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

Caleb Miller

BABAR

Workshop on Beam Polarization
Hiroshima 2023

Chiral Belle

- Motivation behind development of beam polarimetry technique is the Chiral Belle proposal
- The Chiral Belle proposal is an planned upgrade to Belle II/SuperKEKB to add electron beam polarization
- Beam polarization enables a diverse physics program including precision EW, tau g-2, etc…

Project described in recent white paper submitted to SNOWMASS

Snowmass 2021 White Paper Upgrading SuperKEKB with a Polarized Electron Beam: Discovery Potential and Proposed Implementation

https://arxiv.org/abs/2205.12847

Beam Polarization Requirements

Design goal is to achieve:

70% longitudinal beam polarization at IP and be known to **0.5%** precision

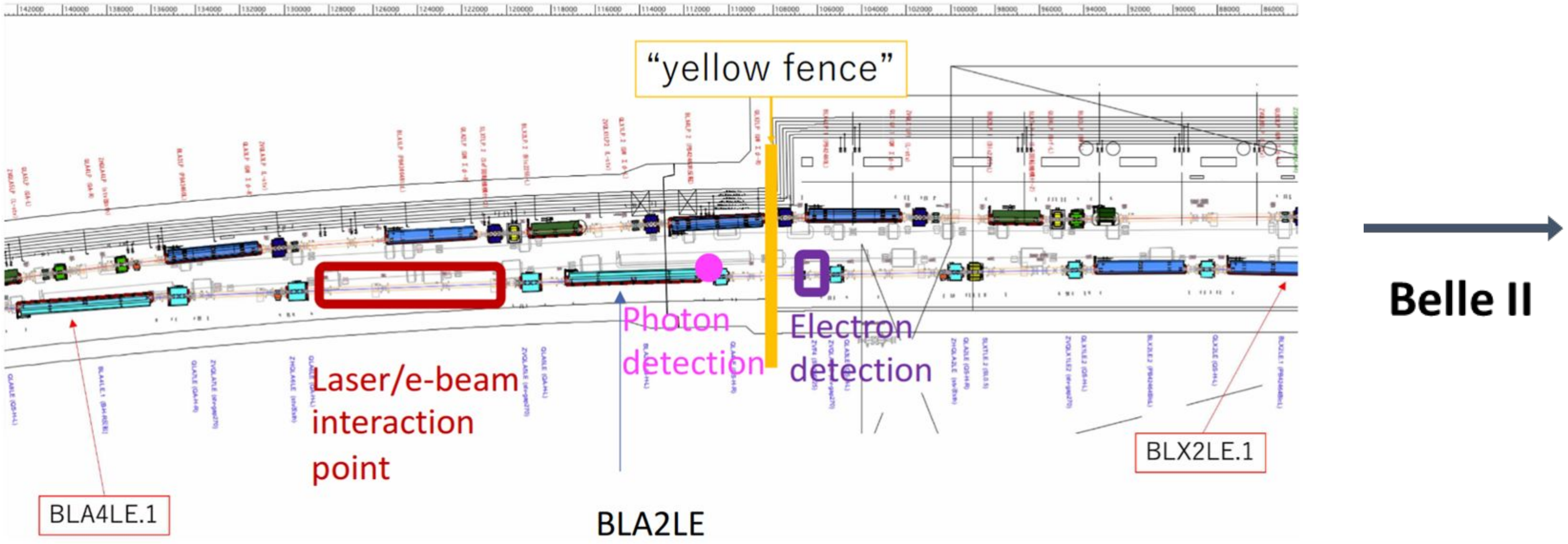
Requires:

- Electrons injected into ring with vertical transverse polarization
- Rotate spin to longitudinal for collision
- Compton polarimeter to monitor time dependent polarization to better than 1%
- Precision average beam polarization measurement

International team lead by M. Roney at UVic tackling this challenge

Compton Polarimeter

- Intention to install polarimeter upstream of the detector which can monitor the beam polarization continually to better than 1%
- For Belle II physics, uncertainty arises in the modeling of the beam transport to the IP
- Tau Polarimetry can compliment compton polarimeters



Polarimetry from Data

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

Polarization of the beam couples to the polarization of the tau[a]

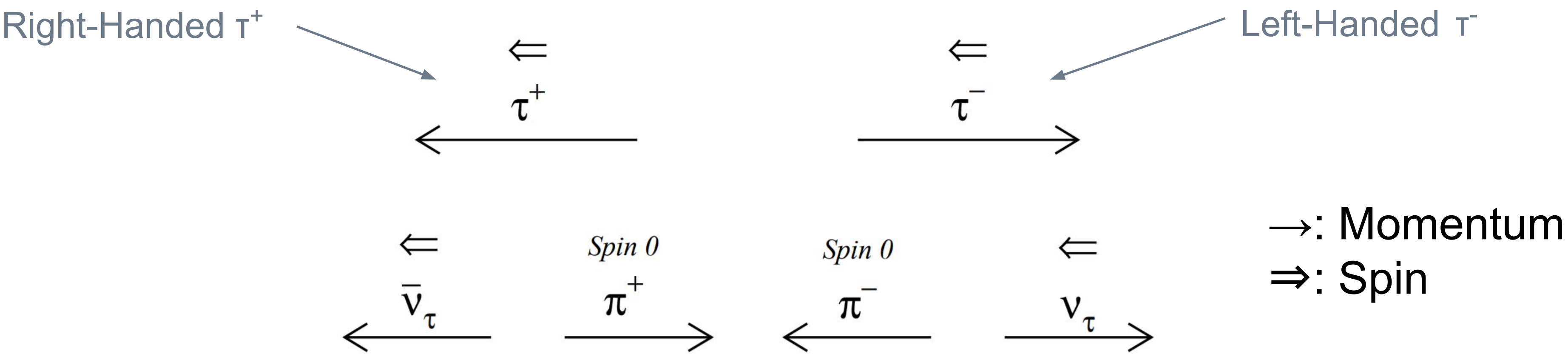
$$P_\tau = P_e \frac{\cos\theta}{1+\cos^2\theta} - \frac{8G_F s}{4\sqrt{2}\alpha} \mathrm{Re}\left[\frac{g_V^\tau - Q_b g_V^b Y_{1S,2S,3S}(s)}{1+Q_b^2 Y_{1S,2S,3S}(s))}\right]\left(g_A^\tau \frac{|\vec{p}|}{p^0} + 2g_A^e \frac{\cos\theta}{1+\cos^2\theta}\right)$$

Note: cosθ defined as the polar angle of the τ^- with respect to the electron beam. At $\mathcal{O}$(10 GeV) second term is $\mathcal{O}(10^{-3})$

a) J. Bernabeu, F.J. Botella, O. Vives, P-odd observables at the ϒ peak, Eur.Phys.J.C 7 (1999), DOI: 10.1007/s100529801007

Polarimetry from Data

- Tau polarization information can be extracted from the kinematics of the tau decay
- Same technique was performed at LEP to measure $\sin^2\theta_W$[b]



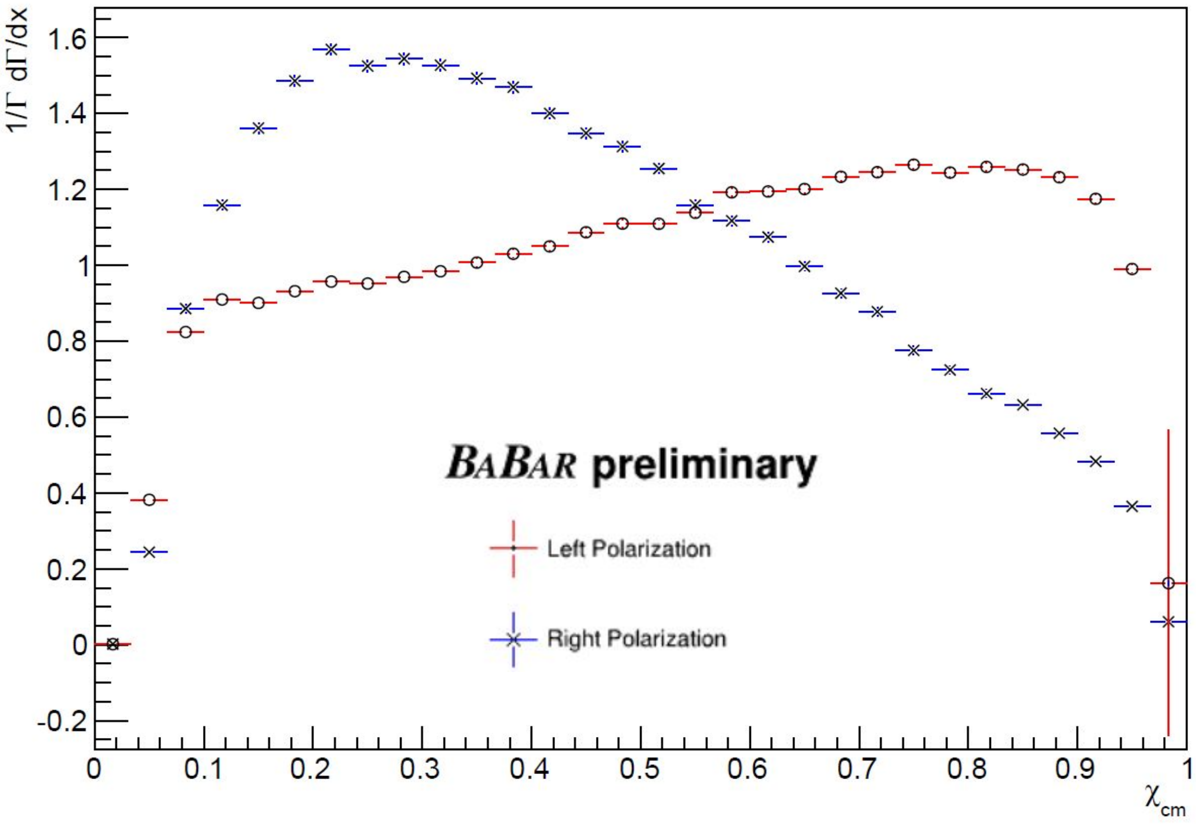
- Pion momentum directly corresponds to tau spin state
- Note: effects are correlated between taus

b) ALEPH, DELPHI, L3, OPAL, and SLD Collaborations. Precision electroweak measurements on the Z resonance, Phys.Rept.427 (2006). DOI: 10.1016/j.physrep.2005.12.006

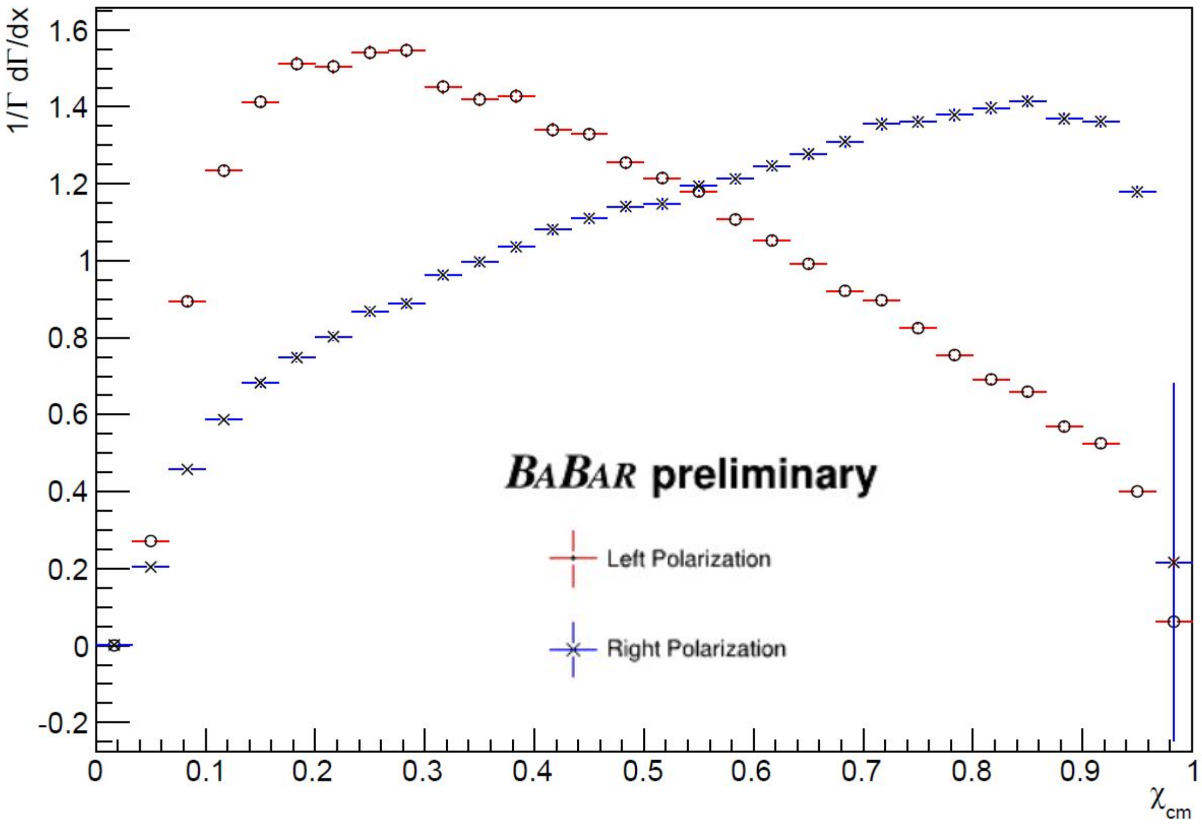
Polarization Observables

- For the τ□πν decay, the momentum of the charged pion is the optimal polarization observable
- $X_{CM} \equiv p/E_{beam}$

cosθ<0

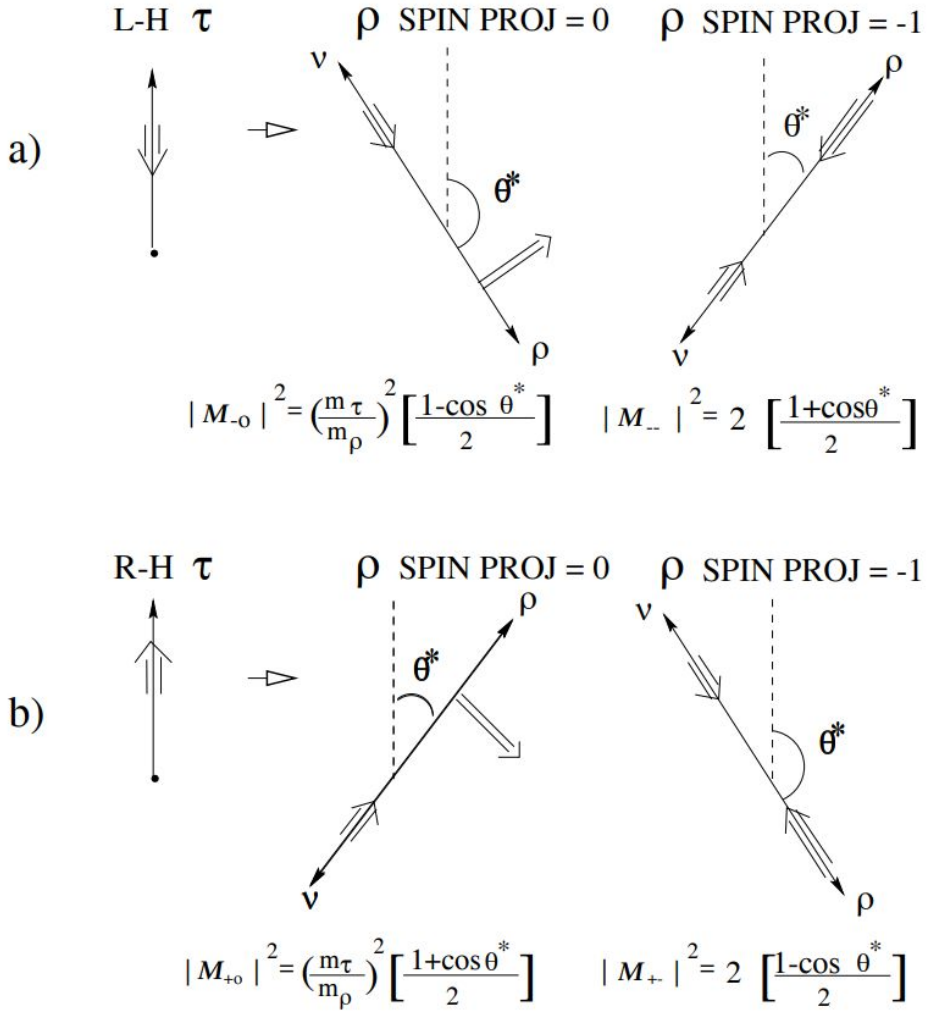


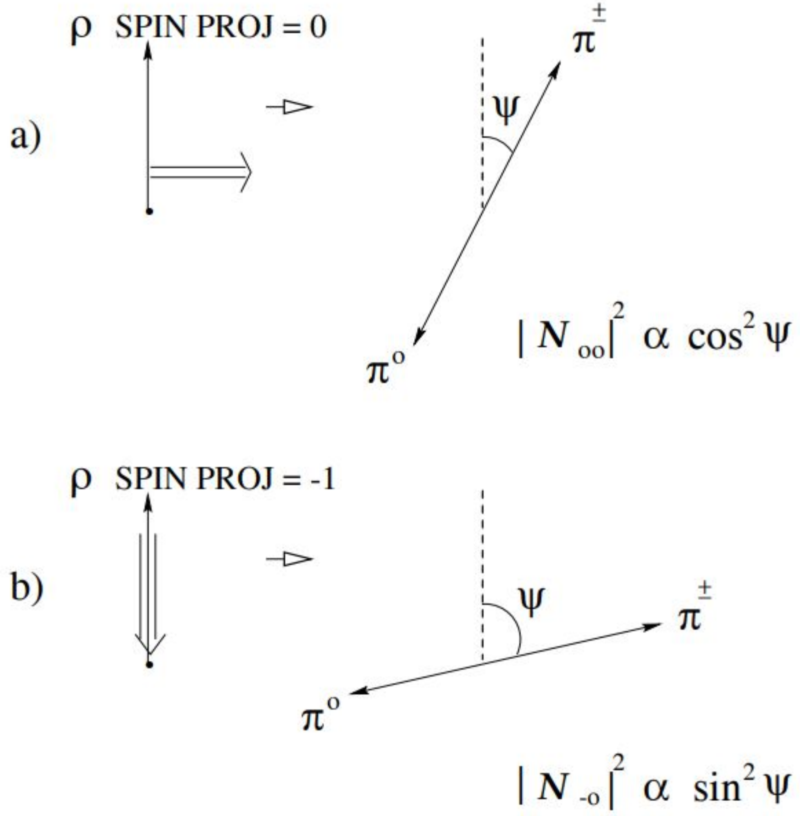
cosθ>0



Rho Spin Analysis

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



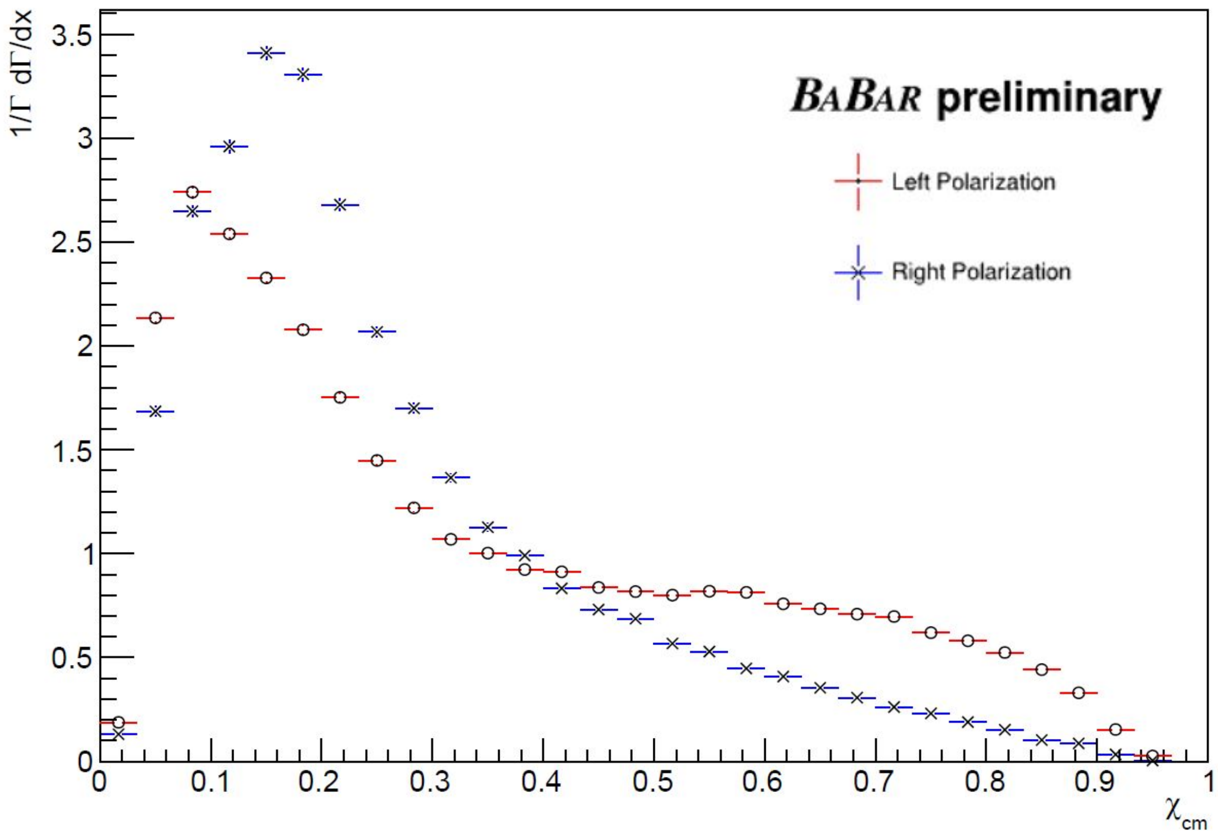


From Dr. Manuella Vincter, PhD thesis, UVIC, 1996

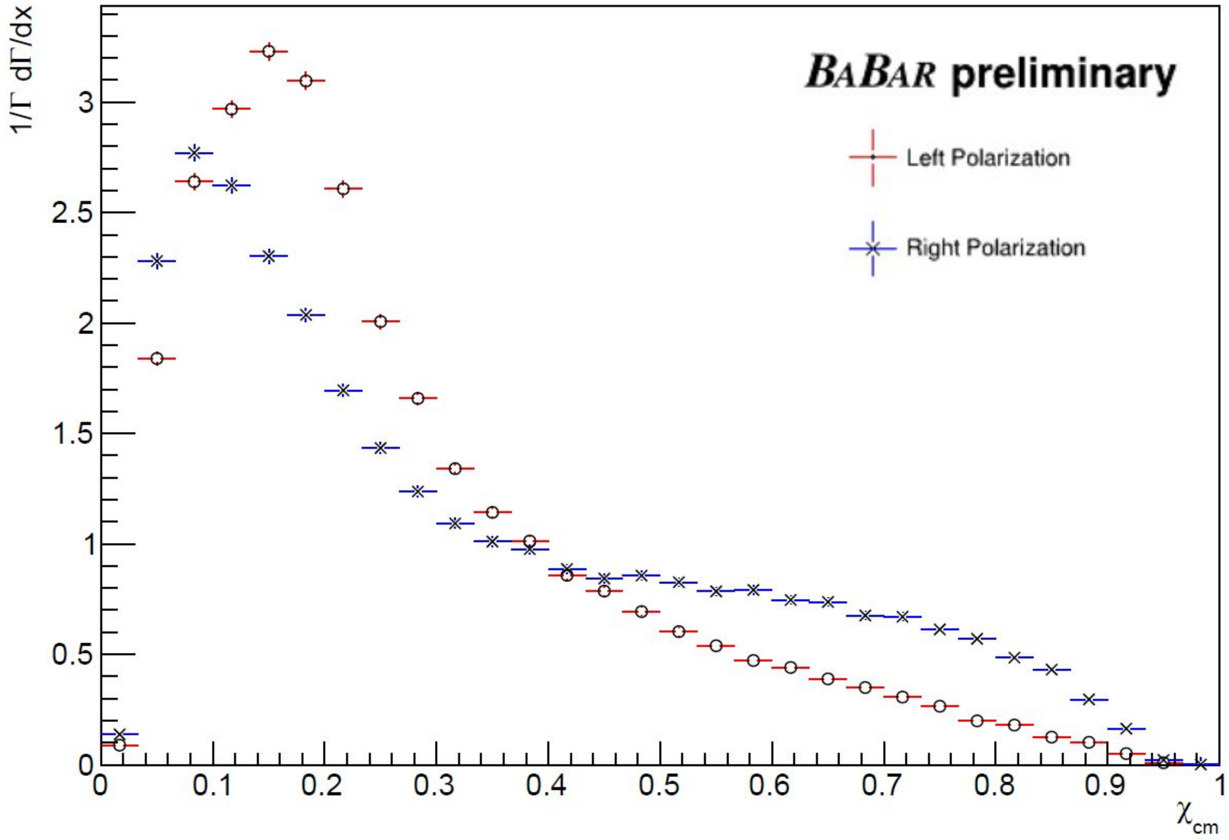
Polarization Observables

- For the τ□ρν decay, the momentum of the charged pion is sensitive to the polarization but is not optimal
- $X_{CM} \equiv p/E_{beam}$

cosθ<0



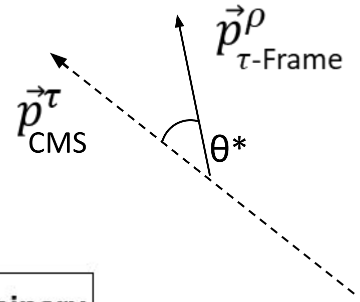
cosθ>0



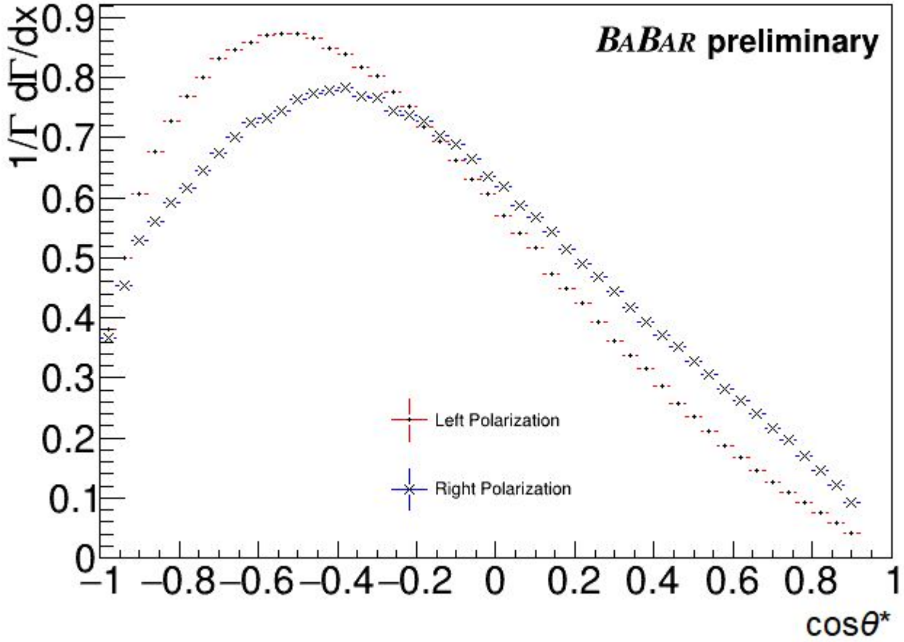
Polarization Observables

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

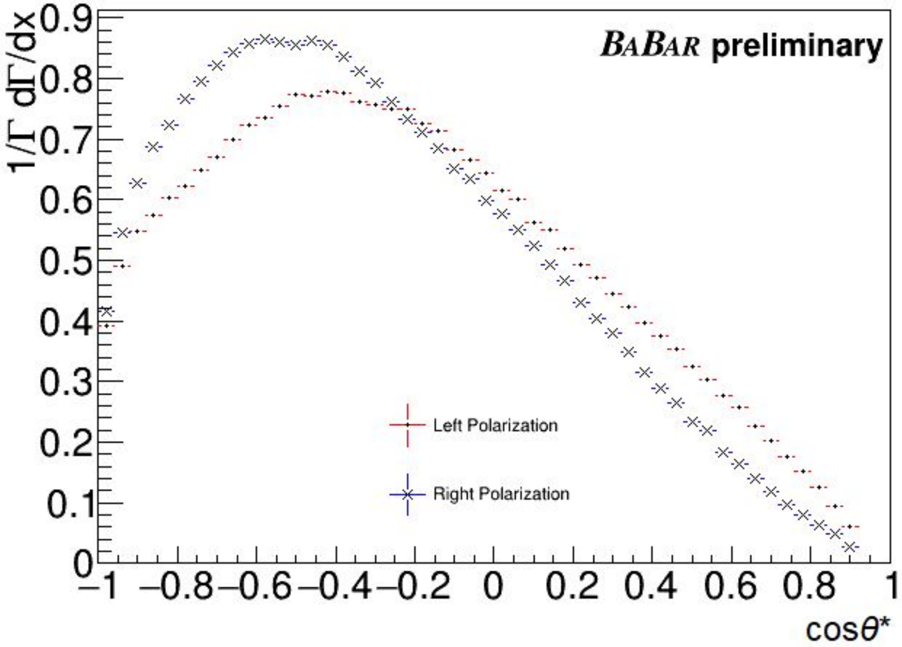
$$\cos\theta^* = \frac{2z - 1 - m_\rho^2/m_\tau^2}{1 - m_\rho^2/m_\tau^2} \qquad z \equiv {}^{E_\rho}\!/_{E_{\text{beam}}}$$



cosθ<0



cosθ>0

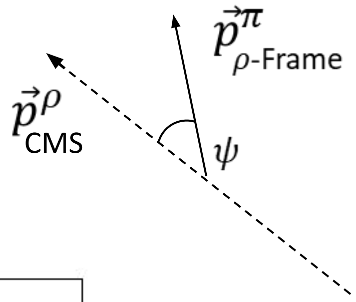


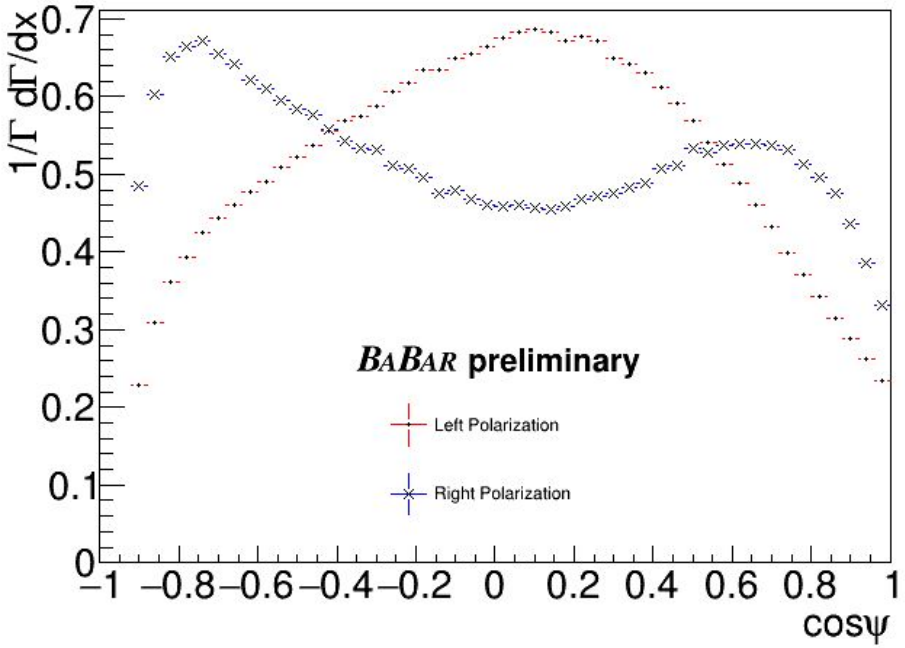
c) K. Hagiwara, A. Martin, D. Zeppenfeld, Tau Polarization Measurements at LEP and SLC, Phys. Lett. B. 235, 1998, DOI: 10.1016/0370-2693(90)90120-U

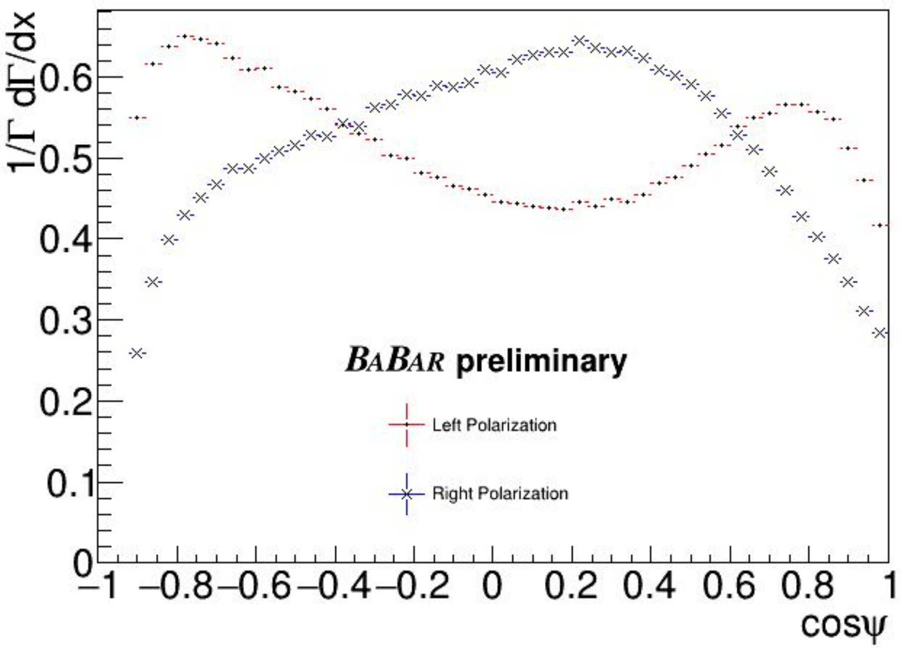
Polarization Observables

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

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



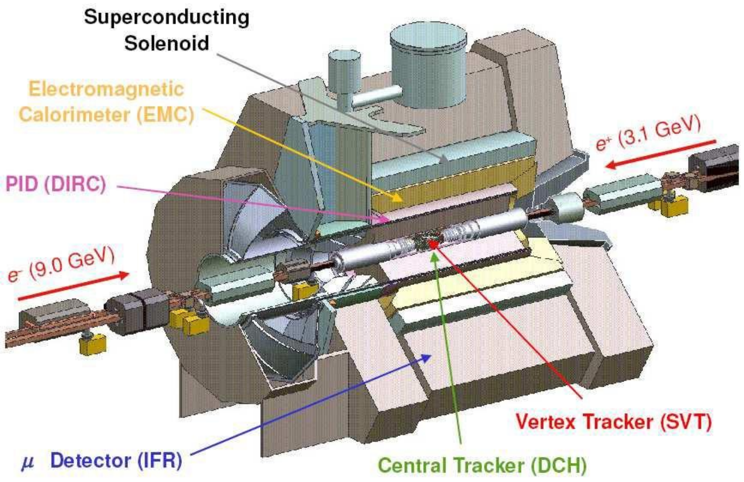


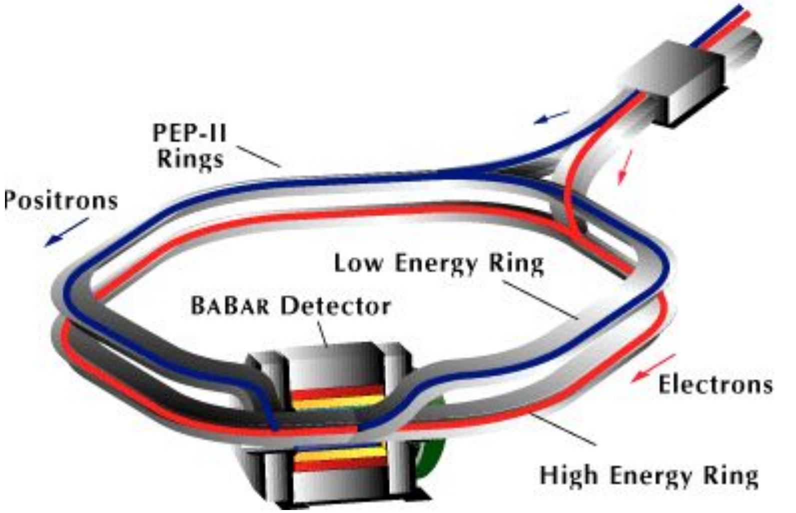


c) K. Hagiwara, A. Martin, D. Zeppenfeld, Tau Polarization Measurements at LEP and SLC, Phys. Lett. B. 235, 1998, DOI: 10.1016/0370-2693(90)90120-U

BaBar and PEP-II

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



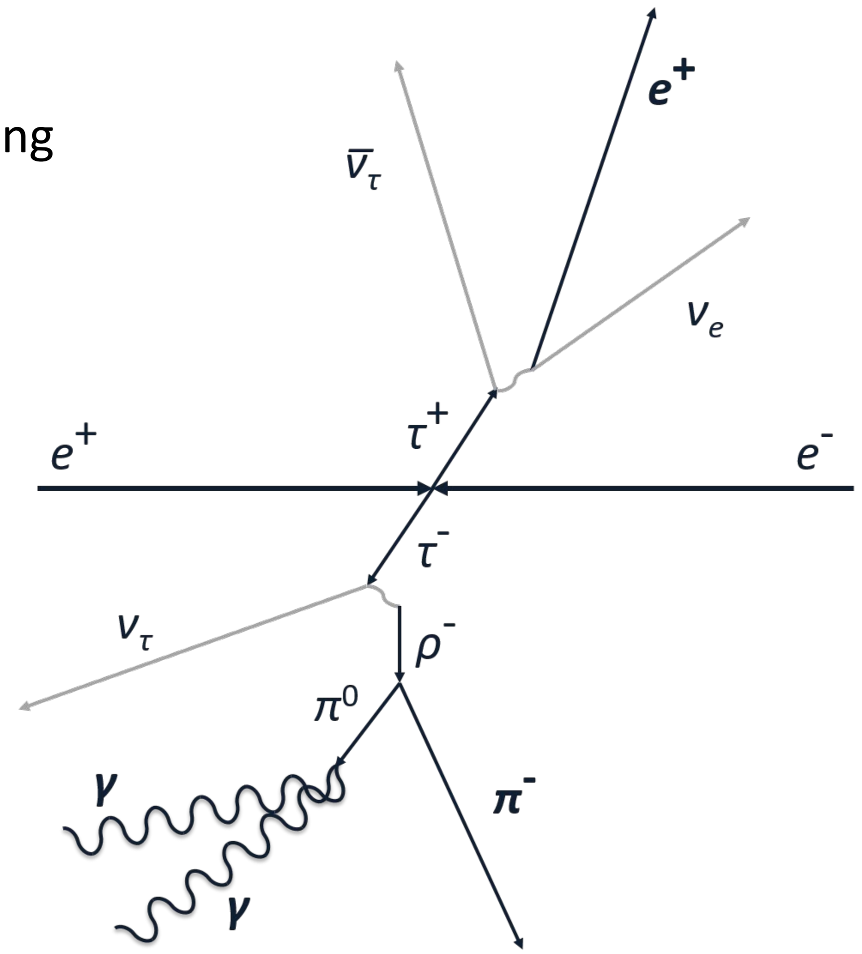


- Over 6 run periods *BaBar* collected 432 fb^{-1} of data on the Υ(4S) resonance (10.58 GeV)
- PEP-II collided electrons and positrons together at 9.0 and 3.1 GeV
- No beam polarization is expected at PEP-II
- Analysis began before Belle II started physics data runs
- Similarities between *BaBar* and Belle II detectors means results should be comparable
- Belle II plans to reproduce the analysis in the future

Tau Event Selection

- As a proof of concept we have developed Tau Polarimetry at *BABAR* using $\tau^{\pm} \to \rho^{\pm}\nu_{\tau} \to \pi^{\pm}\pi^{0}\nu_{\tau}$ decays
- ρ decay of the τ has the largest branching fraction

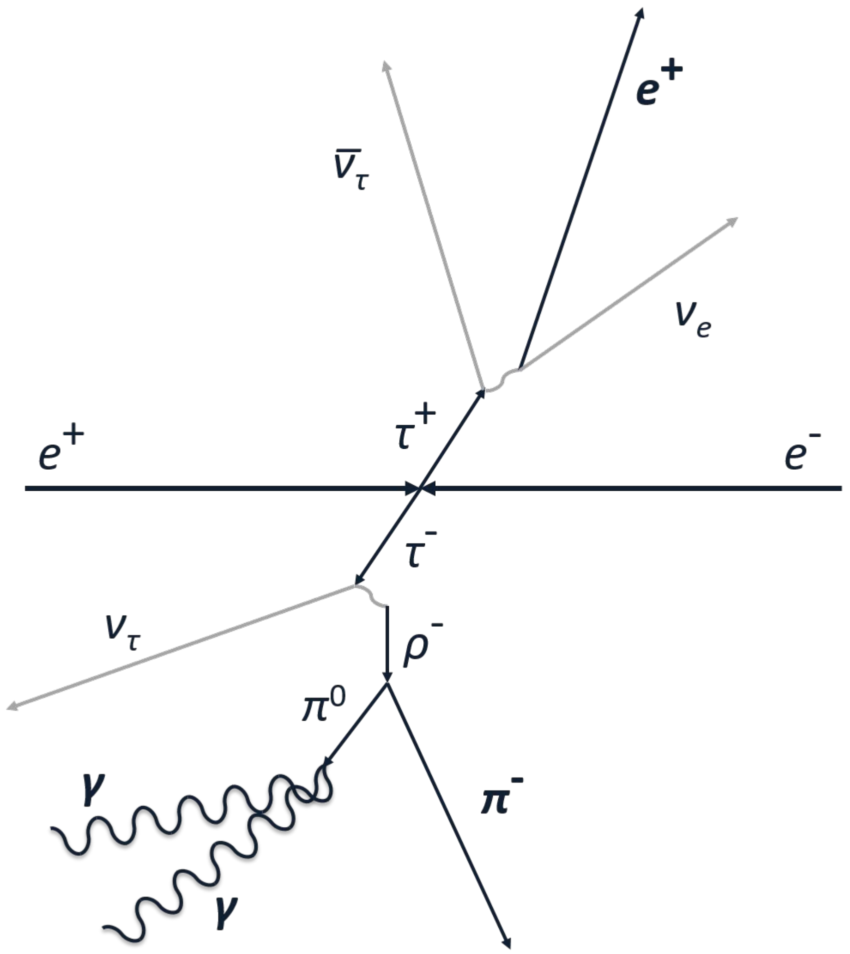
Tau Decay	Branching Fraction
$\tau^{\pm} \to \rho^{\pm}\nu_{\tau} \to \pi^{\pm}\pi^{0}\nu_{\tau}$	25.49%
$\tau^{\pm} \to e^{\pm}\nu_{\tau}\overline{\nu}_{e}$	17.82%
$\tau^{\pm} \to \mu^{\pm}\nu_{\tau}\overline{\nu}_{\mu}$	17.39%
$\tau^{\pm} \to \pi^{\pm}\nu_{\tau}$	10.82%
$\tau^{\pm} \to a_{1}^{\pm}\nu_{\tau} \to \pi^{\pm}\pi^{0}\pi^{0}\nu_{\tau}$	9.26%
$\tau^{\pm} \to a_{1}^{\pm}\nu_{\tau} \to \pi^{\pm}\pi^{\pm}\pi^{\pm}\nu_{\tau}$	9.31%



Caleb Miller. calebmiller@uvic.ca

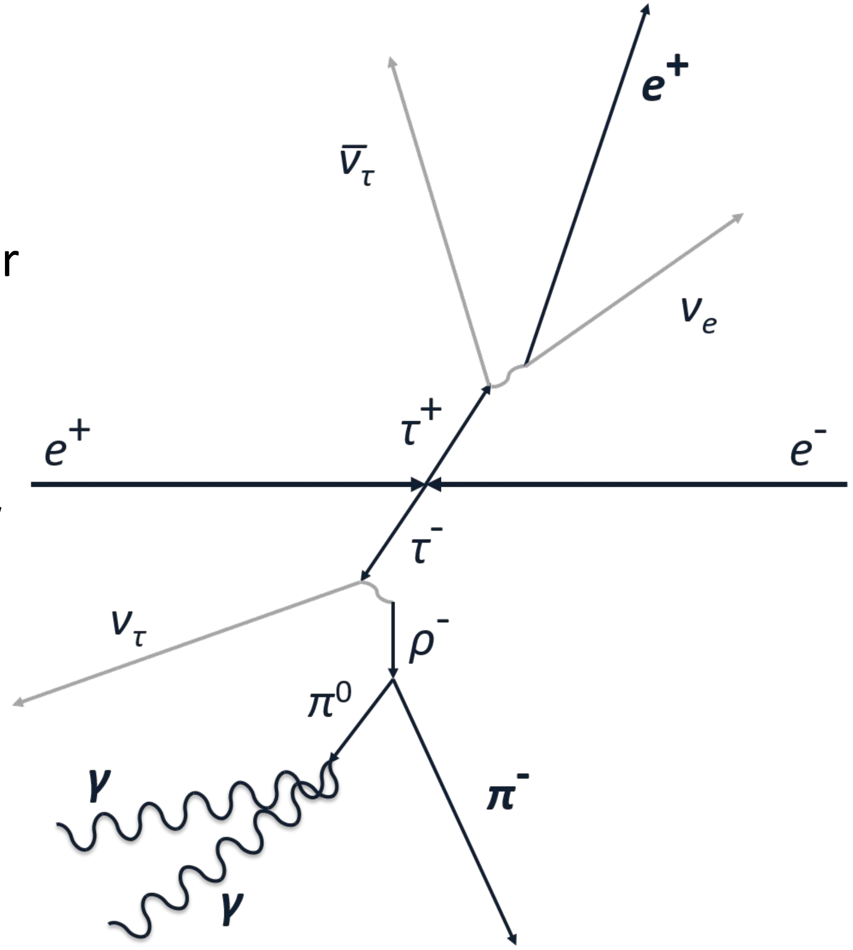
Tau Event Selection

- Developed the technique on 32.28 fb^{-1} of data
  - Final measurement performed on remaining 391.90 fb^{-1}
  - Unbiased analysis approach
- Selected tau events in a 1v1 topology, (ρ vs. e)
  - ρ has large branching fraction, e for clean tag
- Signal candidates are defined as a charged particle with a π^0
- $q\bar{q}$ events are eliminated with the electron requirement
- Avoid PID requirements on signal pion to reduce bias



Tau Event Selection

- Total event transverse is required to be less than 1.2 GeV to reduce two-photon and Bhabha backgrounds
- Charged particles required to be in the acceptance of the drift chamber and the calorimeter
- A neutral pion identified from 1 or 2 calorimeter clusters
  - For 1 cluster, must have a high likelihood as defined by BABAR PID
  - For 2 clusters, reconstructed mass within 115 to 155 MeV window
- Reconstructed ϱ mass greater than 300 MeV
- Tag-side electron passes BABAR PID and has no neutrals in hemisphere



- Achieve a 99.7% pure tau-pair sample (0.3% Bhabha)
- 90% of selected events contain a $\tau^\pm \to \pi^\pm\pi^0\nu_\tau$ decay
  - 8% a_1 □ $\pi^\pm\pi^0\pi^0$ decays, 2% other hadronic

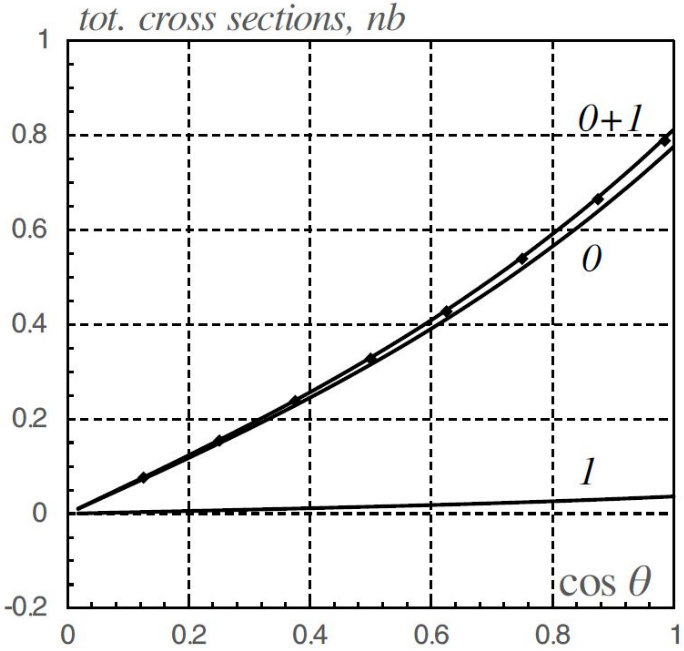
KKMC generation of polarized tau MC

- In order to model and study the effects of beam polarization in the tau selection KKMC[d] is used
- KKMC is capable of changing a number of parameters related to the e^+e^- collision process
  - Beam polarization, centre-of-mass energy, standard model values, etc…
  - Powerful tool to model and study the effects of polarization
- Roughly twice the luminosity equivalent amount of MC was generated for 100% polarized e^- beams
  - Both left and right polarized e^- beam
- The generated MC can be processed through the *BABAR* reconstruction algorithms to end up with MC in the same format as the rest of the *BABAR* MC
- This allows for the polarized MC to undergo analysis selection identical to data

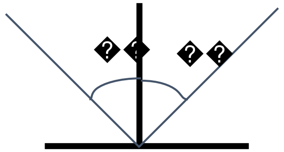
d) S. Jadach, B.F.L. Ward, Z. Wąs; Computer Physics Communications, Volume 130, Issue 3, 2000, Pages 260-325, https://doi.org/10.1016/S0010-4655(00)00048-5

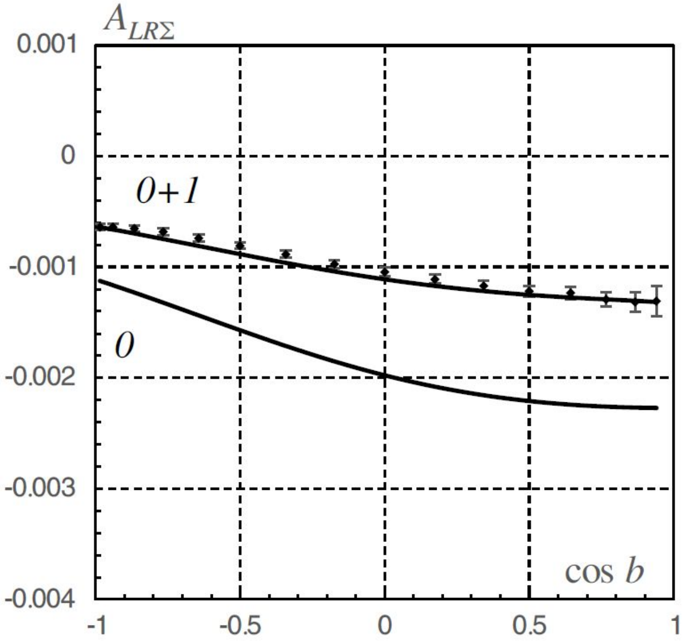
KKMC validation

- As Chiral Belle is expecting unprecedented levels of precision in its future EW measurements new levels of theoretical precision is required
- This provides an opportunity to validate the agreement between KKMC and the theory calculations
- A 2020 theory paper[e] on the $e^+e^- \rightarrow \mu^+\mu^-$ process has a number of observables that can be compared to KKMC

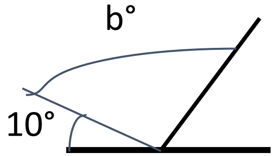


cross-section as function of a symmetric acceptance from $|\cos\theta|$=0 to $|\cos\theta|$=1. *0* and *1* refer to Born and NLO respectively





left-right asymmetry as a function of acceptance from $\cos\theta$=-0.985 to cos *b.* *0* and *1* refer to Born and NLO respectively



$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$

e) A. Aleksejevs, S. Barkanova, C. Miller, J.M. Roney, V. Zykunov; NLO radiative corrections for forward-backward and left-right asymmetries at a B-factory; Phys.Rev.D 101 (2020) DOI: 10.1103/PhysRevD.101.053003

Polarization Fit

- To extract the average beam polarization from the data we employ a binned maximum likelihood fit using Barlow and Beeston[f] template fit methodology
- Data and MC is binned in 3D histograms of cosθ*, cosψ, and cosθ
- Polarized tau MC is used to give fit sensitivity to polarization effects
- The data is fit as a linear combination of the MC template histograms

a_l	0.499
a_r	0.499
a_b	$3.8\text{x}10^{-5}$
a_m	$1.4\text{x}10^{-3}$
a_u	$3.8\text{x}10^{-4}$
a_c	$4.8\text{x}10^{-5}$

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

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

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

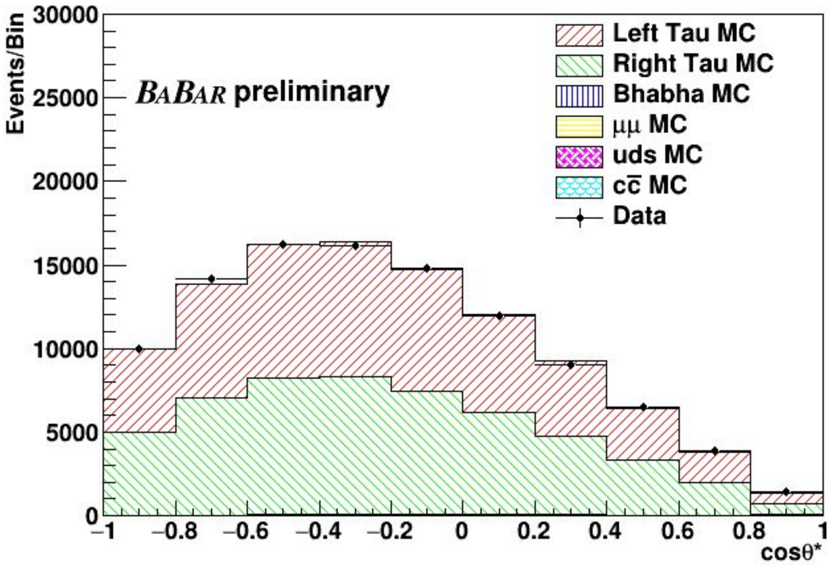
a_i = fit contribution

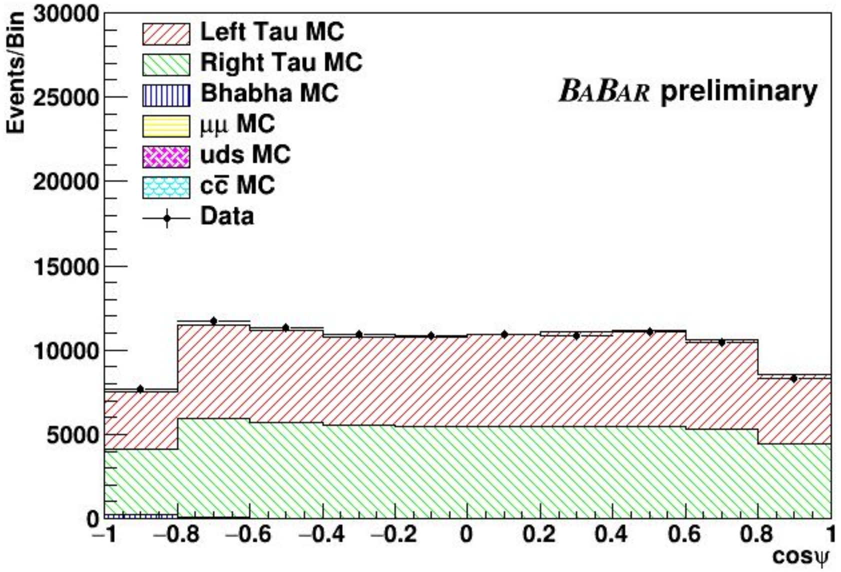
f) R. Barlow, C. Beeston; Computer Physics Communications, Volume 77, Issue 2, 1993, Pages 219-228, https://doi.org/10.1016/0010-4655(93)90005-W

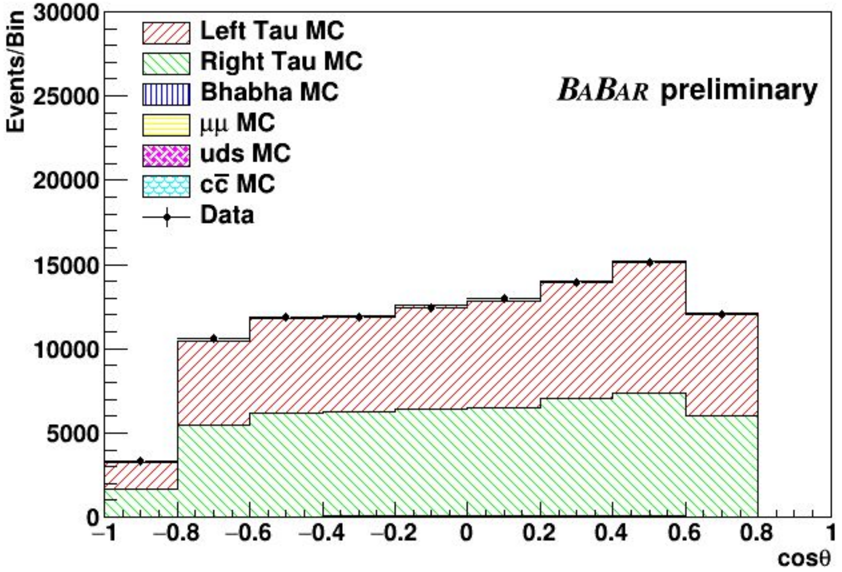
Fit Result

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
- $\langle P \rangle$=-0.0031, χ^2/NDF=770/872

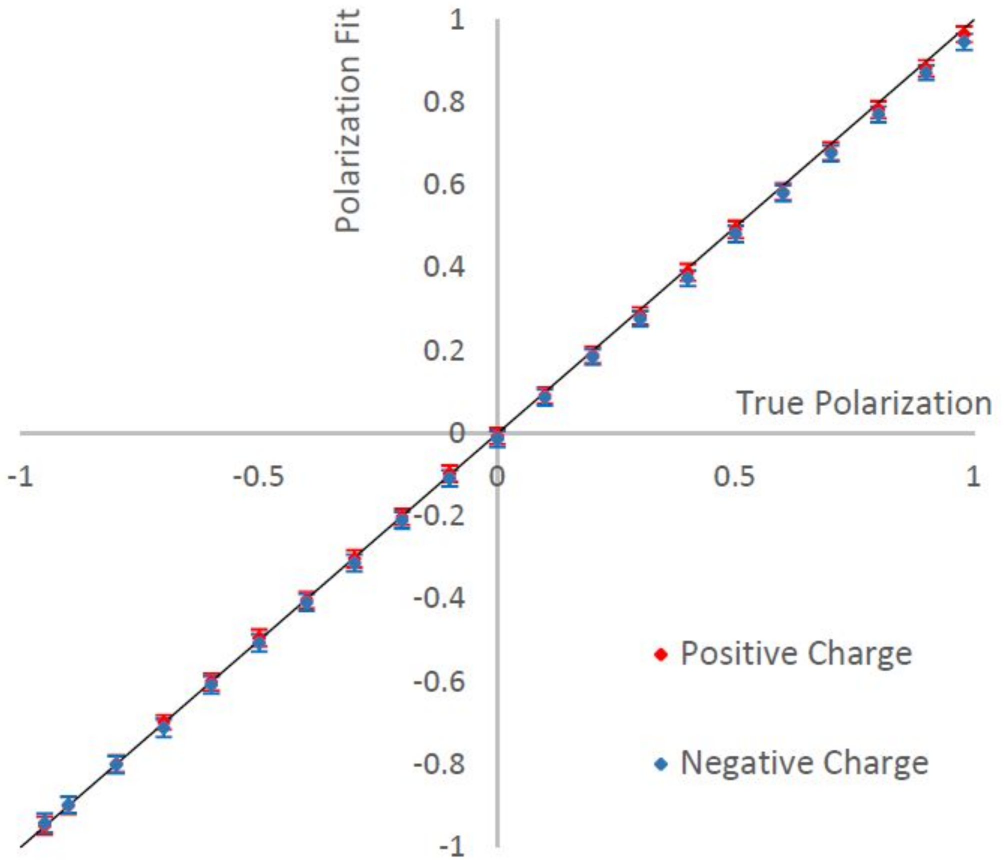






Beam Polarization MC "Measurement"

- 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

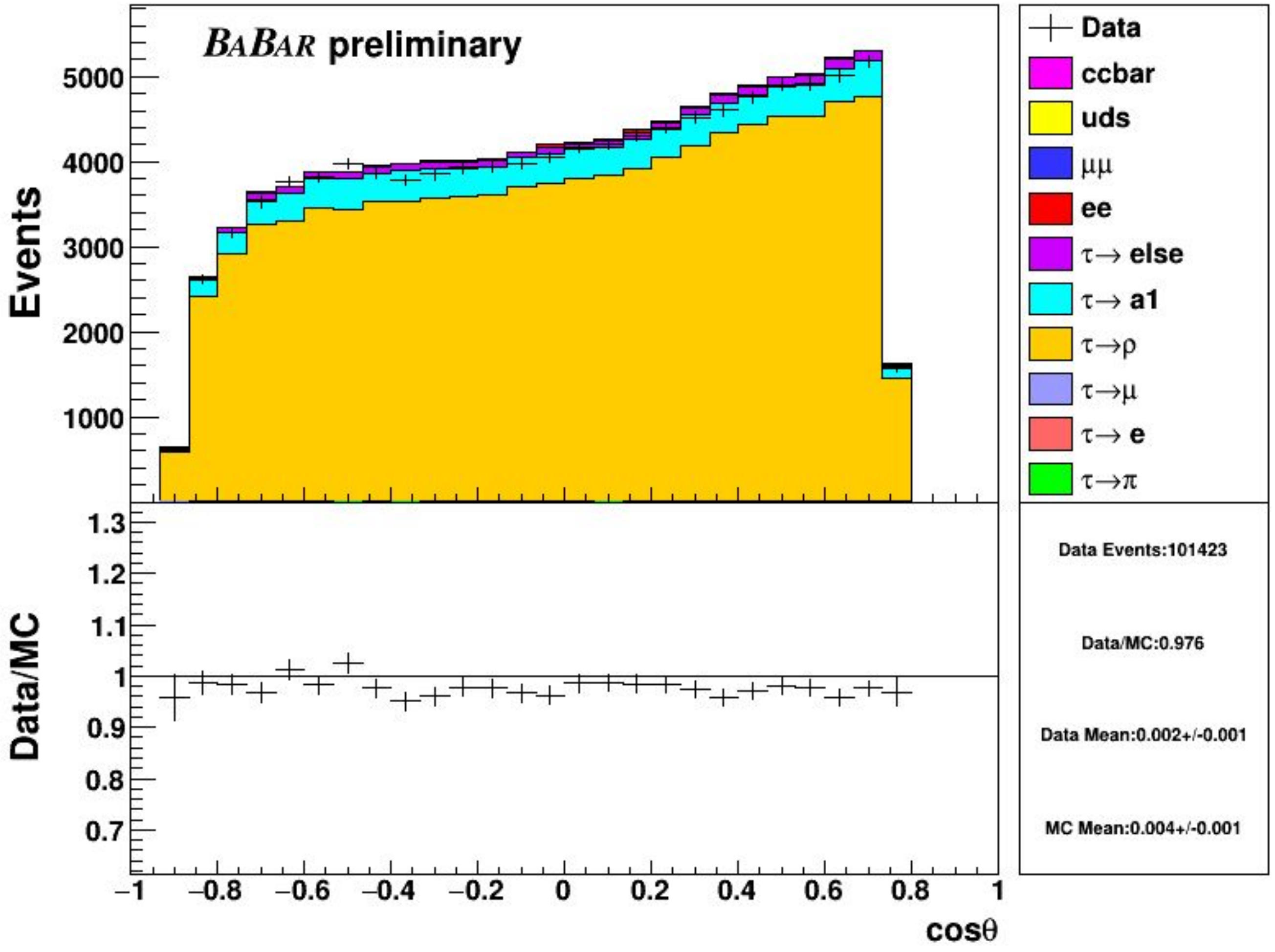


Systematic Uncertainties

- Systematic uncertainties were evaluated under two possible methodologies
  - Systematic variation of MC distributions
  - Systematic variation of cut value
- Variation of the MC distributions is preferred in regions where the MC and data is in good agreement while cut variation is preferred in regions with uncontrolled or poorly modelled MC, particularly Bhabha and two-photon like events.
- The statistical uncertainty on the systematic uncertainty was evaluated by splitting the unpolarized tau MC into 3 samples and performing the same process. The standard deviation among the MC samples is taken as a proxy for the level of statistical fluctuation expected in the data

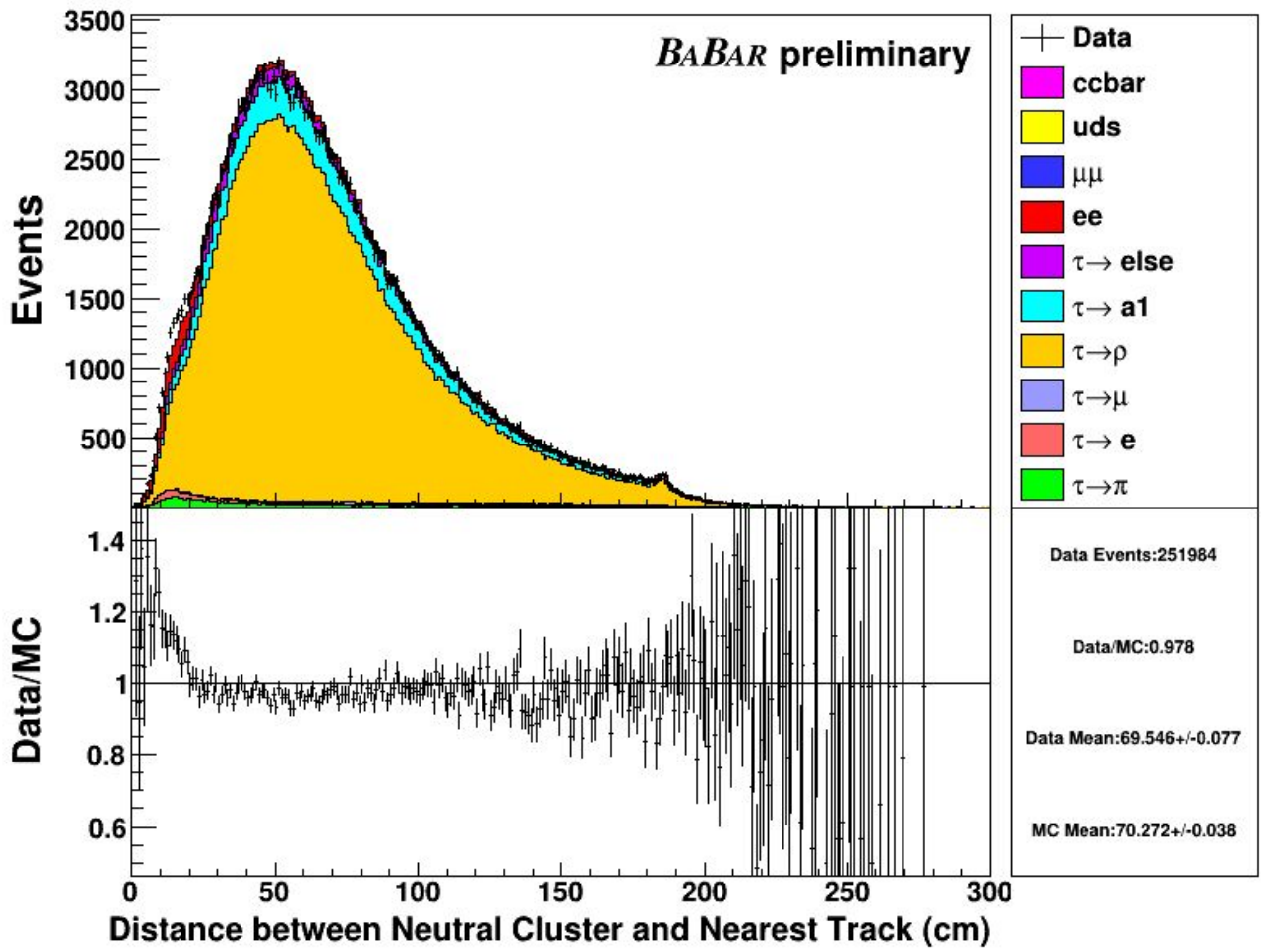
Systematic Uncertainties, $\cos\theta$

- The systematic uncertainty in the angular distributions was evaluated by varying the MC distributions by the angular resolution (± 0.000897 radians)
- The effect this has on the polarization fits is taken as the systematic uncertainty



Systematic Uncertainties, Hadronic split-offs

- The modelling of neutrals near the charged tracks was found to be particularly poorly modelled
- This region is treated with a 40cm separation cut, where neutrals within 40cm are recombined with the track
- The poor modelling means a cut variation is more appropriate than a variation of the MC distribution



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:

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

Preliminary

Study	Run 1	Run 2	Run 4	Run 5	Run 6	Final
π^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**
π^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**
π^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**

Tau Polarimetry at *BABAR*

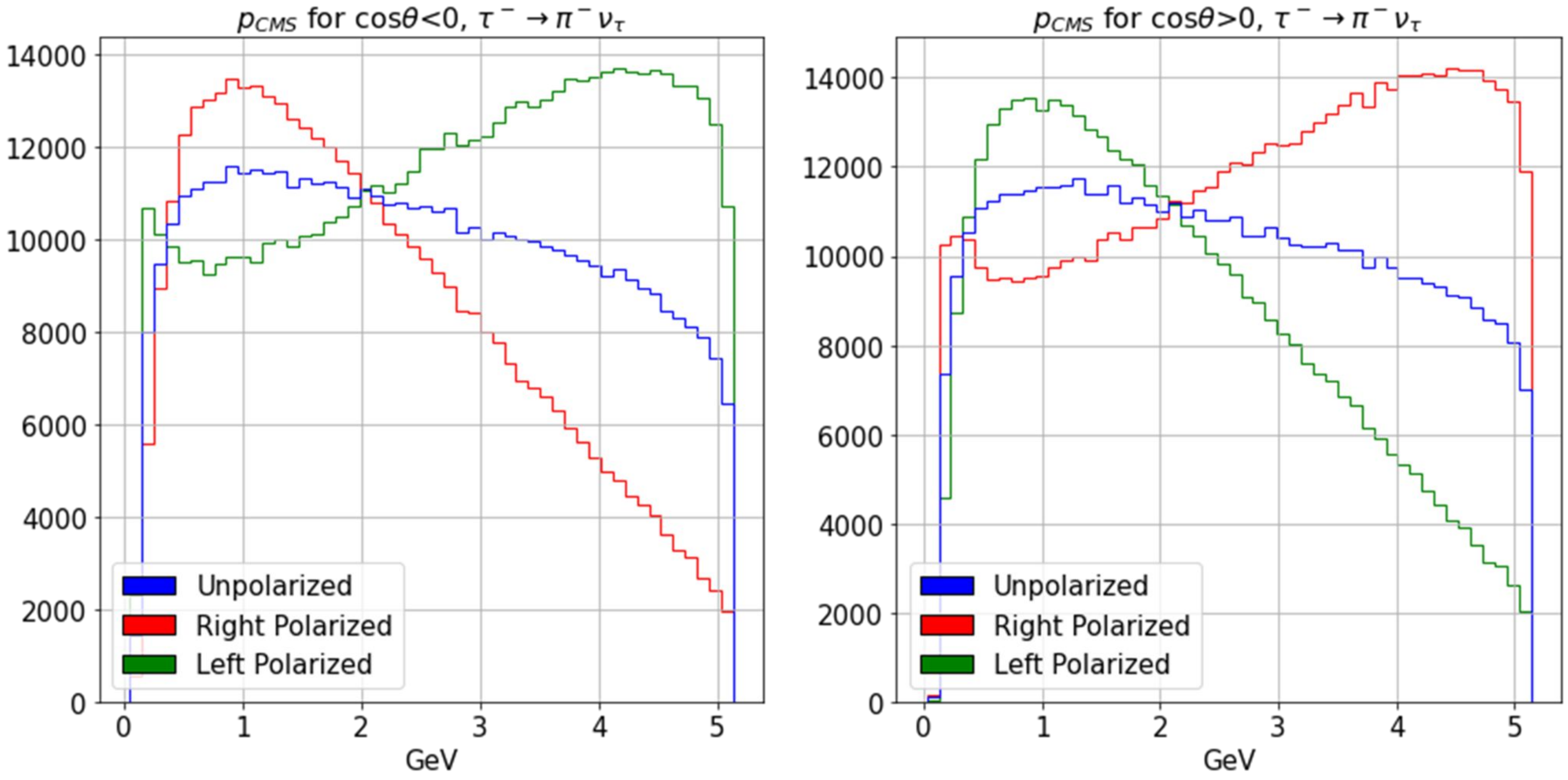
- Identifying the dominant systematic uncertainties is one of the major goals of this analysis
  - Demonstrates the feasibility of the technique
  - Identifies areas where Belle II could improve
- For the *BABAR* analysis the systematic uncertainties are dominated by the MC modelling and resolution effects on neutral particles
- This measurement technique assumes no new physics
  - New physics sources are larger suppressed at 10.58 GeV due to QED dominance
- Systematic uncertainties still exhibit some statistical dependence
- *BABAR* has ongoing work to add muon tag to this analysis for increased statistics
  - See if we can reach a systematic limit to most of the uncertainties

Generator Studies at Future Collider Energies

- While Tau Polarimetry has been developed for Chiral Belle it's use at future polarized sources could be interesting
- Using the KKMC generator the polarization sensitivity above the Z-pole can be studied
- Carried out the study at a centre-of-mass energy of 500 GeV
- The KKMC generator allows for the effects of the weak exchange to separated from QED effects
- Only examined the τ$\square$πν mode so far

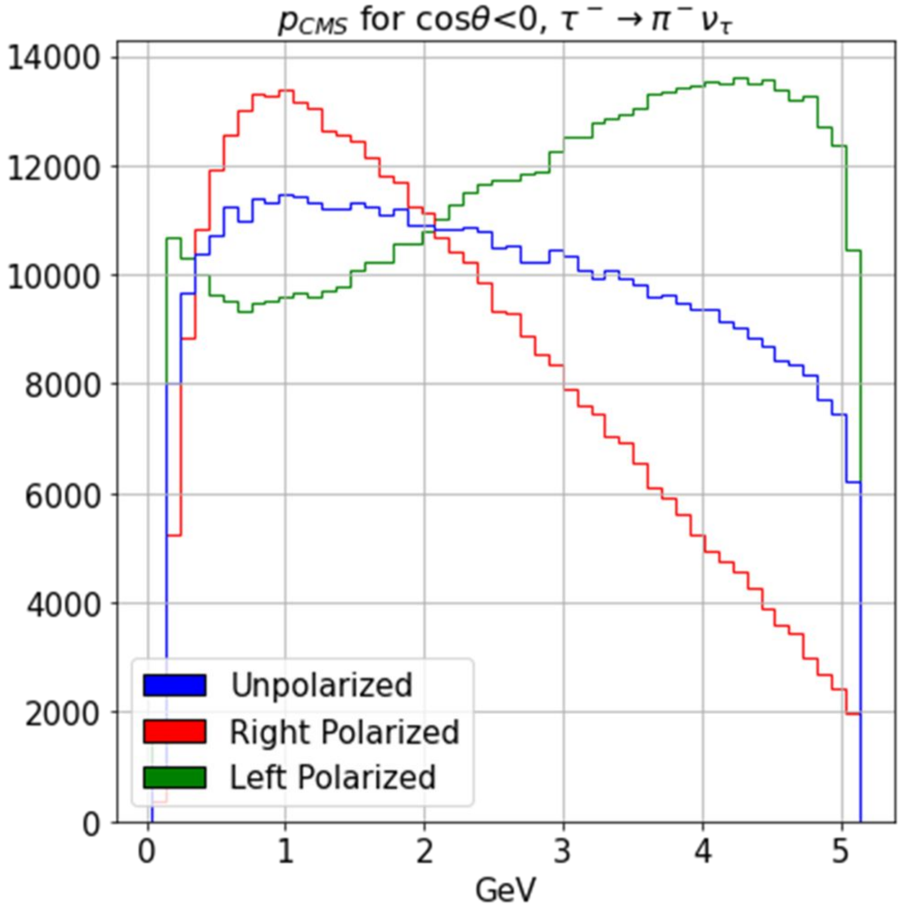
τ□πν at 10.58 GeV, All couplings on

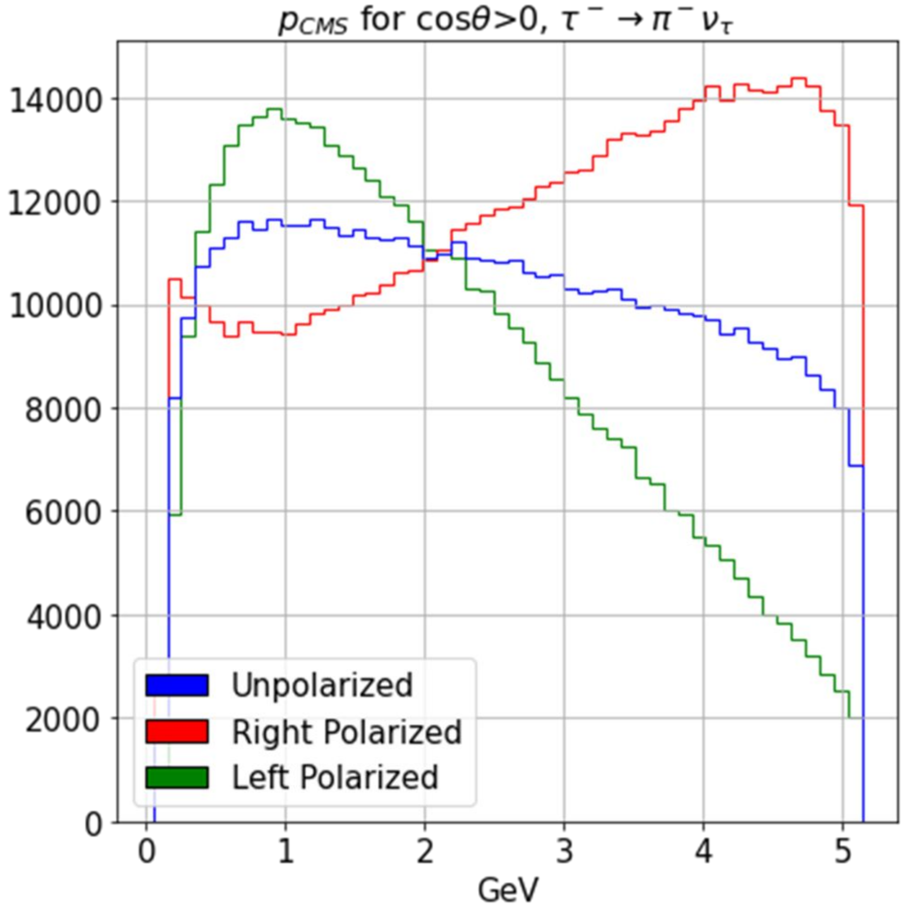
- Momentum distributions at 10.58 GeV look as expected



τ□πν at 10.58 GeV, no Z interaction

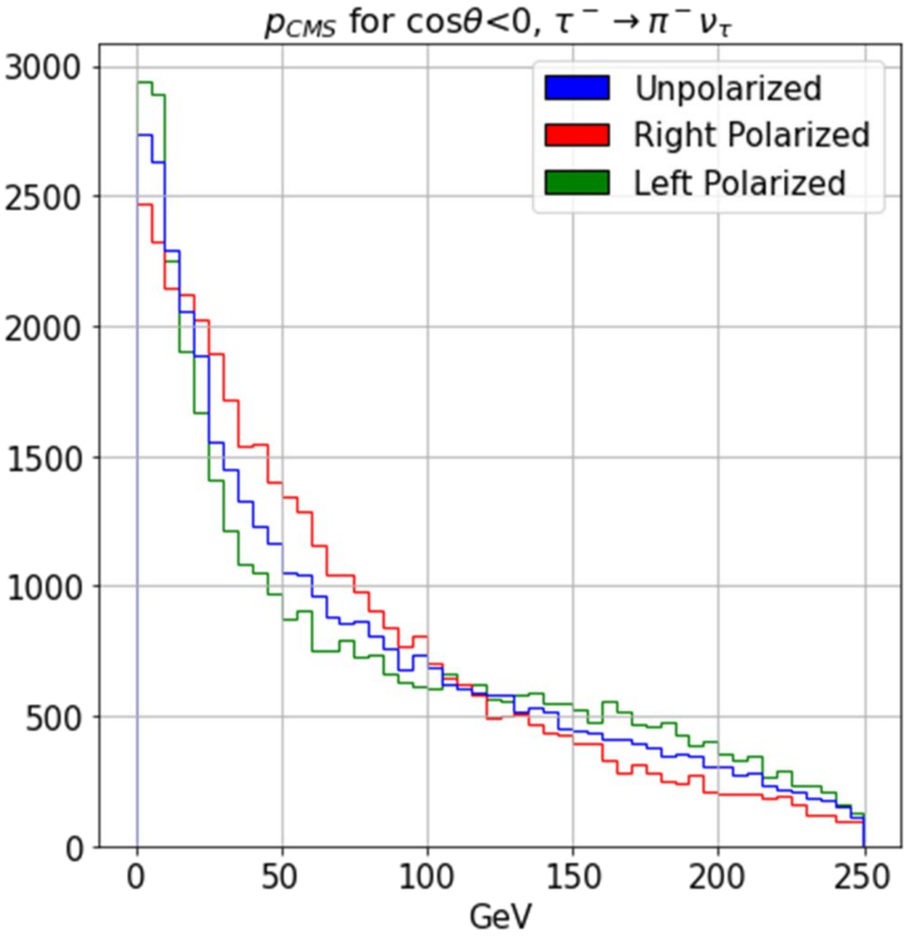
- These distributions remain relatively unchanged with QED interactions only as expected

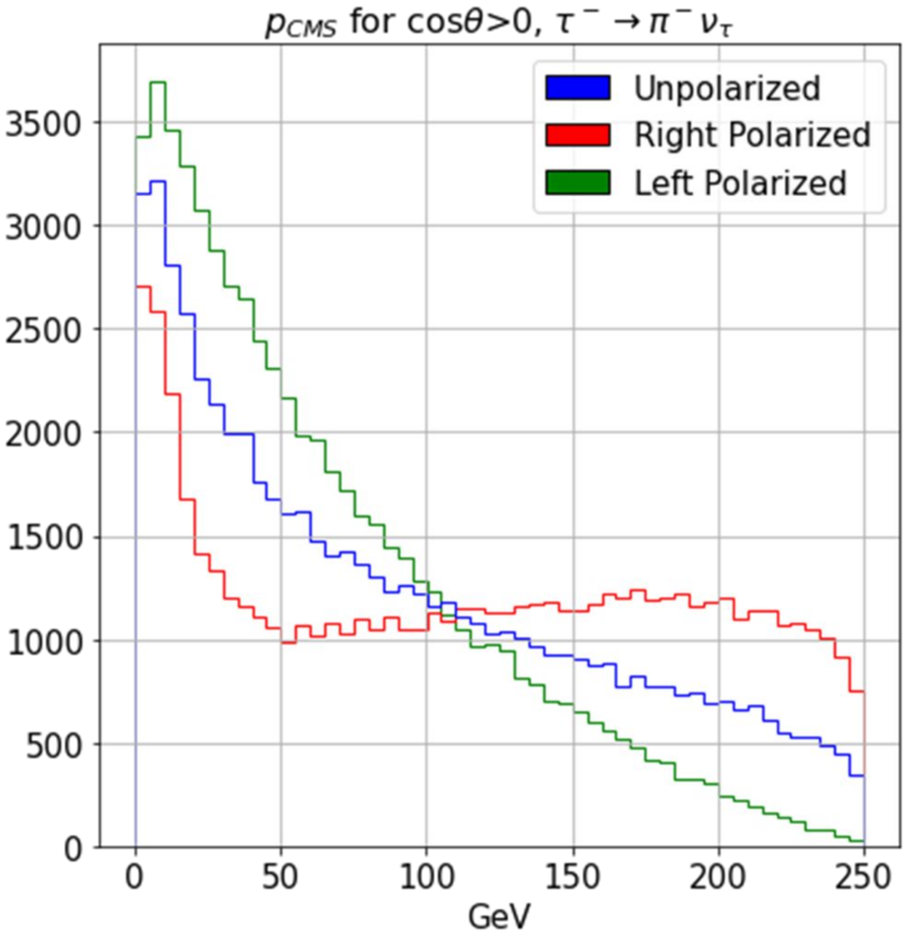




τ□πν at 500 GeV, All couplings on

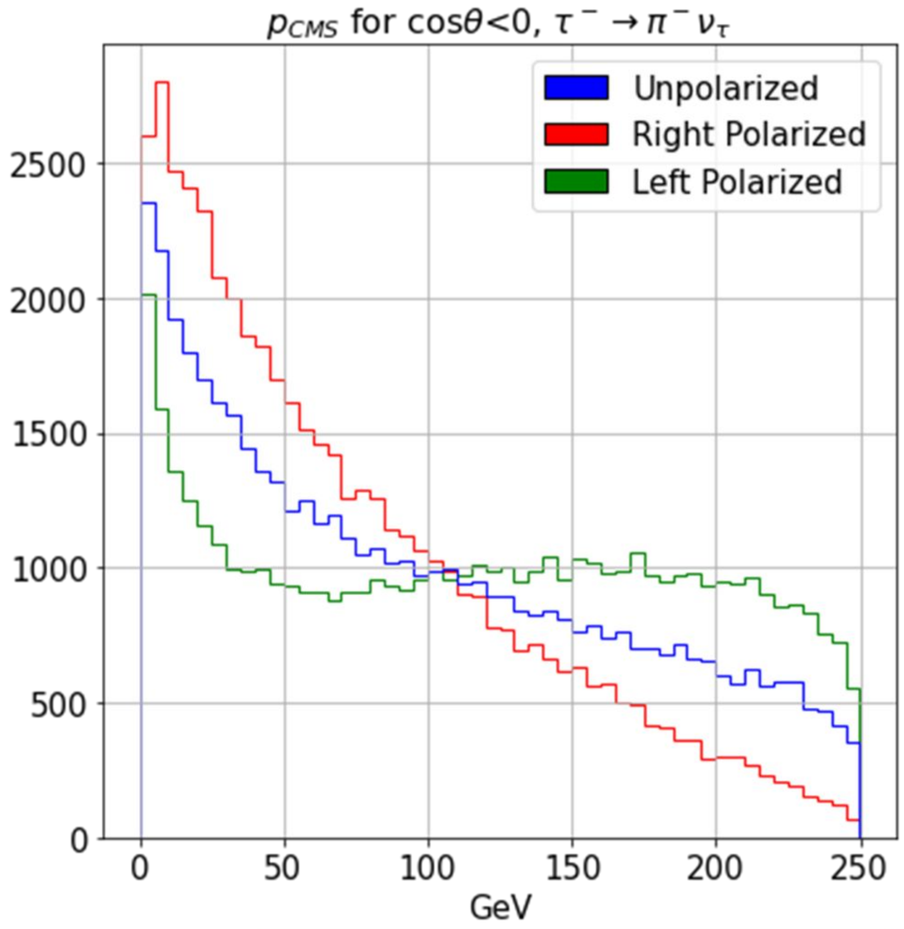
- Polarization dependence seems to only appear in the forward direction

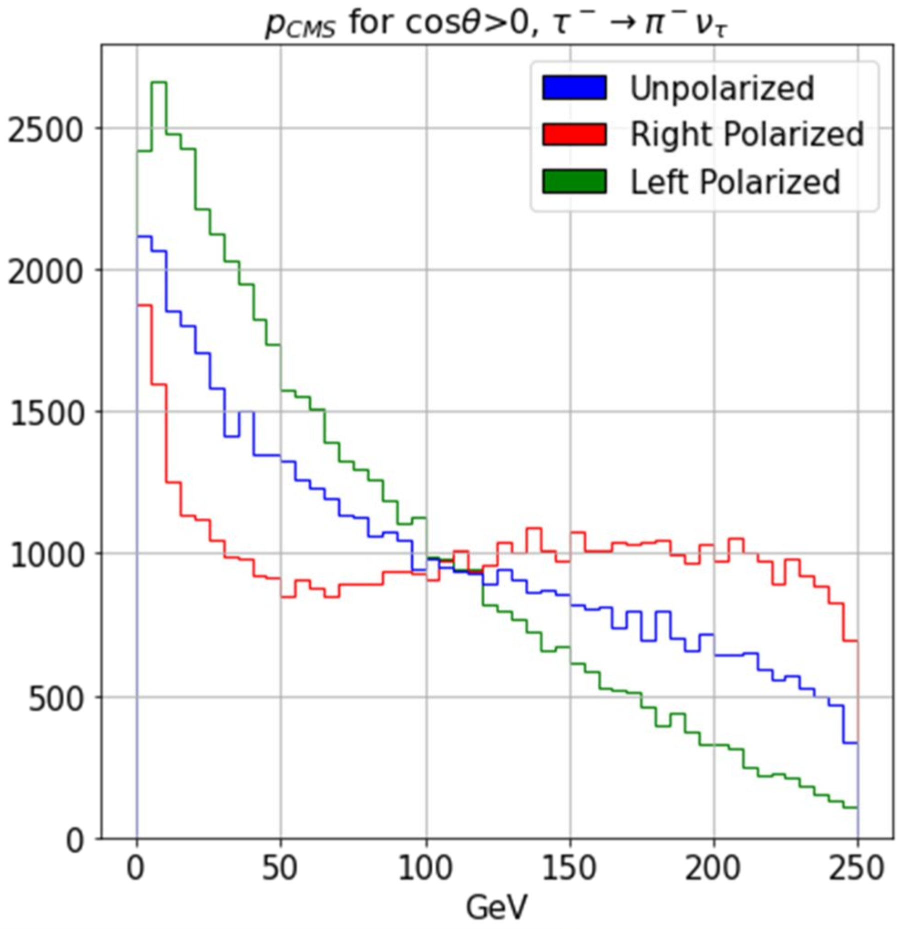




τ□πν at 500 GeV, no Z interaction

- With only QED interactions, the loss of sensitivity in backward region regained





Polarimetry and cross-sections

- If both beams are polarized the cross-section enhancement adds additional complementary information to the polarization knowledge
- Interaction matrix helps to visualize the process:

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

- Only the L^+R^- and R^+L^- crossing result in a collision, the L^+L^- and R^+R^- crossings continue down the beam pipe
- For unpolarized beams L=R=0.5, and each quadrant represent 25% of crossings
- The average beam polarization, <P>, is $(R^+L^- - L^+R^-)/(R^+L^- + L^+R^-)$
- The cross-section multiplier, σ, is $(R^+L^- + L^+R^-)/(R^+L^-_{\textbf{unpolarized}} + L^+R^-_{\textbf{unpolarized}})$

70% polarized e^- beam

$e^+ \backslash e^-$	0.85	0.15
0.5	0.425	0.075
0.5	0.425	0.075

$$\langle P \rangle = \frac{0.5 * 0.85 - 0.5 * 0.075}{0.5 * 0.85 + 0.5 * 0.075} = 0.7$$

$$\sigma = \frac{0.425 + 0.075}{0.25 + 0.25} = 1$$

Polarimetry and cross-sections

- <P> is the variable physics is sensitive to, e.g. 10% increase in <P> is a 10% increase in A_{LR}
- Polarizing both beams enhances <P> and cross-section

70% polarized e^- beam

$e^+ \backslash e^-$	0.85	0.15
0.5	0.425	0.075
0.5	0.425	0.075

<P> = 0.7
σ = 1

80% polarized e^- beam
30% polarized e^+ beam

$e^+ \backslash e^-$	0.90	0.10
0.65	0.585	0.065
0.35	0.315	0.035

<P> = 0.887
σ = 1.24

70% polarized e^- beam
70% polarized e^+ beam

$e^+ \backslash e^-$	0.85	0.15
0.85	0.722	0.128
0.15	0.128	0.022

<P> = 0.940
σ = 1.49

- Polarizing both beams significantly improves the physics sensitive <P>
- Also gain additional statistics through cross-section enhancement
- cross-section is not unique to a specific <P> but is highly correlated
  - 75% polarized e^-, 65.3% polarized e^+, results in <P>=0.942, σ=1.49
- Precision measurements of production cross-sections can cross-check Tau Polarimetry technique and vice-versa

Conclusions

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

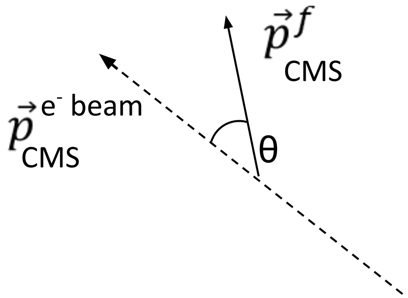
$$\langle P \rangle = -0.0010 \pm 0.0036_{\text{stat}} \pm 0.0030_{\text{sys}}$$

Preliminary

- Strongly motivates adding a polarized electron beam to SuperKEKB
- Technique is less sensitive at energies above the Z-pole but needs a more detailed study
- Many potential studies at various energies and via different decay modes still available
- Initial publication working its way through the *BaBar* review process now

Thank You!

Backup Slides


$\vec{p}^{\,f}_{CMS}$
$\vec{p}^{\,e^- \text{beam}}_{CMS}$
θ

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 π^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
π^0 Likelihood	0.0013
Hadronic Split-off Modelling	0.0027
Minimum Neutral Energy	0.0013
π^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
π^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