

# Precision $e^-$ beam polarimetry

*at an  $e^+e^-$  B-factory using tau-pair events*



**BABAR**

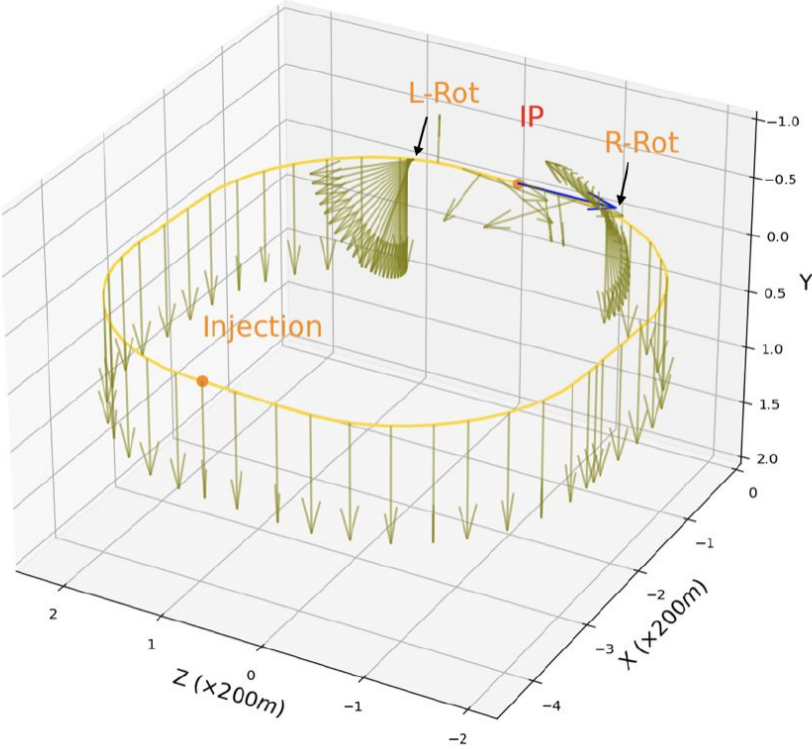
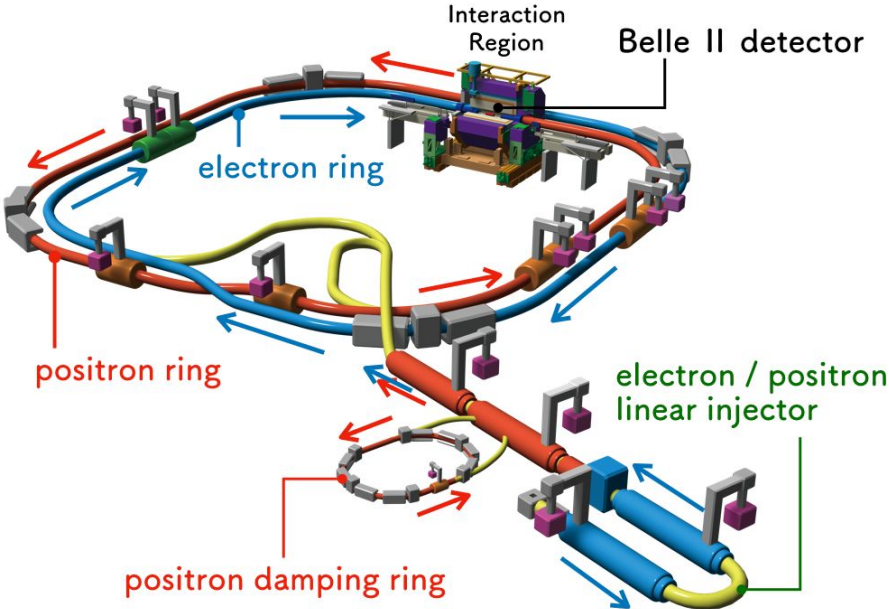
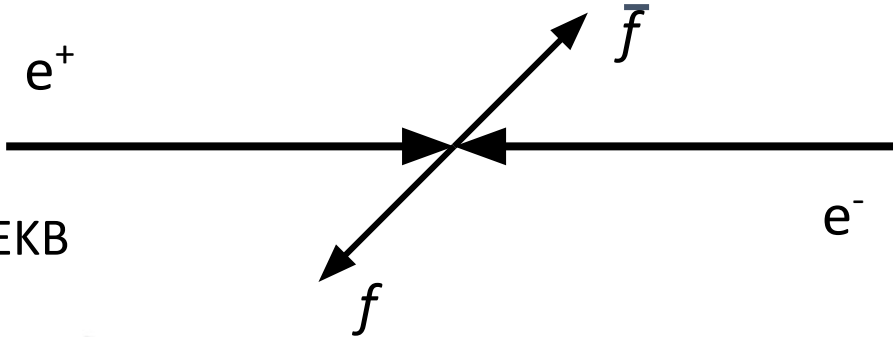
Caleb Miller  
*on behalf of BaBar*



Lake Louise 2024

# Motivation - Chiral Belle

- Beam polarization is being considered as a future upgrade to SuperKEKB



- Plan is to achieve a 70% polarized  $e^-$  beam
- Measure the polarization to within 0.5%
- Enables a wide physics program

# Motivation - Physics

- 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  $e, \mu, \tau, c, b$ . For Born level s-channel process:

Production cross-sections for (L)eft and (R)ight polarization

Average beam polarization

$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \frac{4}{\sqrt{2}} \left( \frac{G_{FS}}{4\pi\alpha Q_f} \right) \underbrace{g_A^e g_V^f}_{\text{Axial and Vector neutral current couplings}} \langle P \rangle \propto T_3^f - 2Q_f \underbrace{\sin^2 \theta_W}_{\text{Weak mixing angle}}$$

# Motivation - Physics

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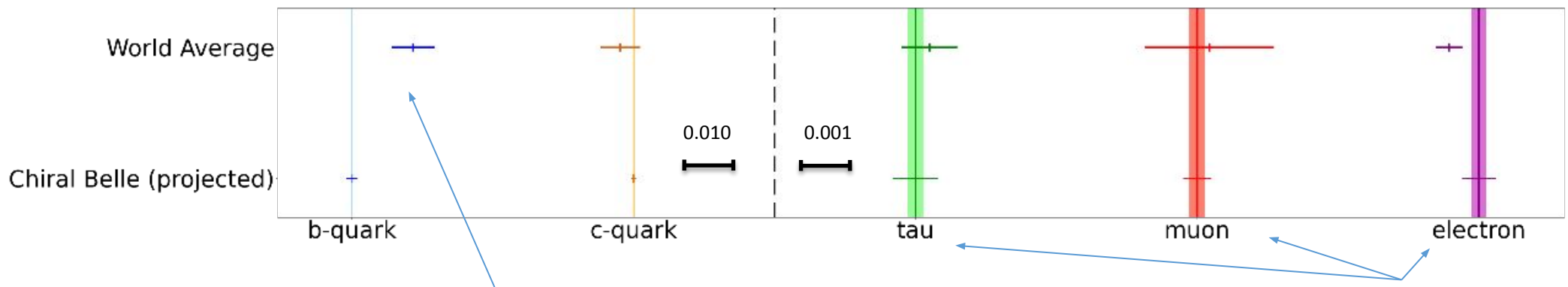
	<i>Standard Model</i>	<i>World Average</i>	<i>Chiral Belle 40ab<sup>-1</sup></i>
Fermion			
b-quark	-0.3437±0.0001	-0.3220 ±0.0077	0.0020(4x improvement)
c-quark	0.1920±0.0002	0.1873 ±0.0070	0.0010(7x improvement)
Tau	-0.0371±0.0003	-0.0366 ±0.0010	0.0008
Muon	-0.0371±0.0003	-0.03667±0.0023	0.0005(4x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

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



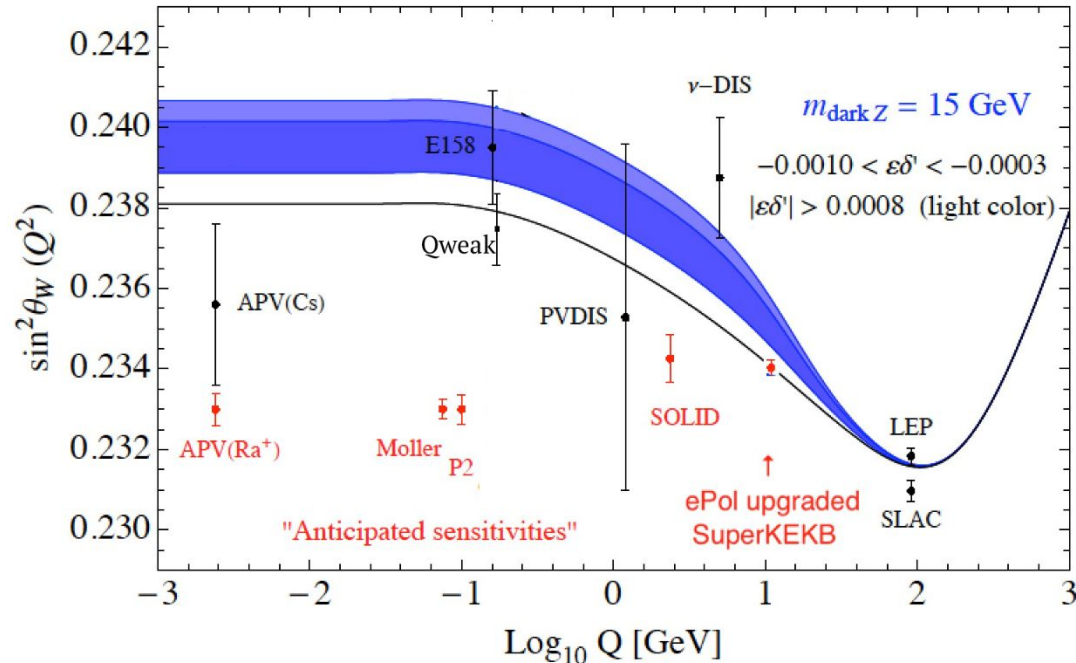
2.8 $\sigma$  between SM and WA

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

# Motivation - Physics

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

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

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

# Beam Polarization Motivation

The physics projections assume a 70% polarized  $e^-$  beam and requires measuring the polarization to within 0.5% to meet projections

Compton polarimeters can precisely measure the polarization, but in a location removed from the main detector, this comes with 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**

Chiral Belle White Paper  
<https://arxiv.org/abs/2205.12847>

# Tau Polarimetry

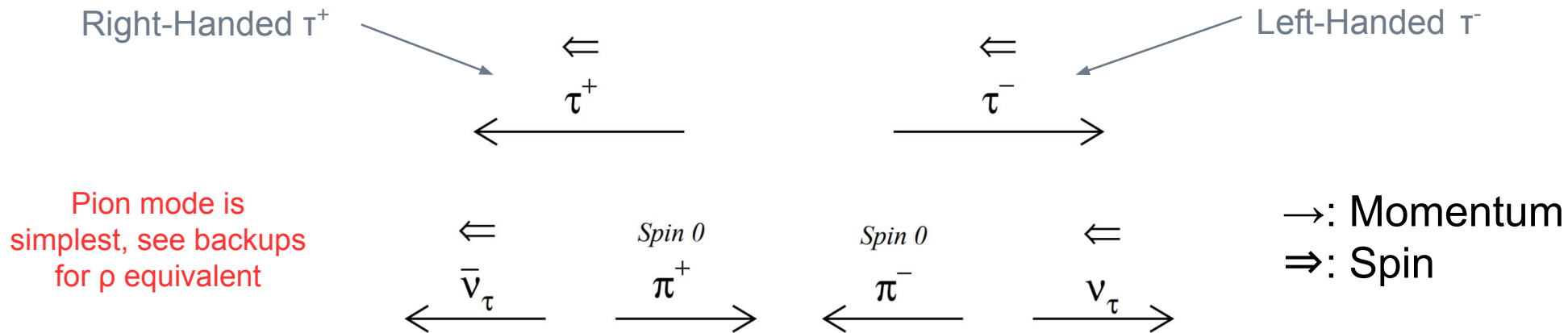
- The polarization of tau's ( $P_\tau$ ) produced in  $e^+e^-$  collisions at 10.58 GeV is related to the electron beam polarization ( $P_e$ ) through:

$$P_{\tau^-} = P_e \underbrace{\frac{\cos \theta}{1 + \cos^2 \theta}}_{\text{EM term}} - \underbrace{\frac{8G_F s g_V^\tau}{4\sqrt{2}\pi\alpha} \left( g_A^\tau \frac{|\vec{p}|}{p^0} + 2g_A^e \frac{\cos \theta}{1 + \cos^2 \theta} \right)}_{\text{Electroweak correction } \sim 0.003}$$

Note:  $\cos\theta$  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

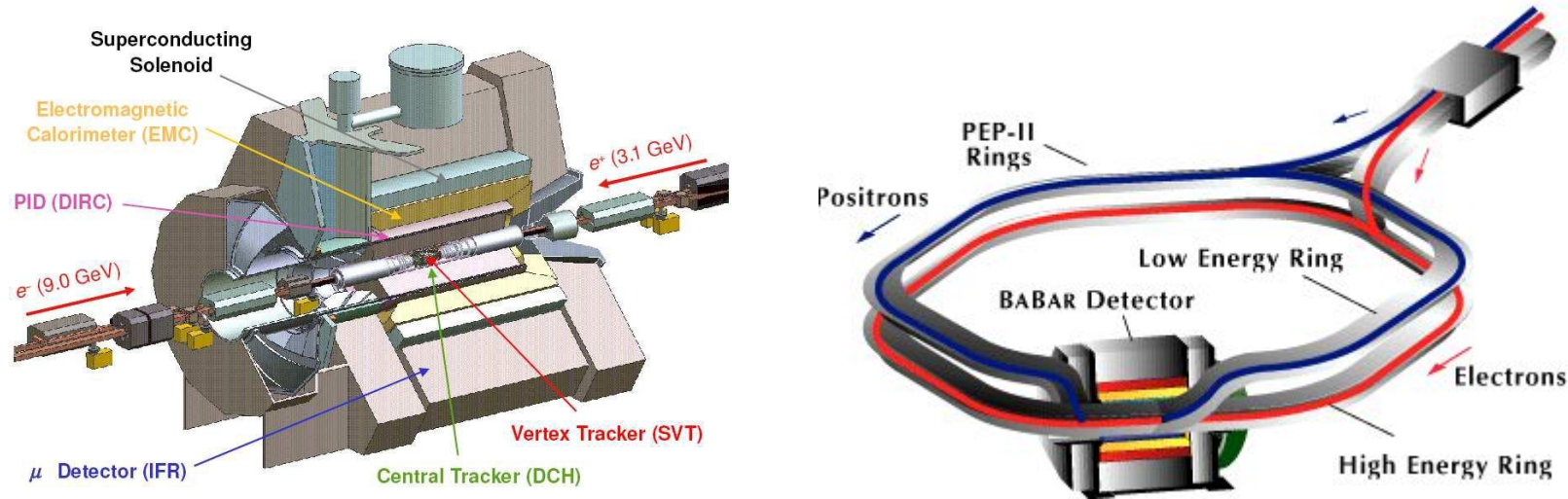
Assumes only SM physics





# BABAR and PEP-II

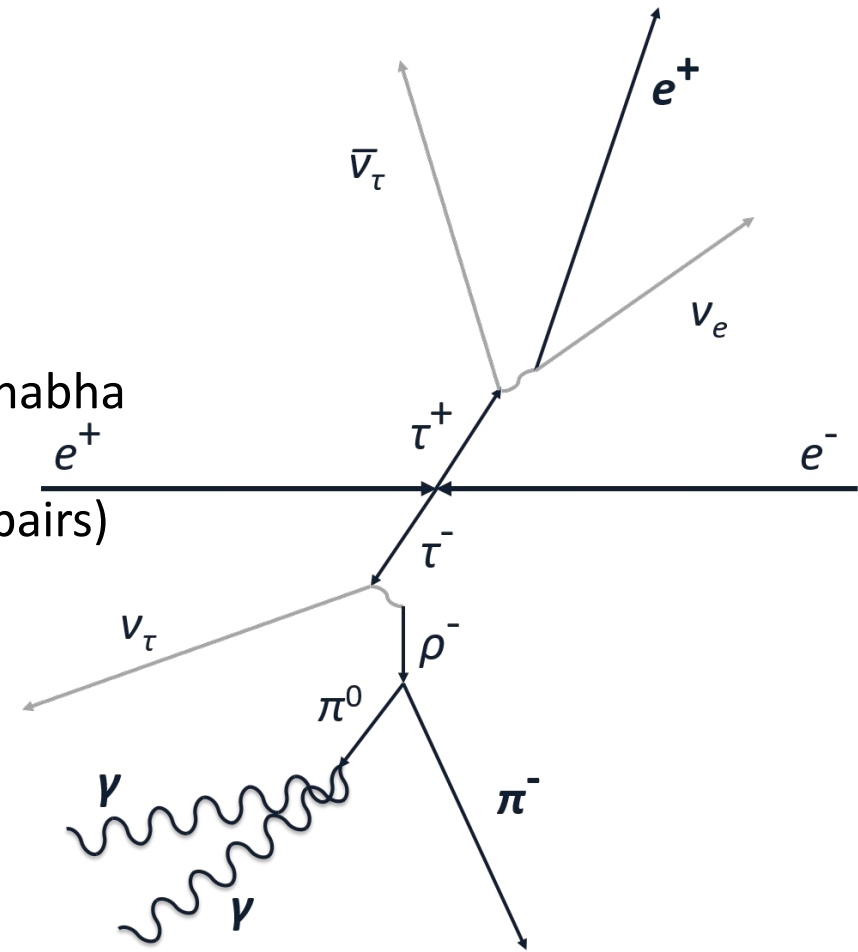
BABAR and PEP-II operated at SLAC from 1999-2008



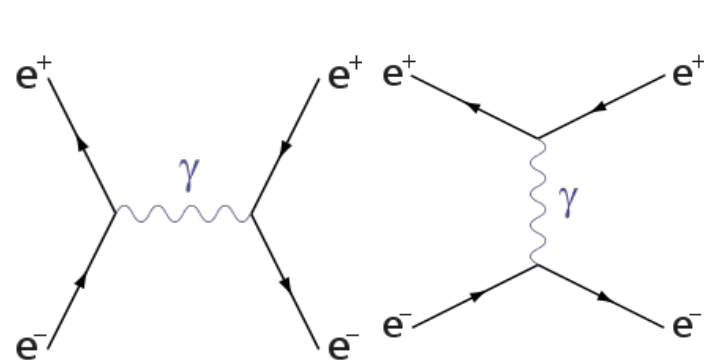
- Similar design of *BABAR* and Belle II also us to benchmark the technique on *BABAR*
  - Statistical sensitivity
  - Dominant systematic sources
- Over 6 run periods *BABAR* collected  $432 \text{ fb}^{-1}$  of data on the  $\Upsilon(4S)$  resonance
- PEP-II collided electrons and positrons together at 9.0 and 3.1 GeV
- No beam polarization is expected at PEP-II

# Tau Event Selection

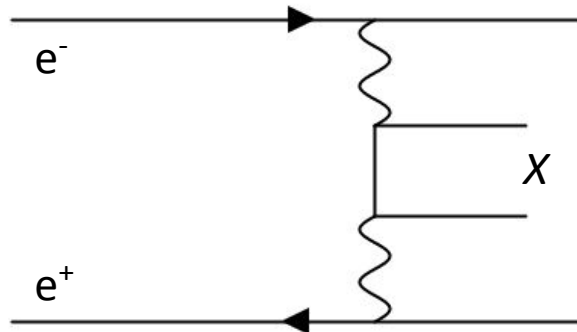
- Selected tau events in a 1v1 topology, ( $\rho$  vs.  $e$  or  $\mu$ )
  - $\tau$  to  $\rho$  has large branching fraction, lepton for clean tag
- Signal candidates are defined as a charged particle with a  $\pi^0$
- $q\bar{q}$  events are eliminated with the lepton requirement
- Angular cuts and a minimum  $p_T$  of 350 MeV reduce two photon and Bhabha contamination
- Results in a 99.9% pure tau-pair sample (0.05% Bhabha, 0.05% muon pairs)
- 88% of selected events contain a  $\tau^\pm \rightarrow \pi^\pm \pi^0 \nu_\tau$  decay
  - 12% other hadronic decays
- ~5.5 Million tau-pairs in final selection



Bhabha process



Two-photon process

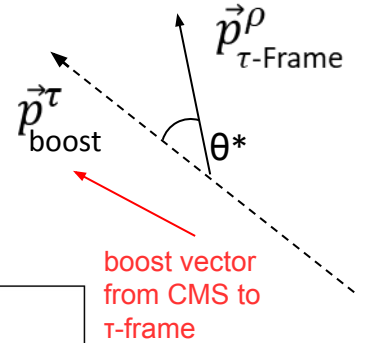


# Polarization Observables

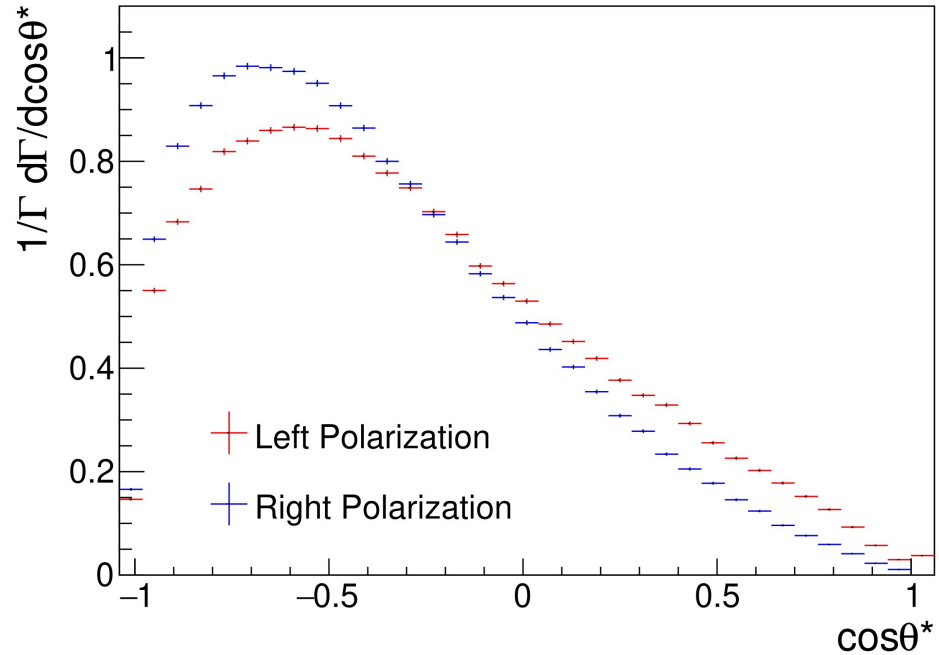
- Polarization sensitivity in a rho decay is maximized by analyzing two angular variables<sup>2</sup> in addition to  $\cos\theta$

$$\cos\theta^* = \frac{2z - 1 - m_\rho^2/m_\tau^2}{1 - m_\rho^2/m_\tau^2}$$

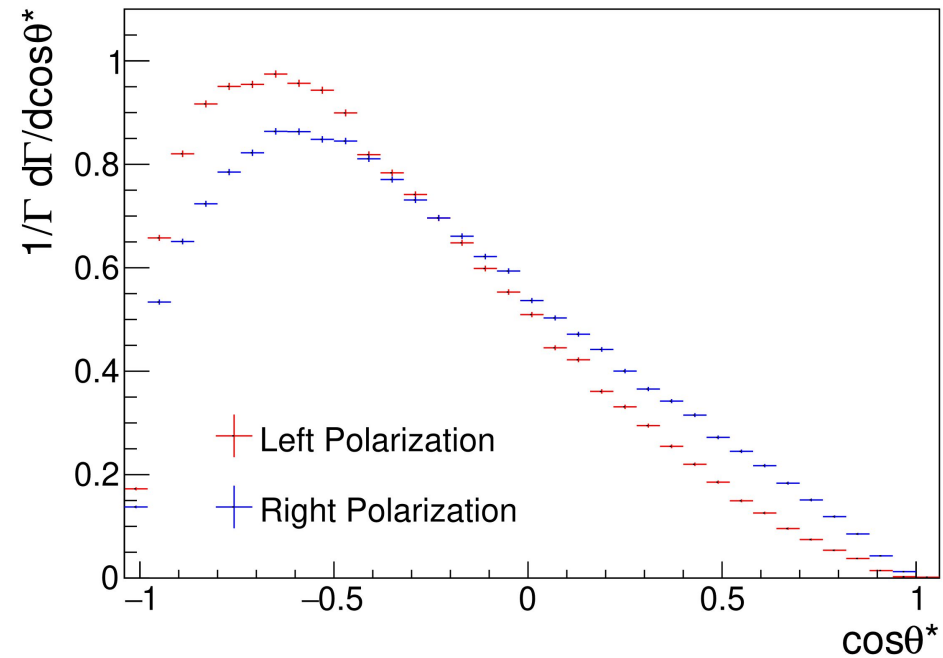
$$z \equiv E_\rho / E_{\text{beam}}$$



$\cos\theta < 0$



$\cos\theta > 0$



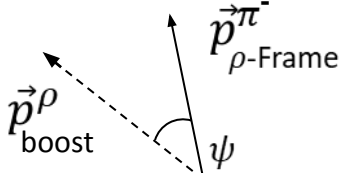
<sup>2</sup>K. Hagiwara, A. Martin, D. Zeppenfeld, Tau Polarization Measurements at LEP and SLC, Phys. Lett. B. 235, 1998, DOI: 10.1016/0370-2693(90)90120-U

# Polarization Observables

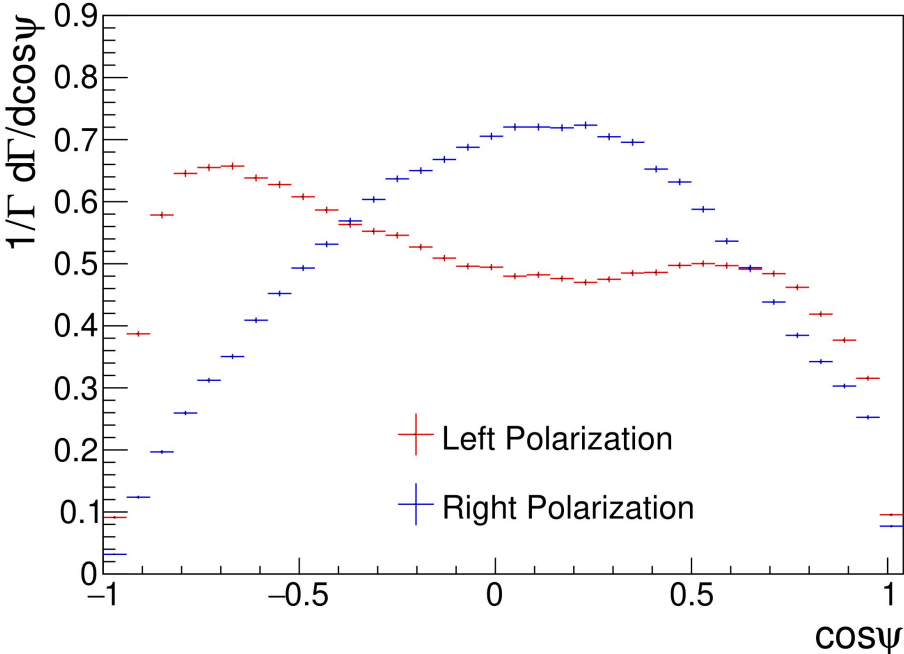
- Polarization sensitivity in a rho decay is maximized by analyzing two angular variables<sup>2</sup> in addition to  $\cos\theta$

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

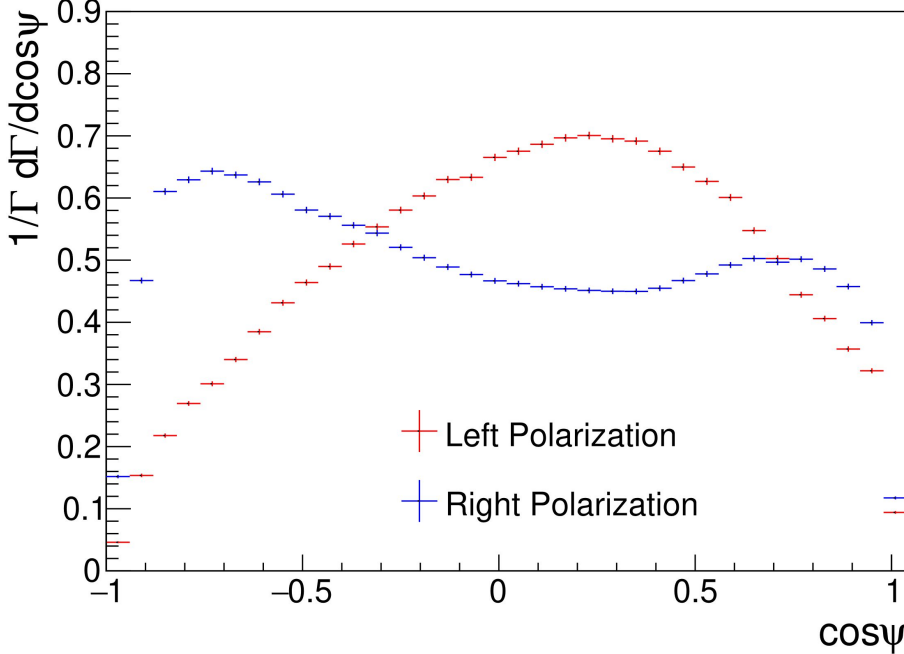
$$x \equiv \frac{E_{\pi^-}}{E_{\rho}}$$



$\cos\theta < 0$



$\cos\theta > 0$



boost vector from CMS to rho-frame

<sup>2</sup>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<sup>3</sup> template fit methodology
- Data and MC is binned in 3D histograms of  $\cos\theta^*$ ,  $\cos\psi$ , and  $\cos\theta$
- Tau MC was produced for a left and right polarized electron beam
- The data is fit as a linear combination of the histograms

Data / sample to be fit

Backgrounds  
B: Bhabha ( $e^+e^-$ ), M:  $\mu^+\mu^-$ , U:  $u\bar{u}, d\bar{d}, s\bar{s}$ , C:  $c\bar{c}$   
(fixed in fit)

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

(L)eft and (R)ight polarized Tau MC  
(floats in fit)

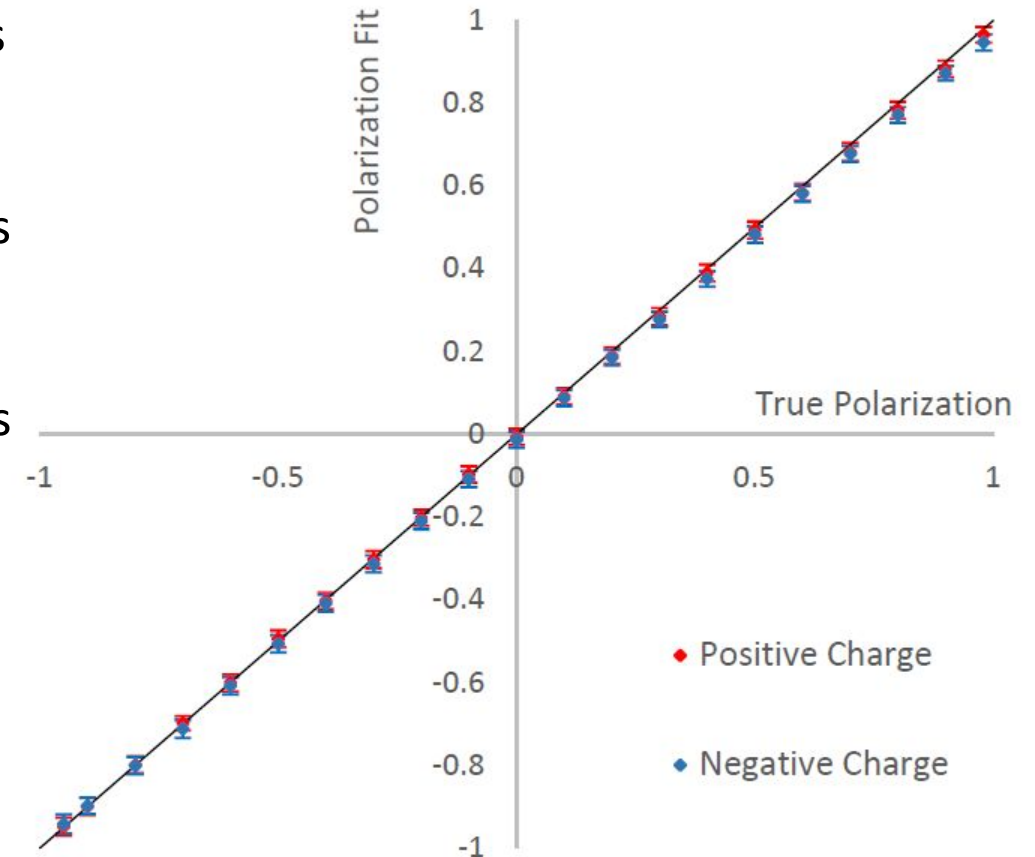
$a_l$	0.499
$a_r$	0.499
$a_b$	$3.8 \times 10^{-5}$
$a_m$	$1.4 \times 10^{-3}$
$a_u$	$3.8 \times 10^{-4}$
$a_c$	$4.8 \times 10^{-5}$

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

<sup>3</sup>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](https://doi.org/10.1016/0010-4655(93)90005-W)

# Beam Polarization MC “Measurement”

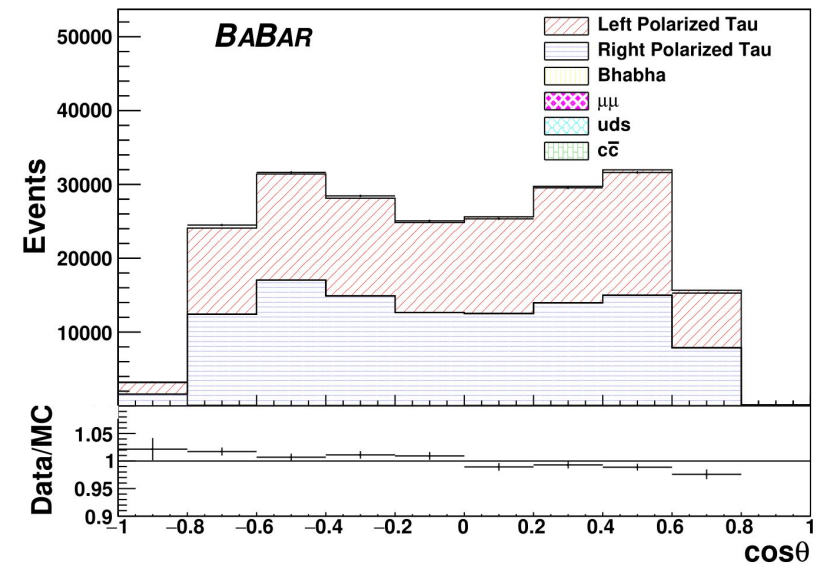
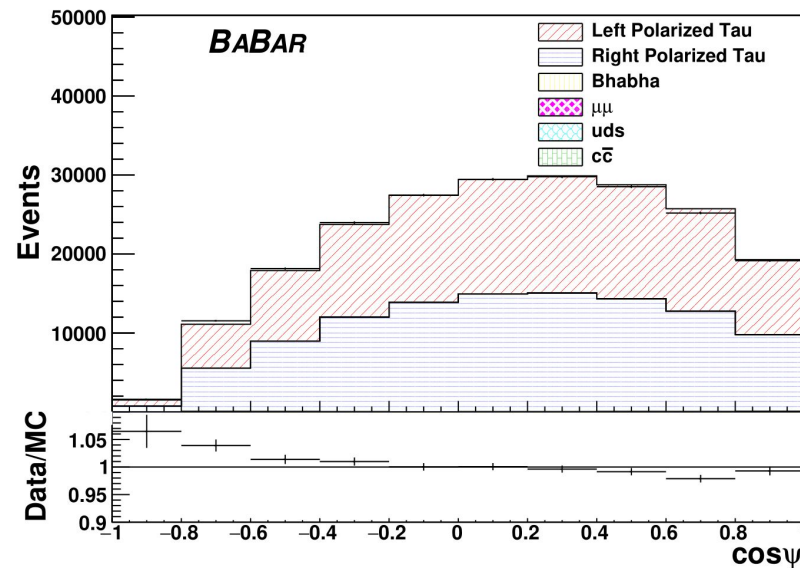
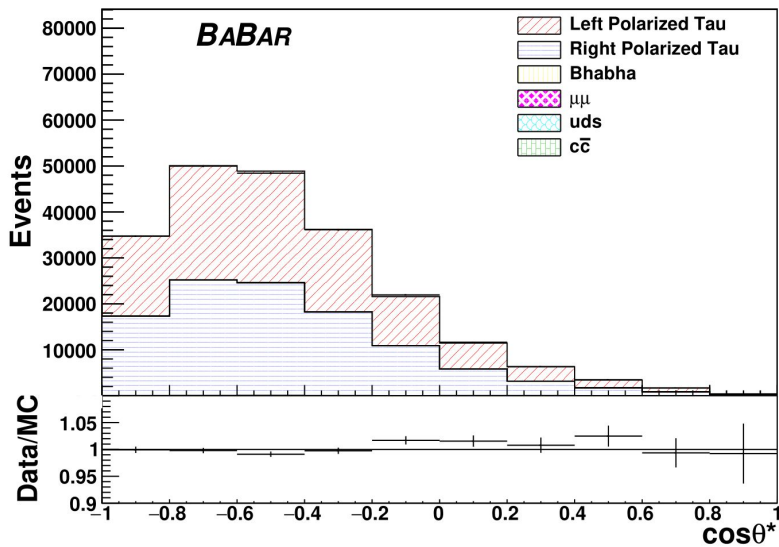
- As PEP-II had no beam polarization we performed MC studies of the polarimetry technique for arbitrary beam polarization states for validation of the method
- This is done by splitting each of the polarized tau MC samples in half
- One half of each is used to perform the polarization fit
- The other 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



# Example Fit Result

Sample	Positive	Negative	Total
Run 3 (32.28 fb <sup>-1</sup> )	0.0151±0.0120	-0.0047±0.0120	0.0048±0.0083

- Fit result projected to each of the fit variables
- Result from Run 3 fit, Negative charged signals
- $\langle P \rangle = 0.0048$





# Full Measurement

- Performing the measurement on the full  $424.2 \text{ fb}^{-1}$

Sample	Luminosity ( $\text{fb}^{-1}$ )	Average Polarization
Run 1	20.4	$-0.0014 \pm 0.0100$
Run 2	61.3	$0.0041 \pm 0.0059$
Run 3	32.3	$0.0048 \pm 0.0083$
Run 4	99.6	$-0.0011 \pm 0.0049$
Run 5	132.3	$0.0052 \pm 0.0045$
Run 6	78.3	$0.0084 \pm 0.0062$
<b>Total</b>	<b>424.2</b>	<b><math>0.0035 \pm 0.0024</math></b>

- Final measurement:

$$\langle P \rangle = 0.0035 \pm 0.0024_{\text{stat}} + 0.0029_{\text{sys}}$$

Source	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Combined
$\pi^0$ efficiency	0.0025	0.0016	0.0013	0.0018	0.0006	0.0017	<b>0.0013</b>
Muon PID	0.0018	0.0018	0.0029	0.0011	0.0006	0.0016	<b>0.0012</b>
Split-off modeling	0.0015	0.0017	0.0016	0.0006	0.0016	0.0020	<b>0.0011</b>
Neutral energy calibration	0.0027	0.0012	0.0023	0.0009	0.0014	0.0008	<b>0.0010</b>
$\pi^0$ mass	0.0018	0.0028	0.0010	0.0005	0.0004	0.0004	<b>0.0008</b>
$\rho$ decay collinearity	0.0015	0.0009	0.0016	0.0007	0.0005	0.0005	<b>0.0007</b>
$\pi^0$ likelihood	0.0015	0.0009	0.0015	0.0006	0.0003	0.0010	<b>0.0006</b>
Electron PID	0.0011	0.0020	0.0008	0.0006	0.0005	0.0001	<b>0.0005</b>
Particle transverse momentum	0.0012	0.0007	0.0009	0.0002	0.0003	0.0006	<b>0.0004</b>
Boost modeling	0.0004	0.0019	0.0003	0.0004	0.0004	0.0004	<b>0.0004</b>
Momentum calibration	0.0001	0.0014	0.0005	0.0002	0.0001	0.0003	<b>0.0004</b>
Max EMC acceptance	0.0001	0.0011	0.0008	0.0001	0.0002	0.0005	<b>0.0003</b>
$\tau$ direction definition	0.0003	0.0007	0.0008	0.0003	0.0001	0.0004	<b>0.0003</b>
Angular resolution	0.0003	0.0008	0.0003	0.0003	0.0002	0.0003	<b>0.0003</b>
Background modeling	0.0005	0.0006	0.0010	0.0002	0.0003	0.0003	<b>0.0003</b>
Event transverse momentum	0.0001	0.0013	0.0005	0.0002	0.0002	0.0004	<b>0.0003</b>
Momentum resolution	0.0001	0.0012	0.0004	0.0002	0.0001	0.0005	<b>0.0003</b>
$\rho$ mass acceptance	0.0000	0.0011	0.0003	0.0001	0.0002	0.0005	<b>0.0003</b>
$\tau$ branching fraction	0.0001	0.0007	0.0004	0.0002	0.0002	0.0002	<b>0.0002</b>
$\cos \theta^*$ acceptance	0.0002	0.0006	0.0004	0.0001	0.0001	0.0004	<b>0.0002</b>
$\cos \psi$ acceptance	0.0002	0.0003	0.0002	0.0002	0.0002	0.0003	<b>0.0002</b>
<b>Total</b>	<b>0.0058</b>	<b>0.0062</b>	<b>0.0054</b>	<b>0.0030</b>	<b>0.0026</b>	<b>0.0038</b>	<b>0.0029</b>

<https://doi.org/10.1103/PhysRevD.108.092001>



# Conclusions

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

$$\langle P \rangle = 0.0035 \pm 0.0024_{\text{stat}} + 0.0029_{\text{sys}}$$

- Identified 21 sources of systematic uncertainty
- Modelling/Understanding of neutral processes dominates the largest systematics
- Tau Polarimetry could be applied at other  $e^+e^-$  colliders interested in polarization
- Final uncertainty exceeds Chiral Belle assumptions suggesting the experiment could make even more precise measurements

Thank You!

<https://doi.org/10.1103/PhysRevD.108.092001>

# Backup Slides

# 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:

$e^+e^-$	L <sup>-</sup>	R <sup>-</sup>
R <sup>+</sup>	R <sup>+</sup> L <sup>-</sup>	R <sup>+</sup> R <sup>-</sup>
L <sup>+</sup>	L <sup>+</sup> L <sup>-</sup>	L <sup>+</sup> R <sup>-</sup>

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

70% polarized e<sup>-</sup> beam

$e^+e^-$	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

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

70% polarized  $e^-$  beam

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

$$\langle P \rangle = 0.7$$

$$\sigma = 1$$

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

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

$$\langle P \rangle = 0.887$$

$$\sigma = 1.24$$

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

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

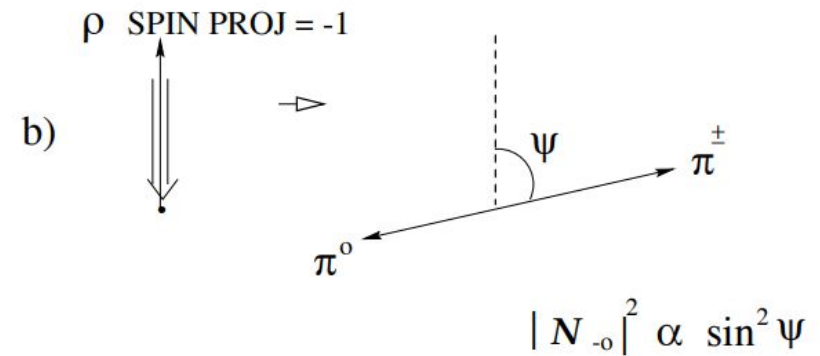
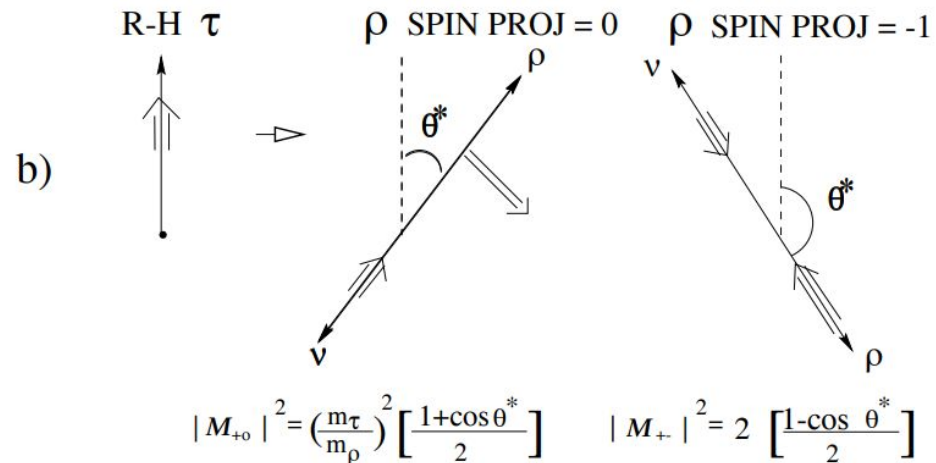
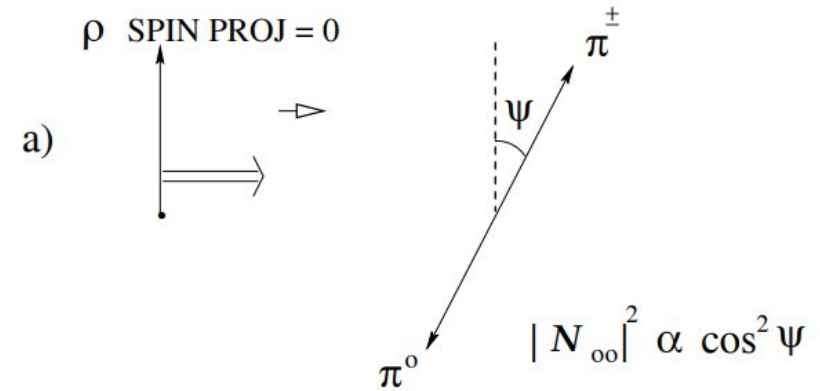
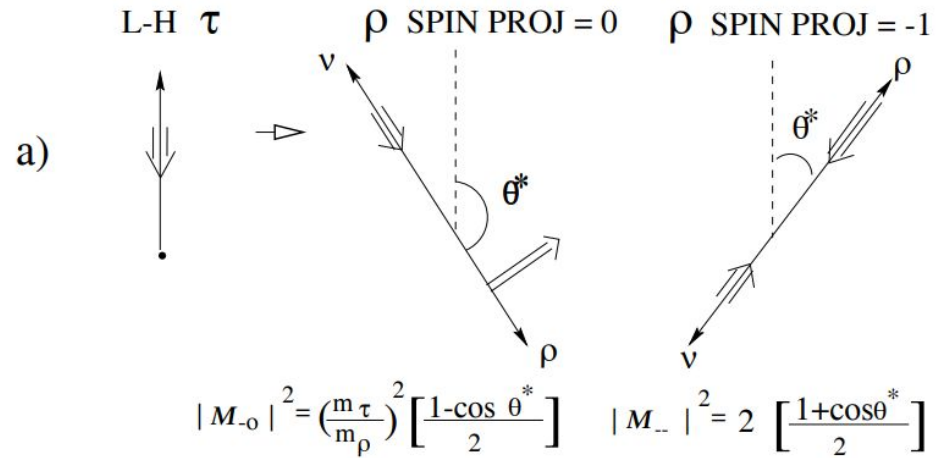
$$\langle P \rangle = 0.940$$

$$\sigma = 1.49$$

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

# Rho Spin Analysis

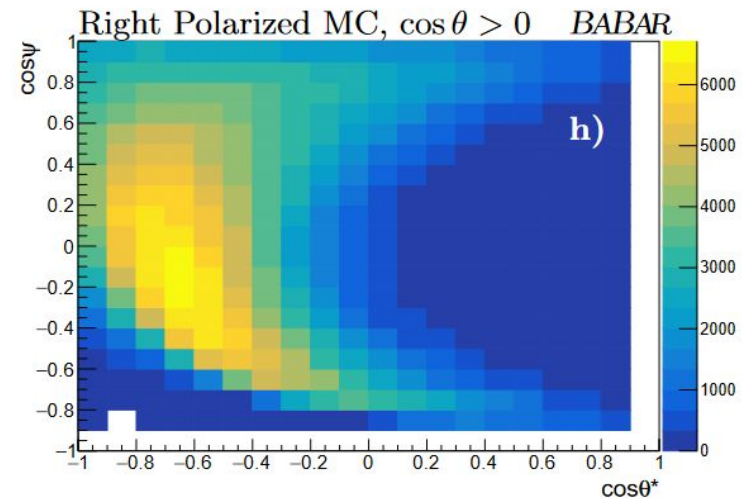
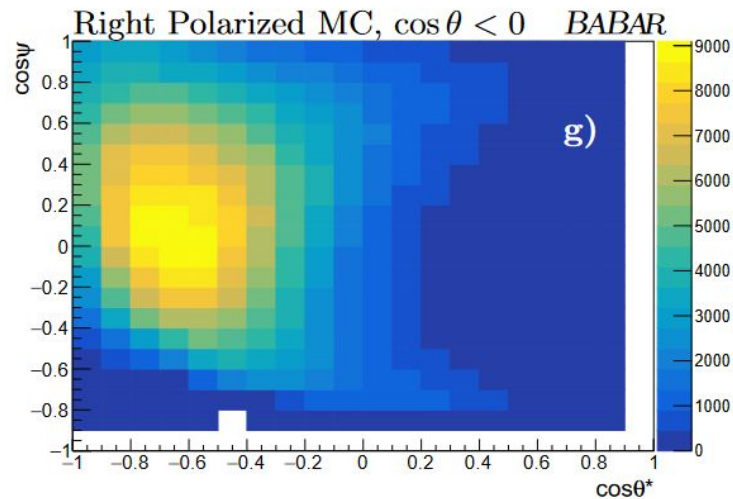
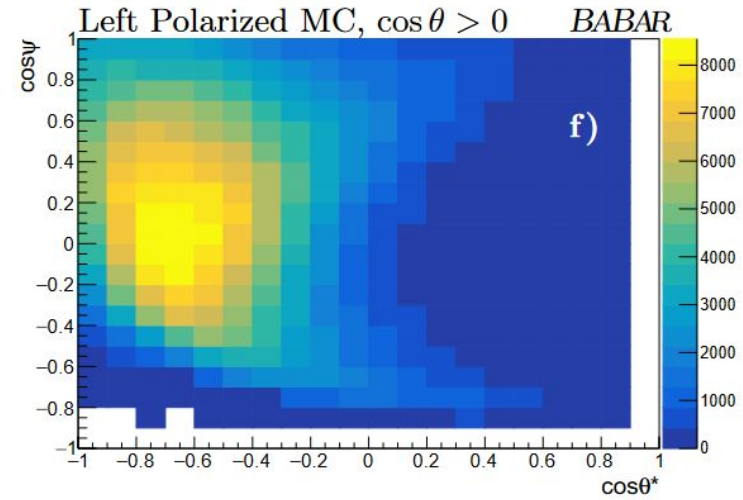
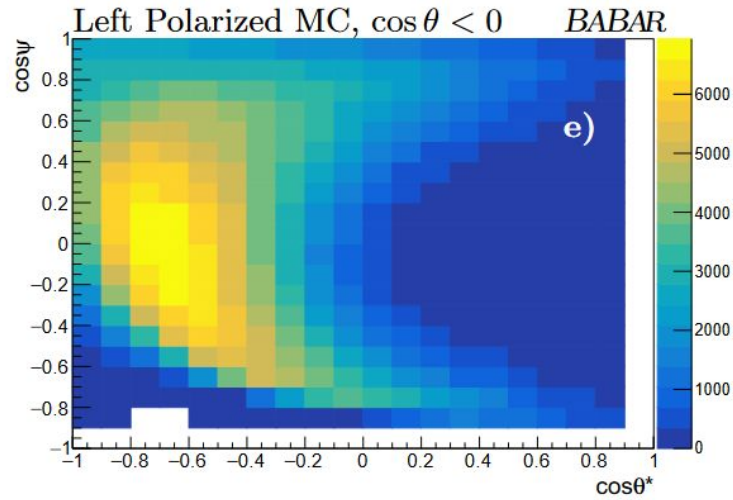
- The rho complicates the spin projections, which necessitates two variables to extract the polarization



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

# 2D Projections

- 2D projections of the polarization sensitivity



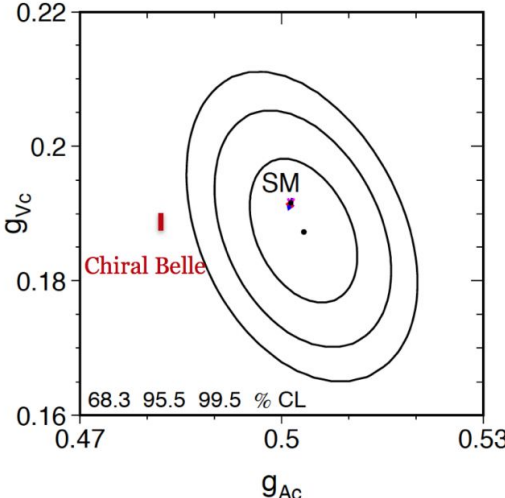
# Beam Polarization Motivation

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- A polarized electron beam would allow Belle II to make many precise measurements of electroweak parameters. Including  $A_{LR}$  for  $e, \mu, \tau, c, b$ . For Born level s-channel process:

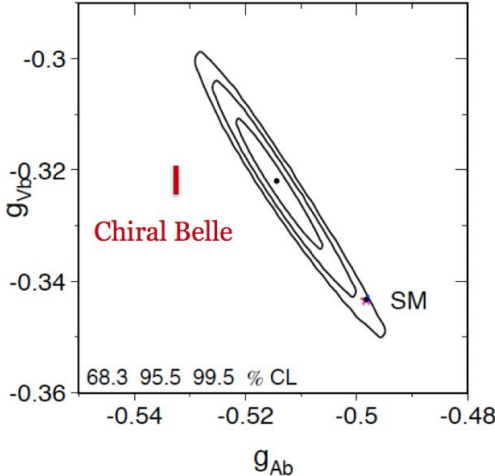
$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \frac{4}{\sqrt{2}} \left( \frac{G_f S}{4\pi\alpha Q_f} \right) g_A^e g_V^f \langle P \rangle \propto T_3^f - 2Q_f \sin^2 \theta_W$$

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

**c-quark:** with 20  $ab^{-1}$   
Chiral Belle ~7 times more precise



**b-quark:** with 20  $ab^{-1}$   
Chiral Belle ~4 times more precise



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