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Measuring the tau polarisation at the ILC

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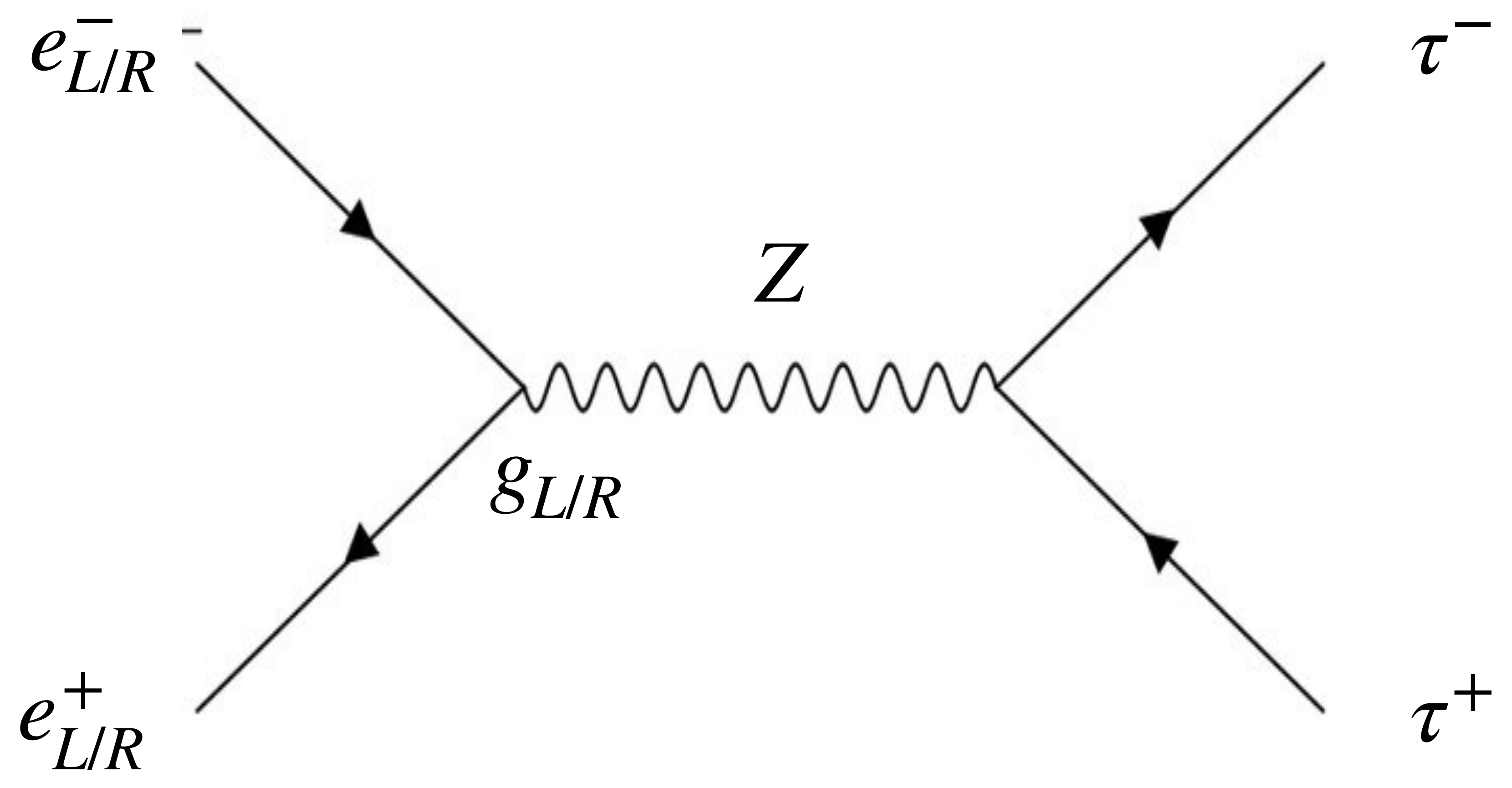
Motivation 1

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

Left- and right-handed coupling g_R, g_L to Z boson are different

⇒Left- and right-handed polarisation asymmetry is expected.

$$A_f = \frac{g_R^2 - g_L^2}{g_R^2 + g_L^2}$$



Thanks to ILC's polarised beams, A_e can be measured

⇒ A_f can be extracted from $A_{\rm FB}$

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

Motivation 2

Tau has extra information

tau is the only particle that can measure the polarisation of the final state in the ILC250

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

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

The aim of this study

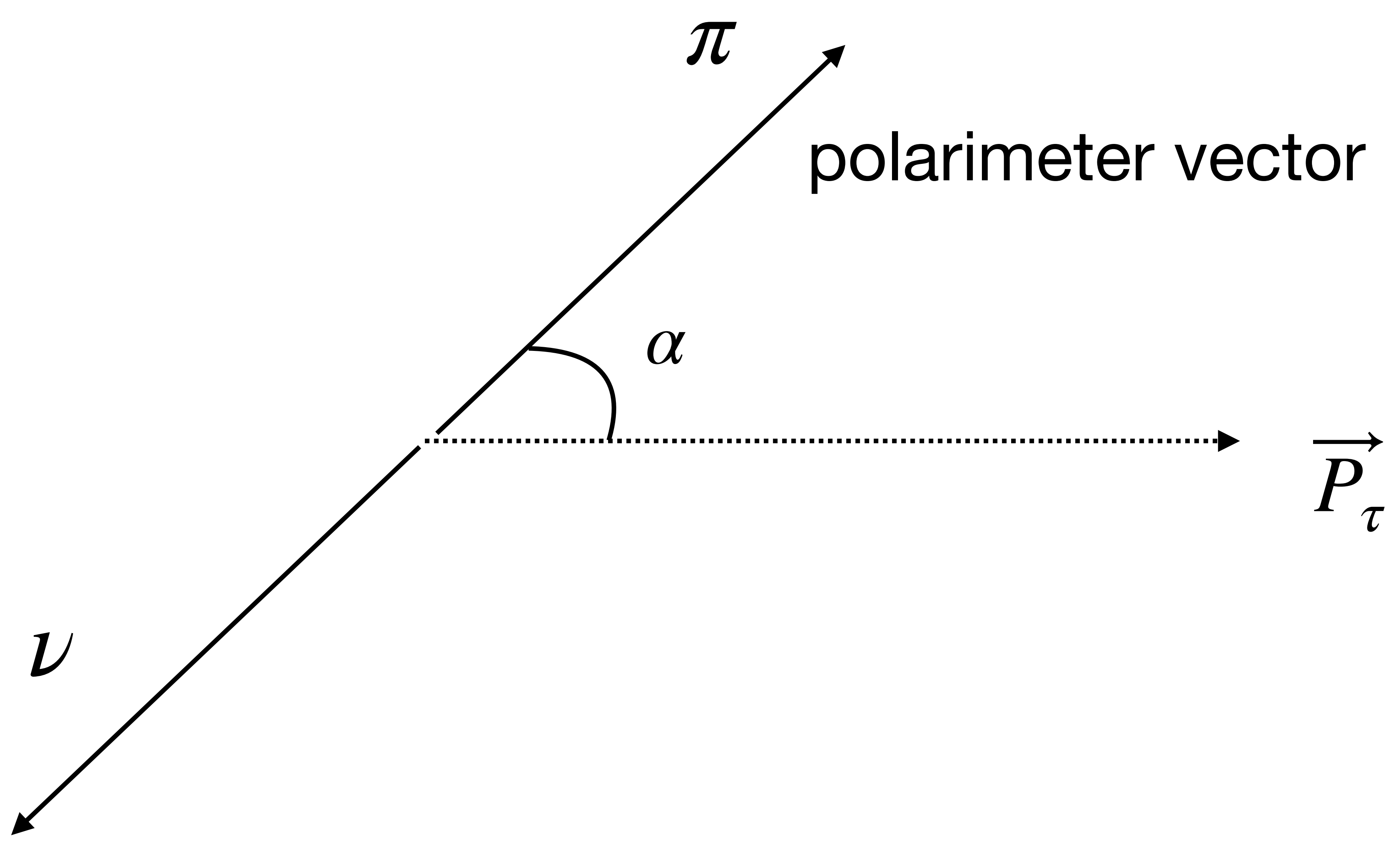
The reconstruction of tau spin orientation (“**Polarimeter**”) in order to measure polarisation to investigate new physics.

Polarimeter

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

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

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



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

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

"Polarimeter"

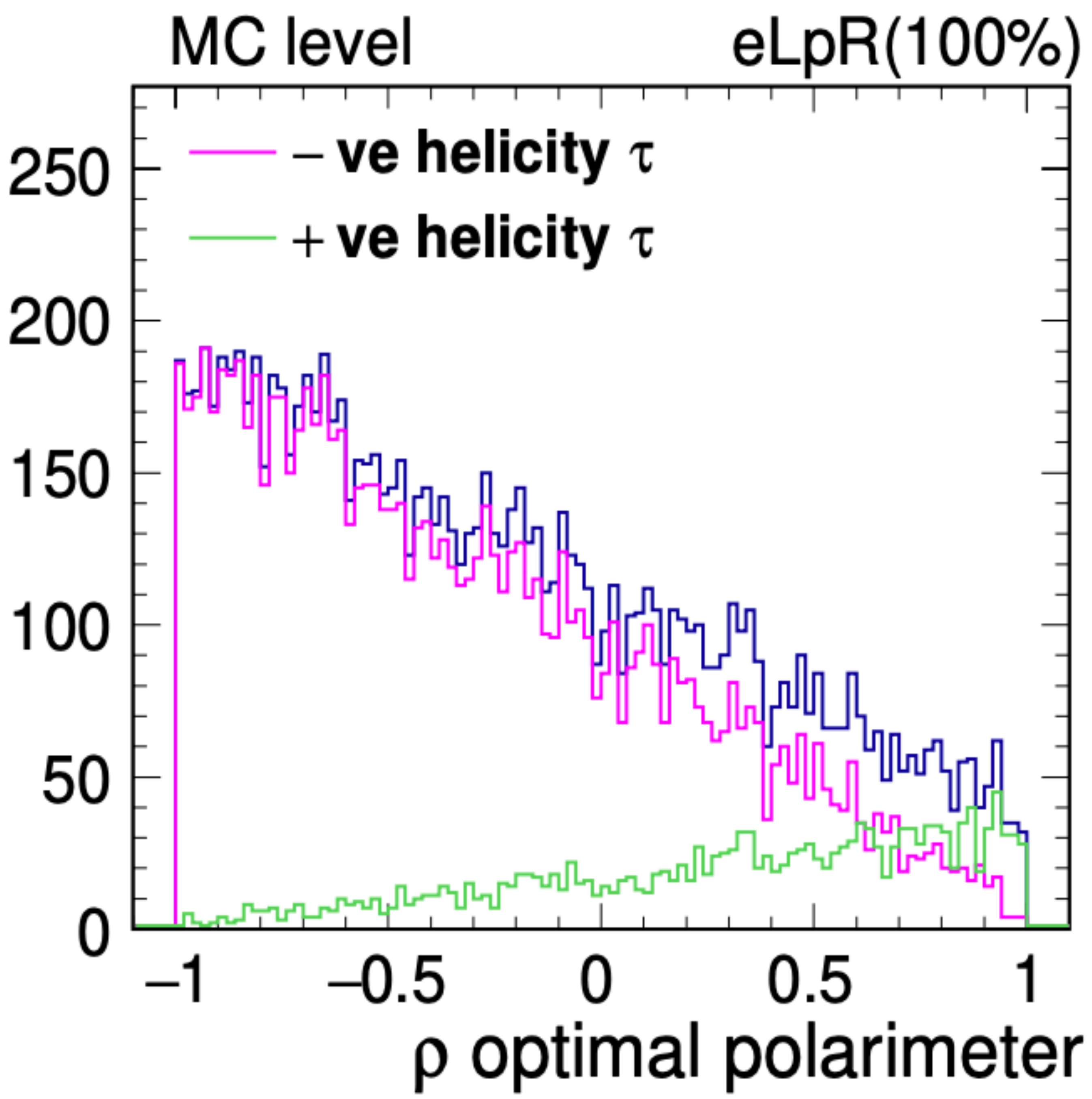
The cosine of the angle this polarimeter vector makes to the tau flight direction

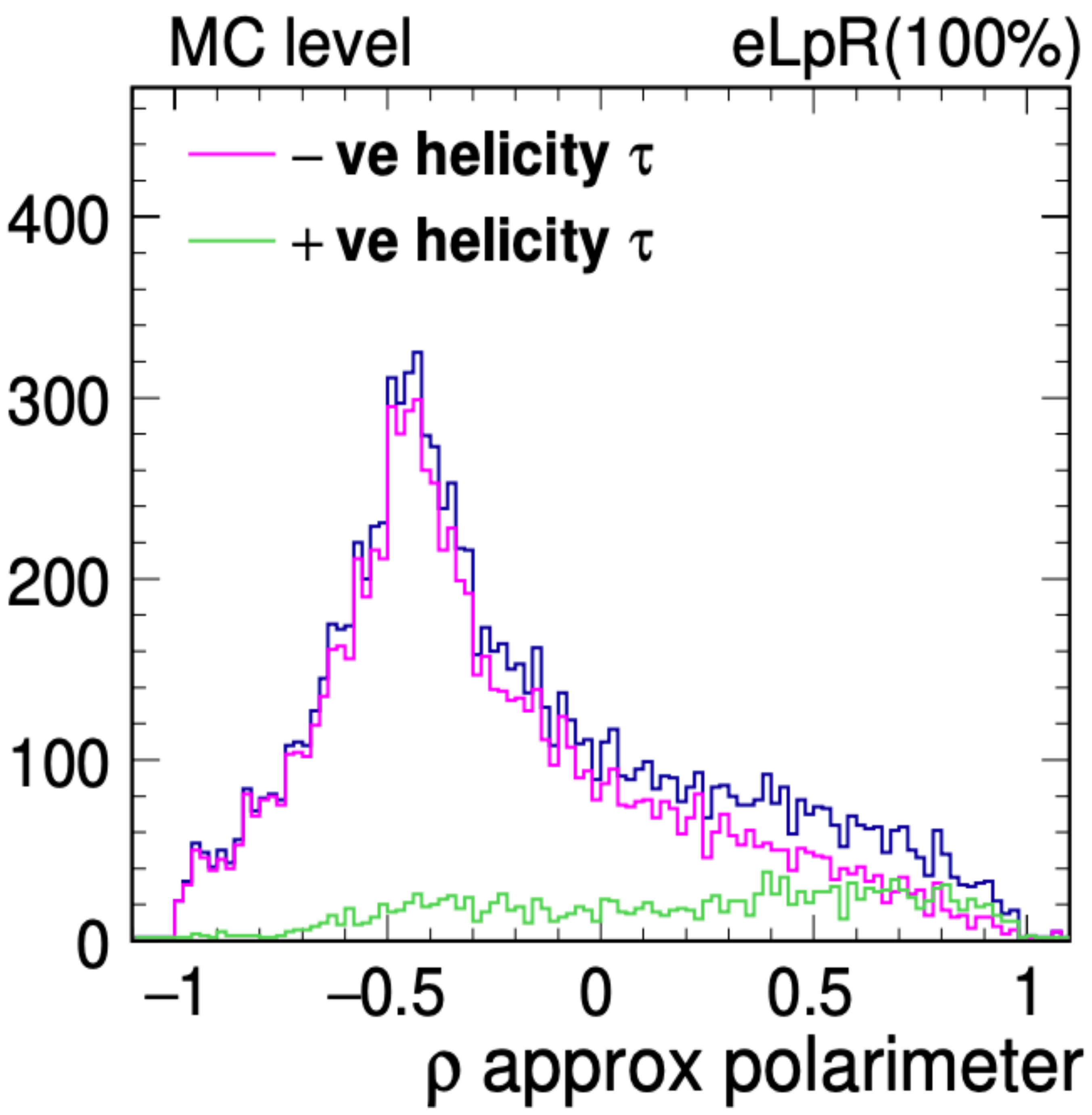
Previous study

Extract polarimeter without using neutrino information

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

"Optimal" polarimeters including the neutrino component





mean statistical error on tau polarisation: 0.30 % (optimal), 0.40 % (approximate)

We explicitly extract the neutrino momentum and reconstruct polarimeters

Simulation setup

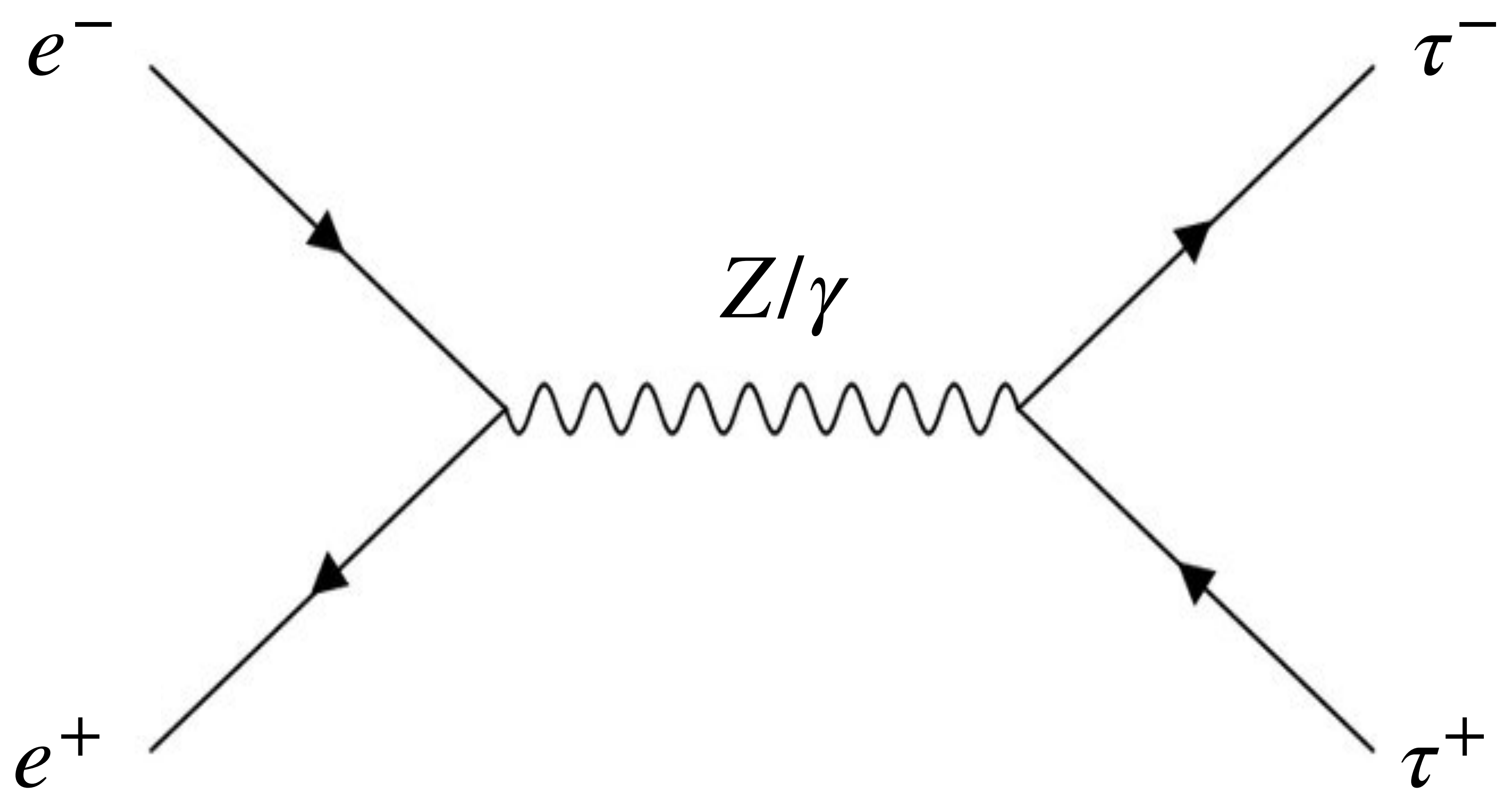
- Signal event sample with 100 % $e_L^- e_R^+$ beam polarisations were generated using WHIZARD ver 2.8.5.
- The decay of the polarised tau was done using TAUOLA.
- MC truth information was used.

currently

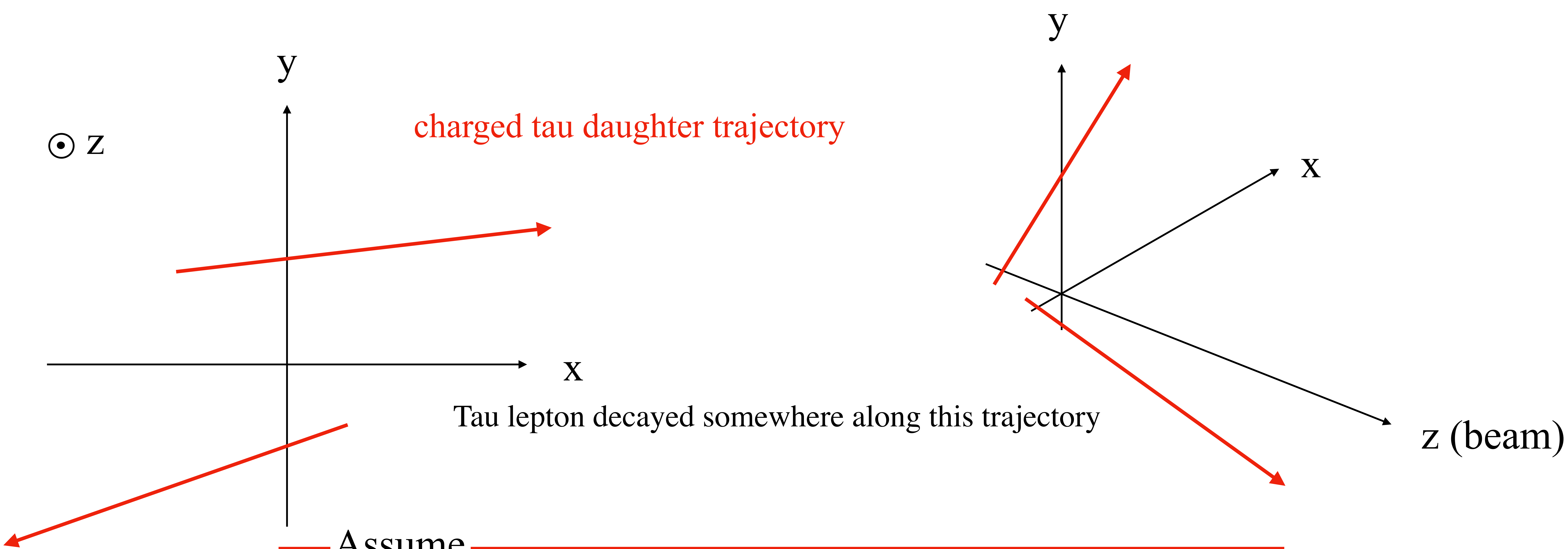
- only look at

  $\tau \rightarrow \pi\nu$ (BR ~ 10 %)

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



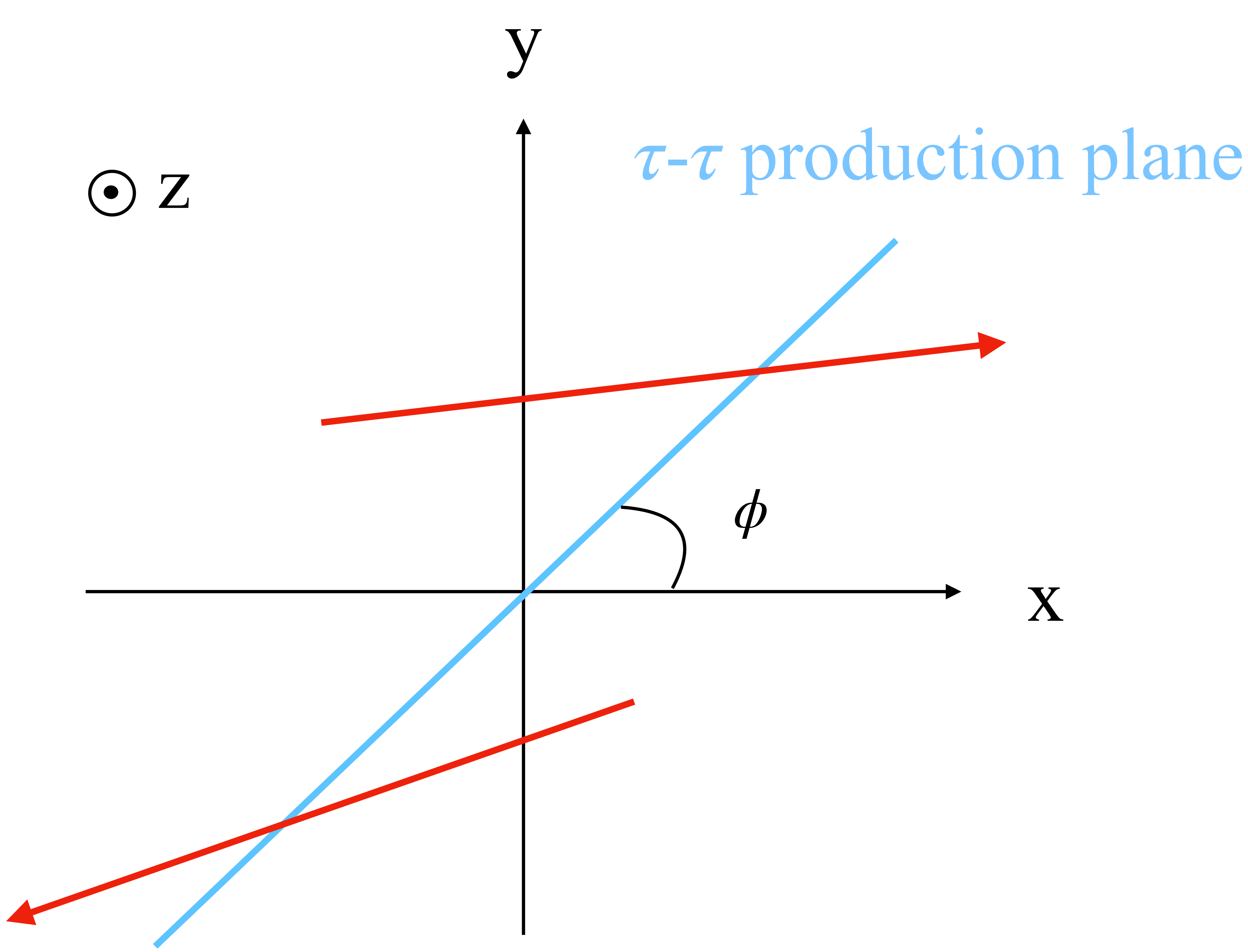
τ reconstruction method

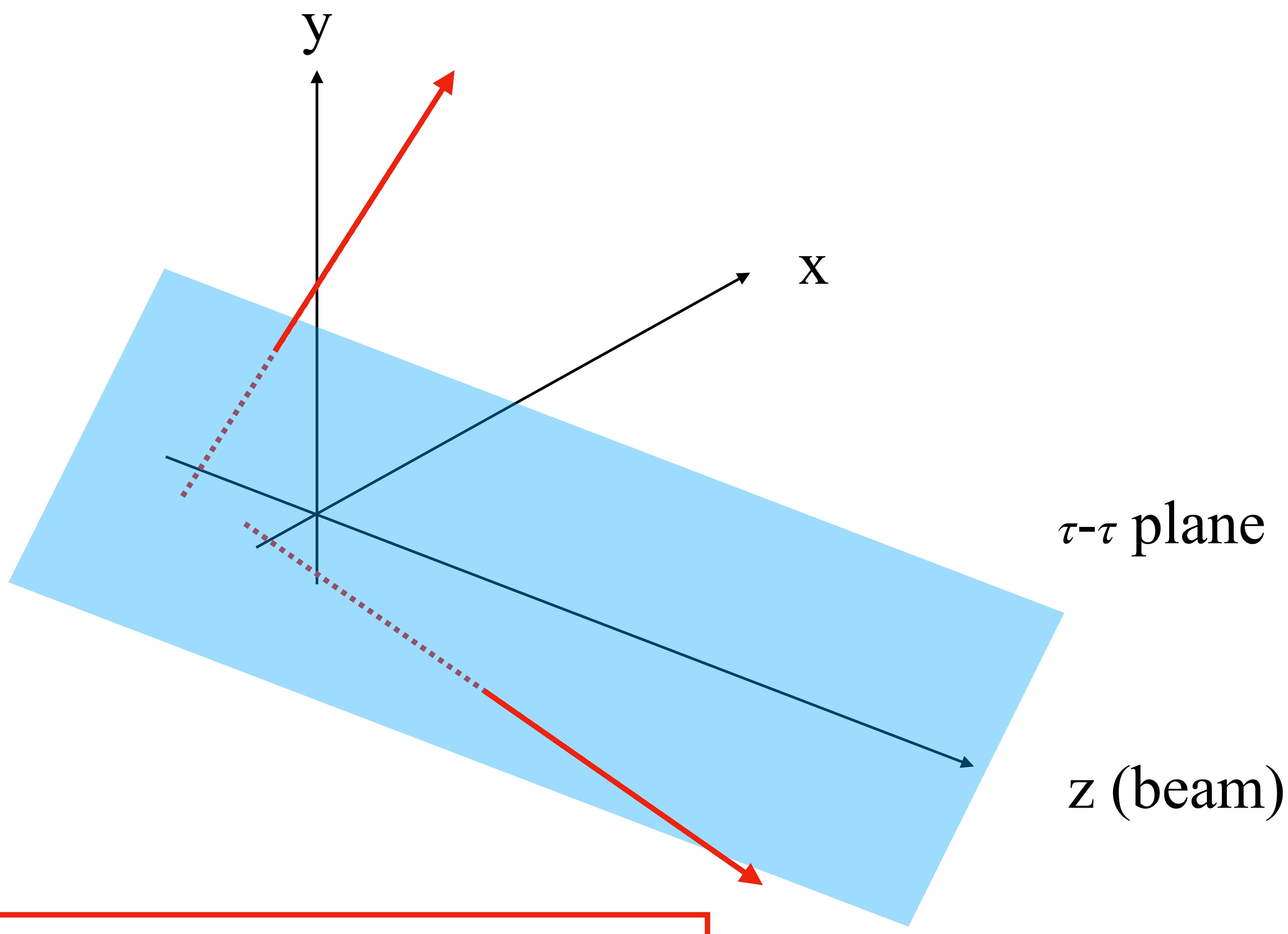


Assume

- 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 along a straight line.

τ reconstruction method



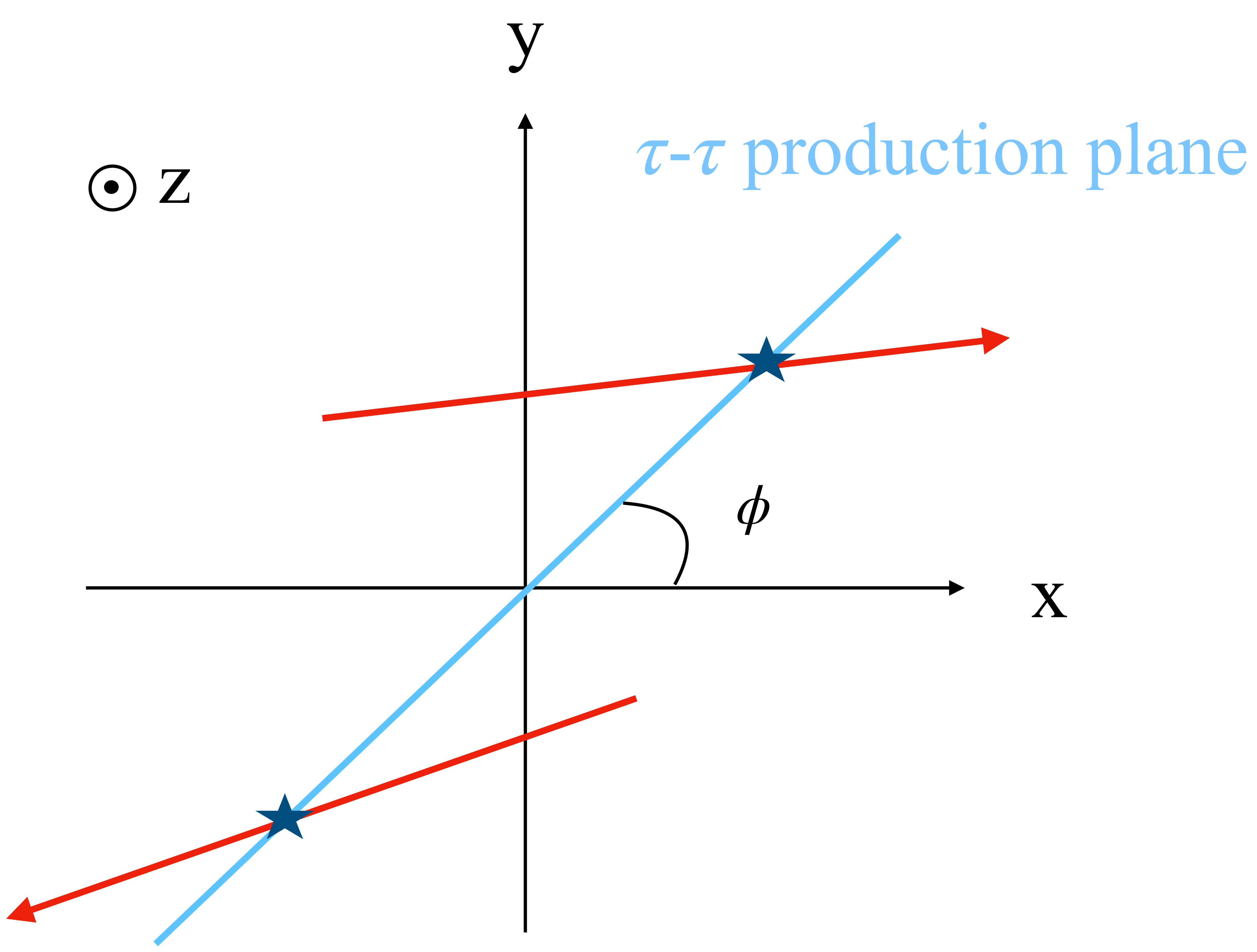


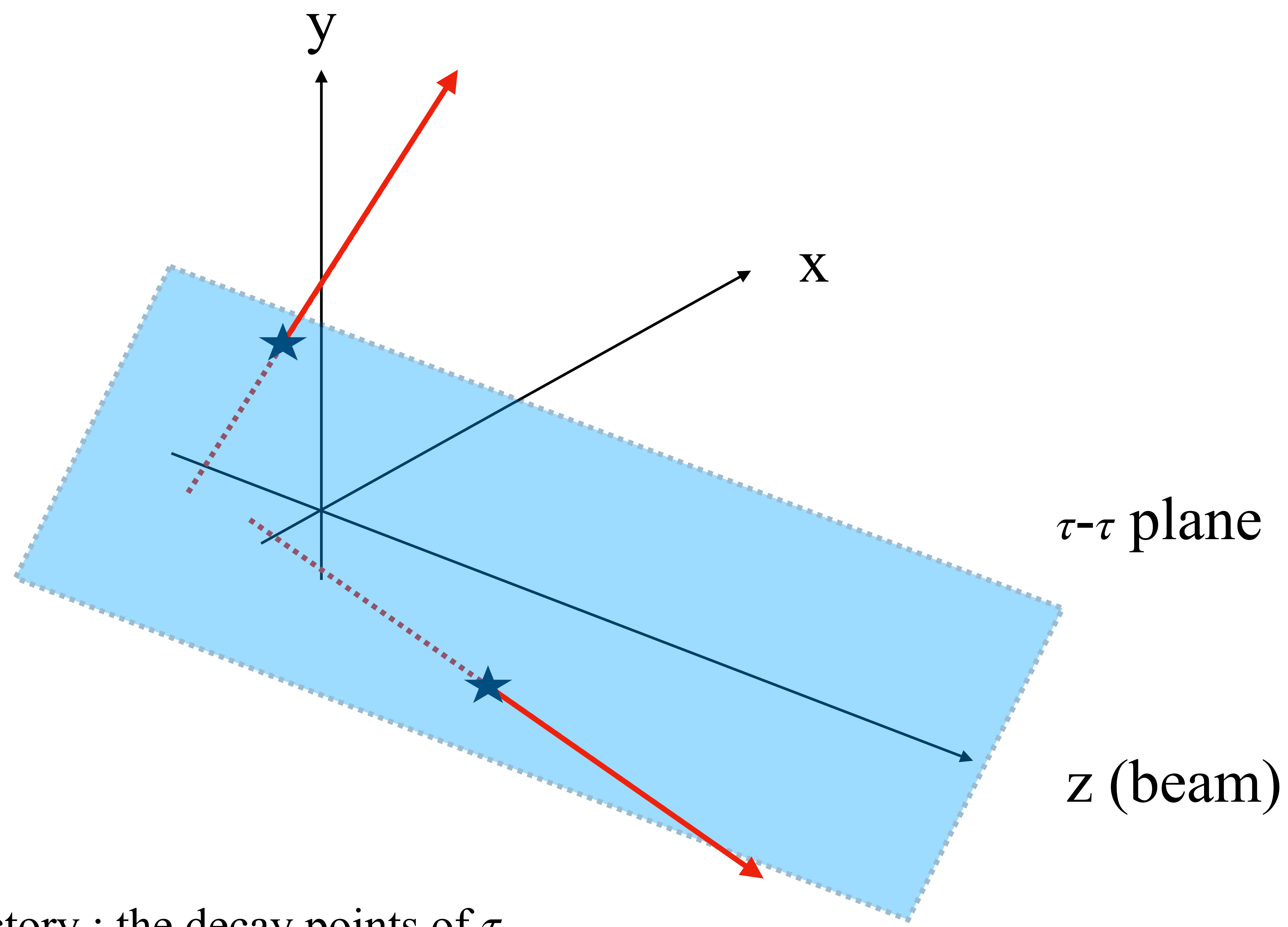
Assume

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

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

τ reconstruction method



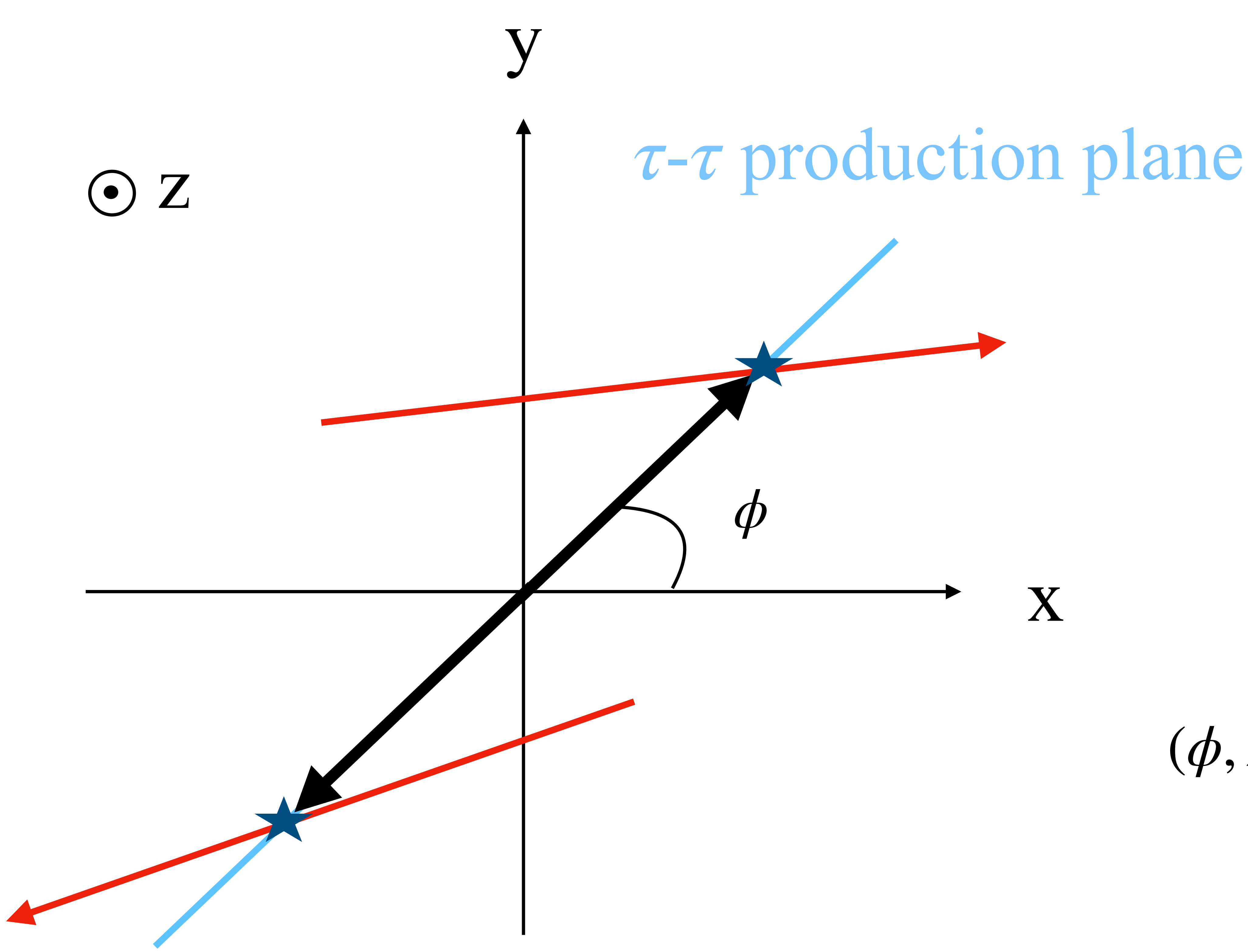


★ The intersection between plane and trajectory : the decay points of τ

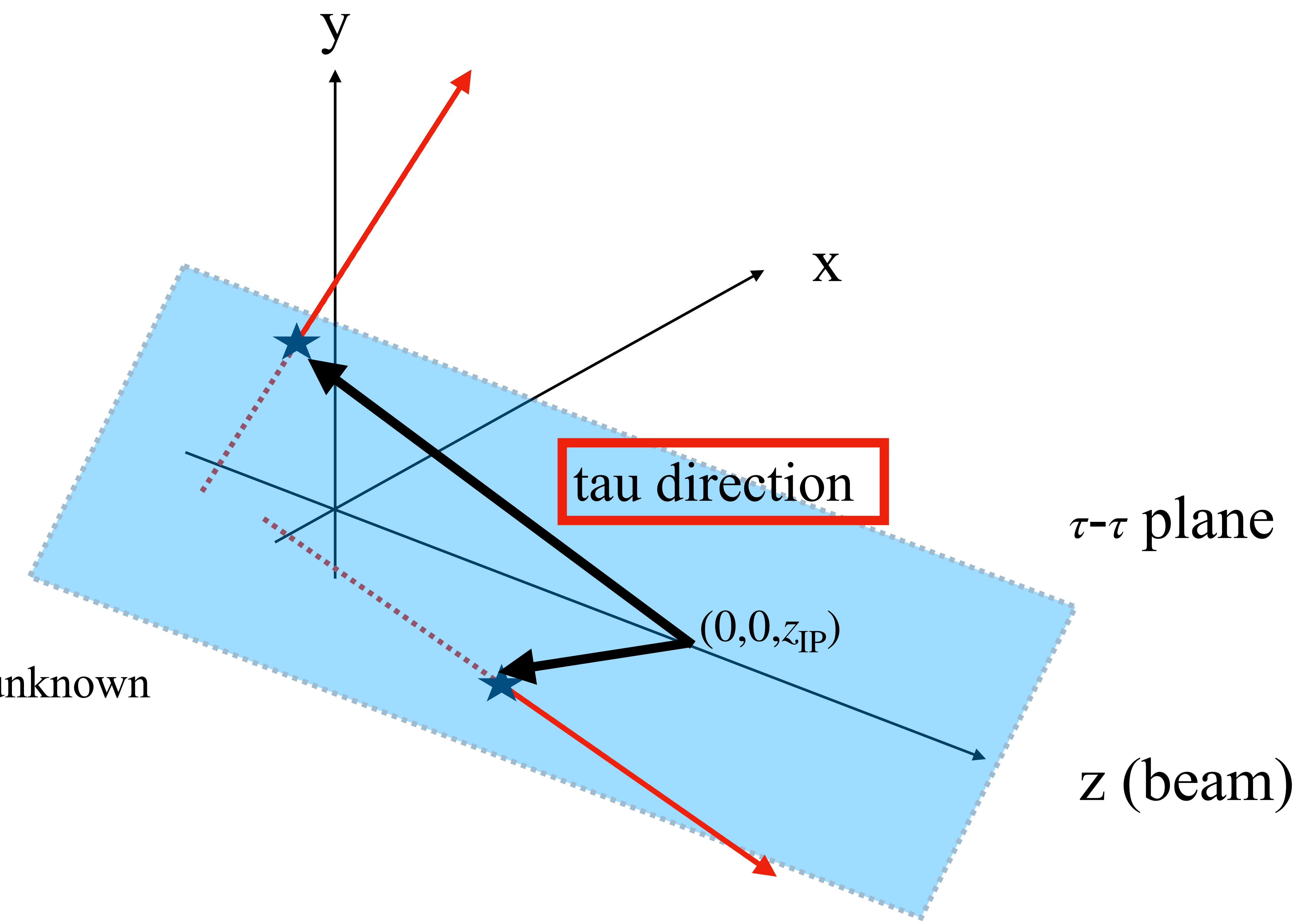
For a plane with azimuthal angle ϕ,

the intersection of trajectories with this plane can be calculated.

τ reconstruction method



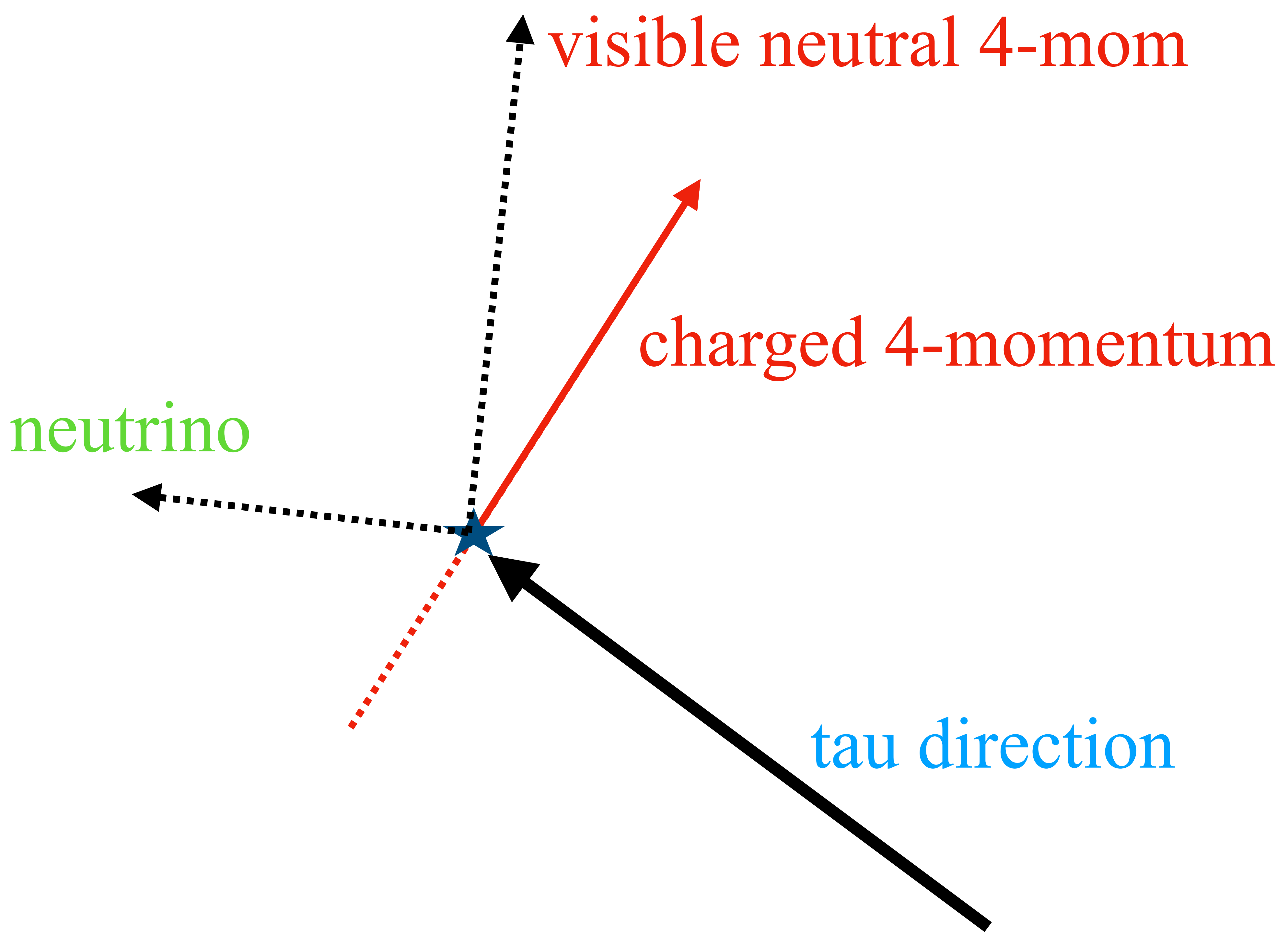
(ϕ, z_{IP}) : unknown



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

⇒How can we choose ϕ, z_{IP} ?

τ reconstruction method



by applying additional constraints:

- $p_T^{\tau_1} = p_T^{\tau_2}$
- Single ISR photon
- 1 neutrino / τ
- $E_{\text{CM}} = E_{\tau_1} + E_{\tau_2} + E_{ISR}$

we can calculate tau 4-momenta P_τ

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

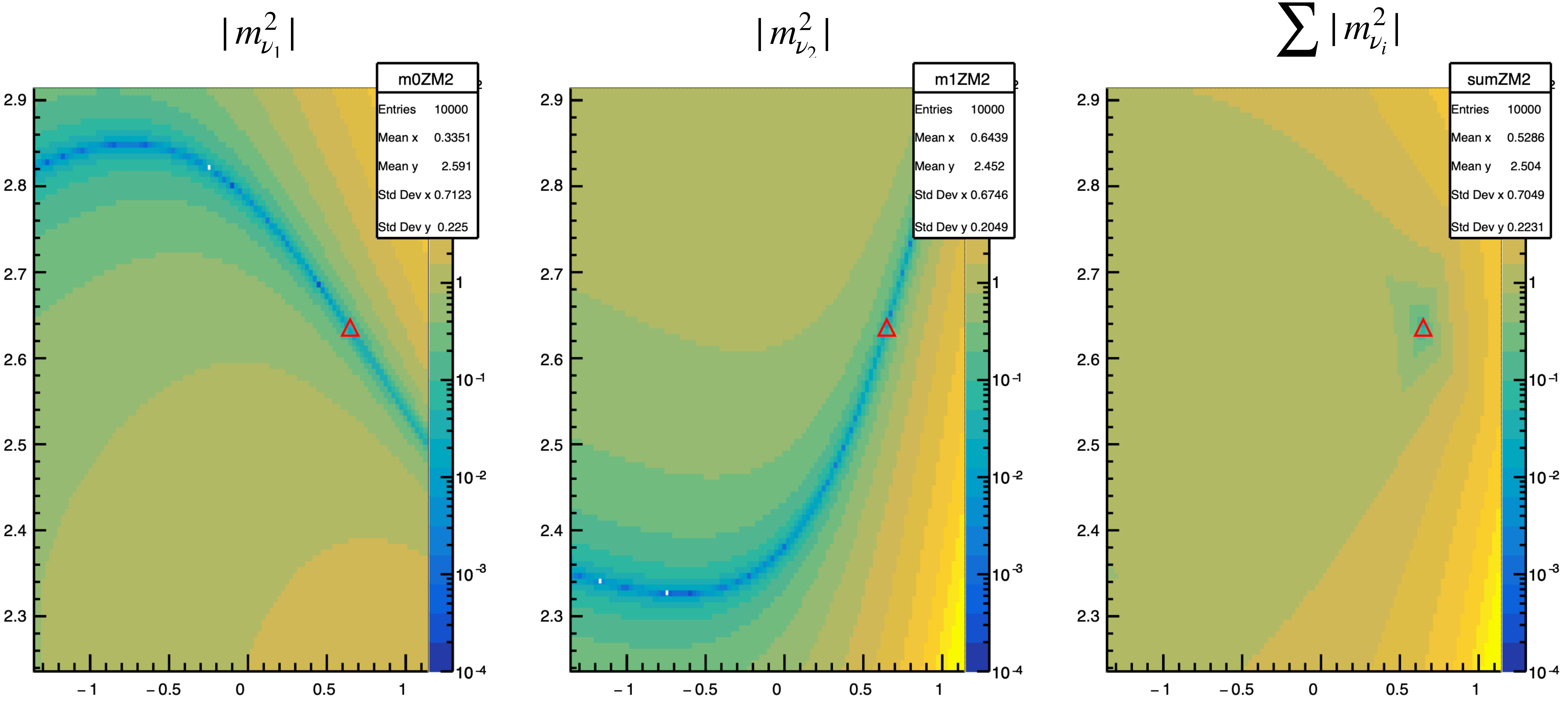
the invariant mass of the missing (neutrino) momentum for each tau can be calculated

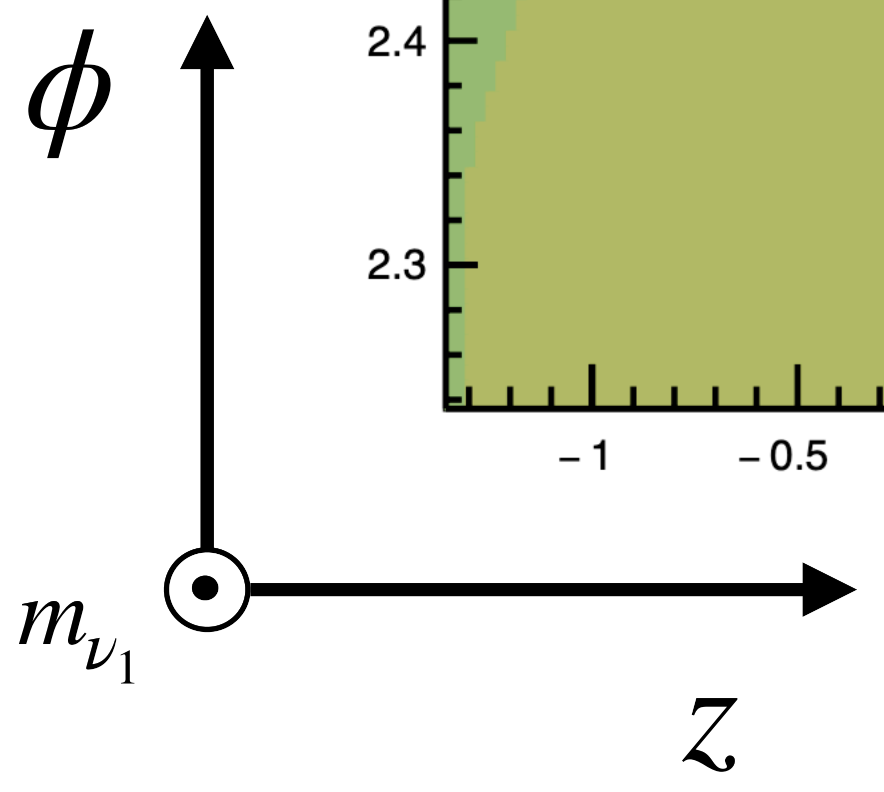
We choose the values of z and ϕ which result in neutrino masses closest to zero

Find solutions

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

example event with 1 solution





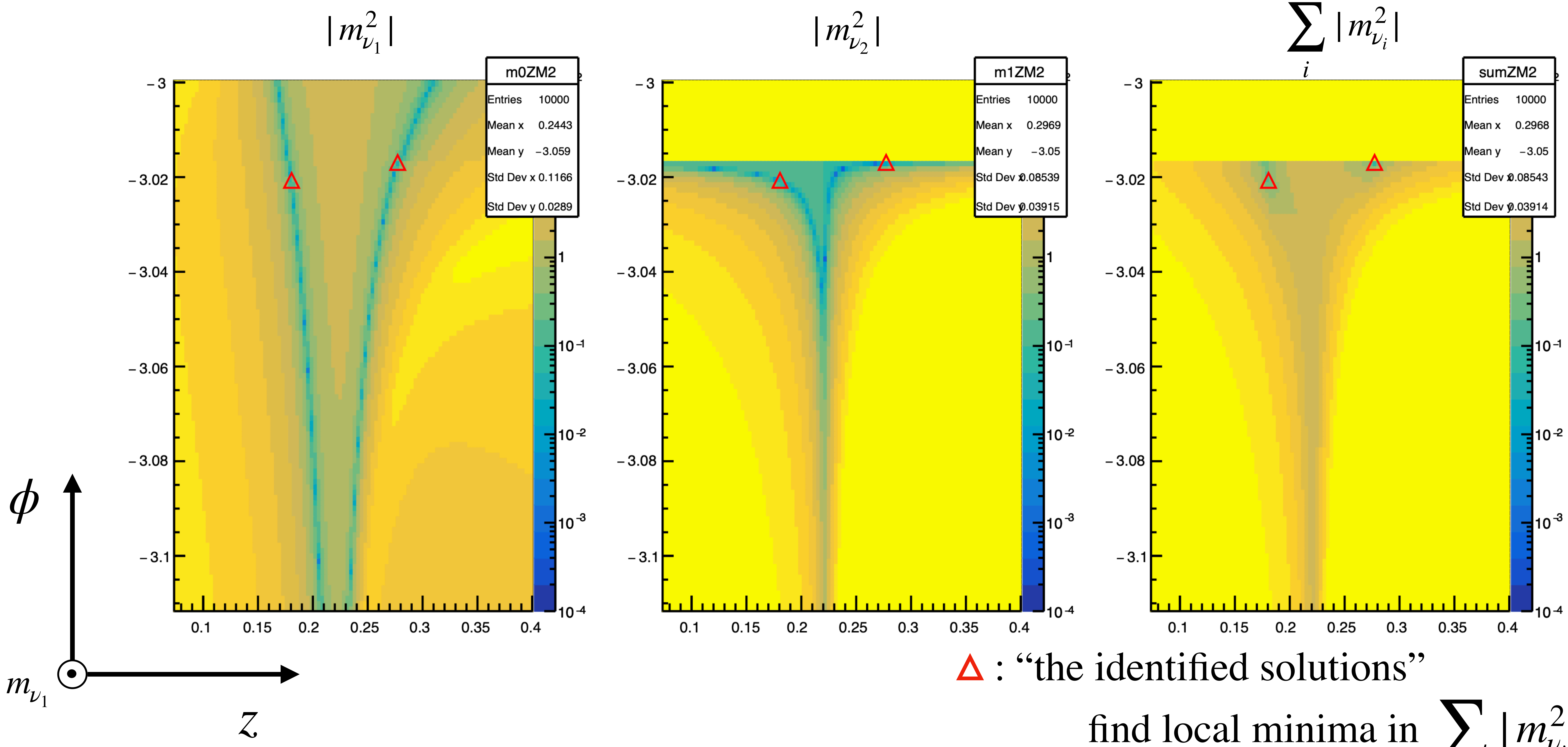
△ : "the identified solutions"

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



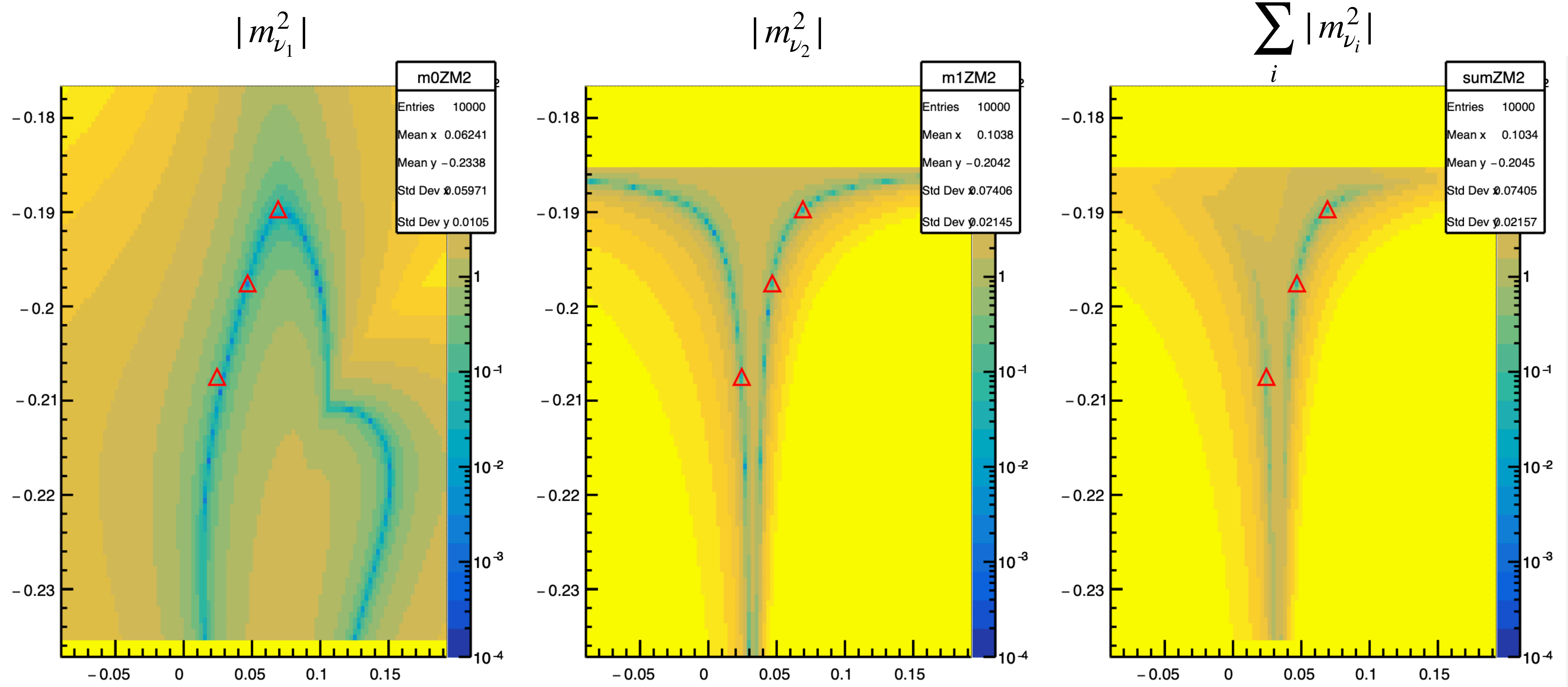
△ : "the identified solutions"

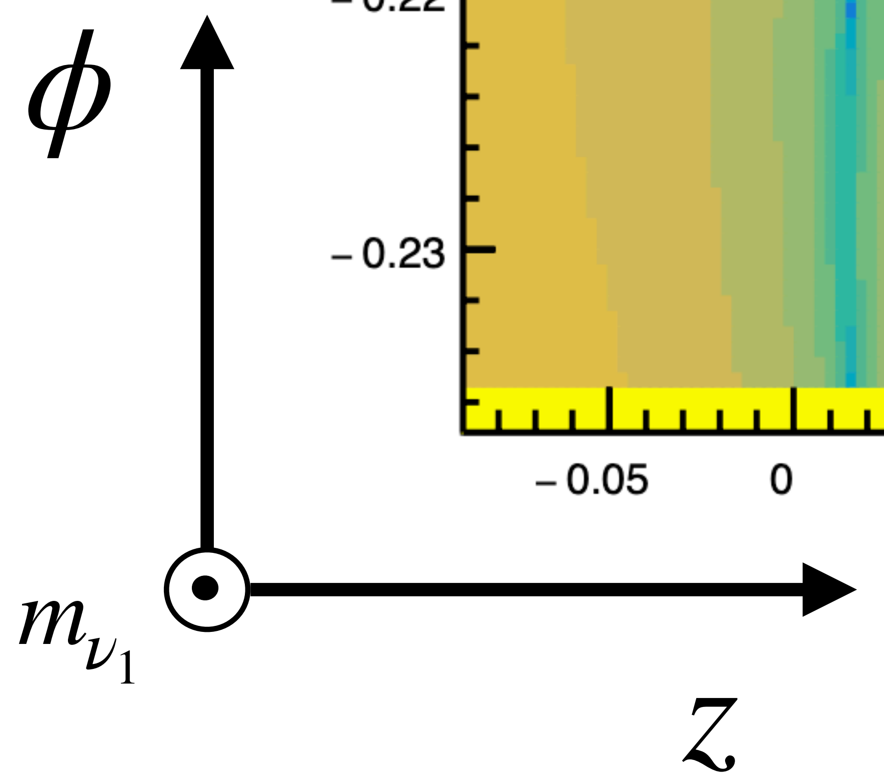
find local minima in $\sum_i |m_{\nu_i}^2|$

Find solutions

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

example event with 3 solutions





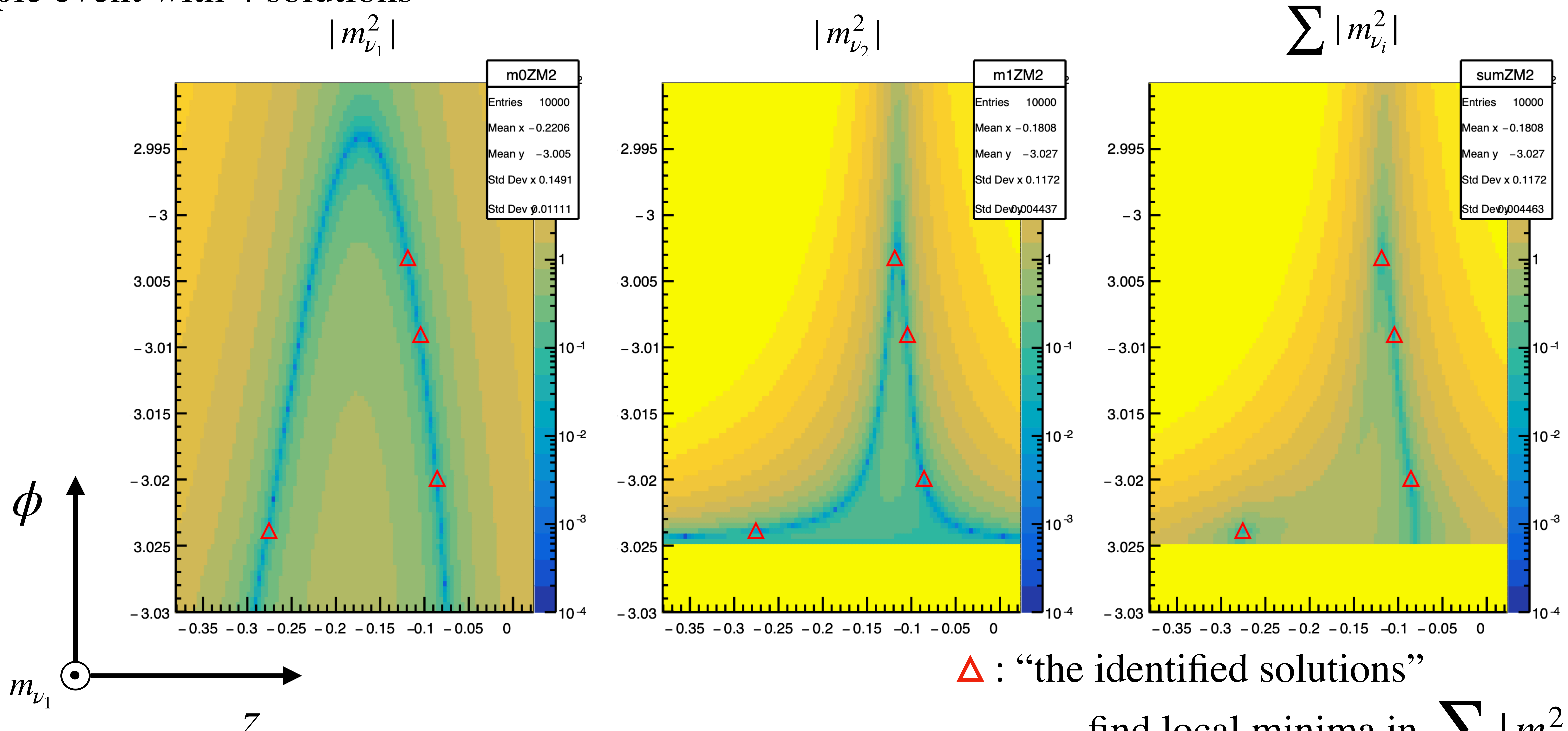
△ : "the identified solutions"

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

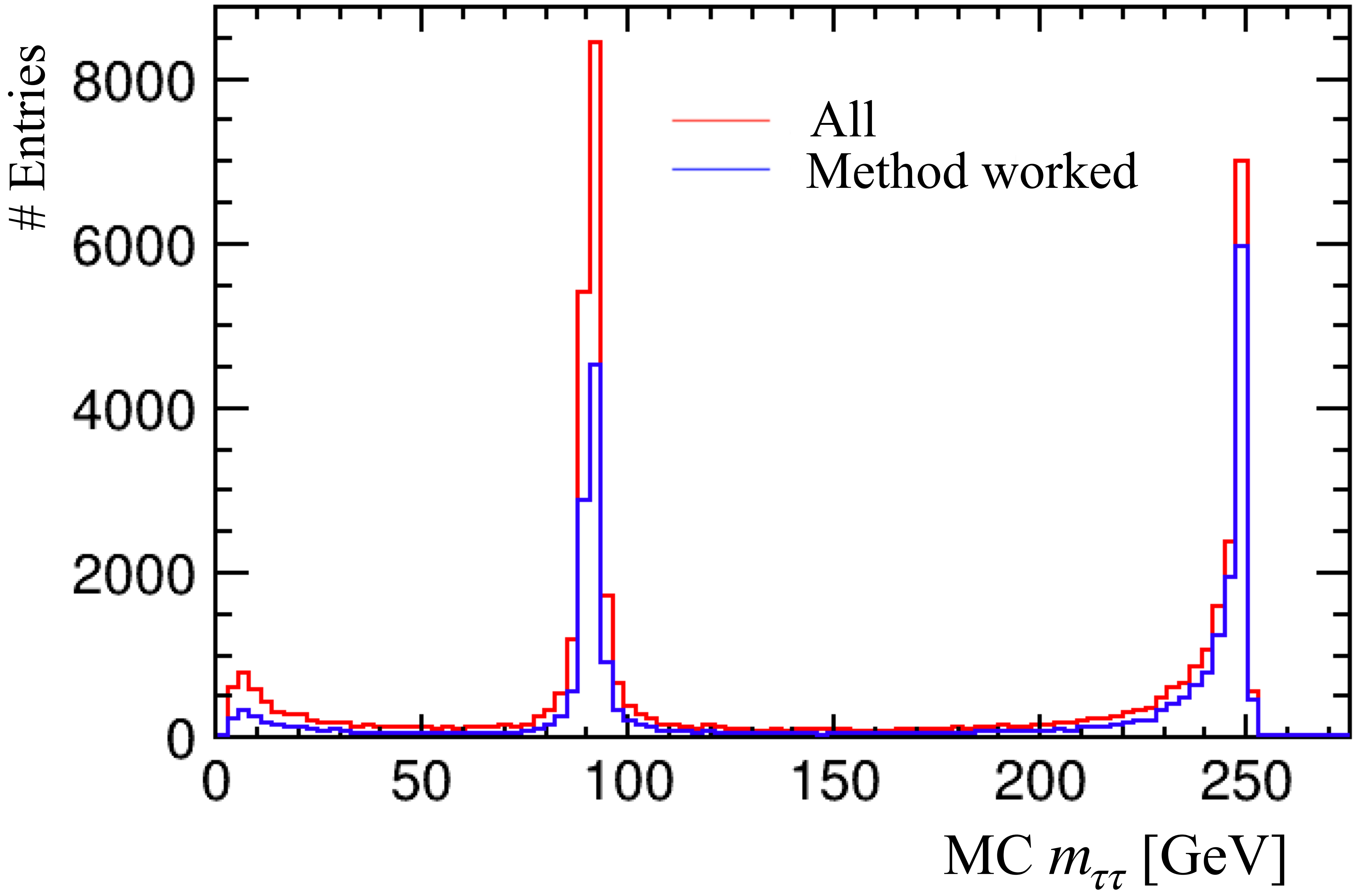
example event with 4 solutions



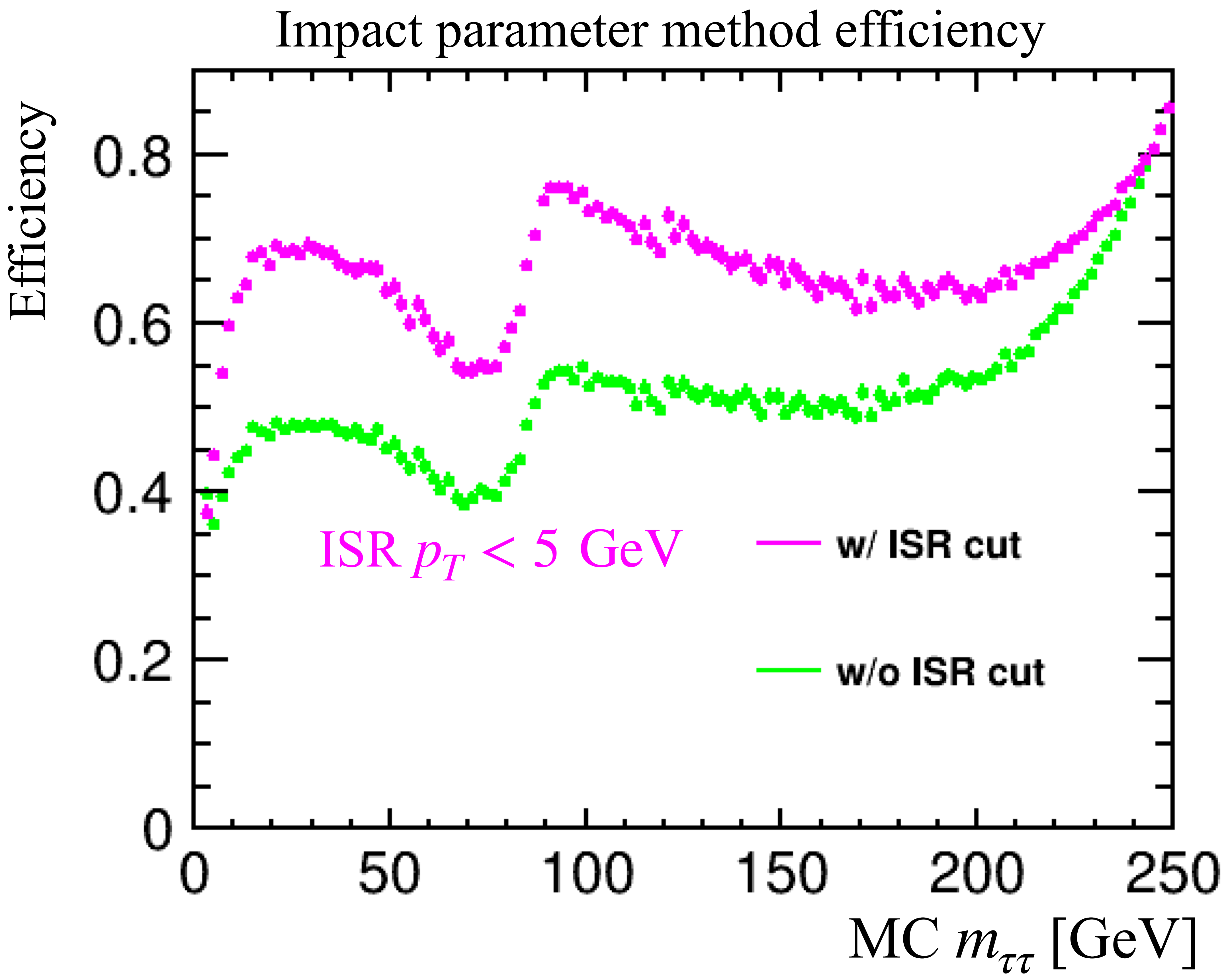
△ : "the identified solutions"

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

Method efficiency



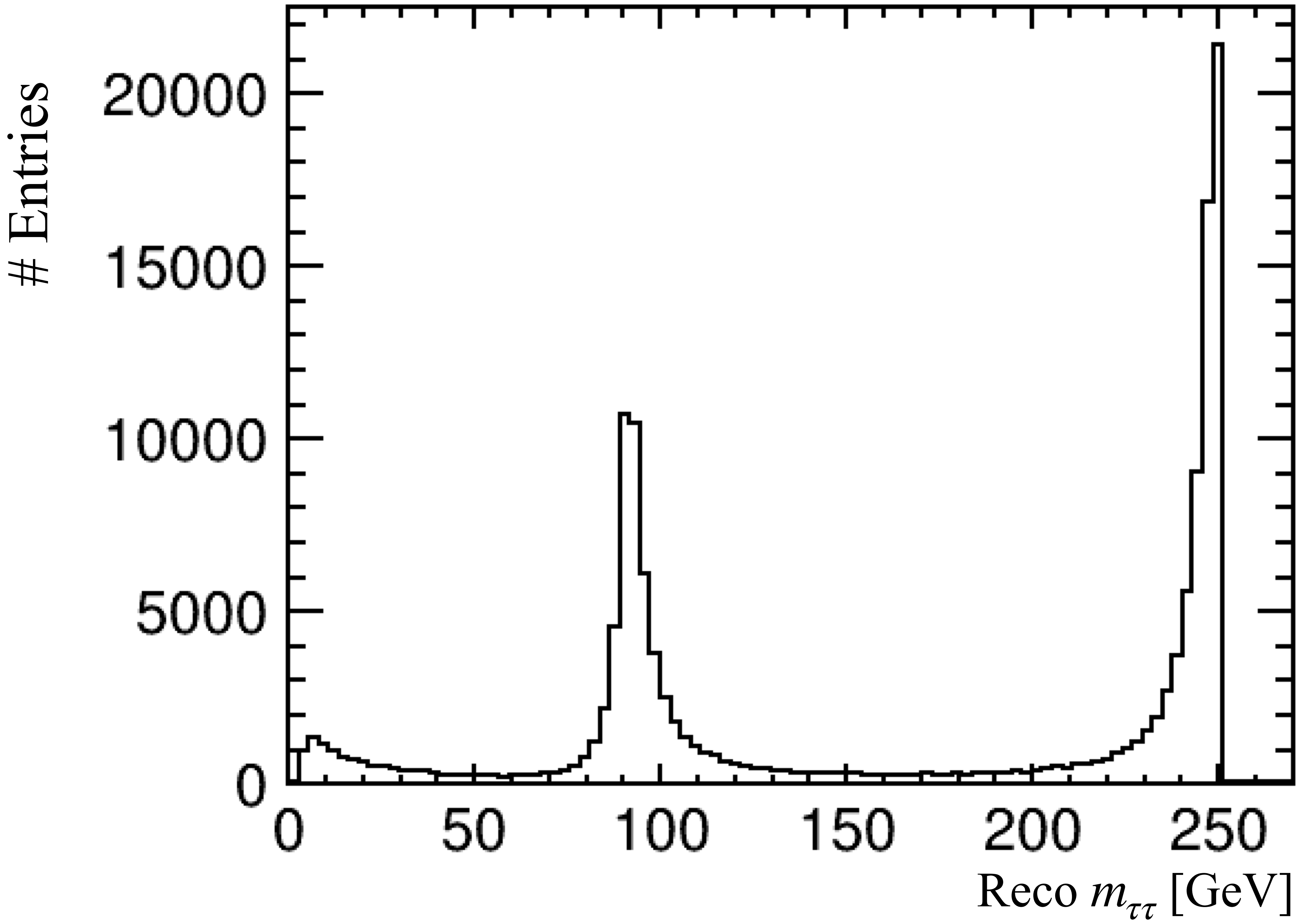
Method worked : at least 1 solution is found

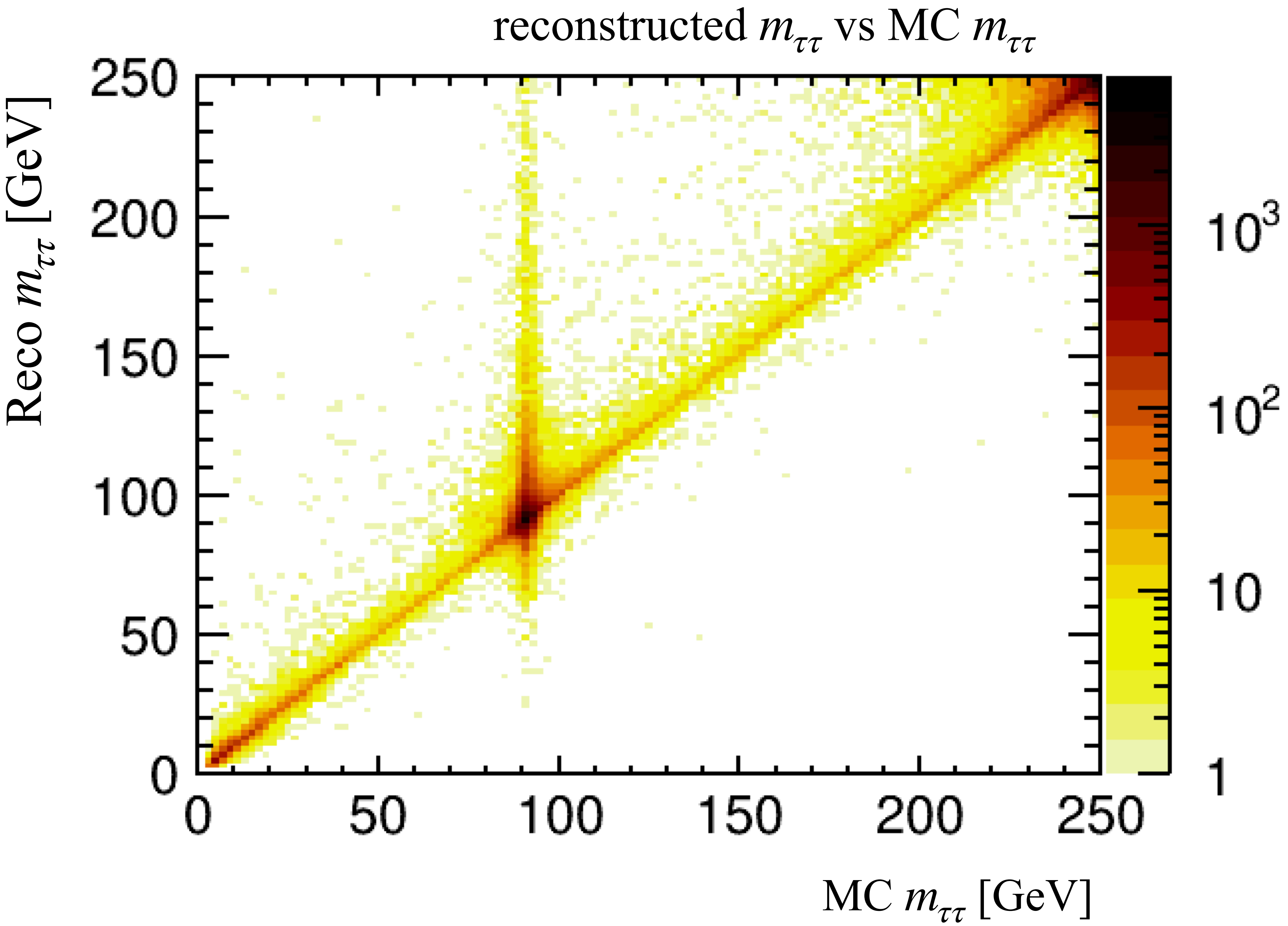


Impact parameter method efficiency is > 80 % for events with $m_{\tau\tau} \sim 250$ GeV

Comparison with MC

Reconstructed $m_{\tau\tau}$ based on new method solutions



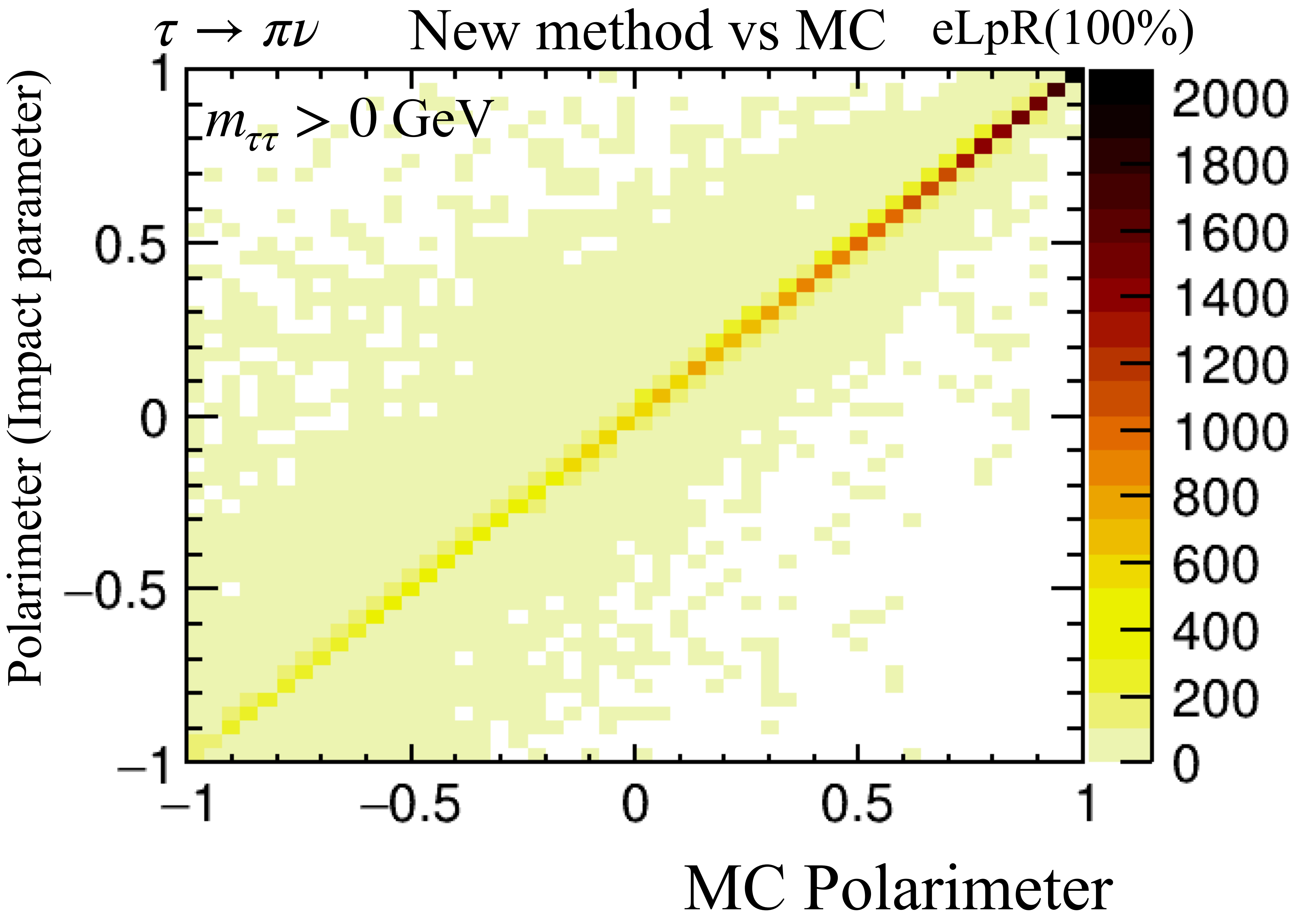


Reasonable agreement between MC and reconstructed $m_{\tau\tau}$

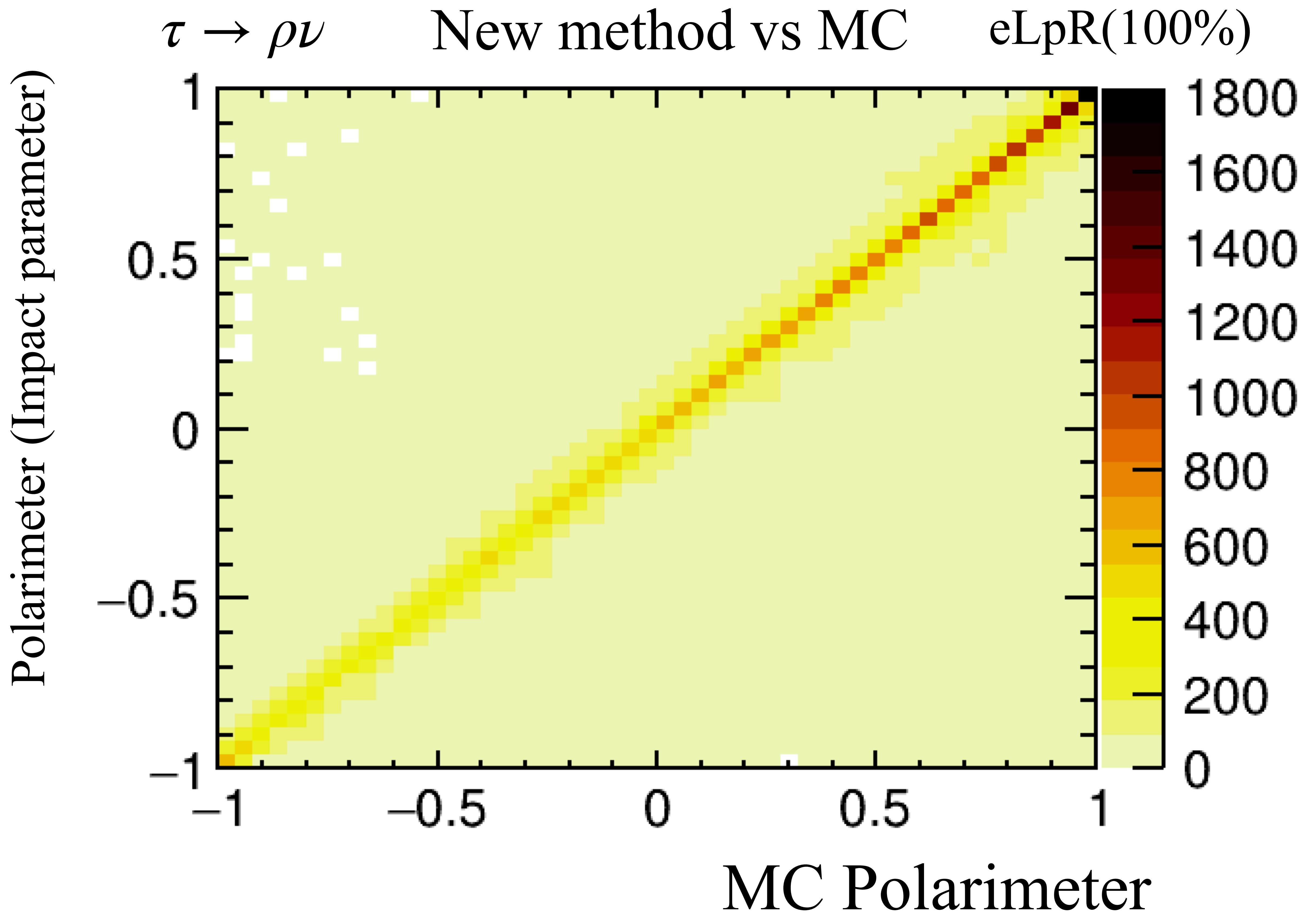
Polarimeter

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

$\tau \rightarrow \pi\nu$



$\tau \rightarrow \rho\nu$

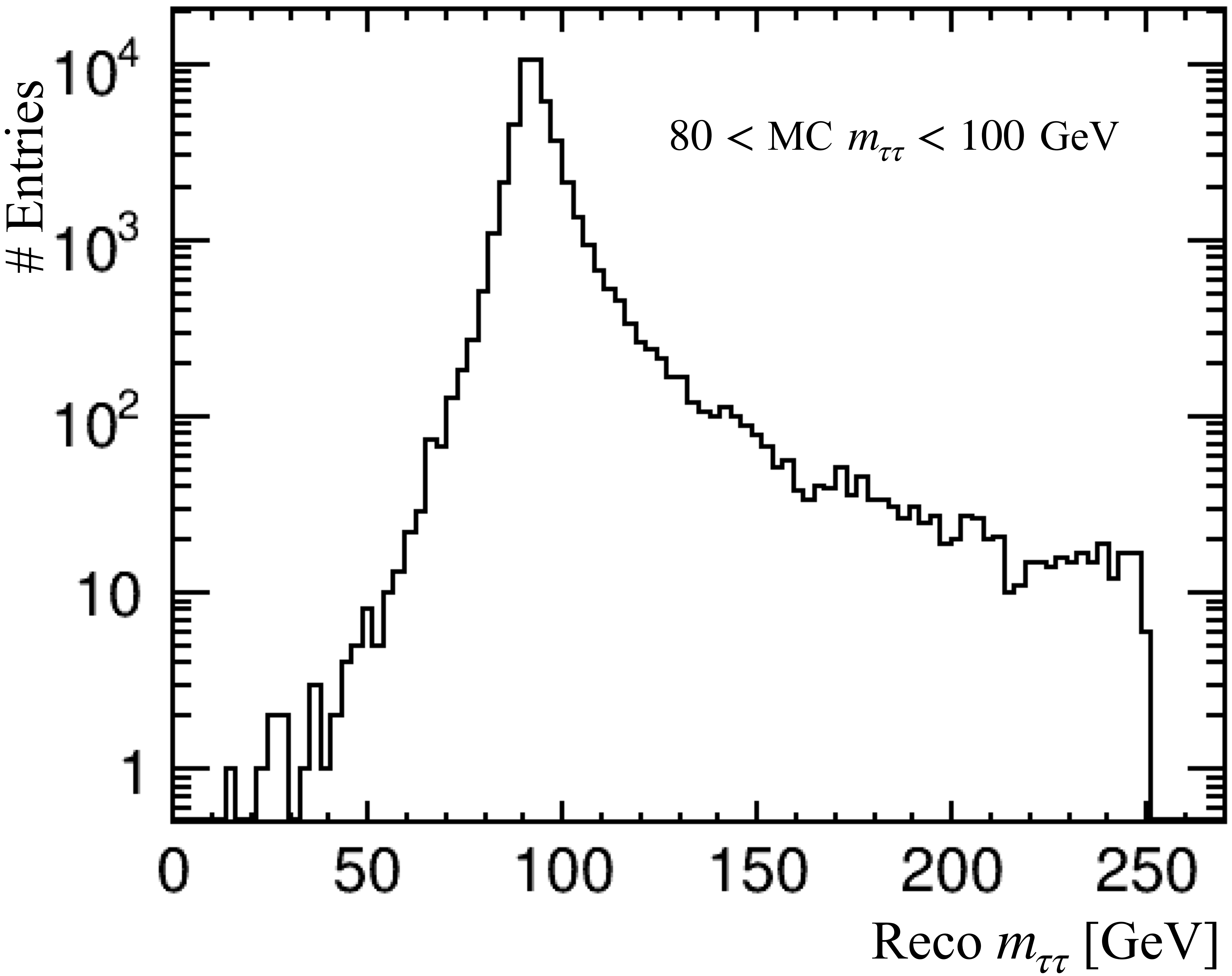


Summary

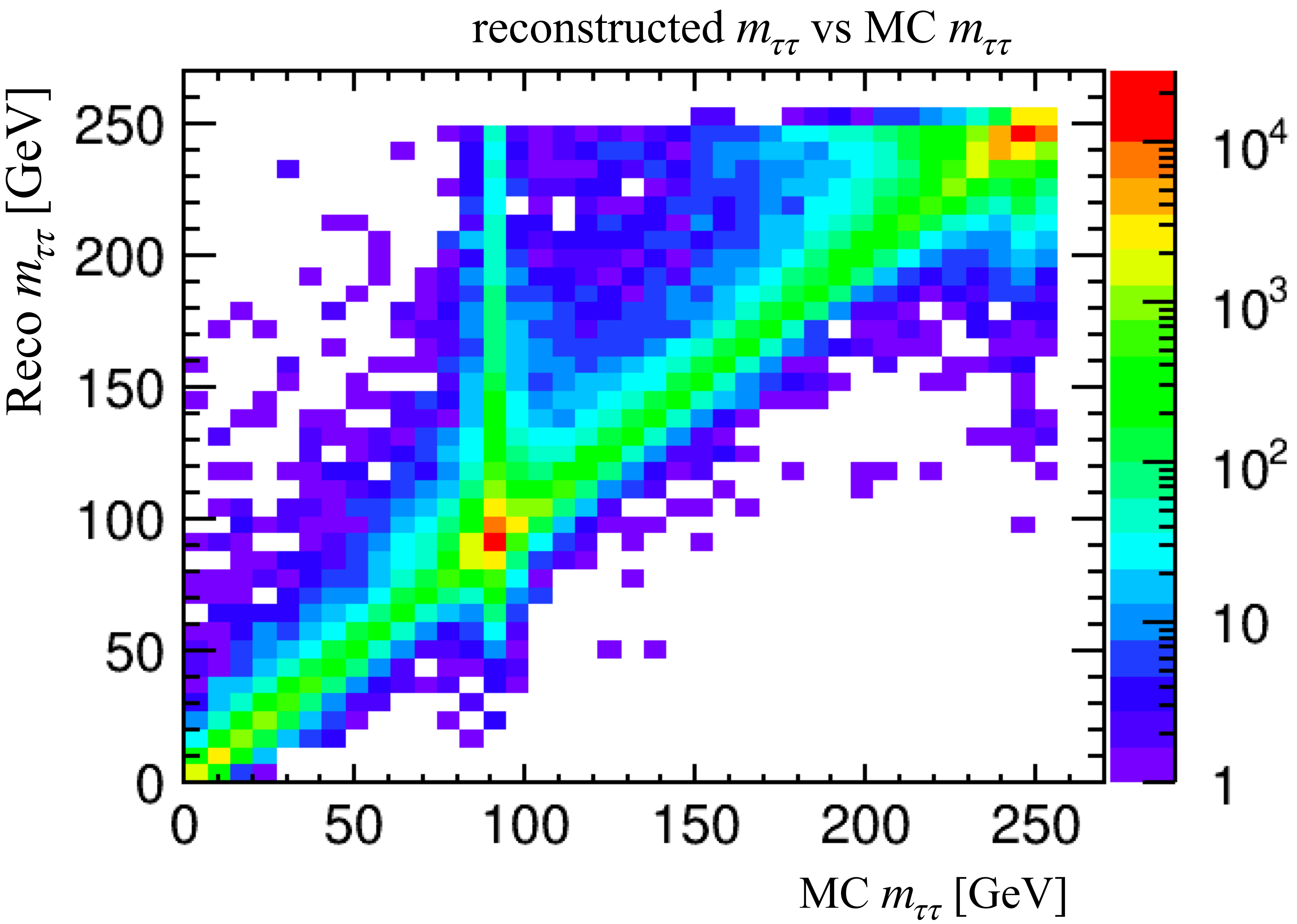
- Full reconstruction of $e^+e^- \to \tau^+\tau^-$ using impact parameter was investigated.
- For events with $m_{\tau\tau} \sim 250\ \text{GeV}$, new method efficiency is $> 80\,\%$.
  $m_{\tau\tau} \sim 91\ \text{GeV}$ $\sim 70\,\%$
- Polarimeters were reconstructed in the $\tau \to \pi\nu$ and $\tau \to \rho\nu$ decay modes.
- Reasonable agreement between MC truth polarimeter and the one from "Impact parameter method" for both $\tau \to \pi\nu$ and $\tau \to \rho\nu$ decay were found.

Future plan

- Understand the structure of the method's efficiency around the Z peak.
- Investigate the effect of full detector simulation and reconstruction.
- Quantify the precision with which the tau polarisation can be measured at ILC-250.
- Investigate search for new physics by using the tau polarisation.

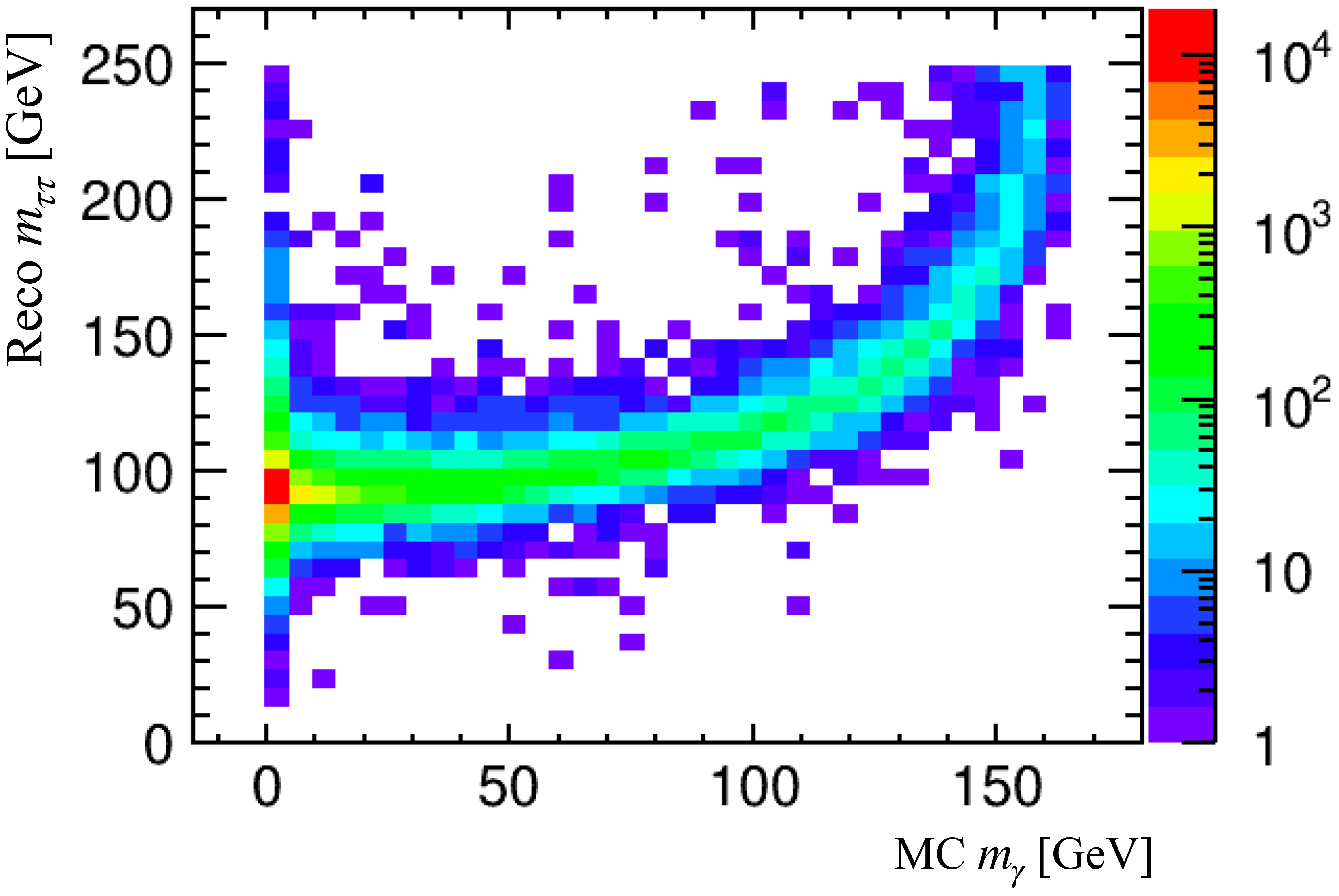


Entries
10^4
10^3
10^2
10
1
80 < MC $m_{\tau\tau}$ < 100 GeV
0
50
100
150
200
250
Reco $m_{\tau\tau}$ [GeV]

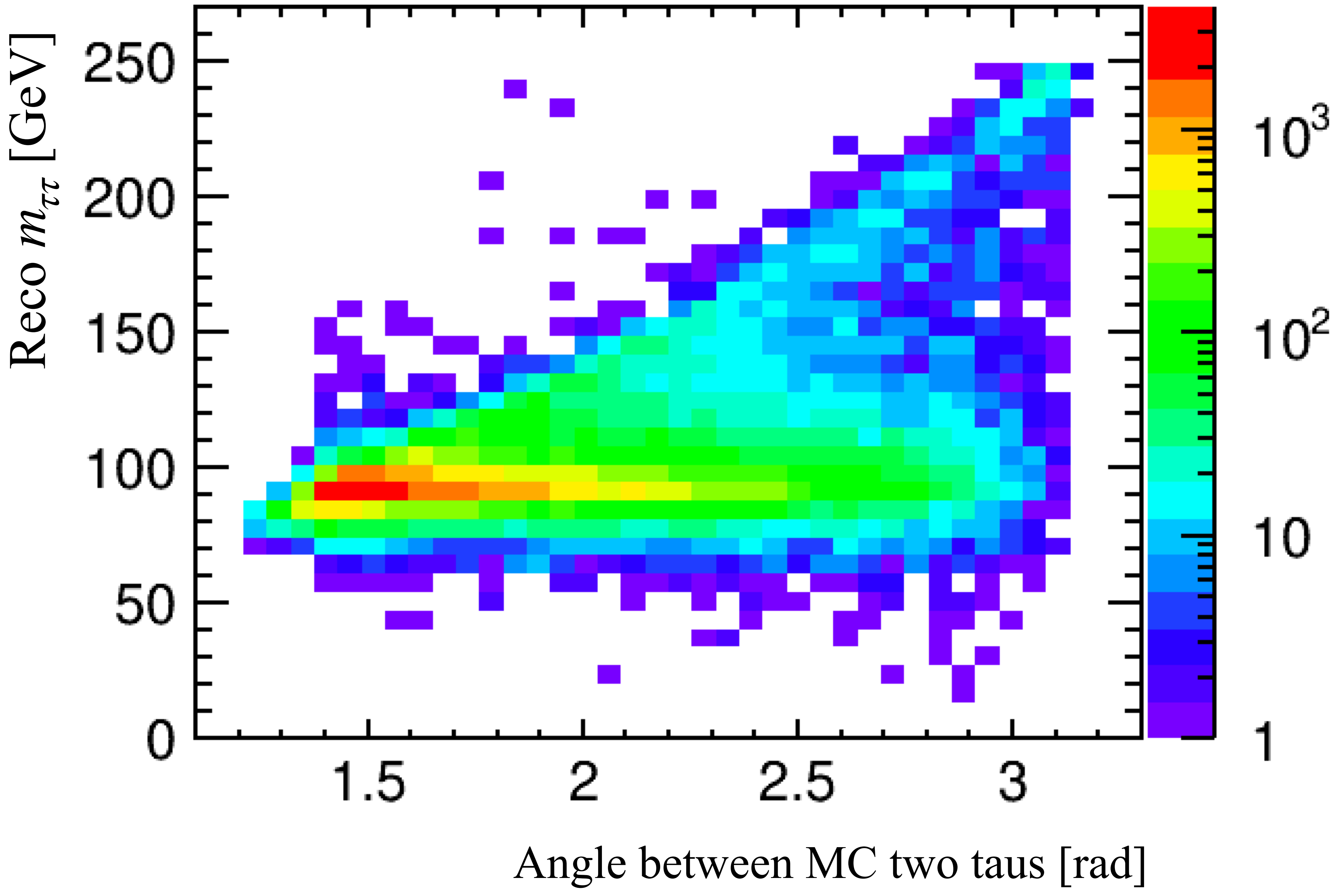


reconstructed $m_{\tau\tau}$ vs MC $m_{\tau\tau}$
Reco $m_{\tau\tau}$ [GeV]
250
200
150
100
50
0
0
50
100
150
200
250
MC $m_{\tau\tau}$ [GeV]
10^4
10^3
10^2
10
1

Entries
10^4
10^3
10^2
10
1
0
50
100
150
200
250
$80 < \text{MC } m_{\tau\tau} < 100$ GeV
ISR $p_T < 5$ GeV
Reco $m_{\tau\tau}$ [GeV]
reconstructed $m_{\tau\tau}$ vs MC $m_{\tau\tau}$
Reco $m_{\tau\tau}$ [GeV]
MC $m_{\tau\tau}$ [GeV]




```
tr->Draw("newmeth_mtt[0]:mc_isr_m","newmeth_mtt[0]>-9999 && MCttMass > 80 && MCttMass<100","colz")
```

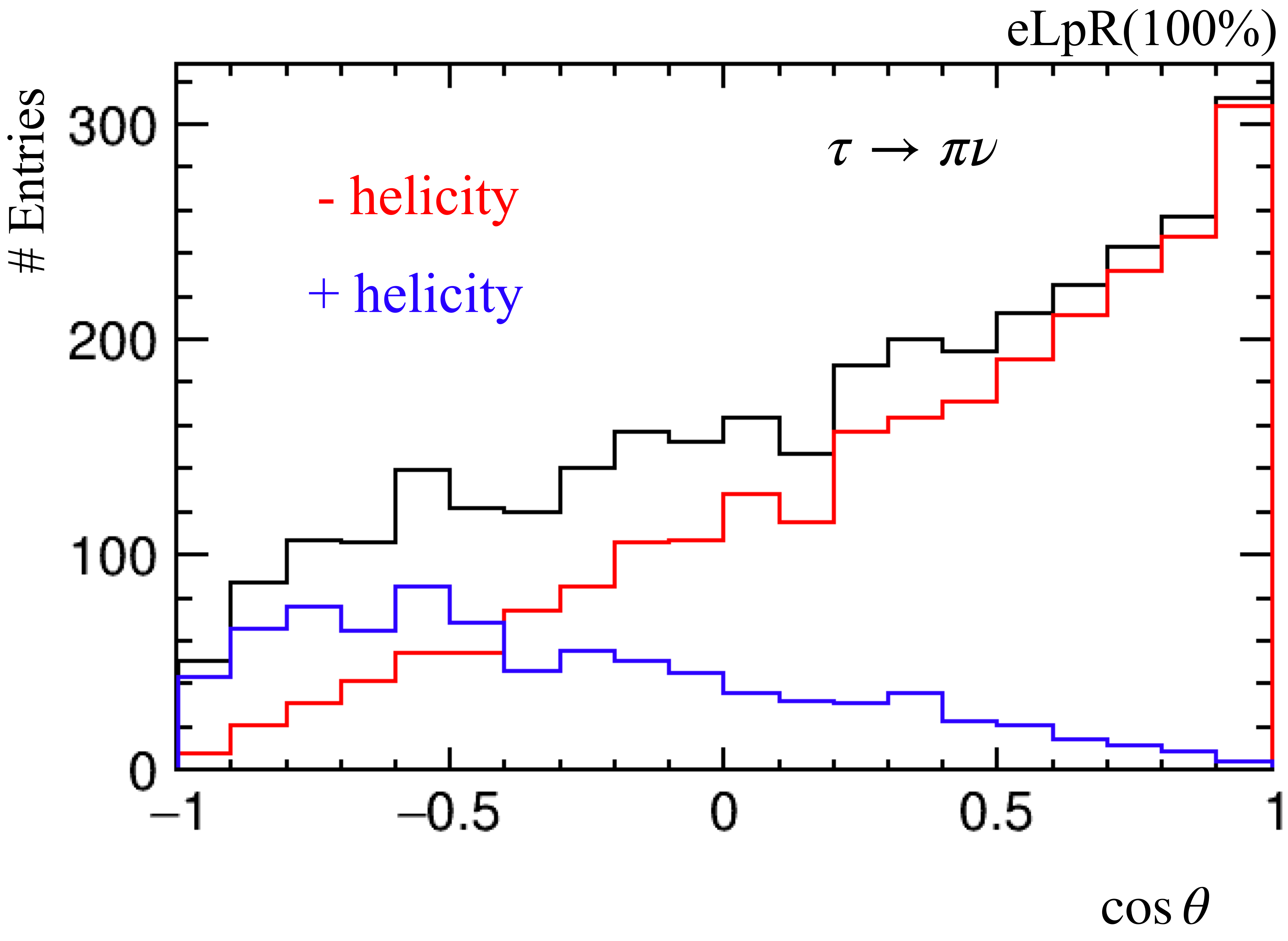



```
tr->Draw("newmeth_mtt[0]:BMCAngTauTau","newmeth_mtt[0]>-9999 && MCttMass > 80 && MCttMass<100","colz")
```

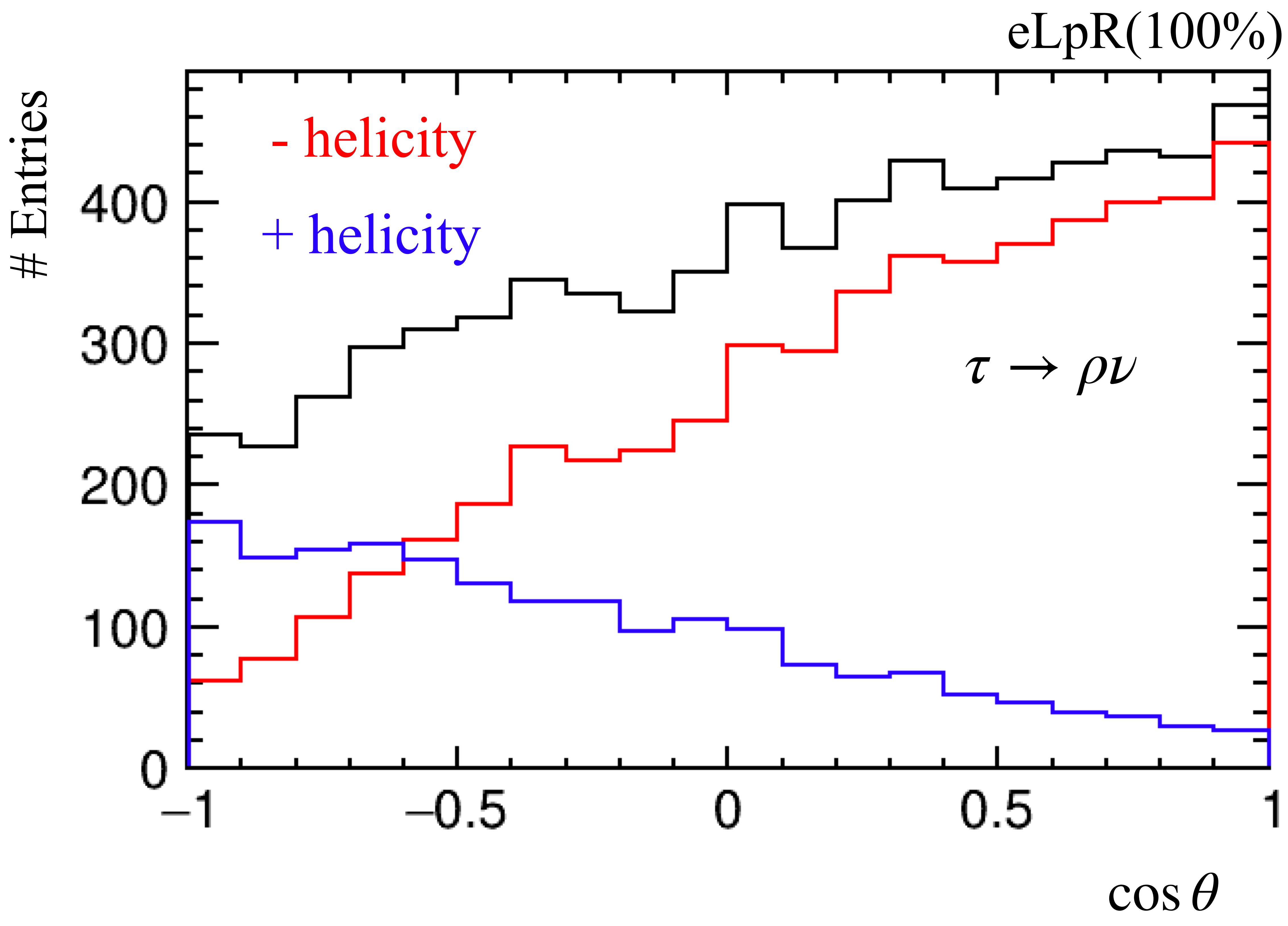
Polarimeter

Polarimeter using reconstructed ν

$\tau \rightarrow \pi\nu$

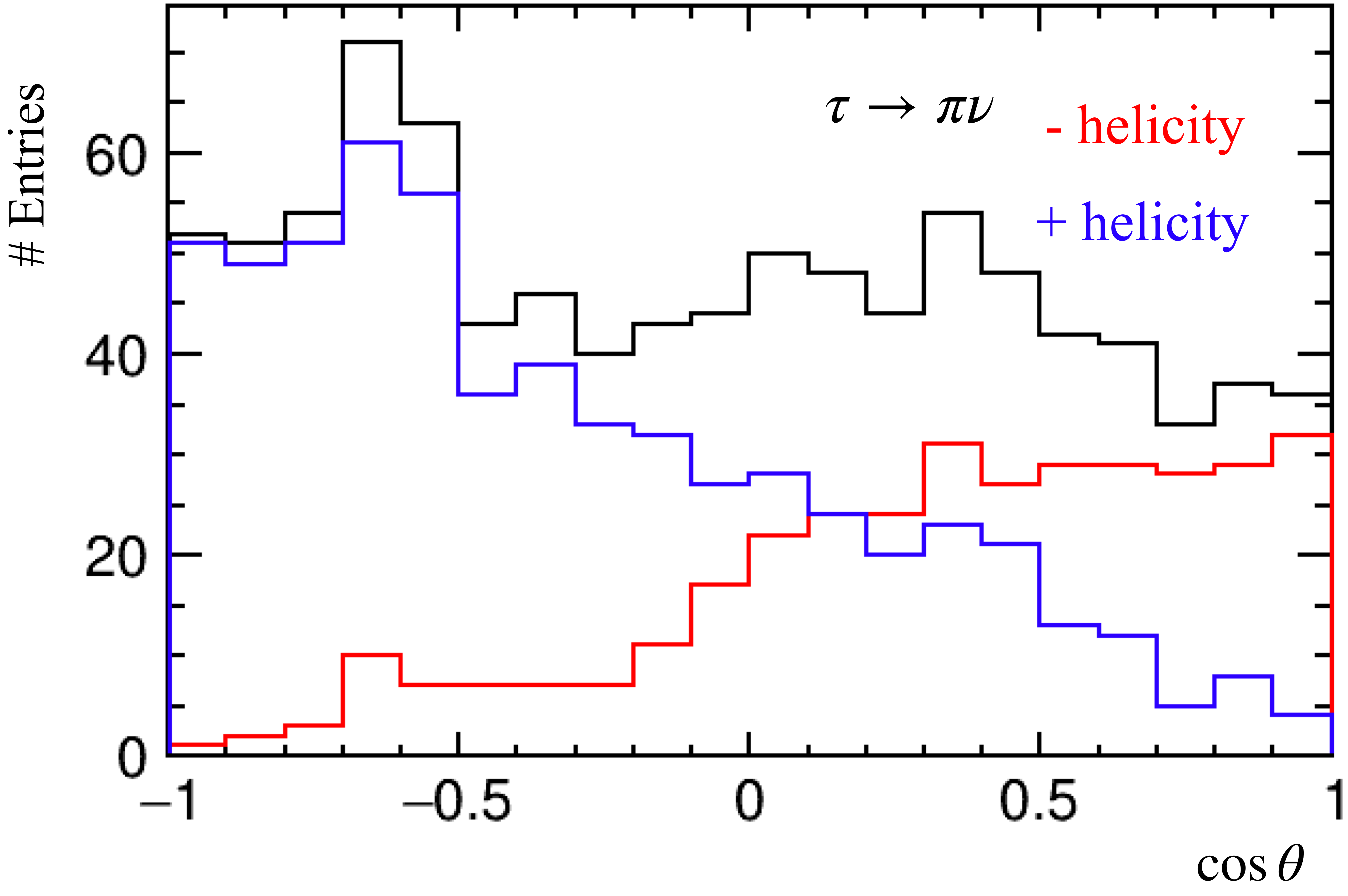


$\tau \rightarrow \rho\nu$

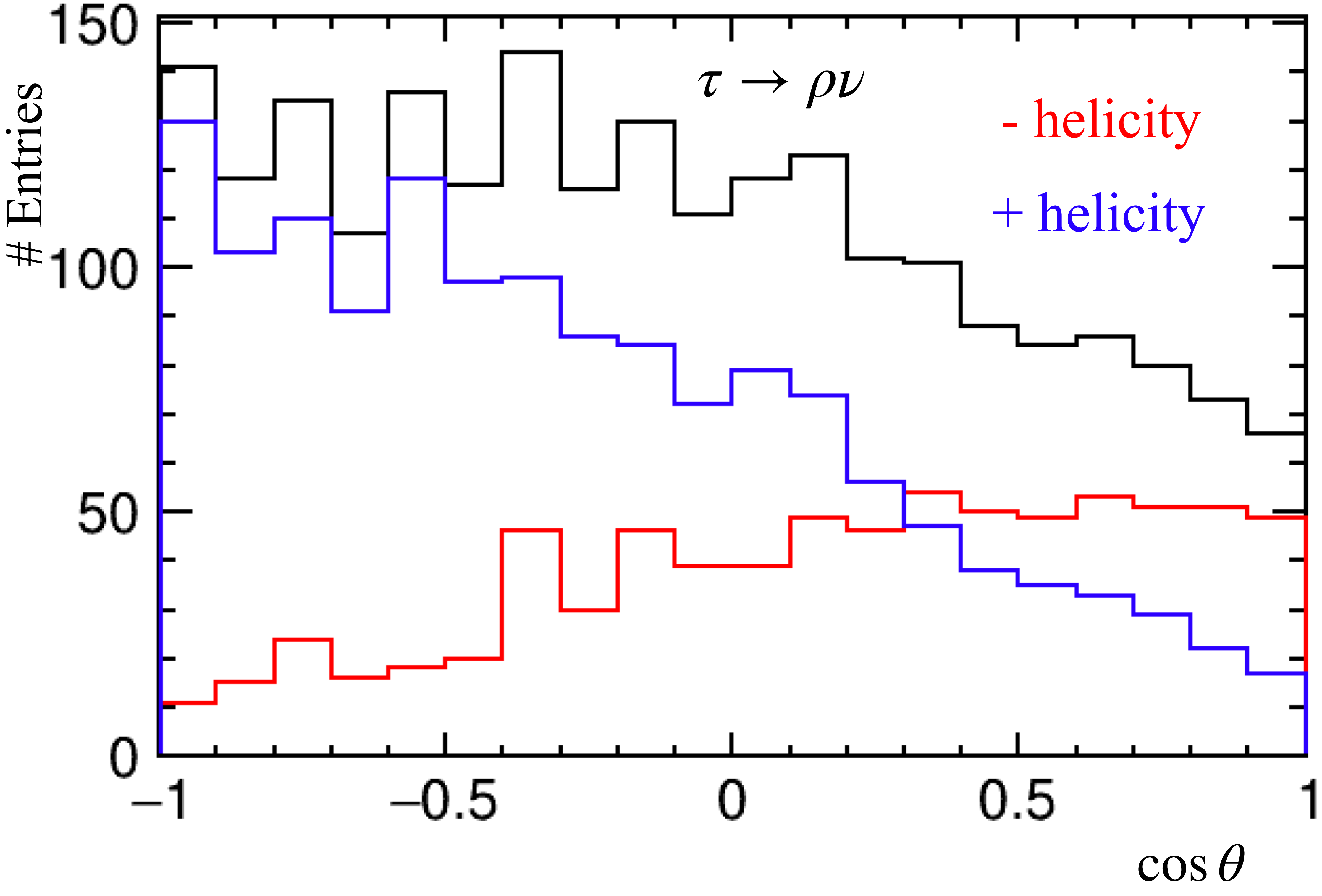


Polarimeter using reconstructed ν

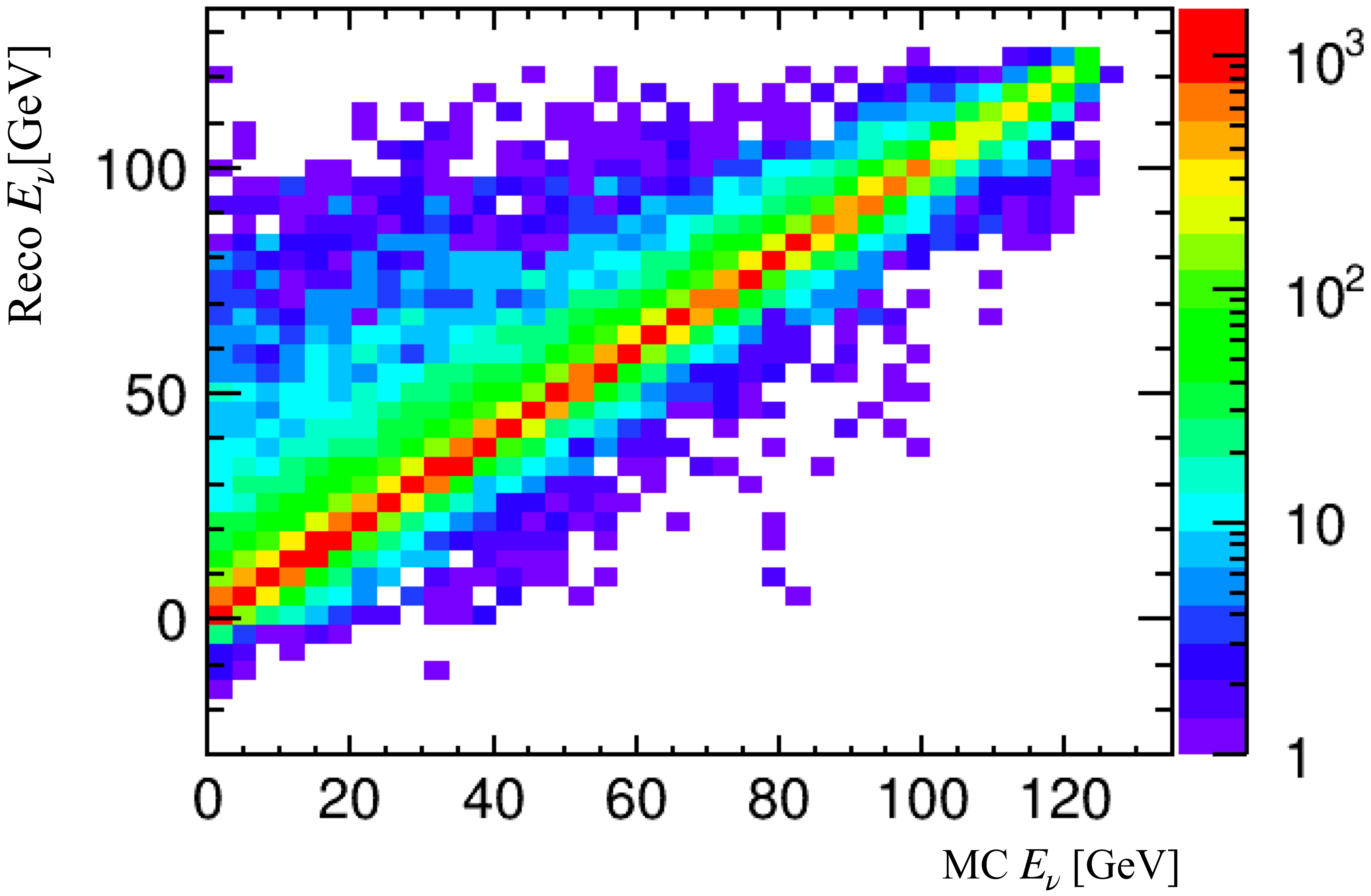
$\tau \to \pi\nu$



$\tau \to \rho\nu$



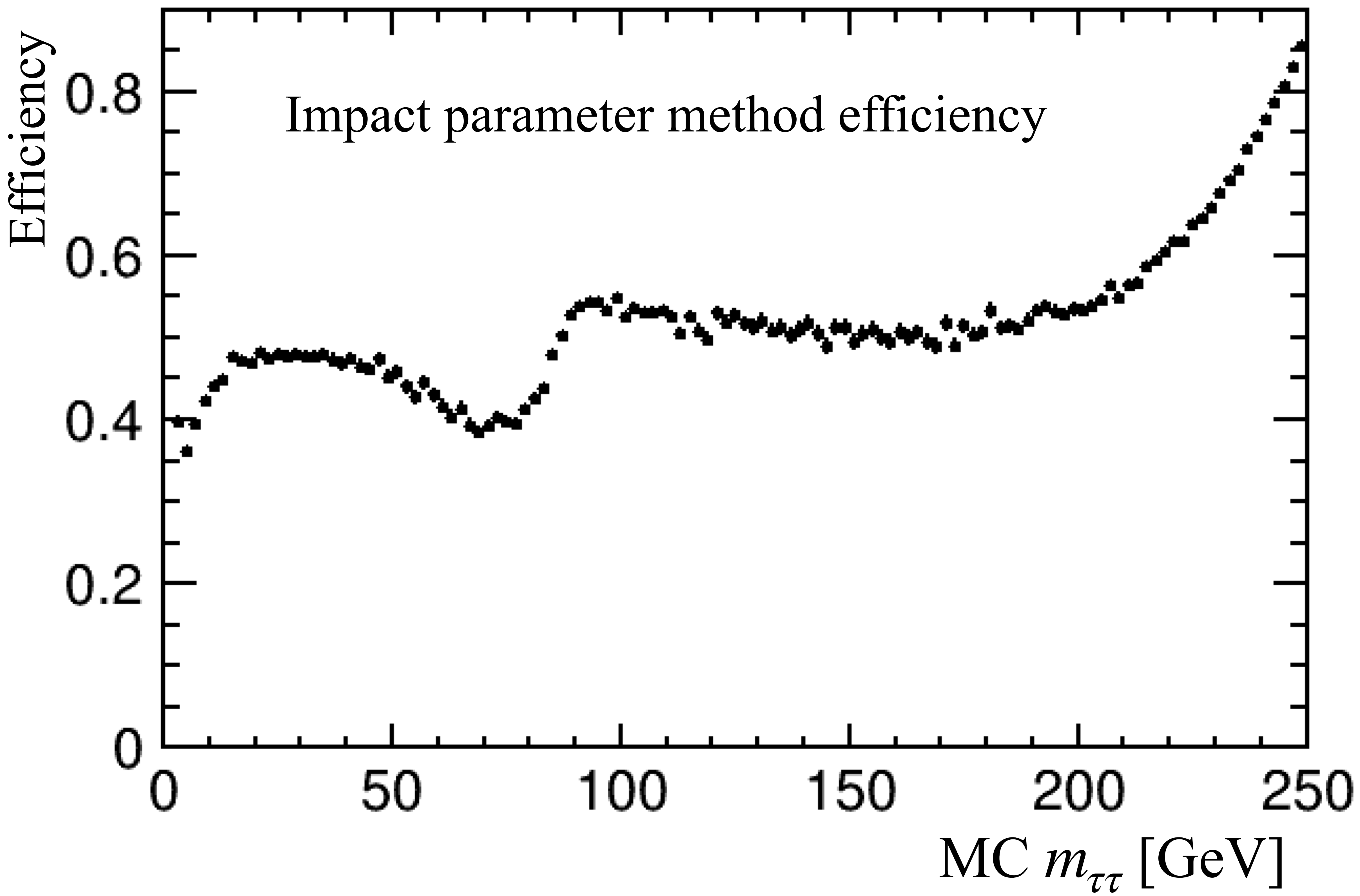
Reconstructed E_ν

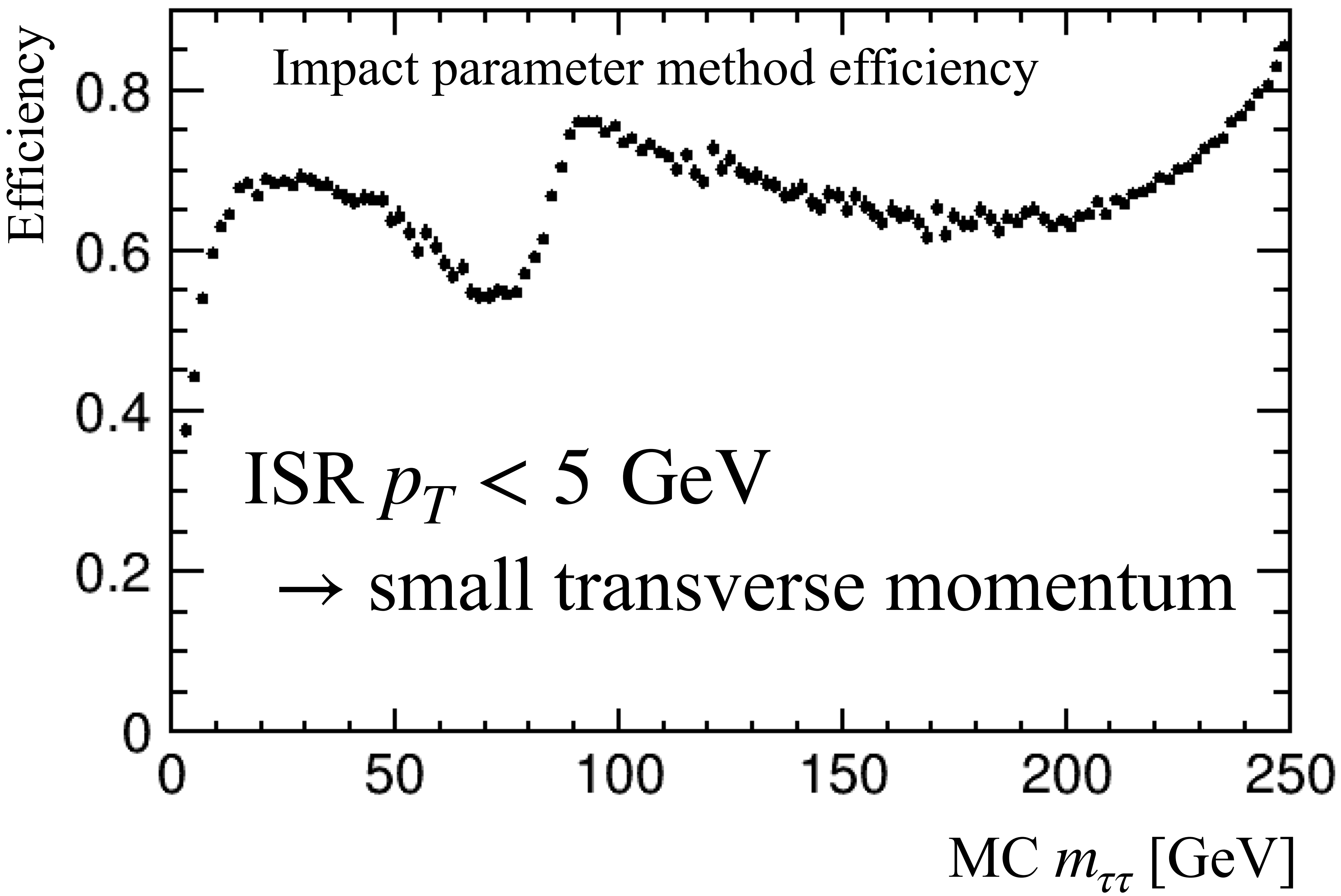


Future plan

- Investigate search for new physics by using the tau polarisation.
- Investigate the effect of full detector simulation and reconstruction.
- Quantify the precision with which the tau polarisation can be measured at ILC-250.
- Understand the structure of the method's efficiency around the Z peak.
- Consider how to handle up to four possible solutions that can be found.

Find solutions





Efficiency improved even for low $m_{\tau\tau}$ region

There is an interesting structure around Z peak which is not yet fully understood

Future plan

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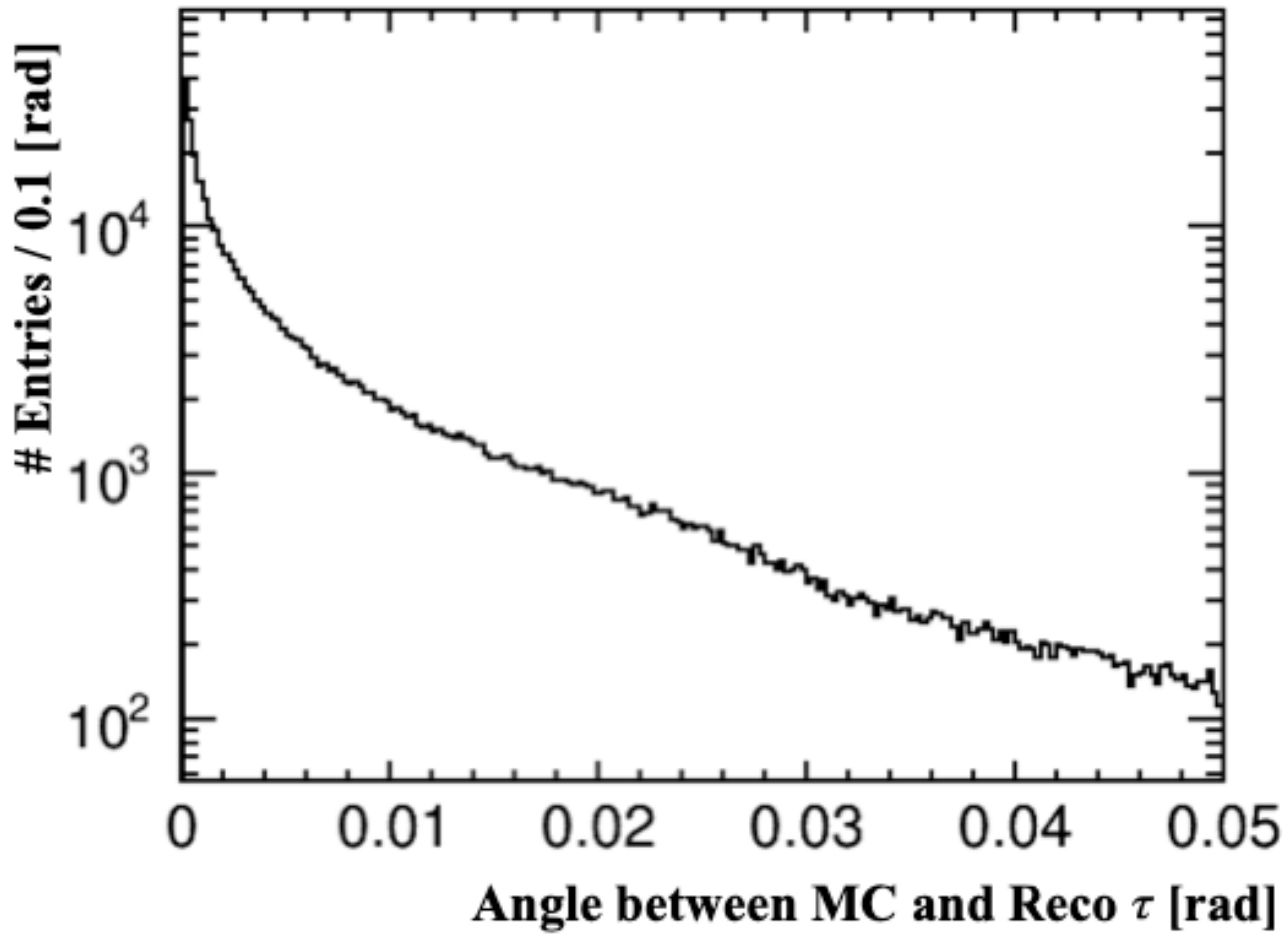
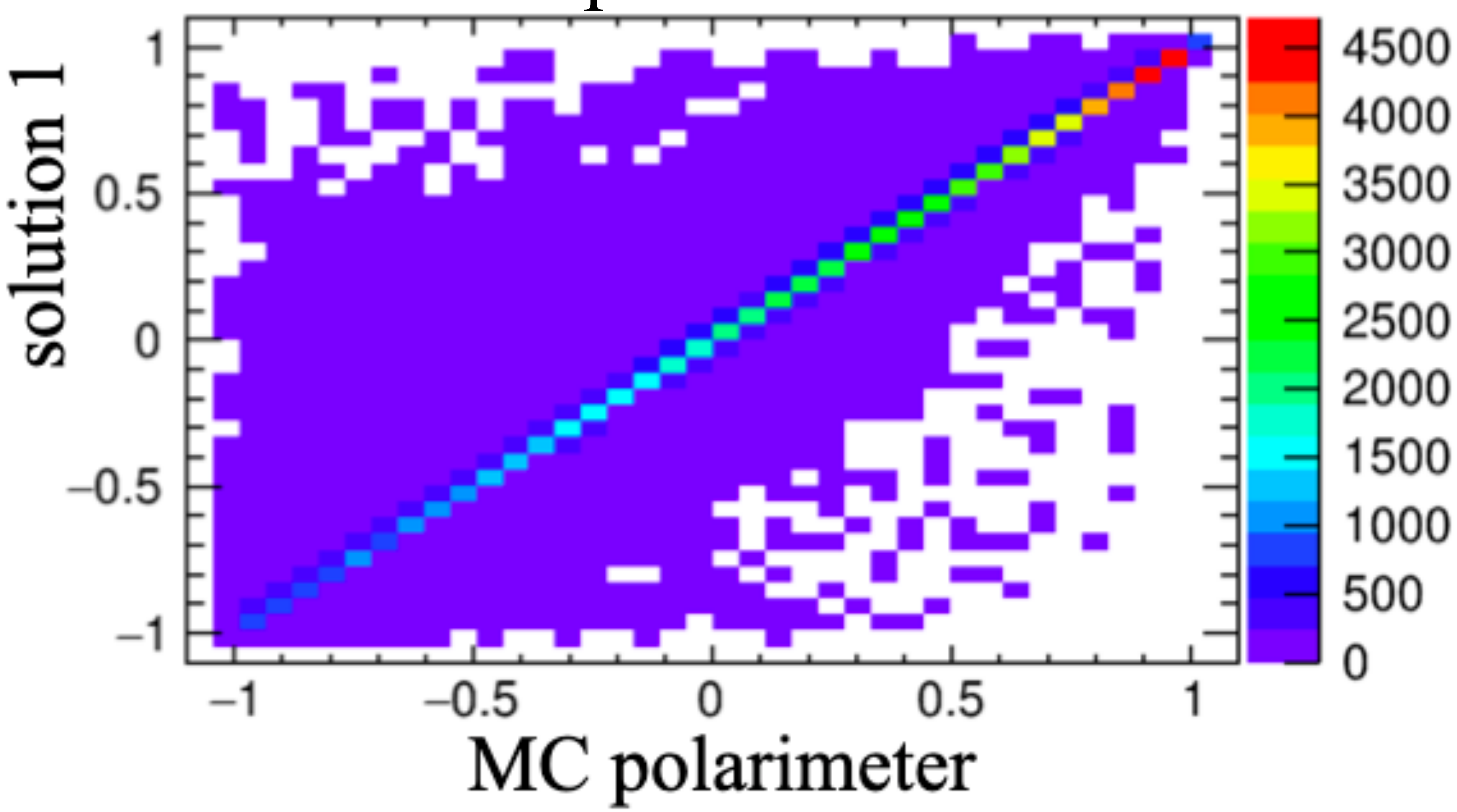
Future plan

Comparison with MC

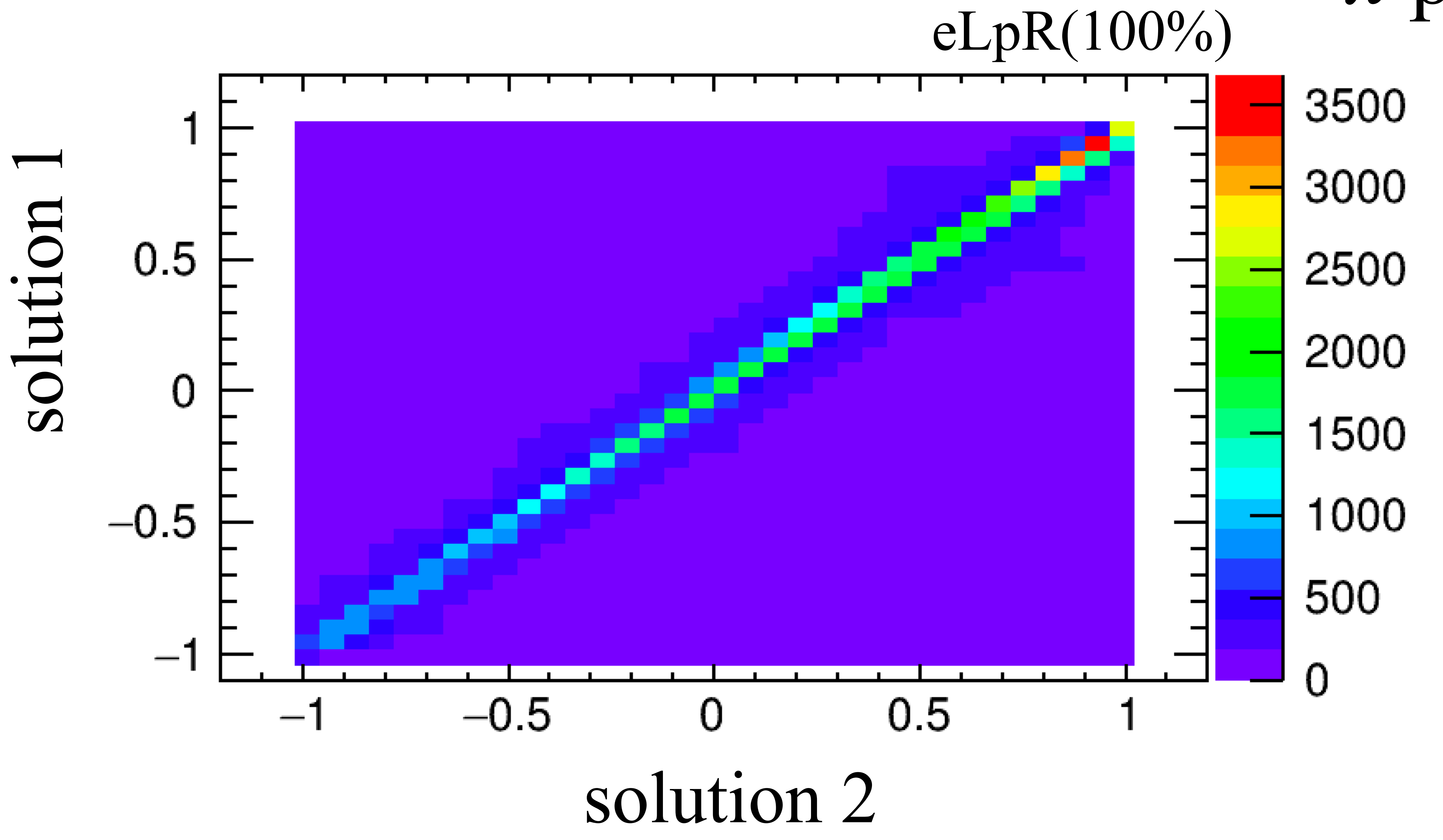


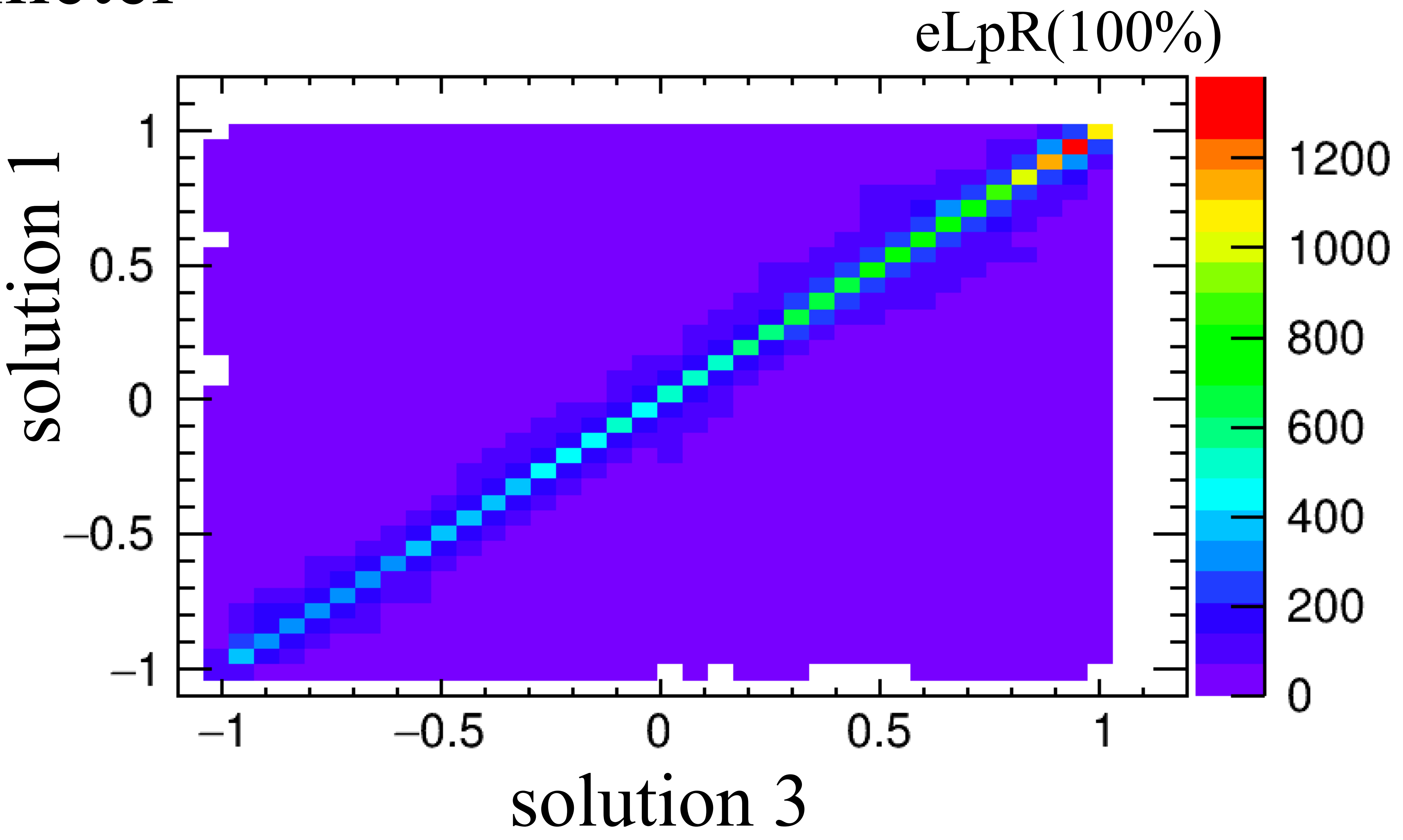


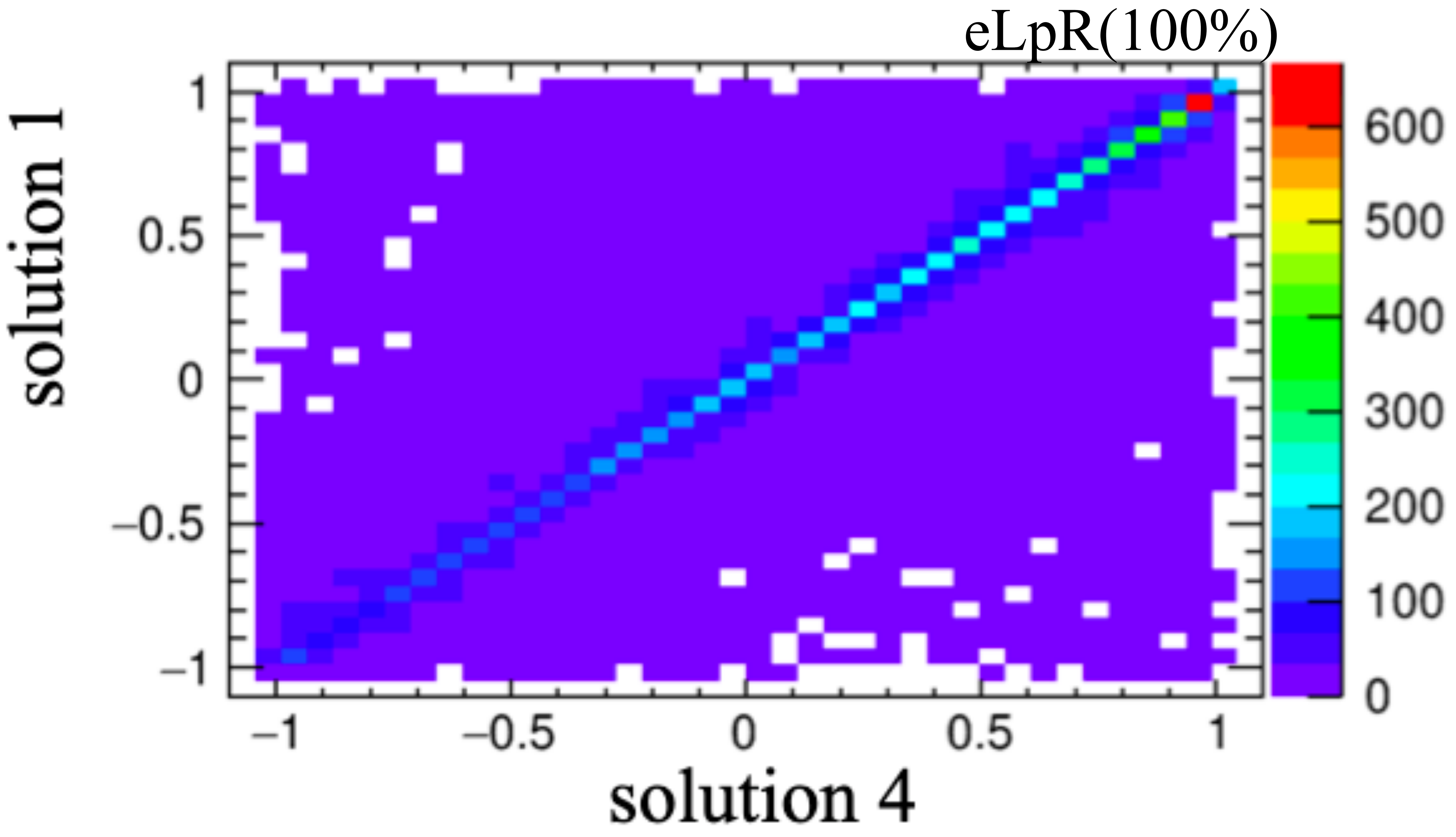
The reconstructed direction is typically within a few mrad of the true direction.

reasonable agreement between MC and reconstructed tau

π polarimeter





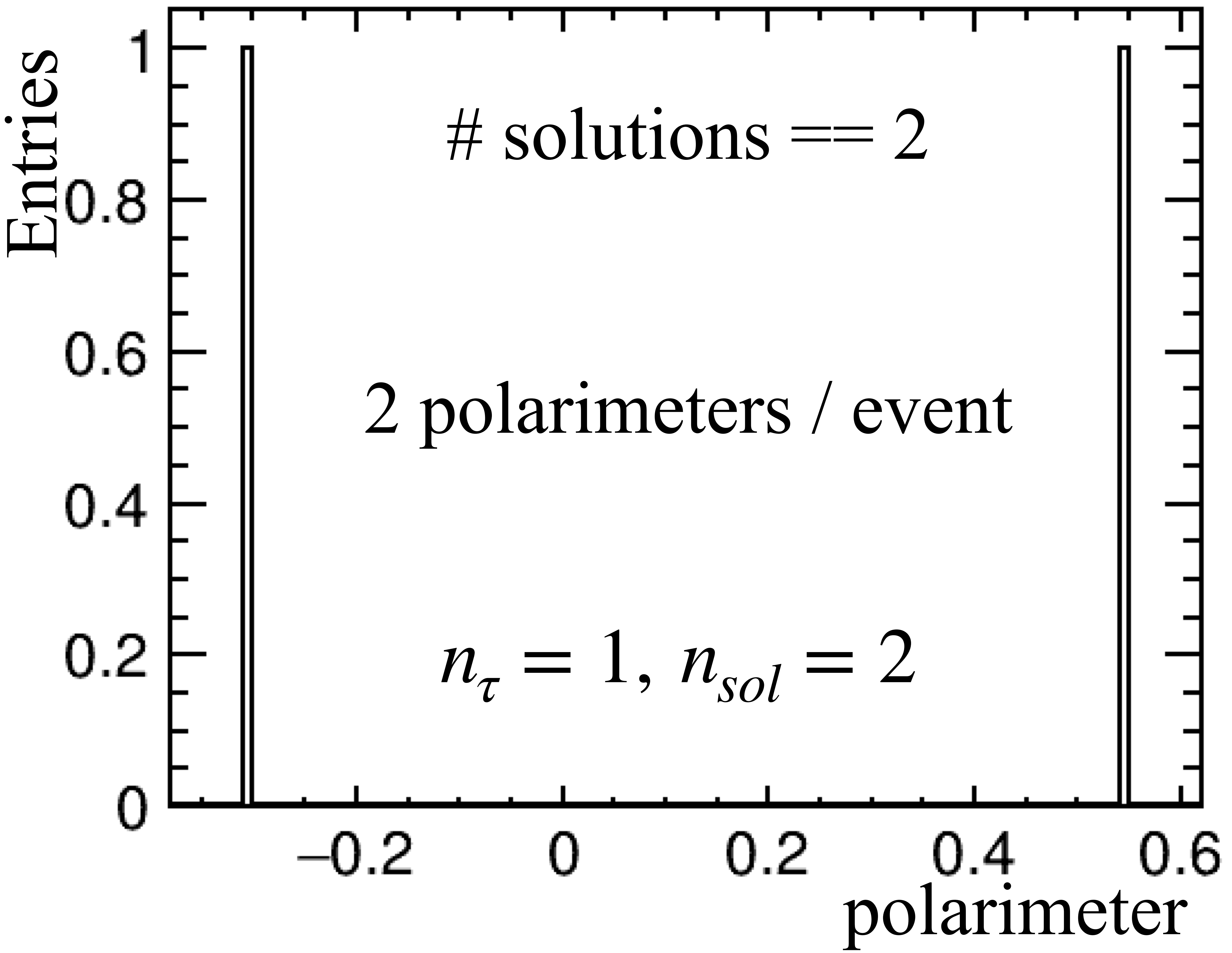


Correlations are found in 4 possible solutions.

Consider how to handle these solutions to extract the polarimeter

If each tau has several solutions, apply <u>equal</u> weight

$$\text{weight} = \frac{1}{n_\tau \cdot n_{sol}}$$



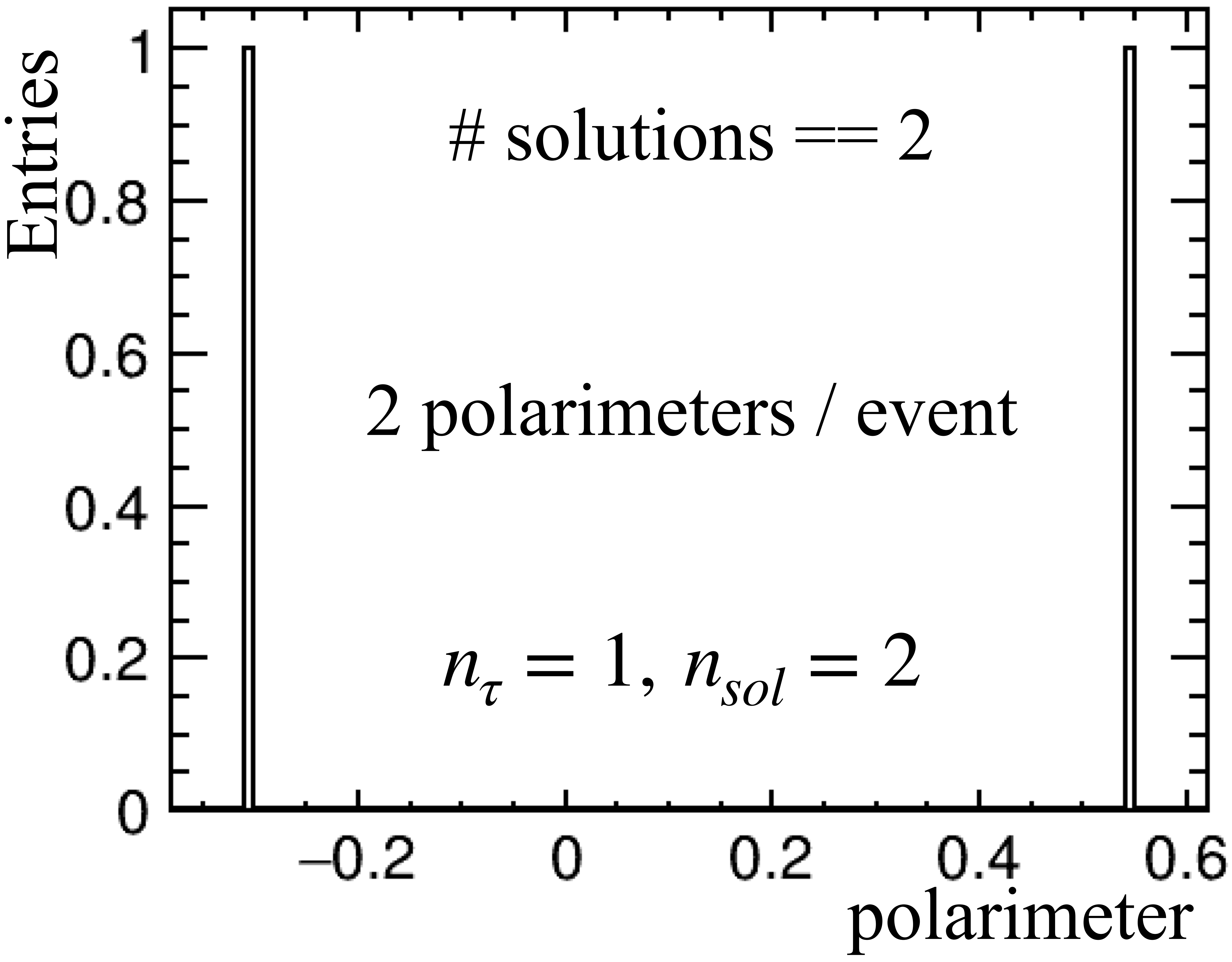
cf.

two taus have a polarimeter : each tau has one solution => $n_\tau = 2,\ n_{sol} = 1$

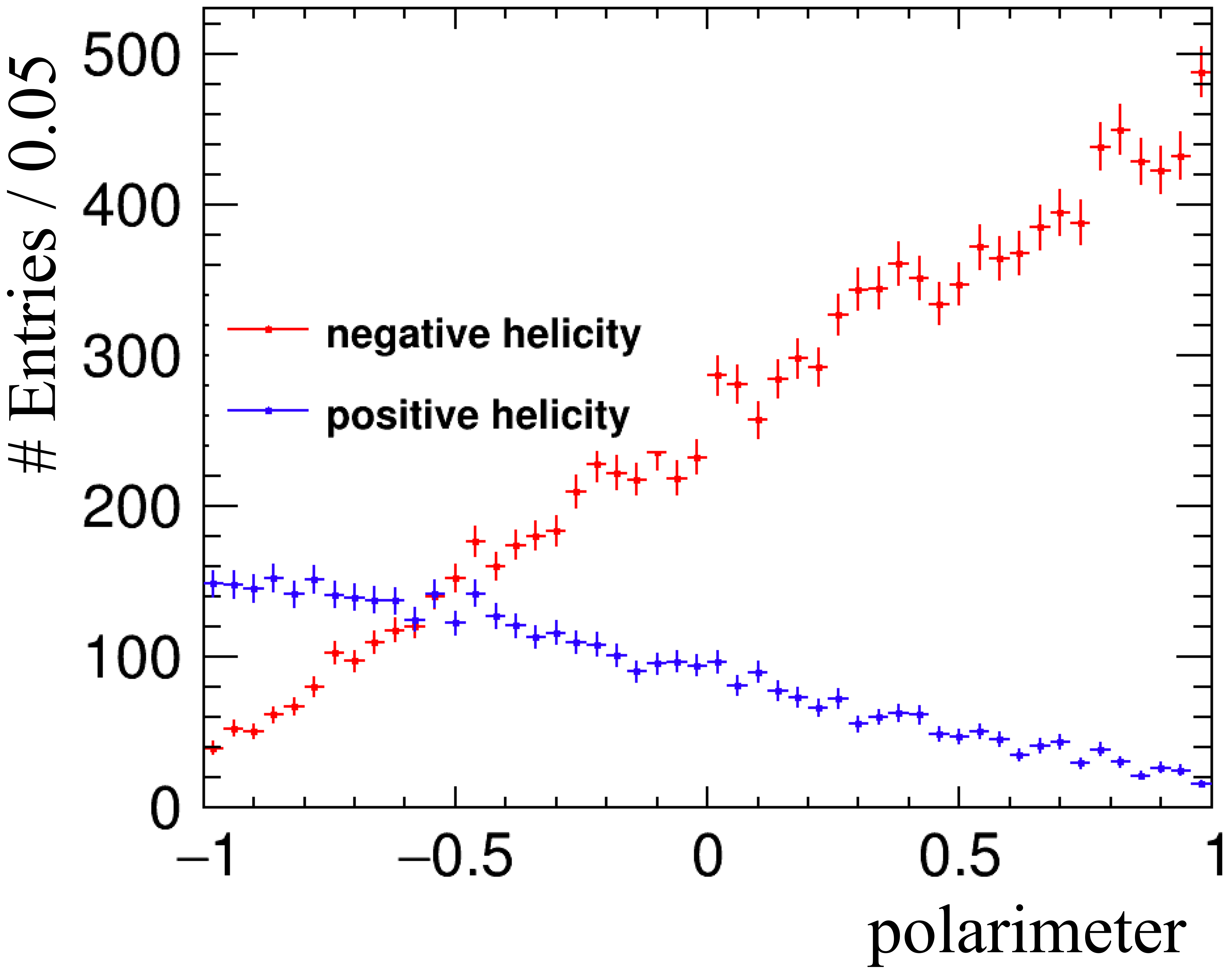
two solutions => $n_\tau = 2,\ n_{sol} = 2$

If each tau has several solutions, apply <u>equal</u> weight

$$\text{weight} = \frac{1}{n_\tau \cdot n_{sol}}$$



we are also currently applying weights to take into account tau life-time, decay length likelihood

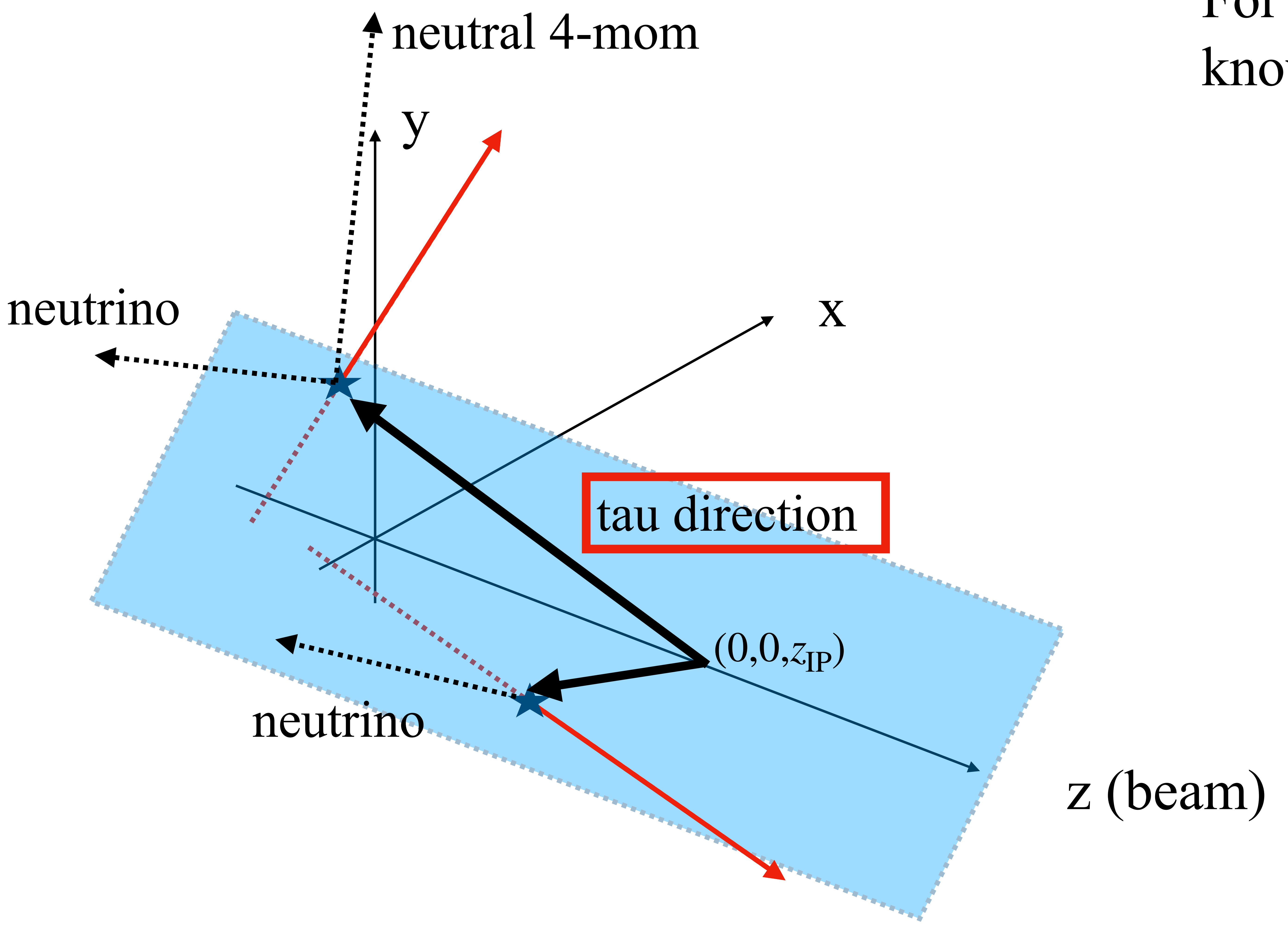


weighted histogram

several polarimeters / event

=>we cannot do pseudo-exp

=> use Jacknife method



For a given (ϕ, z_{IP}),
know two tau's momentum direction

- visible daughter momentum
- tau mass constraint
- 1-neutrino assumption

⟹ 2 solutions for each tau's energy

⟹ 4 solutions / event

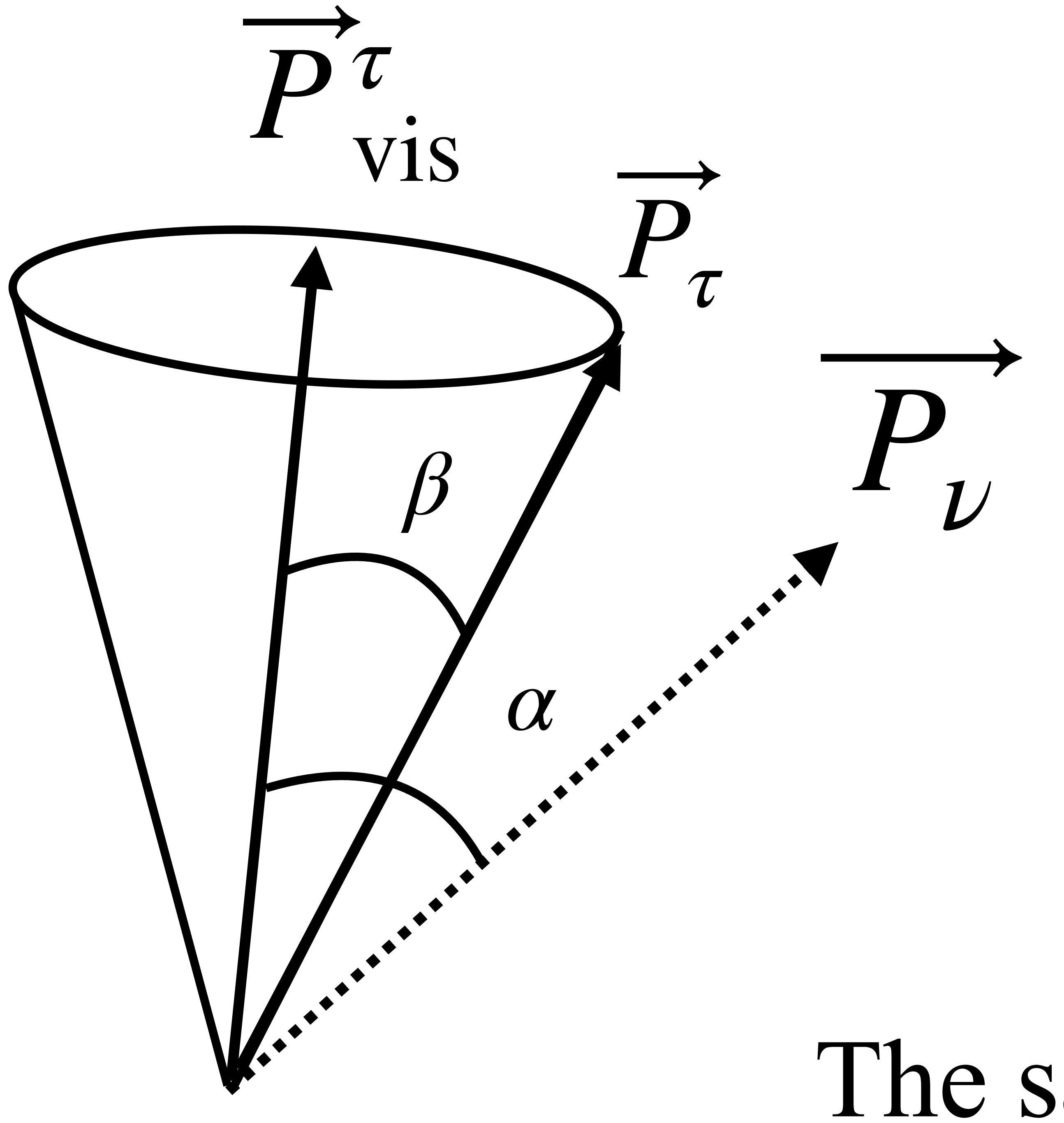
τ reconstruction method

Assume

- 1 neutrino per tau
- $m_\tau = 1.776$ GeV
- $E_\tau = \dfrac{E_{cm}}{2}$

from these assumptions, τ direction must make an angle β to the visible τ momentum

$$\cos\beta = f(\overrightarrow{P}^{\tau}_{\text{vis}}, m_\tau, E_\tau)$$



$\overrightarrow{P}^{\tau}_{\text{vis}}$: tau visible daughter momentum

$\overrightarrow{P}_{\nu}$: neutrino momentum

$\overrightarrow{P}_{\tau}$: tau momentum

The same for the other tau

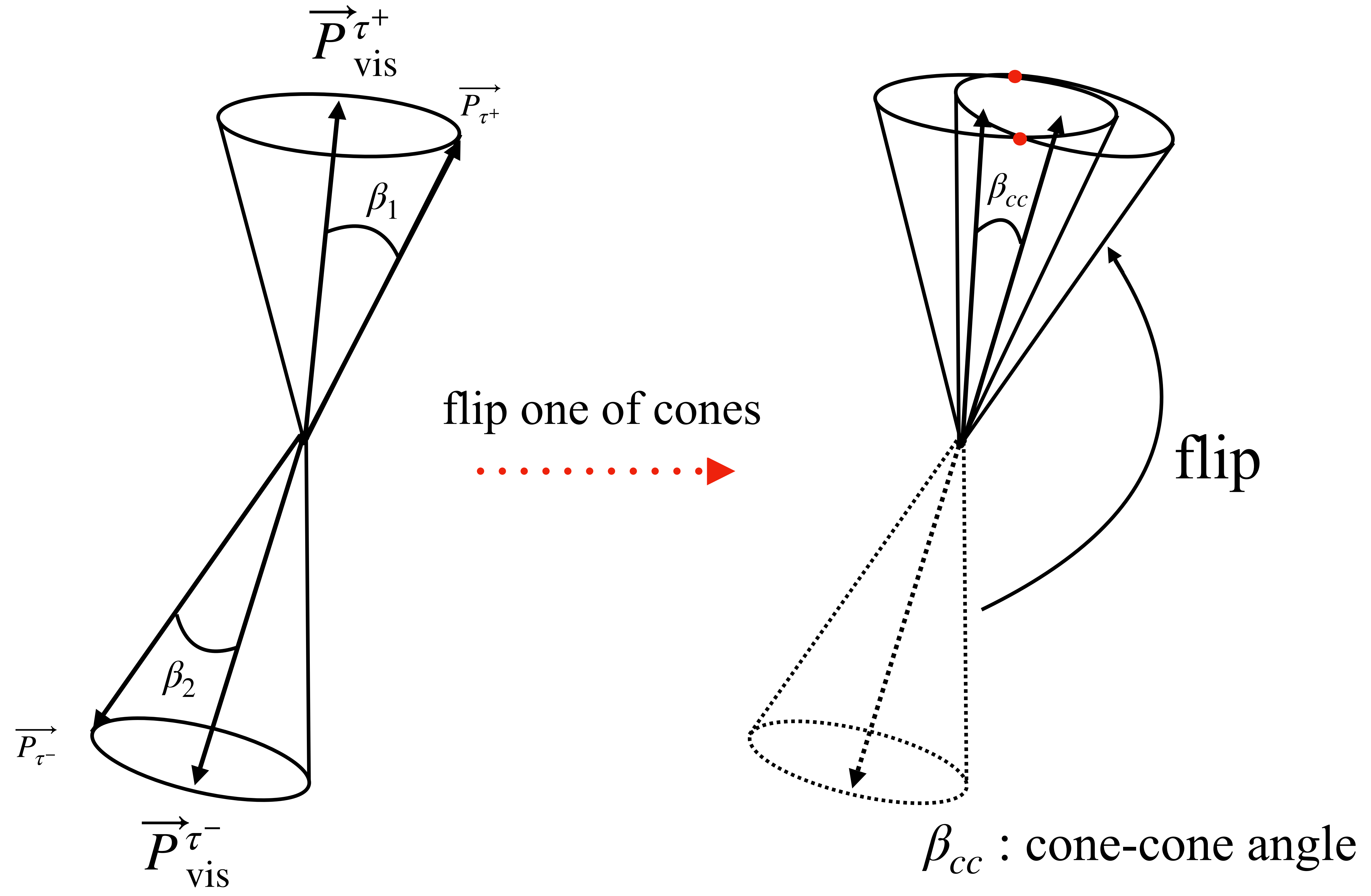
τ reconstruction method

We further assume

- two taus are back-to-back

To reconstruct tau momentum, flip one of the cones and find the intersections.

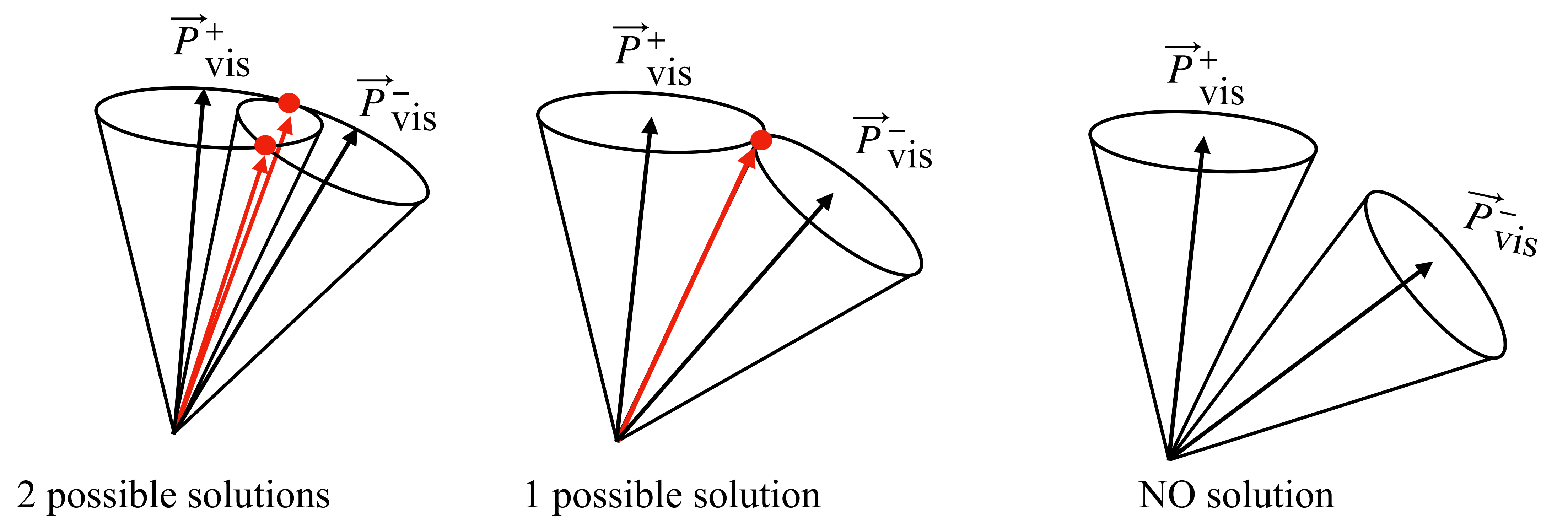
The intersection of the cones are the candidate τ momentum directions.

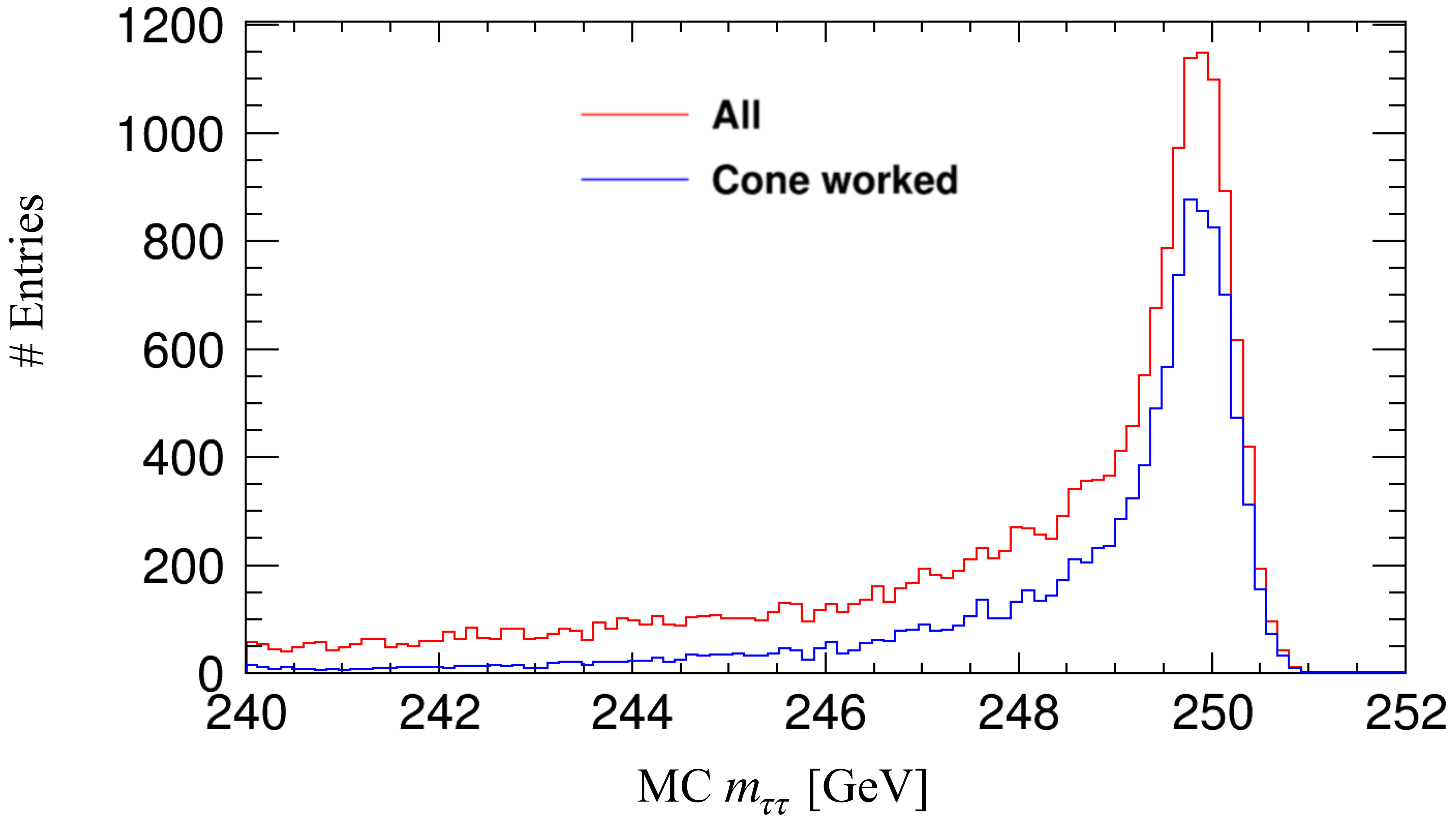


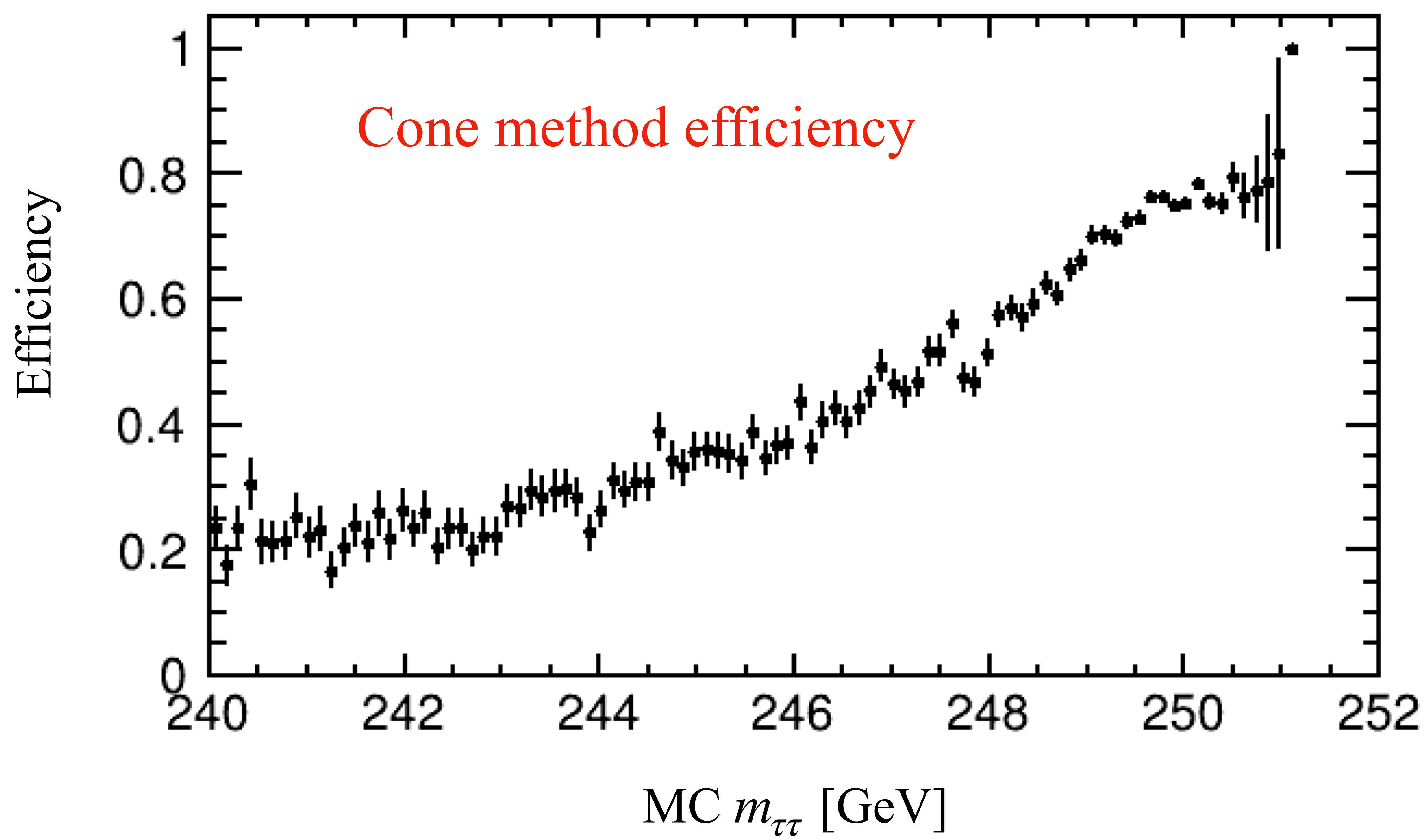
We call this "Cone method"

Find solutions

If at least one intersection point was found, there is a solution.



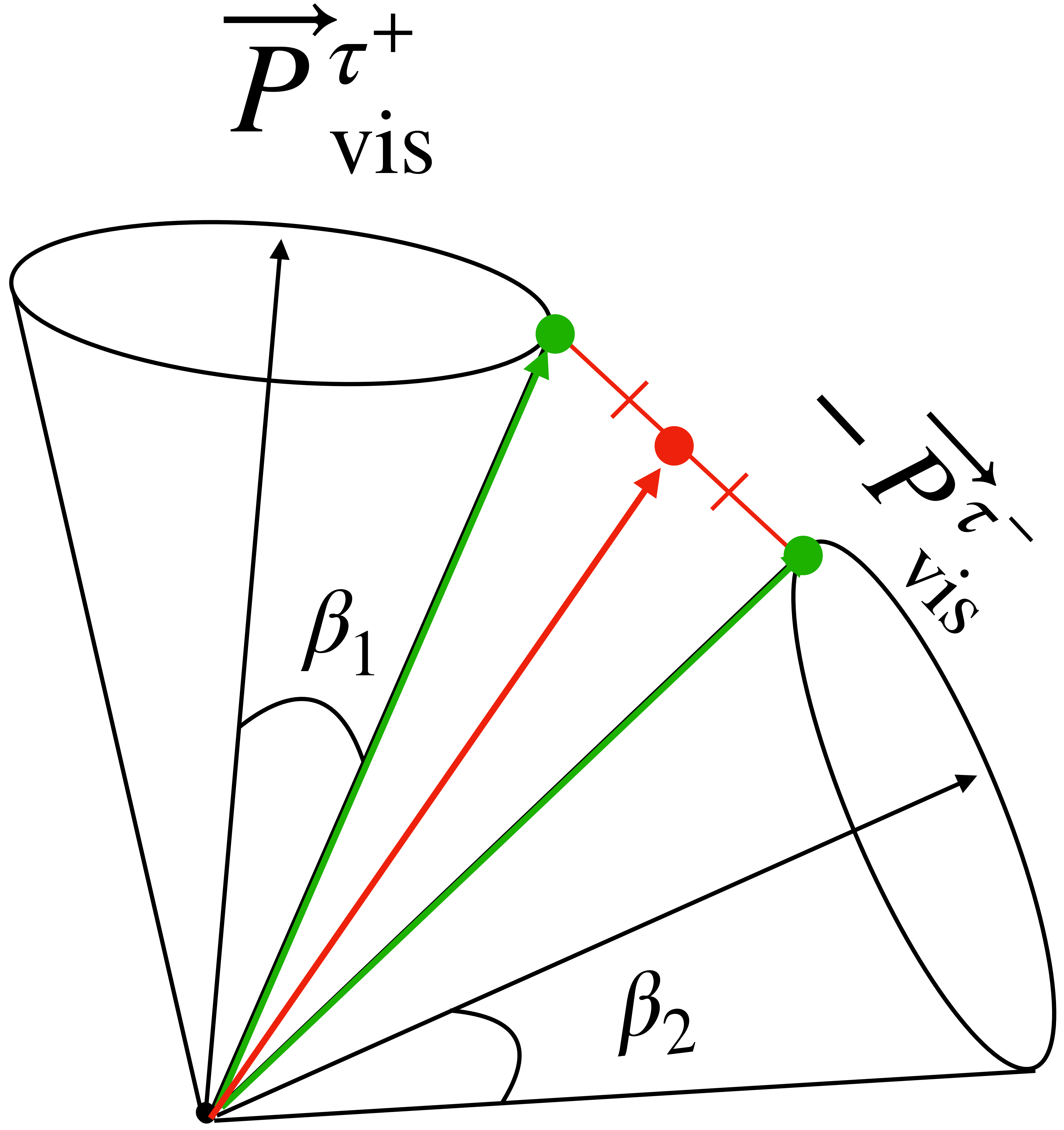




Cone method efficiency is ~ 80 % for events with $m_{\tau\tau}$ ~ 250 GeV

Midpoint method

For events for which "Cone Method" cannot find a solution



take a midpoint of the closest approach points of the two cone edges

and use this new vector as a solution

We call this "Midpoint method"

Various levels of "cheating" and methods

Two levels of cheating

1. Using true neutrino momentum from MC.
2. Using true MC visible tau daughters.

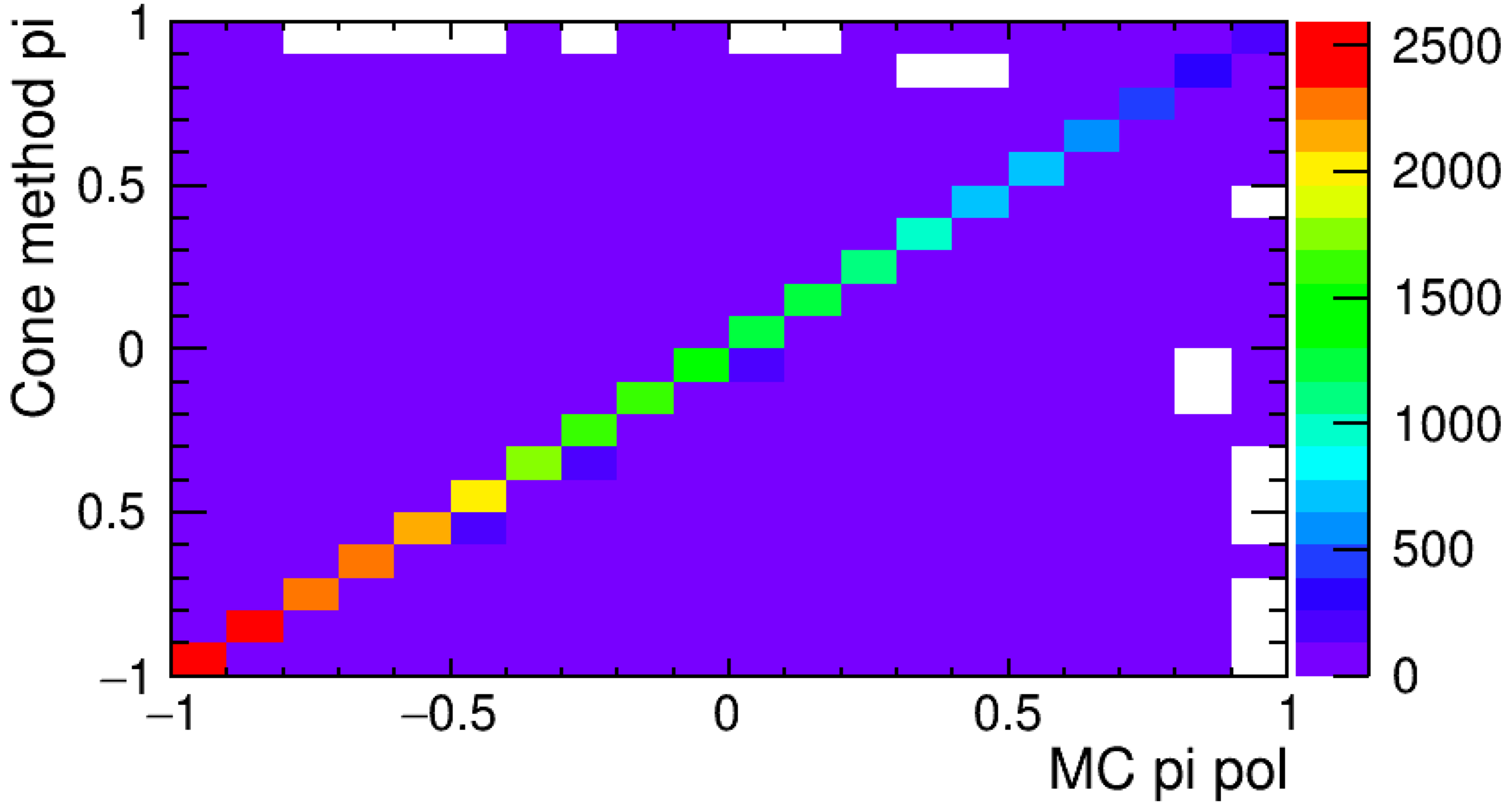
   2.1 "Cone method" to estimate the neutrino momentum.

   2.2 If Cone method fails, "Midpoint method"

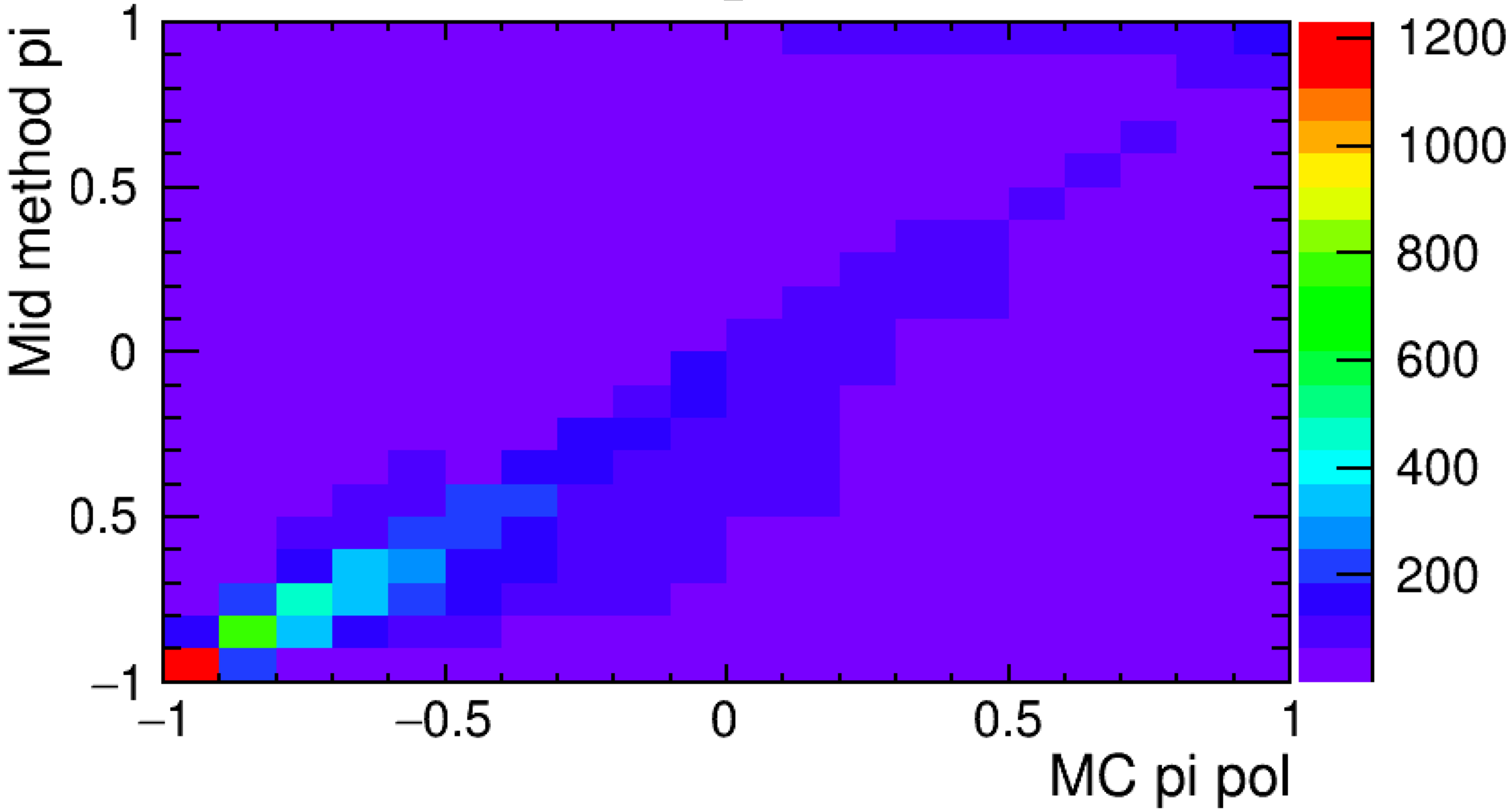
Polarimeter: single pi decay

Polarimeter vectors of $\tau \to \pi\nu$ in τ rest frame $\qquad h(\tau^{\pm} \to \pi^{\pm}\nu) \propto p_{\pi^{\pm}}$

true vs Cone method



true vs Midpoint method



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

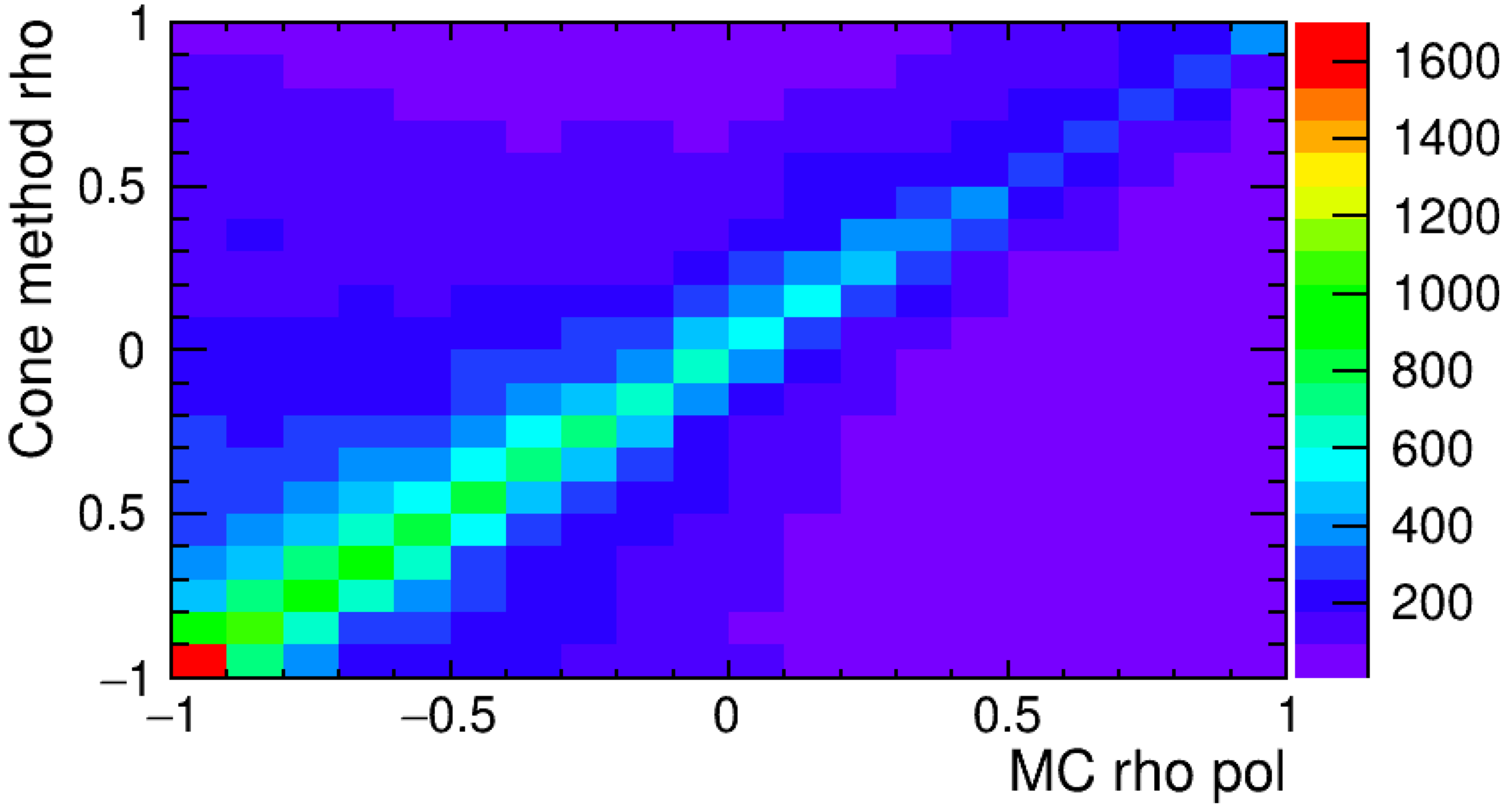
Cone method works better than Midpoint method.

Polarimeter: rho decay

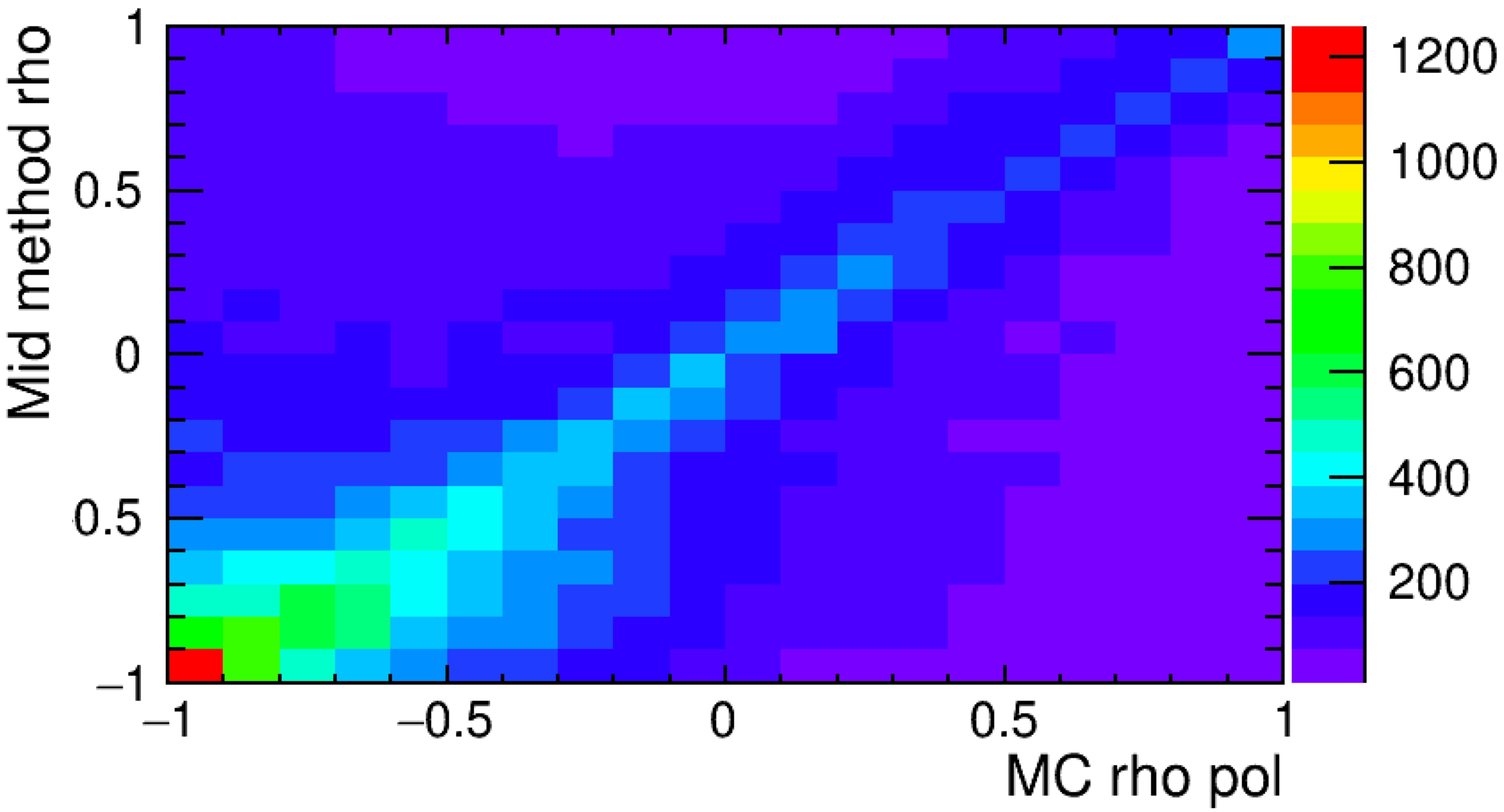
Polarimeter vectors of $\tau \to \rho\nu$ in τ rest frame

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

true vs Cone method



true vs Midpoint method



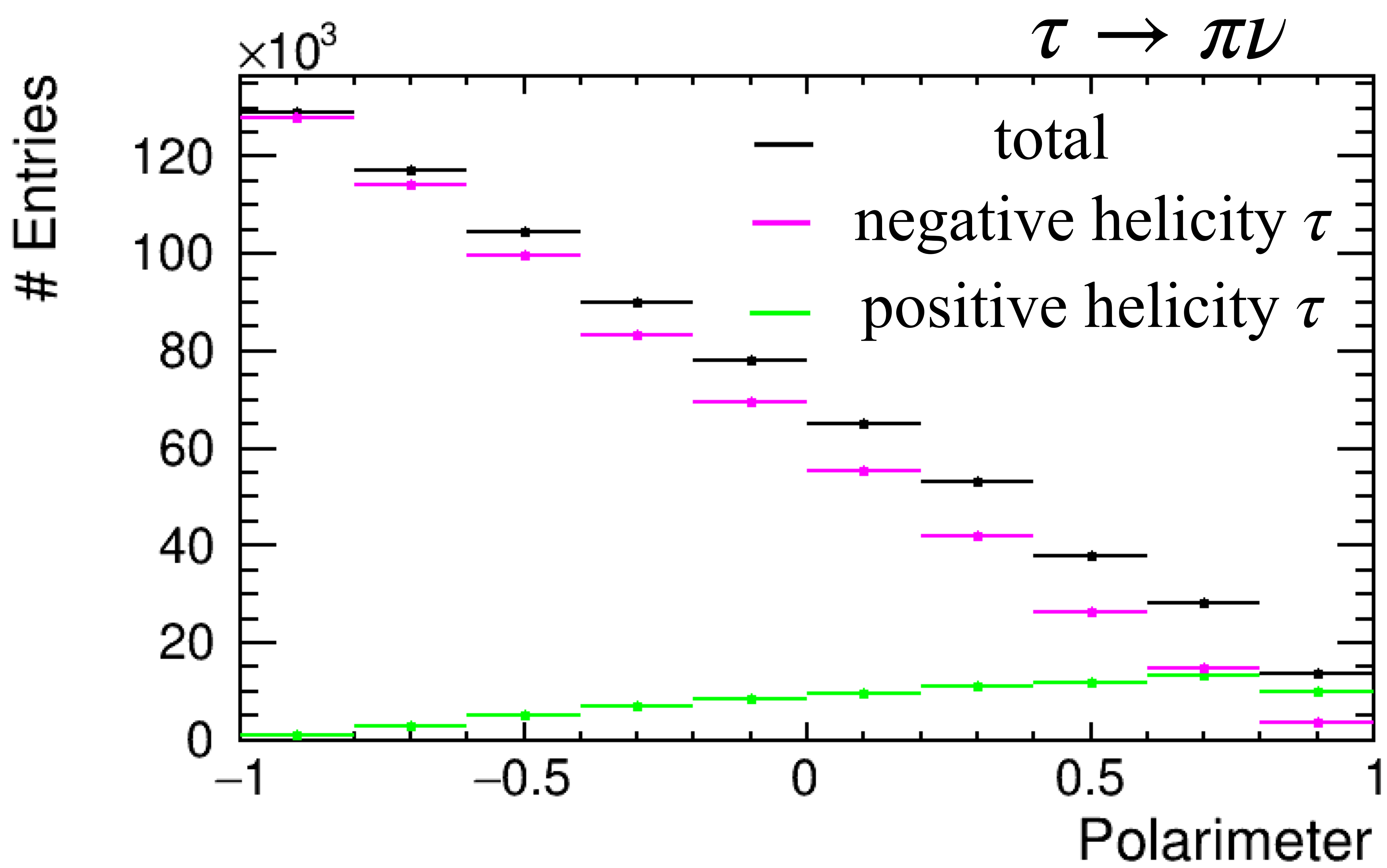
Extracted polarimeter is less precise than $\tau \to \pi\nu$

Tau Polarisation Accuracy

Q.How accurately can tau polarisation be measured?

Reconstructed polarimeter templates for $\tau \to \pi\nu$ and $\tau \to \rho\nu$ decays.

Scaled to the integrated luminosity of 1000 fb^{-1} with 100 % $e_L^- e_R^+$.



Polarisation

$$P = \frac{N_R - N_L}{N_R + N_L}$$

Use likelihood method to analytically estimate polarisation uncertainty.

Tau Polarisation Accuracy

Scaled to the luminosity of 1000 fb^{-1}

Sample with 100 % $e_L^- e_R^+$ beam polarisations

N_τ: the expected total number of taus, σ_P: the expected polarisation uncertainty

$\tau \to \pi\nu$	N_τ	σ_P
MC	0.58 M	0.27 %
Cone	0.36 M	0.35 %
Mid	0.22 M	0.55 %
Combined	0.58 M	0.30 %

$\tau \to \rho\nu$	N_τ	σ_P
MC	1.31 M	0.18 %
Cone	0.70 M	0.28 %
Mid	0.59 M	0.42 %
Combined	1.29 M	0.23 %

Precision on the polarisation σ_P of "Cone method" + "Midpoint method"

$$\tau \to \pi\nu :\sim 0.30\,\%, \quad \tau \to \rho\nu :\sim 0.23\,\%$$