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

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on behalf of

BaBar Collaboration

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BEACH 2022

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
- Many technical challenges to solve
  - Dominant systematic uncertainty expected to be knowledge of average beam polarization

Project summarized in recent white paper submitted to SNOWMASS

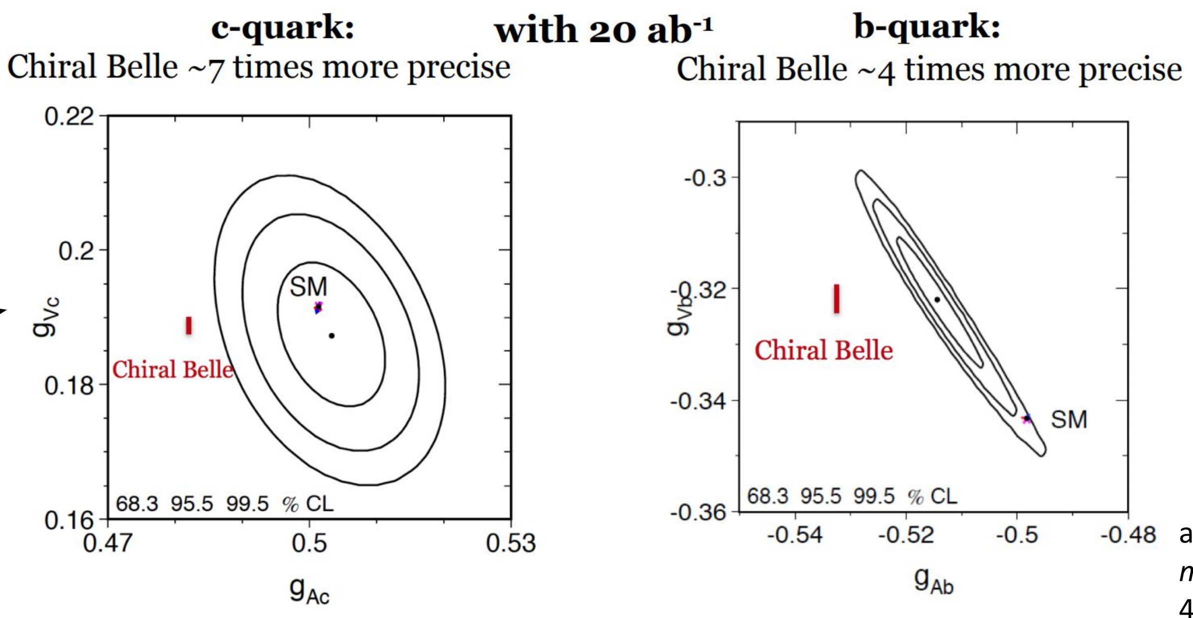
https://arxiv.org/abs/2205.12847

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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Dominant systematics cancel in ratio of A_{LR} measurements for different fermions

	SM	World Average	Chiral Belle 20ab^{-1}	Chiral Belle 50ab^{-1}	Chiral Belle 250ab^{-1}
g_V^b/g_V^c	-1.7901	-1.719	±0.0058	±0.0034	±0.00015
Ratio	±0.0005	±0.082	Improve 14x	Improve 24x	Improve 53x
Relative Error	0.18%	4.8%	0.32%	0.19%	0.09%

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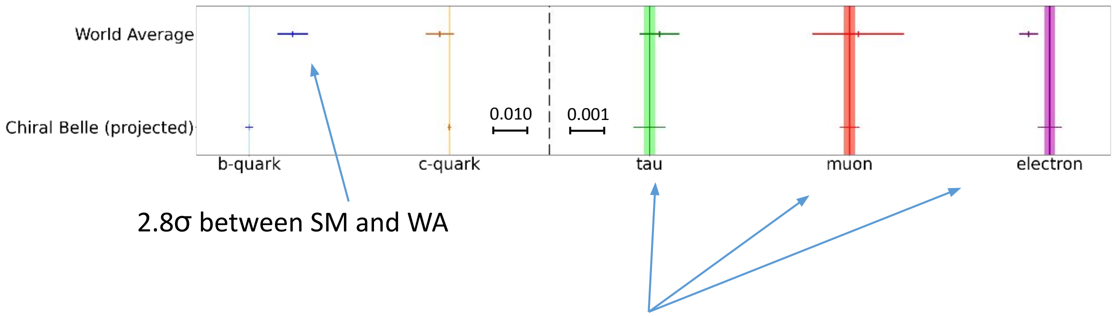
Fermion	*Standard Model*	*World Average*	*Chiral Belle 40ab^{-1}*
b-quark	-0.3437±0.0001	-0.3220 ±0.0077	0.0020(4x improvement)
c-quark	0.1920±0.0002	0.1873 ±0.0070	0.0010(7x improvement)
Tau	-0.0371±0.0003	-0.0366 ±0.0010	0.0008
Muon	-0.0371±0.0003	-0.03667±0.0023	0.0005(4x improvement)
Electron	-0.0371±0.0003	-0.03816±0.00047	0.0006

Visualization of Chiral Belle projections of g_V^f vs World Averages and Standard Model(vertical line) from table



Assuming universality a combined lepton analysis reaches a uncertainty of $0.00033_{stat} \pm 0.00018_{sys}$ compared to a SM uncertainty of 0.0003

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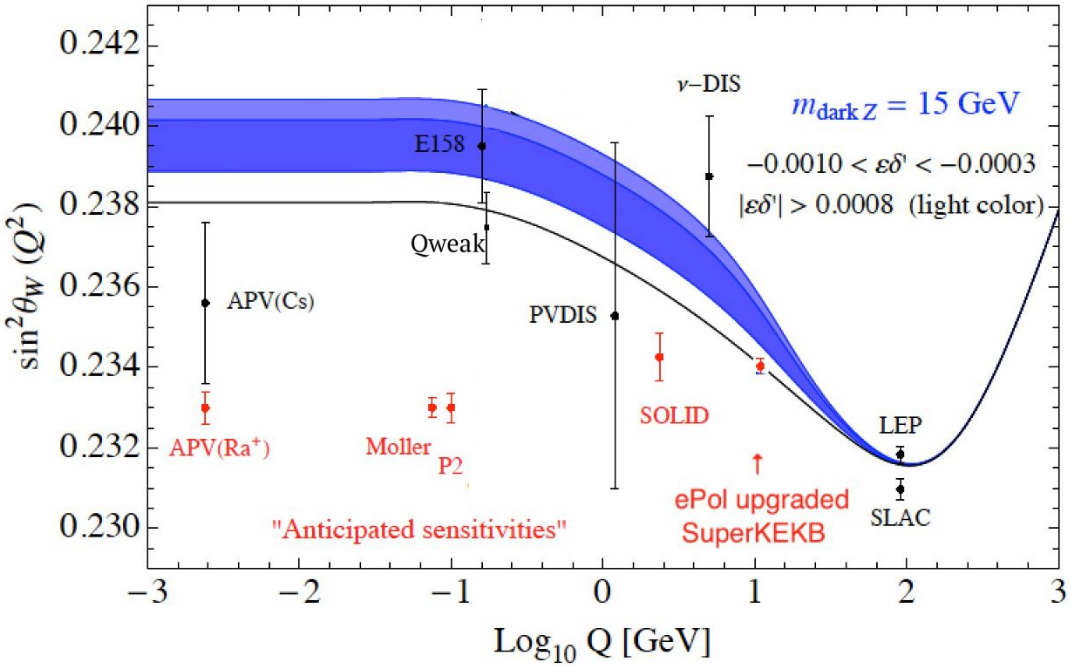


Red bars show expected sensitivity of future experiments. position arbitrary.

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

- 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*

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

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

- Current bound for tau is $\mathcal{O}(10^{-2})$
- Chiral Belle reach with 50ab^{-1} is $\mathcal{O}(10^{-5})$
- Starts to probe interesting parameter space

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

Beam Polarization Requirements

Design goal is to achieve:

70% 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 bunch polarization
- Precision average beam polarization measurement

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

Beam Polarization Requirements

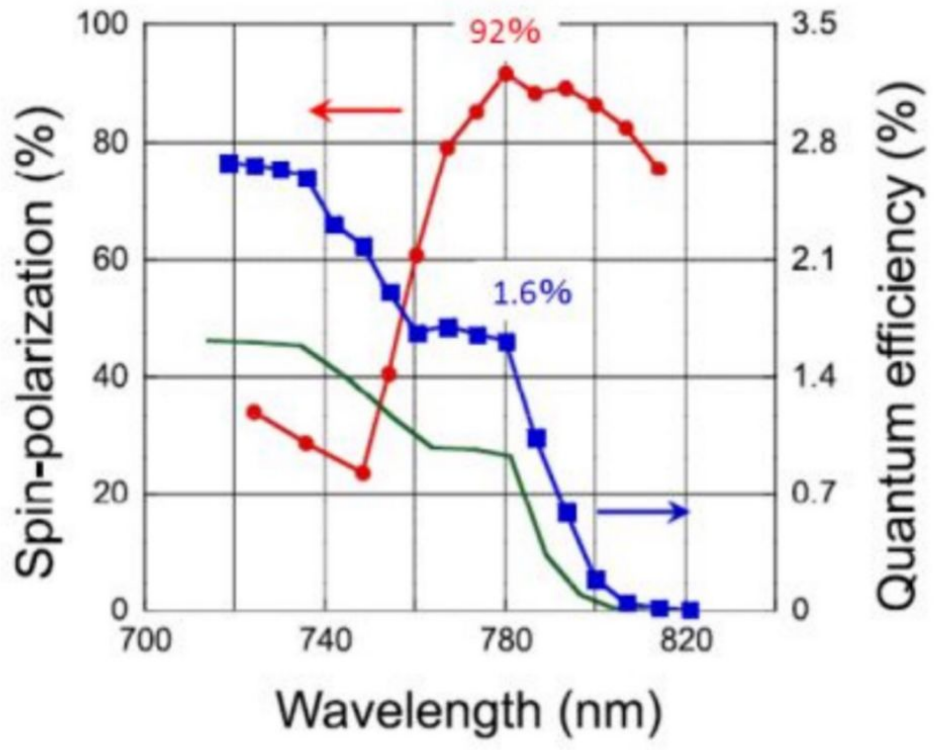
- Low Emittance Source
- Spin Rotators
- Compton Polarimeter
- Polarimetry from data

Circular polarized laser on GaAs cathode results in 92% polarized electrons with 1.6% QE

Challenge in accelerating electrons due to large band gap

Working on application of Negative-Electron Affinity (NEA) film to lower the band gap

Test cathodes in production at Hiroshima University

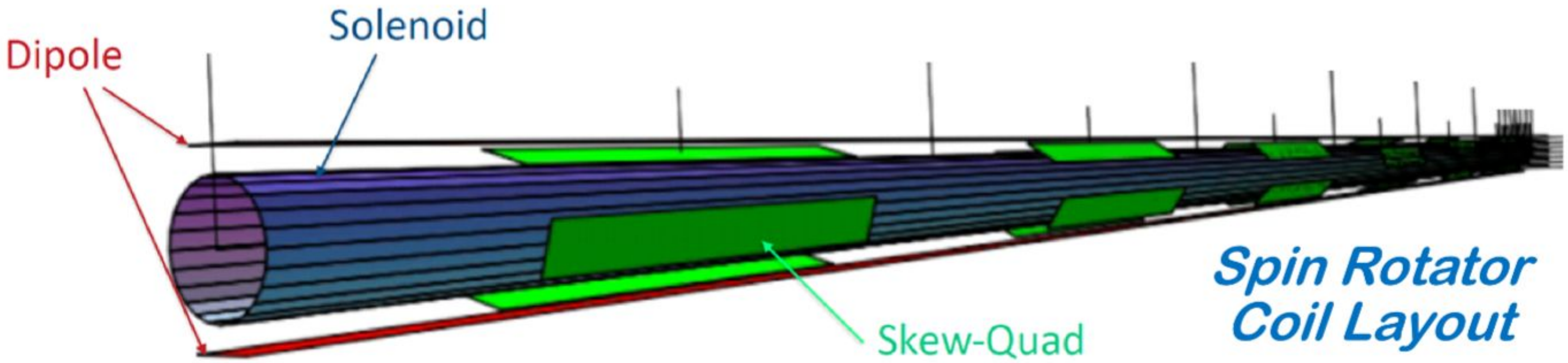


Beam Polarization Requirements

- Low Emittance Source
- Spin Rotators
- Compton Polarimeter
- Polarimetry from data

Bending magnets on either side of the detector can be replaced with a combined function magnet

Proposed by Argonne National Laboratory (ANL), Magnet production intended for BNL, optics matching done at UVic

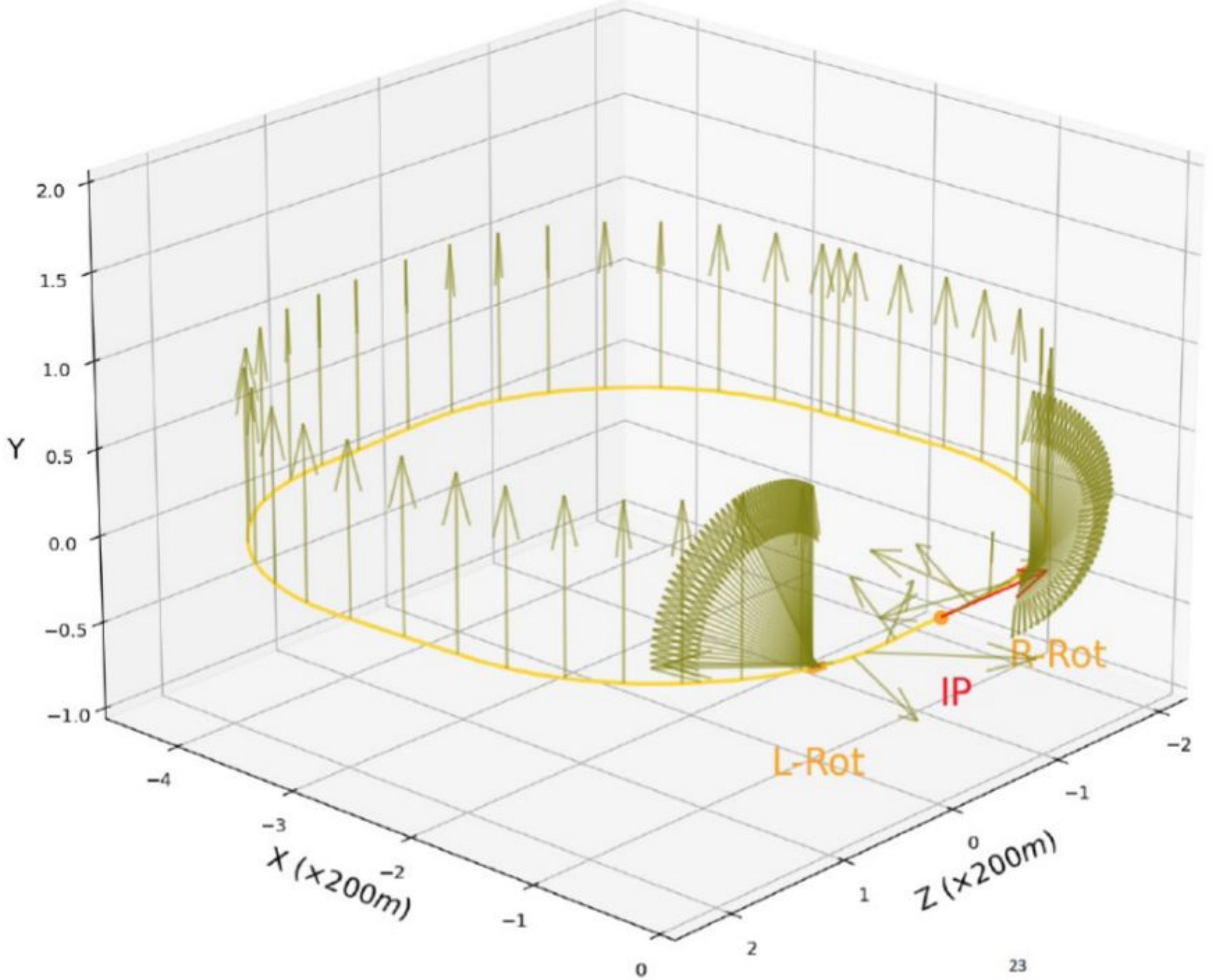


Beam Polarization Requirements

- Low Emittance Source
- Spin Rotators
- Compton Polarimeter
- Polarimetry from data

BMAD software used to model effect of rotators on spin

Achieves near 100% conversion of transverse polarization to longitudinal polarization at IP



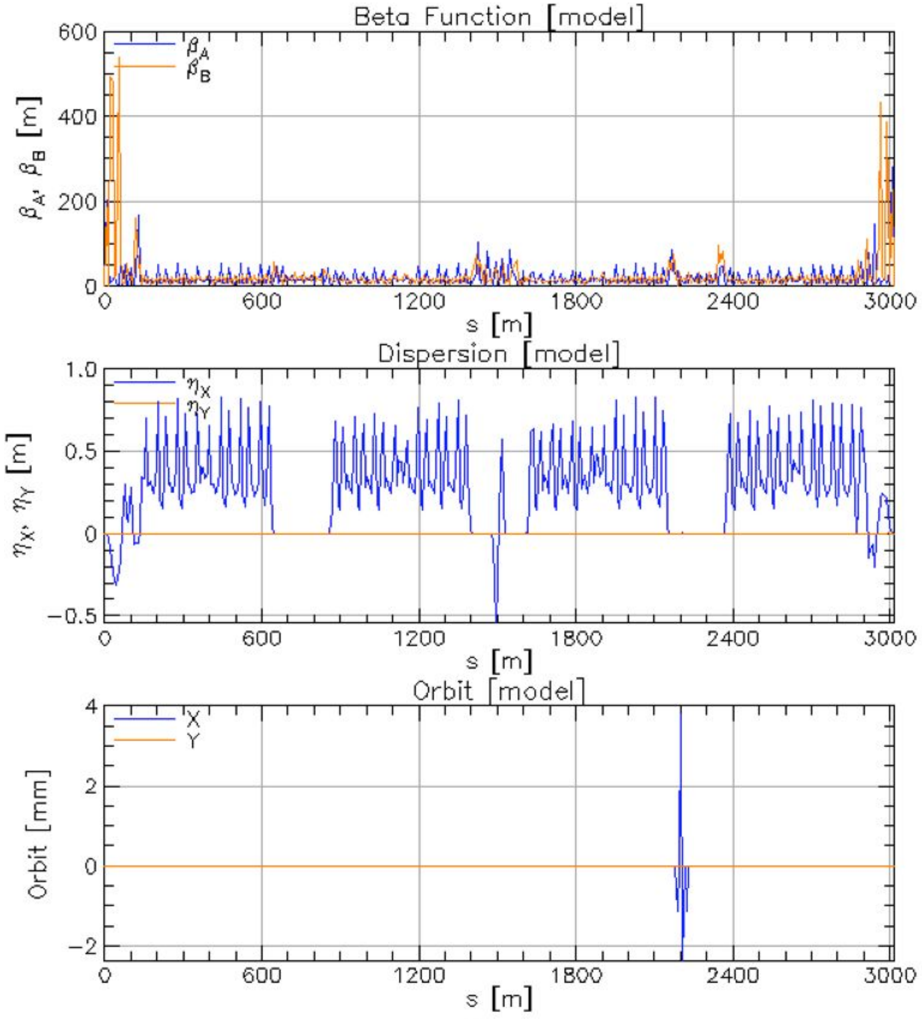
Beam Polarization Requirements

- Low Emittance Source
- Spin Rotators
- Compton Polarimeter
- Polarimetry from data

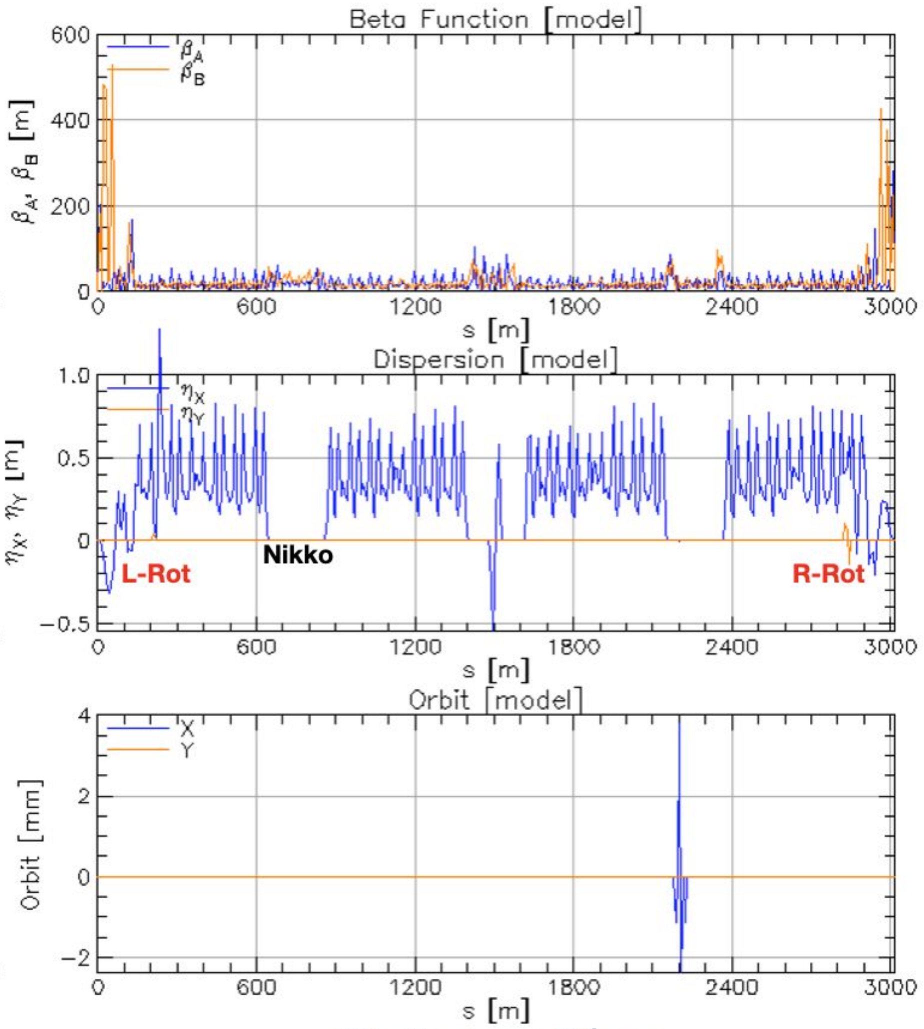
Addition of rotators has no effect on rest of beam after tuning

effectively “invisible”

Work done by UVic student Yuhao Peng



Original Ring



Rotator Ring

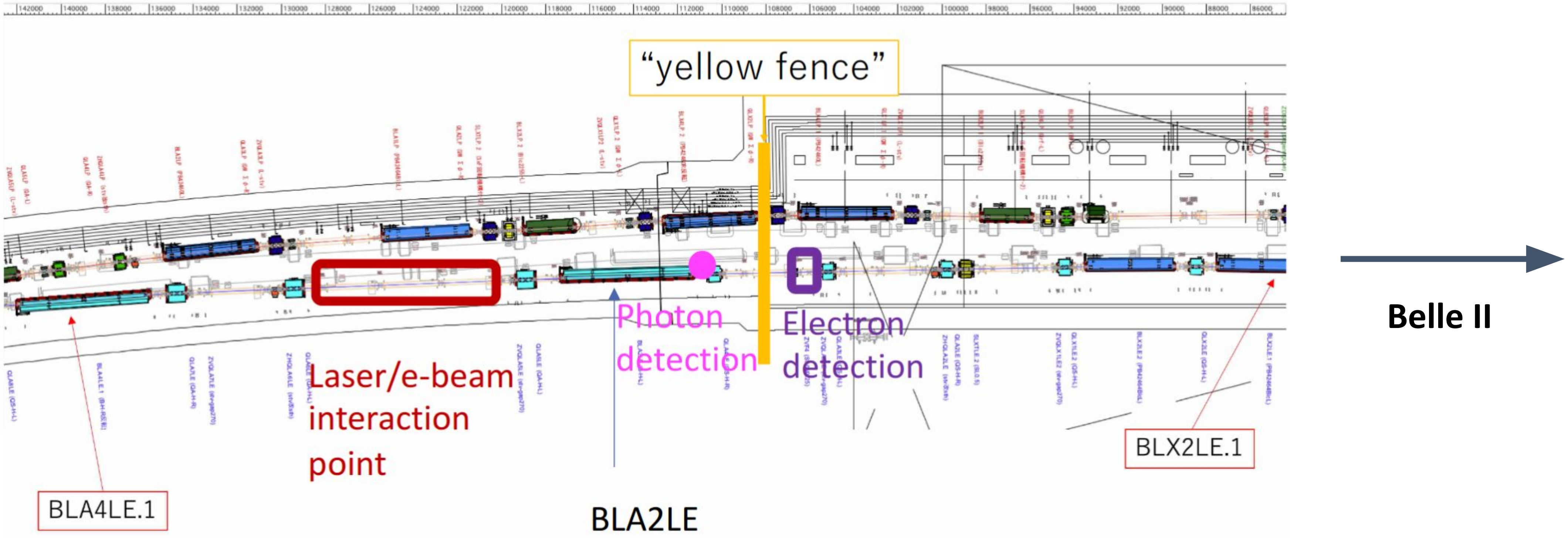
Beam Polarization Requirements

- Low Emittance Source
- Spin Rotators
- Compton Polarimeter
- Polarimetry from data

Polarimeter being worked on by LAL Orsay and U. Manitoba groups

Working on measurements from both photon and electron detection

Identified location on beam line where >85% of longitudinal polarization is present



Polarimetry from Data

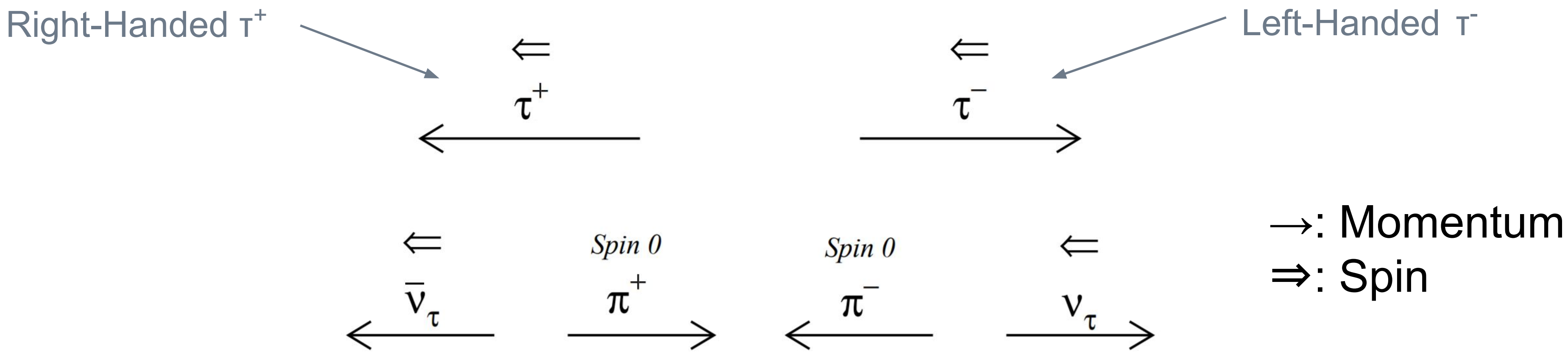
Compton polarimeters, have an uncertainty associated with modelling the spin transport from the polarimeter to the interaction point (IP)

By using Tau Polarimetry we can extract the average beam polarization directly from the data at the IP

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

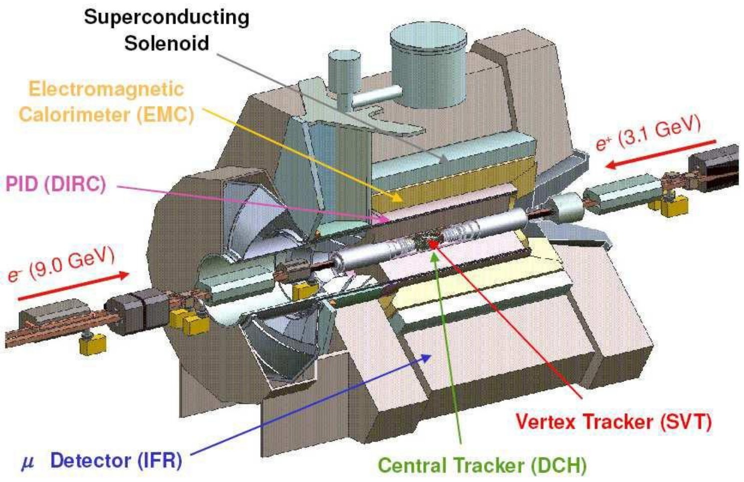
Note: cosθ defined as the polar angle of the τ^- with respect to the electron beam. At $\mathcal{O}$(10 GeV) second term is $\mathcal{O}(10^{-3})$

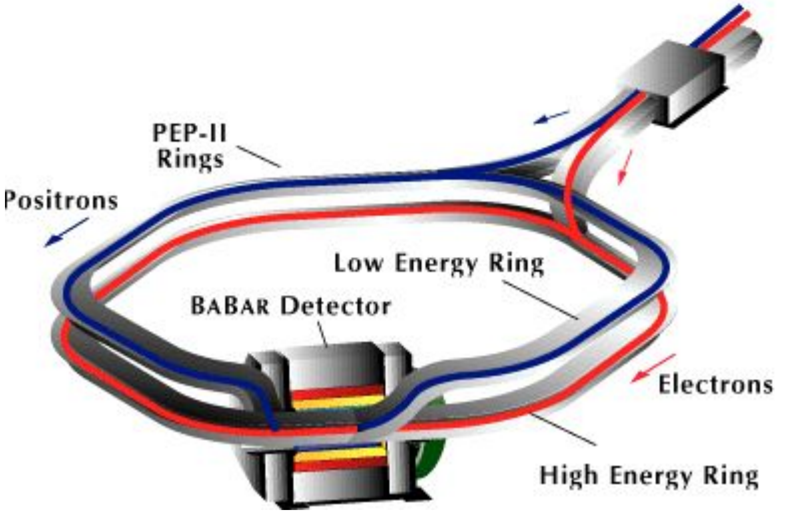
Tau polarization information can be extracted from the kinematics of the tau decay



BaBar and PEP-II

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

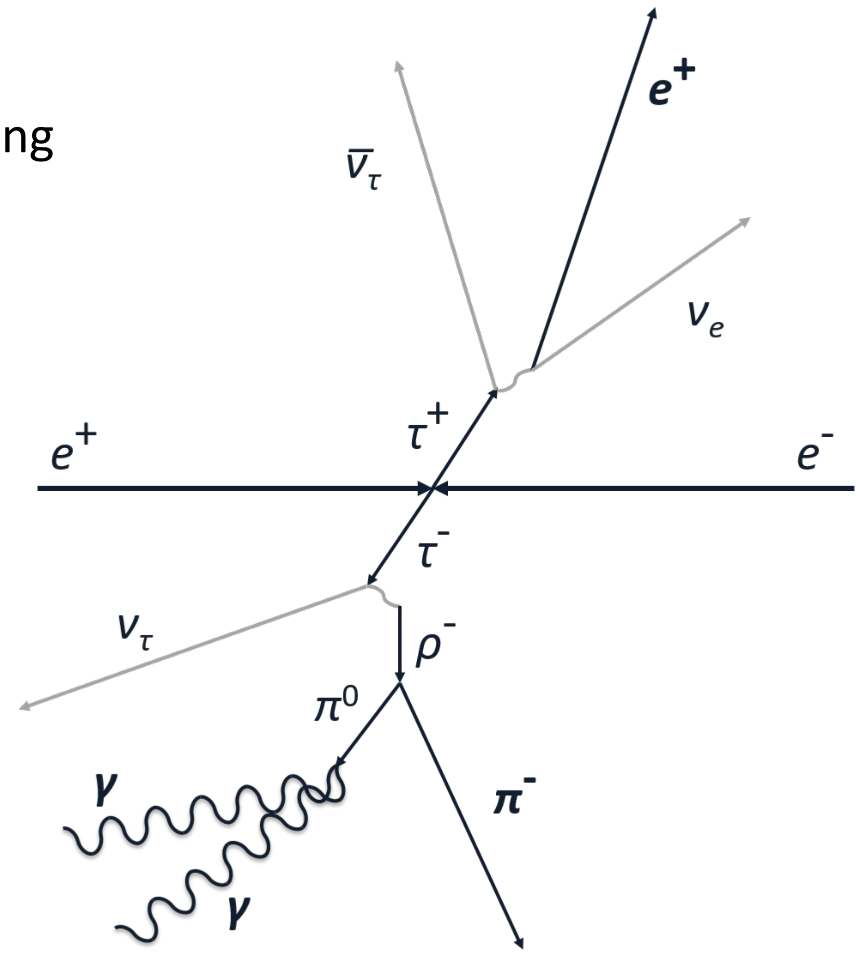




- Over 6 run periods *BaBar* collected 432 fb^{-1} of data on the Υ(4S) resonance (10.58 GeV)
- PEP-II collided electrons and positrons together at 9.0 and 3.1 GeV
- No beam polarization is expected at PEP-II
- Similarities between *BaBar* and Belle II detectors means results should be comparable

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
- 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, (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
- Angular cuts and a minimum p_T of 1.2 GeV reduce two photon and Bhabha contamination

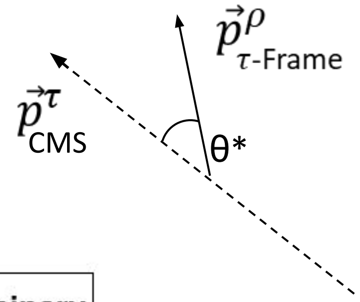


- Achieve a 99.7% pure tau-pair sample (0.3% Bhabha)
- 90% of selected events contain a $\tau^{\pm} \rightarrow \pi^{\pm}\pi^{0}\nu_{\tau}$ decay
  - 8% a1 decays, 2% other hadronic

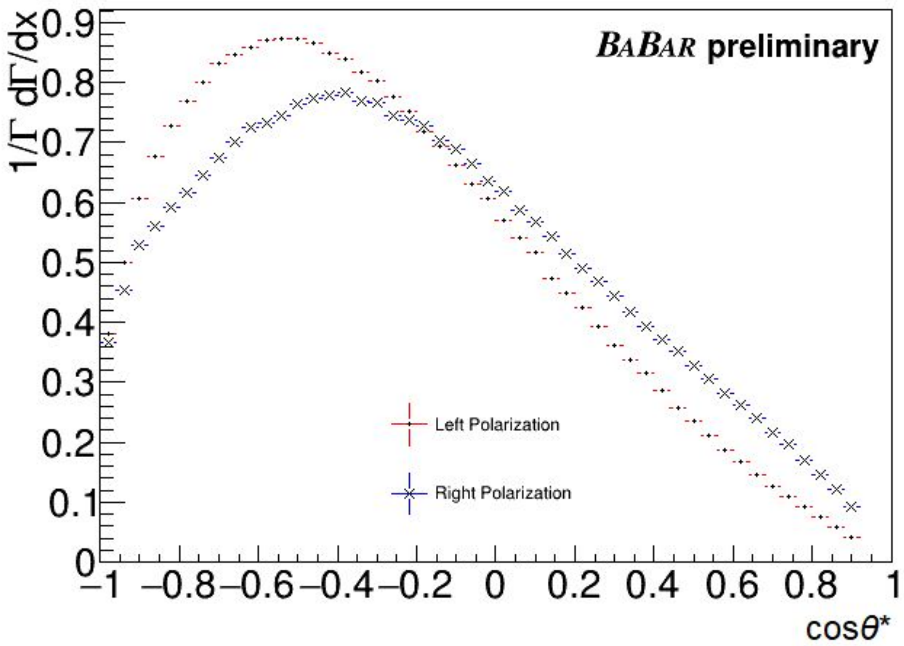
Polarization Observables

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

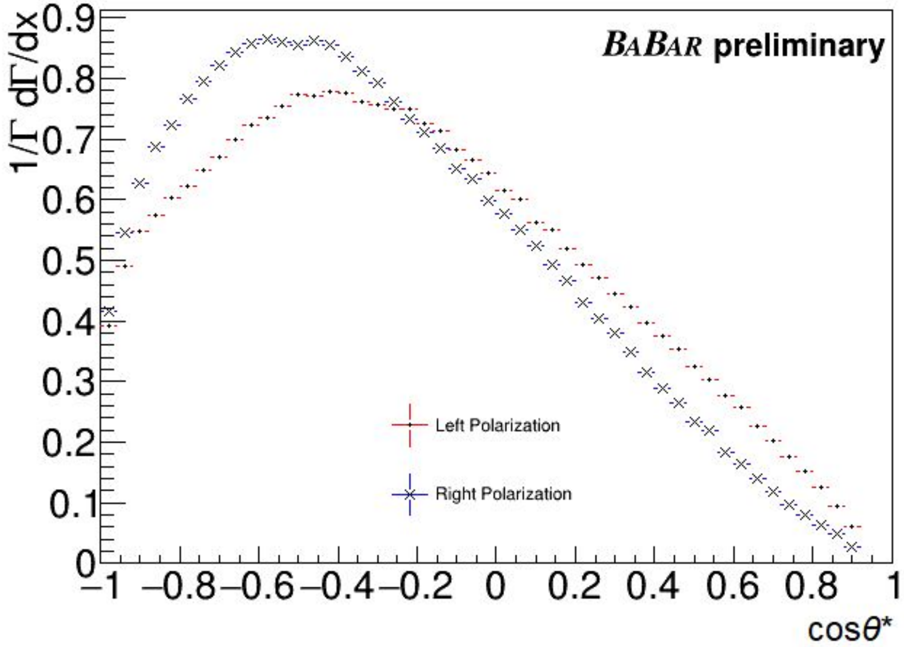
$$\cos\theta^* = \frac{2z - 1 - m_\rho^2/m_\tau^2}{1 - m_\rho^2/m_\tau^2} \qquad z \equiv {E_\rho}/{E_{\text{beam}}}$$



cosθ<0



cosθ>0



[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

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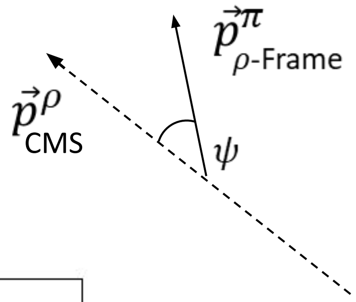
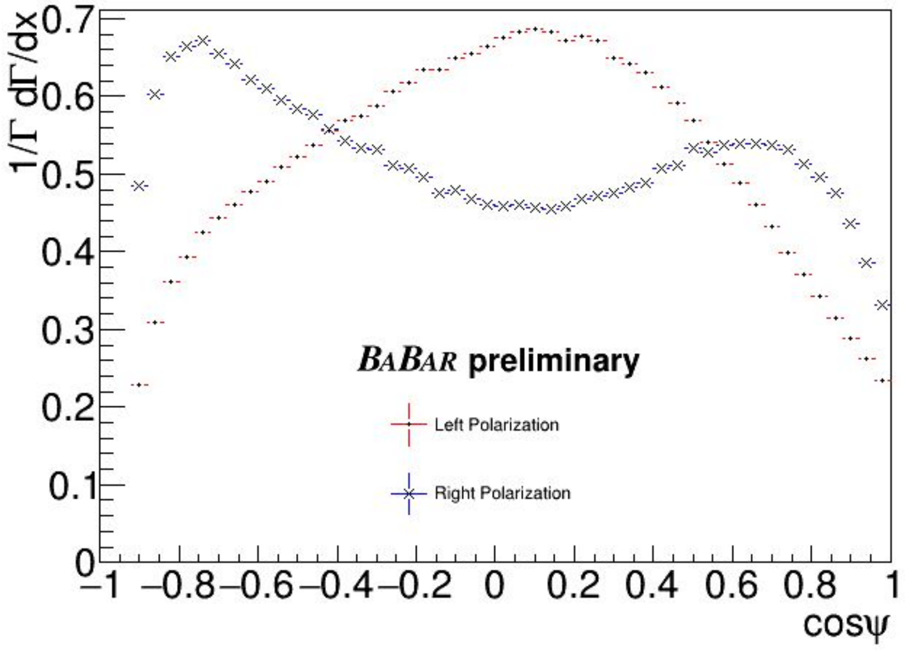
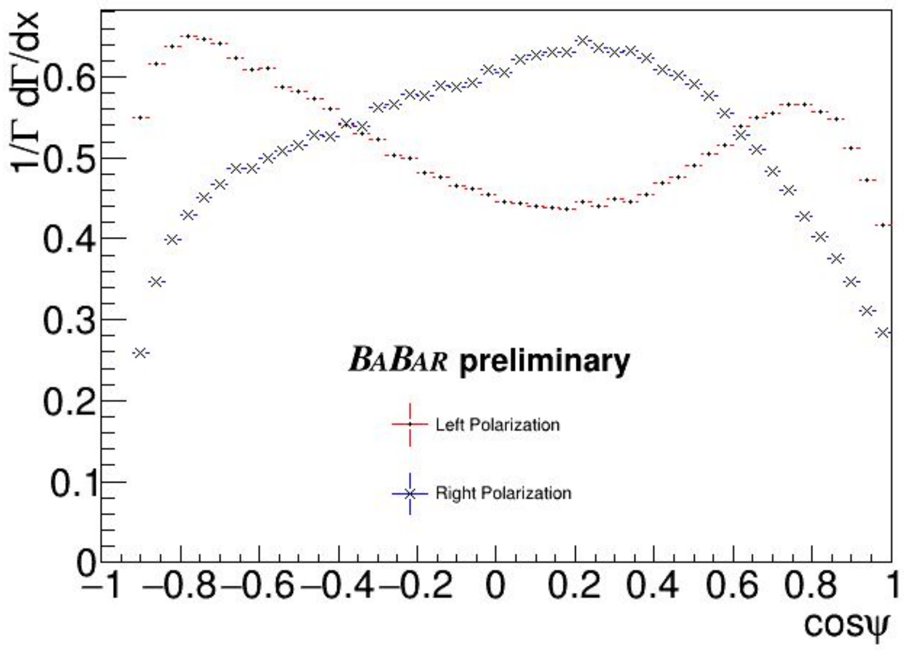
$$\cos\psi = \frac{2x-1}{\sqrt{1-4m_\pi^2/m_\rho^2}} \qquad x \equiv E_\pi / E_\rho$$



cosθ<0



cosθ>0



[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 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*, cosψ, and cosθ
- Tau MC was produced for a left and right polarized electron beam
- The data is fit as a linear combination of the histograms

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

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

a_l	0.499
a_r	0.499
a_b	3.8×10^{-5}
a_m	1.4×10^{-3}
a_u	3.8×10^{-4}
a_c	4.8×10^{-5}

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

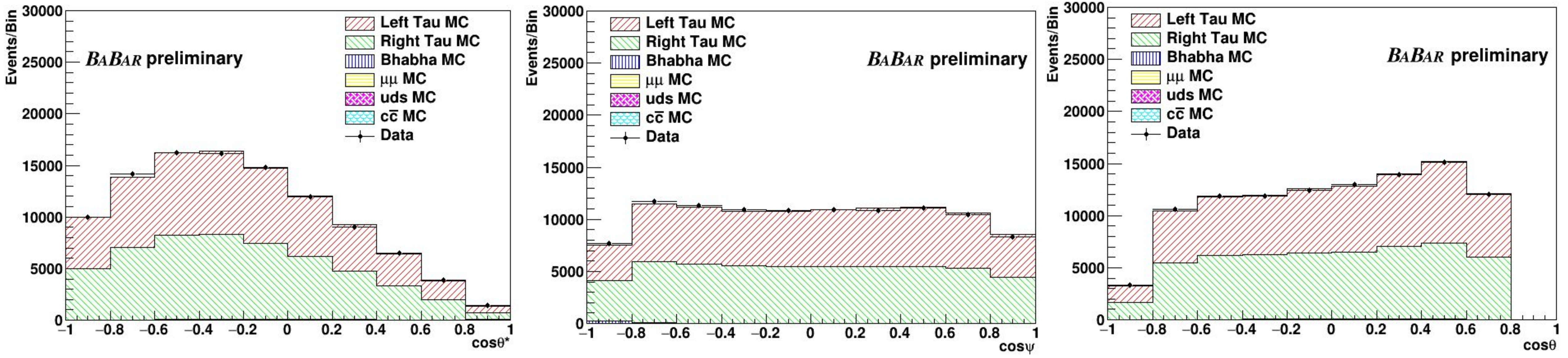
a_i = fit contribution

[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

Fit Result

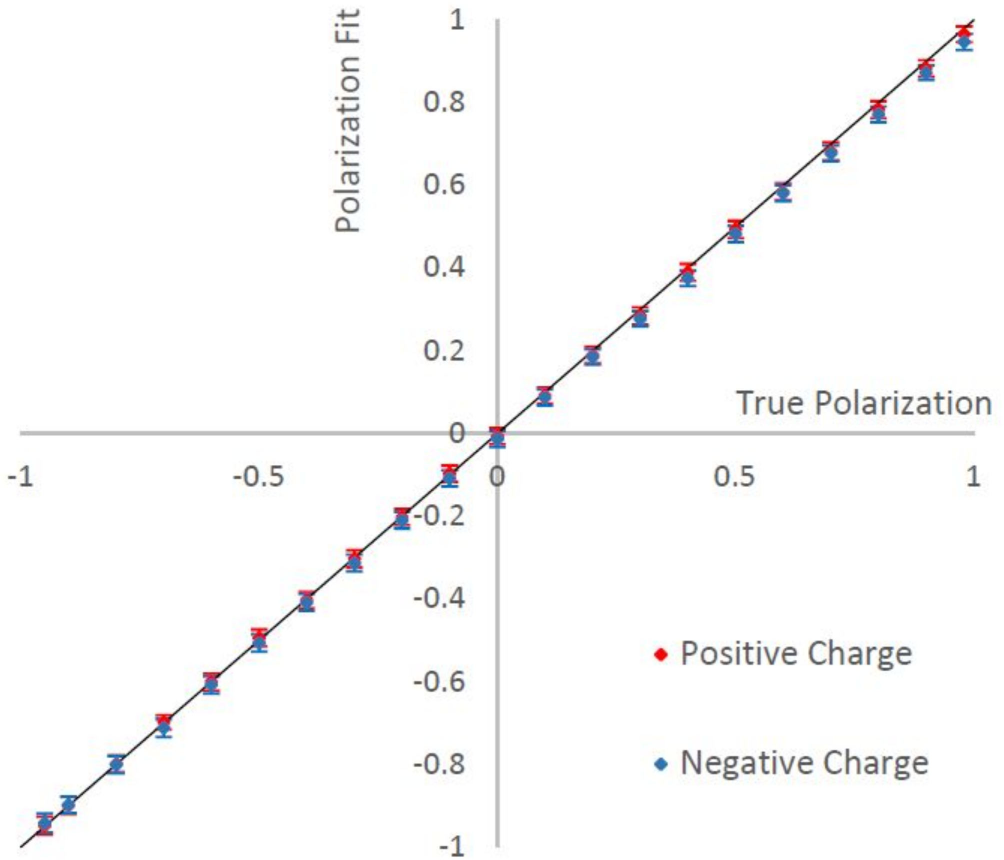
Sample	Positive	Negative	Total
Run 3 (32.28 fb^{-1})	0.0277±0.0177	-0.0031±0.0177	0.0123±0.0125

- Fit result projected to each of the fit variables
- Result from preliminary Run 3 fit, Negative charges
- <P>=-0.0031, 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



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
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**

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
- Currently processing rho vs muon selection 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

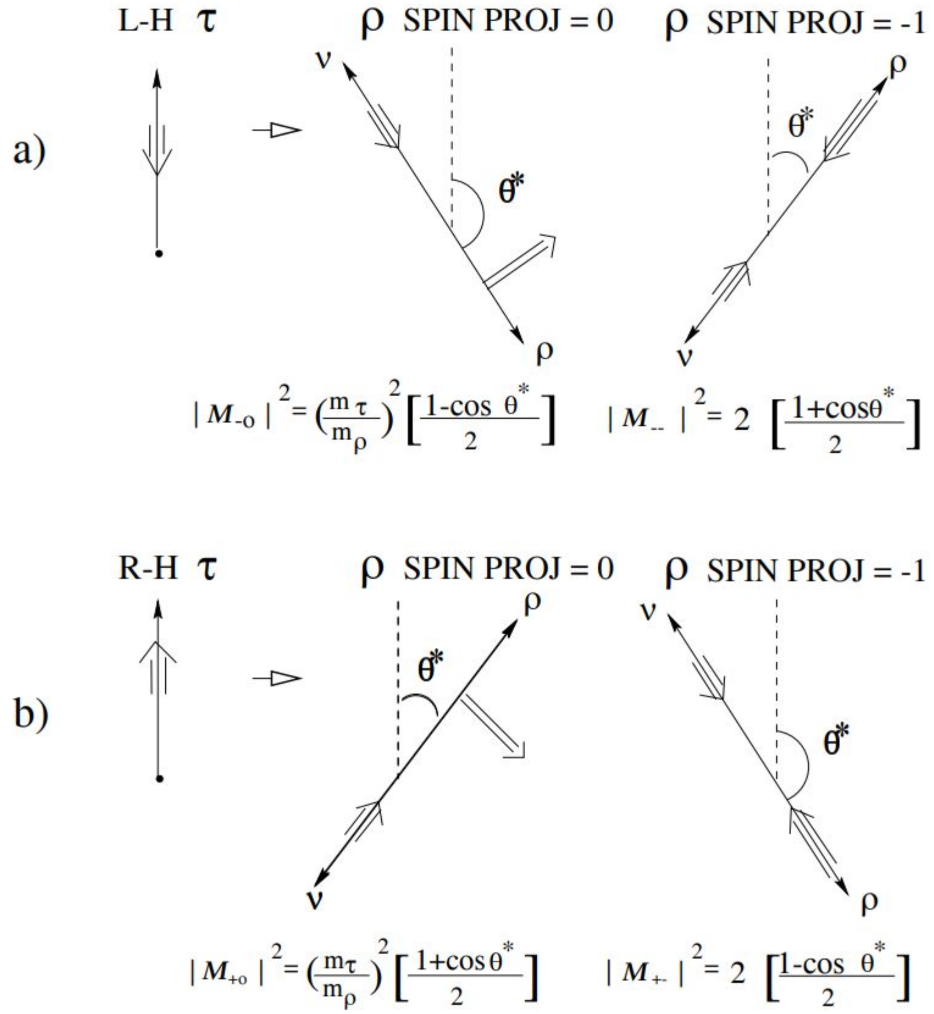
- For 70% polarized electron beam, L^-=0.85 R^-=0.15
- Average beam polarization is $\frac{0.425-0.075}{0.425+0.075}$=0.7

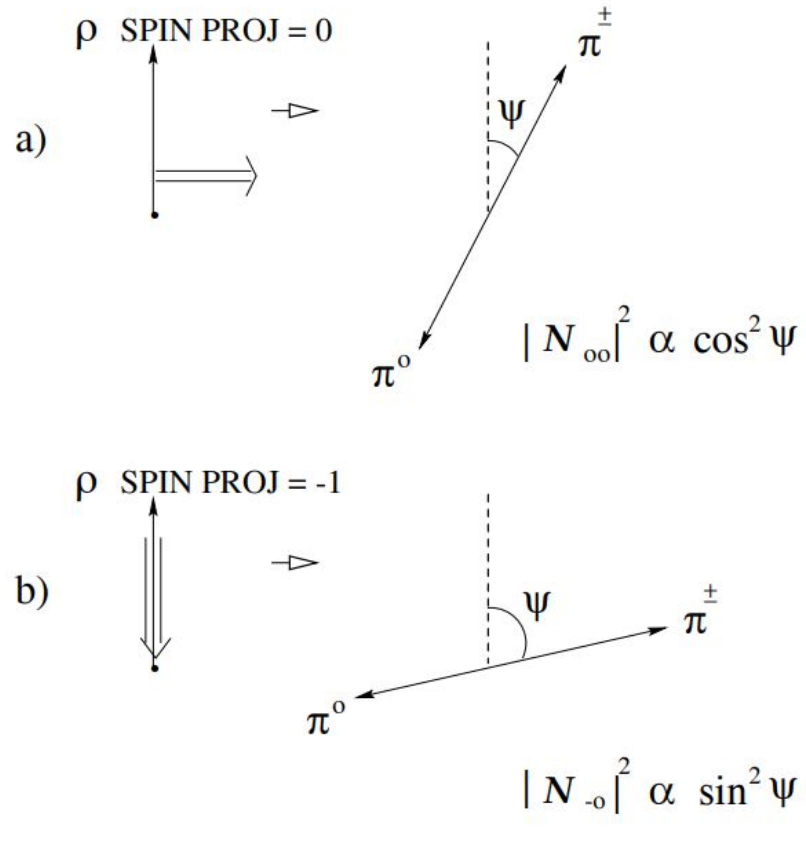
$e^+\backslash e^-$	L^-	R^-
L^+	0.49	0.21
R^+	0.21	0.09

- 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

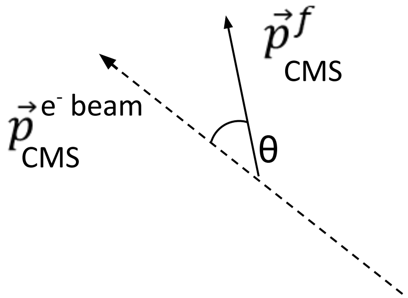
Rho Spin Analysis

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





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


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