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

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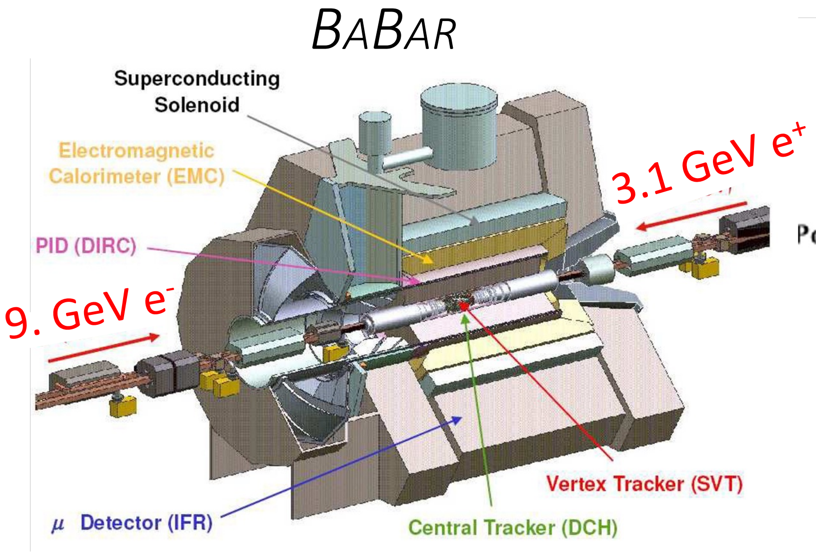
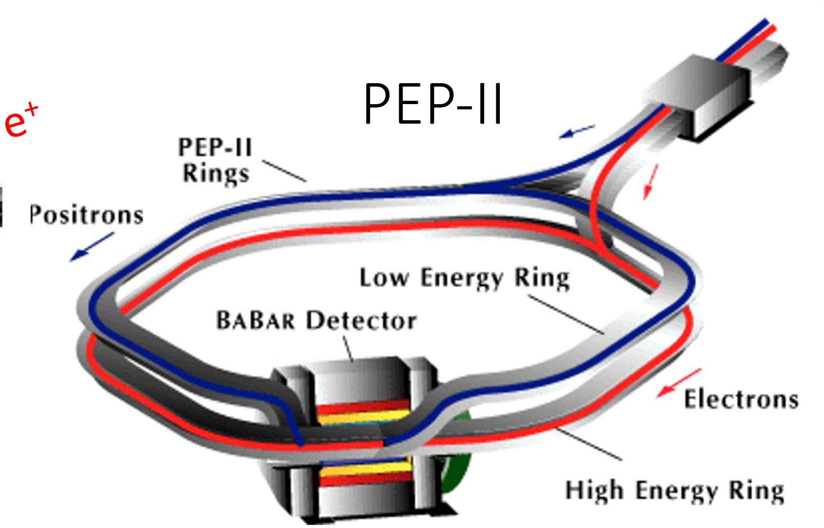
on behalf of the

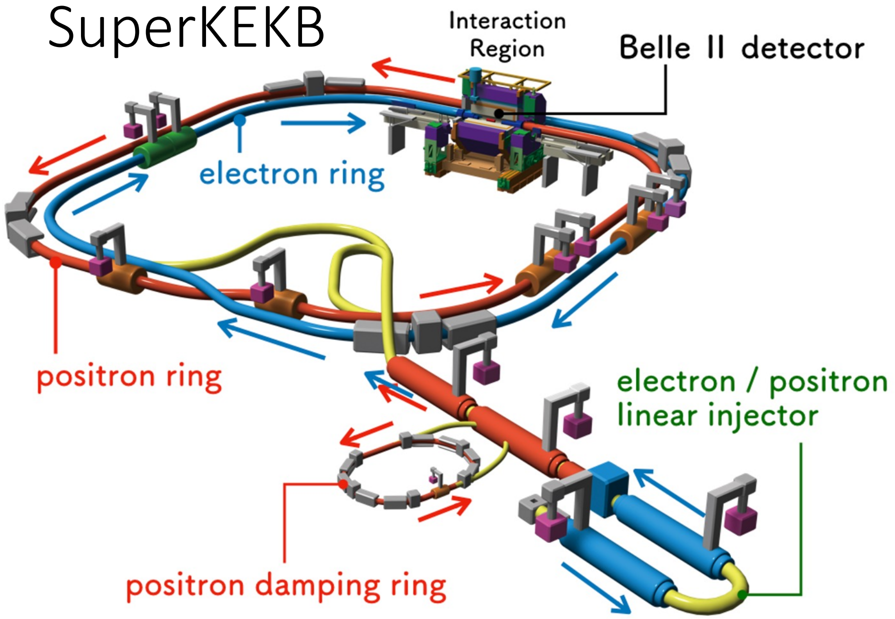
BABAR Collaboration

19 July 2023

Study e$^-$ Beam Polarization in *BABAR*

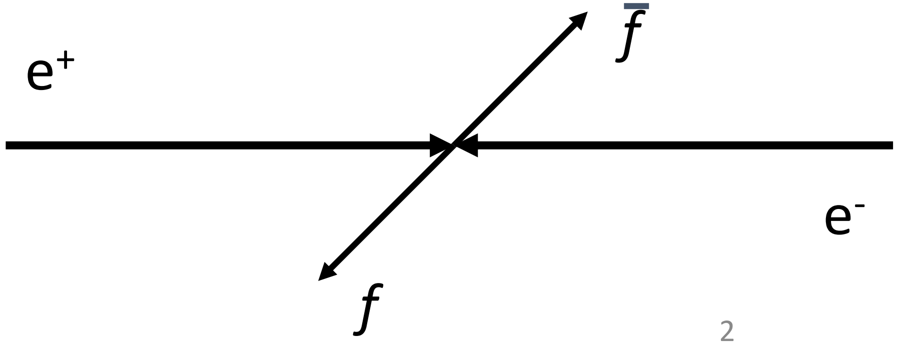






- *BABAR* and PEP-II operated at SLAC from 1999-2008
- Beam polarization was expected to be zero
- We developed a method that could be use at any e$^+$e$^-$ collider
- *BABAR* collected 432 fb^{-1} of data on the ϒ(4S) resonance

- In Chiral Belle plan is to achieve a 70% polarized e$^-$ beam



Beam Polarization Motivation

- 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 the Born level s-channel process:

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

g_A^e neutral current axial vector coupling to e

g_V^f neutral current vector coupling to fermion f

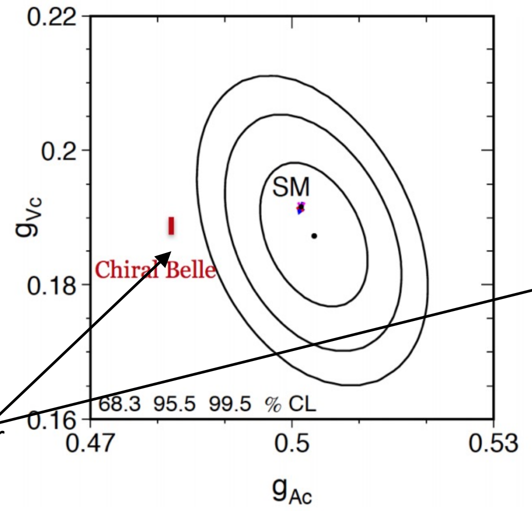
$\langle P \rangle$ = average beam polarization
= $(R^+L^- - L^+R^-)/(R^+L^- + L^+R^-)$

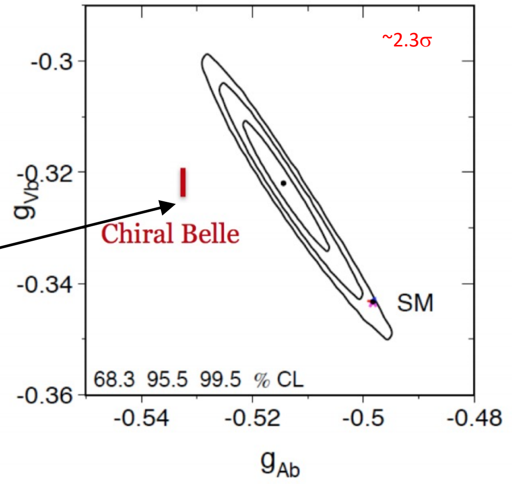
Q_f: fermion charge

c-quark: Chiral Belle ~7 times more precise

with 20 ab^{-1}

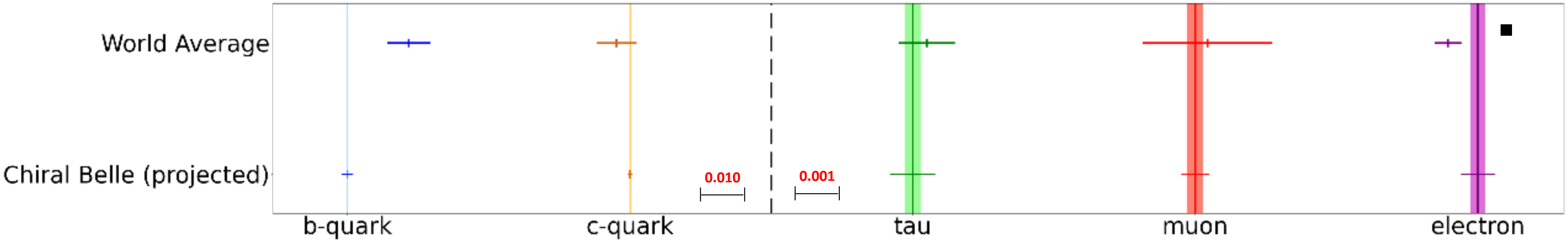
b-quark: Chiral Belle ~4 times more precise





Red bars show expected ±1σ error dominated by <P> error

adapted from fig 7.4 Physics Reports 427(5), 2006

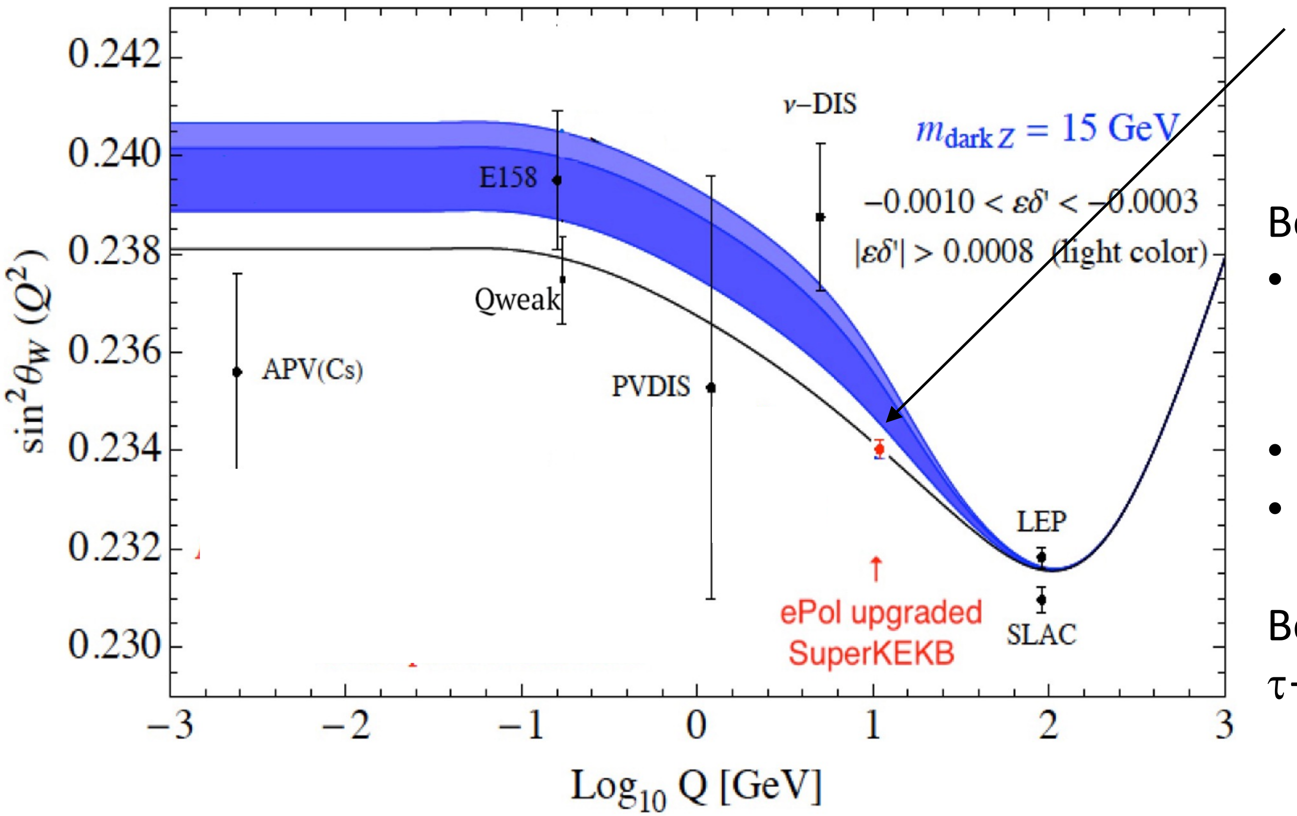


- Projected errors are tied to the uncertainty of the beam polarization measurement

Beam Polarization Motivation

- Precision measurement of running of weak mixing angle: sensitive to new dark Z boson when away from Z-pole

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



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

Beam Polarization also enables precision measurements of

- Tau Lepton Magnetic Form factor F_2(10GeV) → τ g-2 with precision approaching regime in tau that is sensitive to Minimal Flavour Violation equivalent of muon g-2 anomaly
- Tau EDM
- Tau Michel parameters

Beam Polarization also reduces backgrounds in searches for τ→μγ and τ→eγ

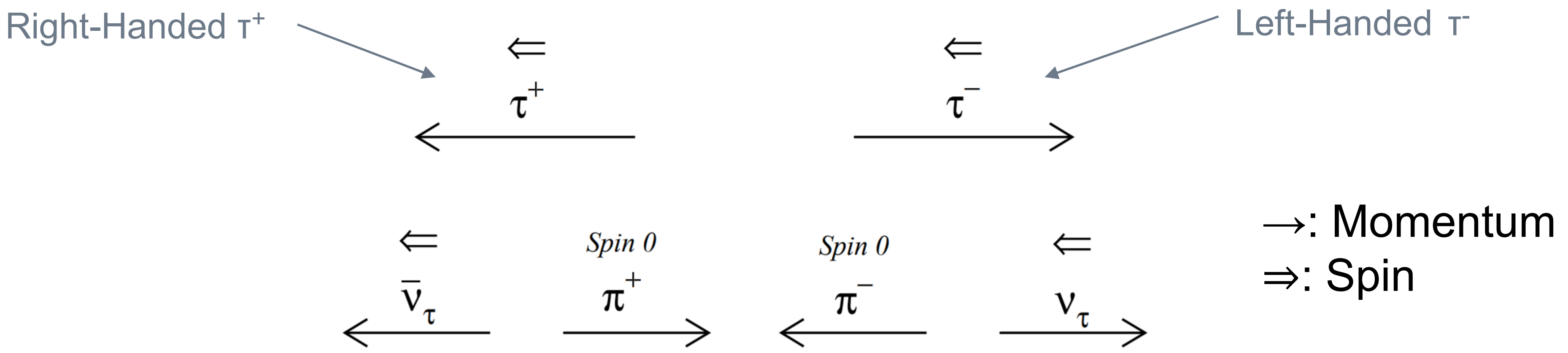
Other measurements to come from APV(Ra^+), Moller, P2, and the SoLID experiments– all but Chiral Belle use only first generation fermions and have lower sensitivity (see backup slides)

Tau Polarimetry

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

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

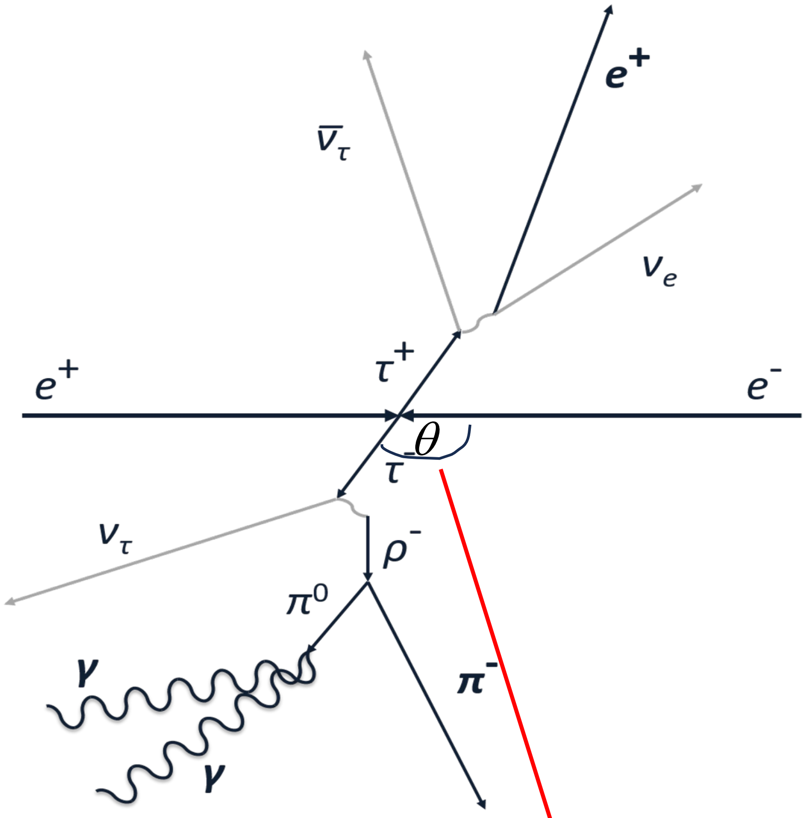
- Tau polarization information can be extracted from the kinematics of the tau decay

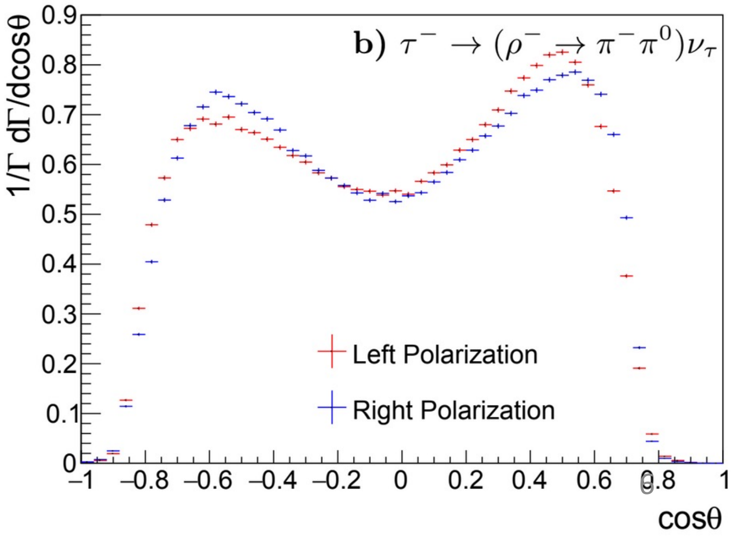


- The Belle II physics program assumes a 70% polarized e^- beam where the polarization is measured $\lesssim 0.5\%$
- Compton polarimeters have an uncertainty associated with modelling the spin transport from the polarimeter to the interaction point (IP)
- **By using Tau Polarimetry we can extract the average beam polarization directly from the data at the IP**

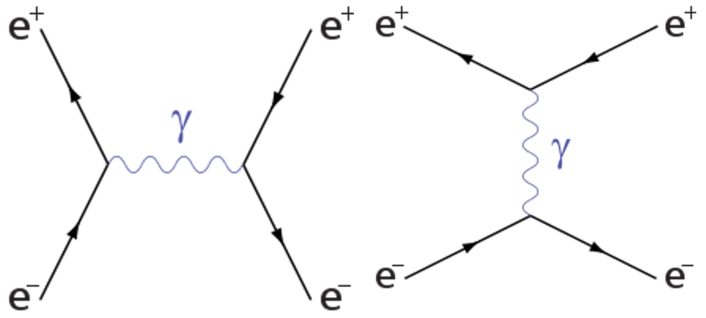
Tau Event Selection

- Selected tau events in a 1v1 topology, (ρ vs. e or μ)
  - ρ has large branching fraction, lepton for clean tag
- Signal candidates are defined as a charged particle with a π^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% $\mu^+\mu^-$)
- 88% of selected events contain a $\tau^\pm \longrightarrow \pi^\pm\pi^0\nu_\tau$ decay
  - 12% other tau hadronic decays

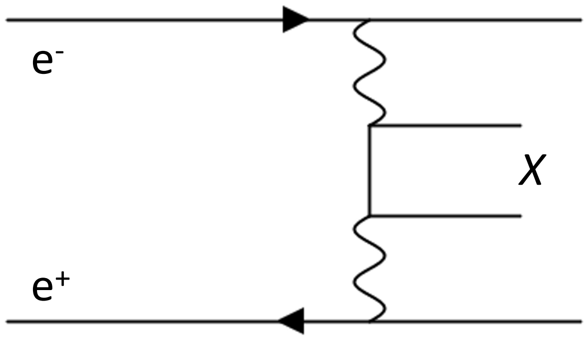




Bhabha process



Two-photon process

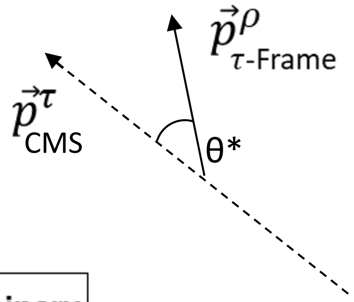


Polarization Observable cos θ^*

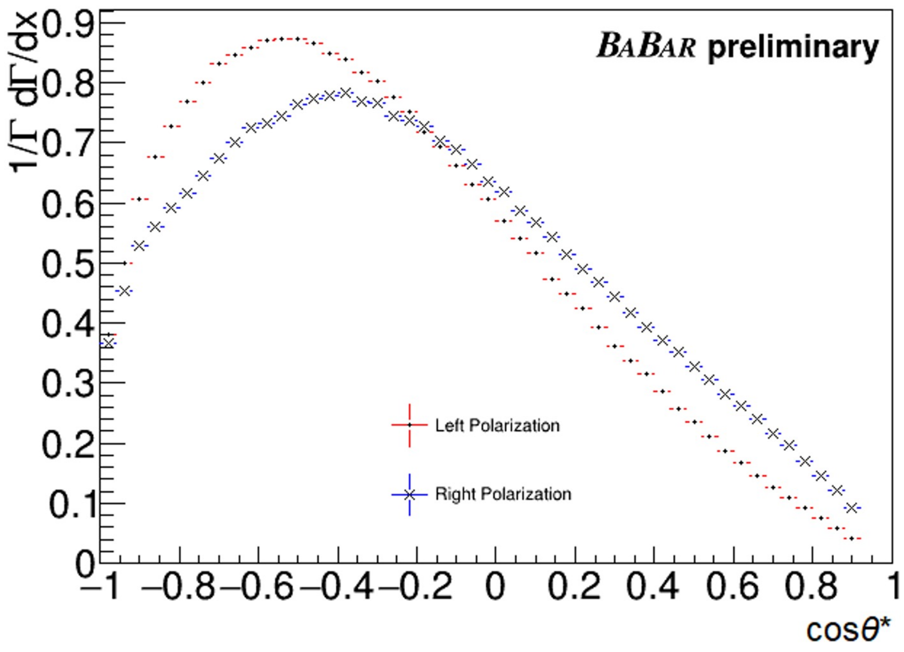
- Polarization sensitivity in a rho decay is maximized by analyzing two angular variables[2] (cos θ^* and cos ψ) in addition to cos θ

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

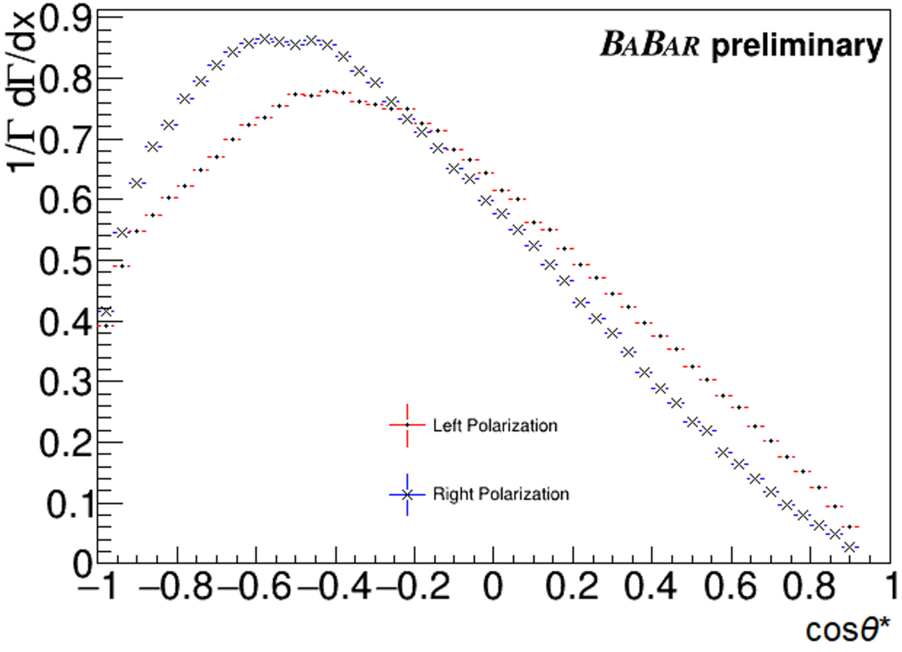
$$z \equiv E_\rho / E_{\mathrm{beam}}$$



cosθ<0, τ^-



cosθ>0, τ^-



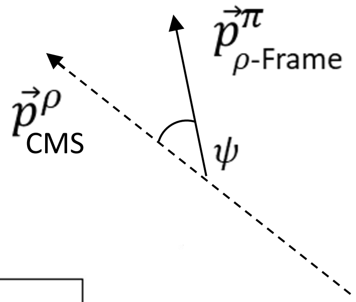
[2] K. Hagiwara, A. Martin, D. Zeppenfeld, Tau Polarization Measurements at LEP and SLC, Phys. Lett. B. 235, 1998, DOI: 10.1016/0370-2693(90)90120-U

Polarization Observable cos ψ

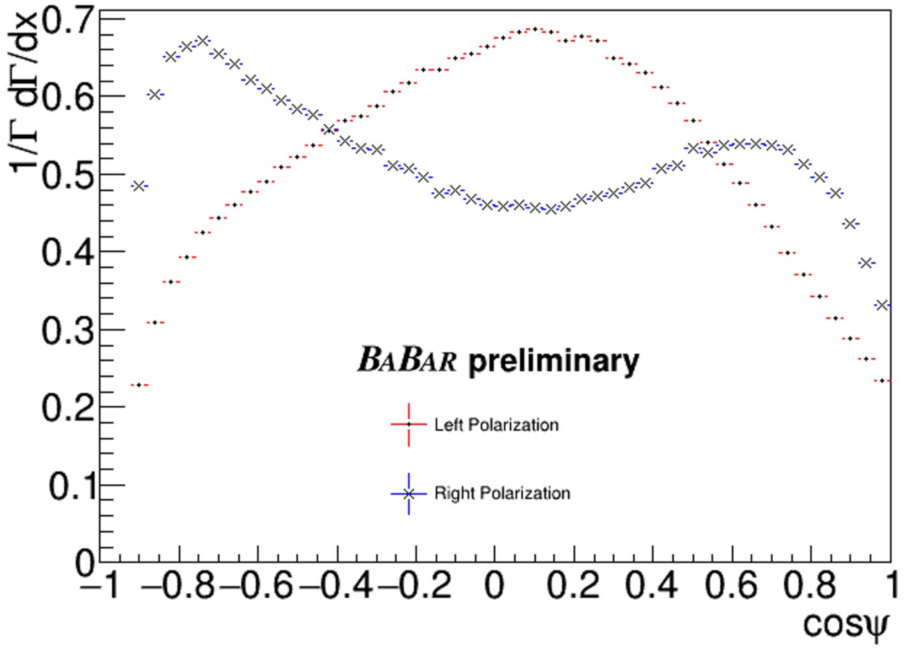
- Polarization sensitivity in a rho decay is maximized by analyzing two angular variables[2] in addition to cosθ

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

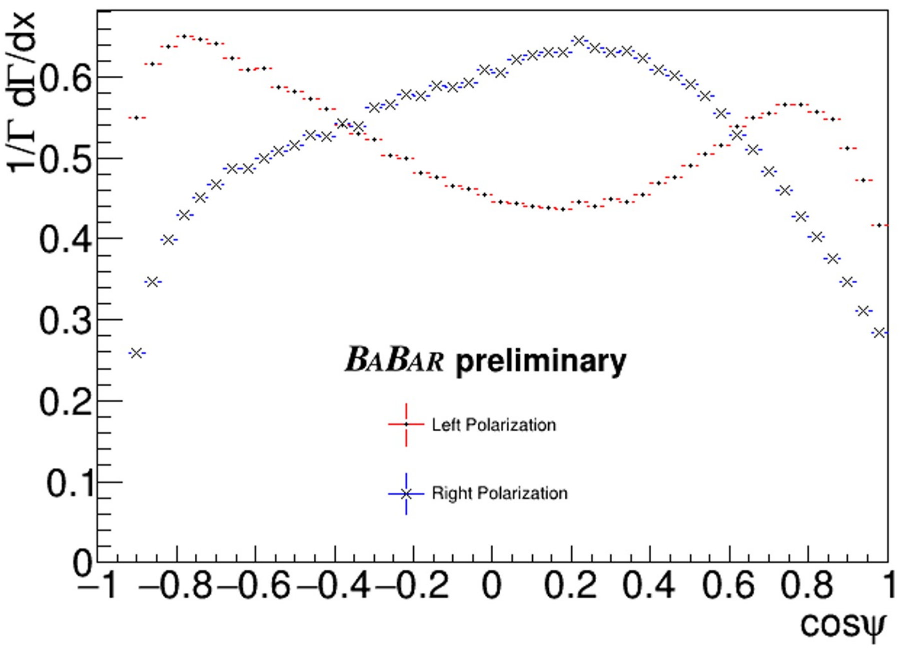
$$x \equiv E_\pi / E_\rho$$



$\cos\theta<0$, τ^-



$\cos\theta>0$, τ^-



[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

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=$c\bar{c}$

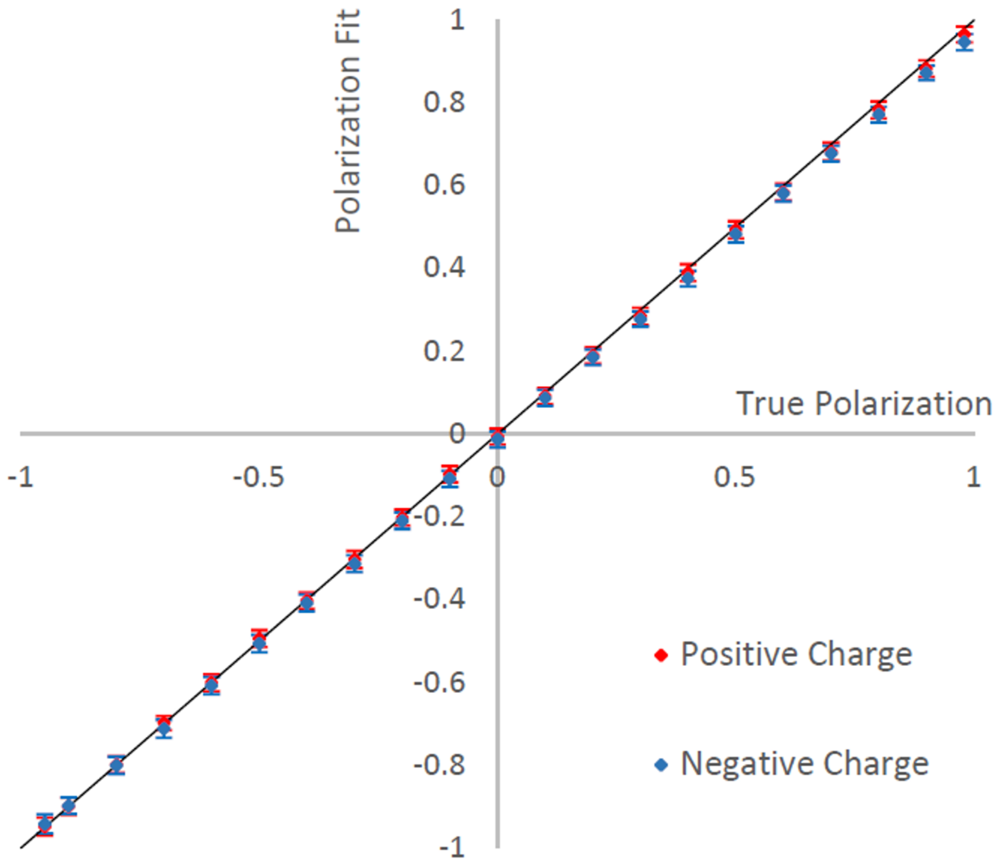
a_i = fit contribution

- For the τ^+ and τ^- combined result, some systematic errors cancel

[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 Fit Validation

- 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

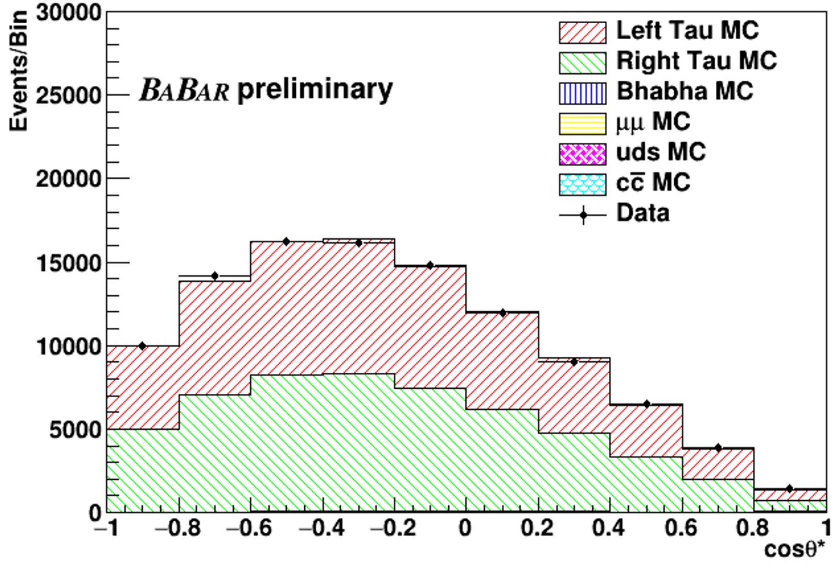


Example Fit Result for <P>

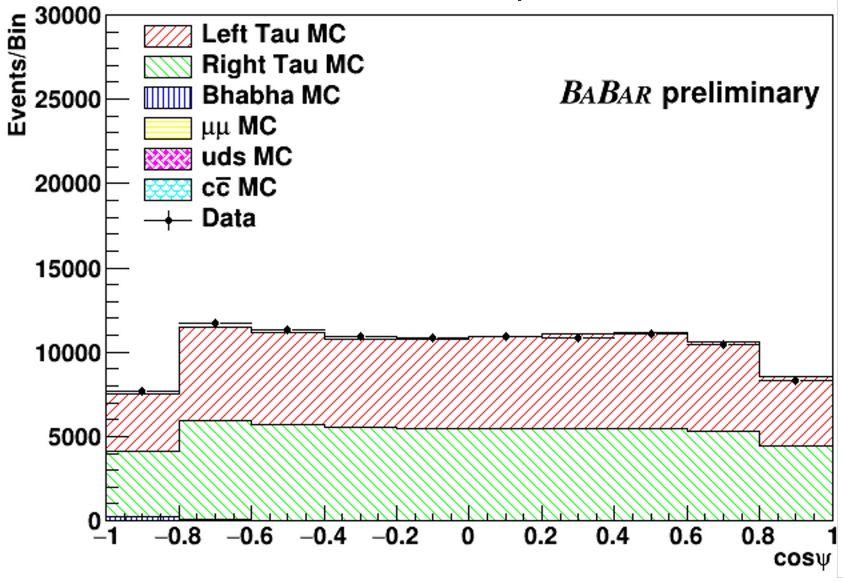
Sample	Positive charge	Negative charge	Total
Run 3 (32.28 fb^{-1})	0.0151±0.0120	-0.0047±0.0120	0.0048±0.0083

- Fit result projected to each of the fit variables
- Result from preliminary Run 3 fit, Negative charges

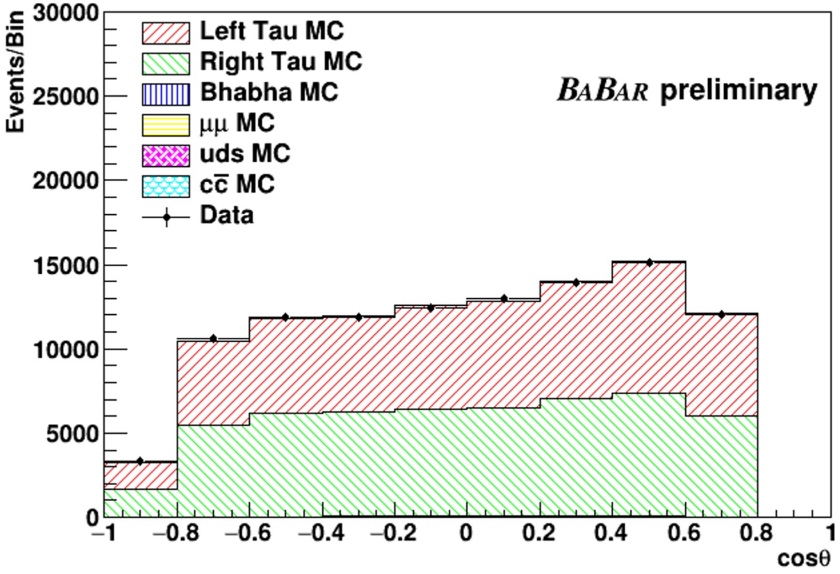
$\cos\theta^*$



$\cos\psi$



$\cos\theta$



Full Measurement

- Performing the measurement on the full 424.2 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 3	32.28	0.0048±0.0083
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	424.2	0.0035±0.0024

- Preliminary measurement:

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

PRELIMINARY

Systematic Uncertainties (21)

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

Conclusions

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

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

PRELIMINARY

- We identified 21 sources of systematic uncertainty
- Modelling and understanding of neutral processes dominates the largest systematics
- The precision is better than 0.5%
- This new tau polarimetry technique could be applied at other e^+e^- colliders interested in polarization, like Chiral Belle and ILC
- Paper should be on the arXiv this week and is aimed for publication in Phys. Rev. D

Thank You!

Snowmass 2021 White PaperUpgrading SuperKEKB with a Polarized Electron Beam:Discovery Potential and Proposed Implementation arXiv:2205.12847

Backup Slides

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:

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

	Standard Model	*World Average*	*Chiral Belle 40ab⁻¹*
Fermion	g_V^f **SM**	g_V^f **WA**	$\sigma\left(g_V^f\right)$ **CB**
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

b- and c- uncertainties dominated by uncertainty on <P>

Beam Polarization Motivation

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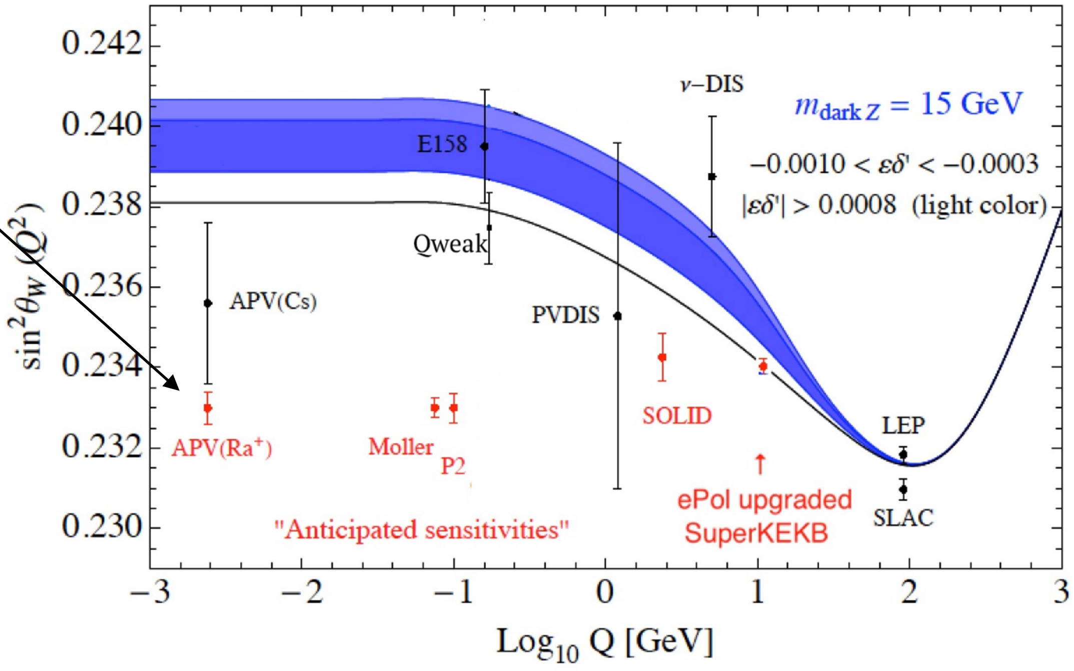
$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \frac{4}{\sqrt{2}}\left(\frac{G_F s}{4\pi\alpha Q_f}\right) g_A^e g_V^f \langle P \rangle \propto T_3^f - 2Q_f \sin^2\theta_W$$

Red bars show expected 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

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 $(R^+L^- + L^+R^-)/(R^+L^-_{\text{unpolarized}} + L^+R^-_{\text{unpolarized}})$

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

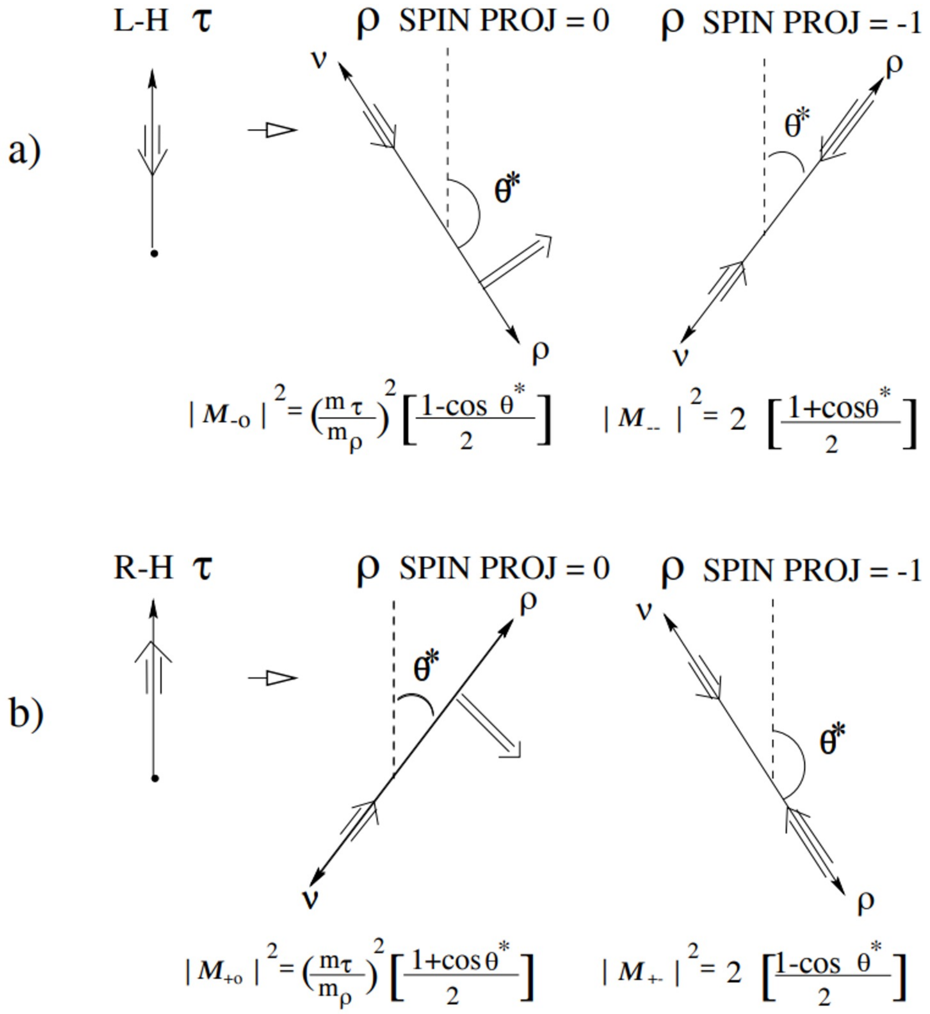
$e^+\backslash e^-$	0.85	0.15
0.85	0.722	0.128
0.15	0.128	0.022

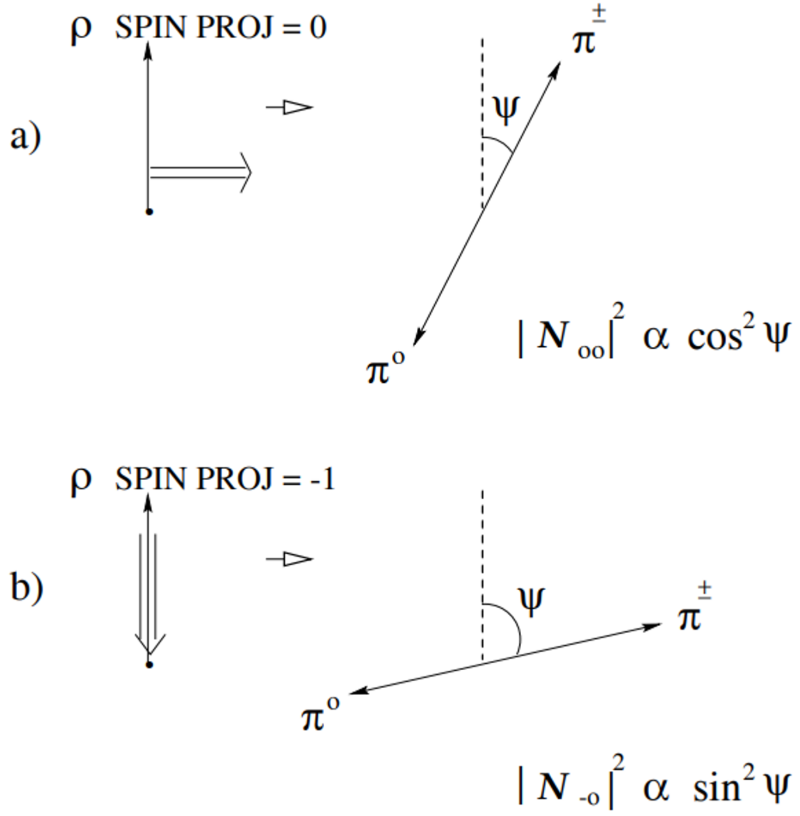
<P> = 0.940
σ = 1.49

- 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

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