Tau reconstruction in $e^+e^- \rightarrow \tau^+\tau^-$ at the ILC250

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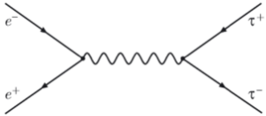
Introduction

Tau is the heaviest lepton and is the only lepton that can decay to hadrons.
Collision of e^+ and e^- generates tau lepton pair in ILC

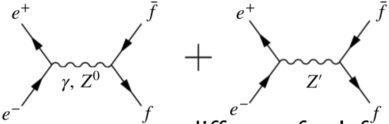


with its rather short lifetime $(2.9 \times 10^{-13}\ \mathrm{sec})$ allows reconstruction of its spin direction by the distribution of its decay products.

Maximum sensitivity to the spin orientation requires reconstruction of the tau decay mode and the kinematics of its decay.

Motivation 1

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



couplings to Z boson g_R, g_L are different for left- and right-handed fermions and left-right polarisation asymmetry A_f are expected in the Standard Model.

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

Thanks to ILC's polarised beams ($e^-_{L80} e^+_{R30}$) A_e can be measured
$\rightarrow A_f$ can be extracted from A_{FB}

Motivation 2

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

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

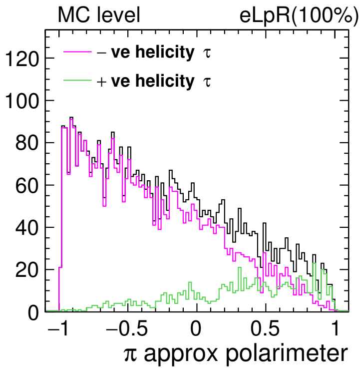
$$\frac{dP(\tau)}{d\cos\theta} = \alpha A_e(1+\cos^2\theta) + \beta A_\tau \cos\theta$$

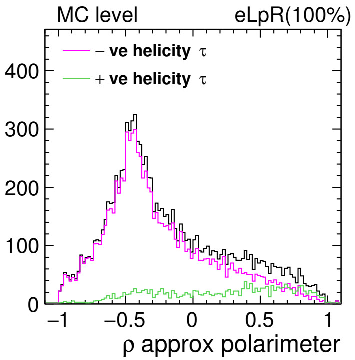
where α, β: coefficients predicted by SM.

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

The aim of this study is reconstruction of tau spin in order to measure polarisation to investigate new physics.

Previous study:look at polarimeter without using neutrino information
"Approximate" polarimeters which are reconstructed based only on the momenta of visible tau decay products.



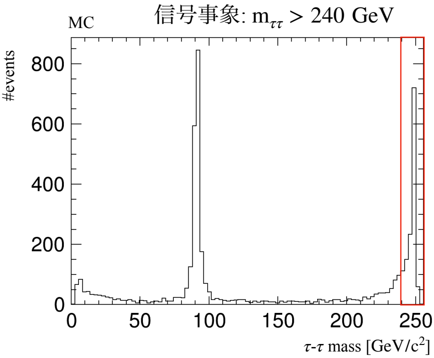


arXiv:1912.08403

In today's talk, we explicitely extract neutrino momentum and look at 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
- Full simulation of ILD detector based on Geant4 and realistic reconstruction were performed.

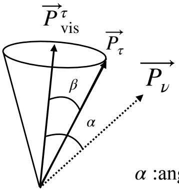


- ◇ only look at
  $\tau \to \pi\nu$ and $\tau \to \rho\nu$
- ◇ $m_{\tau\tau} > 240$ GeV

τ reconstruction method

Assume

- tau-tau is back-to-back
- 1 neutrino per tau
- $m_\tau = 1.776$ GeV
- $E_\tau = \frac{E_{cm}}{2}$



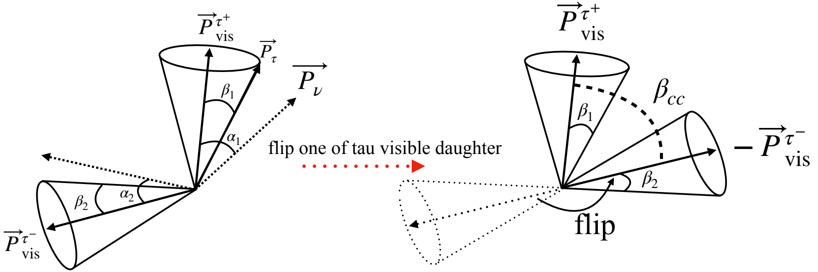
$\vec{P}^{\tau}_{\mathrm{vis}}$: tau visible daughter momentum

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

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

α :angle between tau visible daughter and neutrino

β :angle between tau visible daughter and tau

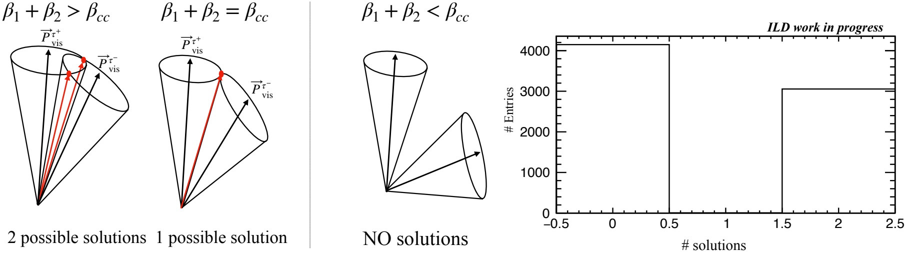


β_{cc} :cone-cone angle

We call this "Cone method"

Find solutions

Look at angle between tau visible daughter and candidate solution.
If at least one intersection point was found, there is a solution.

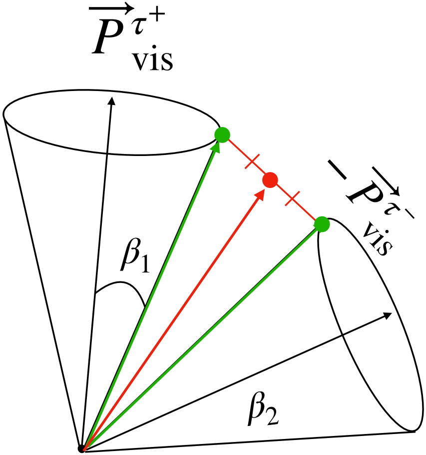


red line:solution = candidate tau direction

use these information to look at tau polarimeter.

Midpoint method

For events for which “Cone Method” cannot find a solution



take a midpoint of cone surface

and use this new vector as a solution

We call this “Midpoint method”

Various levels of "cheating" and methods.

2-levels of cheating

1. Using true neutrino momentum from MC.
2. "Cone method" using MC.

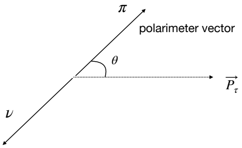
   using true MC visible tau daughters.

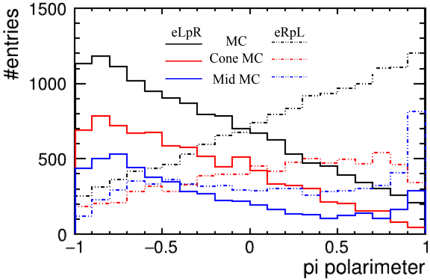
and

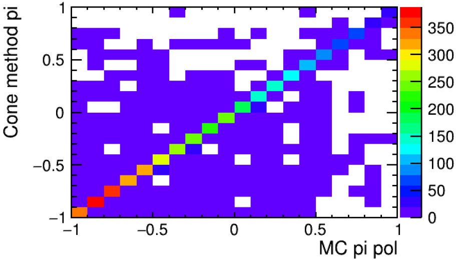
"Midpoint method" using MC

using true MC visible tau daughters..

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



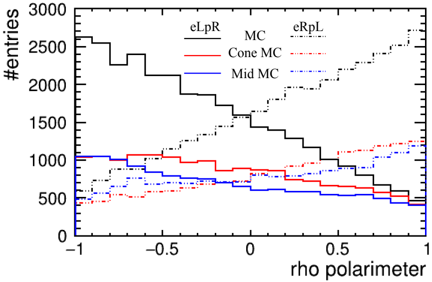


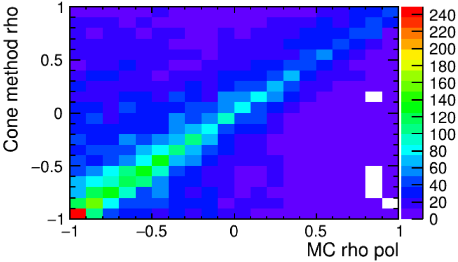


Polarimeter using reconstructed ν information is good agreement with MC one.

Polarimeter vectors in τ rest frame.

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





Polarimeter using reconstructed ν information is roughly close to MC one.

Tau Polarisation Accuracy (Previous study)

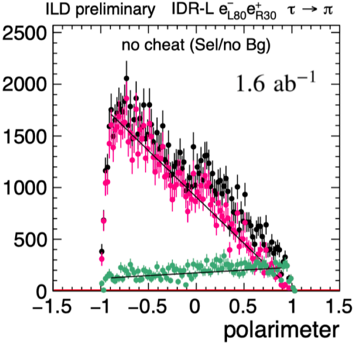
Q.How accurately can tau polarisation be measured?

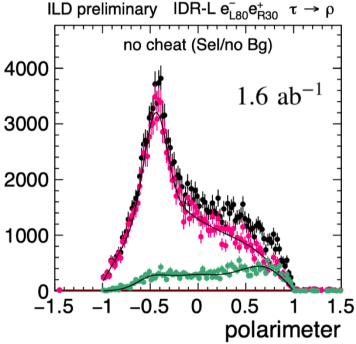
Reconstructed polarimeter templates for $\tau^{\pm} \to \pi^{\pm}\nu$ and $\tau^{\pm} \to \pi^{\pm}\pi^{0}\nu$ decays in the IDR-L model scaled to the expected integrated luminosity in the $e^-_{L80}e^+_{R30}$and $e^-_{R80}e^+_{L30}$

Black $= a \times$ **Red** $+ \; b \times$ **Green**

a, b:coefficient of Red / Green

polarisation $\quad \mathbf{P} = \dfrac{a-b}{a+b}$





Tau Polarisation Accuracy

We want to find normalisation factors for l (-ve helicity τ) and r (+ve helicity τ)

the number of expected events $\mu = \alpha \cdot l + \beta \cdot r$

by minimising the log-likelihood

$$-\frac{\partial^2 L}{\partial \alpha^2} = \sum_i \frac{l^2}{l+r} \equiv S$$

$$-\frac{\partial^2 L}{\partial \beta^2} = \sum_i \frac{r^2}{l+r} \equiv B$$

$$-\frac{\partial^2 L}{\partial \alpha \partial \beta} = \sum_i \frac{l \cdot r}{l+r} \equiv C$$

expected uncertainty $\sigma_\alpha = \sqrt{\frac{B}{S \cdot B - C^2}}$

eLpR	-ve helicity τ	+ve helicity τ
MC	$\sigma_l = 0.0107788$	$\sigma_r = 0.0446907$
Cone	$\sigma_l = 0.0144563$	$\sigma_r = 0.103395$
Mid	$\sigma_l = 0.0222733$	$\sigma_r = 0.0865553$

Summary and Future plan

Summary

- The reconstruction of neutirno momentum at ILC-250 was investigated
- "The cone method" works well so far for $m_{\tau\tau} > 240\ \mathrm{GeV}$.
- Reasonable agreement between MC truth polarimeter value and the one from the cone method for both $\pi\nu$ and $\rho\nu$ decay were found.

Future Plan

- ◇ Check the polarimeters for each tau decay modes without using true tau visible daughter from MC.
- ◇ Investigate the power of searching for new physics by using the tau polarisation.
- ◇ Apply method to radiative return events with visible photon.
- ◇ Use impact parameter information for tau reconstruction.

s_i, b_i : signal and background

n_i : the number of observed events in each bin

the number of expected events $\mu_i = \underline{\alpha} \cdot s_i + \underline{\beta} \cdot b_i$ $\quad i = 1...N$

$$\mathscr{L}(\alpha, \beta) = \prod_i \frac{\mu^{n_i} e^{-\mu_i}}{n_i!} \quad \text{or} \quad L(\alpha, \beta) \equiv \log \mathscr{L}(\alpha, \beta) = \sum_i n_i \log \mu_i - \mu_i - \log n!$$

Find normalisation factors, $\underline{\alpha}$ and $\underline{\beta}$ ≡ solving a set of equations

$$\frac{\partial L}{\partial \alpha} = \frac{\partial L}{\partial \beta} = 0$$

$$-\frac{\partial^2 L}{\partial \alpha^2} = \sum_i \frac{s_i^2}{s_i + b_i} \equiv S$$

$$-\frac{\partial^2 L}{\partial \beta^2} = \sum_i \frac{b_i^2}{s_i + b_i} \equiv B$$

$$-\frac{\partial^2 L}{\partial \alpha \partial \beta} = \sum_i \frac{s_i b_i}{s_i + b_i} \equiv C$$

the expected uncertainty on S/B normalisation

Signal $\sigma_\alpha = \sqrt{\dfrac{B}{S \cdot B - C^2}}$

Background $\sigma_\beta = \sqrt{\dfrac{S}{S \cdot B - C^2}}$

Comments to the paper draft "Measurement of $\sigma(e^+e^- \to HZ) \times Br(H \to ZZ^*)$ at the 250 GeV ILC"
by E. Antonov and A. Drutskoy
https://agenda.linearcollider.org/event/9320/contributions/48460/attachments/36933/57792/reviewer_comments.pdf

Tau Polarisation Accuracy

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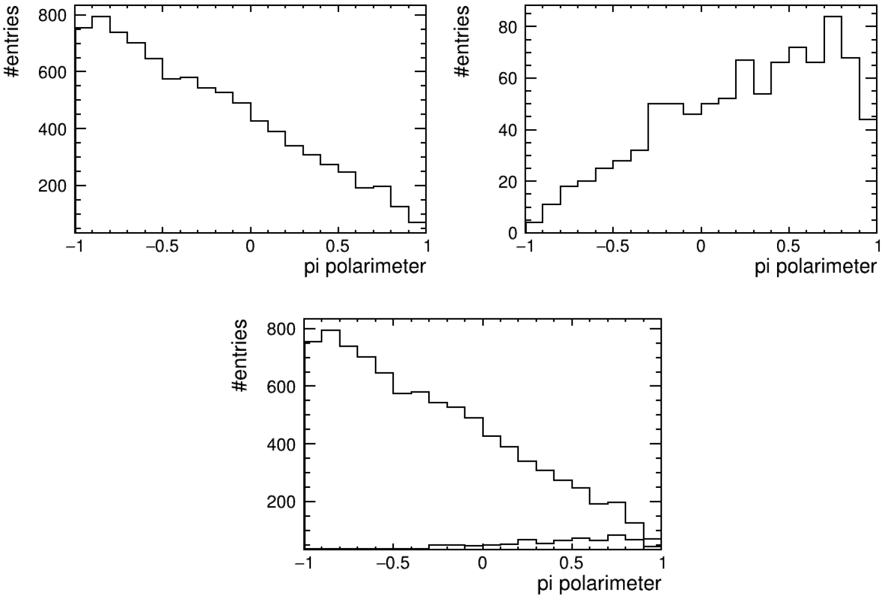
$$-\frac{\partial^2 L}{\partial \alpha \partial \beta} = \sum_i \frac{l \cdot r}{l+r} \equiv C$$

by minimising the log-likelihood

expected uncertainty $\sigma_\alpha = \sqrt{\frac{B}{S \cdot B - C^2}}$

ρ

eLpR	-ve helicity τ	+ve helicity τ
MC	$\sigma_l = 0.00730892$	$\sigma_r = 0.0316177$
Cone	$\sigma_l = 0.0132585$	$\sigma_r = 0.101384$
Mid	$\sigma_l = 0.0169113$	$\sigma_r = 0.0883877$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