# Measurement of Beam Polarization through Tau Forward-Backward Polarization Asymmetry

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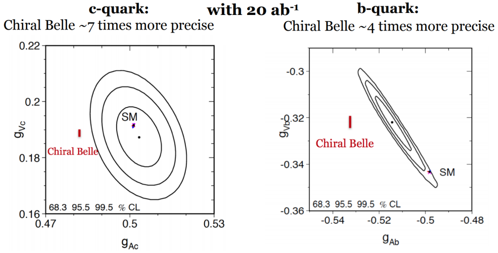
# Motivation

- 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,$\mu$,$\tau$,c,b

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



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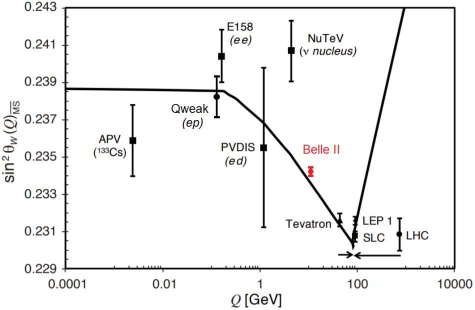
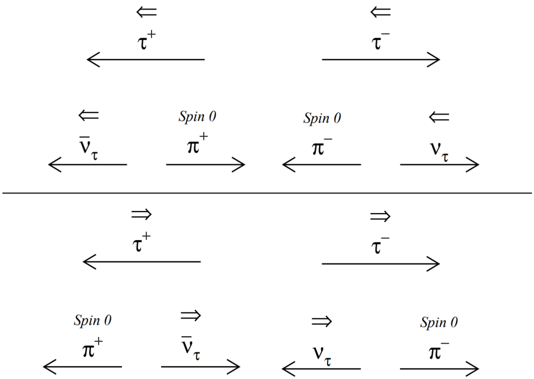



$\sigma(s^2\theta_W) \approx 0.0002$
$(40\mathrm{ab}^{-1})$

# Measuring Beam Polarization with Tau Decays

- The $\tau$ 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

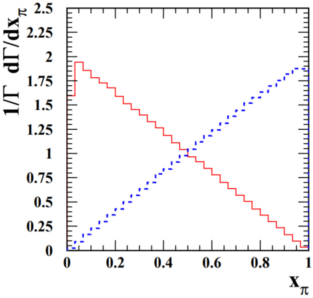



Figure: Pion momentum distributions for a right handed tau(blue) or a lefted handed tau(red)

# 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

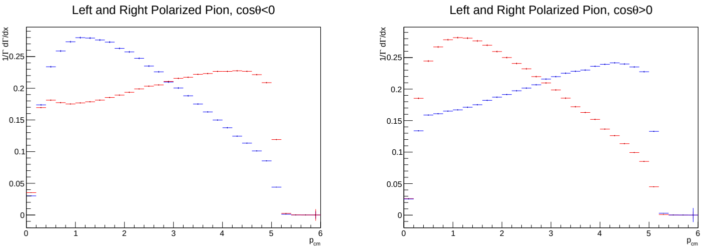
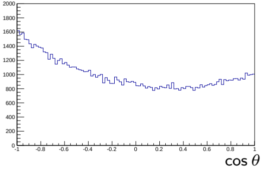


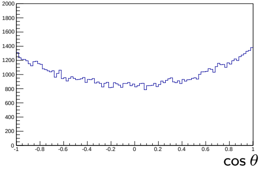

Figure: Pion momentum distributions for a right handed electron(blue) or a lefted handed electron(red)

# Pion Angular Polarization Sensitivity

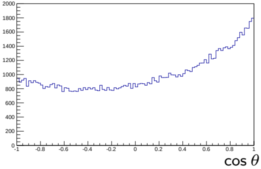
Left Polarization




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 (34.72 $fb^{-1}$)
- Studied multiple tagging options
  - (pion tag)$\tau\tau \to \pi\nu + \pi\bar{\nu}$ large backgrounds from $e^+e^- \to \mu^+\mu^-$
  - (3 pion tag) $\tau\tau \to \pi\pi\pi\nu + \pi\bar{\nu}$ still needs work
  - (electron tag) $\tau\tau \to e\nu + \pi\bar{\nu}$ large backgrounds from $e^+e^- \to e^+e^-$
  - (rho tag) $\tau\tau \to \pi\pi^0\nu + \pi\bar{\nu}$ very pure
- The rho tag has proven to be largely free of non-tau backgrounds and has high statistics

# Event Selection

1. All events that pass the Tau BGF flag and NTrks$>$0 are written to ntuples
2. Selection cuts for one $\tau \to \rho\nu$ and one $\tau \to \pi\nu$ are applied
   2.1 NTrks $= 2$
   2.2 Sum of charge $= 0$
   2.3 Tracks are separated by $> 90^\circ$
   2.4 The event $P_T$ is $>$1.2 GeV
   2.5 One track, signal track, has no neutrals in it's hemisphere
   2.6 One track, tag track, has 1 or 2 neutrals in it's hemisphere
   2.7 The tag track has a $\pi^0$ in its hemisphere
      2.7.1 If one neutral cluster, $\pi^0$ likelihood in the event $>$40
      2.7.2 If two neutral clusters, $\pi^0$ mass between 115 and 150 MeV
   2.8 The signal track fails a loose electron and loose muon PID selector
3. Events that pass have the signal track momentum and cos$\theta$ passed to the fit

# 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 34.7 $fb^{-1}$
- The data (or equivalent MC) is then fit as a linear combination of the templates

$$D = a_l L + a_r R + a_b B + a_m M + a_u U + a_c C \tag{1}$$

$$\sum_i a_i \equiv 1 \tag{2}$$

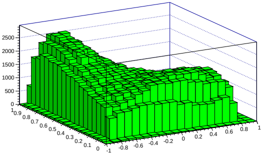
$$\langle Pol \rangle \equiv a_l - a_r \tag{3}$$

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

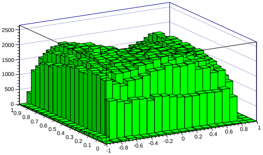
# Template Examples

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

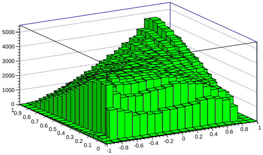
Left Polarization




No Polarization




Right Polarization



# 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 | $P_D^+ \pm \sigma_D^+$ | $P_D^- \pm \sigma_D^-$ | $P_D^A \pm \sigma_D^A$ |

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

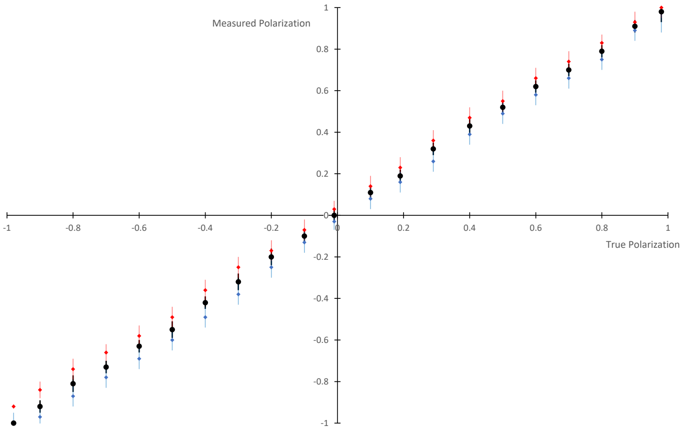
# Fit Results

| | Positive Charge | Negative Charge | Combined Average |
|---|---|---|---|
| Tau MC 1 | -0.0302±0.0260 | 0.0121±0.0252 | -0.0084±0.0181 |
| Tau MC 2 | -0.0380±0.0261 | -0.0346±0.0252 | -0.0362±0.0181 |
| Tau MC 3 | -0.0347±0.0261 | 0.0053±0.0252 | -0.0140±0.0181 |
| Data | -0.0376±0.0284 | 0.0393±0.0270 | 0.0029±0.0196 |

Figure: Run 3 Fit, 34.7 $fb^{-1}$

# 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

- Bins in Fit
- Background ratio in Fit
- Cuts in Selection
- PID Selector
- Boost Vector
- Tau Decay Branching Fraction
- Neutral Cluster Variables
- Shifts in P
- Momentum resolution
- Shifts in $\cos\theta$
- Shifts in $\phi$
- Charged Track List
- Neutral List
- BGF tag
- Total Polarization Sensitivity

# 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

# PID systematics

| PID 1 | Positive Charge | Negative Charge | Combined Averag |
|---|---|---|---|
| MC | ${}^1P^+_{MC}$ | ${}^1P^-_{MC}$ | ${}^1P^A_{MC}$ |
| Data | ${}^1P^+_{Data}$ | ${}^1P^-_{Data}$ | ${}^1P^A_{Data}$ |
| **PID 2** | **Positive Charge** | **Negative Charge** | **Combined Averag** |
| MC | ${}^2P^+_{MC}$ | ${}^2P^-_{MC}$ | ${}^2P^A_{MC}$ |
| Data | ${}^2P^+_{Data}$ | ${}^2P^-_{Data}$ | ${}^2P^A_{Data}$ |
| **Differences** | **Positive Charge** | **Negative Charge** | **Combined Averag** |
| MC Diff | ${}^1P^+_{MC} -{}^2 P^+_{MC} ={}^D P^+_{MC}$ | ${}^DP^-_{MC}$ | ${}^DP^A_{MC}$ |
| Data Diff | ${}^1P^+_{Data} -{}^2 P^+_{Data} ={}^D P^+_{Data}$ | ${}^DP^-_{Data}$ | ${}^DP^A_{Data}$ |
| Total Diff | ${}^DP^+_{MC} -{}^D P^+_{Data} = \tilde{P}^+$ | $\tilde{P}^-$ | $\tilde{P}^A$ |

# PID systematics

| E, M | 16 | 20 | 21 |
|---|---|---|---|
| 1 | 0.0000 | -0.0065 | -0.0039 |
| 7 | 0.0004 | -0.0060 | -0.0035 |
| 8 | 0.0006 | -0.0059 | -0.0034 |
| E, M | 16 | 20 | 21 |
| 1 | $0.0000 \pm 0.0000$ | $-0.0066 \pm 0.0011$ | $-0.0039 \pm 0.0013$ |
| 7 | $0.0002 \pm 0.0002$ | $-0.0062 \pm 0.0011$ | $-0.0037 \pm 0.0014$ |
| 8 | $0.0004 \pm 0.0001$ | $-0.0061 \pm 0.0010$ | $-0.0035 \pm 0.0013$ |

- Taking the average standard deviation of the rows gives the muon systematic uncertainty
- Taking the average standard deviation of the columns gives the electron systematic uncertainty
- $\sigma_{sys}^{\mu PID} = 0.00328 \pm 0.0005$ $\qquad \sigma_{sys}^{ePID} = 0.00021 \pm 0.00045$

# Boost Correction

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

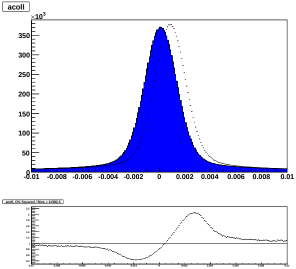



Figure: acollinearity in $\theta$

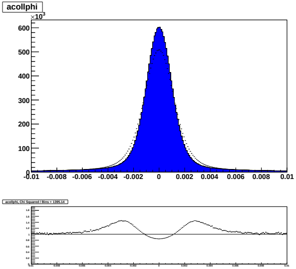
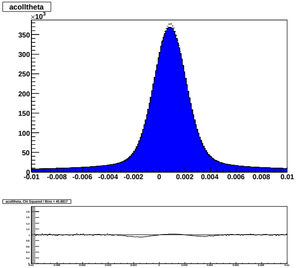



Figure: acollinearity in $\phi$

# Boost Correction

- After correction

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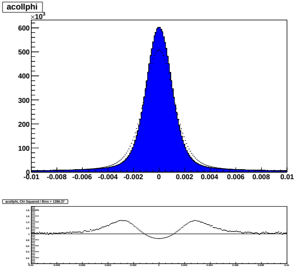


Figure: acollinearity in $\phi$

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

# Systematic Study List

- Bins in Fit ✓
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- $P_T$ Cut ✓
- PID Selector ✓
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- Shifts in P ✓
- Momentum resolution ✓
- Shifts in $\cos\theta$ ✓
- Shifts in $\phi$ ✓
- Charged Track List ✓
- Neutral List ✓
- **BGF tag**
- Total Polarization Sensitivity✓

# Systematic summary

| Study | Systematic |
|---|---|
| P | 0.0015 |
| $\theta$ | 0.0002 |
| $\phi$ | 0 |
| Boost | 0.0005 |
| $\pi^0$ | 0.0005 |
| $E_\gamma$ | 0.0006 |
| non-$\tau$ Backgrounds | 0.0002 |
| $PID_\mu$ | 0.0033 |
| $PID_e$ | 0.0002 |
| $\tau$-BF | 0.0001 |
| Neutrals* | 0.0011 |
| BGFTau* | $\mathcal{O}(0.001)$? |
| Quad Sum | 0.0038 |

Current Data Fit for Run 3

P=-0.0023$\pm$0.0212$_{stat}$ $\pm$ 0.0040$_{sys}$

* Statistically limited

# BaBar Next Steps

- Wrapping up final systematic study
- BaBar review committee is formed and ready to review analysis
- Start unblinding in December hopefully
- So far only Run 3 used, $\sim$7.5% of total
- Expect full measurement uncertainty will be:
  $\sigma_P = 0.0058_{stat} \pm 0.0040_{sys}$

# Polarization at Belle II

- Swagato Banerjee has setup KKMC in basf2
- Michel Hernandez Villanueva produced a sample of $\tau\tau \rightarrow \pi\nu + \pi\nu$ with polarized electron beams
- Currently analyzing the results
- Initial peeks at the pion momentum distributions suggest a bug somewhere
  - Initial tests suggest mdst needs to be scrubbed of mcPDG==0 particles first
- Will verify results and put in a request for full polarized tau MC soon