White Paper:
https://arxiv.org/abs/2205.12847

Chiral Belle

Caleb Miller

on behalf of

Belle II/SuperKEKB e- Polarization Upgrade Working Group

University of Victoria

IPP 50th Anniversary Symposium

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:

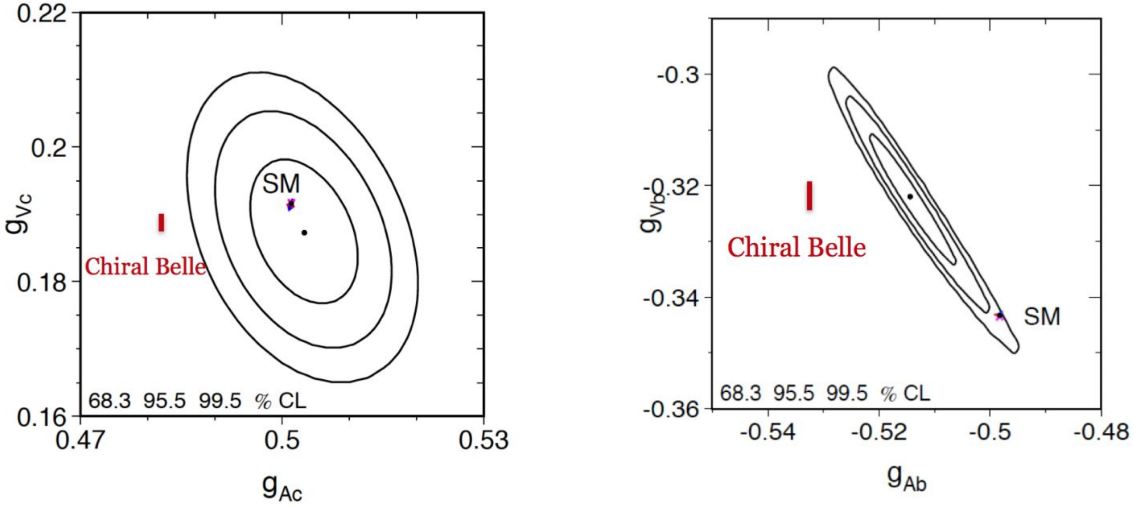
$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \frac{4}{\sqrt{2}}\left(\frac{G_F s}{4\pi\alpha Q_f}\right) g_A^e g_V^f \langle P \rangle \propto T_3^f - 2Q_f \sin^2\theta_W$$

c-quark: **with 20 ab^{-1}** **b-quark:**

Chiral Belle ~7 times more precise

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

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Dominant Systematics Cancel in Ratio

	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%

Caleb Miller. calebmiller@uvic.ca

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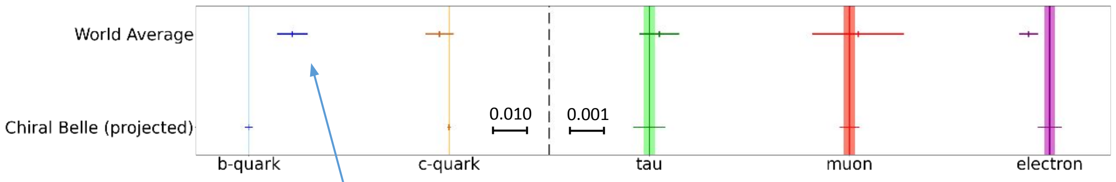
	Standard Model	*World Average*	*Chiral Belle 40ab^{-1}*
Fermion			
b-quark	-0.3437±0.0001	-0.3220 ±0.0077	0.0020(4x improvement)
c-quark	0.1920±0.0002	0.1873 ±0.0070	0.0010(7x improvement)
Tau	-0.0371±0.0003	-0.0366 ±0.0010	0.0008
Muon	-0.0371±0.0003	-0.03667±0.0023	0.0005(4x improvement)
Electron	-0.0371±0.0003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

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



2.8σ between SM and WA

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

Beam Polarization Motivation

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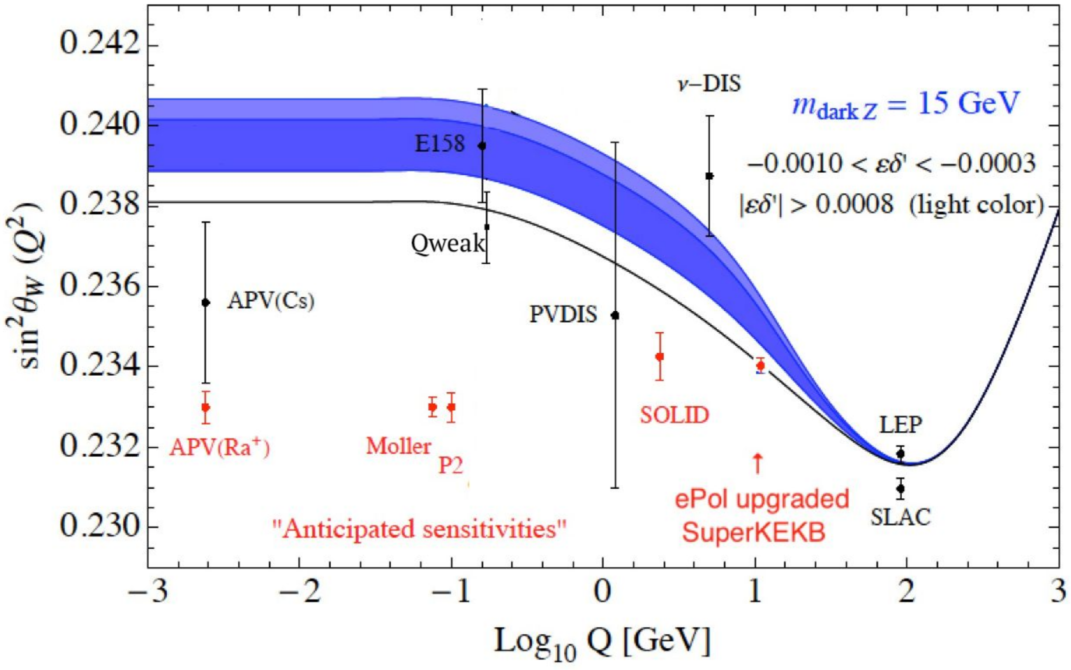

Red bars show expected sensitivity of future experiments. position arbitrary.

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

Caleb Miller. calebmiller@uvic.ca

technically

Beam Polarization Motivation

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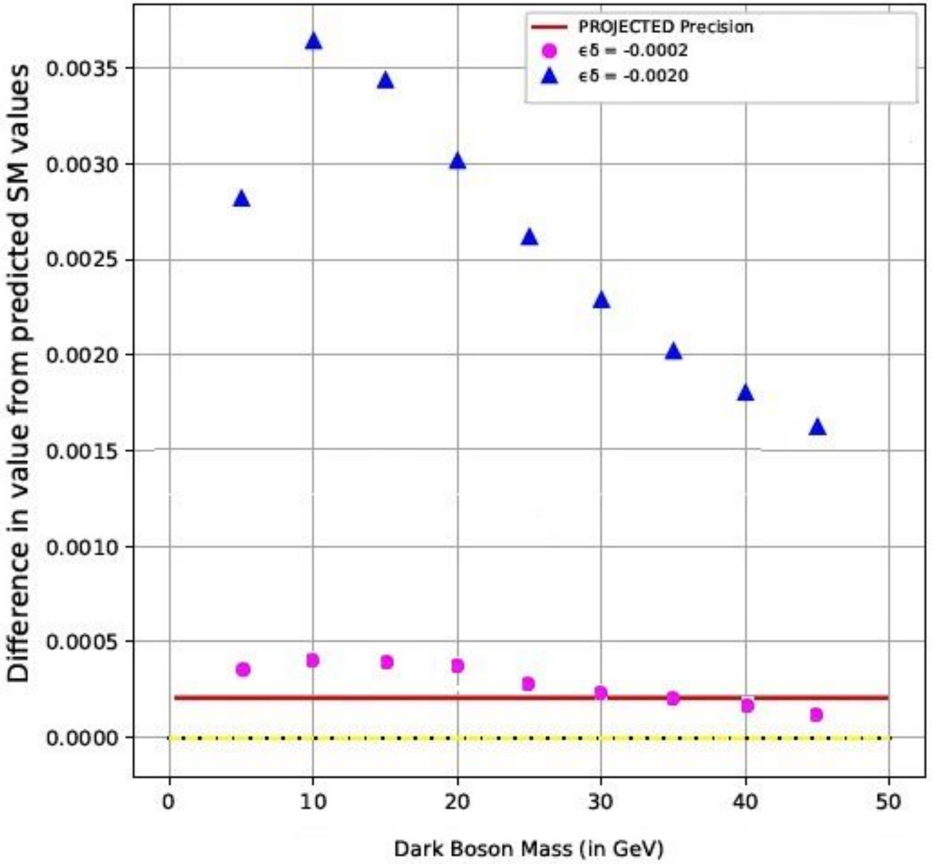

Sensitivity scales with dark Z mass and coupling strengths

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:

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

- 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

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[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 tackling this challenge

Beam Polarization Requirements

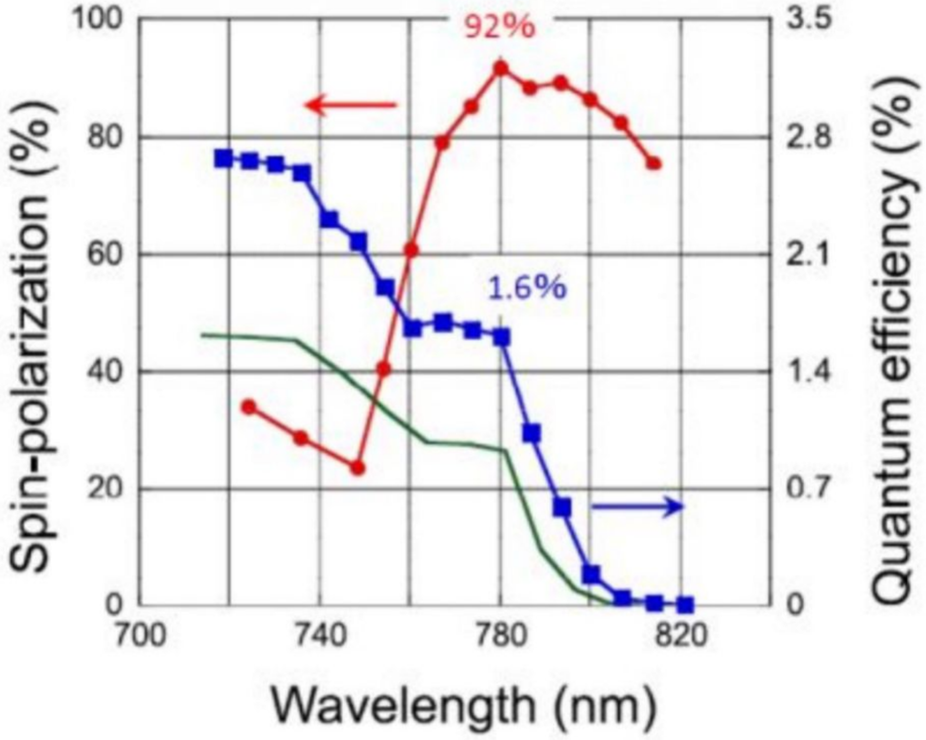
- Low Emittance Source
- Spin Rotators
- Compton Polarimeter
- Polarimetry from data

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



Caleb Miller. calebmiller@uvic.ca

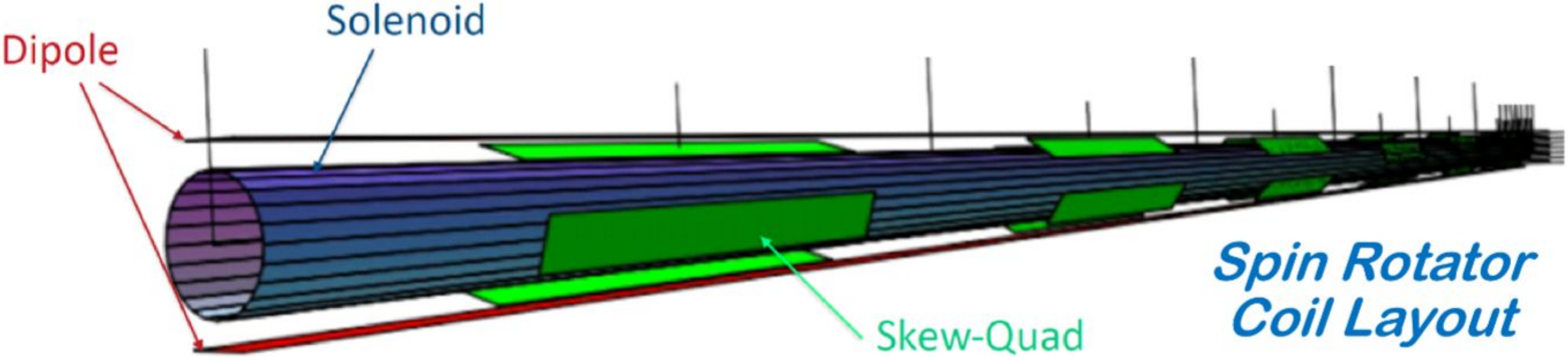
Beam Polarization Requirements

- 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

Polarization lifetime projections under study



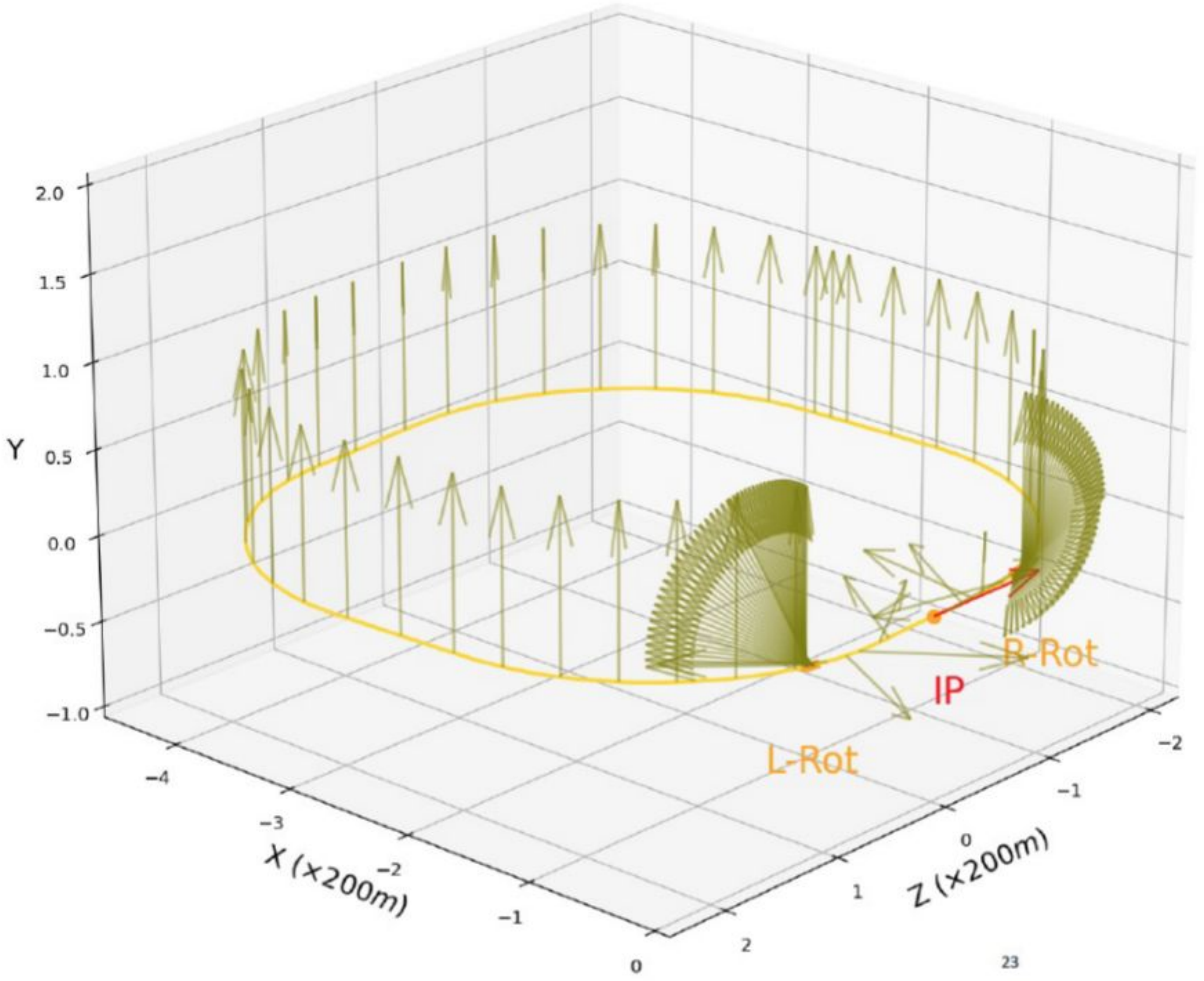
Spin Rotator Coil Layout

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



Caleb Miller. calebmiller@uvic.ca

we

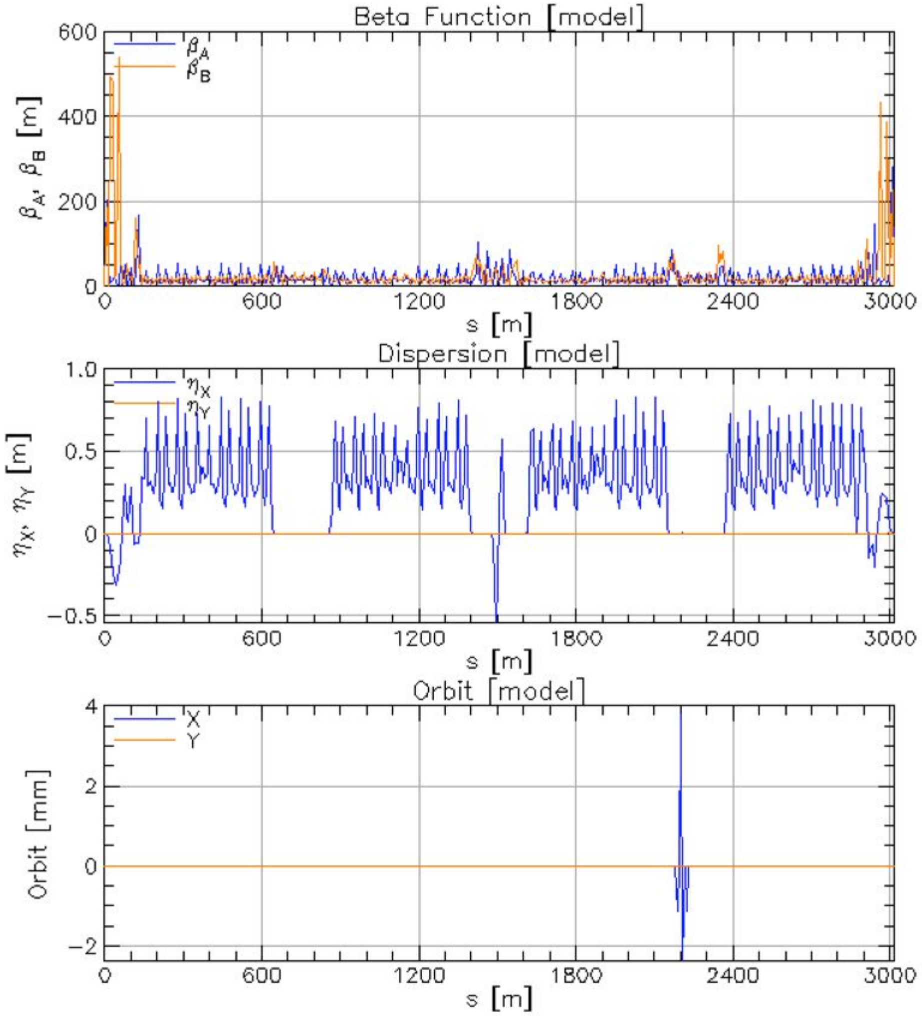
Beam Polarization Requirements

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

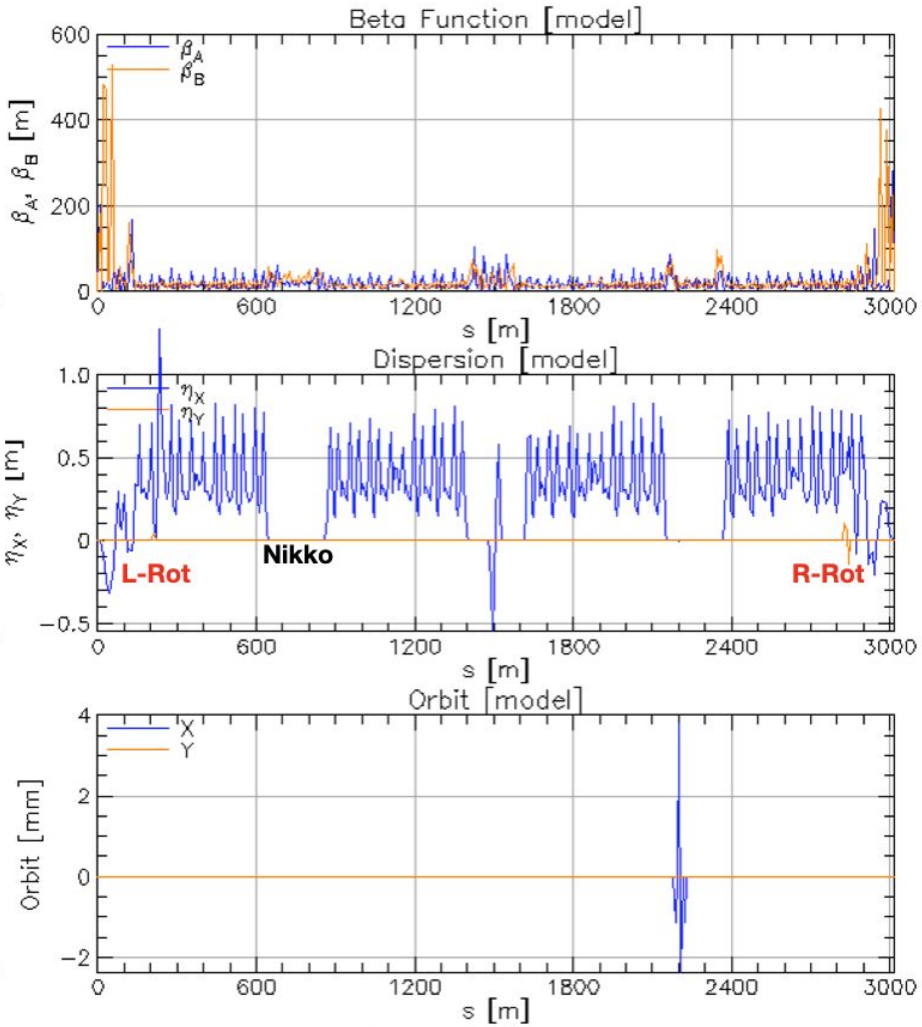
Addition of rotators has no effect on rest of beam after tuning

effectively “invisible”

Work done by UVic student Yuhao Peng



Original Ring



Rotator Ring

Caleb Miller. calebmiller@uvic.ca

call

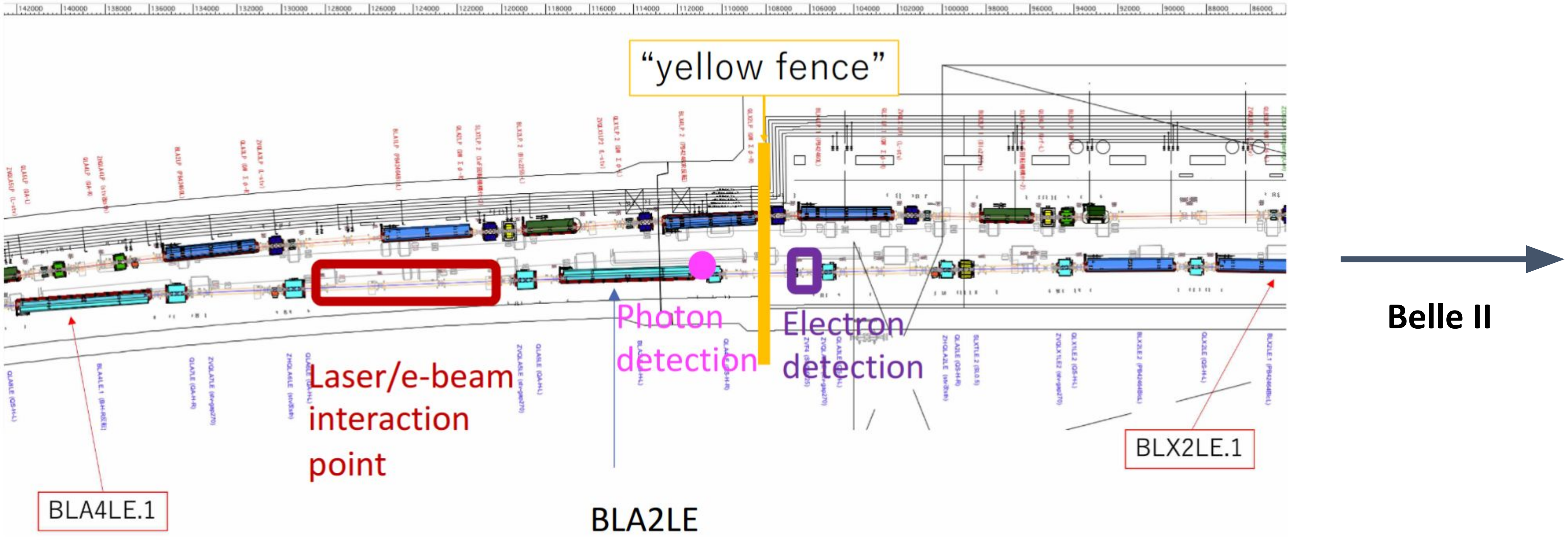
Beam Polarization Requirements

- 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



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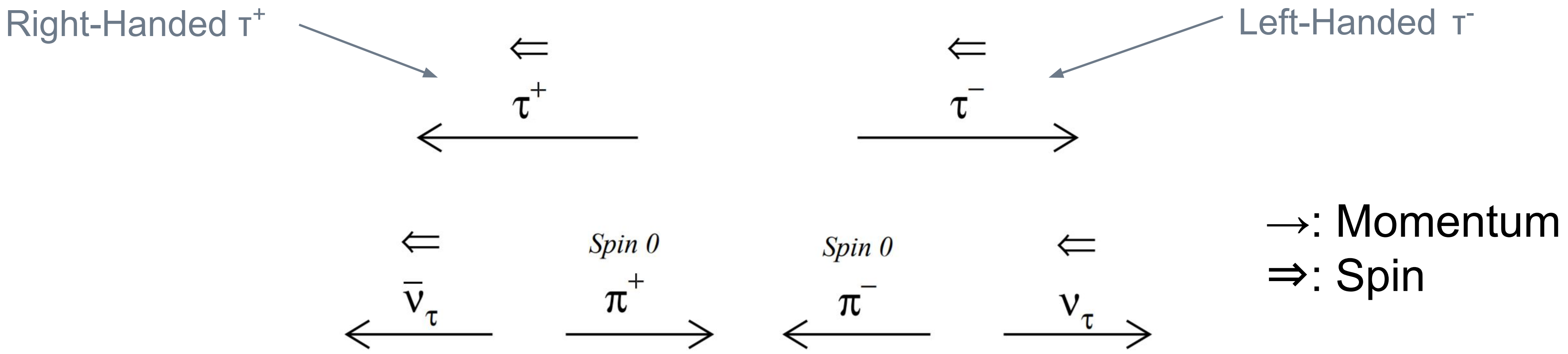
Beam Polarization Requirements

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

Electron polarization couples to Tau polarization

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

Tau decay kinematics couple to Tau polarization



Beam Polarization Requirements

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

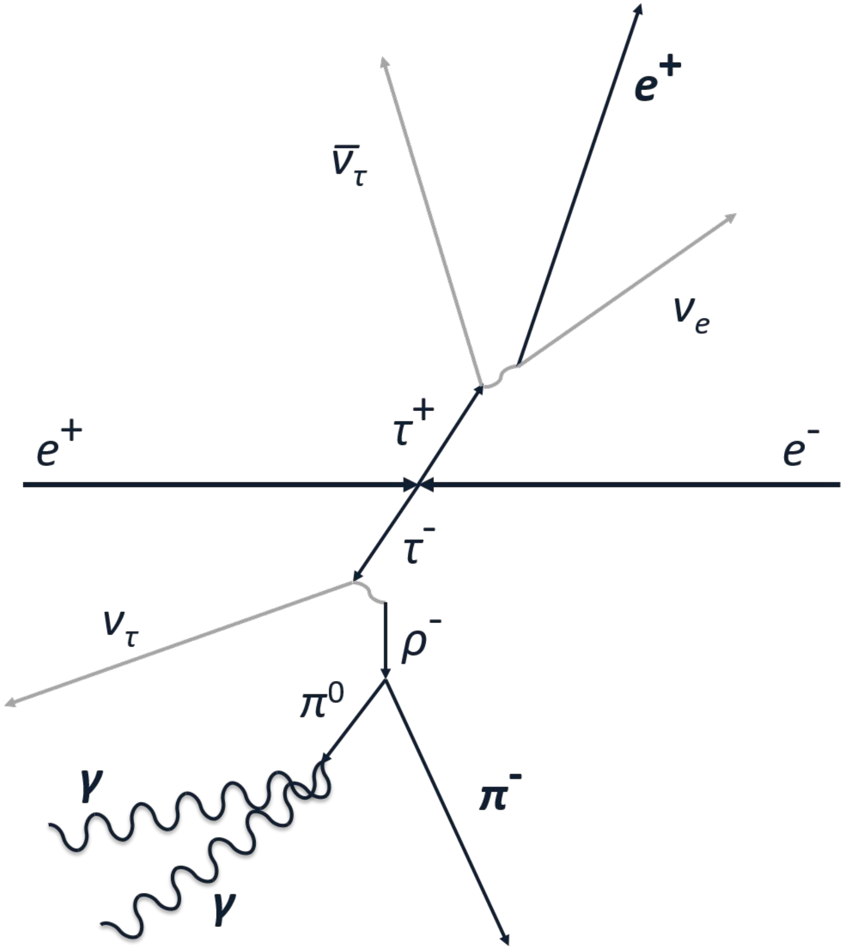
Proof of concept done at BABAR

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**

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

π^0 and Neutral Modelling dominate systematics

Tau events tagged with electron decay



Polarization extracted from rho meson

Conclusions

- Upgrading SuperKEKB with a polarized electron beam would enable Belle II (Chiral Belle) to make a number of world-leading precision measurements
- White Paper submitted to SNOWMASS (https://arxiv.org/abs/2205.12847) and no roadblocks found in the conceptual design
- Source design is on track to deliver >70% beam polarization
- Spin rotators should preserve/deliver ~100% of beam polarization
- Tau Polarimetry should provide resolution of ~0.3% on average beam polarization
- Intention is to perform upgrade during long shutdown 2, late 2020’s

more details at FPCP 2022
talk by C. Miller

Chiral Belle design looks ready to start spinning up

Backup Slides

Caleb Miller. calebmiller@uvic.ca

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

Caleb Miller. calebmiller@uvic.ca

Tau g-2

- A mismatch in the Pauli form factor Re(F_2) can be interpreted as a BSM a^τ
- Experimentally two polarization terms can be measured, a transverse (A_T) and longitudinal (A_L) asymmetry
- Both terms are dependent on F_1 and F_2, so F_1 can be largely cancelled with the following combination

$$\mathrm{Re}\left(F_2^{eff}\right) = \mp\frac{8(3-\beta^2)}{3\pi\gamma\beta^2\alpha^\pm}\left(A_T^\pm - \frac{\pi}{2\gamma}A_L^\pm\right)$$

- Where ± refers to the τ charge, $\gamma = 1/\sqrt{1-\beta^2} = E_\tau/m_\tau$, $\alpha^\pm = (m_\tau^2 - 2m_{h^\pm}^2)/(m_\tau^2 + 2m_{h^\pm}^2)$

- Precision on future measurement is limited by knowledge of m_τ and $M_{\Upsilon(1S)}$
- Current limits on these quantities limit a measurement of a^τ to ~$1\mathrm{x}10^{-5}$
- Motivates precision measurements of these quantities ahead of or soon following beam polarization

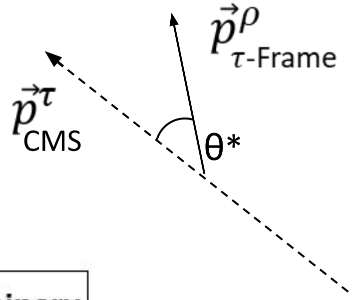
Caleb Miller. calebmiller@uvic.ca

Polarization Observables

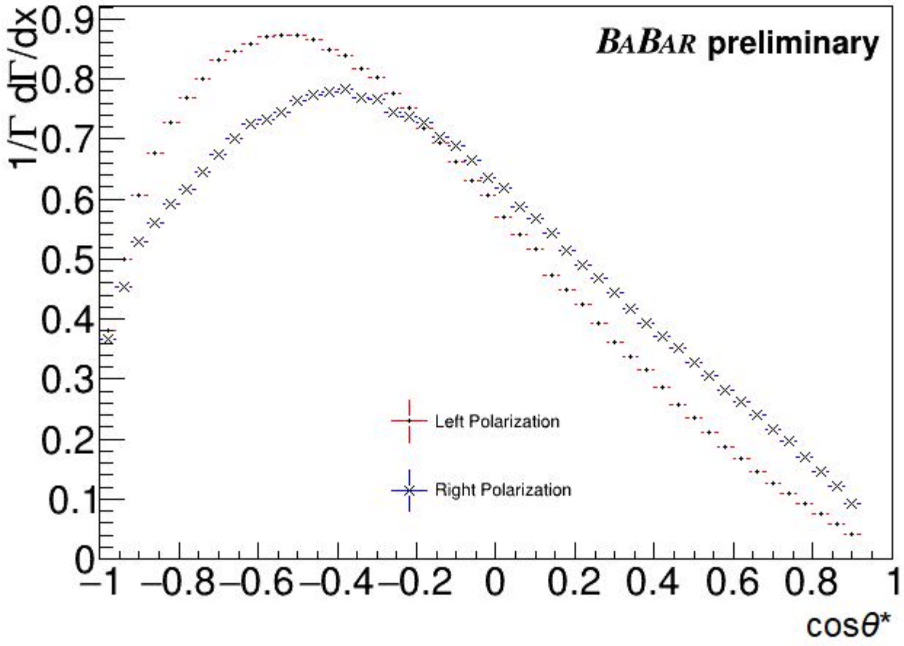
- Polarization sensitivity in a rho decay is maximized by analyzing two angular variables[2] in addition to cosθ

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

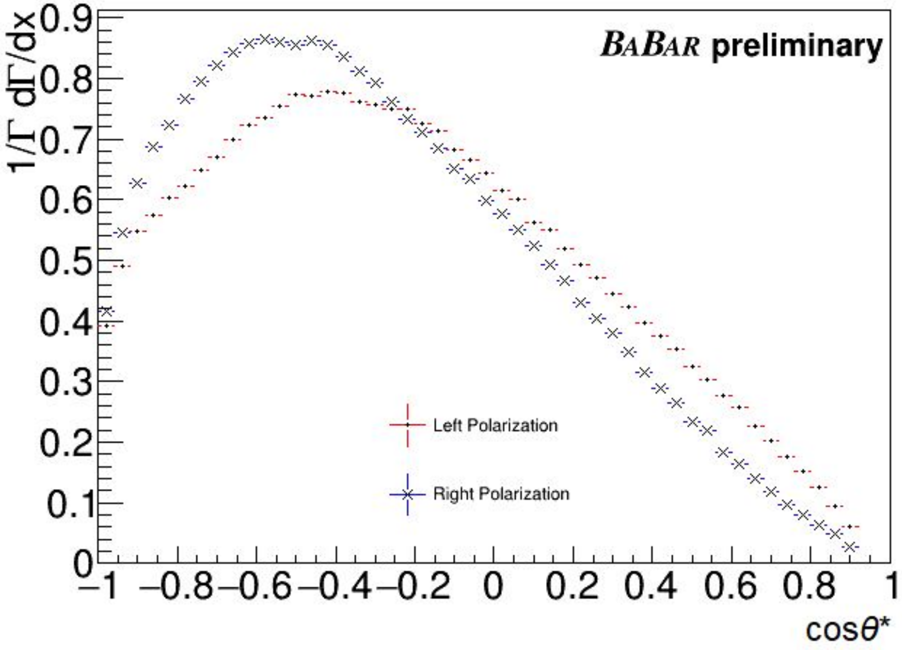
$$z \equiv {}^{E_\rho}\!/_{E_{\text{beam}}}$$



cosθ<0



cosθ>0



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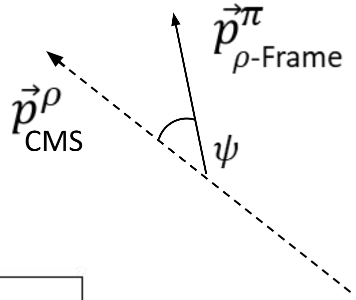
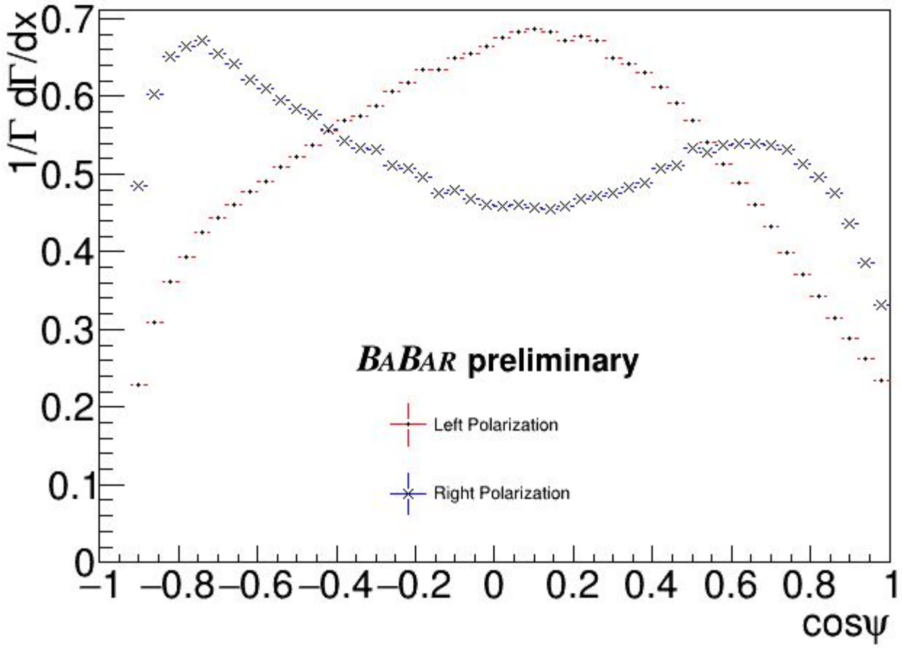
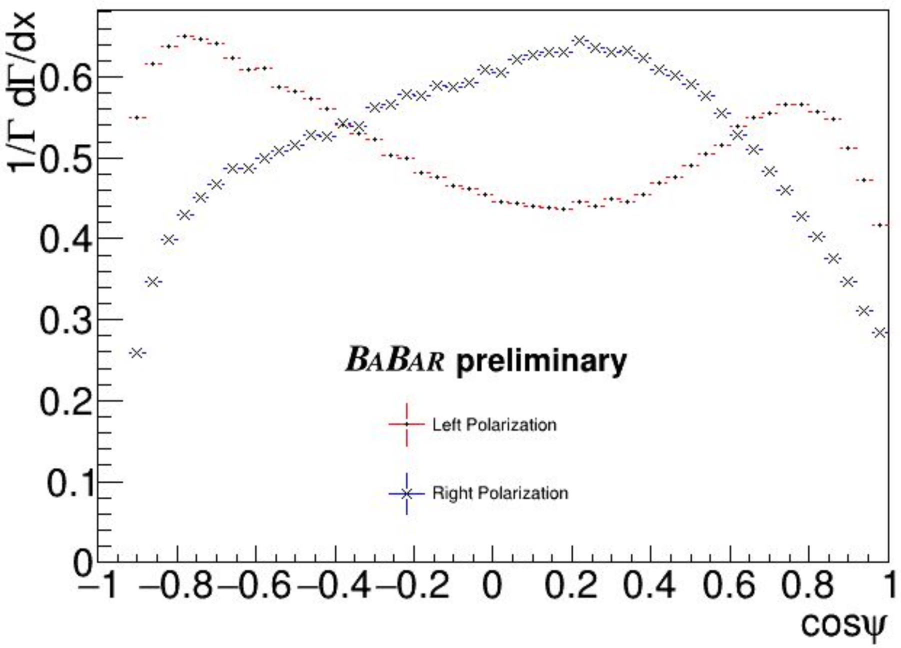
$$\cos\psi = \frac{2x-1}{\sqrt{1-4m_\pi^2/m_\rho^2}} \qquad x \equiv E_\pi / E_\rho$$



cosθ<0



cosθ>0



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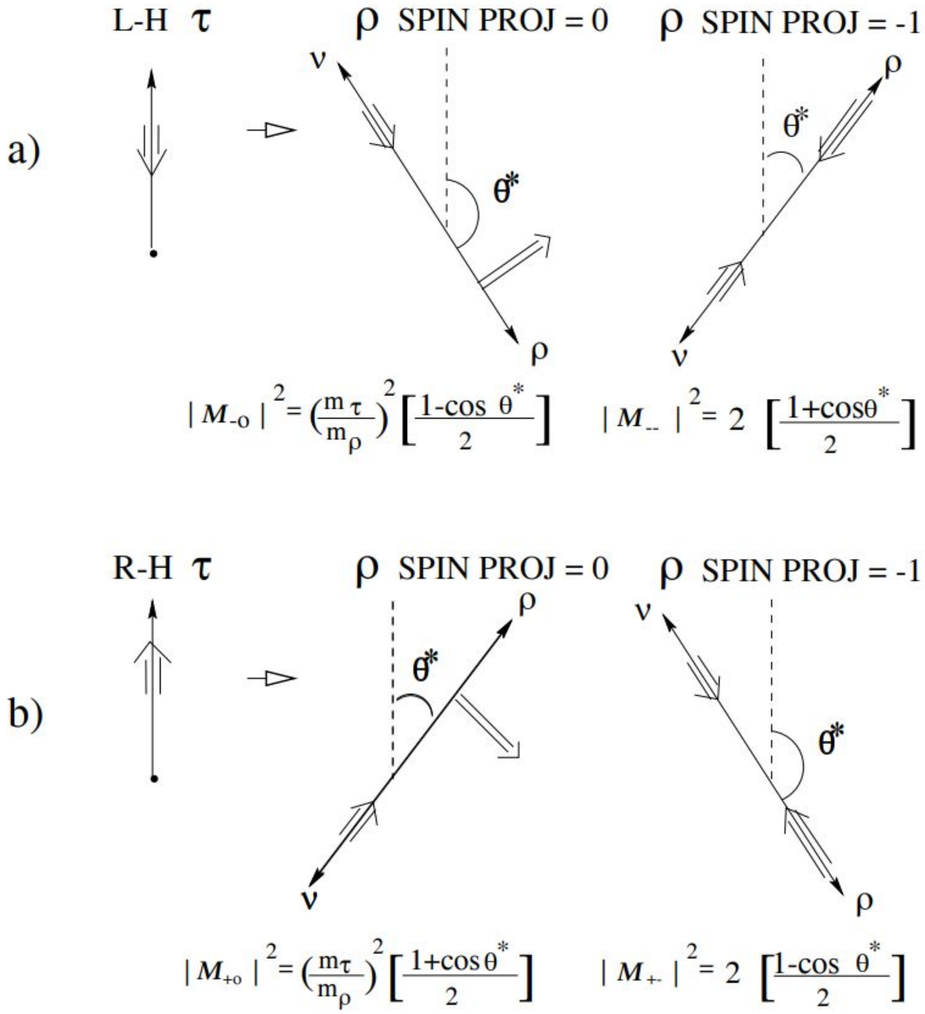
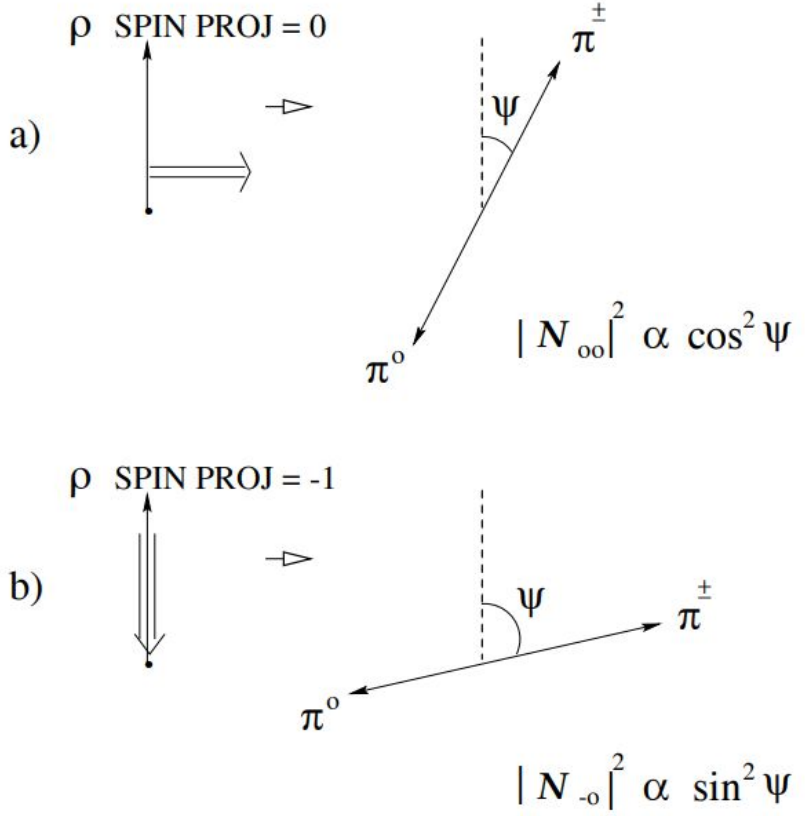
Rho Spin Analysis

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





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

Caleb Miller. calebmiller@uvic.ca

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}

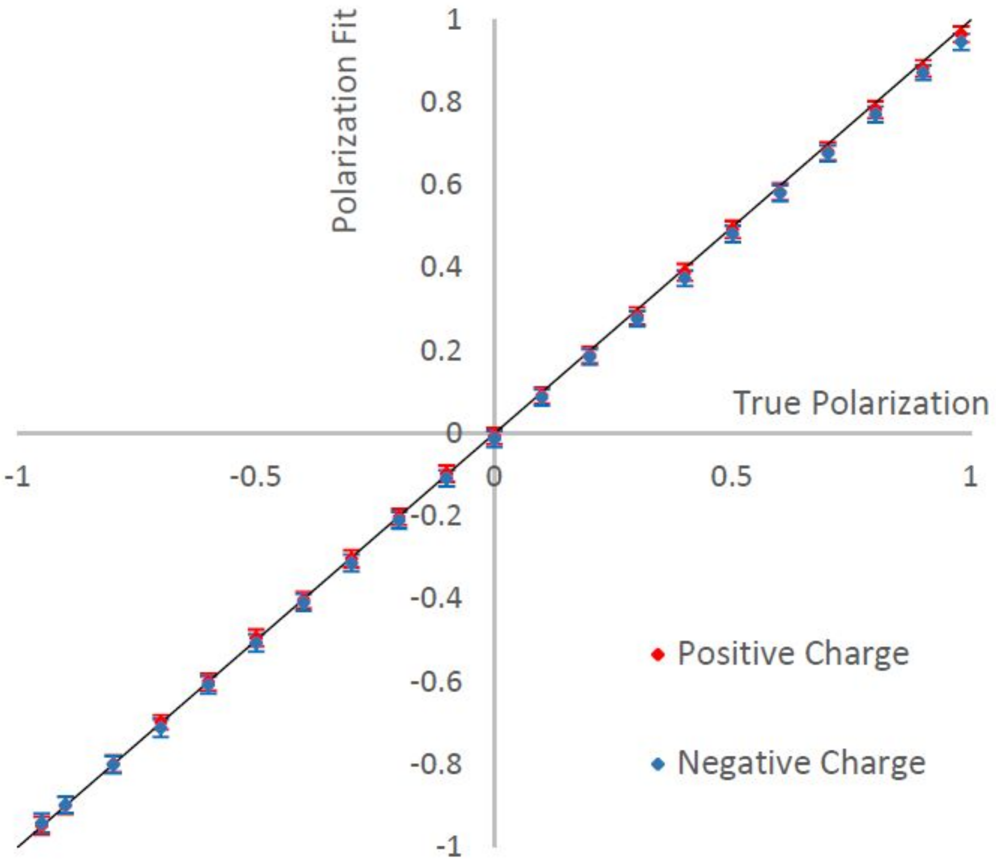
D=data L=Left Polarized Tau MC R=Right Polarized Tau MC B=Bhabha(e^+e^-) M=μμ U=uds C=$c\bar{c}$

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

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



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Full Measurement

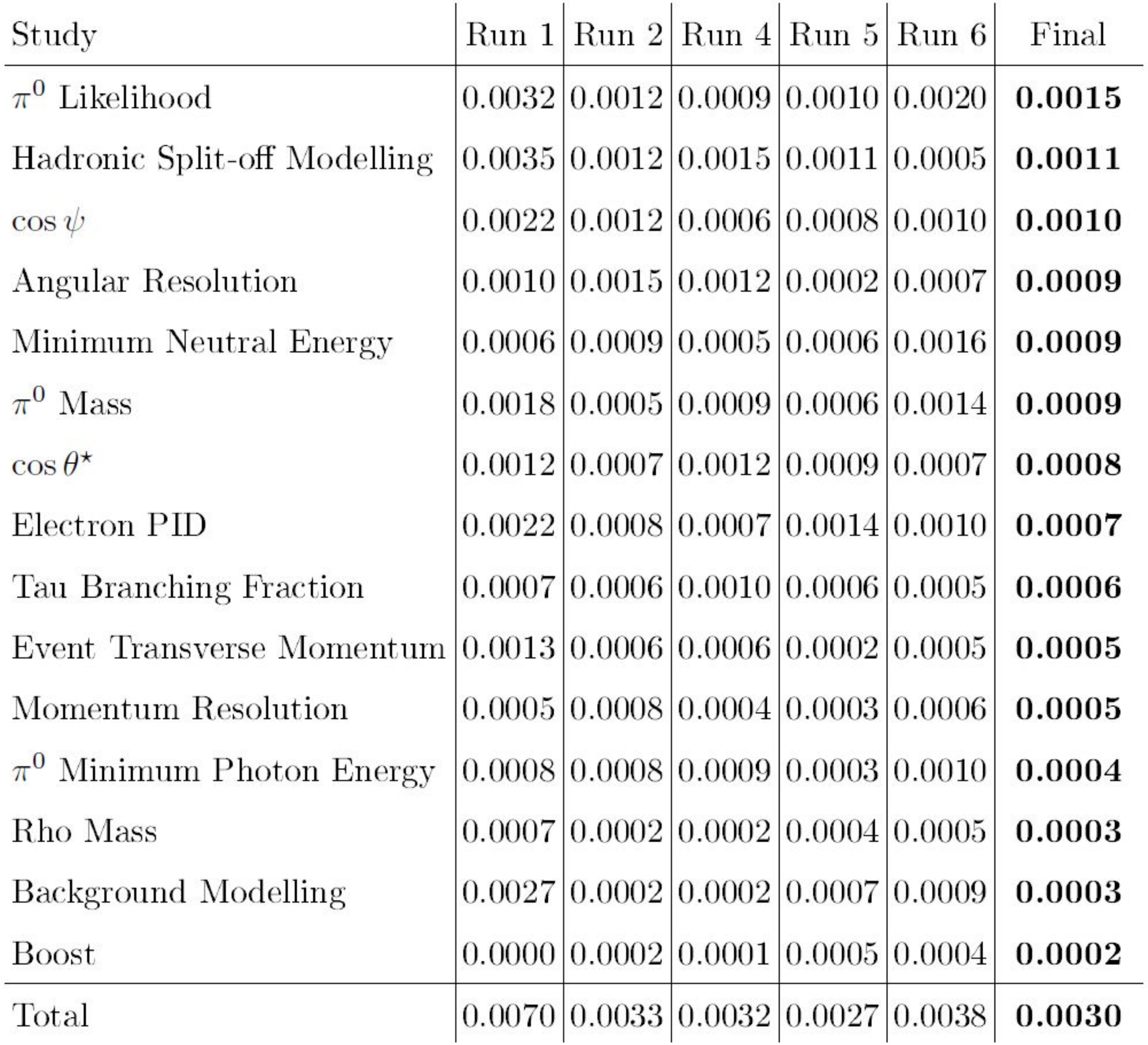
- Performing the measurement on the remaining data, 391.9 fb^{-1}

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**

Caleb Miller. calebmiller@uvic.ca