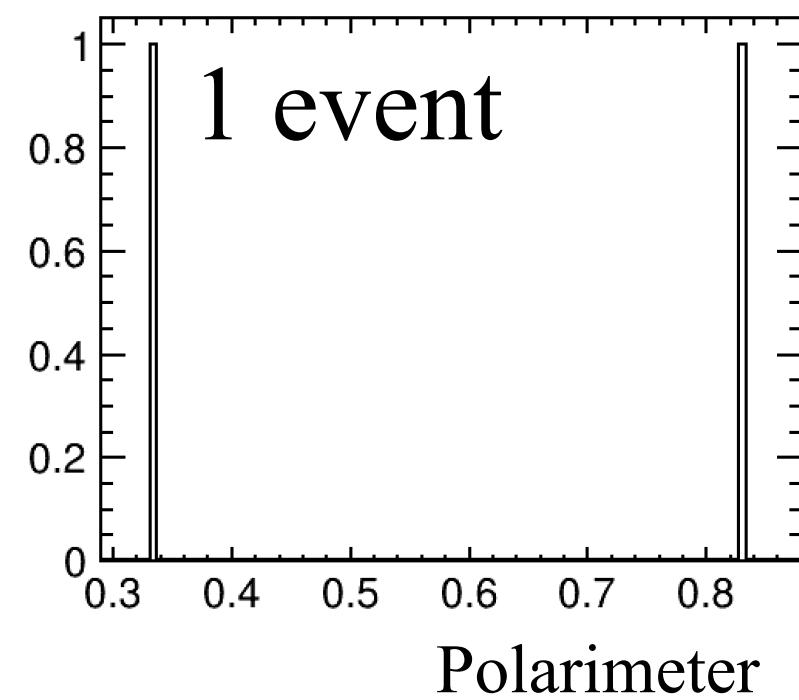
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# Jackknife method

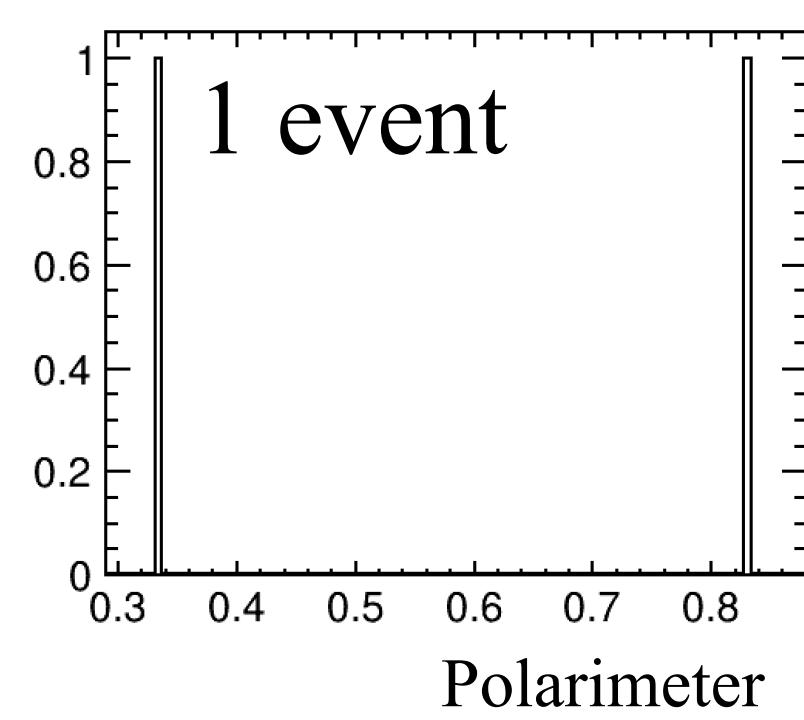
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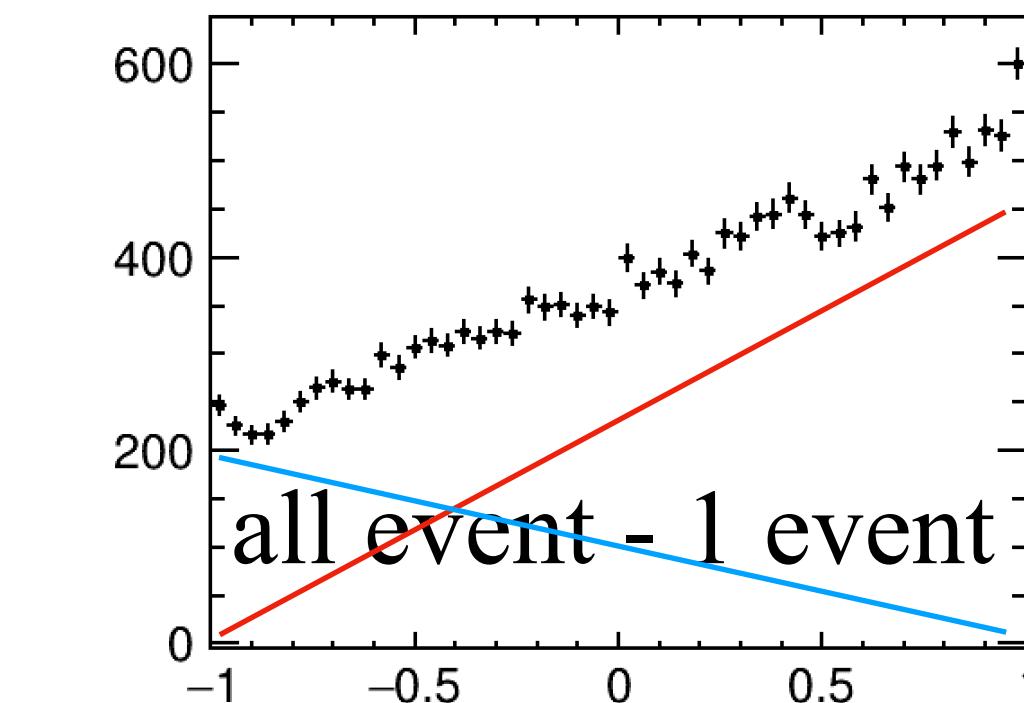
Variation of  $n$  estimates gives

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

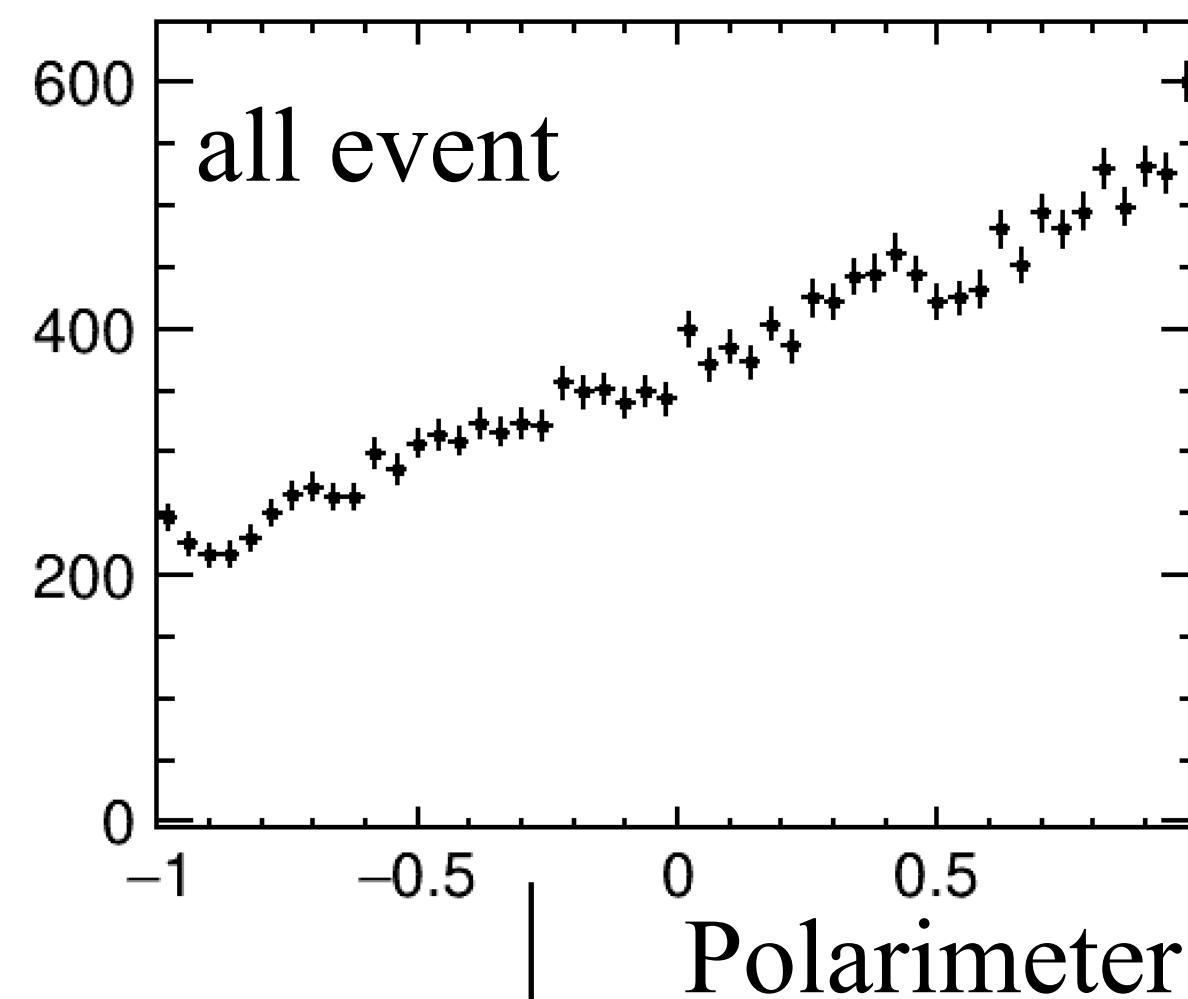
arXiv:1606.00497



delete 1 event

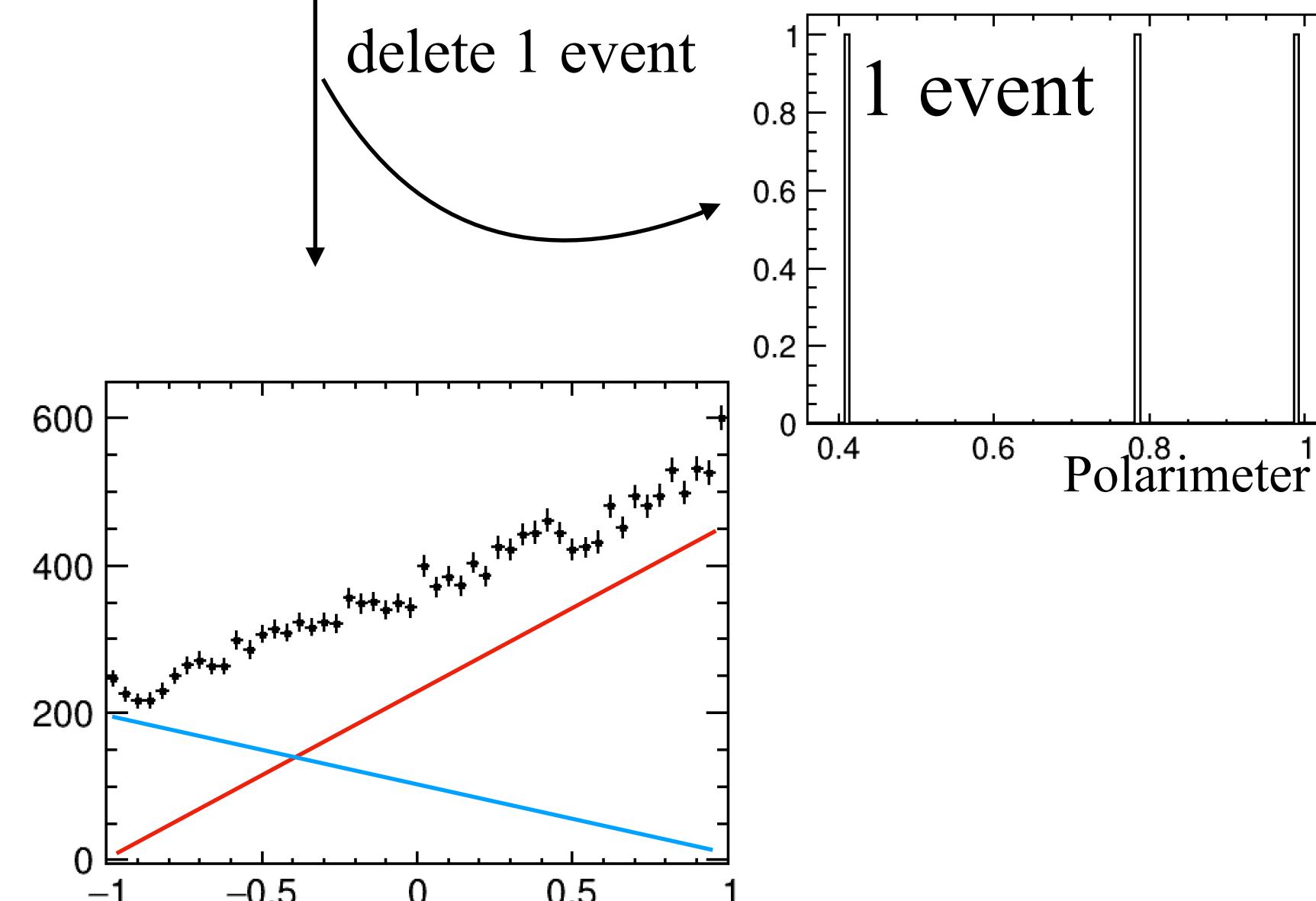


extract tau polarisation from log likelihood fit



Polarimeter

delete 1 event



Polarimeter

# Jackknife method

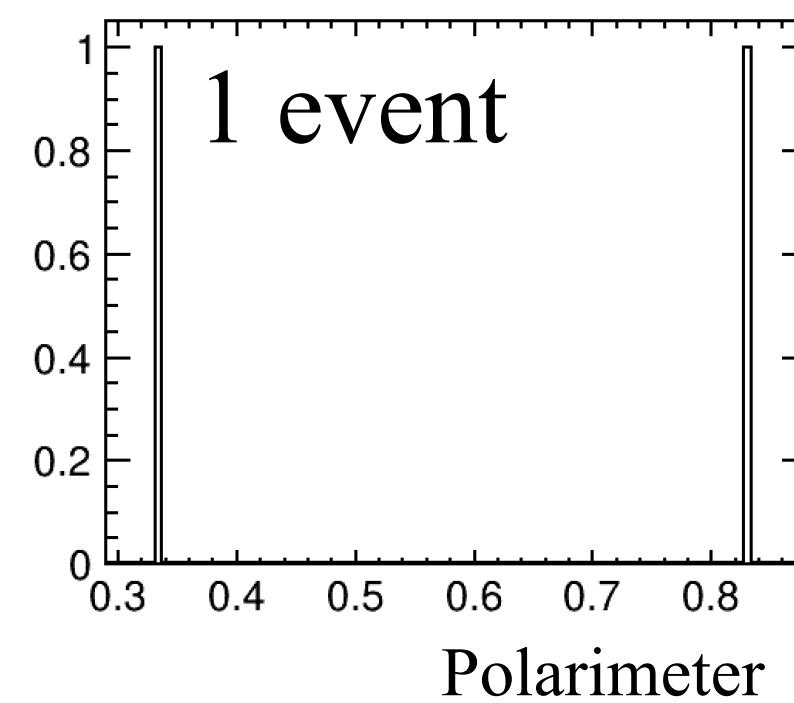
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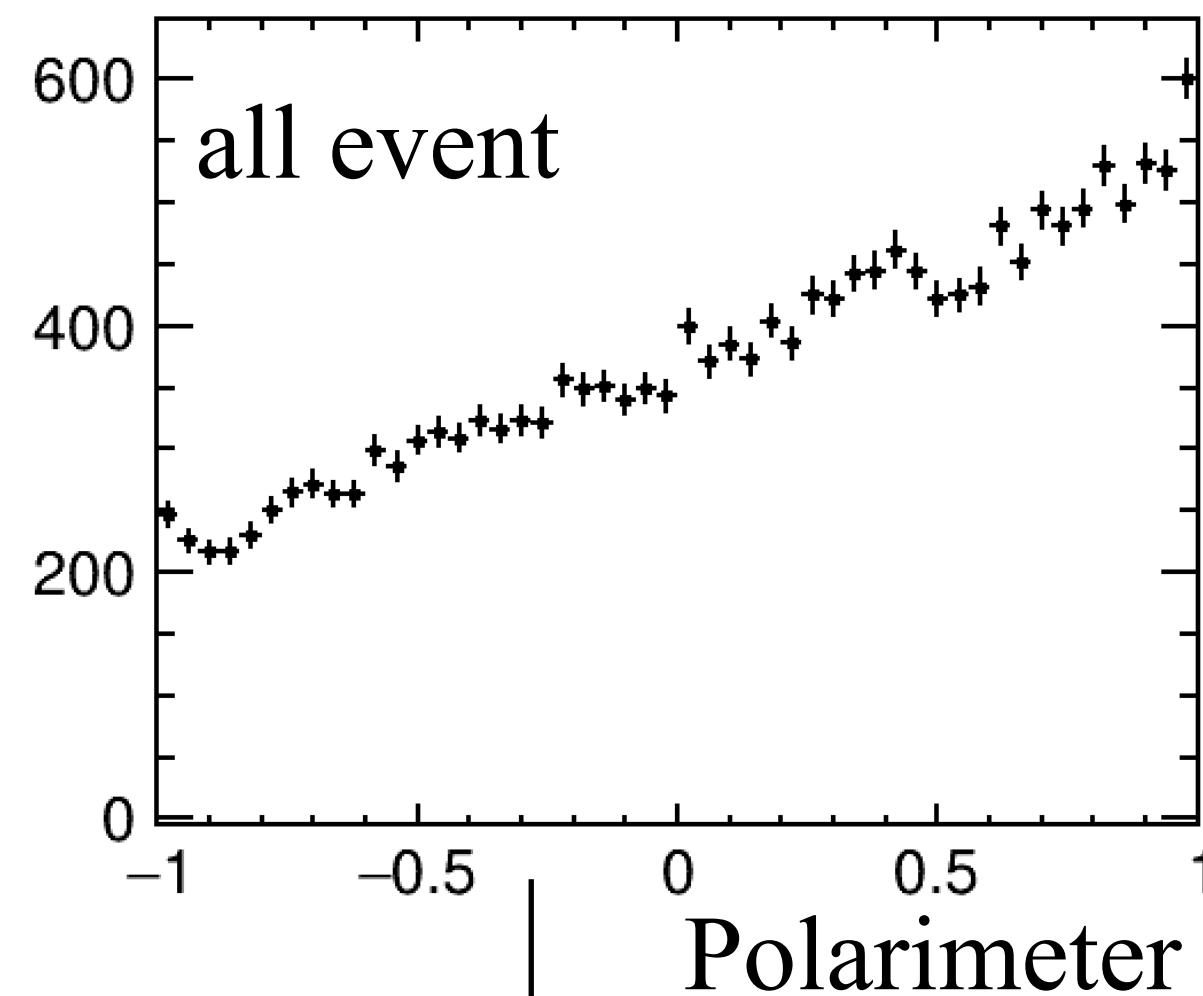
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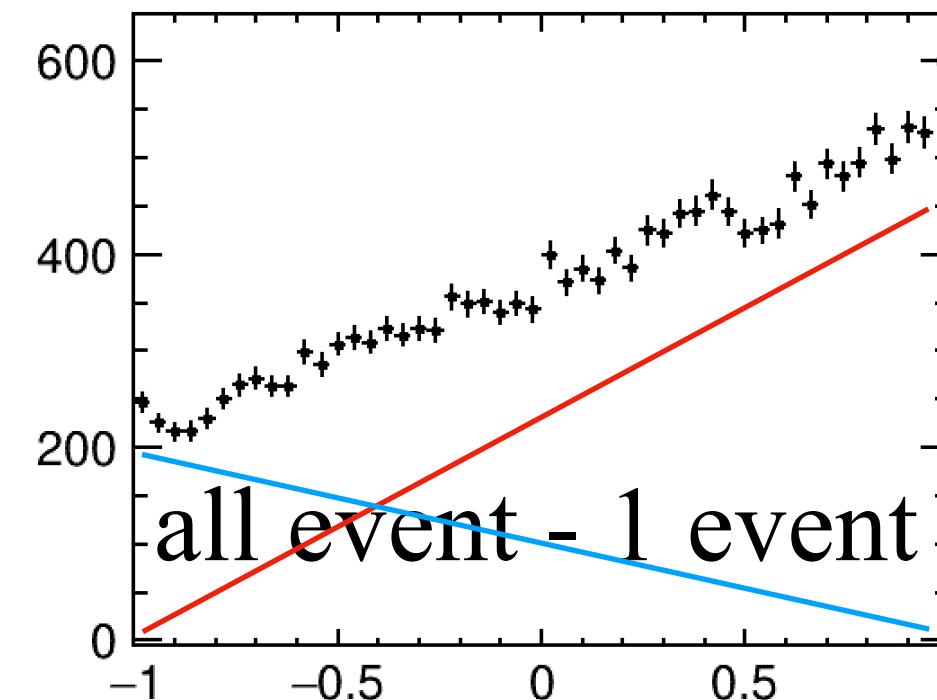
arXiv:1606.00497



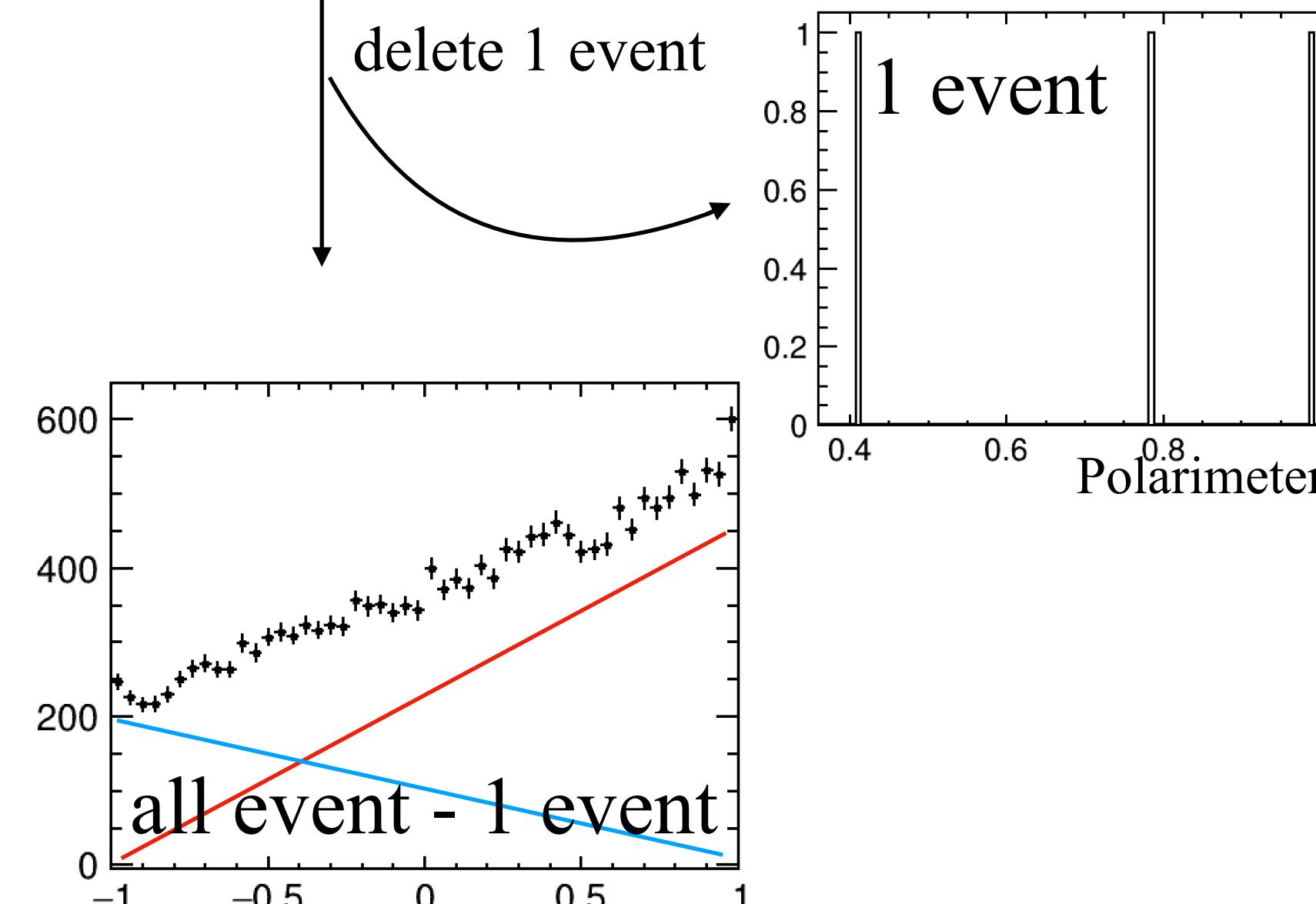
delete 1 event



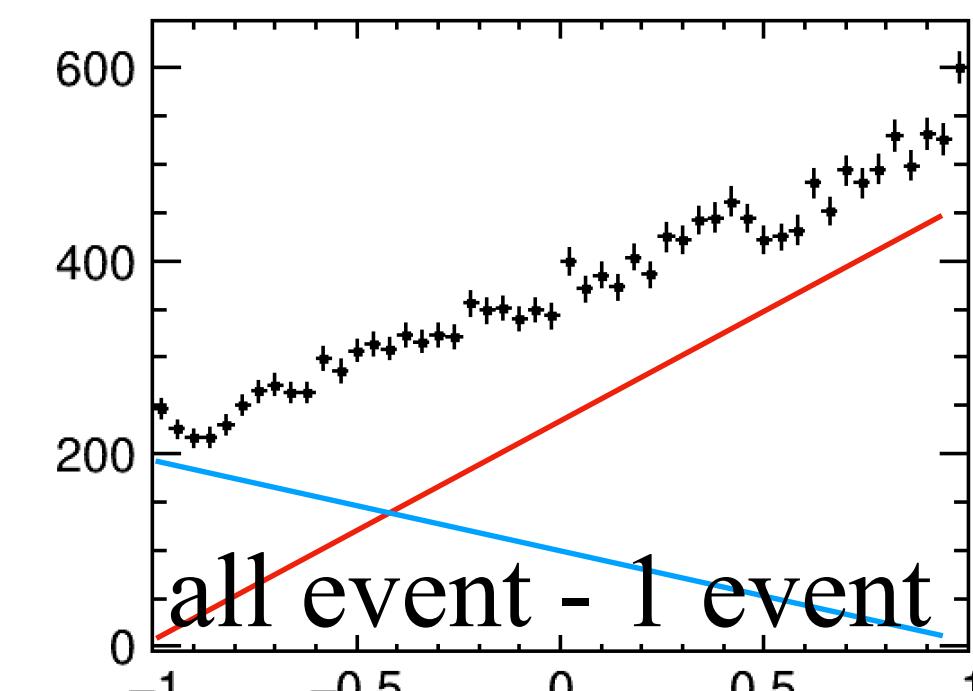
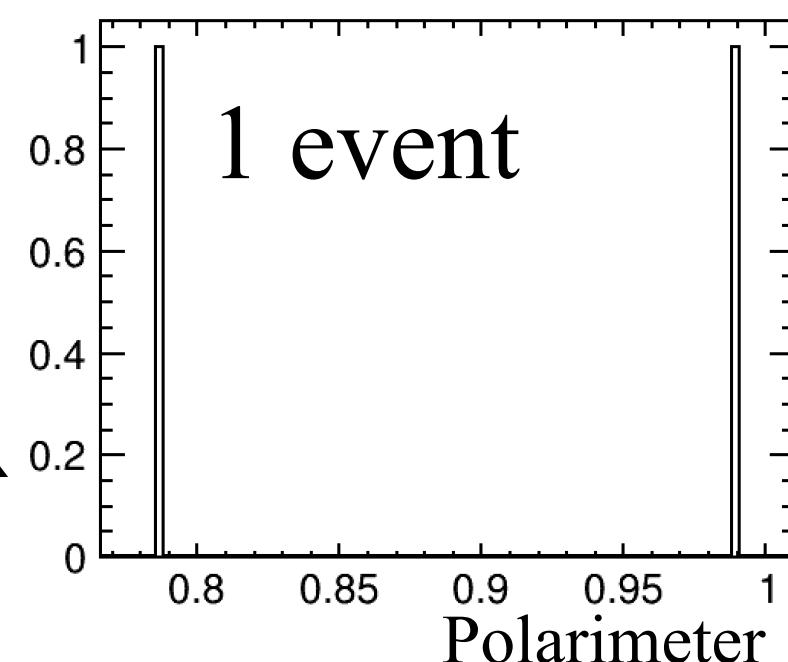
Extract tau polarisation from log likelihood fit



delete 1 event

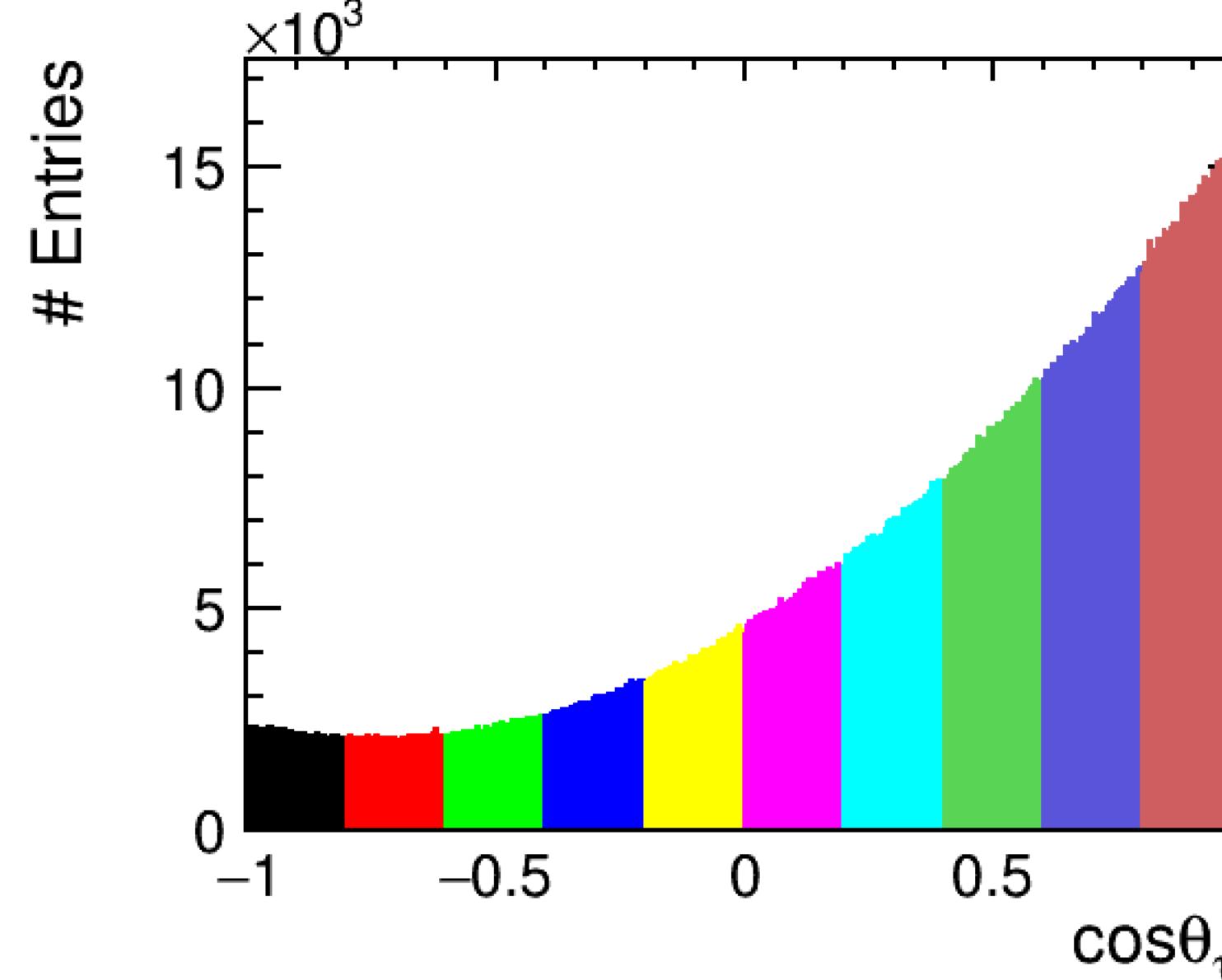


delete 1 event



# Method Calibration

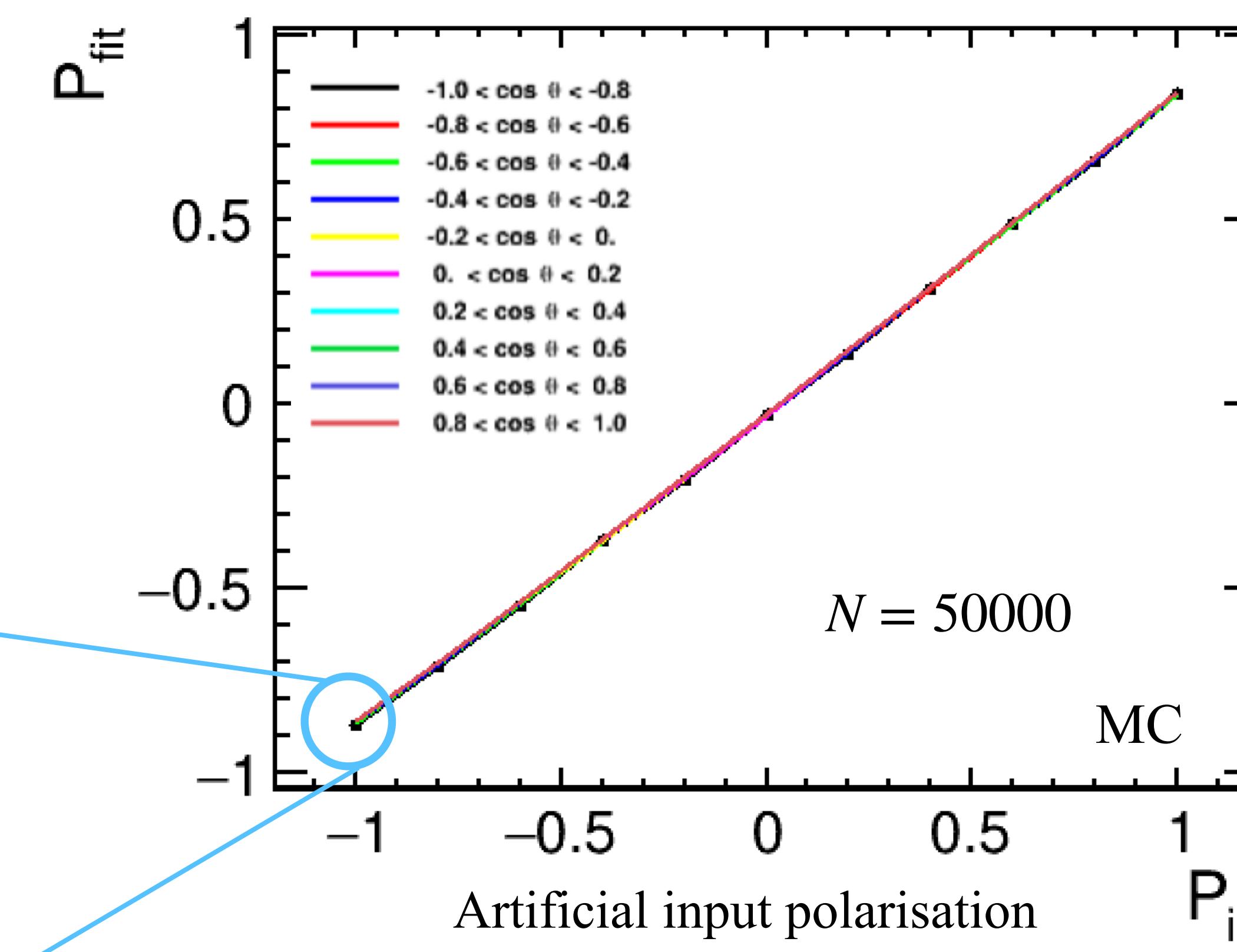
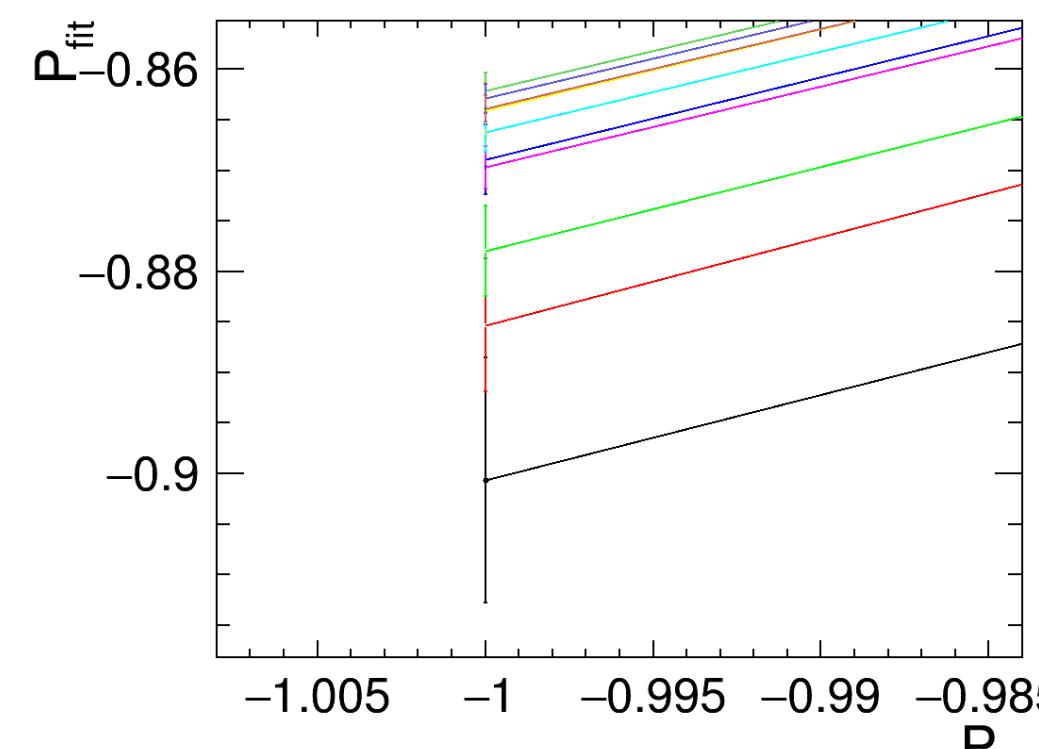
To check the bias, an artificial polarisation was created by changing the ratio of  $N_R$  and  $N_L$  to calculate  $P_{fit}$



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

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

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



Errors from Jackknife method

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

# Summary

- Full reconstruction of  $e^+e^- \rightarrow \tau^+\tau^-$  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  $\sim 250$  GeV, new method efficiency is  $> 90\%$

- Polarimeters were reconstructed in the  $\tau \rightarrow \pi\nu$  and  $\tau \rightarrow \rho\nu$  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.

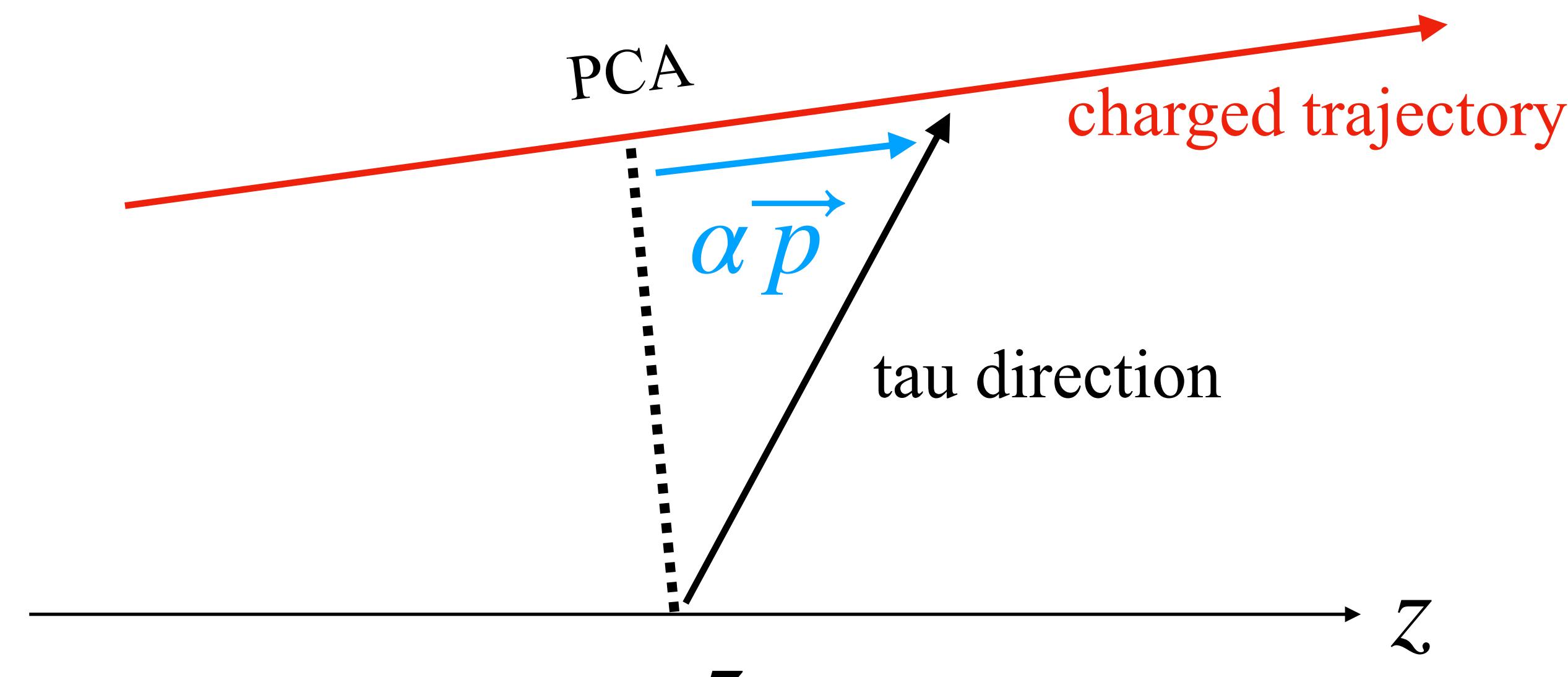
## Future plan

- Quantify the precision with which the tau polarisation can be measured at ILC-250.
- Investigate search for new physics by using the tau polarisation.



# $\tau$ reconstruction method

We have tried another method

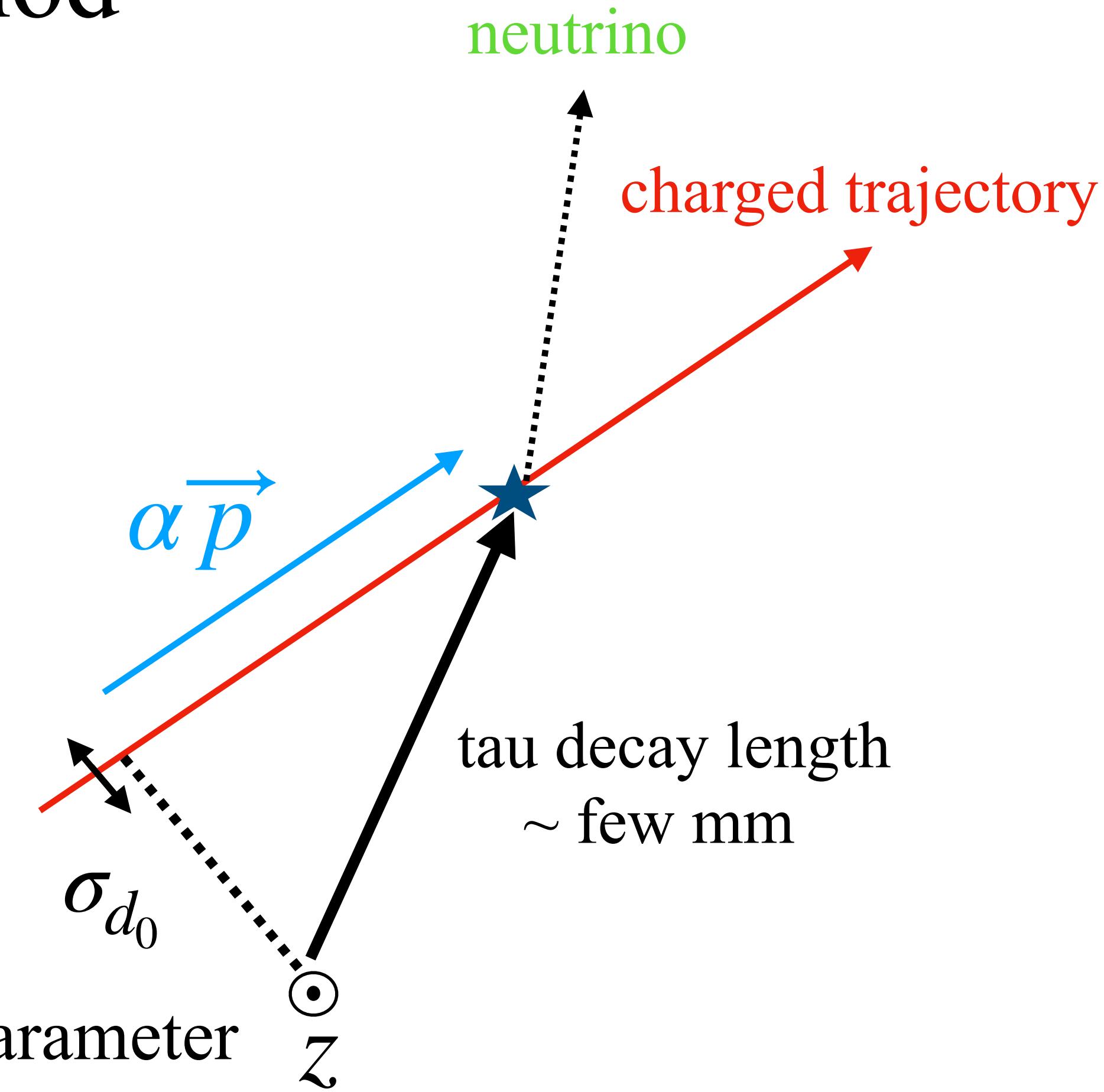


$\vec{p}$  : unit vector

$\alpha$  : real number

expected impact parameter  
resolution  $\sim$  few um

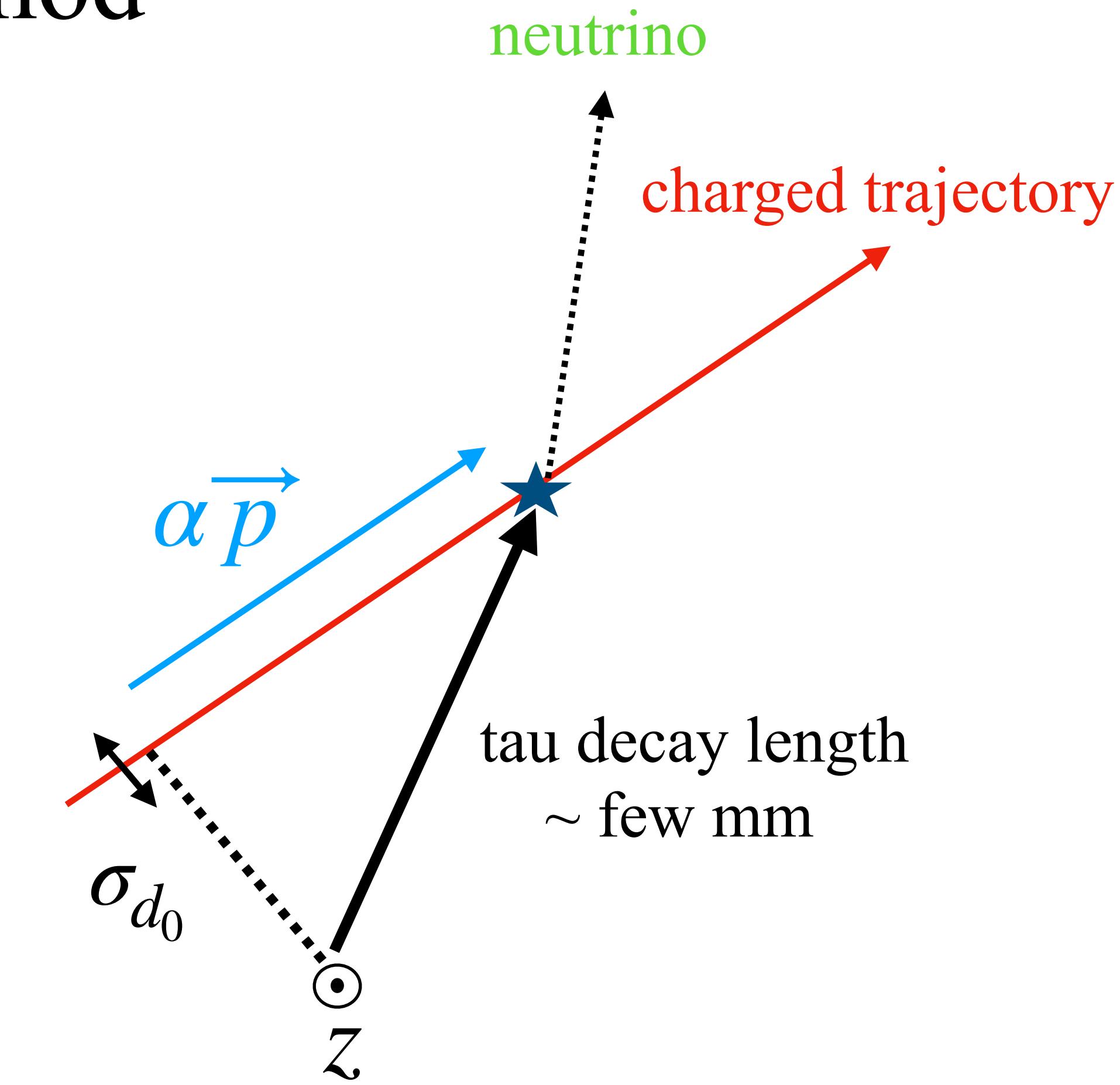
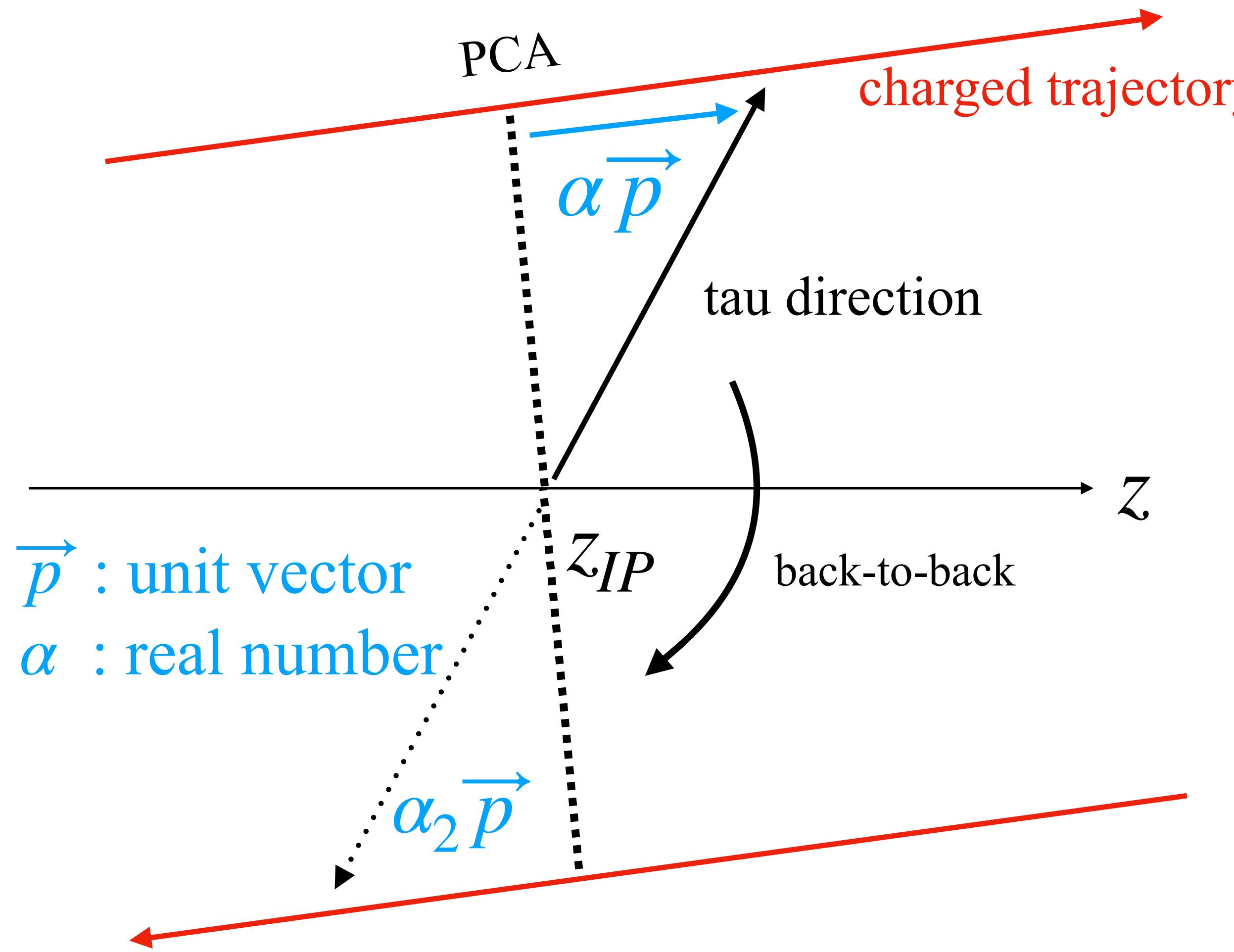
$$(\phi, z_{IP}) \rightarrow (\alpha, z_{IP})$$



tau decay length  
 $\sim$  few mm

# $\tau$ reconstruction method

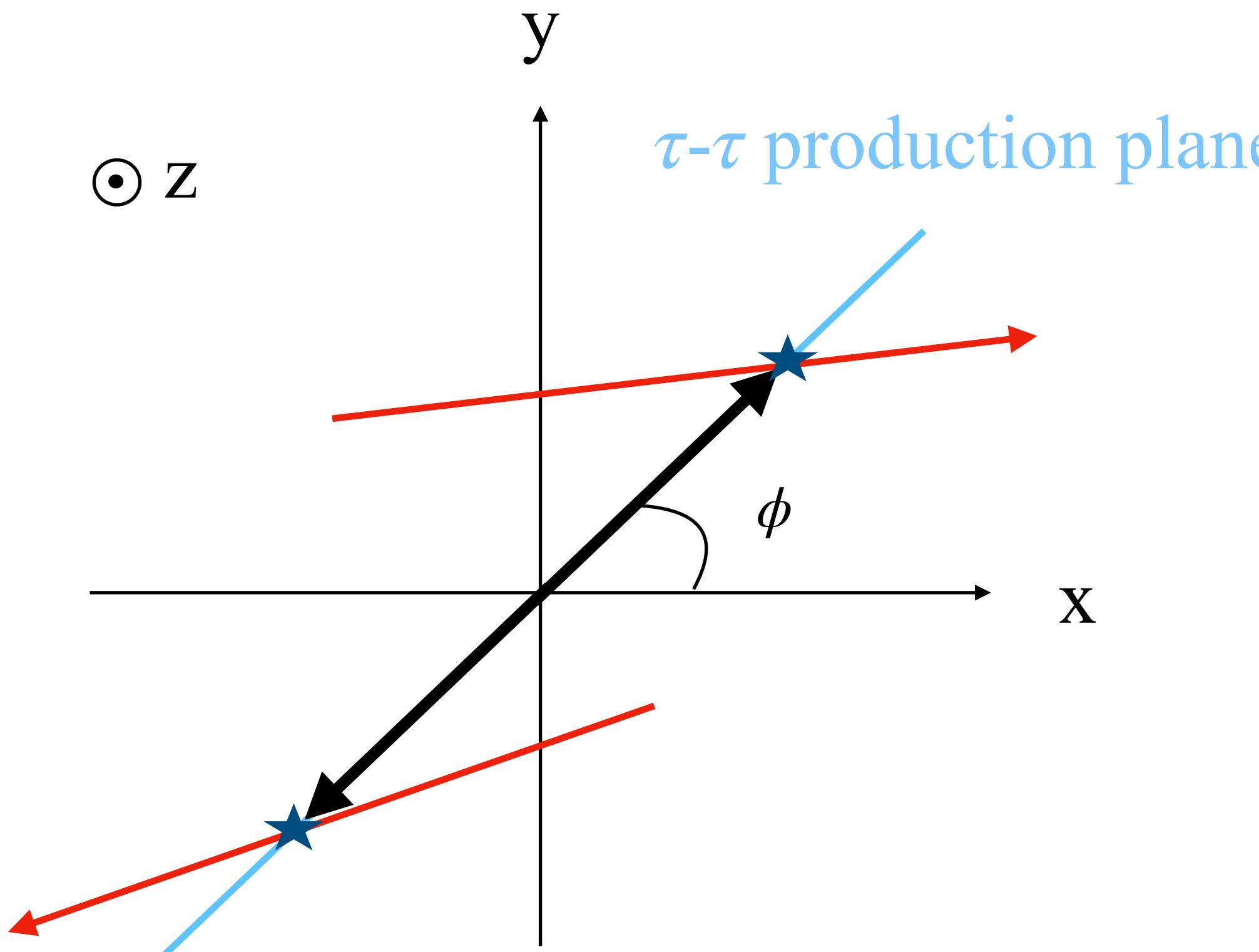
We have tried another method



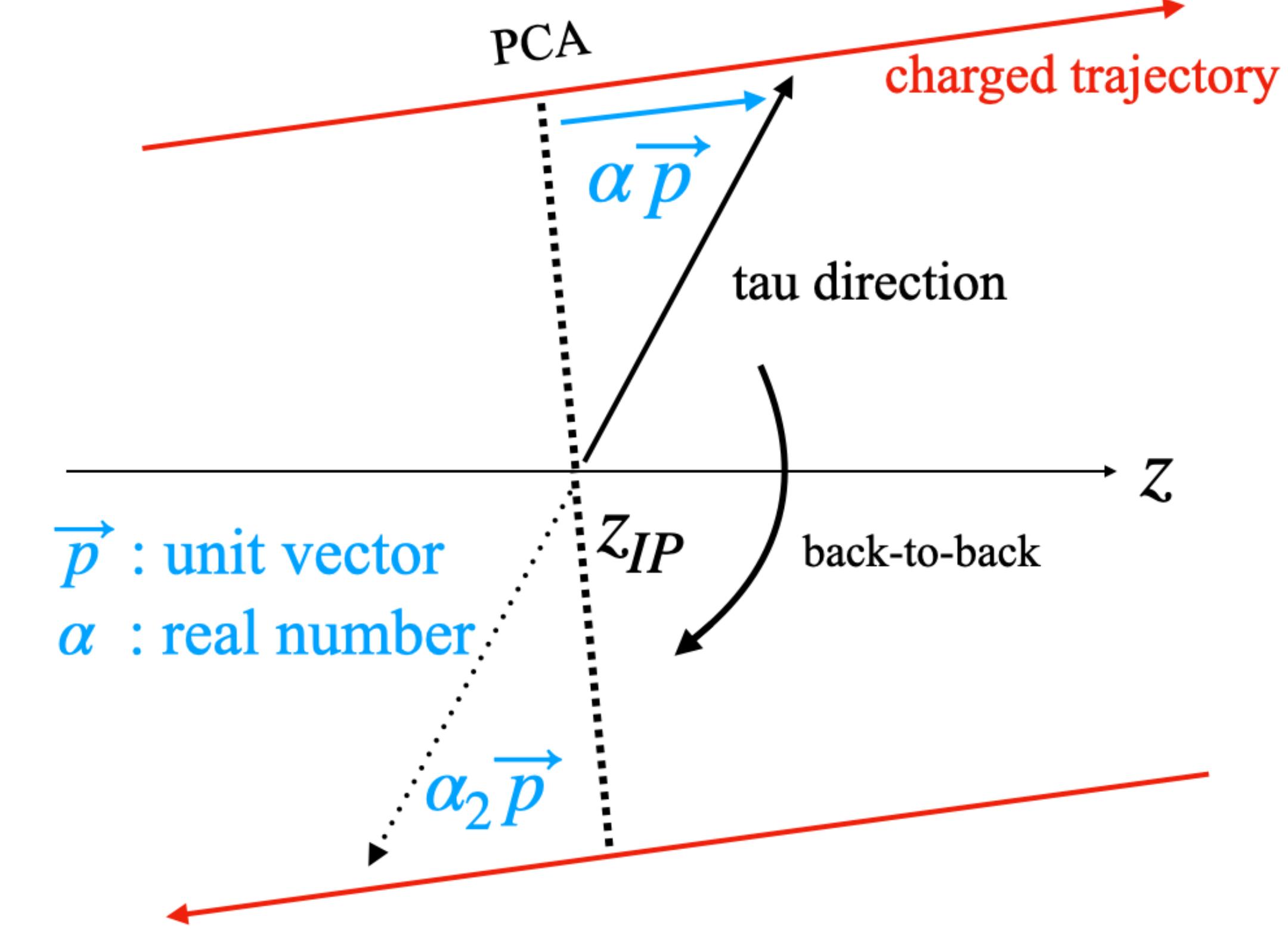
$\alpha_2$  can be calculated by imposing back-to-back-ness in the x-y projection

# $\tau$ reconstruction method

Two methods to find solutions



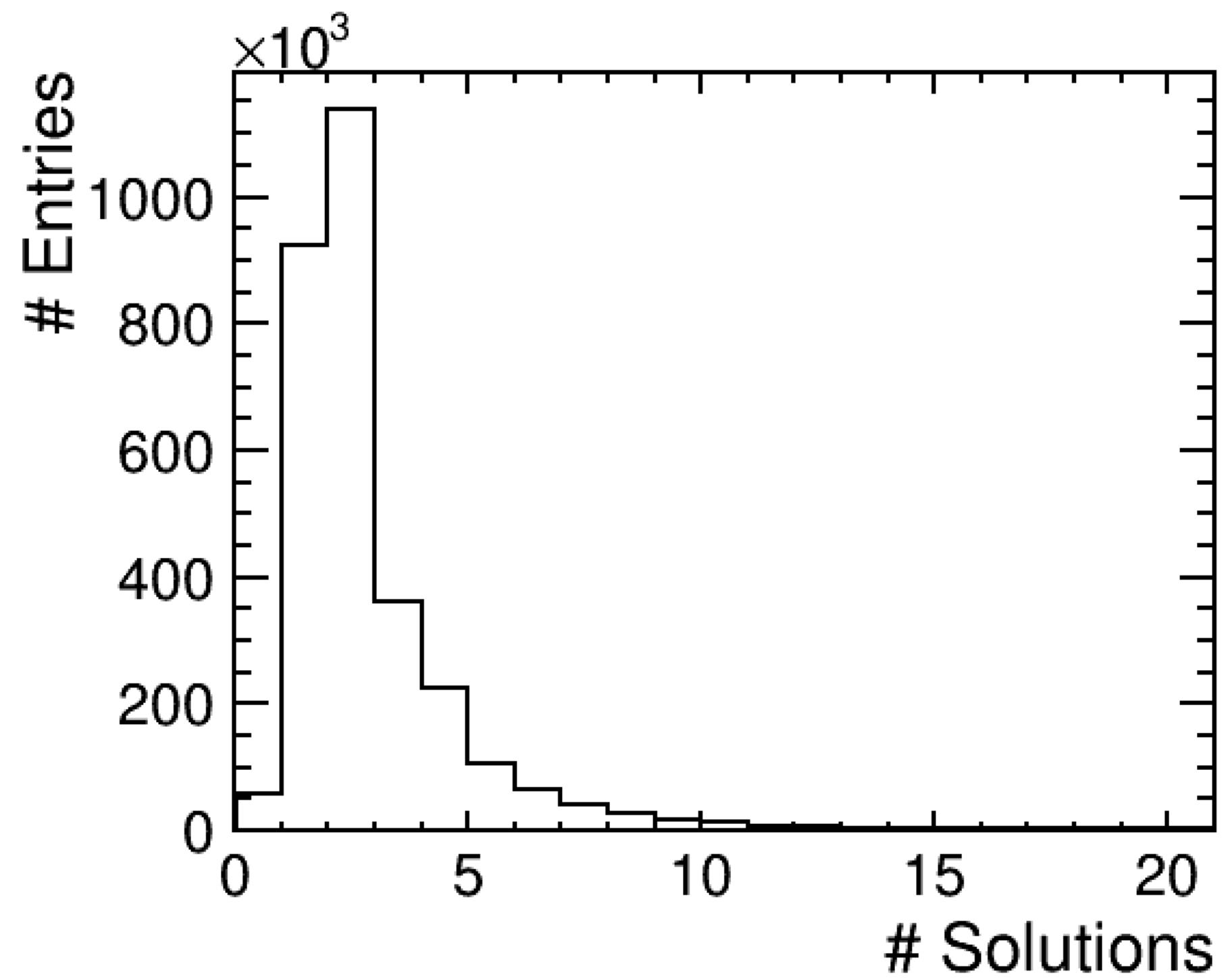
$(\phi, z_{IP})$  : unknown



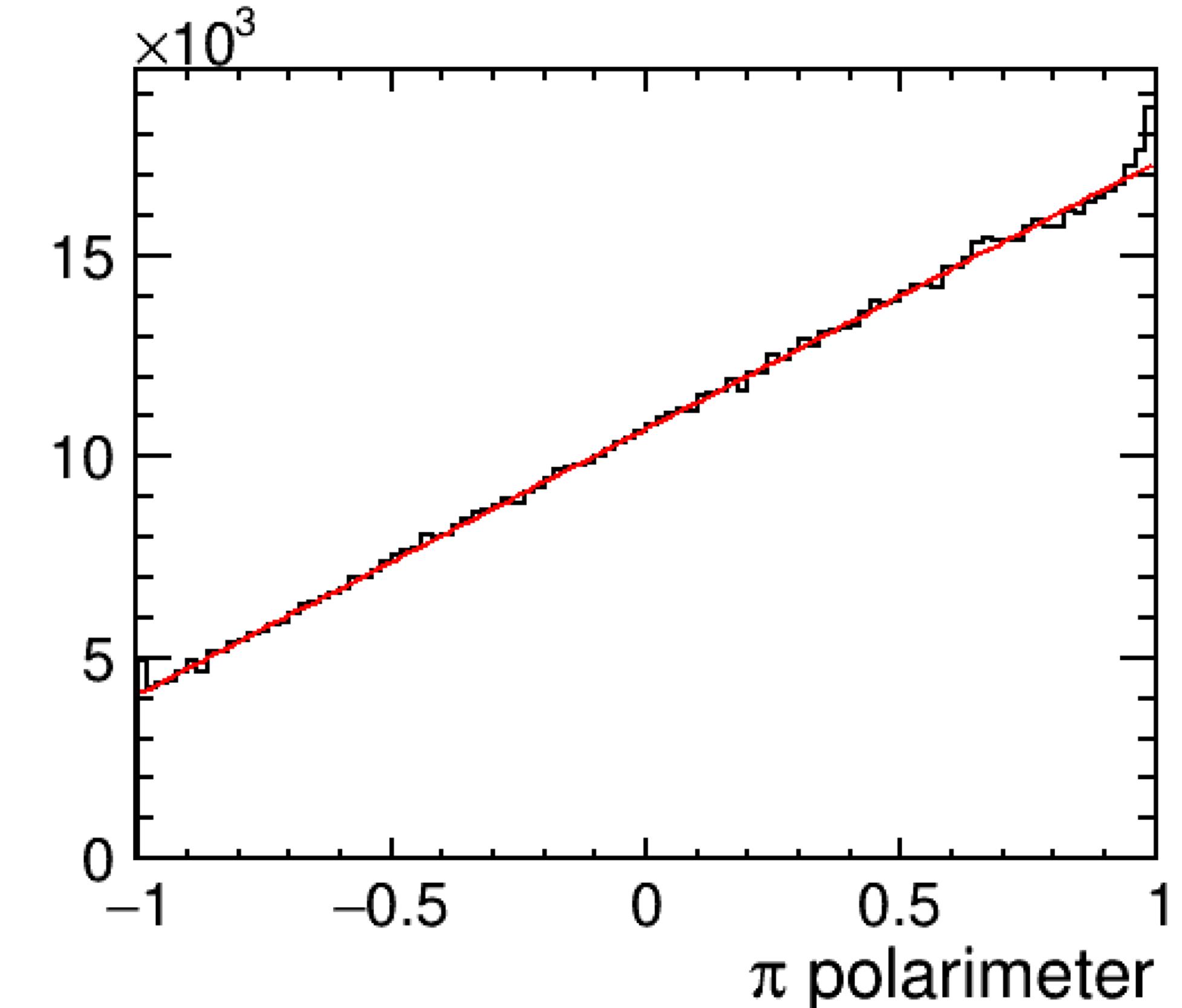
$(\alpha, z_{IP})$  : unknown

We have combined them

## Problem

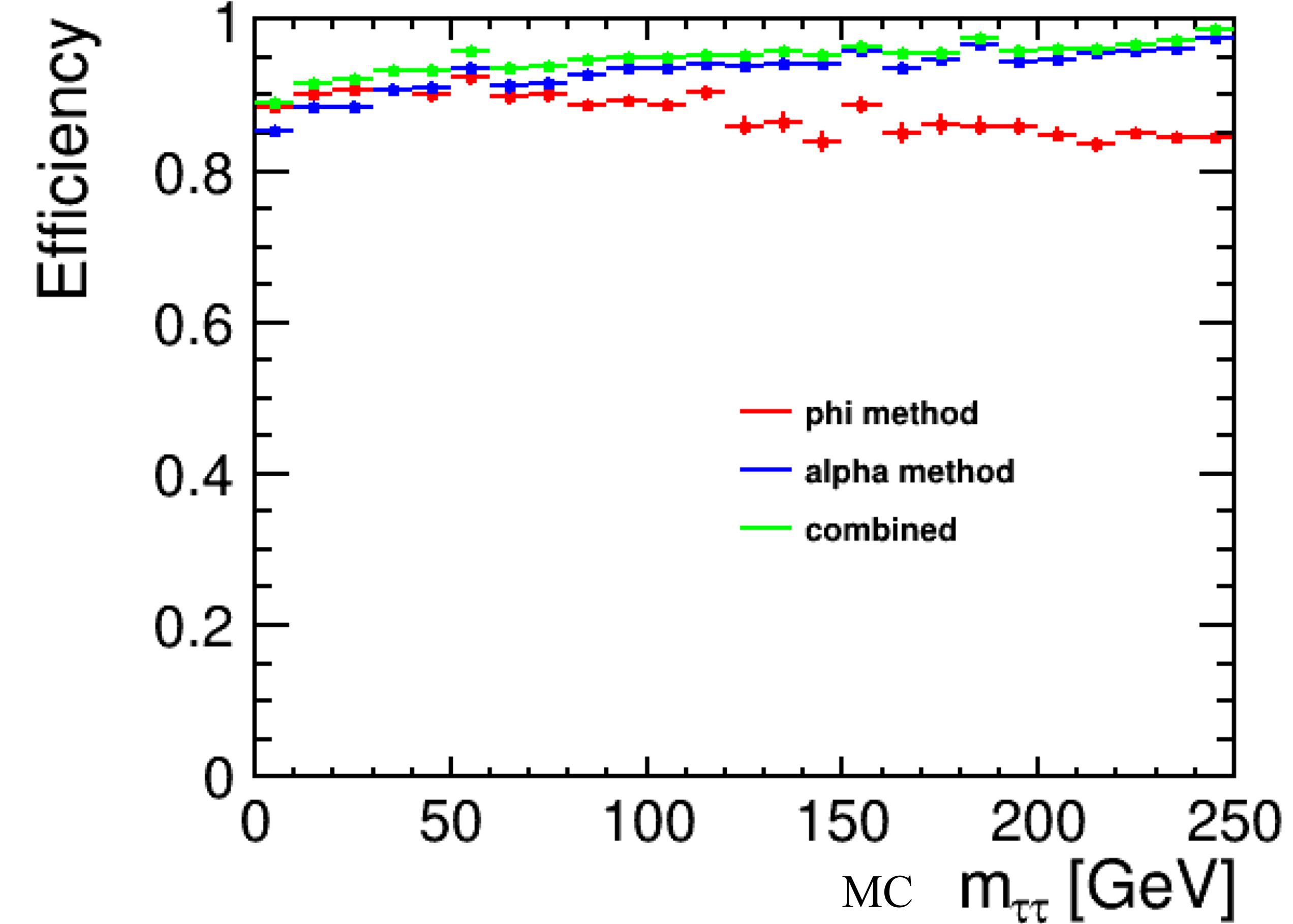
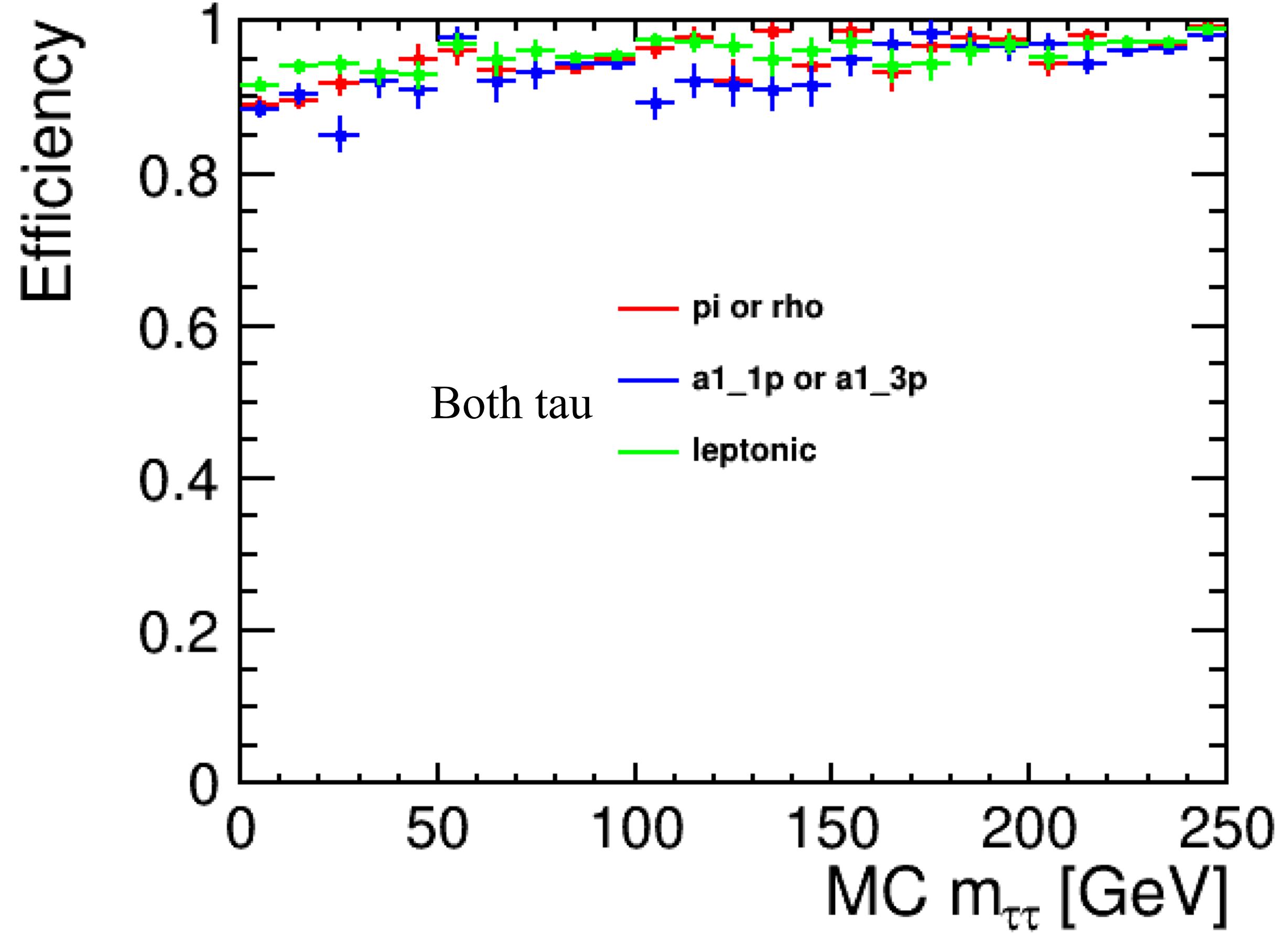


We have up to 20 possible solutions per event

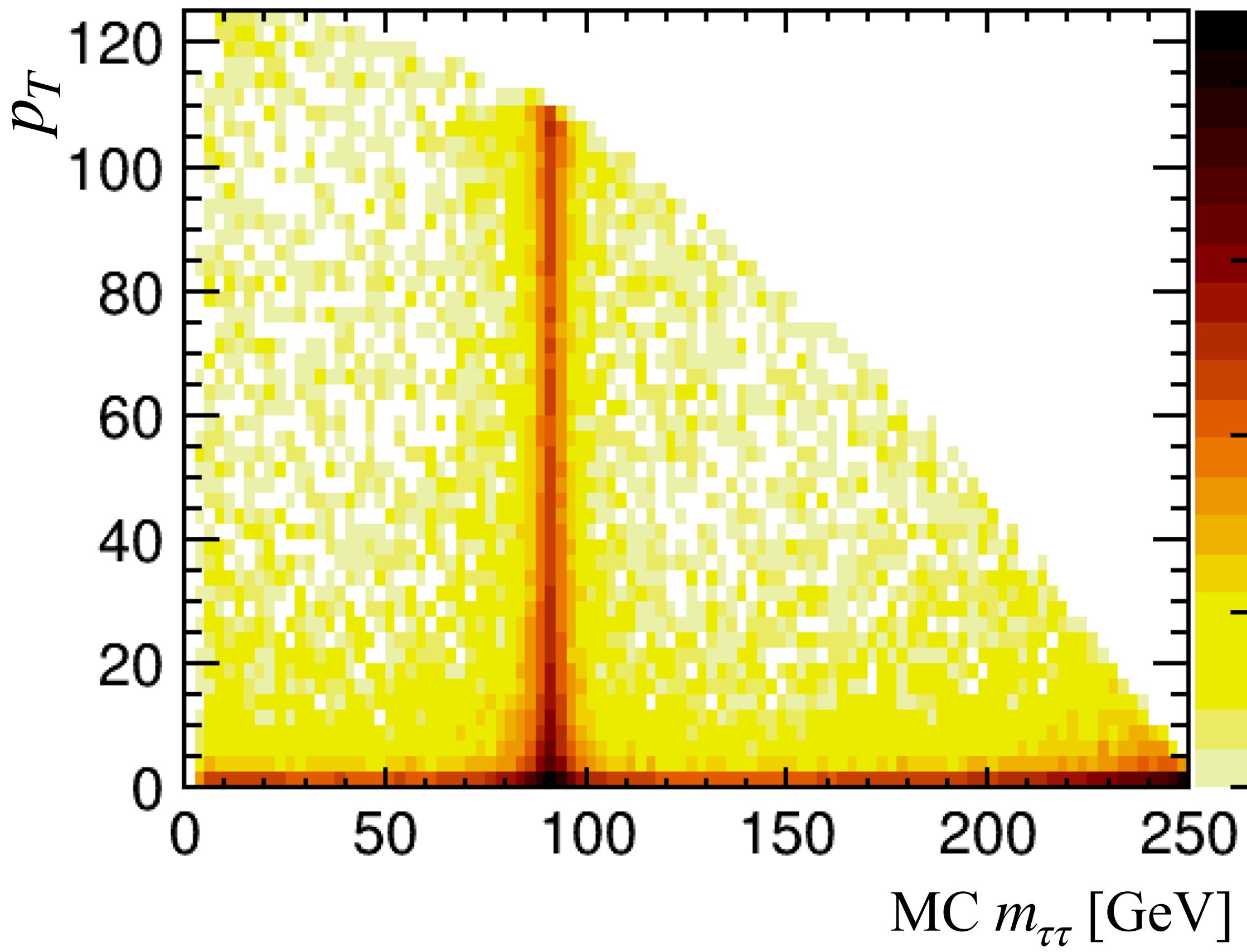


Some entries per event  
=> we cannot trust the statistical errors from simple fit

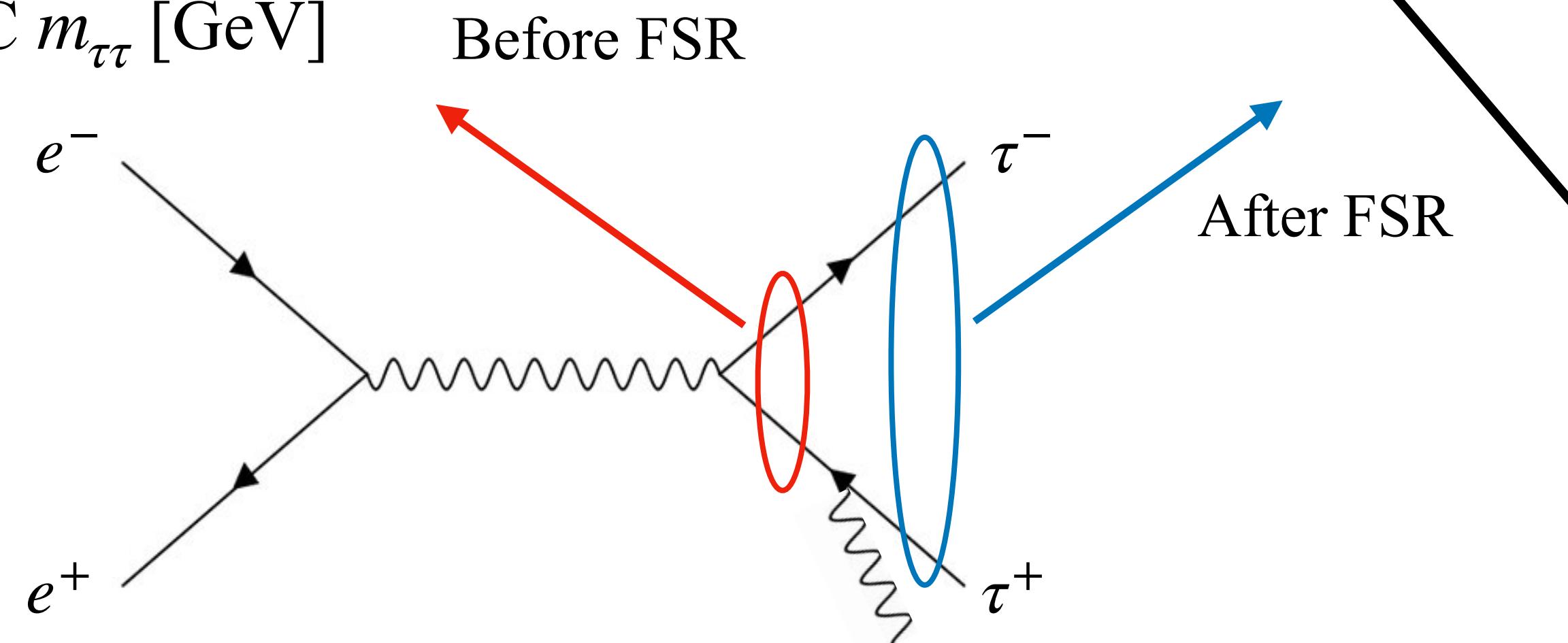
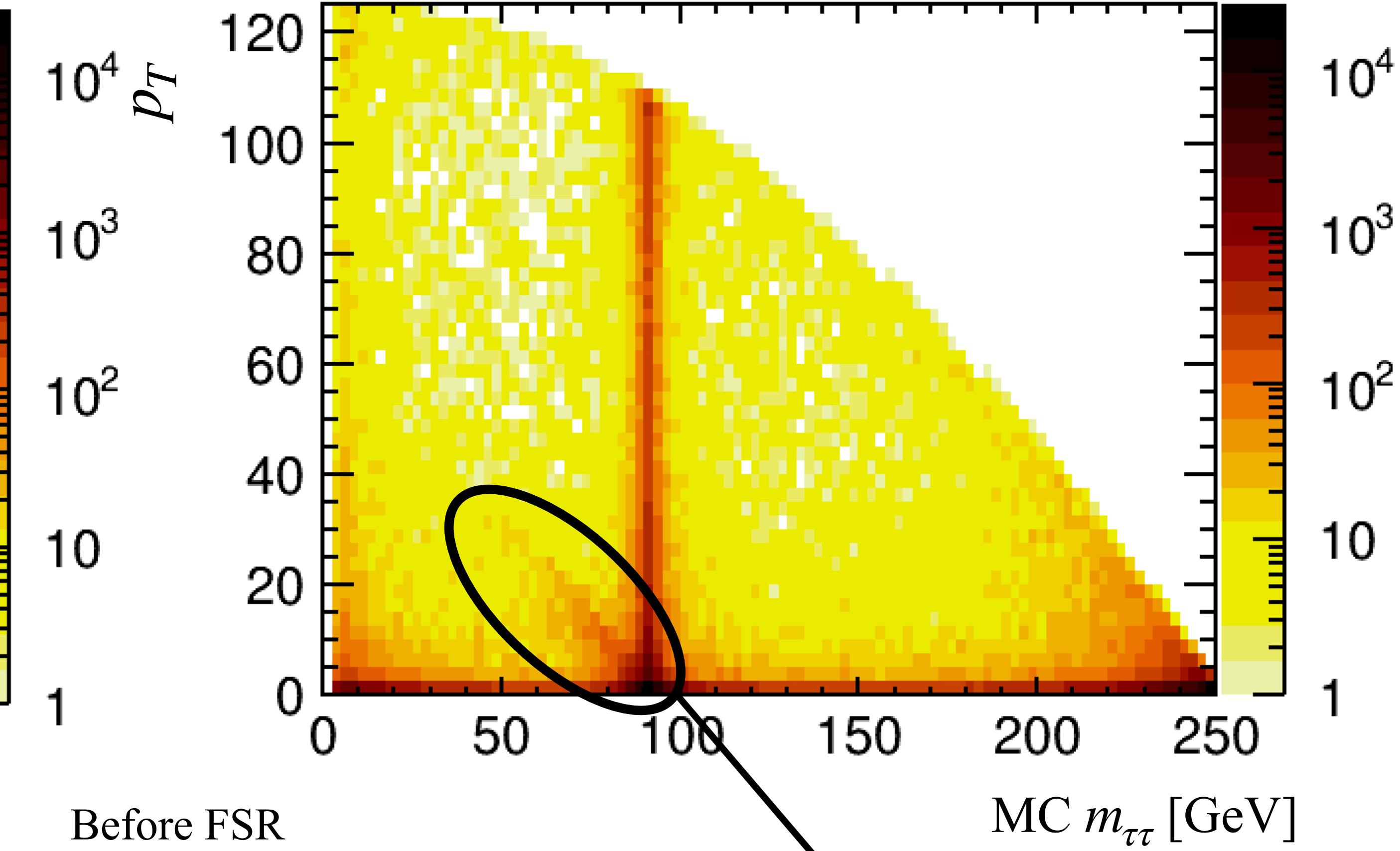
Use Jackknife method



Before FSR



After FSR

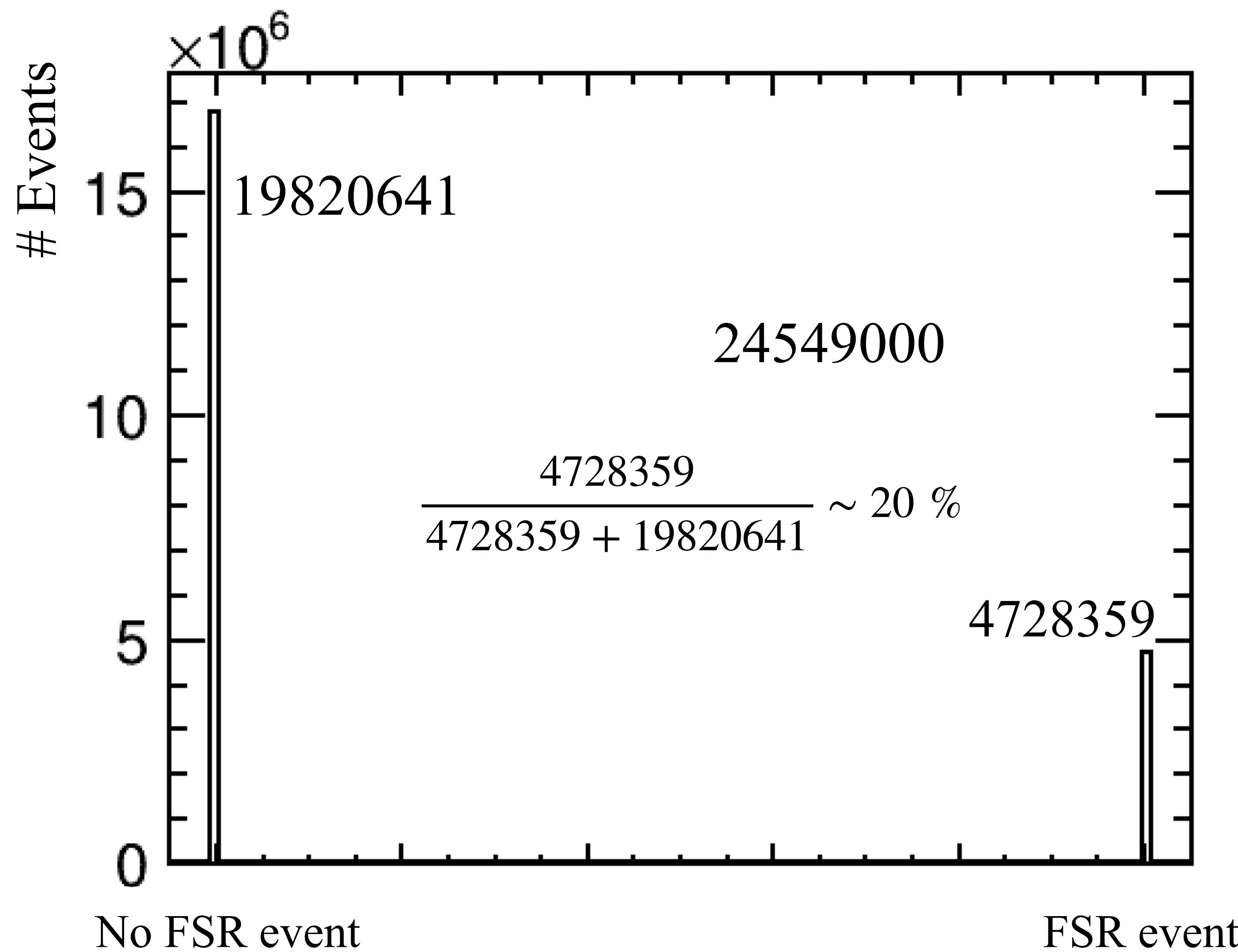


Before FSR

After FSR

on-shell Z is produced  
Significant FSR  
 $\rightarrow m_{\tau\tau} < m_Z$

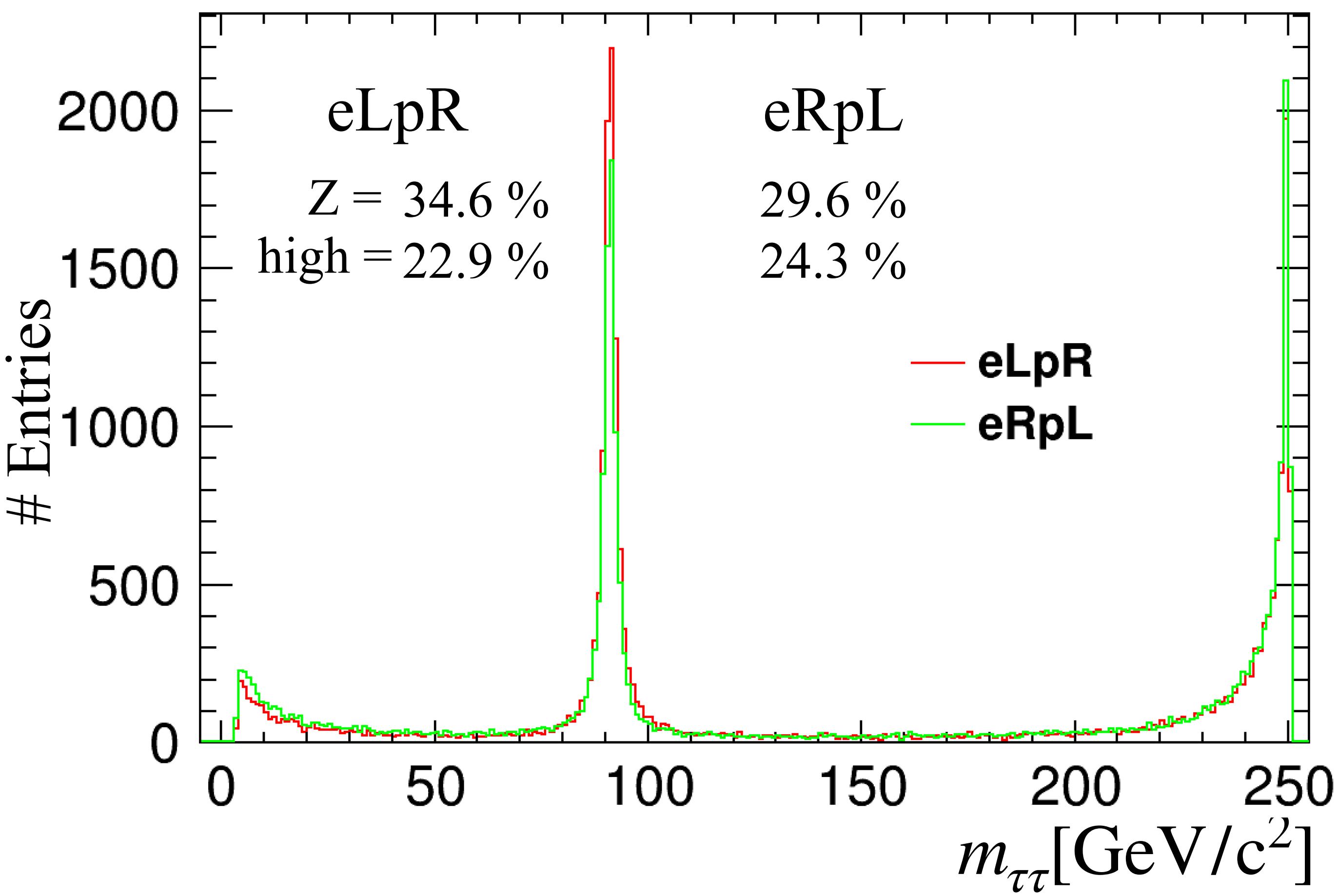
# FSR event



# Tau statistics @ ILC-250

The  $2.0\text{ab}^{-1}$  of integrated luminosity foreseen at ILC-250

beam polarisation	$e_{\text{L}80}^- e_{\text{R}30}^+ (-, +)$	$e_{\text{R}80}^- e_{\text{L}30}^+ (-, +)$
integrated luminosity [ $\text{fb}^{-1}$ ]	900	900
$e^- (\text{L}, \text{R})$	(90 %, 10 %)	(10 %, 90 %)
$e^+ (\text{L}, \text{R})$	(35 %, 65 %)	(65 %, 35 %)



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

$$\hat{P} = \frac{1}{n} \sum_{i=1}^n \hat{P}_i$$

$\hat{P}$  : the empirical average of the Jackknife replicates

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$\hat{P}_i$  : tau polarisation obtained by fitting jackknife samples