Measurement of Beam Polarization with Tau Polarimetry for a Potential SuperKEKB Upgrade

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(Received February 14, 2022)

A polarized electron beam is being considered as an upgrade for the SuperKEKB accelerator. Having a polarized beam at Belle II would enable a strong new precision electroweak physics program, as well as improving sensitivity to dark sector and lepton flavour violating processes. In a number of these precison measurments the limiting factor on the precision is expected to be the uncertainty in the average beam polarization achieved at the interaction point. We present here a Monte Carlo study demonstrating the feasibility of measuring beam polarization through analysis of tau decays. In the future we intend to implement this technique on the *BABAR* data set as a proof of concept while Belle II collects enough data to demonstrate the technique there as well.

KEYWORDS: polarimetry, electroweak precison, tau

1. Introduction

Precision measurements of a number of electroweak parameters can be performed with experimental determinations of the left-right asymmetry, A_{LR}. At an e^+e^- center-of-mass of 10.58 GeV, the non-zero value of this asymmetry arises from $\gamma - Z$ interference [1]. The asymmetry is defined as the normalized difference between the production cross-section for a left and right handed process, as shown in Equation 1.

$$A_{LR} = \frac{\sigma_\mathrm{L} - \sigma_\mathrm{R}}{\sigma_\mathrm{L} + \sigma_\mathrm{R}} \tag{1}$$

Where L and R refer to the helicity of the initial state electrons in the $e^+e^- \to f\overline{f}$ process. In the past the SLD experiment used these asymmetries to set world leading precision measurements of a number of standard model parameters at the Z-pole [2, 3]. At electron positron colliders operating at $\sqrt{s} = 10.58$ GeV, the $\gamma - Z$ interference results in A_{LR} that scales linearly with the average beam polarization as seen in the Born-level expression, Equation 2 [4], where f is the final state fermion in an $e^+e^- \to f\overline{f}$ s-channel process.

$$A^f_{LR} = \frac{4}{\sqrt{2}}\left(\frac{sG_F}{4\pi\alpha Q_f}\right) g^e_A g^f_V \langle P\rangle \tag{2}$$

G_F is the Fermi constant, s is square of the center-of-mass energy, α is the fine structure constant, Q_f the charge, g^e_A is the neutral current axial coupling of the electron, g^f_V is the neutral current vector coupling of the final-state fermion, and $\langle P\rangle$ is the average beam polarization. In these precision measurements the systematic uncertainty in $\langle P\rangle$ can be the limiting factor in the level of precision achievable, in particular for b- and c-quark neutral current couplings. We present here a new technique for performing a precision measurement of the average electron beam polarization from tau lepton pairs created in electron-positron collisions. This measurement technique assumes the $e^+e^- \to \tau^+\tau^-$ process and subsequent tau decays all occur as predicted by the standard model. Equation 3 shows the relationship between the beam polarization and the tau polarization under these assumptions valid for a center-of-mass energy of 10.58 GeV. In most cases deviations from the standard model will be highly suppressed in the second term, however the approach does assume neutrinos are 100% left-handed and the tau neutrino chirality has been measured to be consistent with the SM with a ±0.007% uncertainty.

$$P_\tau = P_e \frac{cos\theta}{1+cos^2\theta} - \frac{8G_F s}{4\sqrt{2}\pi\alpha} g_V^\tau \left(g_A^\tau \frac{|\vec{p}|}{p^0} + 2 g_A^e \frac{cos\theta}{1+cos^2\theta} \right) \tag{3}$$

This beam polarization measurement technique is attractive due to the measurement being made directly at the interaction point using the data being collected by the experimental detector and as such no uncertainty arises from beam polarization measurements made elsewhere in the beam orbit. The tau lepton is particularity well suited for this measurement, due to two convenient properties [5, 6]. First, the tau leptons which being fermions have spin 1/2, will decay within the beam pipe allowing the kinematics of the decay products to be analyzed, secondly the tau lepton spin information is carried in the measurable kinematics of the particles to which it decays. These features have been used in the past to perform measurements of the tau lepton polarization at LEP to extract precision measurements of the weak mixing angle [7–11]. The work we present in here is focused on determining the polarization sensitivity in the $\tau^\pm \to \pi^\pm \nu_\tau$ decay mode with Monte Carlo(MC) studies. This decay mode was chosen for high levels of polarization sensitivity in the decay. The motivation behind this study is a proposed upgrade for SuperKEKB and Belle II where the intent is to longitudinally polarize the electron beam. This polarized beam would allow Belle II to make a number of world leading electroweak measurements [4].

2. Polarization Sensitivity

In order to study the beam polarization sensitivity of $\tau^\pm \to \pi^\pm \nu_\tau$ decays, we use the `KKMC` [12] generator to produce taupairs for both left and right polarized electron beams. For the purposes of our study we also restrict the generator to only allow the tau leptons to decay as $\tau^\pm \to \pi^\pm \nu_\tau$. From Equation 3 we expect the polarization sensitivity to reverse based on the sign of $\cos\theta$, based on this we define $\cos\theta > 0$ as forward and $\cos\theta < 0$ as backward. For the $\tau^\pm \to \pi^\pm \nu_\tau$ decay the most polarization sensitive variable is the momentum, which also accounting for $\cos\theta$ gives two polarization sensitive variables. The distributions for the momentum and $\cos\theta$ are shown in Figures 1 and 2. In order to extract the average polarization from a set of $\tau^\pm \to \pi^\pm \nu_\tau$ decays, we employ a binned maximum likelihood fit as prescribed by Barlow and Beeston [13]. Under this methodology we prepare two dimensional histograms of momentum and $\cos\theta$ for each of the left polarized tau MC, the right polarized tau MC, and a sample of tau MC to be fit. In order to test the fit performance at various beam polarization states we use the generated polarized tau MC to produce various simulated beam polarization states. This is done by mixing the left and right polarized tau MC in specific ratios to produce a desired beam polarization state, i.e. to produce a 70% polarized sample, the mixed sample will be made of 85% left polarized MC and 15% right polarized MC. In order to avoid a potential bias in this process only half of the MC is used to mix the specified beam polarization states while the other half is used to perform the polarization fit. Figure 3 shows the fit performance for beam polarization states from -1 to 1 in steps of 0.1. These studies project a statistical uncertainty of better than 0.5% is achievable for 430 fb^{-1} of data.

3. Conclusions

We have demonstrated that measuring the average electron beam polarization is achievable through analysis of tau decays. This tau polarimetry technique is expected to enable world leading precision measurements at Belle II if the electron beam is polarized. We also expect tau polarimetry could be

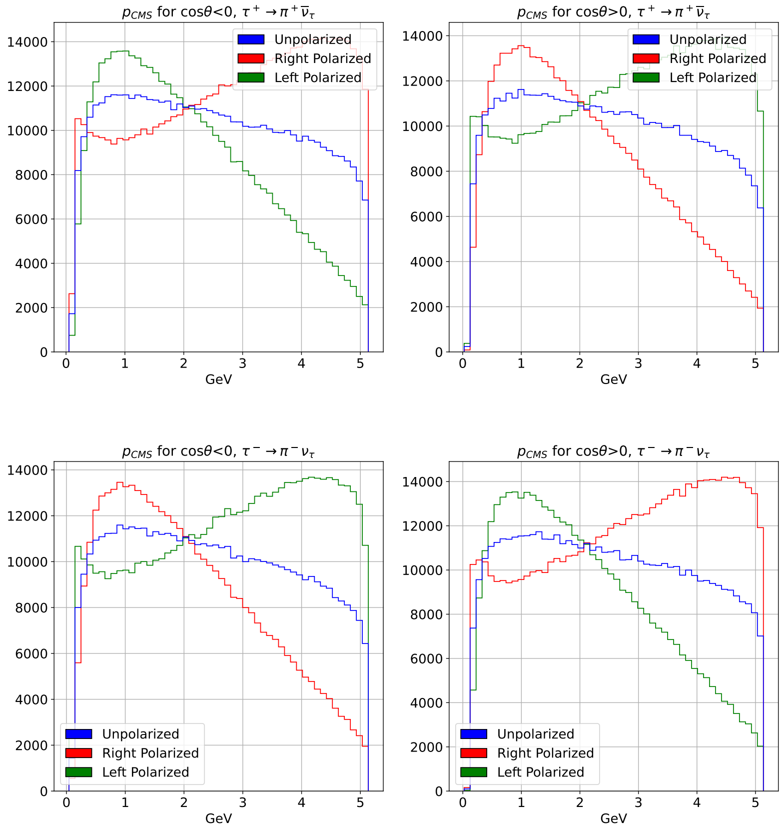

Fig. 1. Polarization sensitivity in the center-of-mass momentum of the final state pions produced in a $\tau^\pm \to \pi^\pm \nu_\tau$ decay. The backward(left) and forward(right) regions flip the polarization effects as predicted by Equation 3. Positive (top) and Negative(bottom) charge also invert the sensitivity.

implemented at any e^+e^- collider including the ILC. As Belle II is still in the early stages of it's data collection program we intend to implement this technique at *BABAR* to measure the PEP-II beam polarization. The beam polarization at PEP-II is expected to be zero, however we will be able to set an expectation for the level of statistical and systematic uncertainties present at B-factories.

References

[1] J. Bernabéu, F. J. Botella, and O. Vives, Nuclear Physics B **472(3)**, 659 (1996)
[2] K. Abe, *et al.*, Phys. Rev. Lett. **79(5)**, 804 (1997)
[3] K. Abe, *et al.*, Phys. Rev. Lett. **86(7)**, 1162 (2001)
[4] M. Roney, PoS **ICHEP2020**, 699 (2021)
[5] J. Bernabéu, F.J. Botella, and O. Vives, The European Physical Journal C - Particles and Fields **7(2)**, 205 (1999)
[6] SuperB Collaboration, arXiv, 2111.10378 (2013)
[7] Physics Reports **427(5)**, 257 (2006)
[8] D. Decamp, *et al.*, Phys. Lett. B **390(1)**, 298 (1997)
[9] P. Abreu, *et al.*, Z. Phys. C. **67**, 183 (1995)
[10] O. Adriani, *et al.*, Phys. Lett. B **294**, 466 (1992)
[11] G. Abbiendi,*et al.*, The European Physical Journal C - Particles and Fields **21(1)**, 1 (2001)
[12] S. Jadach, B.F.L. Ward, and Z. Wąs, Comput. Phys. Commun. **130(3)**, 260 (2000)
[13] R.J. Barlow, and C. Beeston, Comput. Phys. Commun. **77**, 219 (1993)

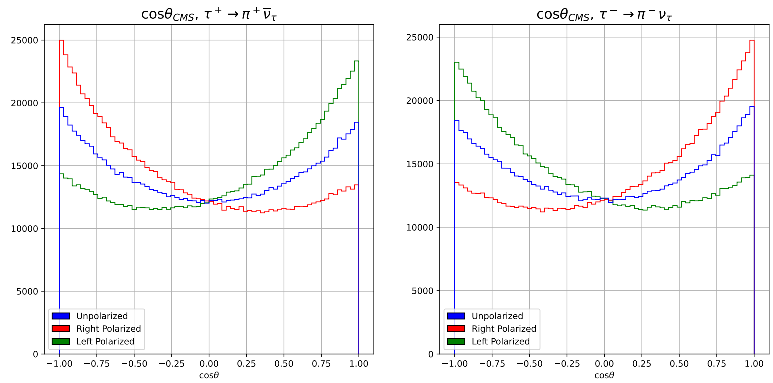

Fig. 2. Polarization sensitivity in $\cos\theta$ for the final state pions produced in a $\tau^{\pm} \to \pi^{\pm}\nu_{\tau}$ decay.

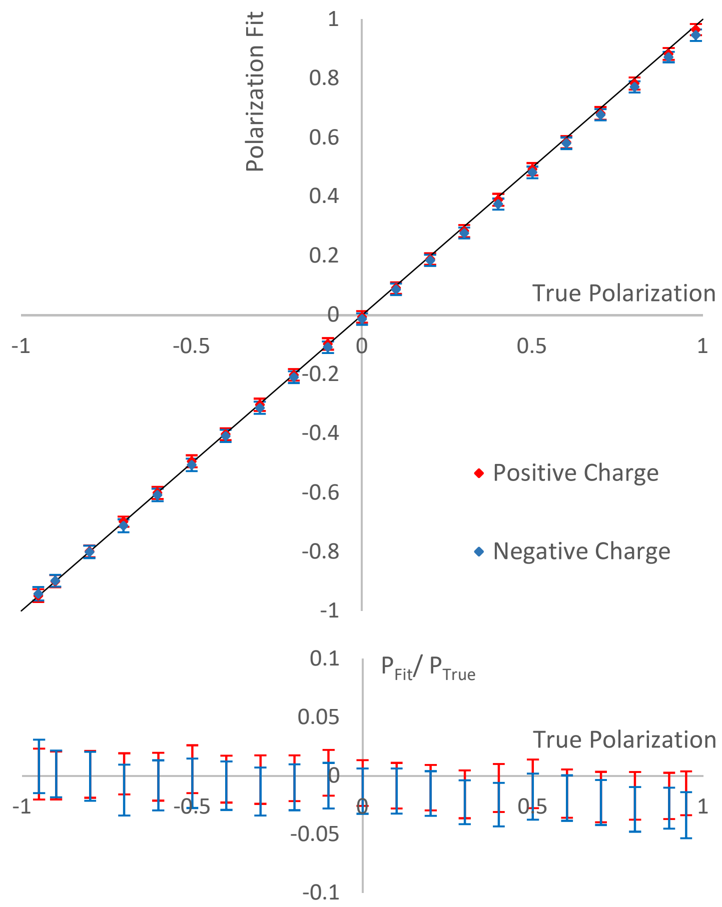

Fig. 3. Average beam polarization reported by fit for various input MC beam polarization states. Error bars are the statistical uncertainty reported by the fit.