arXiv:1912.08403

arXiv:2203.07668

Measuring the tau polarisation at ILC

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Seattle Snowmass Summer Meeting 2022

20th July 2022

Motivation

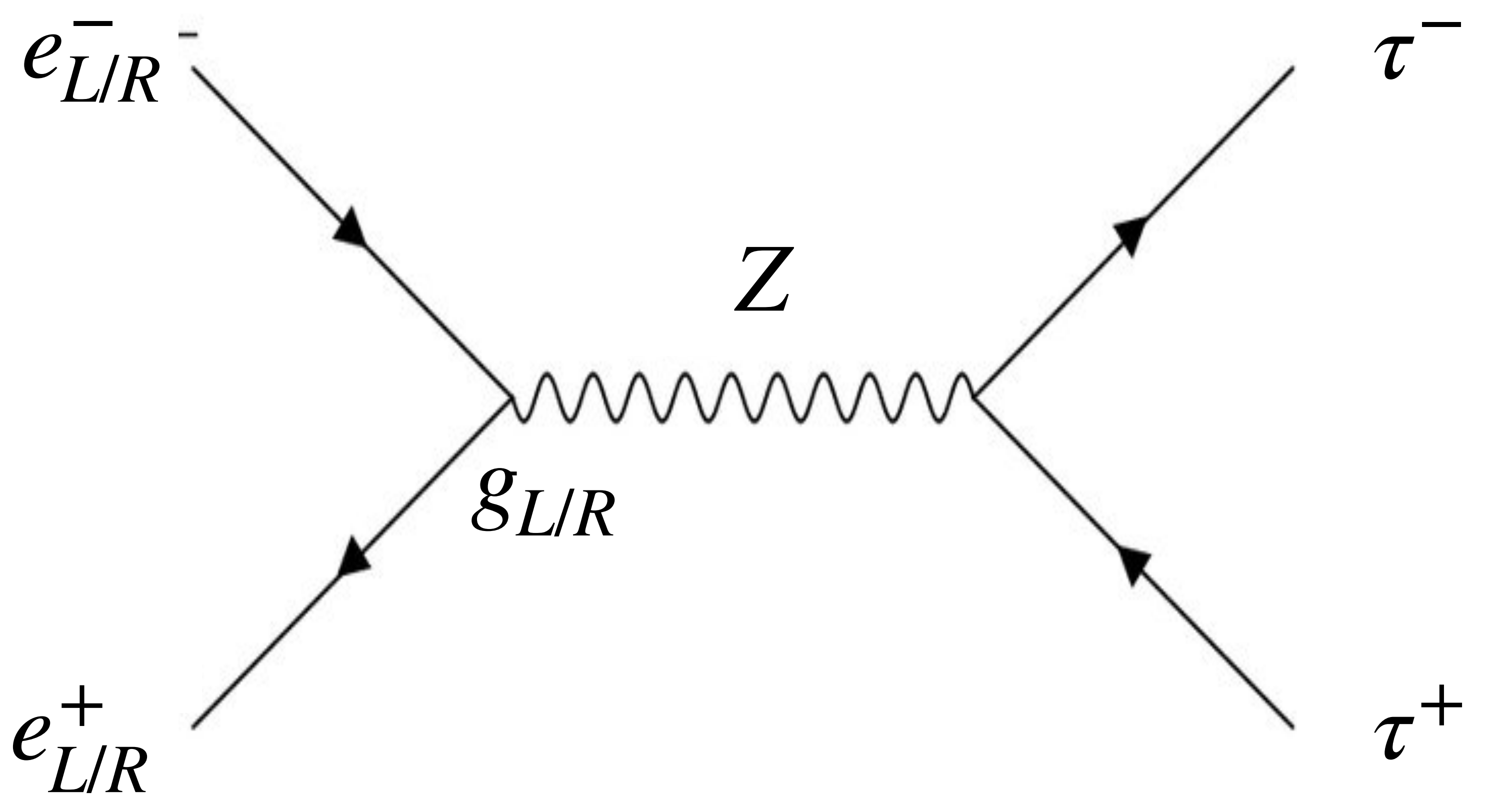
At the ILC, forward-backward asymmetry $A_{FB} = \frac{3}{4} A_e \cdot A_f$ can be measured

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_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

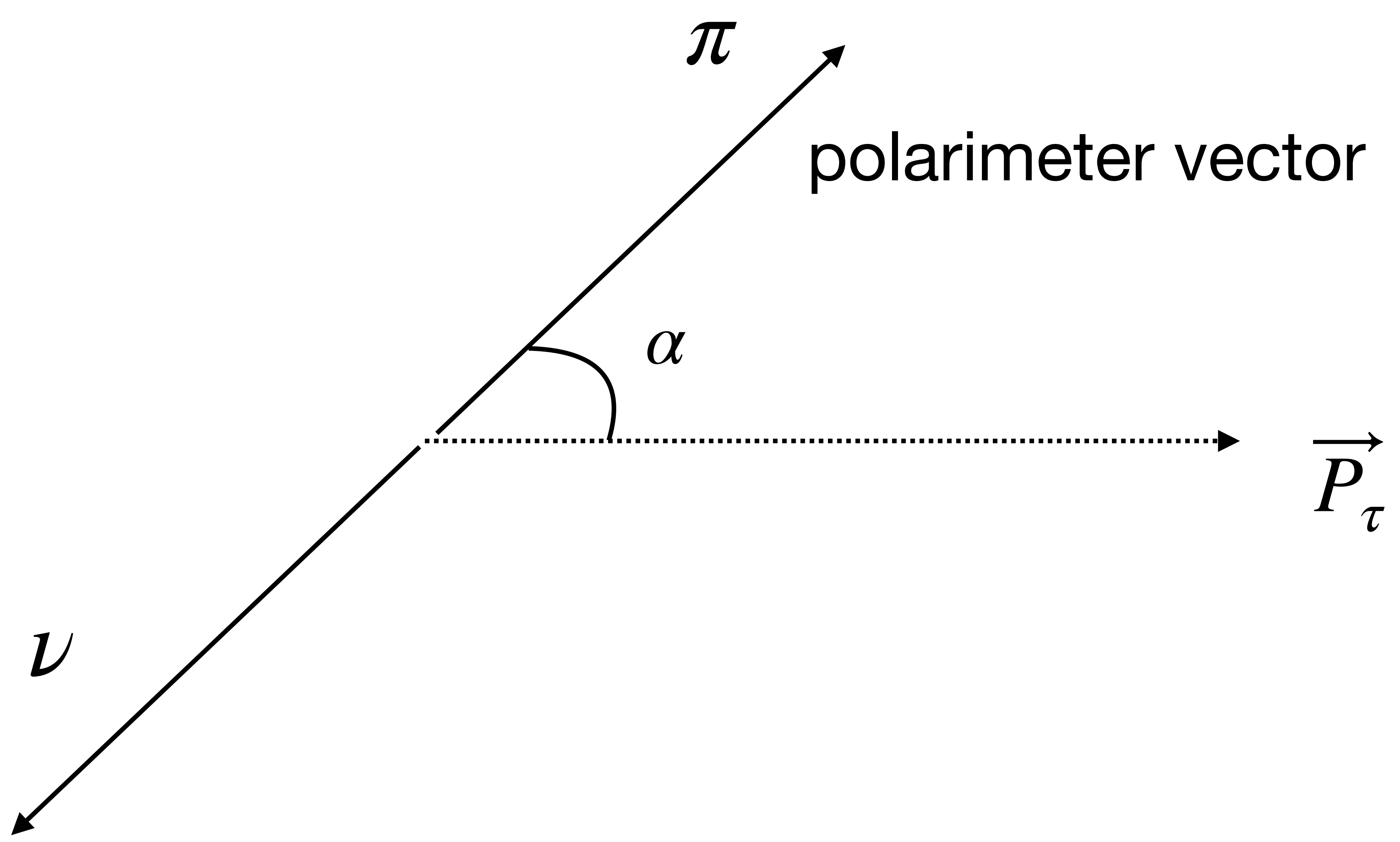
The reconstruction of tau spin orientation (“**Polarimeter**”) in order to measure polarisation to investigate new physics.

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

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

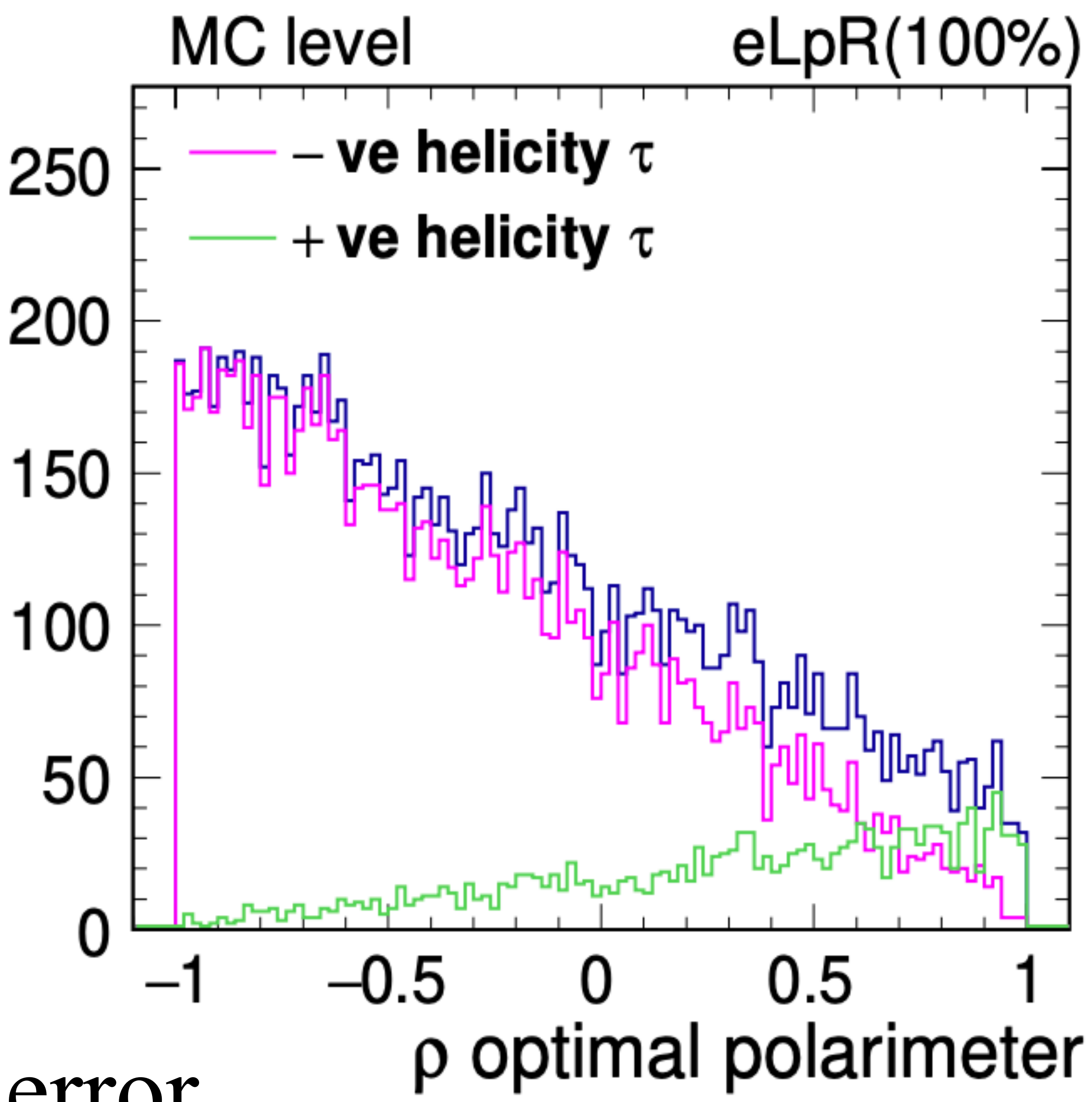
"Polarimeter"

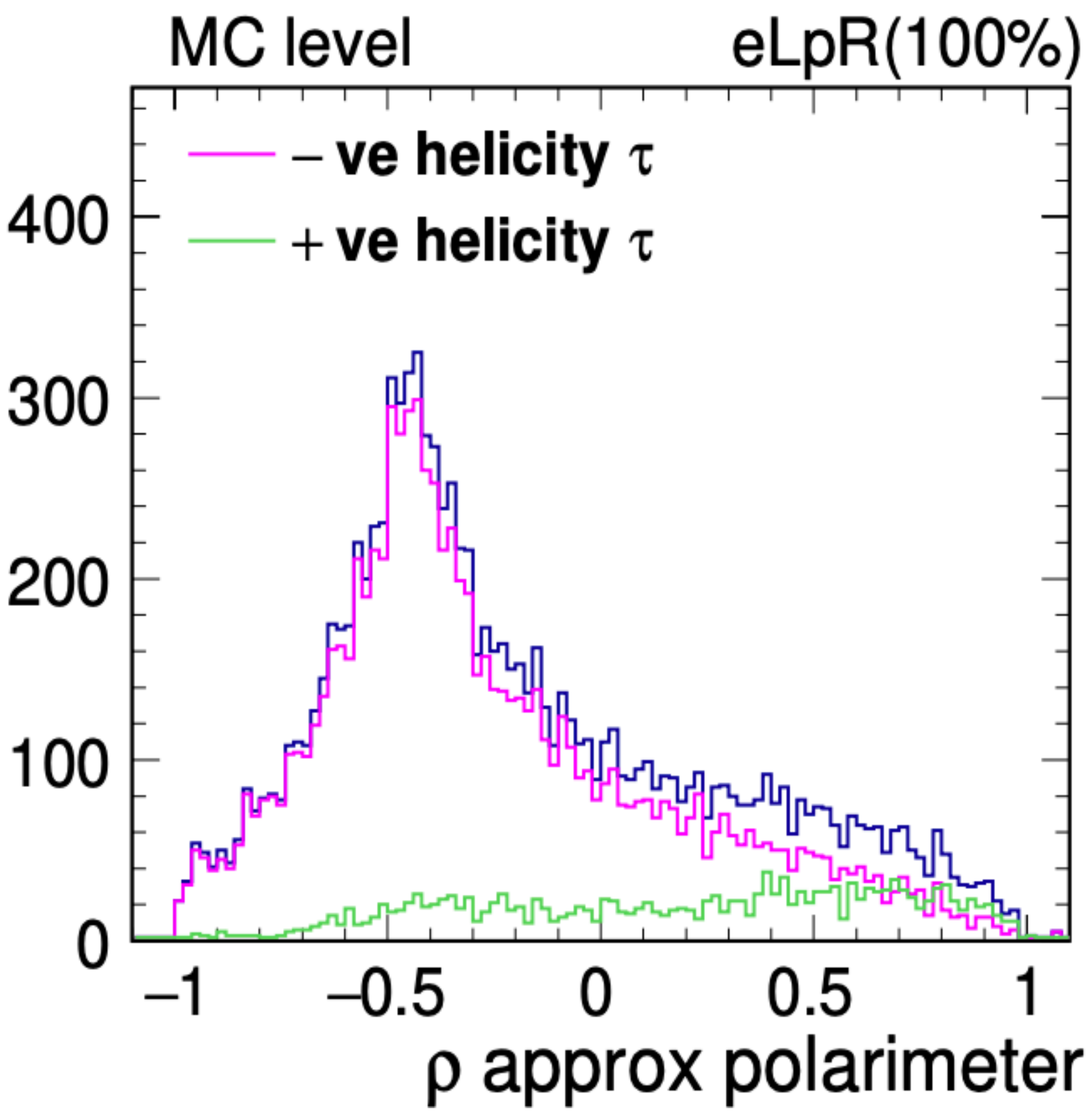
The cosine of the angle this polarimeter vector makes to the tau flight direction

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

0.30 %

0.40 %

arXiv:1912.08403

In this talk: reconstruct neutrino momentum → optimal polarimeters

Simulation setup

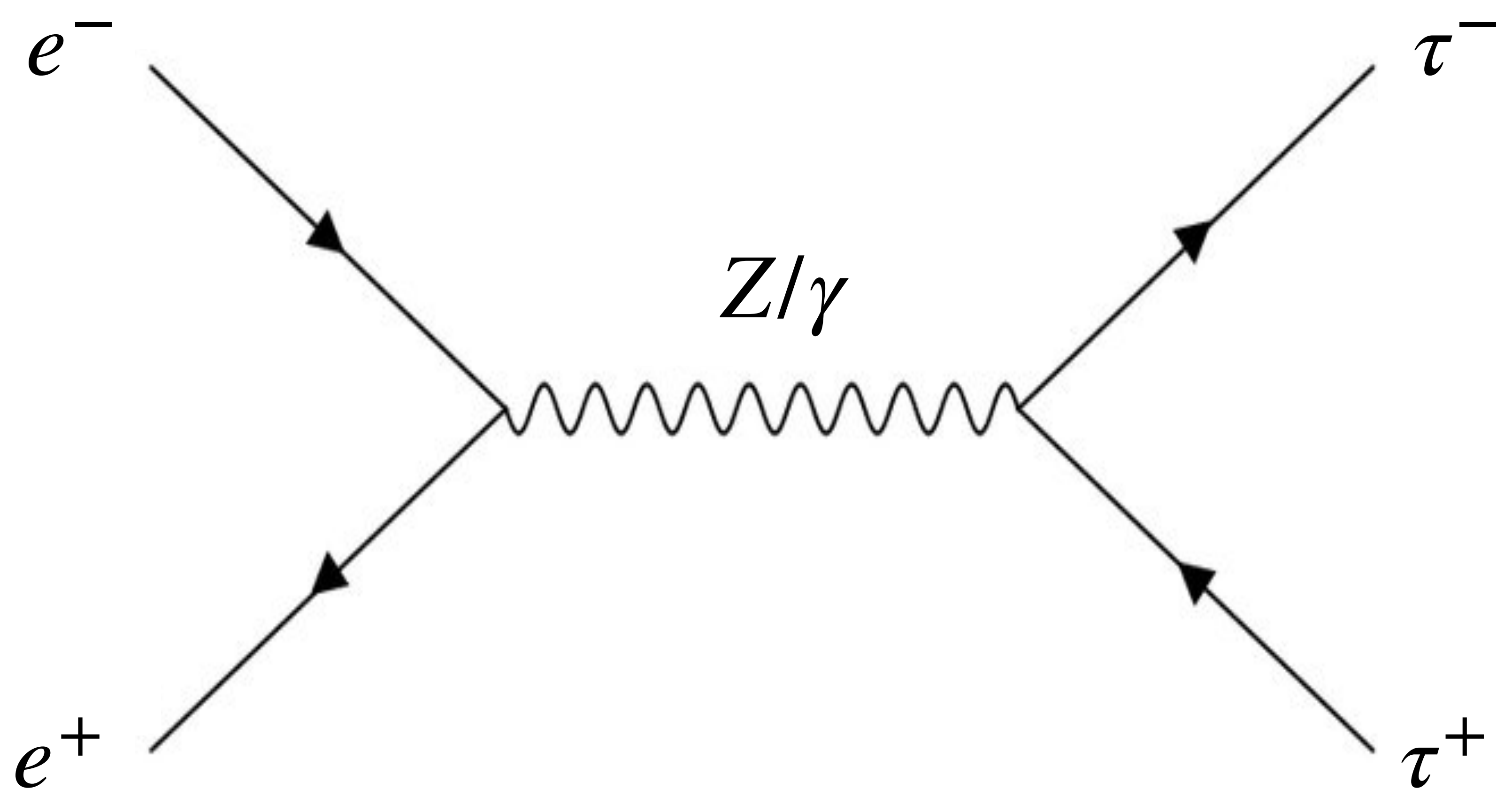
- Signal event sample with 100 % $e_L^- e_R^+$ beam polarisations were generated using WHIZARD ver 2.8.5.
- The decay of the polarised tau was done using TAUOLA.
- MC truth information was used.

currently

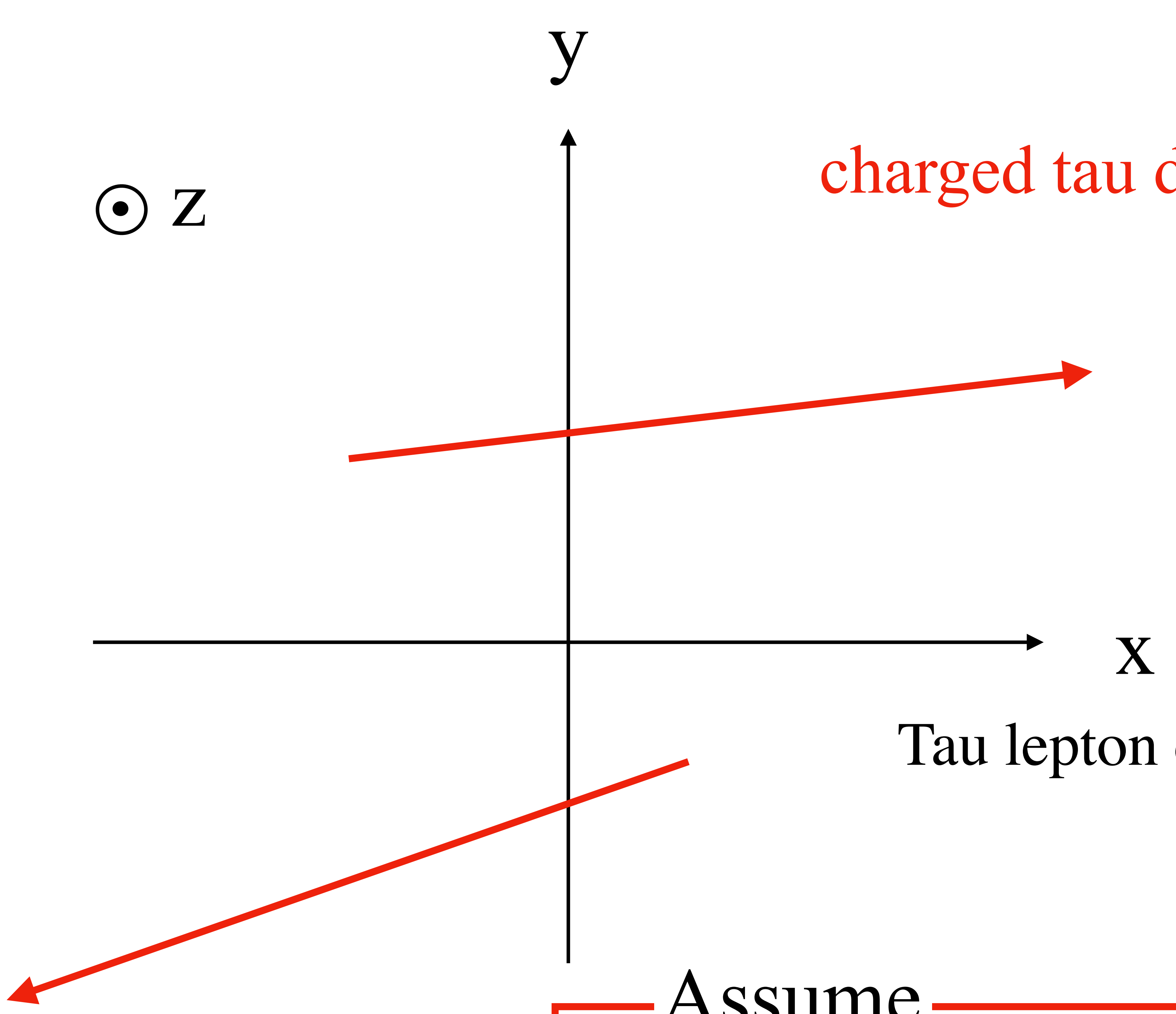
- only look at

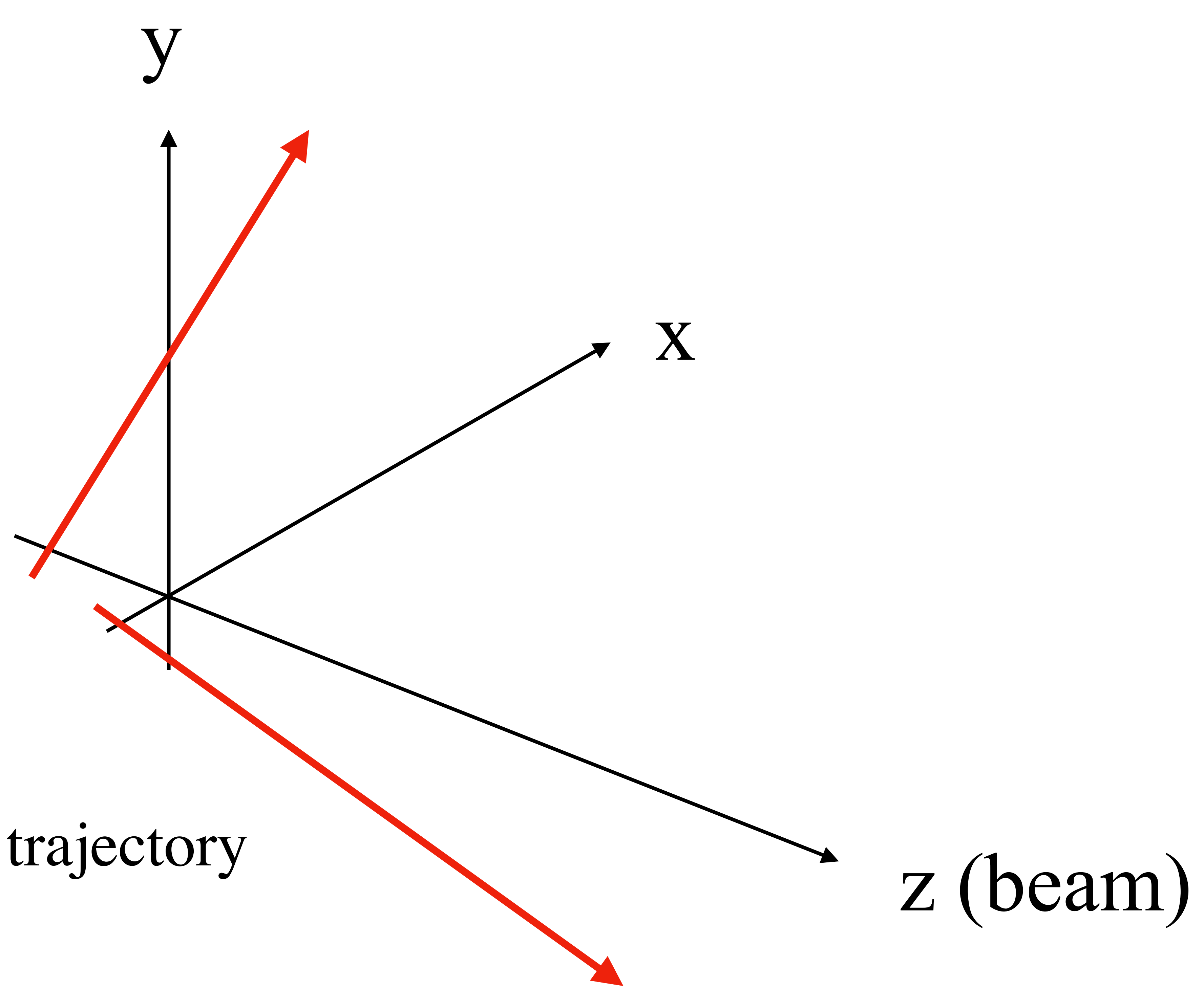
  $\tau \to \pi\nu$ (BR $\sim$ 10 %)

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



τ reconstruction method



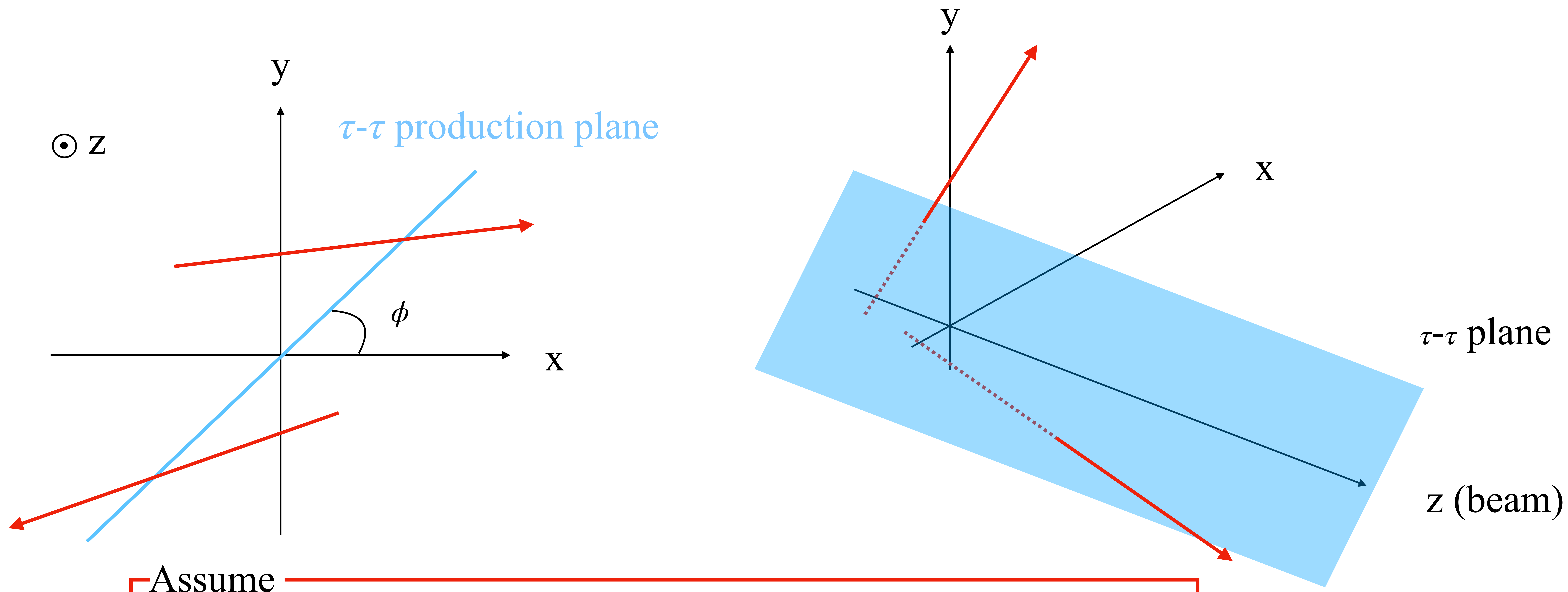


Assume

- 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 approximately in a straight line near IP.

τ reconstruction method

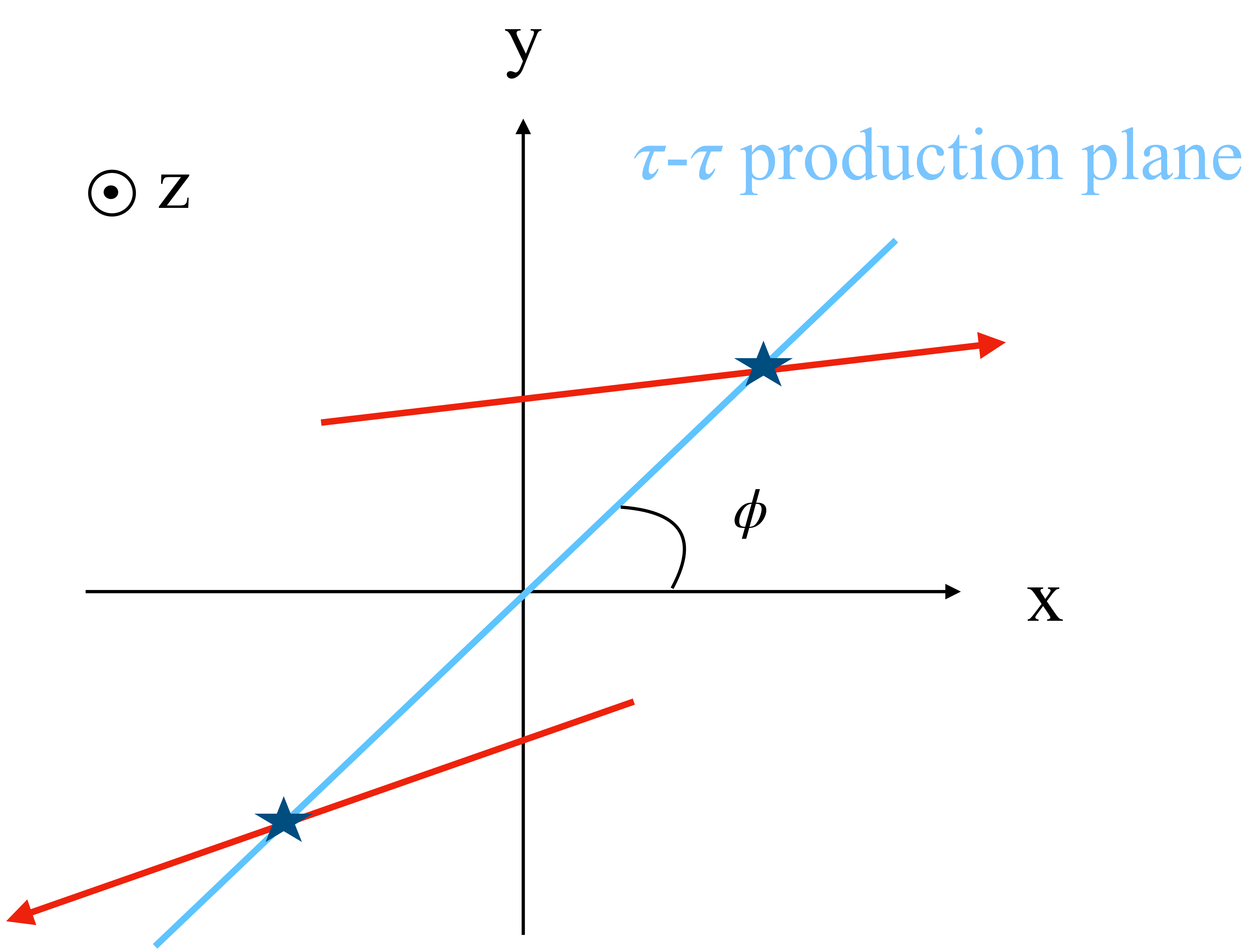


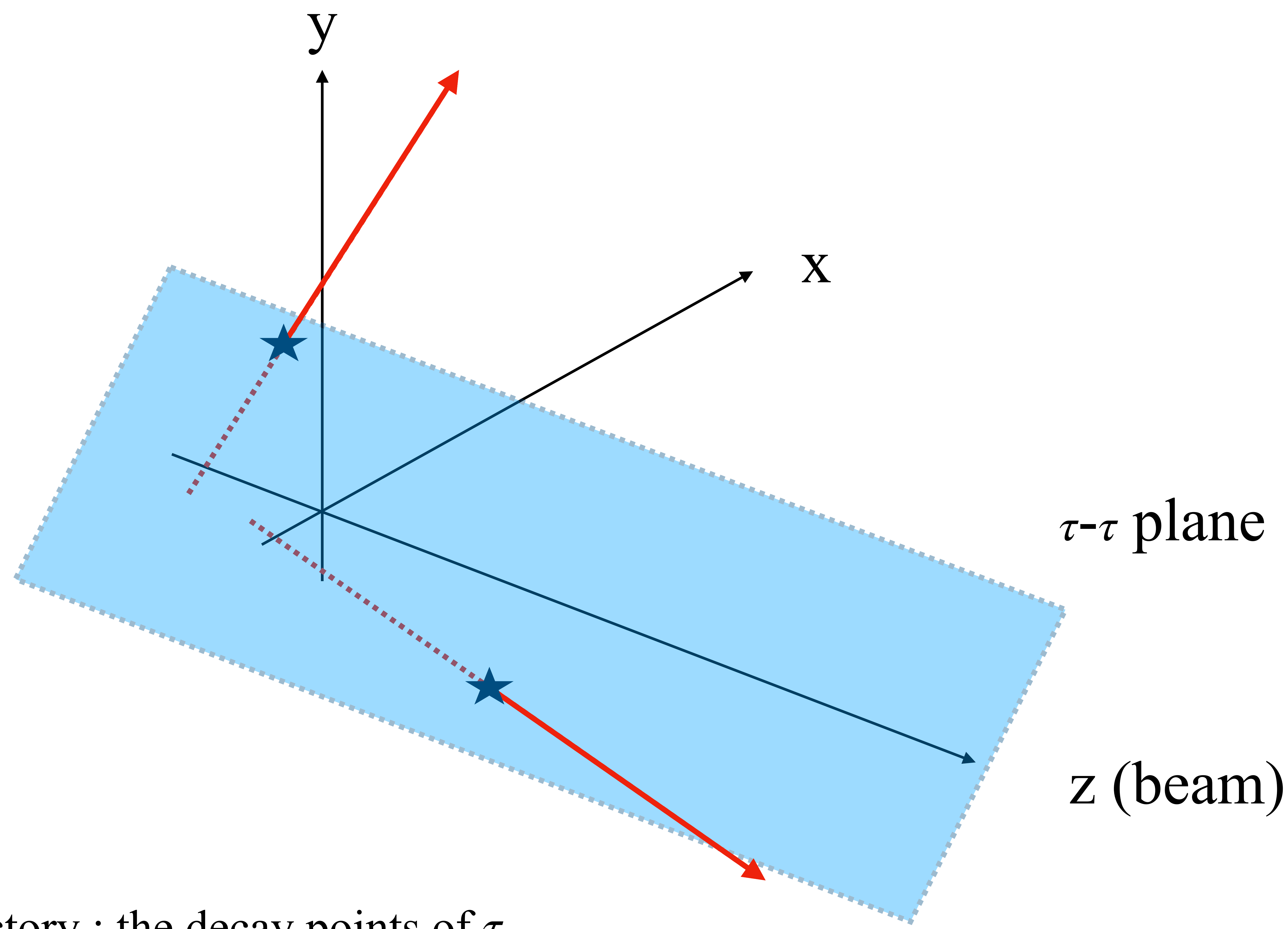
Assume

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

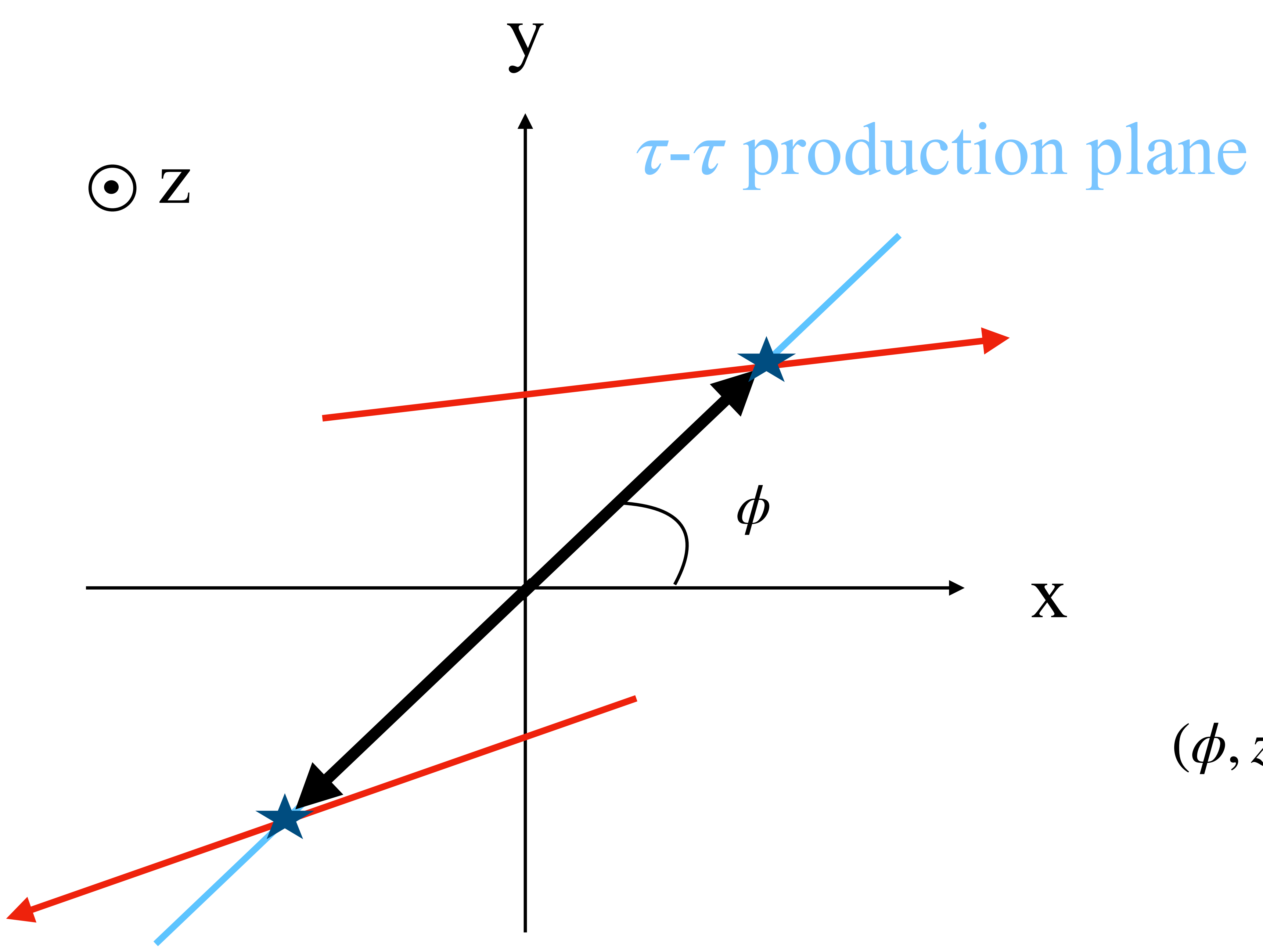




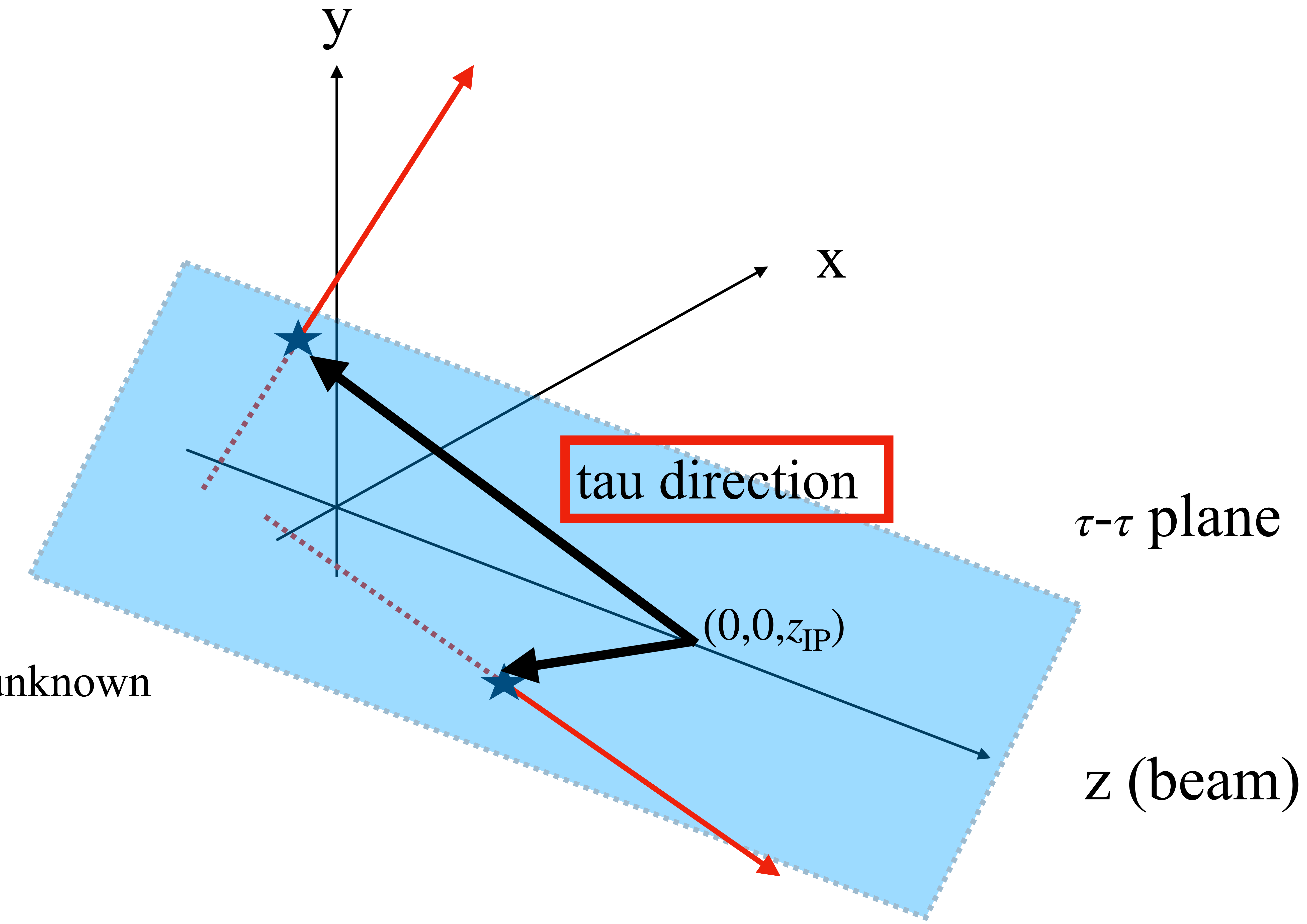
★ The intersection between plane and trajectory : the decay points of τ

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

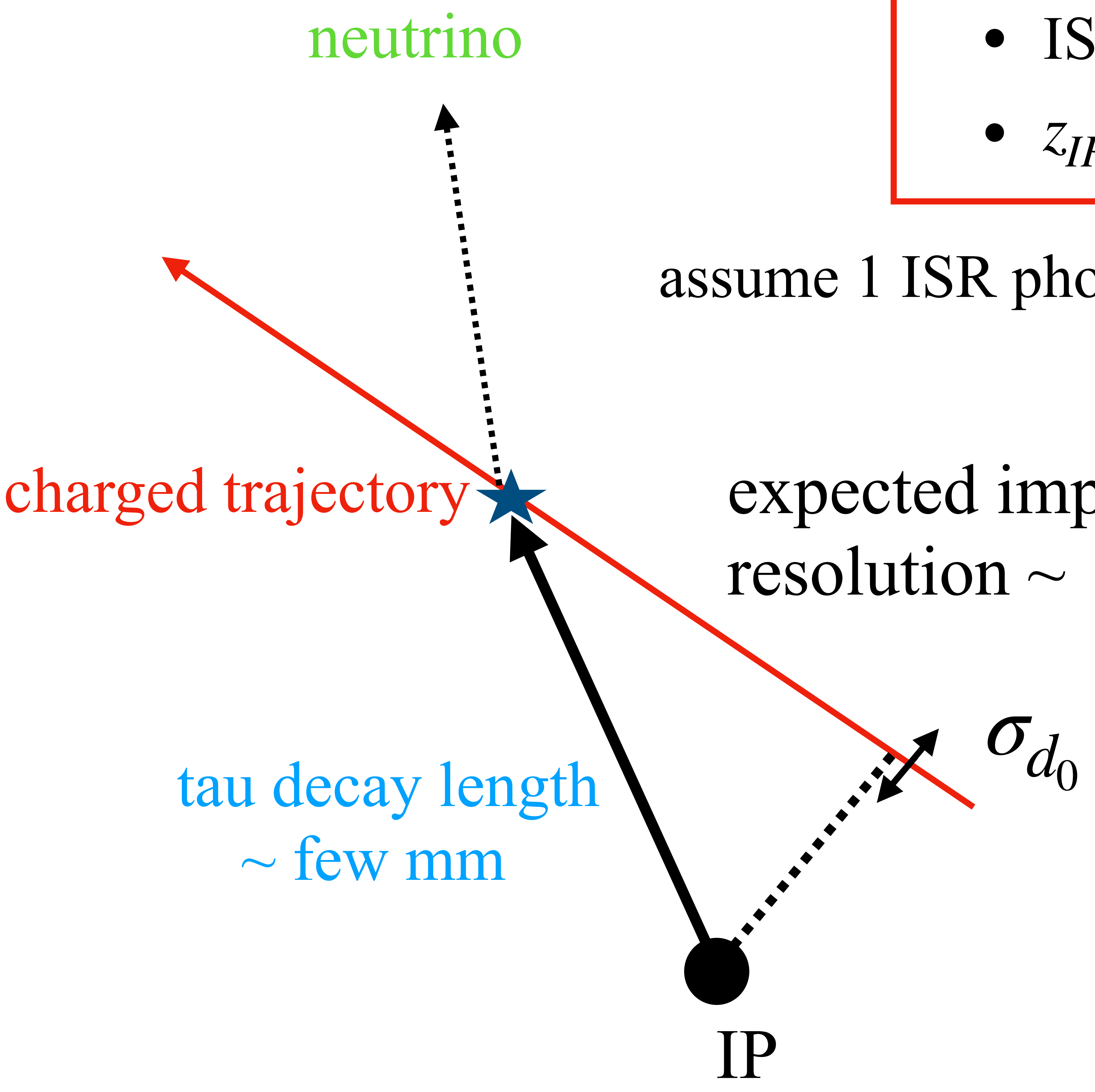
$\Rightarrow$ How can we choose ϕ, z_{IP} ?

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 and each other



expected impact parameter resolution ~ few um

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

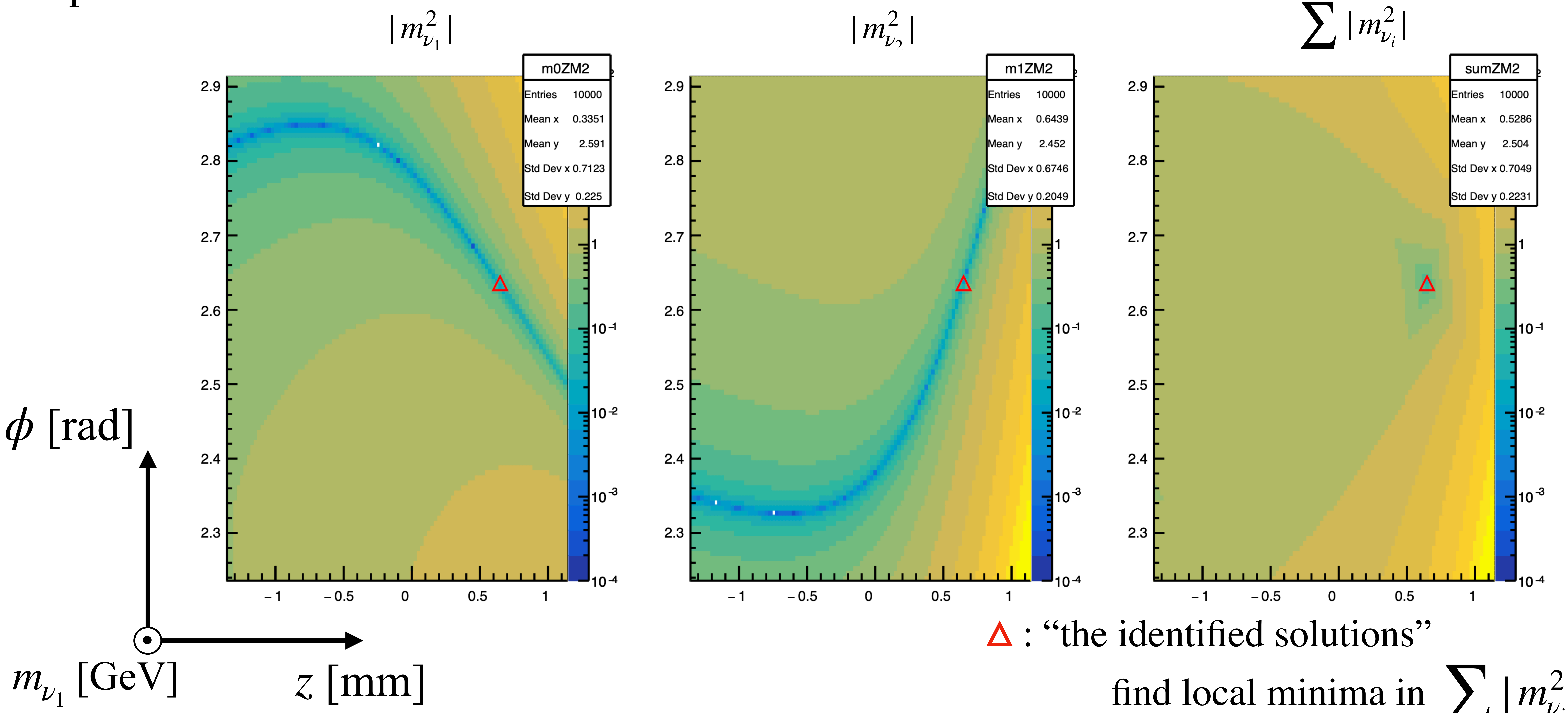
$$P_\nu = P_\tau - P_{vis}$$

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

Find solutions

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

example event with 1 solution

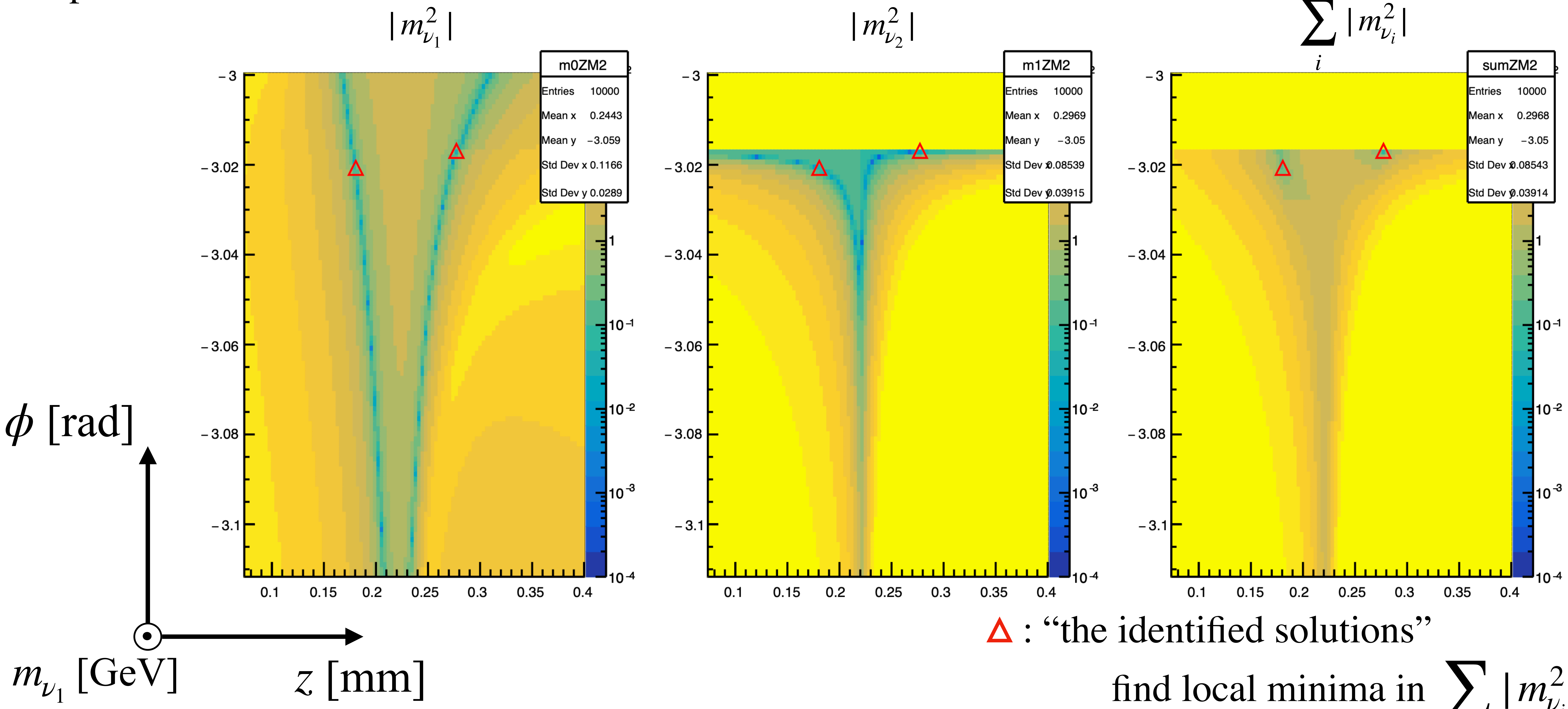


find local minima in $\sum_i |m^2_{\nu_i}|$

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"

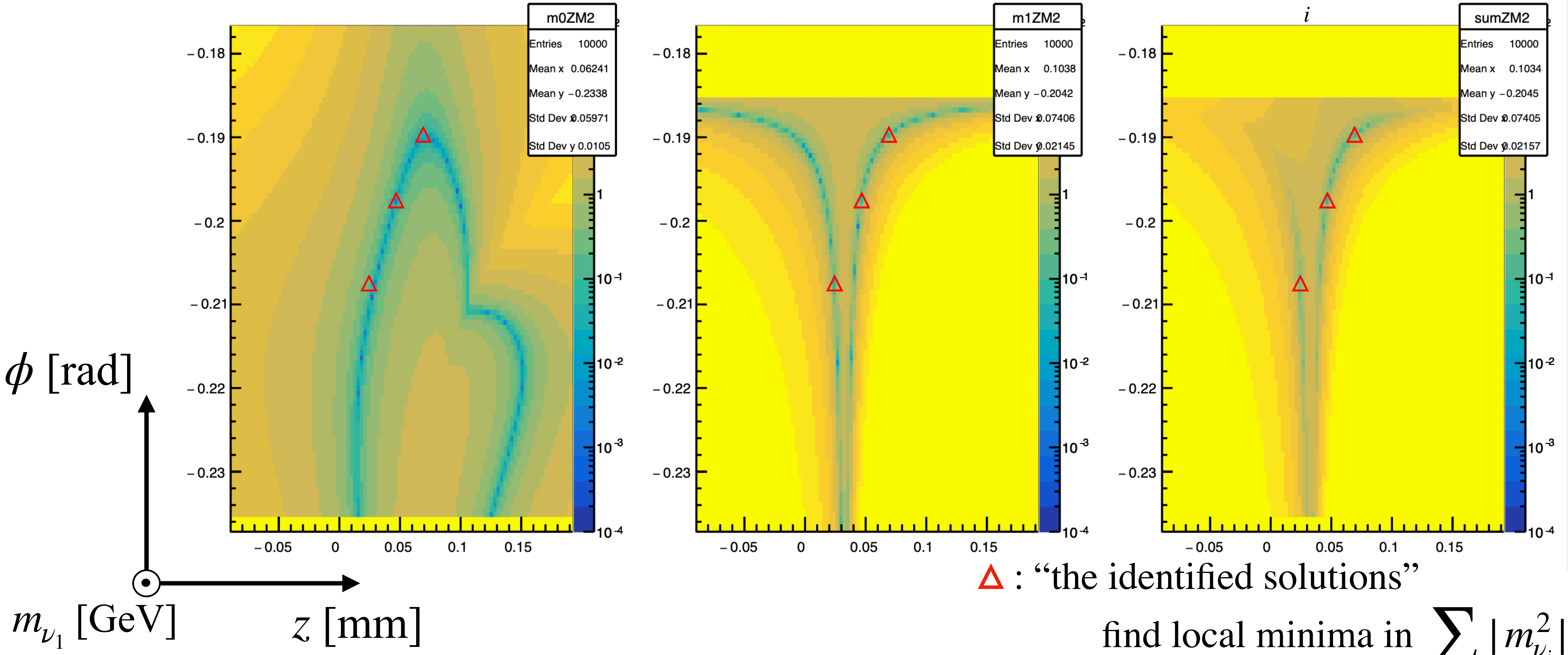
find local minima in $\sum_i |m_{\nu_i}^2|$

Find solutions

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

example event with 3 solutions

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



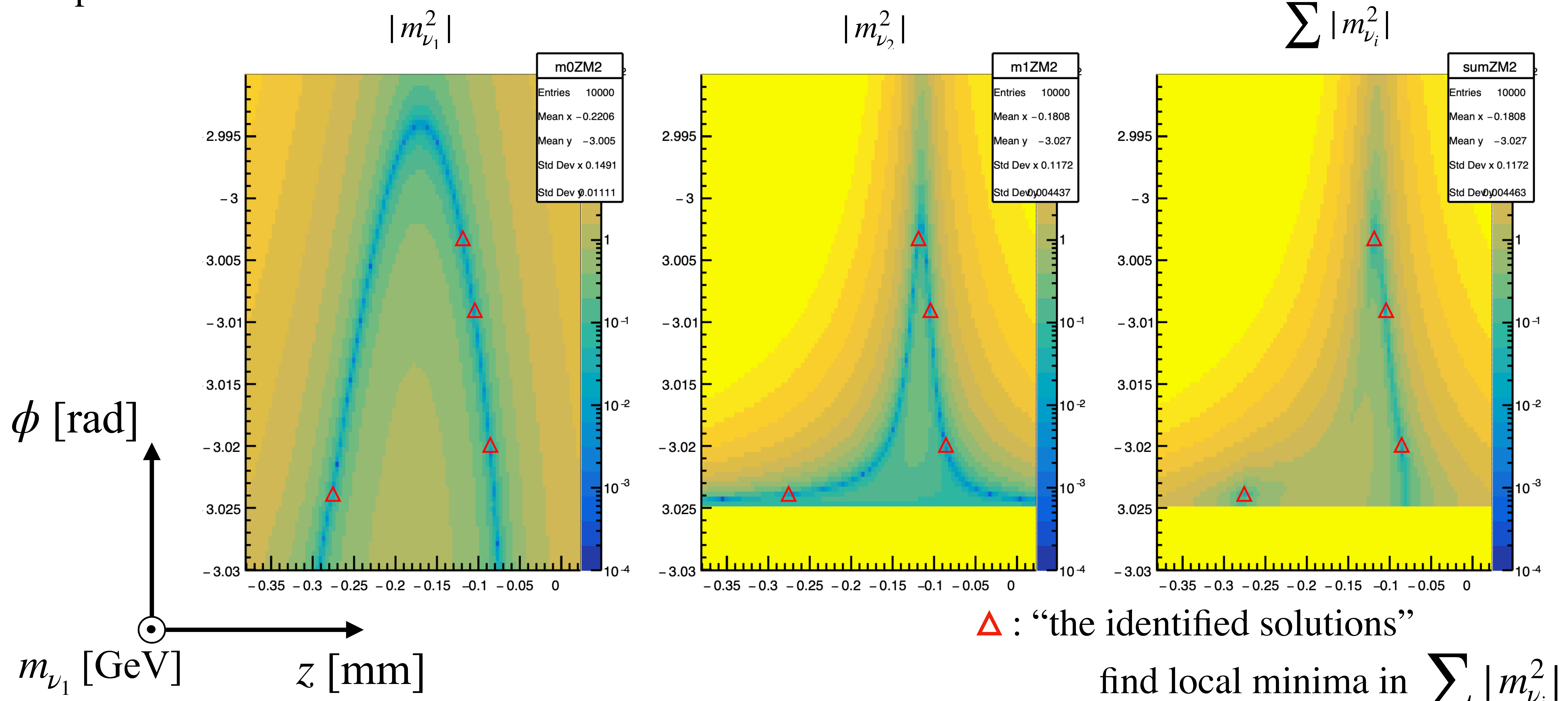
△ : "the identified solutions"

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

Find solutions

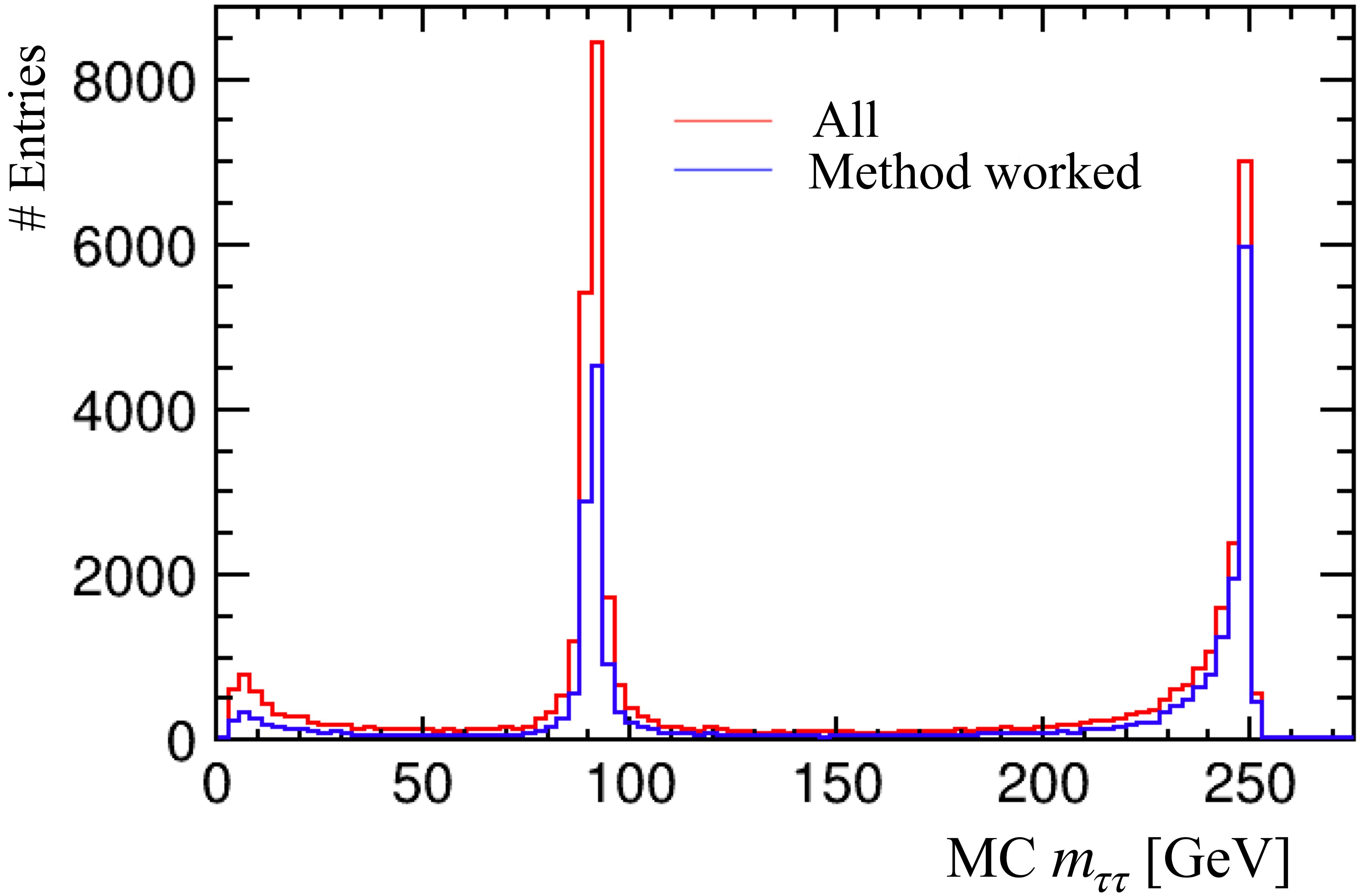
We choose the values of z and ϕ which result in neutrino masses closest to zero

example event with 4 solutions

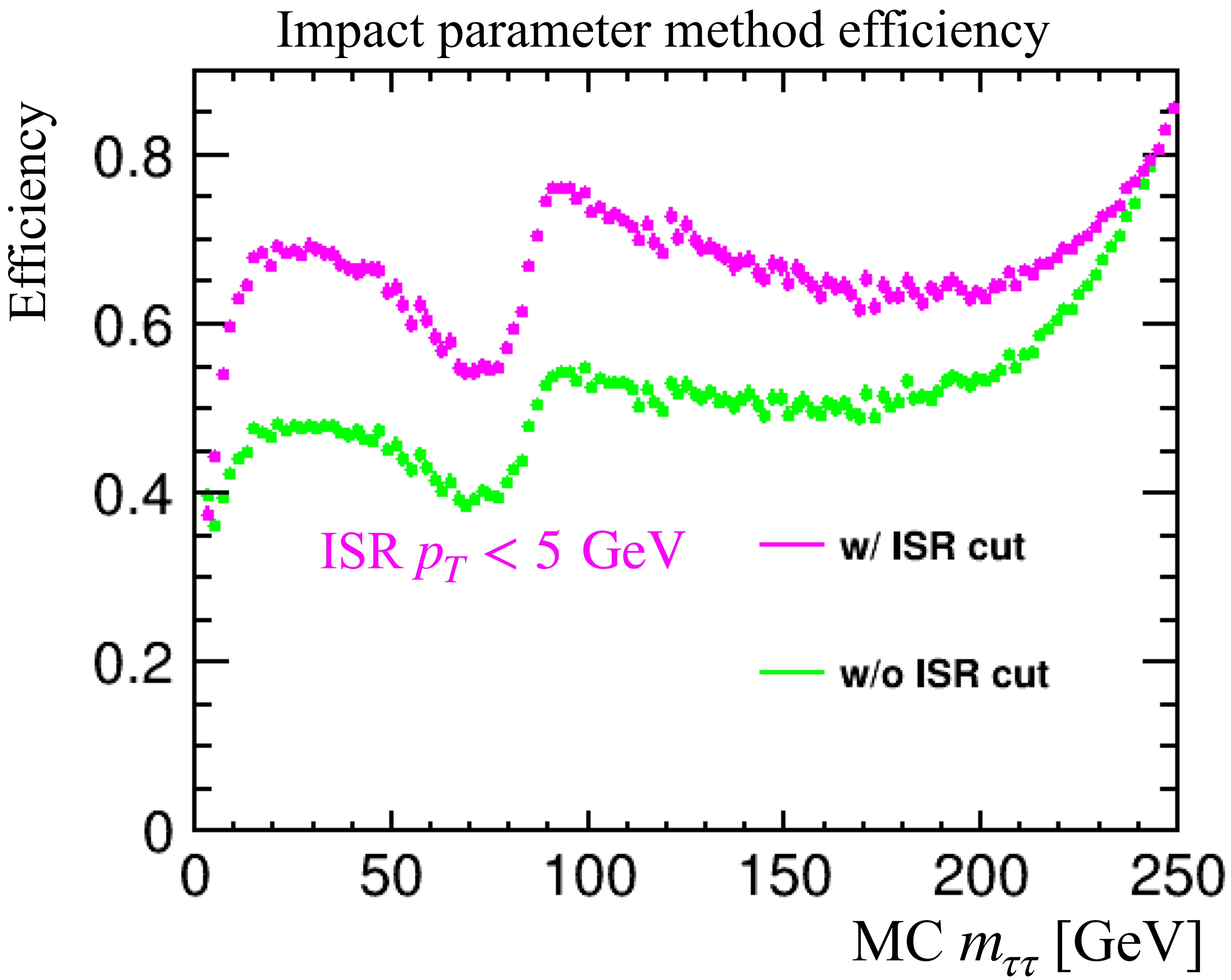


find local minima in $\sum_i |m^2_{\nu_i}|$

Method efficiency



Method worked : at least 1 solution is found

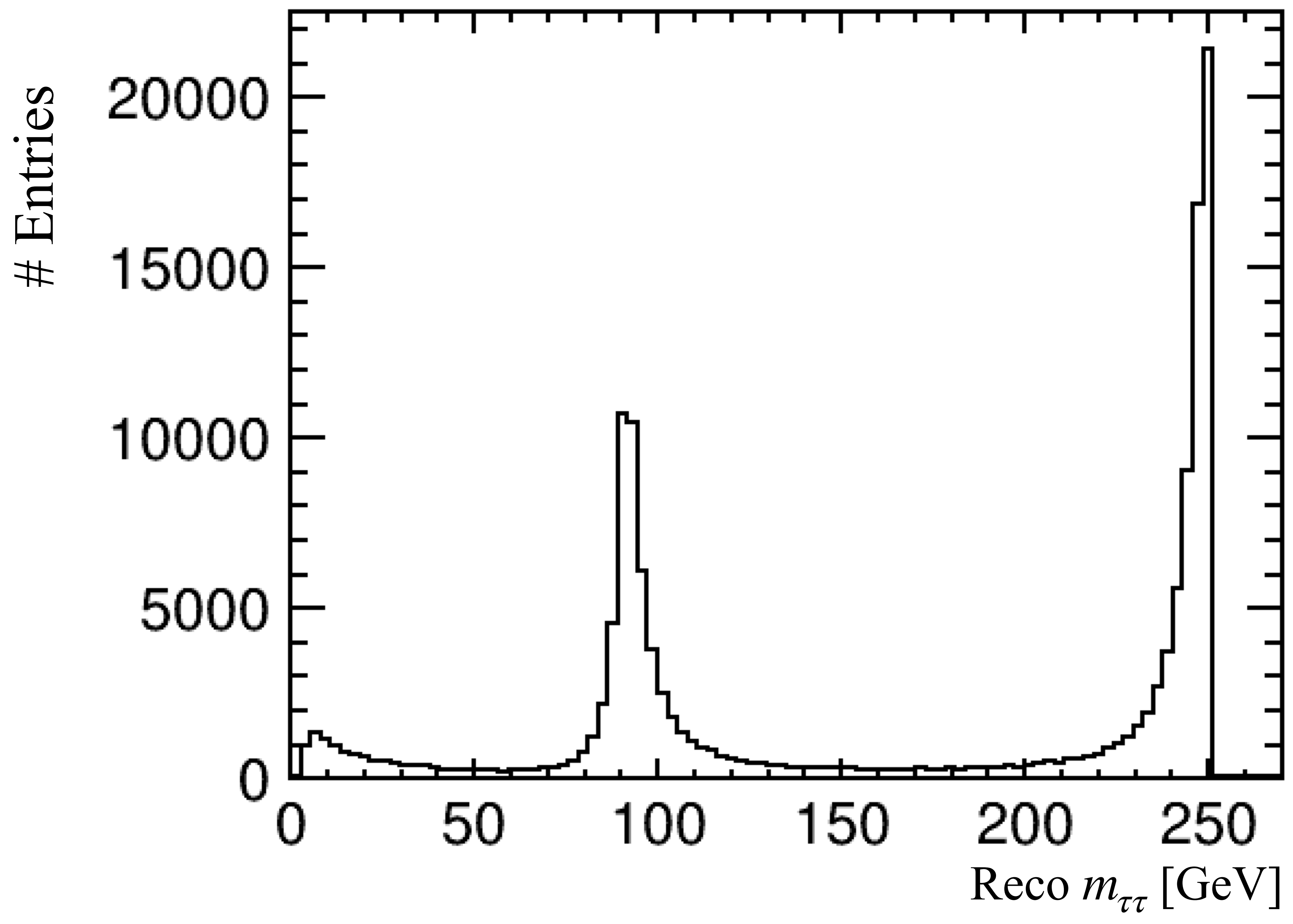


Impact parameter method efficiency is > 80 % for events with $m_{\tau\tau} \sim 250$ GeV

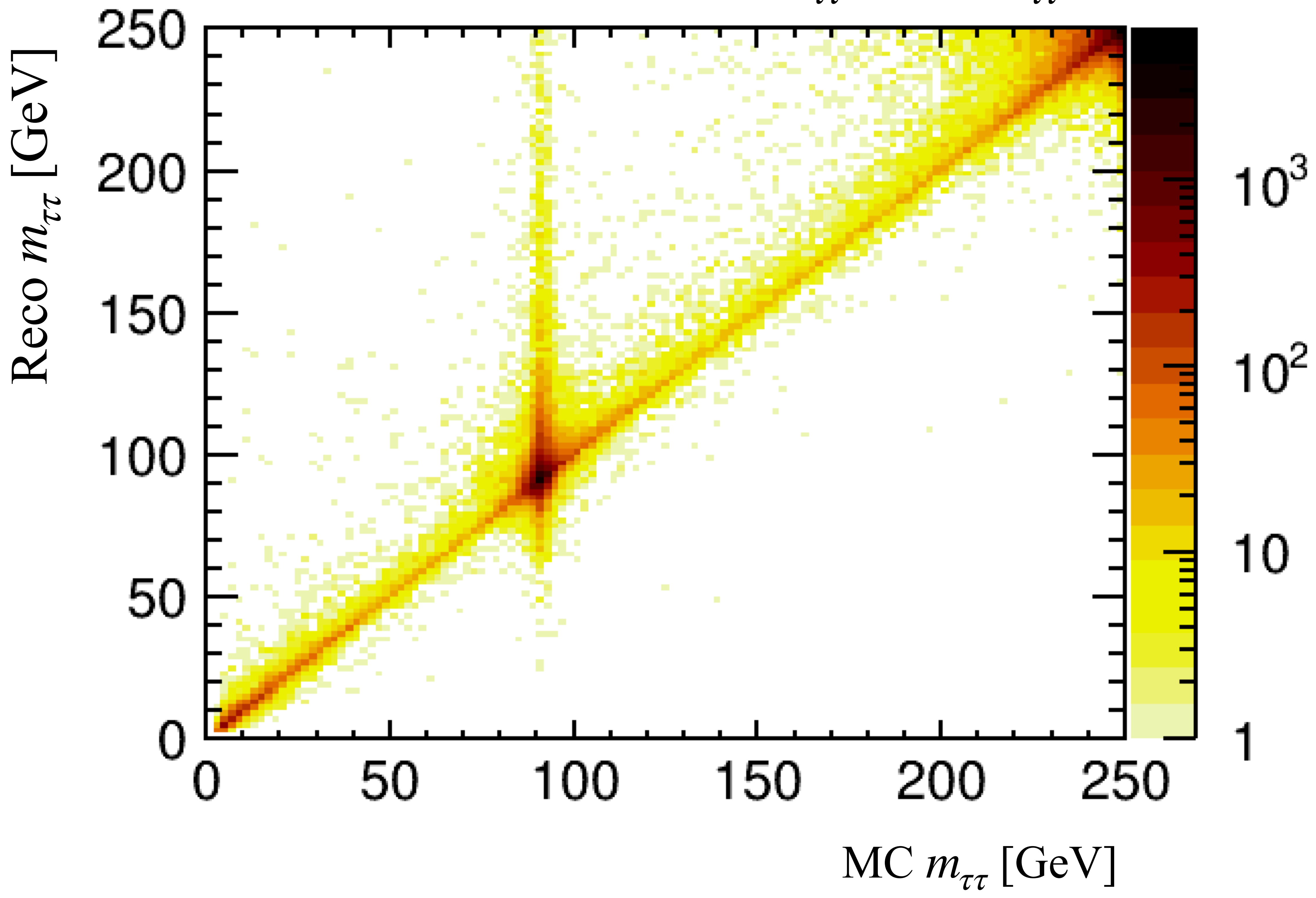
Comparison with MC

Reconstructed $m_{\tau\tau}$ based on Impact parameter method solutions

weighted combination of all solutions



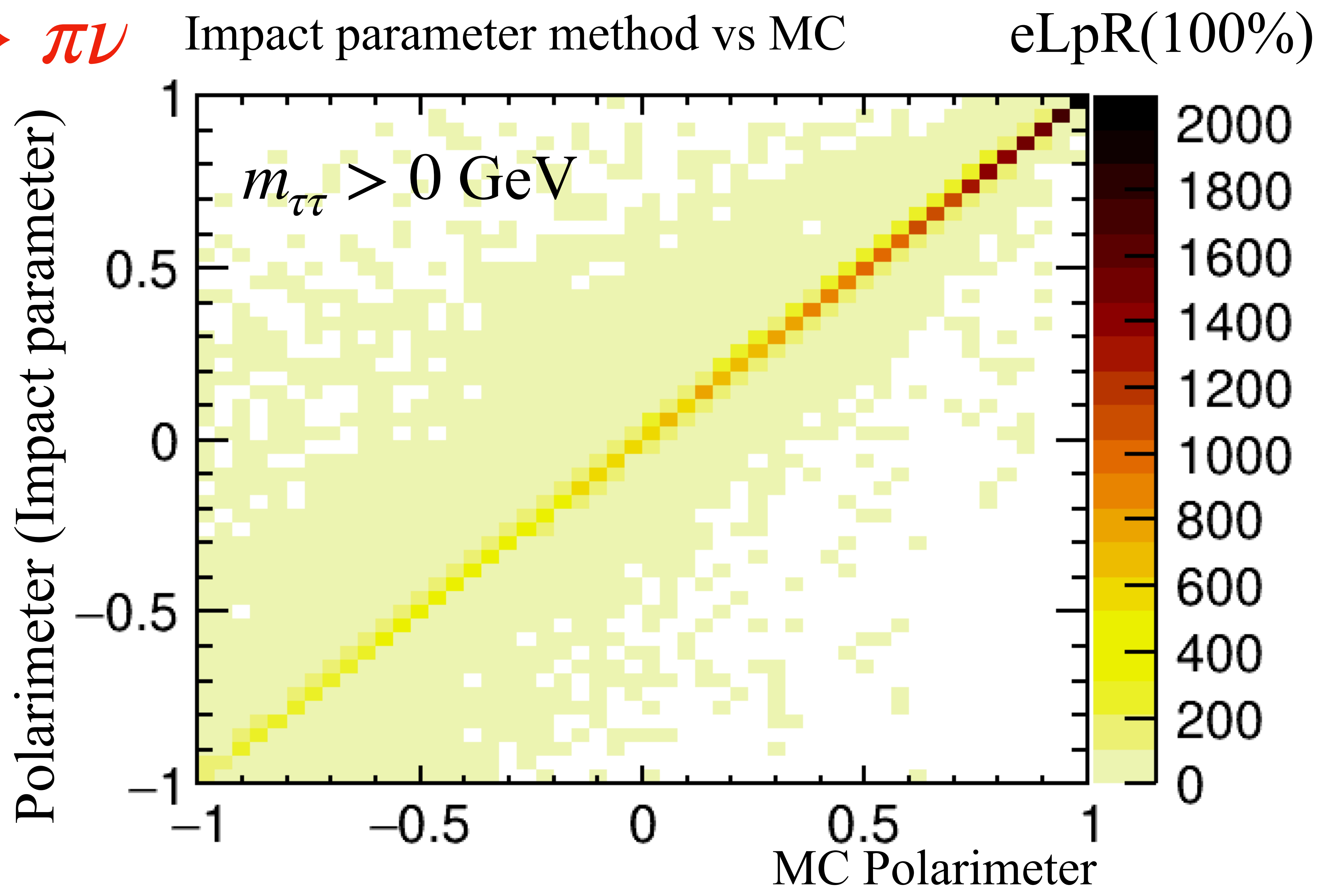
reconstructed $m_{\tau\tau}$ vs MC $m_{\tau\tau}$

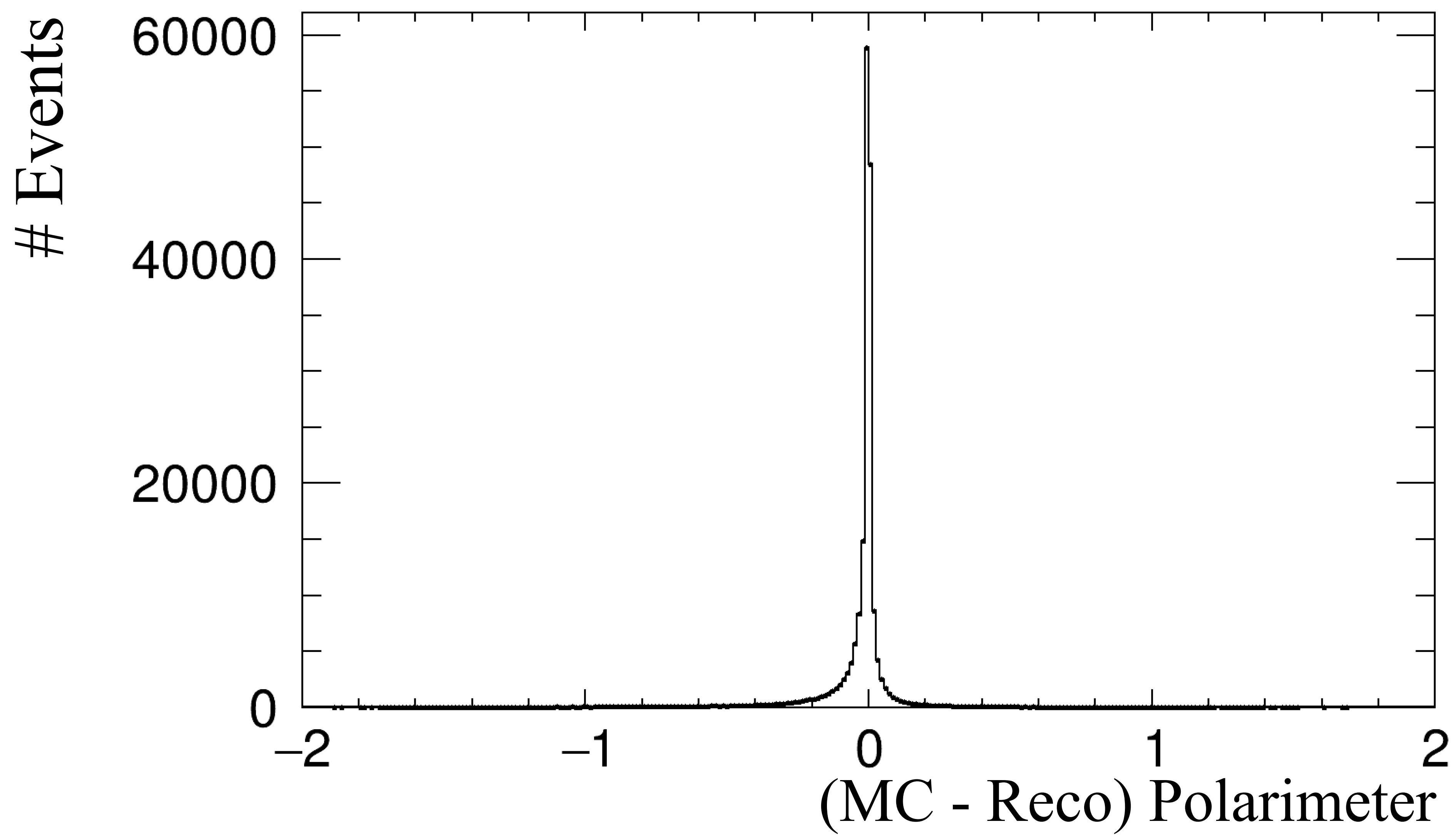


Reasonable agreement between MC and reconstructed $m_{\tau\tau}$

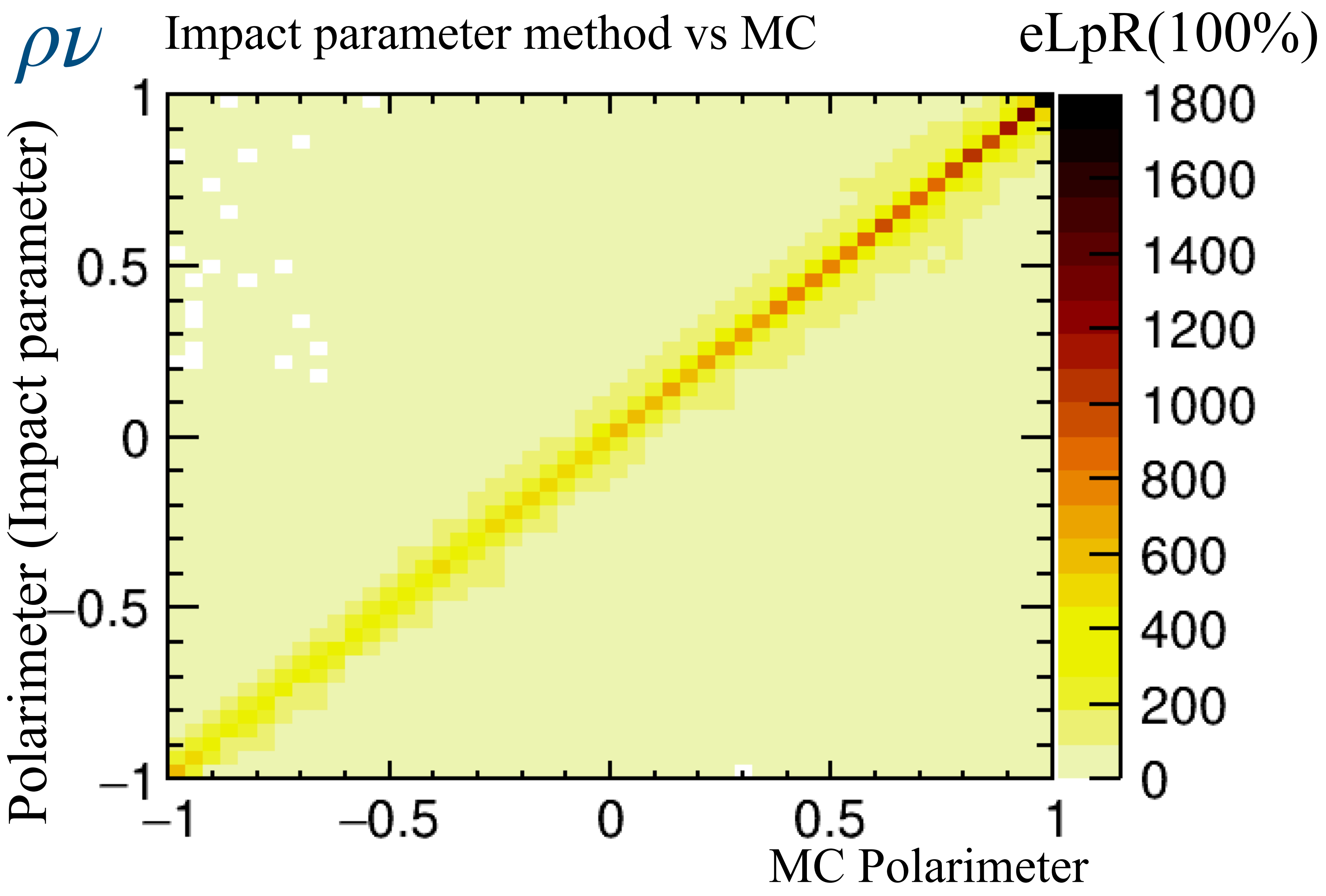
Polarimeter

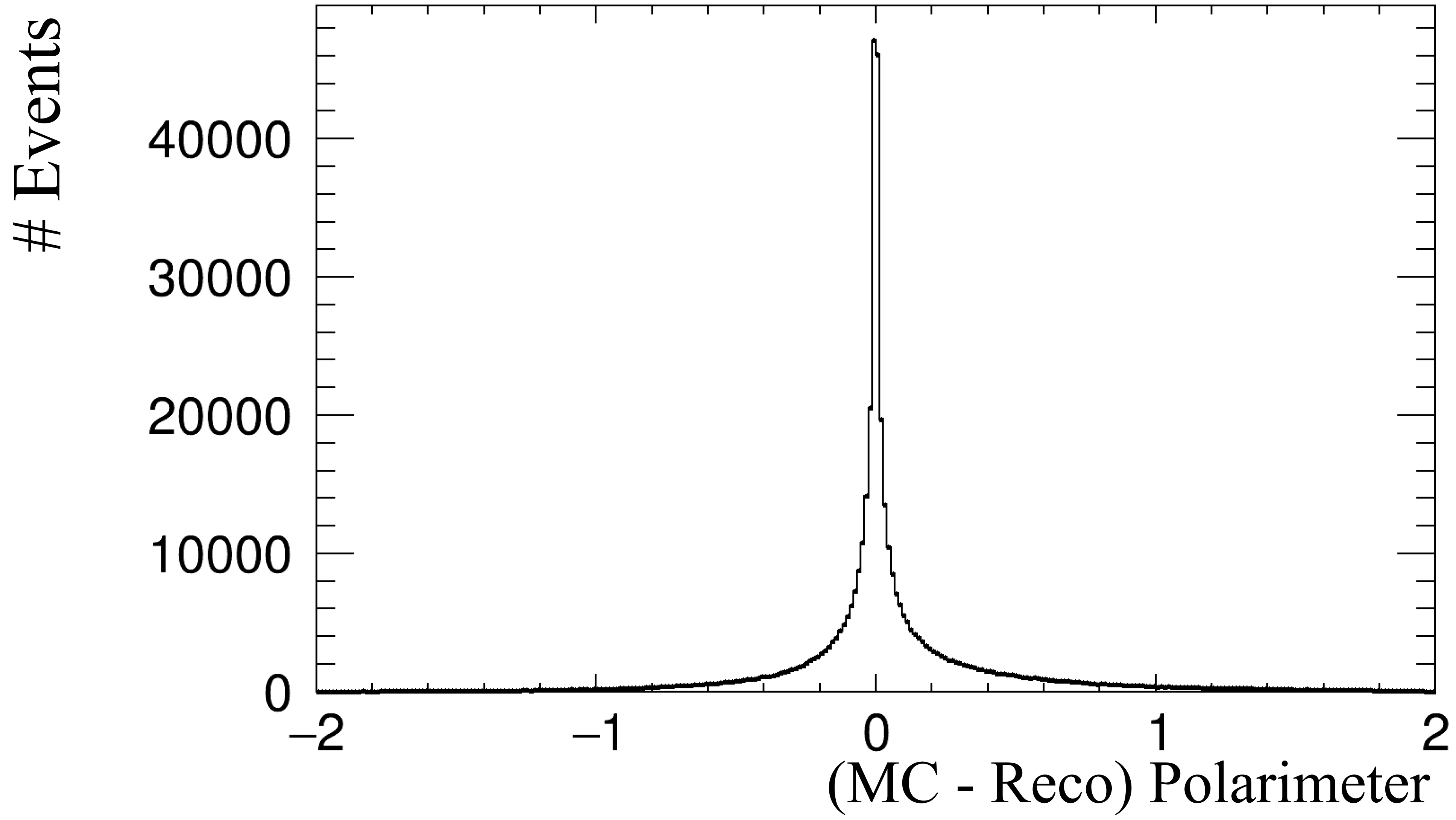
$\tau \to \pi\nu$





$\tau \to \rho\nu$





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

Summary

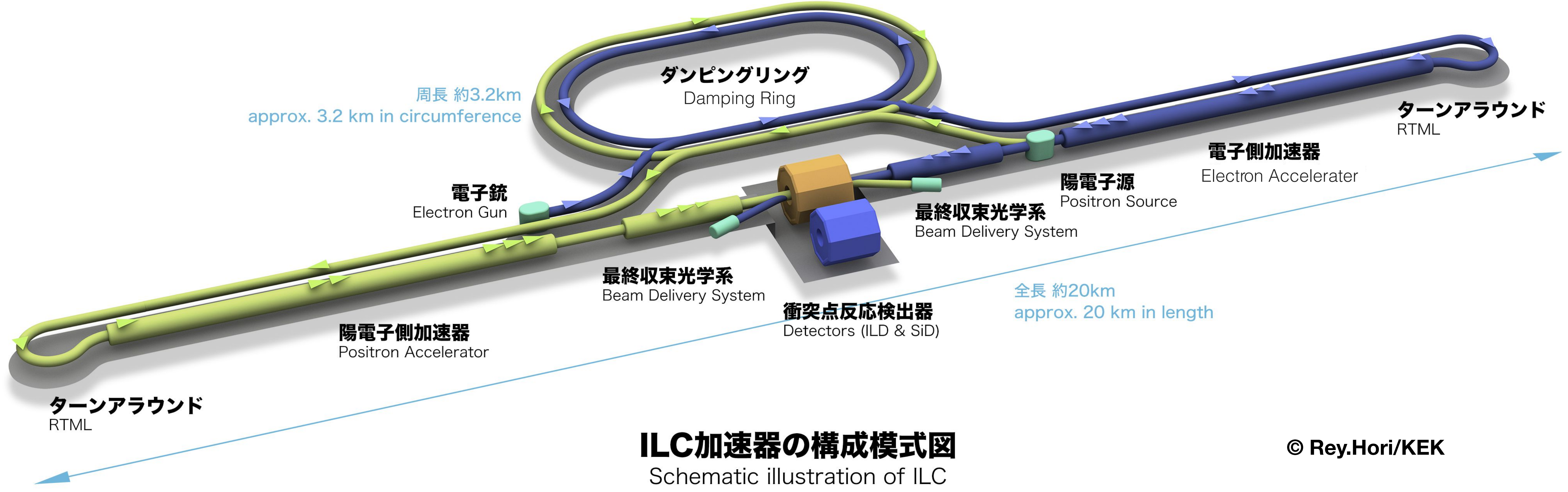
- Full reconstruction of $e^+e^- \to \tau^+\tau^-$ using impact parameter was investigated.
- For events with $m_{\tau\tau} \sim 250$ GeV, impact parameter method efficiency is $> 80\,\%$.
  $m_{\tau\tau} \sim 91$ GeV $\sim 70\,\%$
- Polarimeters were reconstructed in the $\tau \to \pi\nu$ and $\tau \to \rho\nu$ 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.

Introduction

International Linear Collider (ILC)



linear electron-positron collider

centre-of-mass energy : 250 GeV — 500 GeV

integrated luminosities: 2 ab^{-1}— 4 ab^{-1}

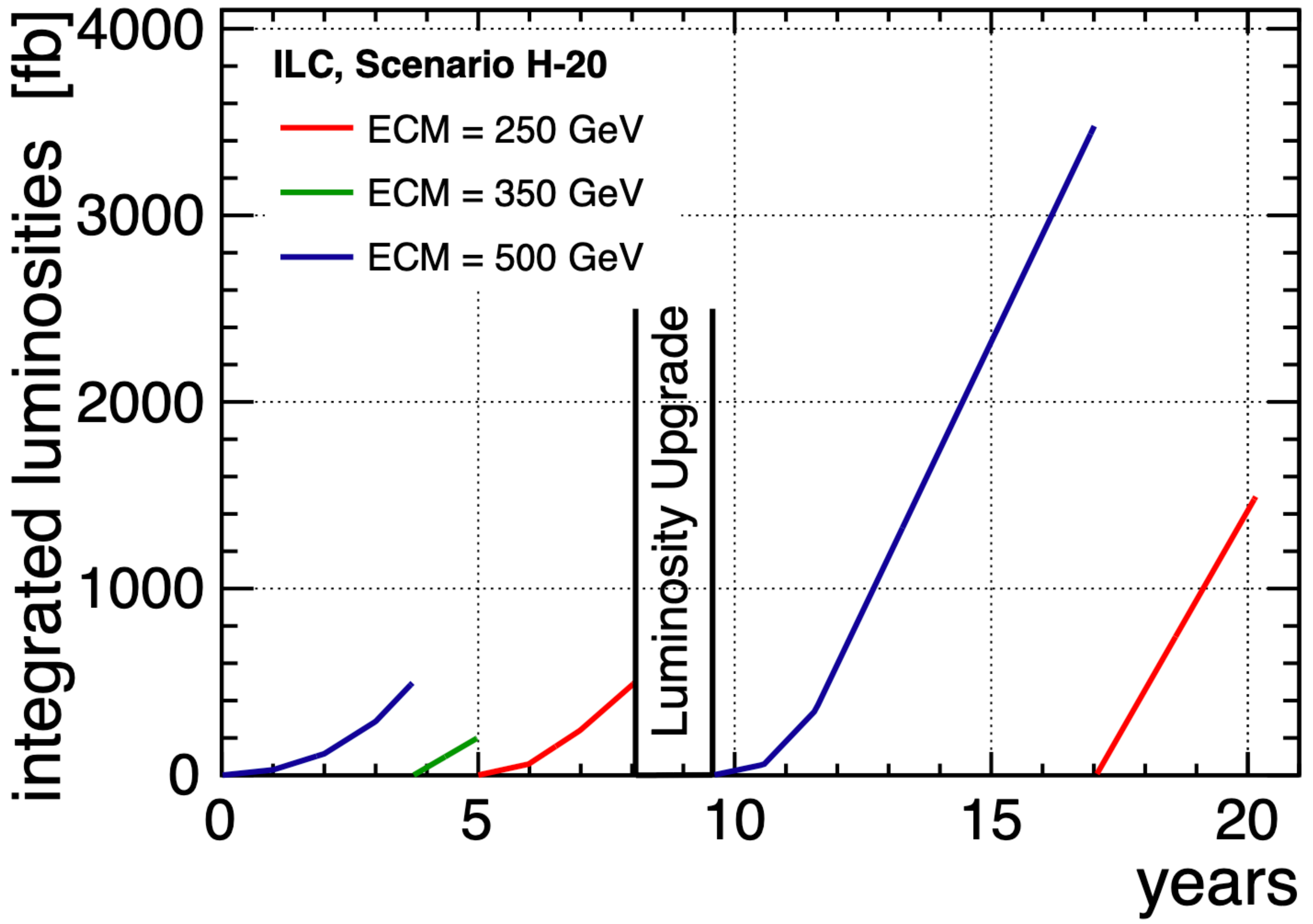
beam polarisation: $(e^-, e^+) = (\pm 80\,\%,\ \pm 30\,\%)$

The aim of ILC experiment

- Precision measurement of the Higgs boson and top quark
- Discovery of physics beyond the Standard Model

  -search for candidates for dark matter

Integrated Luminosities [fb] scenario H-20



The transverse momenta p_T of the two taus are assumed to be equal to conserve the event's transverse momentum. The magnitudes of the total tau momenta are then given by $p_i = p_T / \sin\theta_i$, and the z momenta by $p_{z,i} = p_T / \tan\theta_i$.

Conservation of energy gives $E_{\tau,1} + E_{\tau,2} + E_{ISR} = E_{CM}$, where $E_{\tau,1(2)}$ is the energy of tau 1(2), E_{ISR} the energy carried by ISR photons, and E_{CM} the centre-of-mass energy. If we assume a single ISR photon collinear with the beam, then momentum conservation in the z directions gives $E_{ISR} = |p_{z,1} + p_{z,2}|$. We then write

$$\begin{aligned} E_{CM} &= E_{\tau,1} + E_{\tau,2} + E_{ISR} \\ &= \sqrt{p_1^2 + m_\tau^2} + \sqrt{p_2^2 + m_\tau^2} + |p_{z,1} + p_{z,2}| \\ &\approx p_1\left[1 + \frac{m_\tau^2}{2\,p_1^2}\right] + p_2\left[1 + \frac{m_\tau^2}{2\,p_2^2}\right] + |p_{z,1} + p_{z,2}| \end{aligned}$$

when we consider the limit $p_i \gg m_\tau$. Rewriting in terms of p_T and $\theta_{1,2}$

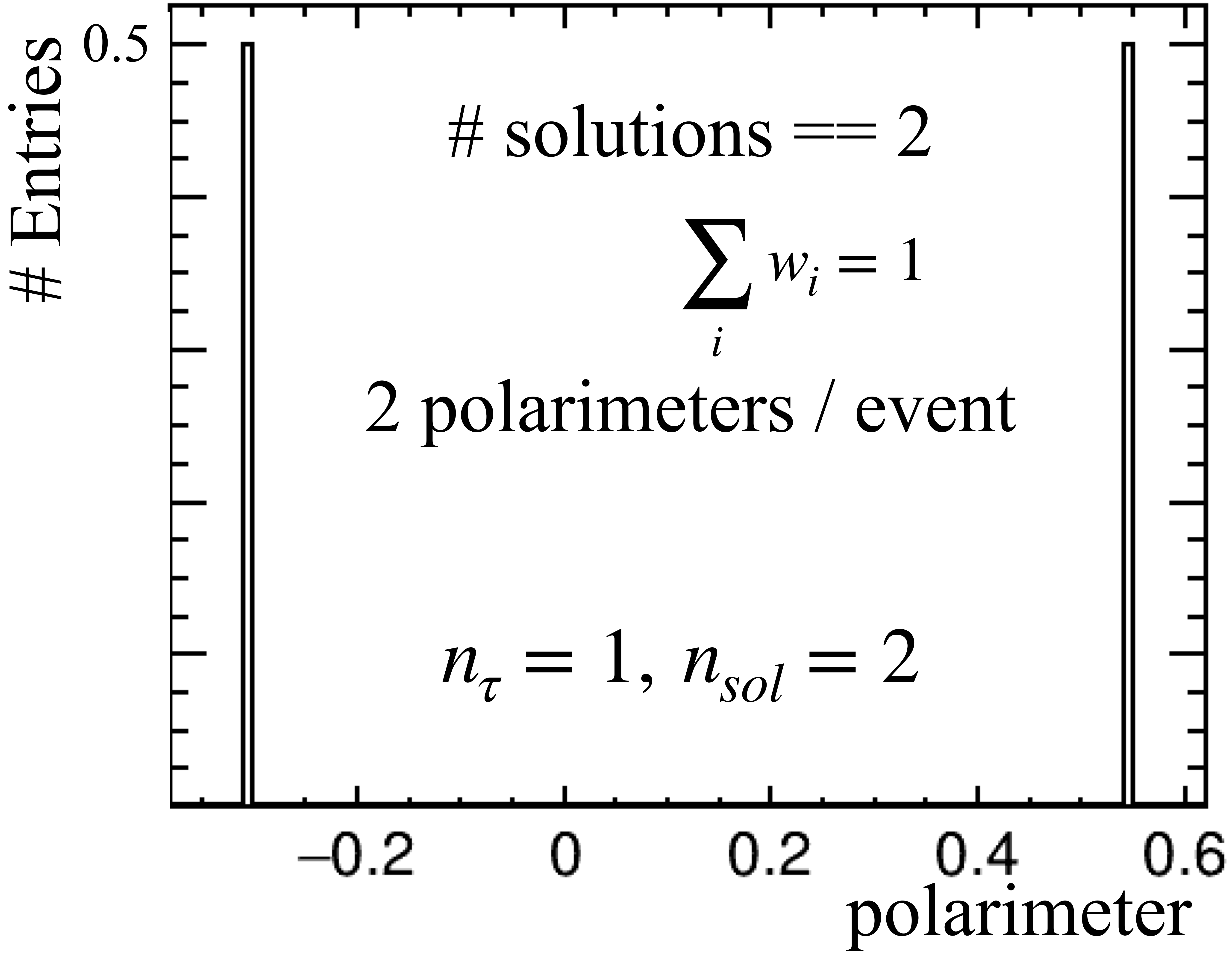
$$
\begin{aligned}
0 \approx\, & p_T^2(|\cot\theta_1 + \cot\theta_2| + \csc\theta_1 + \csc\theta_2) \\
& - p_T E_{CM} \\
& + \frac{1}{2} m_\tau^2 (\sin\theta_1 + \sin\theta_2)
\end{aligned}
$$

which is a quadratic equation in p_T, with solutions

$$
\begin{aligned}
p_T &\approx \frac{E_{CM}}{2A}\left(1 \pm \sqrt{1 - 4AC\frac{m_\tau^2}{E_{CM}^2}}\right), \\
A &= |\cot\theta_1 + \cot\theta_2| + \csc\theta_1 + \csc\theta_2 \\
C &= \frac{1}{2}(\sin\theta_1 + \sin\theta_2).
\end{aligned}
$$

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

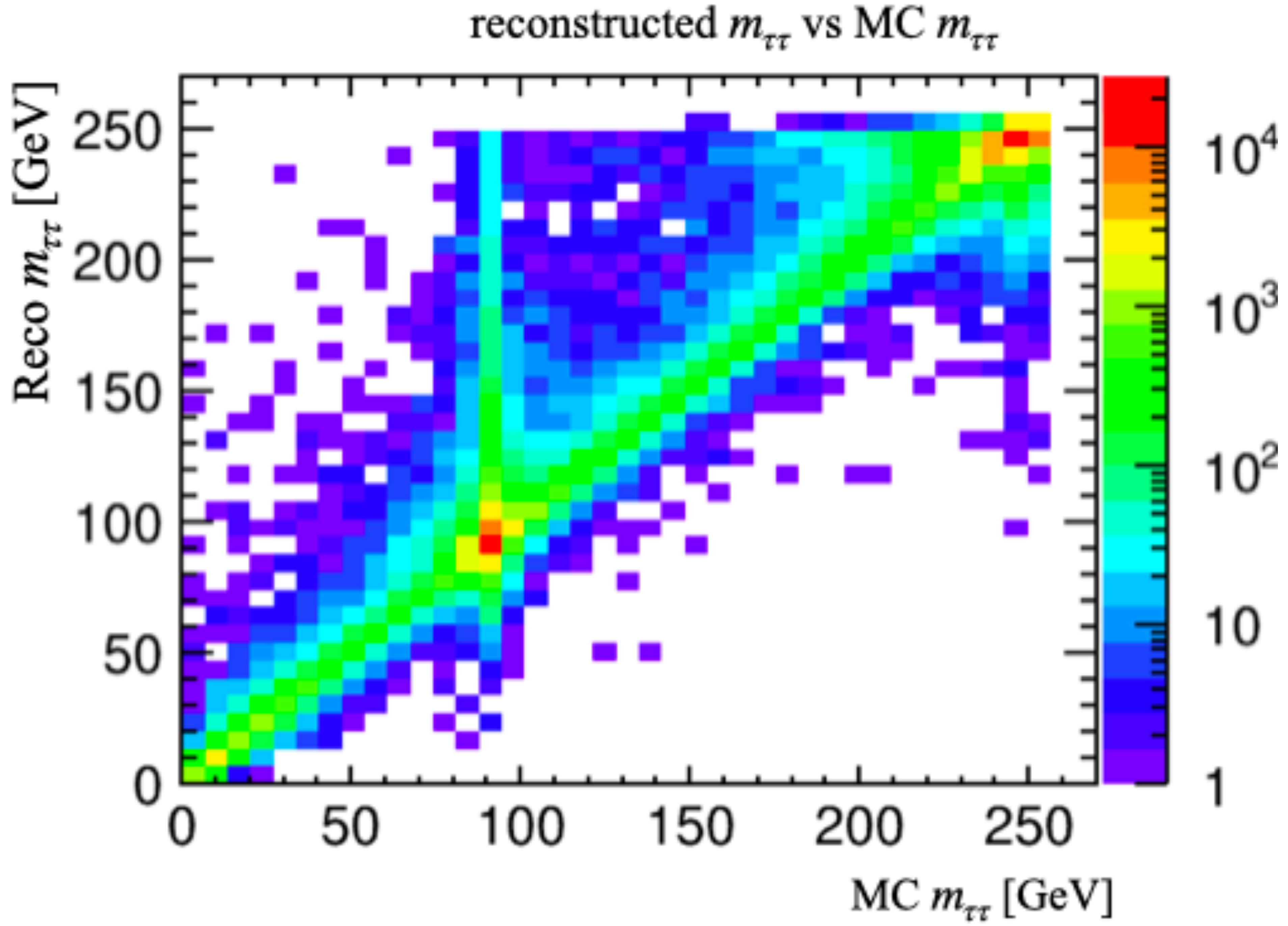
$$\text{weight } w = \frac{1}{n_\tau \cdot n_{sol}}$$



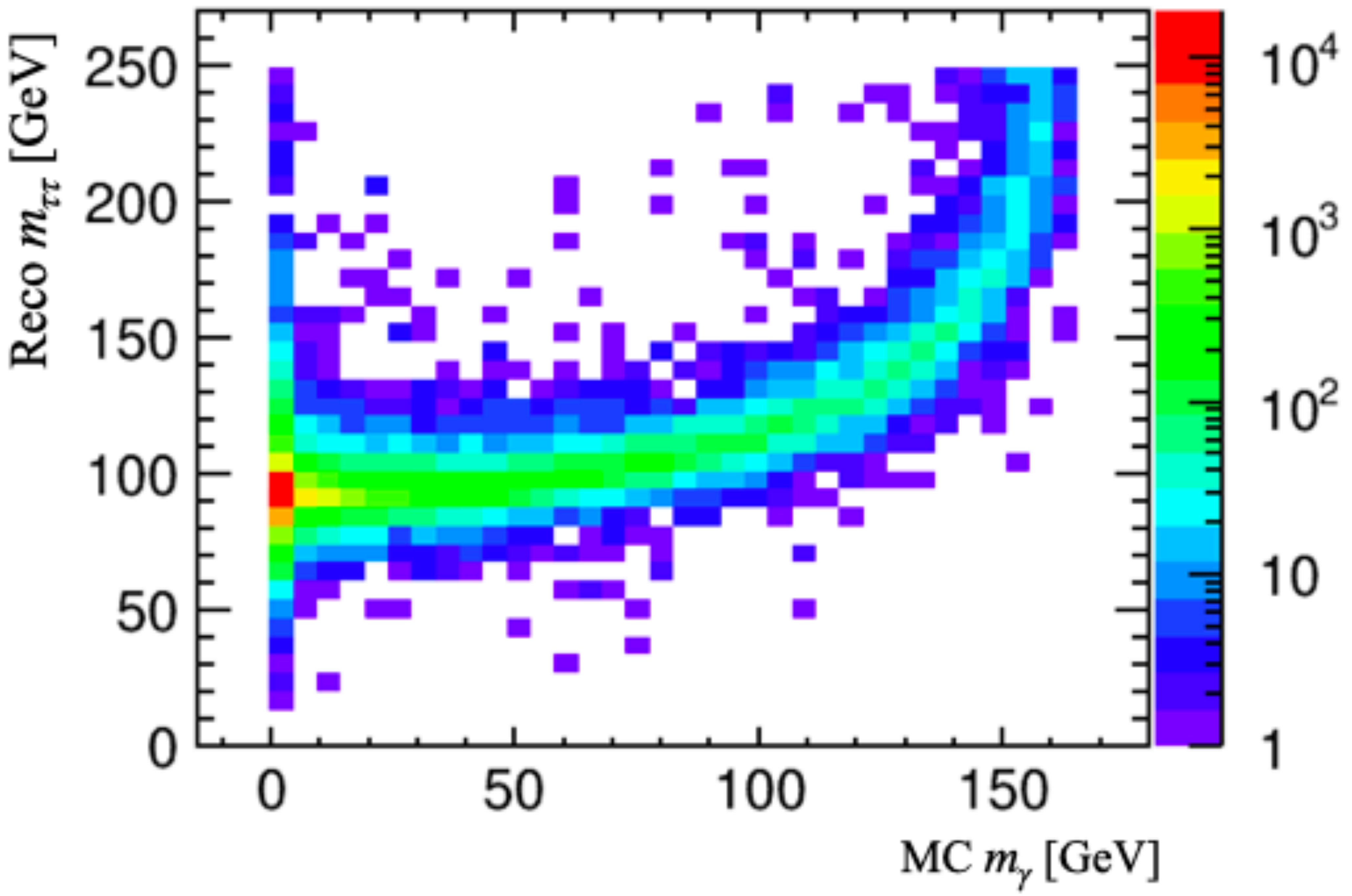
cf.

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

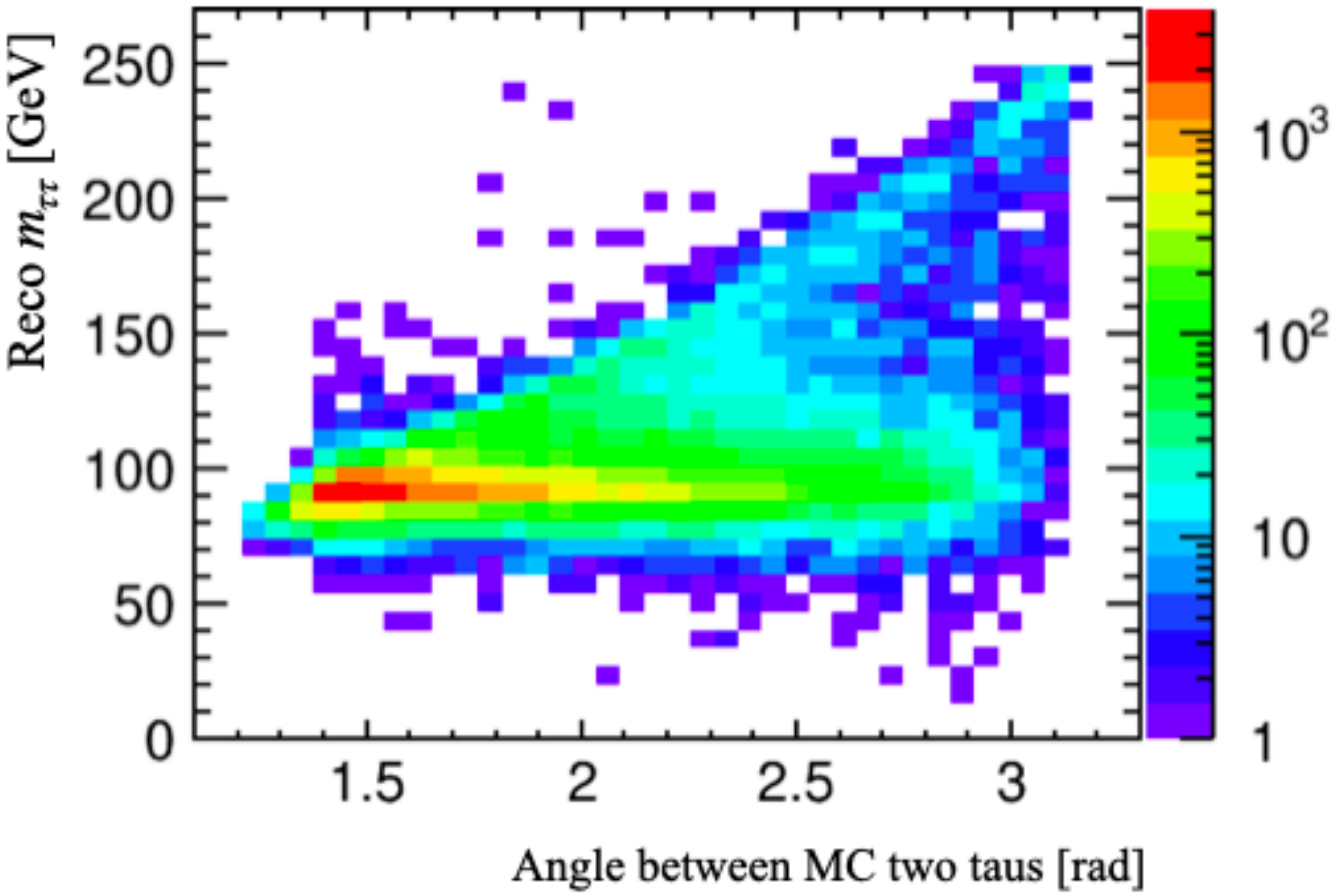
two solutions => $n_\tau = 2$, $n_{sol} = 2$



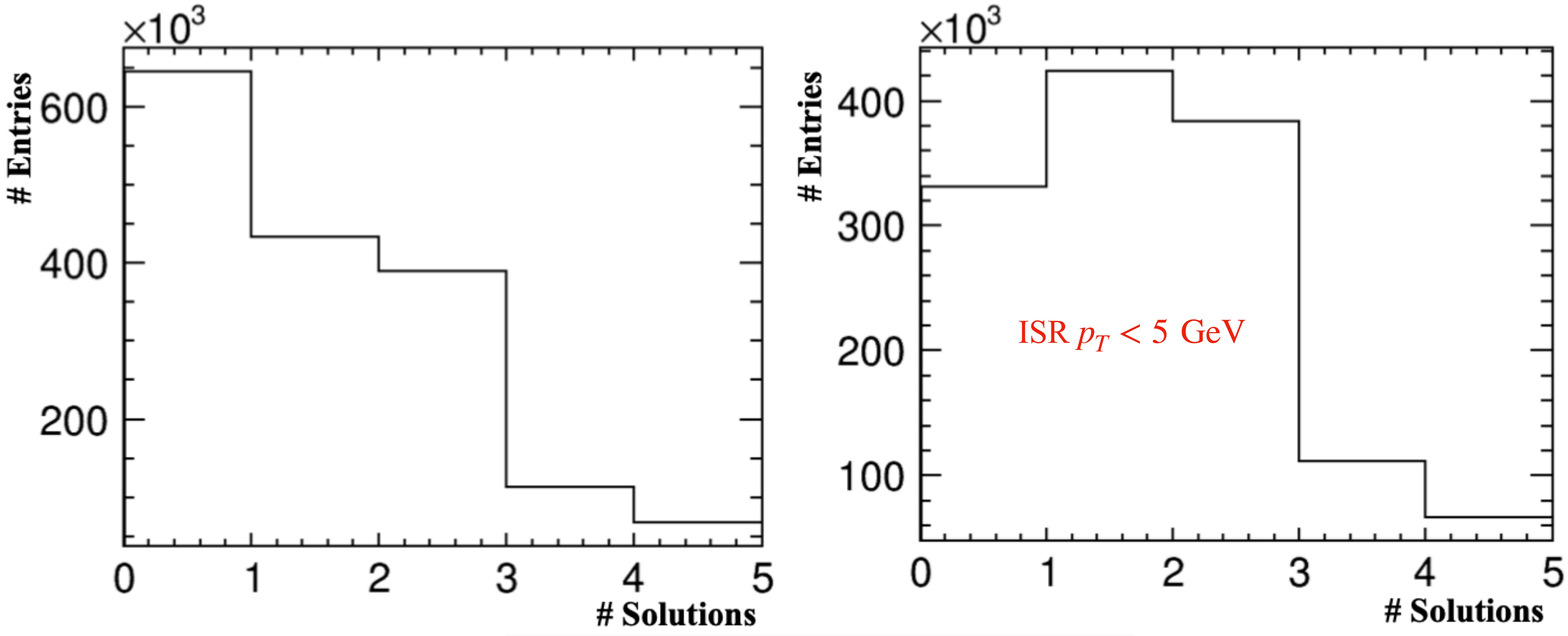
reconstructed $m_{\tau\tau}$ vs MC $m_{\tau\tau}$
Reco $m_{\tau\tau}$ [GeV]
MC $m_{\tau\tau}$ [GeV]



Reco $m_{\tau\tau}$ [GeV]
MC m_{γ} [GeV]

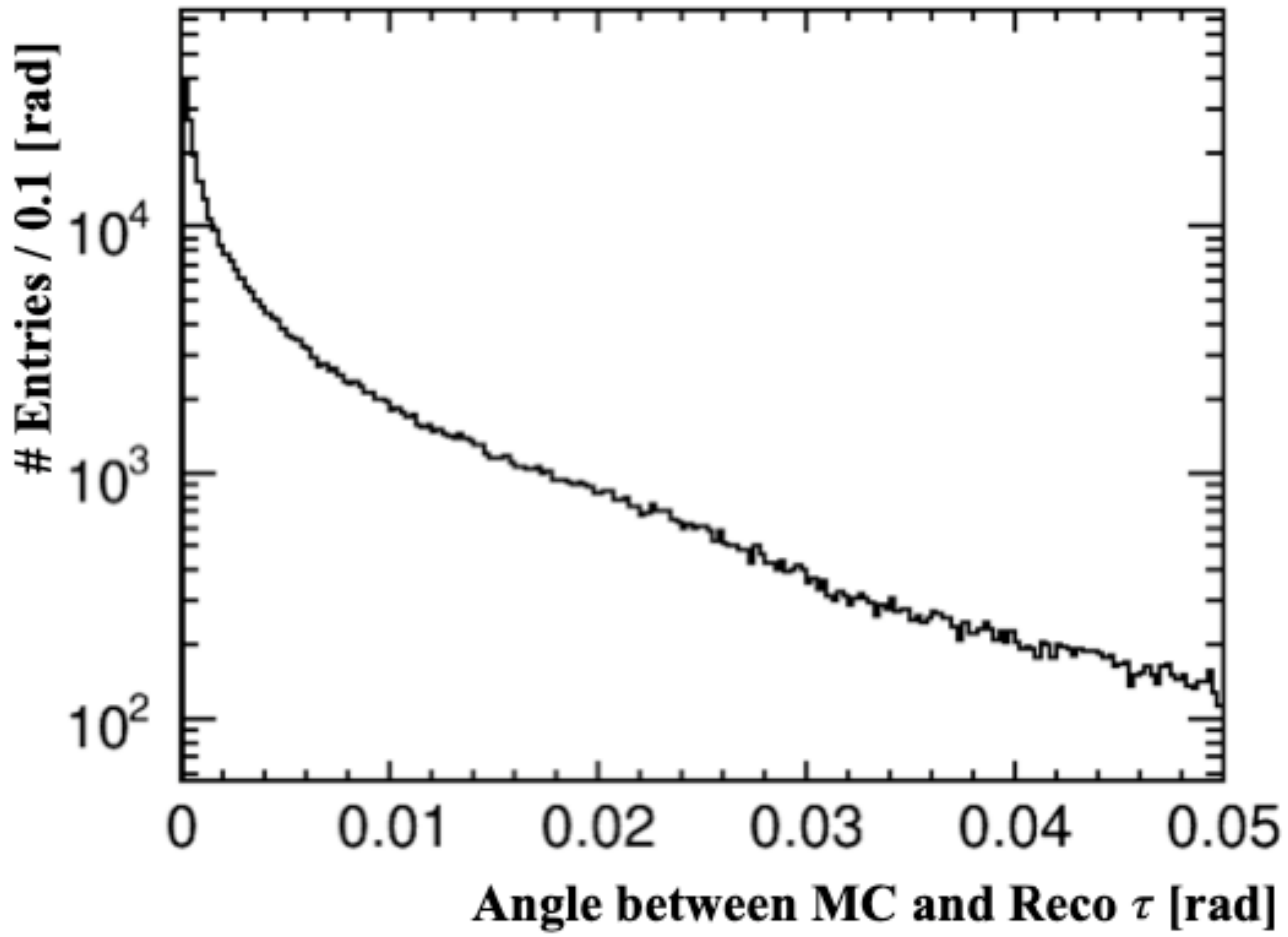


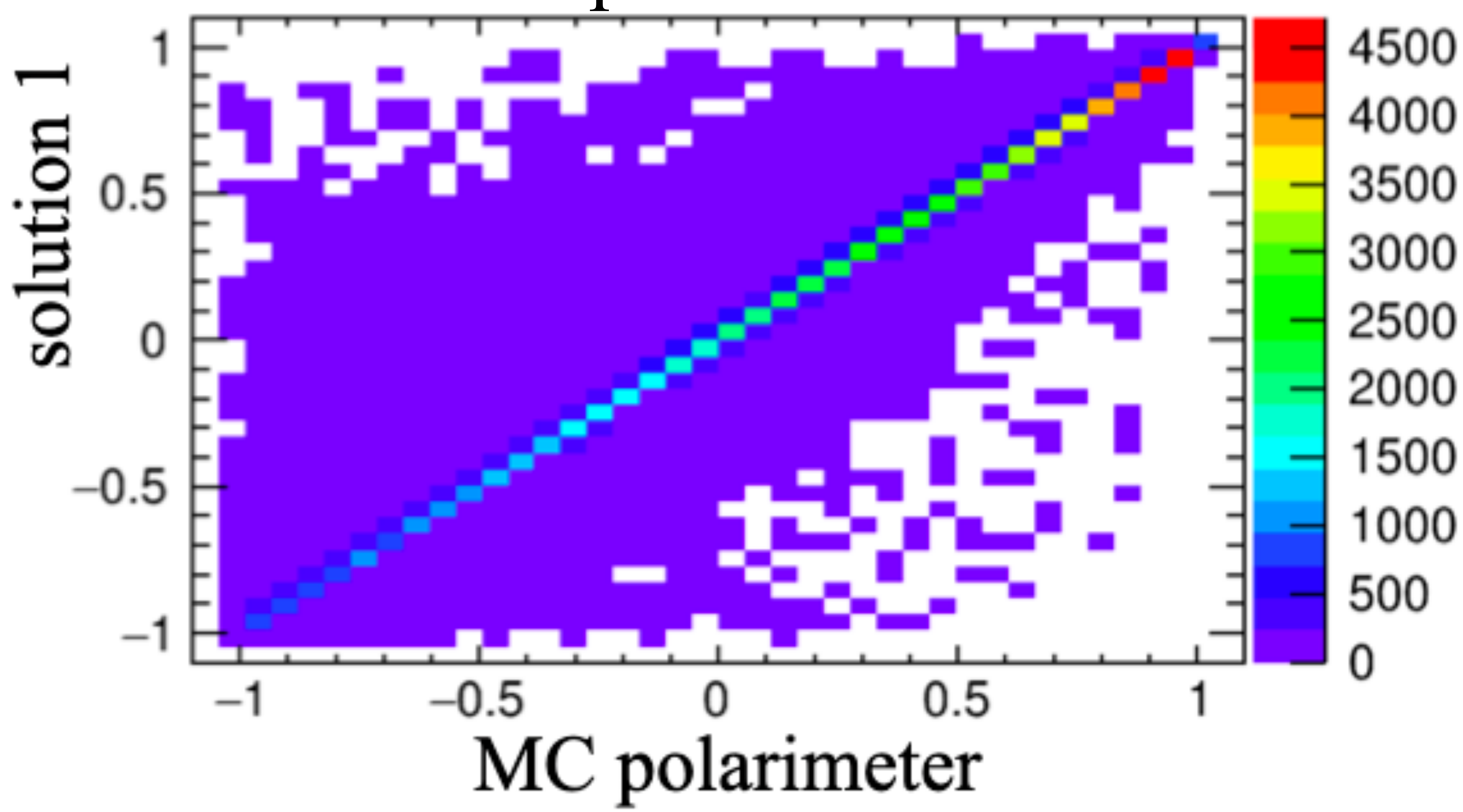
Reco $m_{\tau\tau}$ [GeV]
Angle between MC two taus [rad]



The number of solutions, in all $e^-e^+ \to \tau^-\tau^+$ events (left) and those with small (< 5 GeV)

Comparison with MC





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

reasonable agreement between MC and reconstructed tau