Measurement of Beam Polarization through Tau Forward-Backward Polarization Asymmetry

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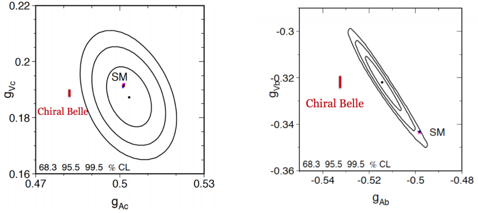
Motivation

- Beam polarization is being considered as a future upgrade to SuperKEKB
- A polarized electron beam would allow Belle II to make many precise measurements of electro-weak parameters. Including A_{LR} for e,μ,τ,c,b

$$\mathrm{A_{LR}} = \frac{\sigma_\mathrm{L} - \sigma_\mathrm{R}}{\sigma_\mathrm{L} + \sigma_\mathrm{R}} = \frac{4}{\sqrt{2}} \left(\frac{G_F s}{4\pi\alpha Q_f} \right) g_A^e g_V^f \langle Pol \rangle \propto T_3^f - 2Q_f \sin^2\theta_\mathrm{W}$$

c-quark: Chiral Belle ~7 times more precise **with 20 ab⁻¹** **b-quark:** Chiral Belle ~4 times more precise



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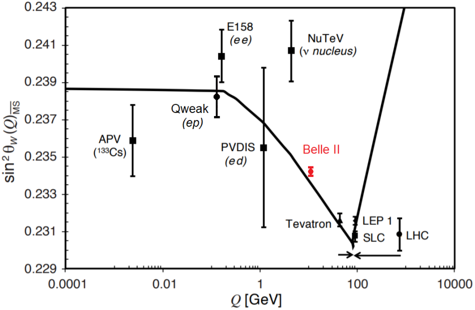
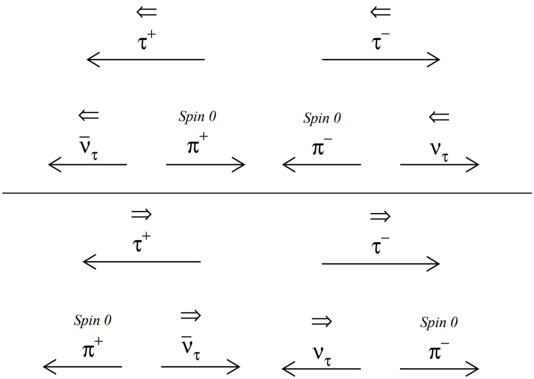


$\sigma(s^2\theta_W) \approx 0.0002$
($40ab^{-1}$)

Measuring Beam Polarization with Tau Decays

- The τ decay, $\tau \to \pi\nu$, provides a powerful technique to measure polarization.



Pion Momentum Polarization Sensitivity

- Assuming a pure sample of $\tau \to \pi\nu$ events

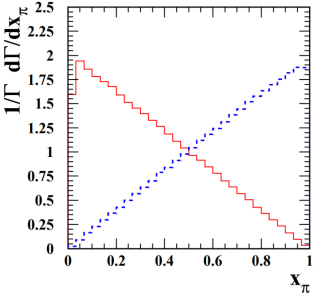


Figure: Pion momentum distributions for a right handed tau(blue) or a lefted handed tau(red)

Pion Momentum Polarization Sensitivity

- In reality it's not easy to determine the tau helicity state but most of the sensitivity still exists from just a polarized electron beam

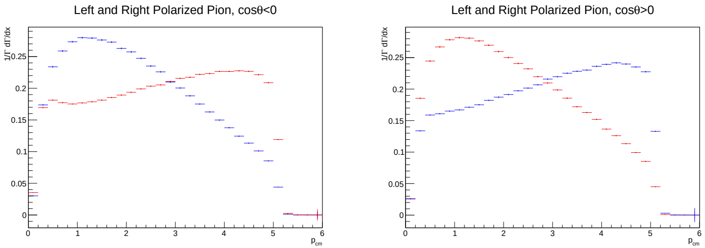
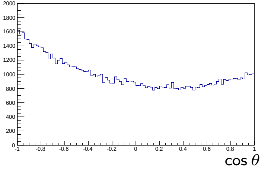


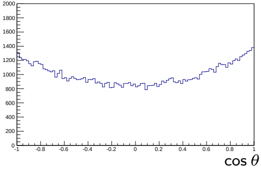
Figure: Pion momentum distributions for a right handed electron(blue) or a lefted handed electron(red)

Pion Angular Polarization Sensitivity

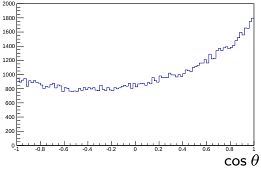
Left Polarization



No Polarization



Right Polarization



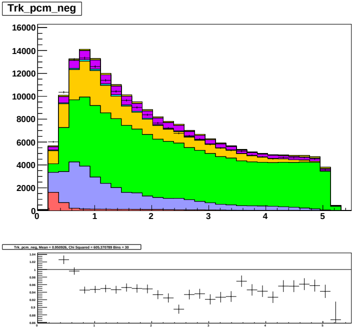
Event Selection

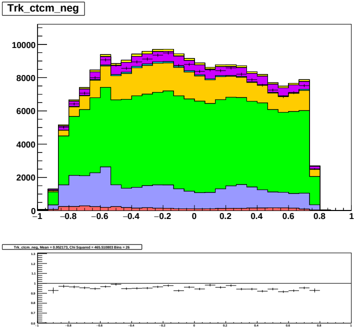
- Using BaBar data to develop technique
  - Full BaBar data set is 513.7 fb^{-1}
  - Using Run 3 as unblinded sample (32.28 fb^{-1})
- Studied multiple tagging options
  - (pion tag)$\tau\tau \rightarrow \pi\nu + \pi\bar{\nu}$ large backgrounds from $e^{+}e^{-} \rightarrow \mu^{+}\mu^{-}$
  - (3 pion tag) $\tau\tau \rightarrow \pi\pi\pi\nu + \pi\bar{\nu}$ still needs work
  - (electron tag) $\tau\tau \rightarrow e\nu + \pi\bar{\nu}$ large backgrounds from $e^{+}e^{-} \rightarrow e^{+}e^{-}$
  - (rho tag) $\tau\tau \rightarrow \pi n\pi^{0}\nu + \pi\bar{\nu}$ very pure
- The "rho tag" was changed to allow multiple pi0's. This doubled the number of signal events which pass the selection

Event Selection

1. Event passes the BGFTau flag and a L3trig
2. Total charge of the event is zero
3. Two charged tracks
4. Both tracks within $0.430 < \theta_{lab} < 2.350$
5. Both tracks satisfy $E/p < 0.75$
6. The total event P_T is greater than 1.2 GeV
7. Neutral clusters less than 50 MeV are removed from the event
8. Neutral clusters within 40cm of a track are associated with the track
9. A good signal track
   9.1 No other neutral clusters in the hemisphere
   9.2 Fails the a BDT VeryLoose muon PID selector
10. A tag track with good π^0(s)
    10.1 Neutral clusters with π^0 PID likelihood>20 or,
    10.2 Pair of clusters with a mass between 115 and 155 MeV

Momentum and $\cos\theta$ distributions





Fitting

- The fit is done with a Barlow template method
- In order to be sensitive to polarization Tau MC was produced for a left and right polarized electron beam
- The unpolarized Tau MC into 3 statistically independent samples and then merged with non-Tau MC to produce data-like samples
- The 3 Tau samples contain 42.7 fb^{-1} equivalent events and are scaled to 32.28 fb^{-1}
- The data (or equivalent MC) is then fit as a linear combination of the templates

$$D = a_l L + a_r R + a_b B + a_m M + a_u U + a_c C \quad (1)$$

$$\sum_i a_i \equiv 1 \quad (2)$$

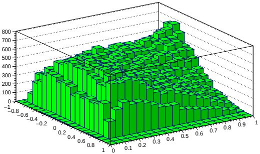
$$\langle Pol \rangle \equiv a_l - a_r \quad (3)$$

L=Left Polarized Tau MC, R=Right Polarized Tau MC, B=Bhabha, M=$\mu\mu$, U=uds, C=$c\overline{c}$

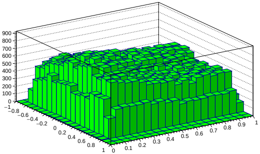
Template Examples

Example distributions for $\tau \to \pi\nu$

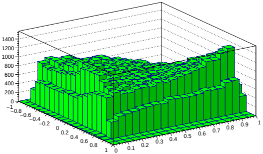
Left Polarization



No Polarization



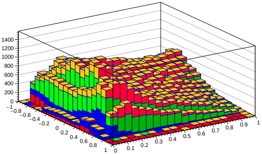
Right Polarization



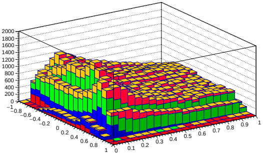
Template Examples

Example distributions for data equivalent MC

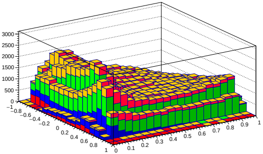
Left Polarization



No Polarization



Right Polarization



Fit Result

	Positive Charge	Negative Charge	Combined Average
Tau MC 1	$P_1^+ \pm \sigma_1^+$	$P_1^- \pm \sigma_1^-$	$P_1^A \pm \sigma_1^A$
Tau MC 2	$P_2^+ \pm \sigma_2^+$	$P_2^- \pm \sigma_2^-$	$P_2^A \pm \sigma_2^A$
Tau MC 3	$P_3^+ \pm \sigma_3^+$	$P_3^- \pm \sigma_3^-$	$P_3^A \pm \sigma_3^A$
Data	$P_D^+ \pm \sigma_D^+$	$P_D^- \pm \sigma_D^-$	$P_D^A \pm \sigma_D^A$

$$P_i^A = \frac{\frac{P_i^+}{(\sigma_i^+)^2} + \frac{P_i^-}{(\sigma_i^-)^2}}{\frac{1}{(\sigma_i^+)^2} + \frac{1}{(\sigma_i^-)^2}} \qquad \sigma_i^A = \frac{1}{\sqrt{\frac{1}{(\sigma_i^+)^2} + \frac{1}{(\sigma_i^-)^2}}} \qquad (4)$$

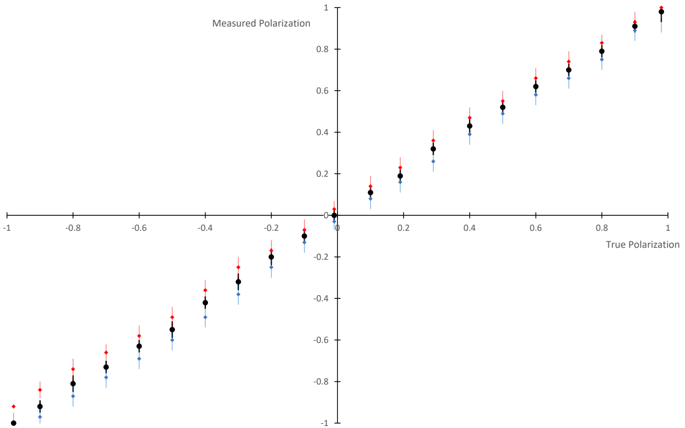
Fit Results

	Positive Charge	Negative Charge	Combined Average
Tau MC 1	-0.0010$\pm$0.0140	0.0034$\pm$0.0140	0.0012$\pm$0.0099
Tau MC 2	-0.0035$\pm$0.0140	-0.0339$\pm$0.0151	-0.0176$\pm$0.0103
Tau MC 3	-0.0074$\pm$0.0150	-0.0184$\pm$0.0151	-0.0128$\pm$0.0106
Data	0.0244$\pm$0.0146	0.0231$\pm$0.0157	0.0238$\pm$0.0107

Figure: Run 3 Fit, 32.3 fb^{-1}

Polarization Sensitivity

- To test the total polarization sensitivity, the polarized Tau MC was split into 2 sets
- One set for measuring polarization, one set for mixing known polarization states



Systematic Study List

- Momentum Resolution
- Angular Resolution
- non-τ Backgrounds
- τ Branching Fraction
- Track List
- π^0 Likelihood
- Event P_T
- $\mathscr{L}$ Weighting
- Boost Vector
- Muon PID
- Neutral Energy Resolution
- π^0 Mass
- BGFTau
- E/p
- Neutral-Track Cluster Association

Systematics Approach

- Method 1: Change in MC-Data agreement
  - In the case where Data and MC are in good agreement, the variable is changed and the relative shift between the Data and MC is taken as the systematic
- Method 2: Change in Data fit
  - In the case where the MC differs significantly from the Data, the MC is corrected and the shift it causes in the Data fit is taken as the systematic

In some cases both methods are used iteratively until the systematic is understood at an acceptable level

Muon PID systematic

- To evaluate the Muon PID uncertainty the effect of switching from the VeryLoose to Loose version of the selector was studied
- In particular the shift in polarization fit for the data and MC was compared

Cut	Sample	Shift in Fit	Shift in Agreement
PID Change	MC	-0.0065$\pm$0.0023	0.0030$\pm$0.0023
	Data	-0.0035	

Boost Correction

- Used muon pairs to look at the boost through the muon pair acollinearity

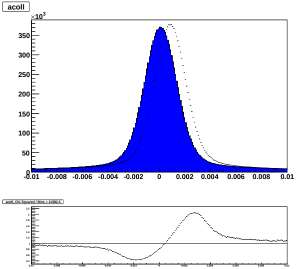


Figure: acollinearity in θ

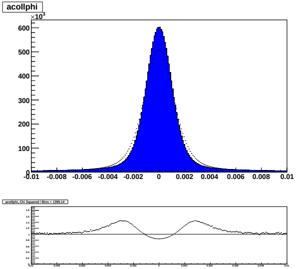
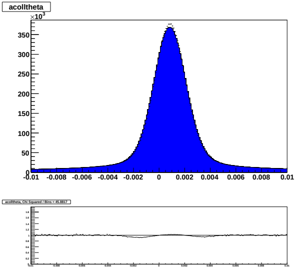


Figure: acollinearity in ϕ

Boost Correction

- After correction



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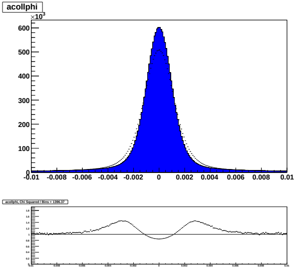

Figure: acollinearity in ϕ

- Correction to MC causes the Data fit to shift by 0.0005

Systematic Study List

- Momentum Resolution ✓
- Angular Resolution ✓
- non-τ Backgrounds ✓
- τ Branching Fraction ✓
- Track List ✓
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- Event P_T ✓
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- π^0 Mass ✓
- BGFTau ✓
- E/p ✓
- Neutral-Track Cluster Association ✓

Systematic summary

Study	Systematic
P	**0.0015**
Boost	0.0005
θ	0.0002
ϕ	0
non-τ Backgrounds	0.0002
PID_{μ}*	**0.0030**
τ-BF	0.0001
E_{γ}*	**0.0016**
Charged List	0.0003
π^0 Mass	0.0008
π^0 Likelihood	0.0003
BGFTau	0.0009
Event P_T	0.0003
E/p*	**0.0015**
$\mathscr{L}$ Weight	0.0001
Neutral-Track Distance	**0.0016**
Quad Sum	**0.0045**

* Statistically limited

BaBar Next Steps

- Previously listed systematic studies all completed
- Currently working on sensitivity to hemisphere definition
- BaBar review committee is formed and ready to review analysis
- BAD note finished and will be sent to BaBar review committee soon
- So far only Run 3 used, $\sim$7.5% of total
- Expect full measurement uncertainty will be: $\sigma_P = 0.0030_{stat} \pm 0.0045_{sys}$
- Many of the dominant systematics are statically limited so final systematic uncertainity is expected to improve still