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Precision e^- beam polarimetry at an e^+e^- B factory using tau-pair events

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Abstract

A novel technique for measuring the average beam polarization in e^+e^- collisions, known as Tau Polarimetry, has been developed by the BABAR collaboration. This technique makes use of the relationship between the polarization of the beams, the resulting polarization of the $\tau^+\tau^-$ produced, and the kinematics of the decay products. Using this technique BABAR has measured the average e^- beam polarization of PEP-II to be $0.0034 \pm 0.0024_{\text{stat}} \pm 0.0029_{\text{sys}}$. This technique is expected to be used at Belle II after a proposed polarization upgrade as the most precise method with which beam polarization can be determined.

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1 Introduction

The BABAR experiment has published the first use of the novel tau polarimetry technique to measure the average beam polarization of PEP-II to be $0.0034 \pm 0.0024_{\text{stat}} \pm 0.0029_{\text{sys}}$ [1]. This analysis was motivated by the proposed upgrade to the SuperKEKB accelerator, which would introduce a polarized e^- beam [2]. Such an upgrade would enable a wide physics program where for many of the measurements the knowledge of the beam polarization is expected to be the dominant systematic uncertainty.

The tau polarimetry technique provides a method for precisely extracting the average beam polarization from a large dataset. This technique is enabled by two relationships, the first being the relationship between the beam polarization and the tau polarization [3]:

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

where P_τ is the polarization of the tau, P_e is the longitudinal polarization of the beams, θ is the angle between the emitted τ^- and the electron beam in the c.m. frame, and $\vec{p}$ and p^0 are the 3-momentum and energy of the tau respectively.

The second property arises from the left-handed nature of neutrinos, which applies kinematic contrints to the tau decay to conserve angular momentum. This is the same property which the LEP experiments exploited in their measurement of the weak mixing angle [4–8].

2 Polarization sensitivity

It is expected that the tau to pion decay exhibits the strongest polarization sensitivity due to the simple final state. However muon mis-identification and the branching fraction led us to choose the $\tau^- \to \rho^- \nu_\tau \to \pi^- \pi^0 \nu_\tau$ decay as the mode from which to extract the beam polarization. In the ρ decay mode there are three angular variables which fully capture the beam polarization sensitivity. The first is $\cos\theta$ which describes the angle between the incident electron beam and the τ^- momentum vector in the centre of mass frame. Next, $\cos\theta^*$,

$$\cos\theta^* = \frac{2z - 1 - m_\rho^2/m_\tau^2}{1 - m_\rho^2/m_\tau^2}, \qquad z \equiv \frac{E_\rho}{E_{\text{beam}}}, \tag{2}$$

is the angle between the ρ^- momentum vector in the τ^- rest frame and the boost vector from the centre of mass frame to the rest frame. Finally, $\cos\psi$,

$$\cos\psi = \frac{2x - 1}{\sqrt{1 - m_\pi^2/m_\rho^2}}, \qquad x \equiv \frac{E_\pi}{E_\rho}, \tag{3}$$

is the angle between the π^- momentum vector in the ρ rest frame and the boost vector from the centre of mass frame to the ρ rest frame.

3 Fit methodology and validation

The polarization is extracted from a fit of the expected MC shapes of the three angular variables using a Barlow and Beeston template fit [9–11]. In order to be sensitive to the beam polarization the `KK2f` generator was used to generate $e^+e^- \to \tau^+\tau^-$ events for both a left and right polarized electron beam [12]. The data can then be fit as a linear combination of all $e^+e^- \to XX$ final states, with the difference between the contributions from the left and right polarized τ MC being the average beam polarization. We validate this methodology by creating MC samples with pre-defined beam polarizations by mixing the left and right polarized τ MC samples. By using half the samples to create the desired polarization state, and the other half in the fitting templates we have an independent but correlated set of fits. Figure 1 shows the response of the fit to various input polarizations, and demonstrates that Tau Polarimetry performs well at any beam polarization state.

4 Fit result

Employing the fit on each of the six data runs collected by BABAR gives the results in Table 1. All runs show reasonable agreement with no beam polarization in both the average fit as well as individual charged fits as expected.

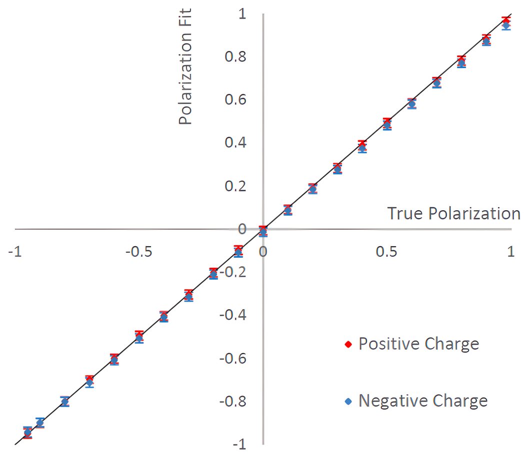

Figure 1: Beam polarization measured in MC samples as a function of input beam polarization [1].

5 Systematic uncertainties

The study of the systematic uncertainties identified 21 sources of systematic bias of which 6 of the top 7 relate to the modelling of neutral processes in the BABAR detector. A summary of all the uncertainties is presented as Table 2.

6 Conclusions

The results of the BABAR measurement of the average beam polarization present in PEP-II, $\langle P \rangle = 0.0034 \pm 0.0024_{\text{stat}} \pm 0.0029_{\text{sys}}$, have demonstrated that a $\sim 0.3\%$ systematic uncertainty is achievable. This is strong confirmation that Belle II experiment will meet or exceed the projected physics measurement sensitivities for the Chiral Belle upgrade. The tau polarimetry technique could be a useful tool for any future e^+e^- collider which produces tau pairs and is interested in beam polarimetry.

Table 1: Average beam polarization measured for each run period of the BABAR data set. The average for each run is obtained from the weighted mean of the positive and negative fit results. The reported uncertainties are statistical only. Adapted from Ref. [1].

Data Set (fb^{-1})	Positive Charge	Negative Charge	Average Polarization
Run 1 (20.4)	0.0018±0.014	-0.0047±0.014	-0.0014±0.010
Run 2 (61.3)	0.0075±0.0083	0.0007±0.0083	0.0041±0.0059
Run 3 (32.3)	0.0151±0.012	-0.0047±0.012	0.0048±0.0083
Run 4 (99.6)	-0.0035±0.0072	0.0010±0.0067	-0.0011±0.0049
Run 5 (132.3)	-0.0028±0.0062	0.0136±0.0064	0.0052±0.0045
Run 6 (78.3)	0.0036±0.0089	0.0133±0.0088	0.0084±0.0062
424.18±1.8	0.0015±0.0034	0.0055±0.0034	0.0035±0.0024

Table 2: Summary of systematic uncertainties associated with the Tau Polarimetry polarization measurement. The combined column accounts for correlations between runs in the combination. Adapted from Ref. [1].

Source	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Combined
π^0 efficiency	0.0025	0.0016	0.0013	0.0018	0.0006	0.0017	**0.0013**
Muon PID	0.0018	0.0018	0.0029	0.0011	0.0006	0.0016	**0.0012**
Split-off modeling	0.0015	0.0017	0.0016	0.0006	0.0016	0.0020	**0.0011**
Neutral energy calibration	0.0027	0.0012	0.0023	0.0009	0.0014	0.0008	**0.0010**
π^0 mass	0.0018	0.0028	0.0010	0.0005	0.0004	0.0004	**0.0008**
$\cos\alpha$	0.0015	0.0009	0.0016	0.0007	0.0005	0.0005	**0.0007**
π^0 likelihood	0.0015	0.0009	0.0015	0.0006	0.0003	0.0010	**0.0006**
Electron PID	0.0011	0.0020	0.0008	0.0006	0.0005	0.0001	**0.0005**
Particle transverse momentum	0.0012	0.0007	0.0009	0.0002	0.0003	0.0006	**0.0004**
Boost modeling	0.0004	0.0019	0.0003	0.0004	0.0004	0.0004	**0.0004**
Momentum calibration	0.0001	0.0014	0.0005	0.0002	0.0001	0.0003	**0.0004**
Max EMC acceptance	0.0001	0.0011	0.0008	0.0001	0.0002	0.0005	**0.0003**
τ direction definition	0.0003	0.0007	0.0008	0.0003	0.0001	0.0004	**0.0003**
Angular resolution	0.0003	0.0008	0.0003	0.0003	0.0002	0.0003	**0.0003**
Background modeling	0.0005	0.0006	0.0010	0.0002	0.0003	0.0003	**0.0003**
Event transverse momentum	0.0001	0.0013	0.0005	0.0002	0.0002	0.0004	**0.0003**
Momentum resolution	0.0001	0.0012	0.0004	0.0002	0.0001	0.0005	**0.0003**
ρ mass acceptance	0.0000	0.0011	0.0003	0.0001	0.0002	0.0005	**0.0003**
τ branching fraction	0.0001	0.0007	0.0004	0.0002	0.0002	0.0002	**0.0002**
$\cos\theta^\star$ acceptance	0.0002	0.0006	0.0004	0.0001	0.0001	0.0004	**0.0002**
$\cos\psi$ acceptance	0.0002	0.0003	0.0002	0.0002	0.0002	0.0003	**0.0002**
Total	0.0058	0.0062	0.0054	0.0030	0.0026	0.0038	**0.0029**

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