# Measurement of Beam Polarization at an $e^+e^-$ B-Factory with New Tau Polarimetry Technique

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*on behalf of*
BaBar Collaboration

BaBar

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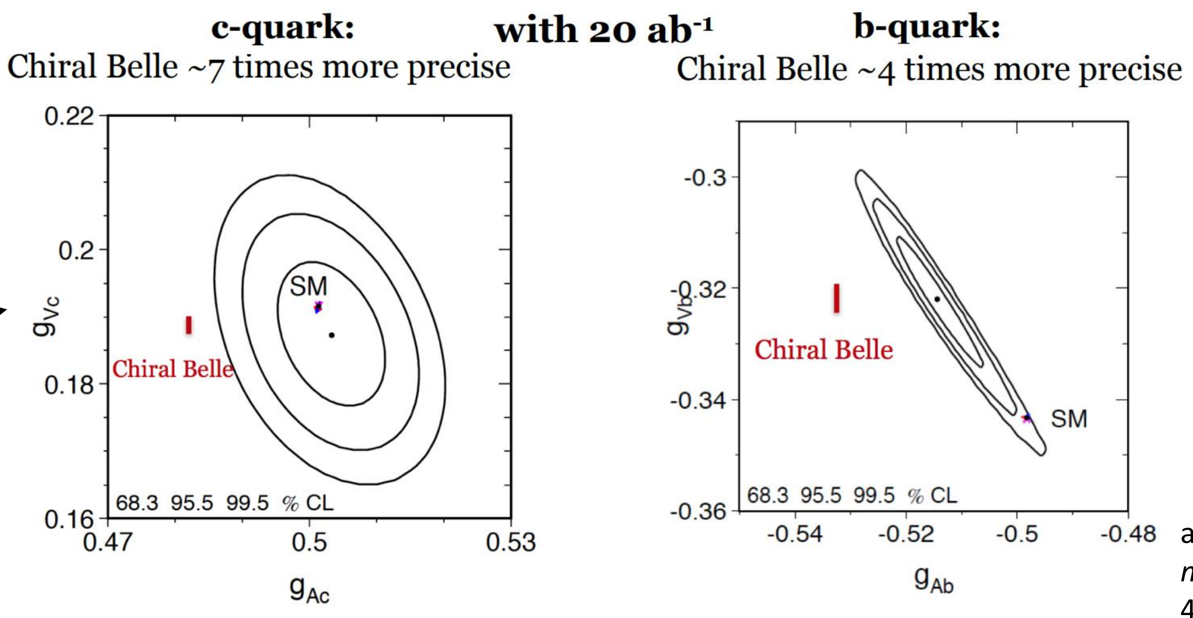
Lake Louise Winter Institute 2022

# Beam Polarization 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 electroweak parameters. Including $A_{LR}$ for e,μ,τ,c,b. For Born level s-channel process:

$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \frac{4}{\sqrt{2}}\left(\frac{G_f s}{4\pi\alpha Q_f}\right) g_A^e g_V^f \langle P \rangle \propto T_3^f - 2Q_f \sin^2\theta_W$$

Red bars show expected +/- 1 sigma uncertainty. Position arbitrary.




adapted from figure 7.4 of *Precision electroweak measurements on the Z resonance*, Physics Reports 427(5), 2006

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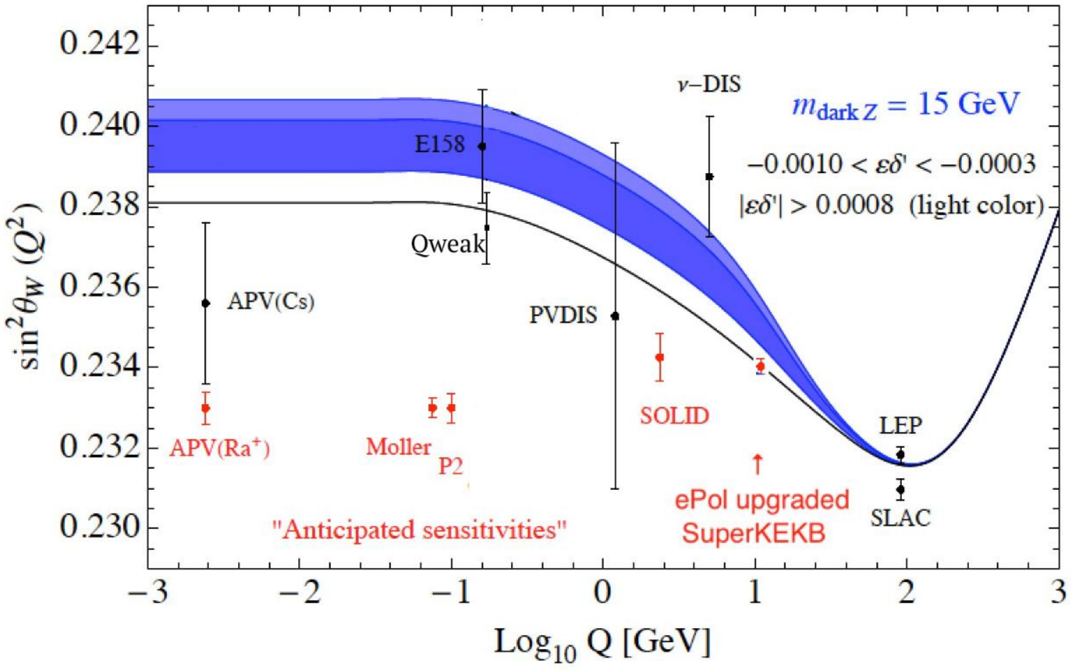



Red bars show expected sensitivity of future experiments. position arbitrary.

Chiral Belle expects:
$\sigma(\sin^2\theta_W) \approx 0.0002$ (40 $ab^{-1}$)

adapted from figure 3 of H. Davoudiasl, H.S. Lee and W.J. Marciano, Phys.Rev.D 92(5),2015

# Beam Polarization Motivation

*see Martin Hoferichter's talk Wednesday Morning*

- Recent theory work suggests a measurement of the tau magnetic moment could be sensitive to new physics[1]
- Results from Fermilab see a large deviation from the Standard Model in g-2 for muons

$$a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (251 \pm 59) \times 10^{-11} [4.2\sigma]$$

*from April 2021 g-2 publication*

*see Hannah Binney's talk Tuesday Evening*

- Under a Minimal Flavour Violation assumption the anomaly scales with the square of the lepton masses:

$$a_\tau^{\text{BSM}} \sim a_\mu^{\text{BSM}} \left(\frac{m_\tau}{m_\mu}\right)^2 \sim 0.7 \times 10^{-6}$$

- Tau magnetic moment anomaly may be larger under other models
- Polarized beams would give Belle II the ability to probe the tau magnet moment with particular asymmetries in tau hadronic decays with unprecedented precision
- Will require more precise theory calculations for Standard Model values

[1] A. Crivellin, M.Hoferichter, M. Roney, arXiv:2111.10378 (2021)

# Beam Polarization Motivation

For these future measurements we expect the dominant and limiting uncertainty to be the precision with which the average beam polarization, <P>, can be measured

Existing technology, such as Compton polarimeters, have an uncertainty associated with modelling the spin transport from the polarimeter to the interaction point (IP)

**By using tau polarimetry we can extract the average beam polarization directly from the data at the IP**

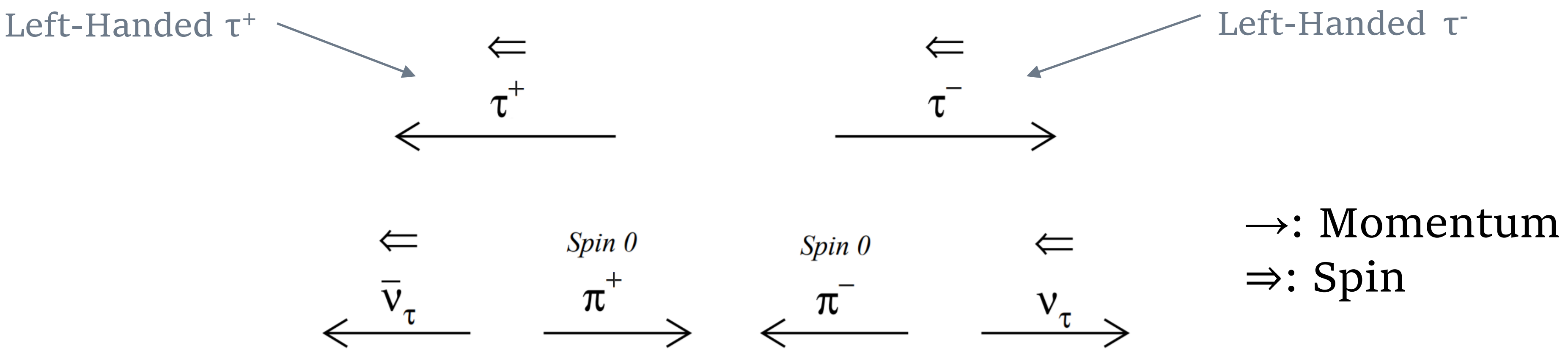
# Tau Polarimetry

- The polarization of tau's ($P_\tau$) produced in $e^+e^-$ collisions at 10.58 GeV is related to the electron beam polarization ($P_e$) through:

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

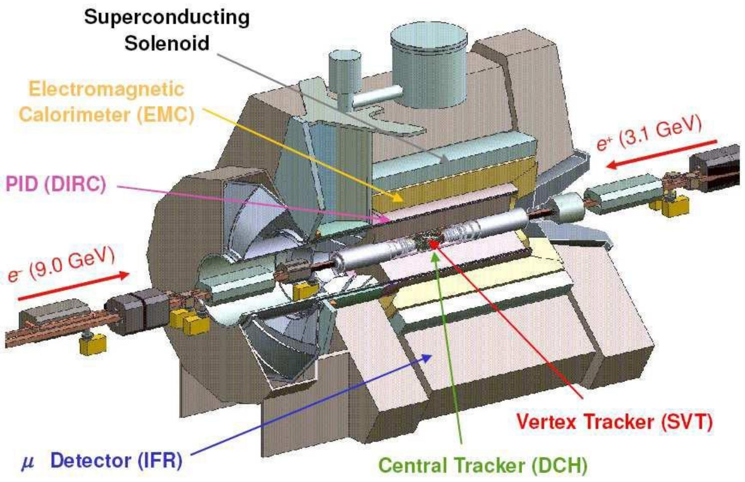
Note: cosθ defined as the polar angle of the $\tau^-$ with respect to the electron beam

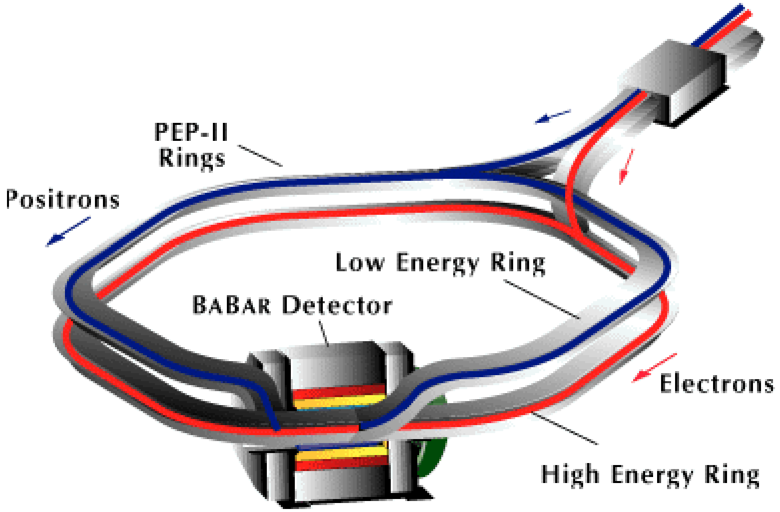
- Tau polarization information can be extracted from the kinematics of the tau decay



# *BaBar* and PEP-II

*BaBar* and PEP-II operated at SLAC from 1999-2008

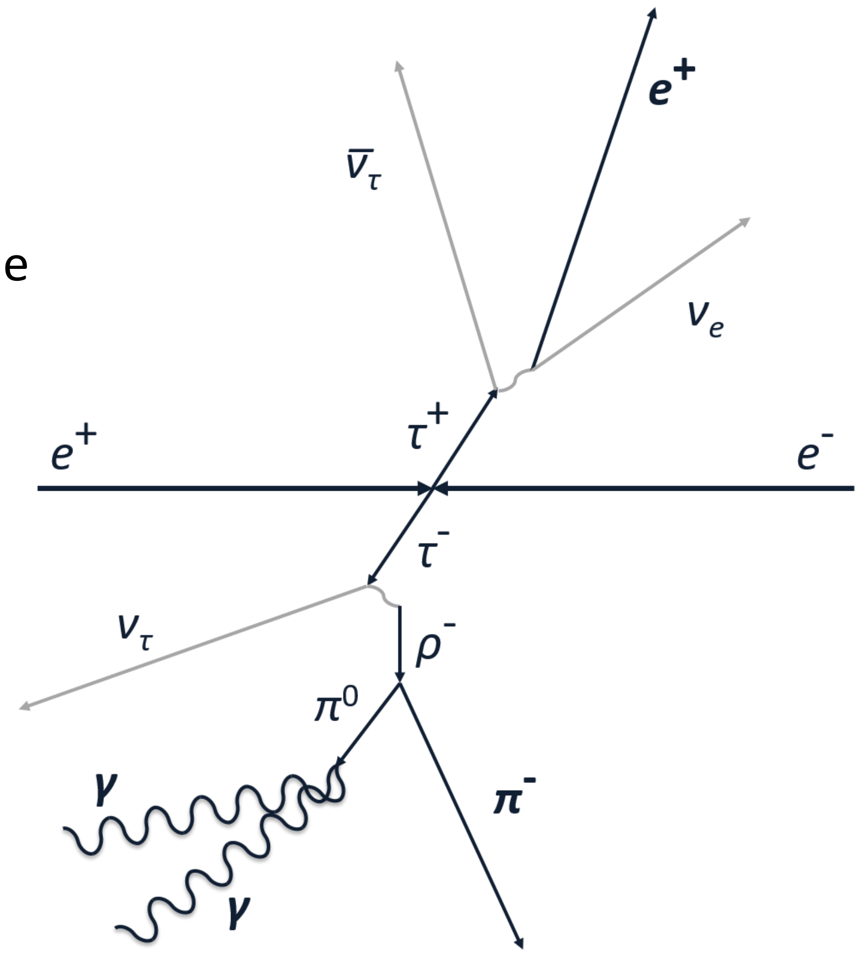



- Over 6 run periods *BaBar* collected 432 $fb^{-1}$ of data on the $\Upsilon(4S)$ resonance
- PEP-II collided electrons and positrons together at 9.0 and 3.1 GeV
- No beam polarization is expected at PEP-II

# Tau Event Selection

- As a proof of concept we have developed Tau Polarimetry at *BABAR* using $\tau^{\pm} \rightarrow \rho^{\pm}\nu_{\tau} \rightarrow \pi^{\pm}\pi^{0}\nu_{\tau}$ decays
- We expect uncertainties to be highly correlated between detectors due to similar designs
- Developed the technique on 32.28 $fb^{-1}$ of data
  - Final measurement performed on remaining 391.90 $fb^{-1}$
- Selected tau events in a 1v1 topology, ($\rho$ vs. e)
- Signal candidates are defined as a charged particle with a $\pi^0$
- $q\bar{q}$ events are eliminated with the electron requirement
- Angular cuts and a minimum $p_T$ of 1.2 GeV reduce two photon and Bhabha contamination

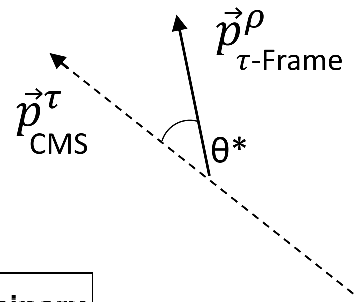


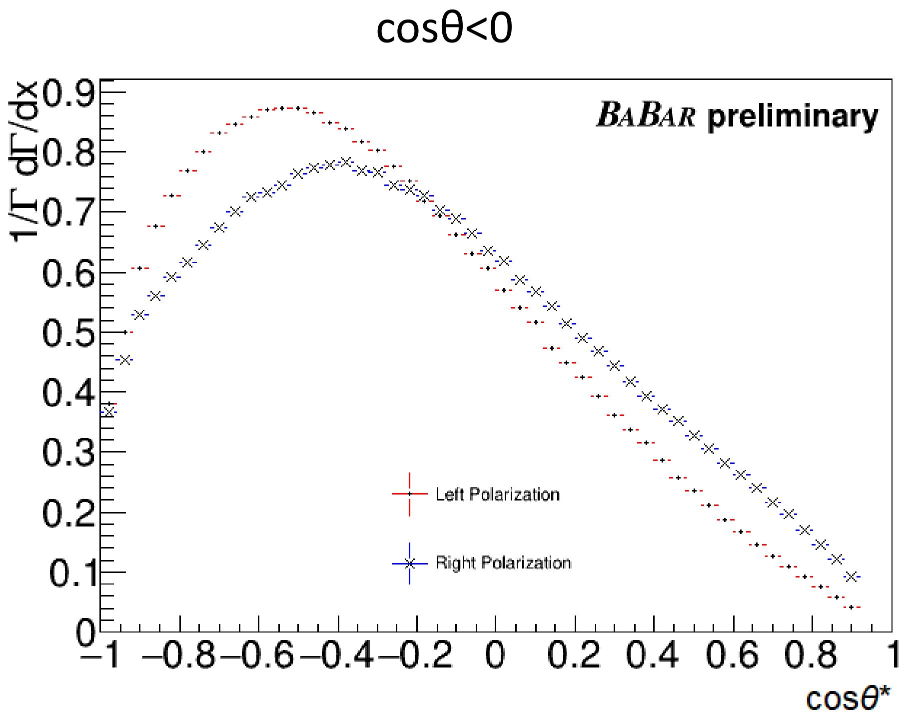

- Achieve a 99.7% pure tau-pair sample
- 90% of selected events contain a $\tau^{\pm} \rightarrow \pi^{\pm}\pi^{0}\nu_{\tau}$ decay

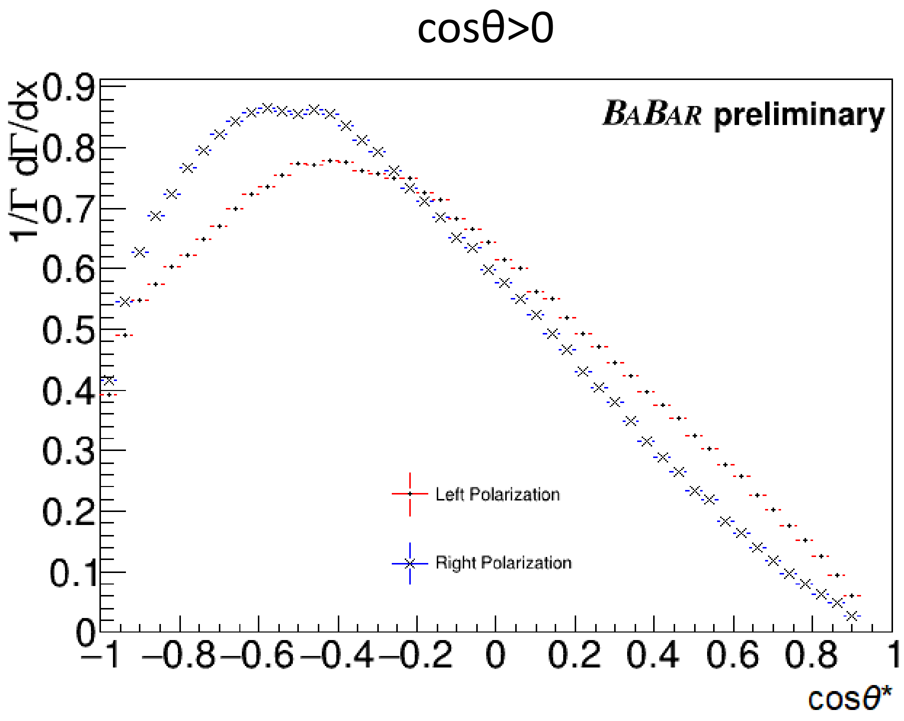
# Polarization Observables

- Polarization sensitivity in a rho decay is maximized by analyzing two angular variables[2] in addition to cosθ

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



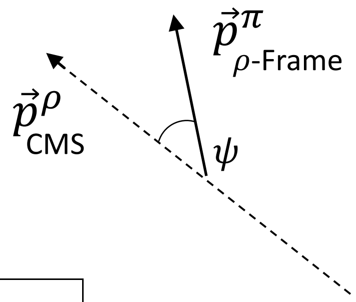




[2] K. Hagiwara, A. Martin, D. Zeppenfeld, Tau Polarization Measurements at LEP and SLC, Phys. Lett. B. 235, 1998, DOI: 10.1016/0370-2693(90)90120-U

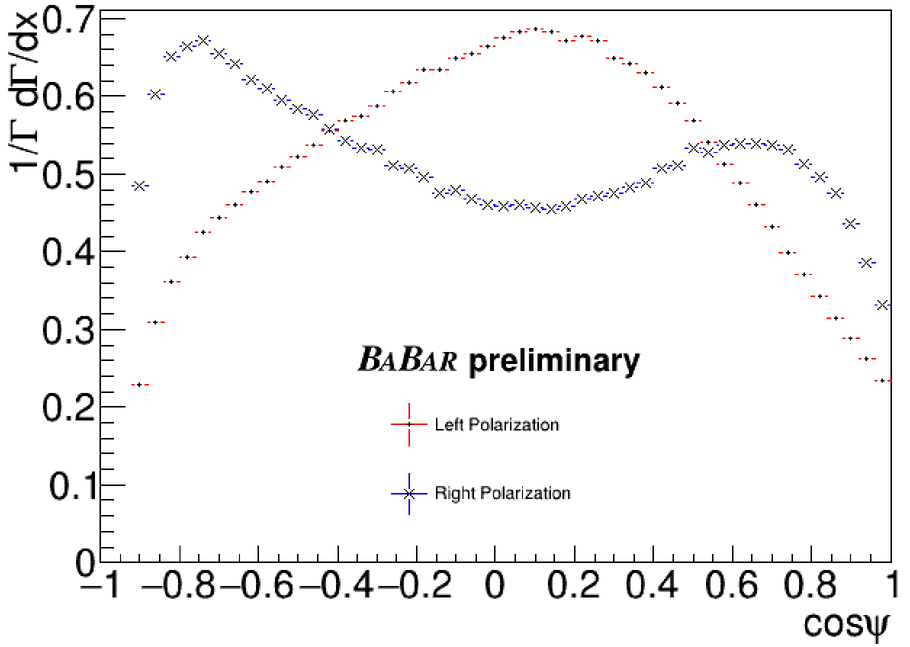
# Polarization Observables

- Polarization sensitivity in a rho decay is maximized by analyzing two angular variables[2] in addition to cosθ

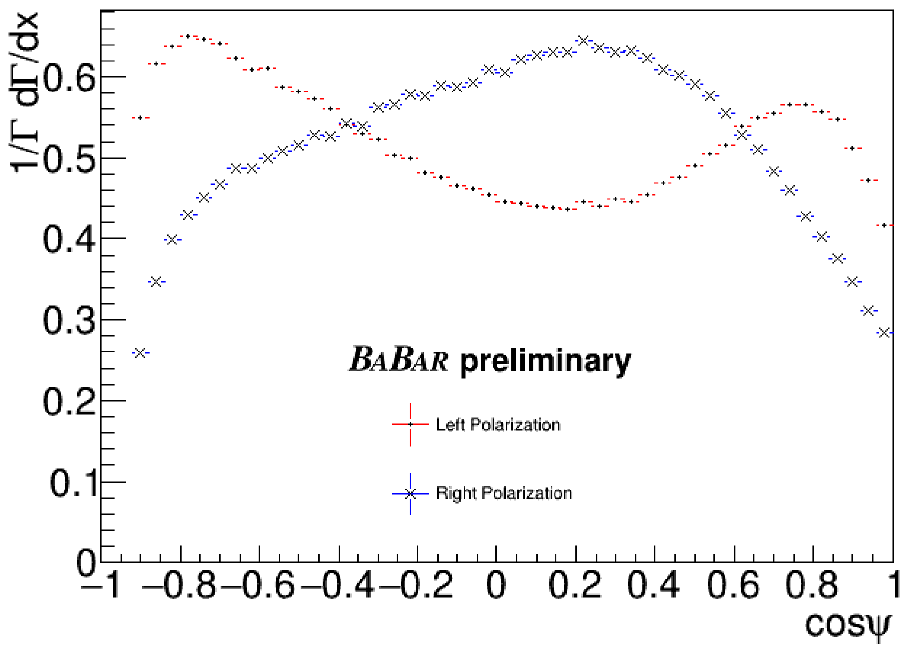
$$\cos\psi = \frac{2x - 1}{\sqrt{1 - 4m_\pi^2/m_\rho^2}} \qquad x \equiv E_\pi / E_\rho$$




cosθ<0




cosθ>0

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# Polarization Fit

- To extract the average beam polarization from a data set we employ a binned maximum likelihood fit using Barlow and Beeston[3] template fit methodology
- Data and MC is binned in 3D histograms of cosθ*, cos$\psi$, and cosθ
- Tau MC was produced for a left and right polarized electron beam
- The unpolarized tau MC is split into 3 samples, of roughly the size of the data set, and mixed with backgrounds to produce data-like samples for verifying the fit performance
- The data is fit as a linear combination of the histograms

$$D = a_l L + a_r R + a_b B + a_m M + a_u U + a_c\, C$$

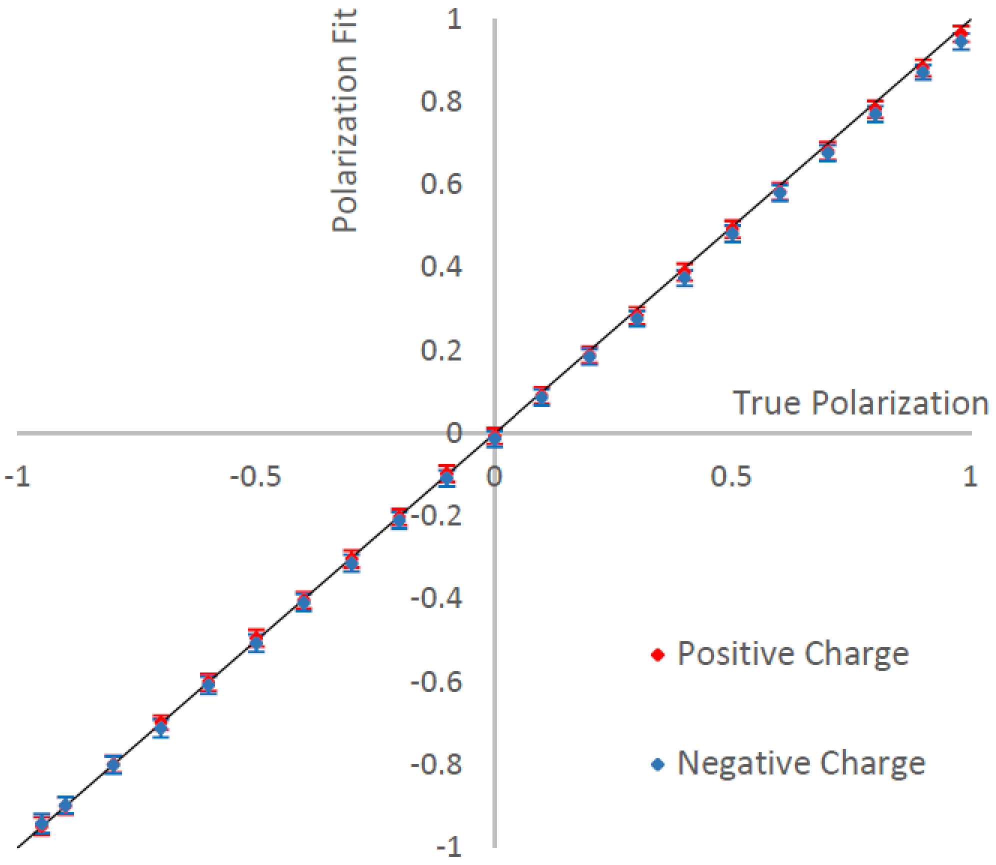
$$\langle P \rangle \equiv a_l - a_r$$

D=data, L=Left Polarized Tau MC, R=Right Polarized Tau MC, B=Bhabha($e^+e^-$),M=μμ, U=uds, C=$c\bar{c}$

[3] R. Barlow, C. Beeston; Computer Physics Communications, Volume 77, Issue 2, 1993, Pages 219-228, https://doi.org/10.1016/0010-4655(93)90005-W

# Beam Polarization MC "Measurement"

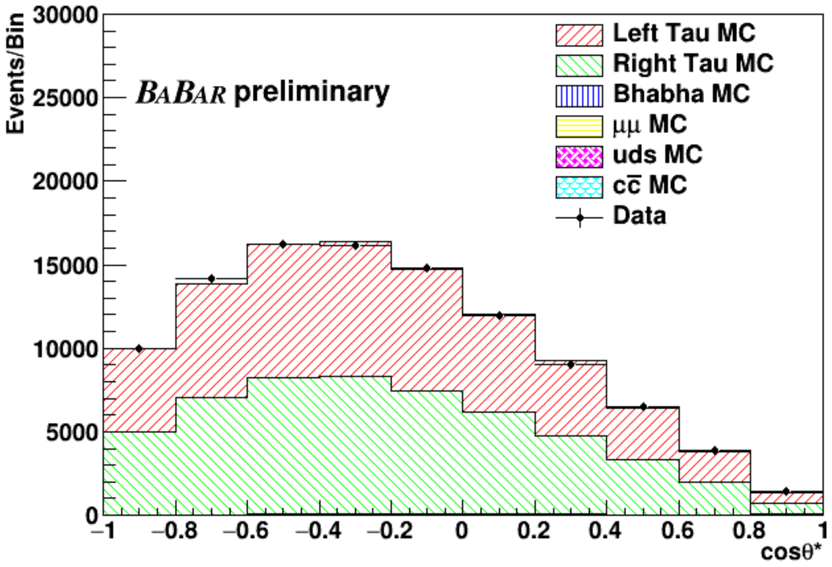
- As PEP-II had no beam polarization we performed MC studies of the polarimetry technique for arbitrary beam polarization states for validation of the method
- This is done by splitting each of the polarized tau MC samples in half
- One half of each is used to perform the polarization fit
- The other half is used to mix specific beam polarization states
  - e.g. 70% polarized = 85% left +15% right
- Simulated beam polarization states are produced in steps of 10% beam polarization
- We found the fit responded well and was able to correctly measure any designed beam state

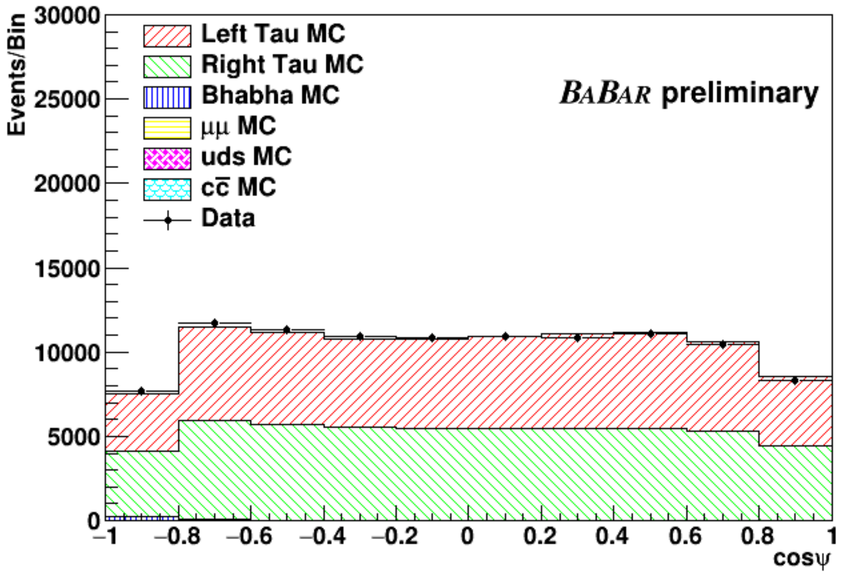


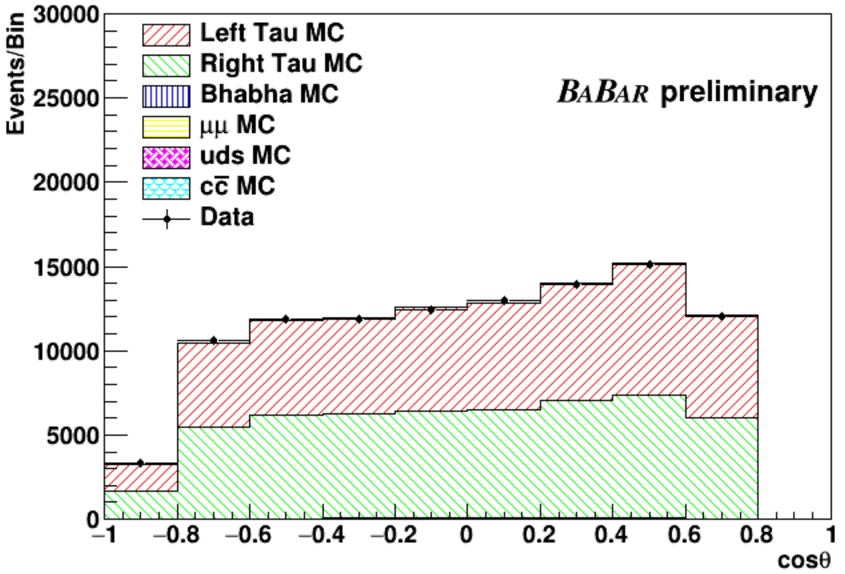
# Fit Result

| Sample | Positive | Negative | Total |
|---|---|---|---|
| Run 3 (32.28 $fb^{-1}$) | 0.0277±0.0177 | -0.0031±0.0177 | 0.0123±0.0125 |

- Fit result projected to each of the fit variables
- Result from preliminary Run 3 fit, Negative charges
- <P>=-0.0031, $\chi^2$/NDF=770/872



# Systematic Uncertainties

- Systematic uncertainties were evaluated by studying the relative shift in agreement between the MC and data polarization fits
- The 3 independent MC measurements from also give us a way to approximate the statistical uncertainty of each systematic uncertainty
- Our study of the Run 3 sample found the MC modelling of the hadronic split-offs to be the largest uncertainty
- Uncertainties associated with $\pi^0$'s also contribute significantly to the final uncertainty
- Study sample (Run 3) measurement:

$$\langle P \rangle = 0.0123 \pm 0.0125_{\text{stat}} \pm 0.0041_{\text{sys}}$$

PRELIMINARY

| Study | Run 3 |
|---|---|
| $\pi^0$ Likelihood | 0.0013 |
| Hadronic Split-off Modelling | 0.0027 |
| Minimum Neutral Energy | 0.0013 |
| $\pi^0$ Mass | 0.0011 |
| $\cos\psi$ | 0.0013 |
| Angular Resolution | 0.0010 |
| Electron PID | 0.0006 |
| $\cos\theta^\star$ | 0.0002 |
| Event Transverse Momentum | 0.0006 |
| Momentum Resolution | 0.0002 |
| $\pi^0$ Minimum Photon Energy | 0.0011 |
| Tau Branching Fraction | 0.0001 |
| Rho Mass | 0.0002 |
| Boost | 0.0002 |
| Background Modelling | 0.0006 |
| Total | 0.0041 |

# Full Measurement

- Performing the measurement on the remaining data, 391.9 $fb^{-1}$

| Sample | Luminosity ($fb^{-1}$) | Average Polarization |
|---|---|---|
| Run 1 | 20.37 | 0.0062±0.0157 |
| Run 2 | 61.32 | -0.0004±0.0090 |
| Run 4 | 99.58 | -0.0114±0.0071 |
| Run 5 | 132.33 | -0.0040±0.0063 |
| Run 6 | 78.31 | 0.0157±0.0082 |
| **Total** | **391.9** | **-0.0010±0.0036** |

- Preliminary measurement:

$$\langle P \rangle = -0.0010 \pm 0.0036_{stat} \pm 0.0030_{sys}$$

PRELIMINARY

| Study | Run 1 | Run 2 | Run 4 | Run 5 | Run 6 | Final |
|---|---|---|---|---|---|---|
| $\pi^0$ Likelihood | 0.0032 | 0.0012 | 0.0009 | 0.0010 | 0.0020 | **0.0015** |
| Hadronic Split-off Modelling | 0.0035 | 0.0012 | 0.0015 | 0.0011 | 0.0005 | **0.0011** |
| $\cos\psi$ | 0.0022 | 0.0012 | 0.0006 | 0.0008 | 0.0010 | **0.0010** |
| Angular Resolution | 0.0010 | 0.0015 | 0.0012 | 0.0002 | 0.0007 | **0.0009** |
| Minimum Neutral Energy | 0.0006 | 0.0009 | 0.0005 | 0.0006 | 0.0016 | **0.0009** |
| $\pi^0$ Mass | 0.0018 | 0.0005 | 0.0009 | 0.0006 | 0.0014 | **0.0009** |
| $\cos\theta^\star$ | 0.0012 | 0.0007 | 0.0012 | 0.0009 | 0.0007 | **0.0008** |
| Electron PID | 0.0022 | 0.0008 | 0.0007 | 0.0014 | 0.0010 | **0.0007** |
| Tau Branching Fraction | 0.0007 | 0.0006 | 0.0010 | 0.0006 | 0.0005 | **0.0006** |
| Event Transverse Momentum | 0.0013 | 0.0006 | 0.0006 | 0.0002 | 0.0005 | **0.0005** |
| Momentum Resolution | 0.0005 | 0.0008 | 0.0004 | 0.0003 | 0.0006 | **0.0005** |
| $\pi^0$ Minimum Photon Energy | 0.0008 | 0.0008 | 0.0009 | 0.0003 | 0.0010 | **0.0004** |
| Rho Mass | 0.0007 | 0.0002 | 0.0002 | 0.0004 | 0.0005 | **0.0003** |
| Background Modelling | 0.0027 | 0.0002 | 0.0002 | 0.0007 | 0.0009 | **0.0003** |
| Boost | 0.0000 | 0.0002 | 0.0001 | 0.0005 | 0.0004 | **0.0002** |
| Total | 0.0070 | 0.0033 | 0.0032 | 0.0027 | 0.0038 | **0.0030** |

# Conclusions

- *BaBar* has implemented the first application of the new Tau Polarimetery technique to preliminarily measure the PEP-II average beam polarization

$$\langle P \rangle = -0.0010 \pm 0.0036_{\text{stat}} \pm 0.0030_{\text{sys}}$$

PRELIMINARY

- Strongly motivates adding a polarized electron beam to SuperKEKB
- Future work could include rho vs muon decay mode for additional statistics
- Parallel development on extracting the beam polarization from tau to pion decays ongoing
- Tau Polarimetry could be applied at other $e^+e^-$ colliders
- Look forward to a publication this summer

Thank You!

# Backup Slides

# Positron Polarization

- In this implementation of tau polarimetry it is assumed only the electron beam is polarized
- Tau polarimetry works for any beam polarizations in both beams

| $e^+\backslash e^-$ | $L^-$ | $R^-$ |
|---|---|---|
| $L^+$ | $L^+L^-$ | $L^+R^-$ |
| $R^+$ | $R^+L^-$ | $R^+R^-$ |

- Interaction matrix, only the LL and RR boxes result in a $e^+e^-$ interaction
- The LR and RL fraction continue down the beam pipe
- For unpolarized beams L=R=0.5
- Average beam polarization can be expressed as $\frac{LL-RR}{LL+RR}$

| $e^+\backslash e^-$ | $L^-$ | $R^-$ |
|---|---|---|
| $L^+$ | 0.425 | 0.075 |
| $R^+$ | 0.425 | 0.075 |

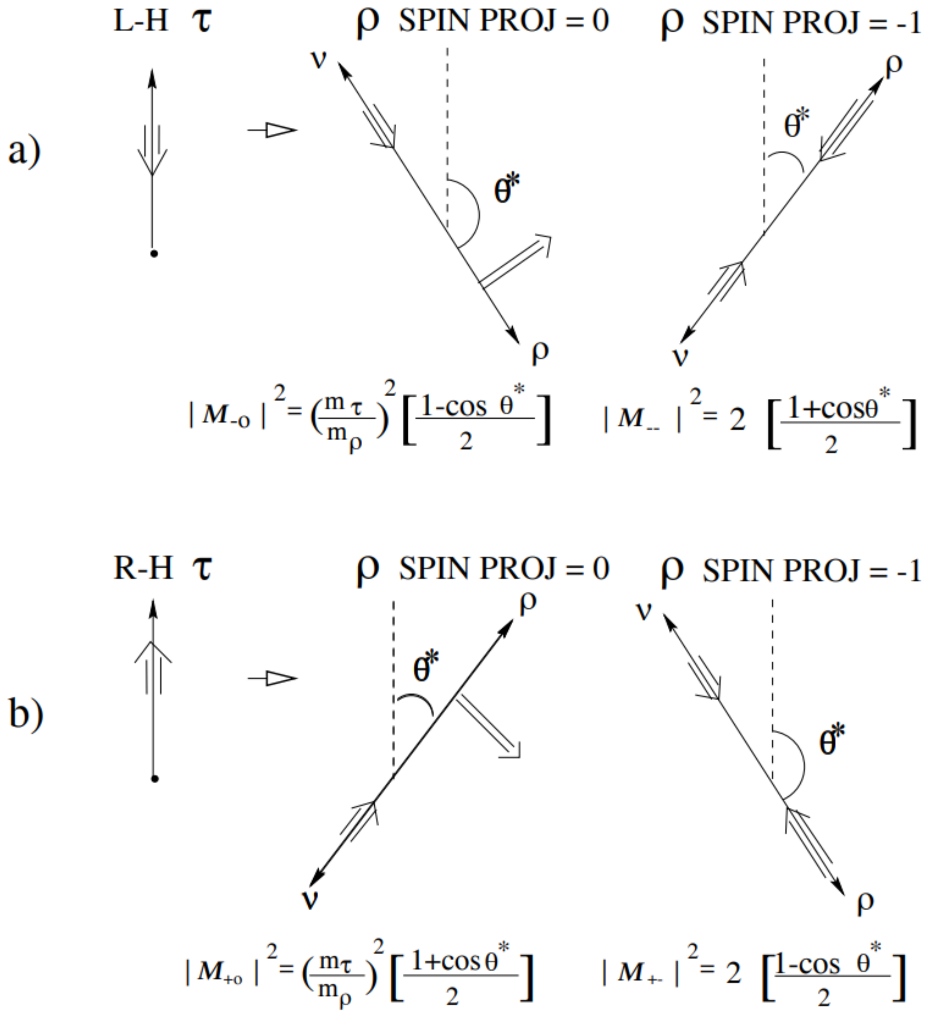
- For 70% polarized electron beam, $L^-$=0.85 $R^-$=0.15
- Average beam polarization is $\frac{0.425-0.075}{0.425+0.075}$=0.7

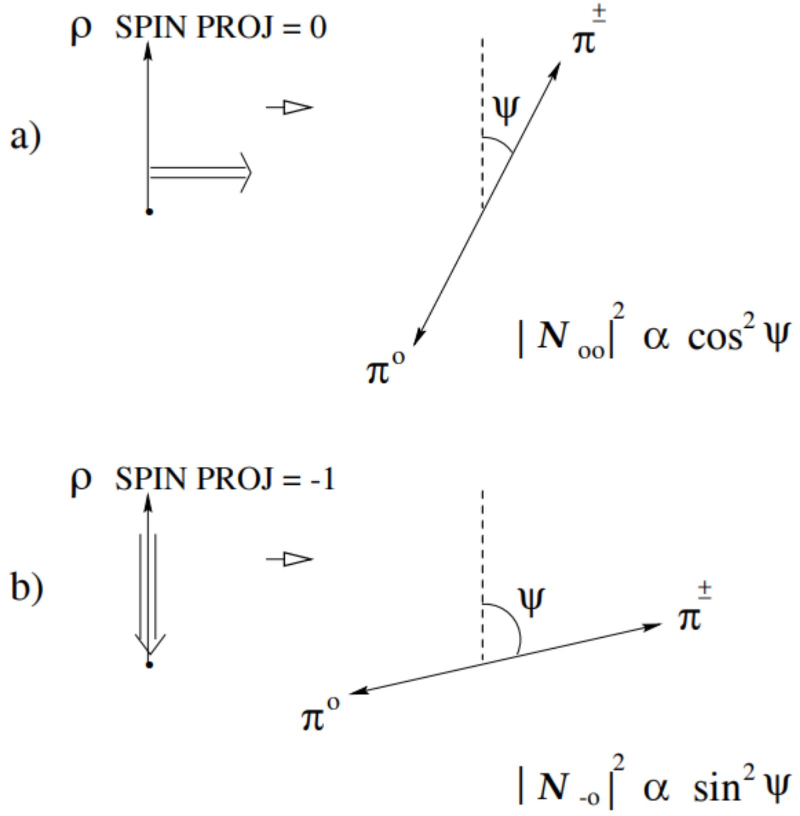
| $e^+\backslash e^-$ | $L^-$ | $R^-$ |
|---|---|---|
| $L^+$ | 0.49 | 0.21 |
| $R^+$ | 0.21 | 0.09 |

- For both beams being 40% polarized, L=0.7, R=0.3
- Average beam polarization is $\frac{0.49-0.09}{0.49+0.09}$=0.69
- Also note 58% of encounters result in a collision, extra data for same luminosity

# Rho Spin Analysis

- The rho complicates the spin projections, which necessitates two variables to extract the polarization




From Dr. Manuella Vincter, PhD thesis, UVIC, 1996