Available at Phys. Rev. D
https://doi.org/10.1103/PhysRevD.108.092001

Precision e^- beam polarimetry

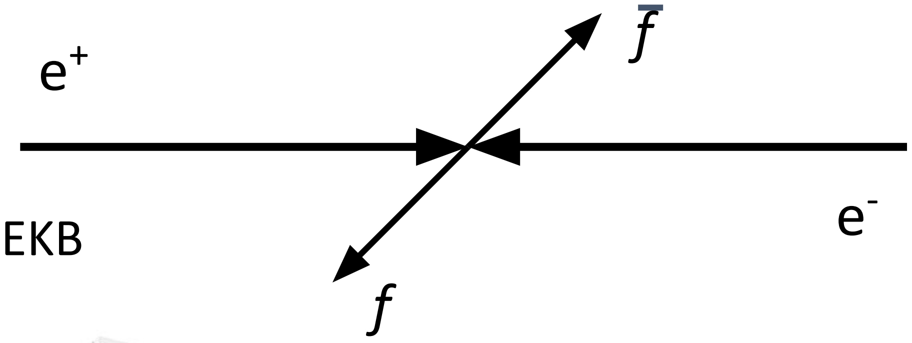
at an e^+e^- B-factory using tau-pair events

Caleb Miller
on behalf of BABAR

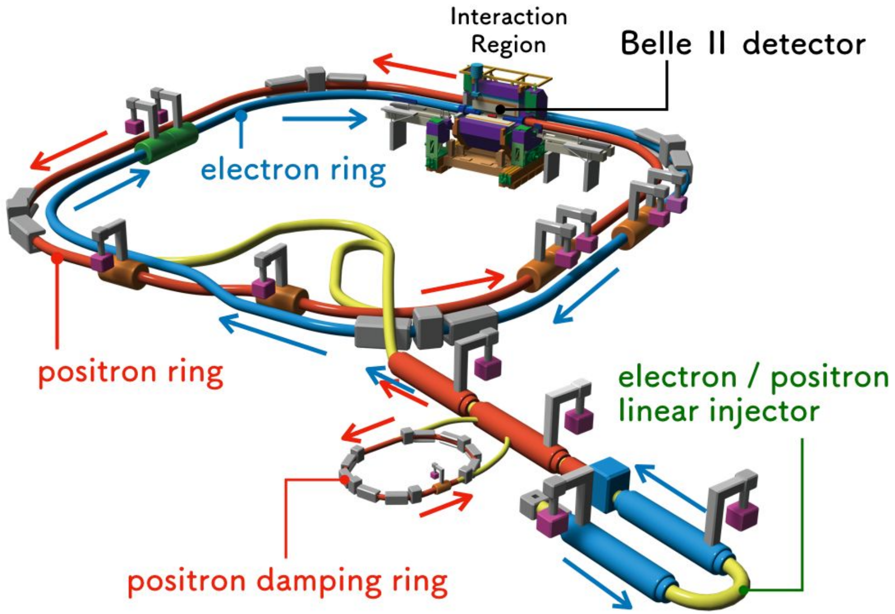
University of Victoria

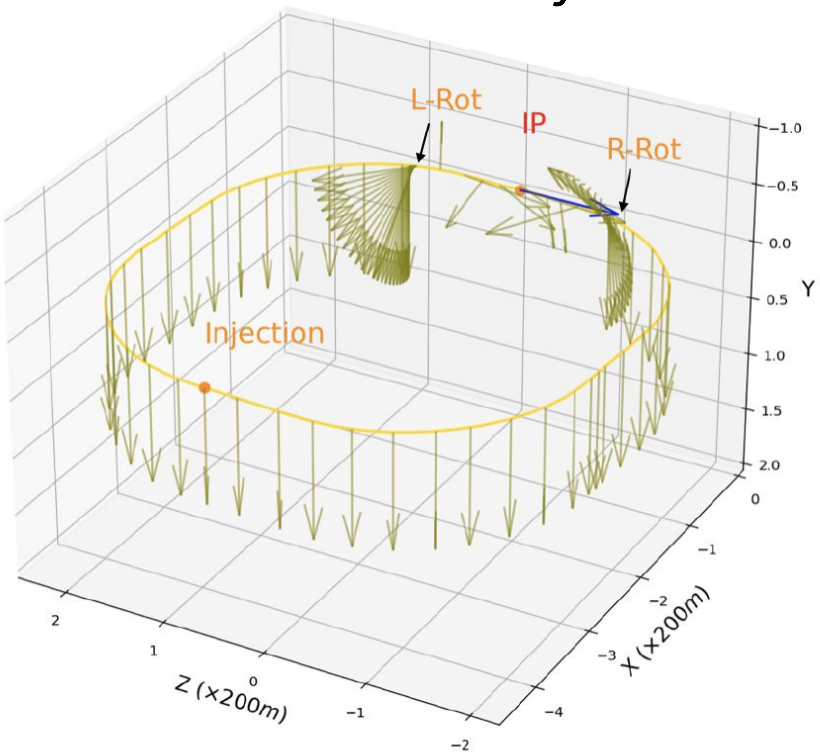
TAU2023

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

See Mike's talk on Friday

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,μ,τ,c,b. For Born level s-channel process:

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

Average beam polarization

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

Axial and Vector neutral current couplings

Weak mixing angle

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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

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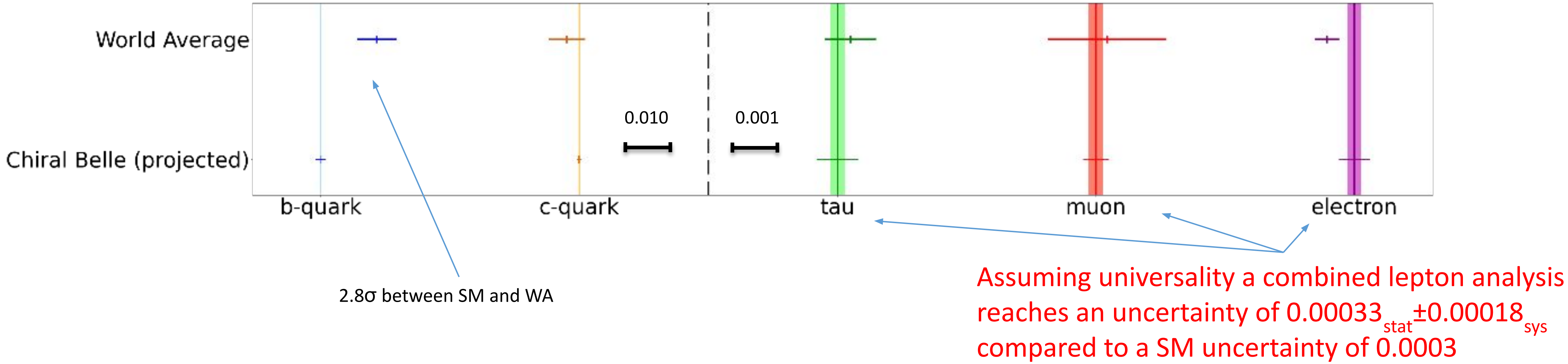
Visualization of Chiral Belle projections of g_V^f vs World Averages and Standard Model(vertical line) from table



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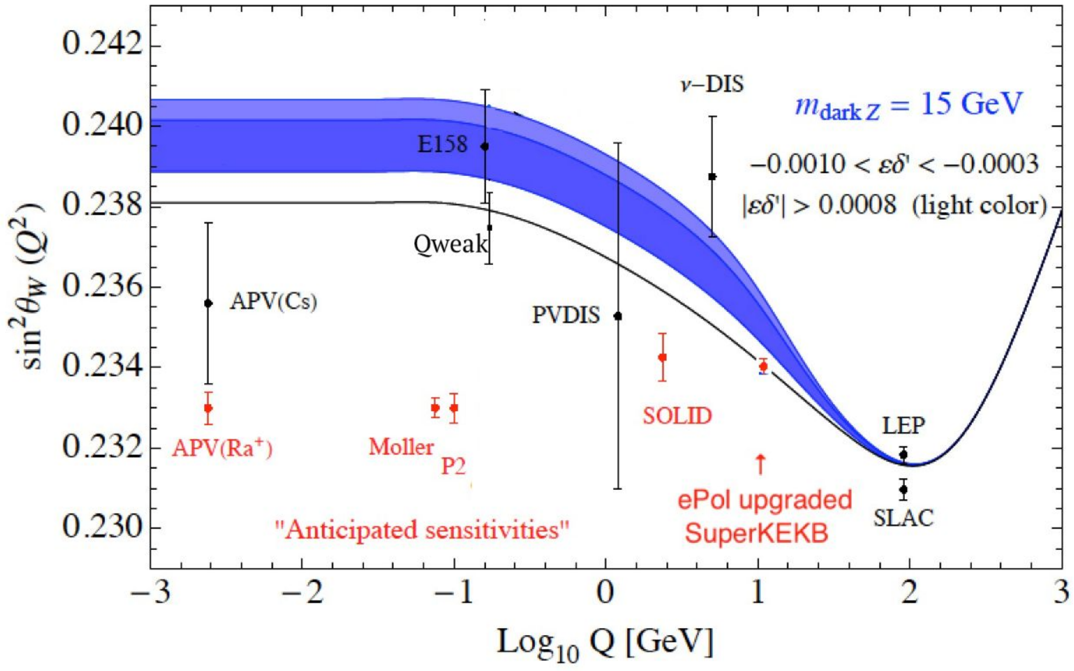


Red bars show expected sensitivity of future experiments. position arbitrary.

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

Motivation - Tau g-2

- 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:

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

- 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)

Motivation Summary

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

See Mike's talk on Friday

Tau Polarimetry

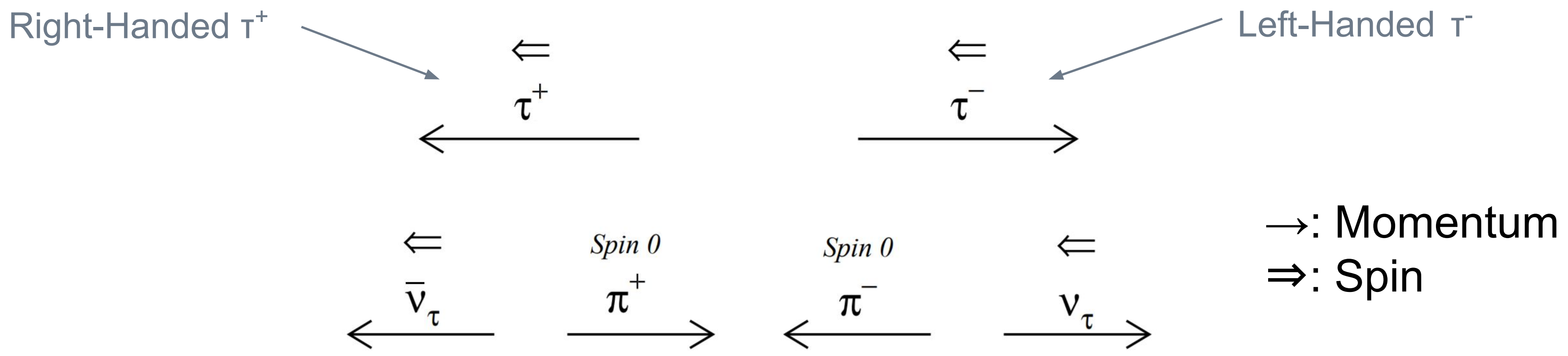
- The polarization of tau's (P_τ) produced in e^+e^- collisions at 10.58 GeV is related to the electron beam polarization (P_e) through:

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

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

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

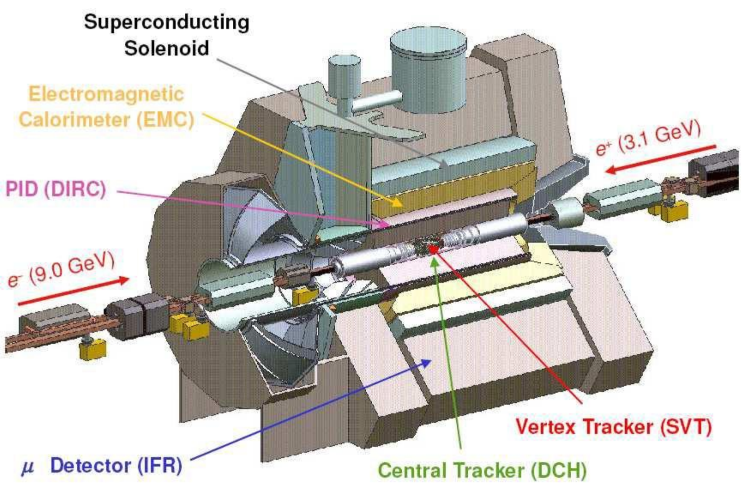
Assumes only SM physics

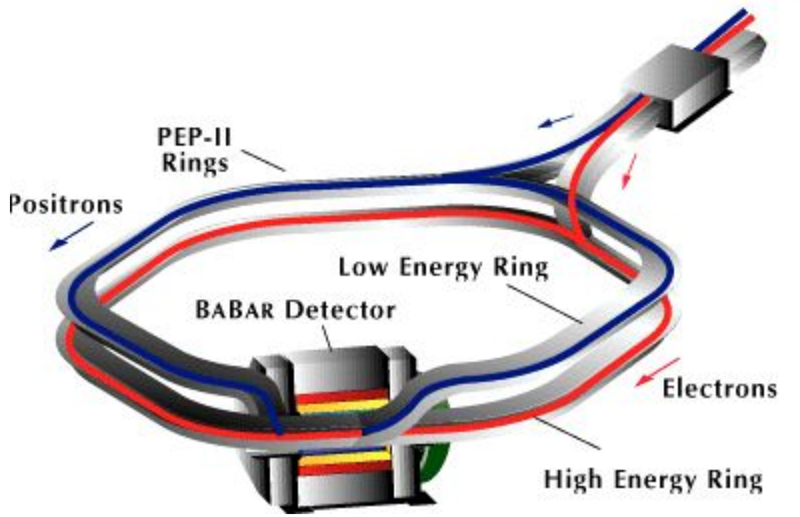


Caleb Miller. calebmiller@uvic.ca

BaBar and PEP-II

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

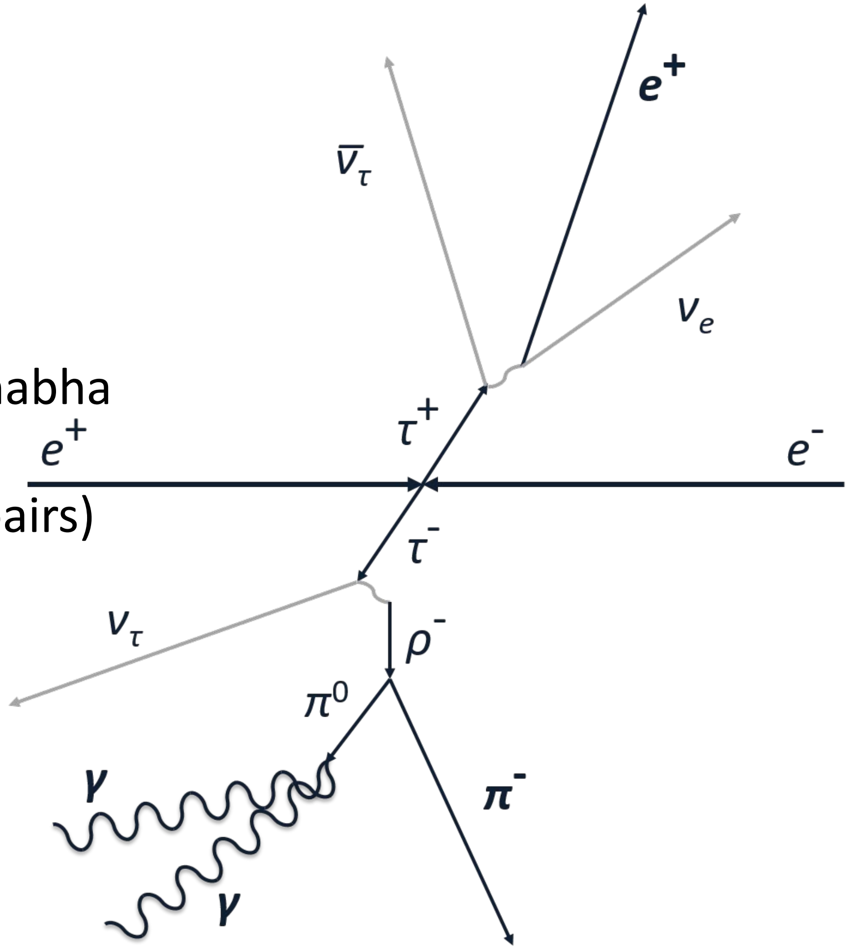




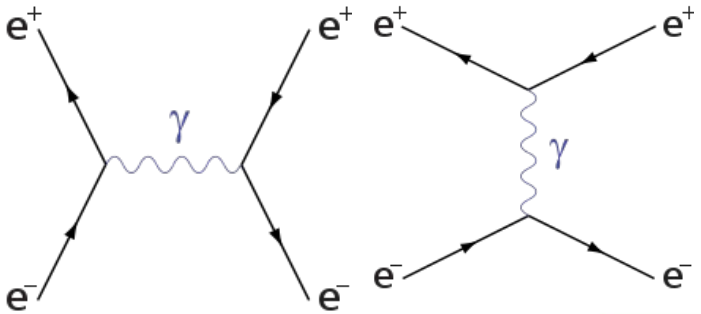
- Similar design of *BaBar* and Belle II also us to benchmark the technique on *BaBar*
  - Statistical sensitivity
  - Dominant systematic sources
- Over 6 run periods *BaBar* collected 432 fb^{-1} of data on the ϒ(4S) resonance
- PEP-II collided electrons and positrons together at 9.0 and 3.1 GeV
-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

Tau Event Selection

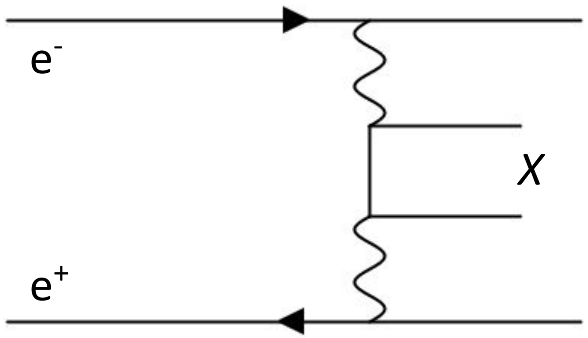
- Selected tau events in a 1v1 topology, (ρ vs. e or μ)
  - τ to ρ has large branching fraction, lepton for clean tag
- Signal candidates are defined as a charged particle with a π^0
- $q\bar{q}$ events are eliminated with the lepton requirement
- Angular cuts and a minimum p_T of 350 MeV reduce two photon and Bhabha contamination
- Results in a 99.9% pure tau-pair sample (0.05% Bhabha, 0.05% 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



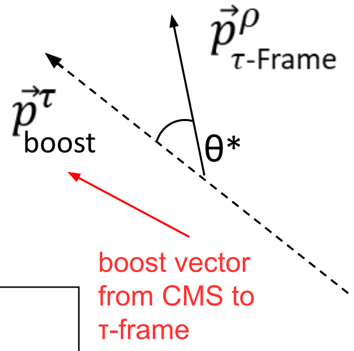
Two-photon process



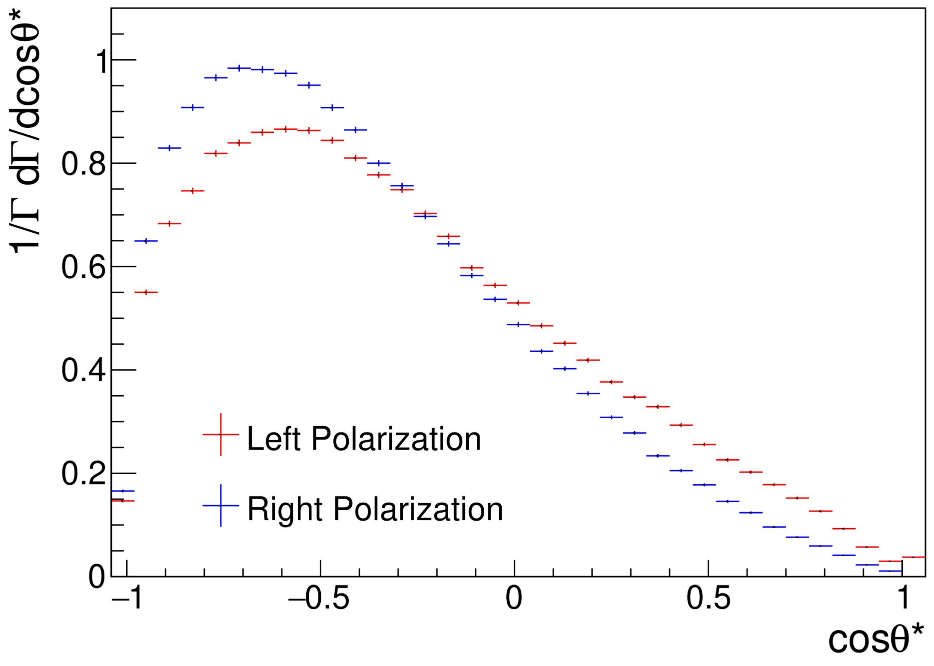
Polarization Observables

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

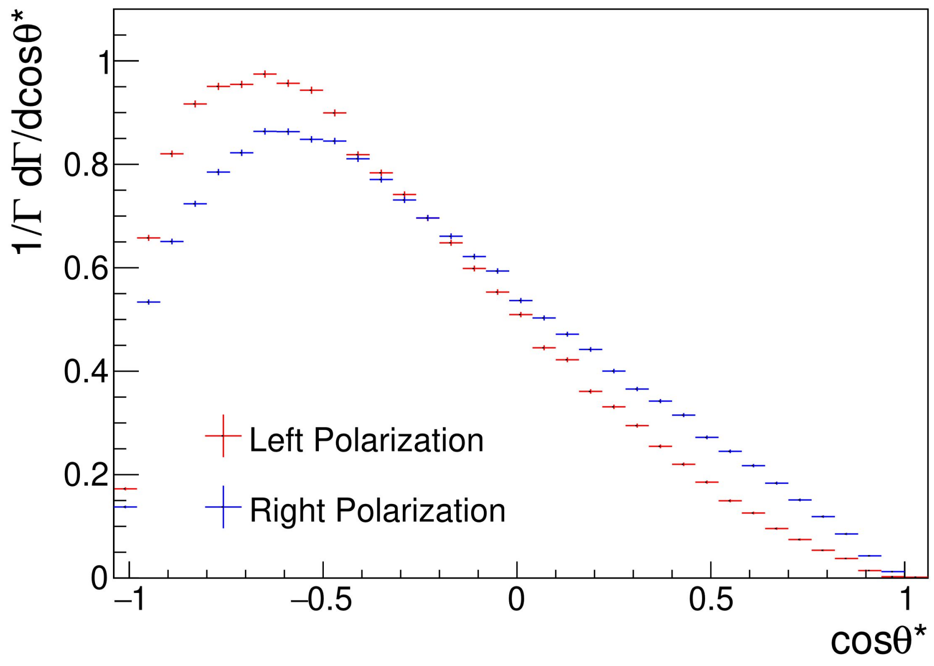
$$\cos\theta^* = \frac{2z - 1 - m_\rho^2/m_\tau^2}{1 - m_\rho^2/m_\tau^2} \qquad z \equiv E_\rho \big/ E_{\mathrm{beam}}$$



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

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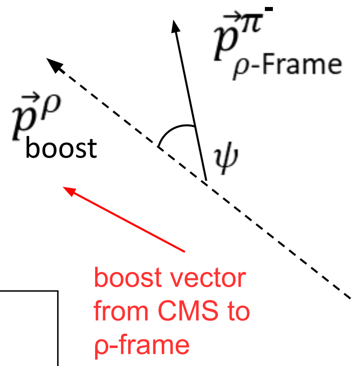
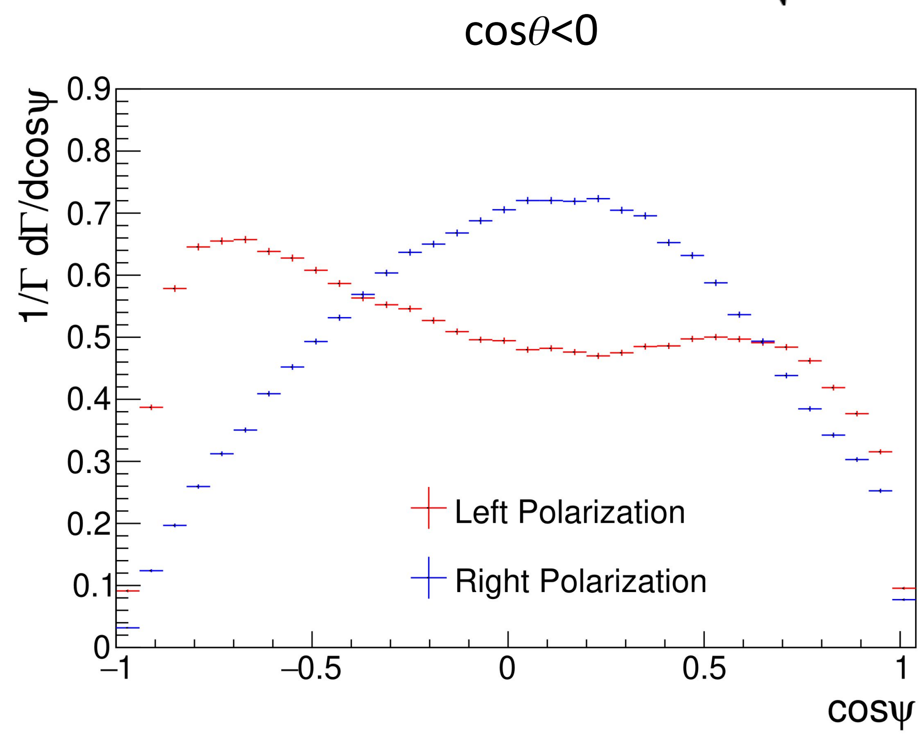
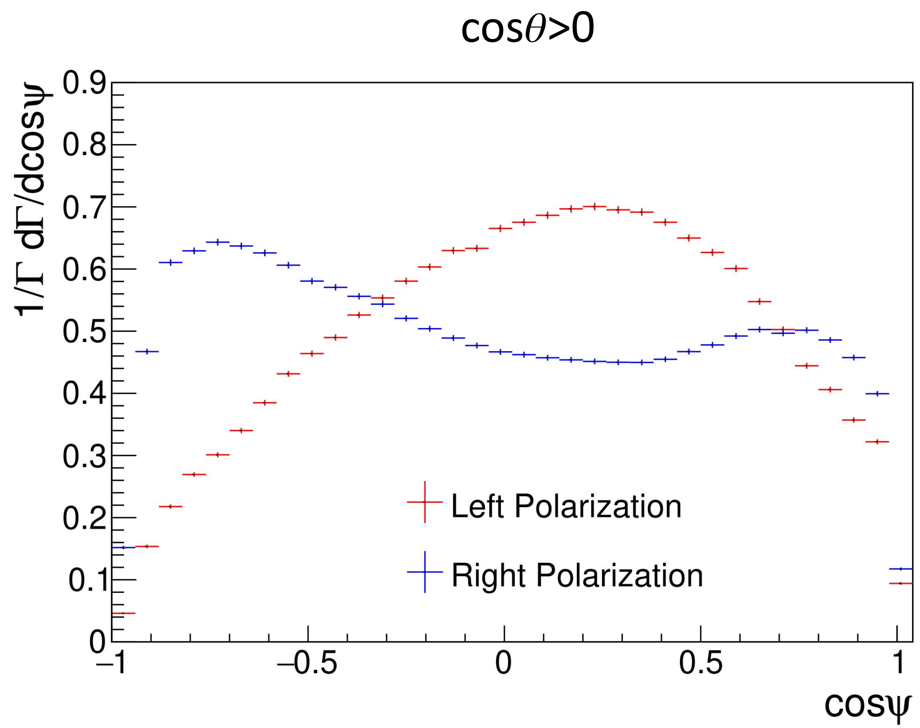
$$\cos\psi = \frac{2x-1}{\sqrt{1-4\,m_\pi^2/m_\rho^2}} \qquad x \equiv {E_{\pi^-}}/{E_\rho}$$







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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*, 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

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)

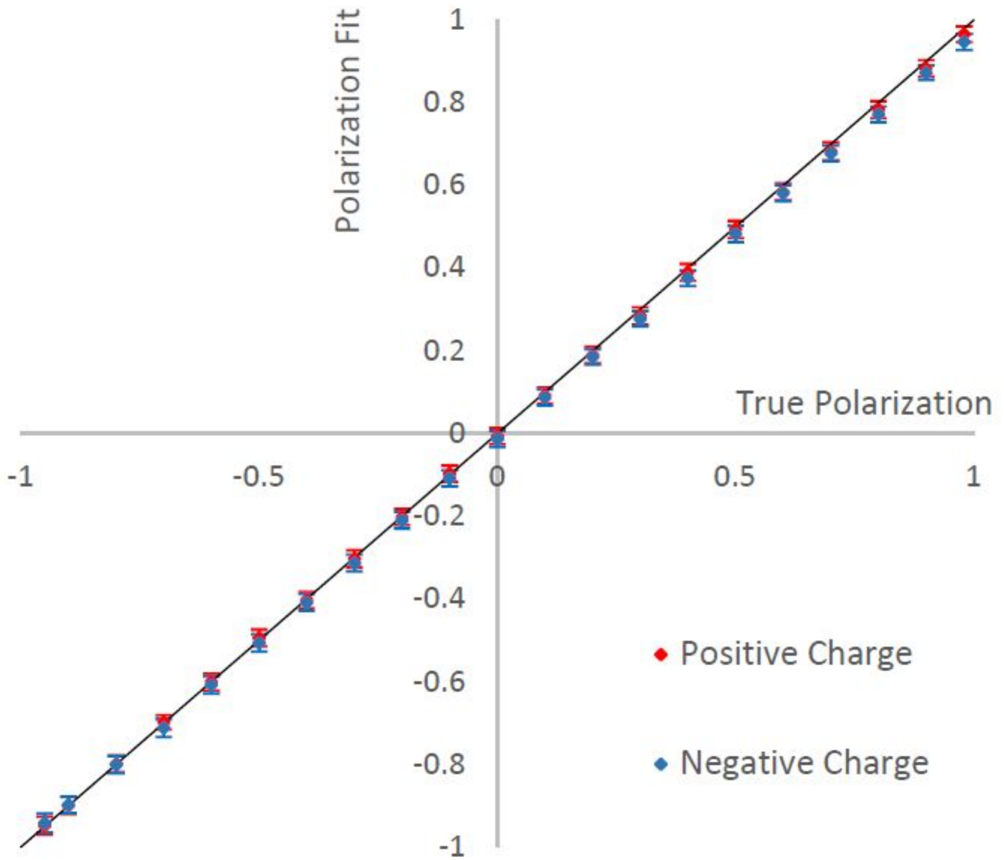
a_l	0.499
a_r	0.499
a_b	3.8×10^{-5}
a_m	1.4×10^{-3}
a_u	3.8×10^{-4}
a_c	4.8×10^{-5}

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

[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"

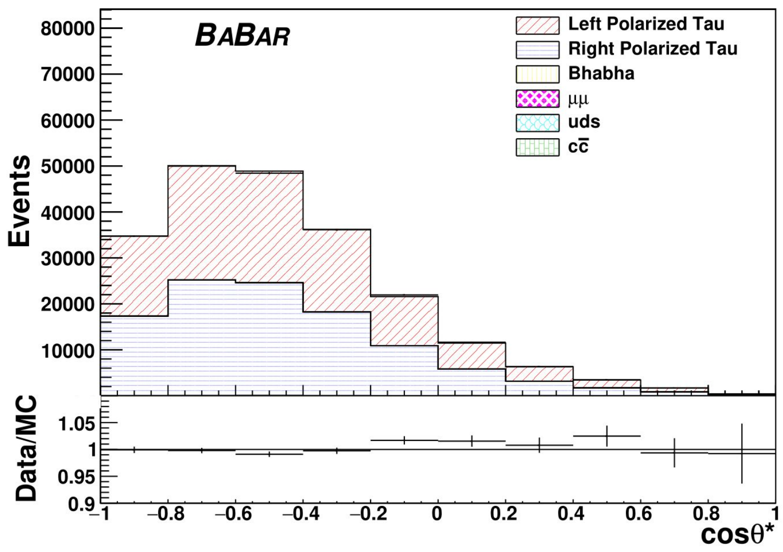
- As PEP-II had no beam polarization we performed MC studies of the polarimetry technique for arbitrary beam polarization states for validation of the method
- This is done by splitting each of the polarized tau MC samples in half
- One half of each is used to perform the polarization fit
- The other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

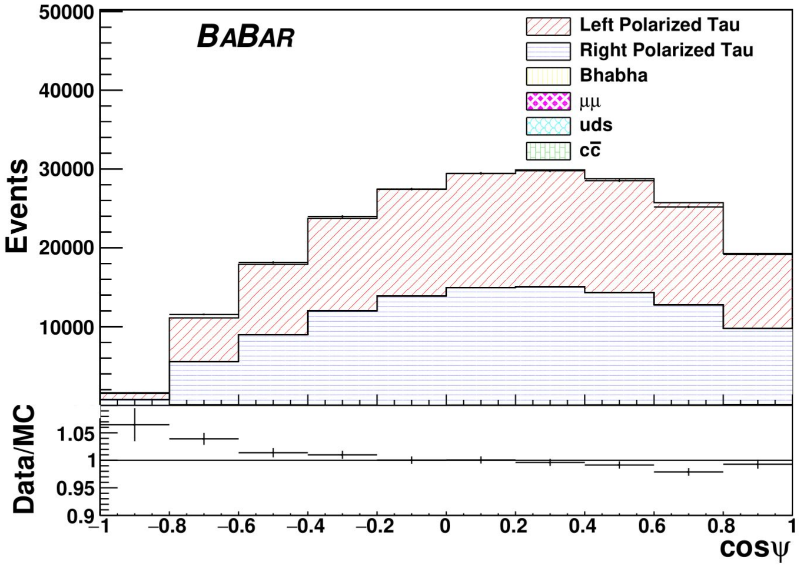


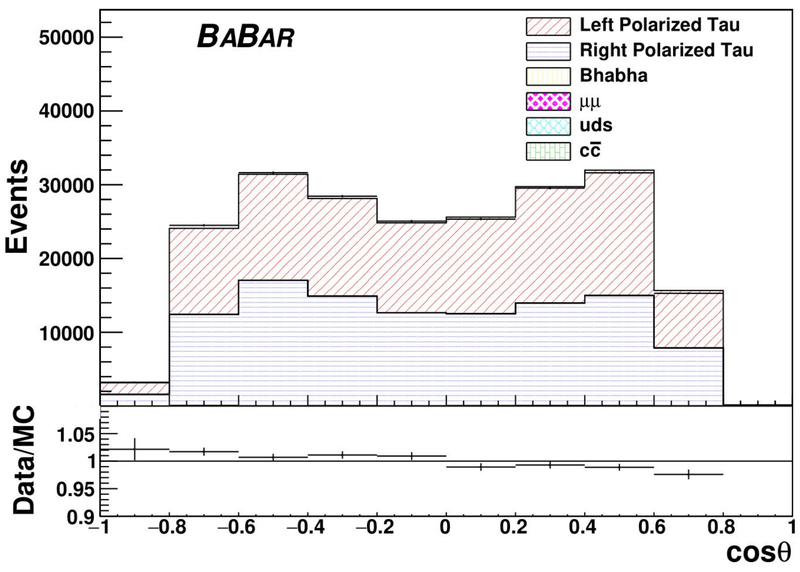
Example Fit Result

Sample	Positive	Negative	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 Run 3 fit, Negative charged signals
- <P>=0.0048







Full Measurement

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

Sample	Luminosity (fb^{-1})	Average Polarization
Run 1	20.4	0.0062±0.0157
Run 2	61.3	-0.0004±0.0090
Run 3	32.3	0.0048±0.0083
Run 4	99.6	-0.0114±0.0071
Run 5	132.3	-0.0040±0.0063
Run 6	78.3	0.0157±0.0082
Total	**424.2**	**0.0035±0.0024**

- 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
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**
$\cos\theta^*$ 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**

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

Conclusions

- *BaBar* has implemented the first application of the new Tau Polarimetery 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:

$e^+\backslash e^-$	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

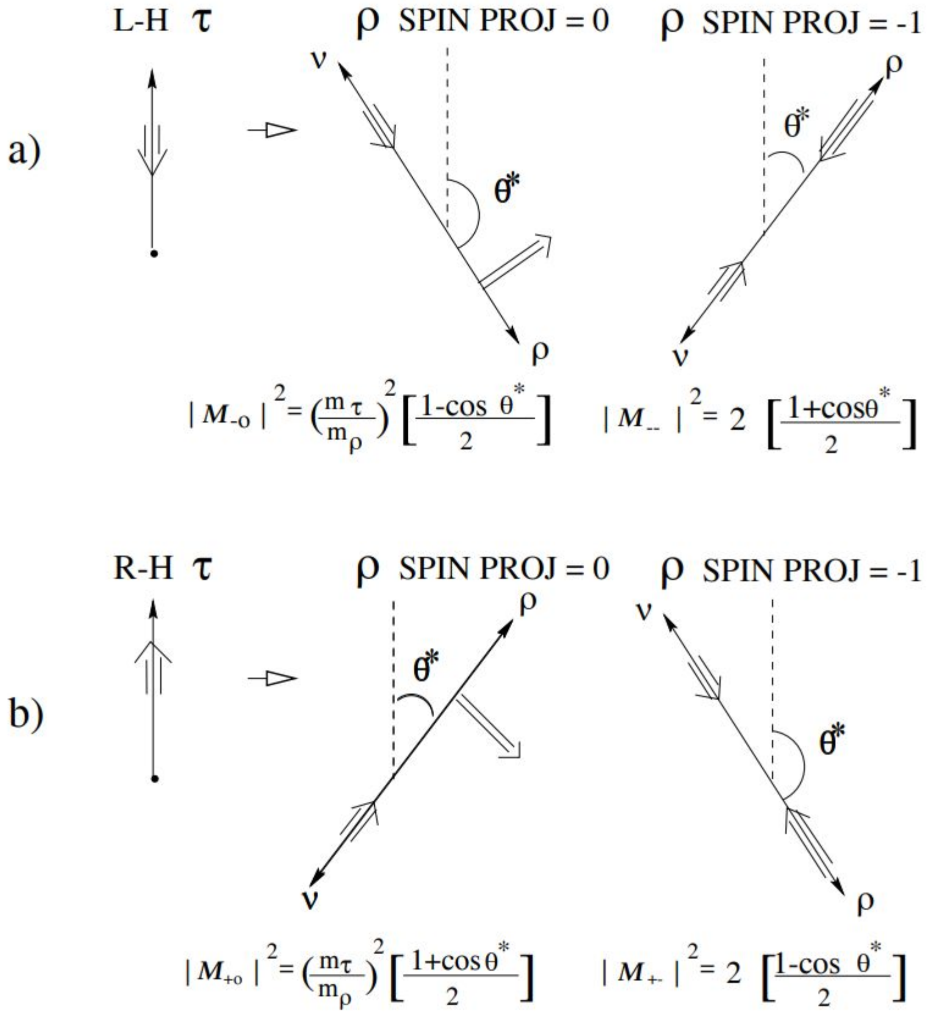
$e^+ \backslash e^-$	0.85	0.15
0.85	0.722	0.128
0.15	0.128	0.022

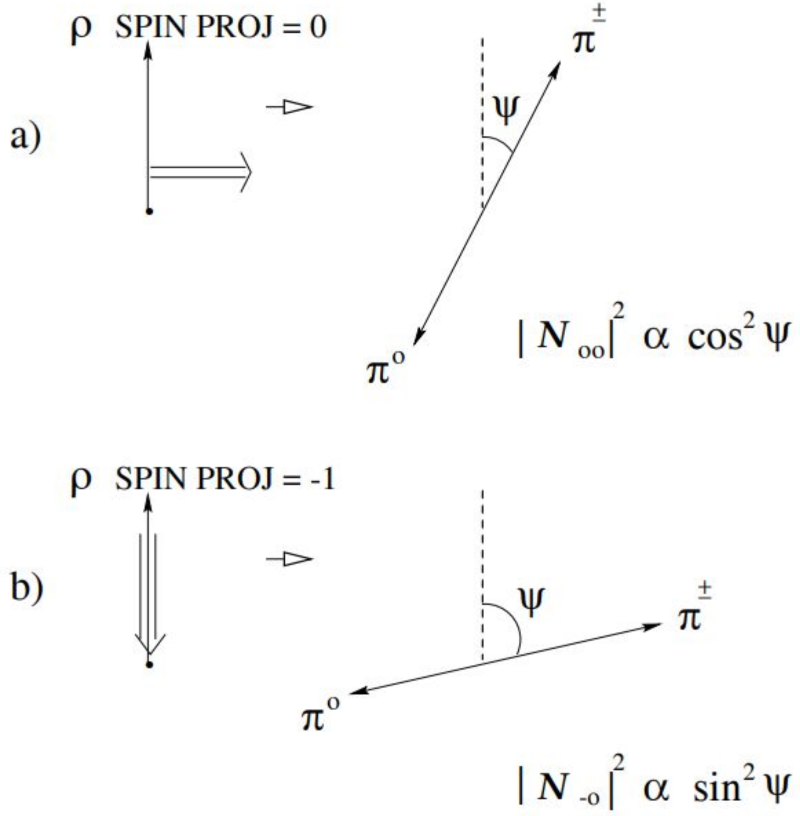
<P> = 0.940
σ = 1.49

- 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

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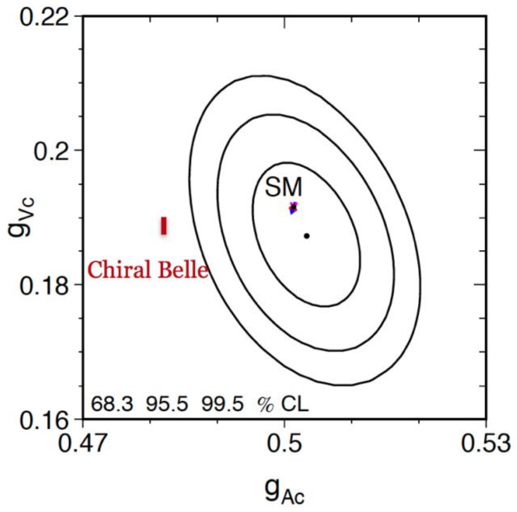
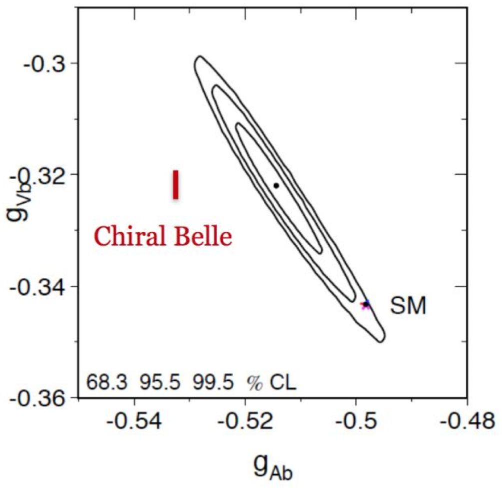
c-quark: Chiral Belle ~7 times more precise

with 20 ab⁻¹

b-quark: Chiral Belle ~4 times more precise

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