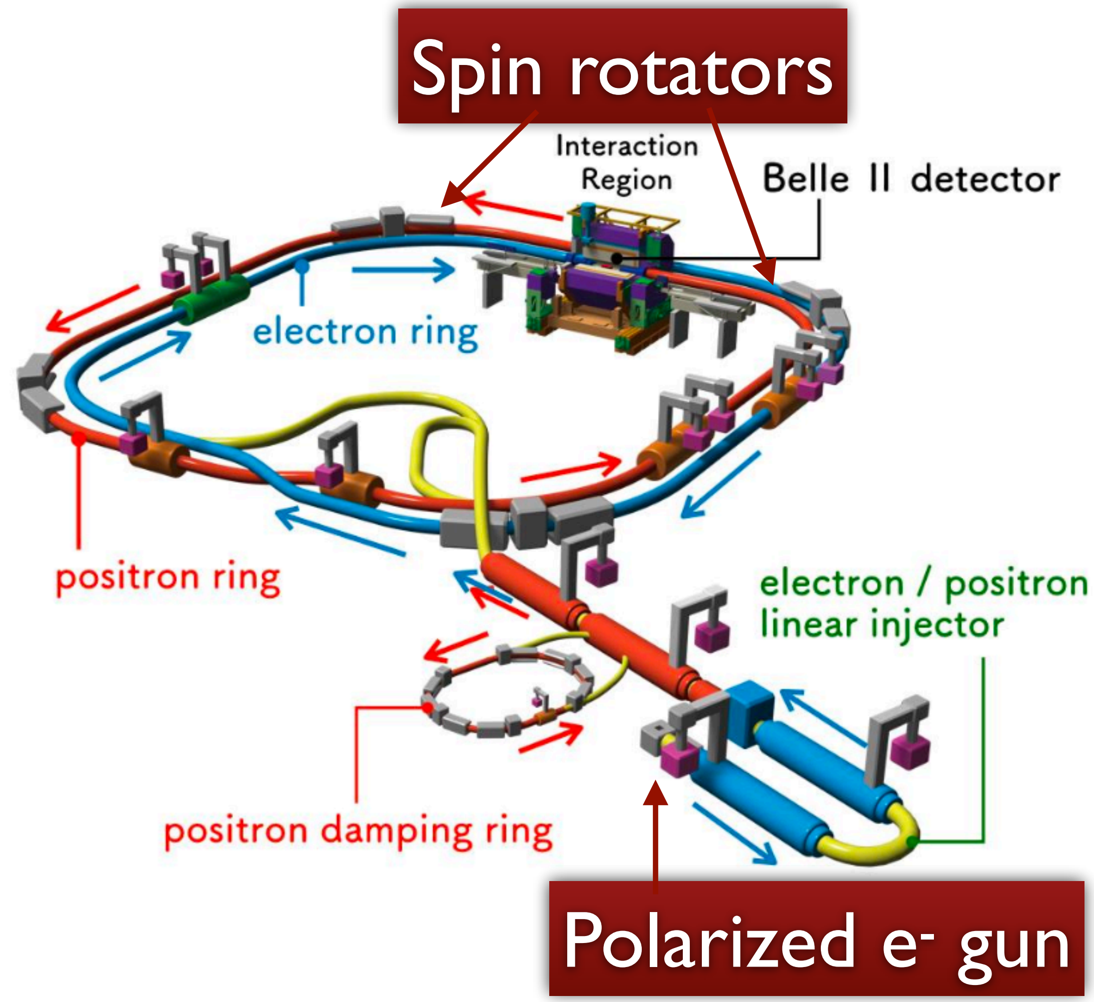
# Measurement of beam polarization at $e^+e^-$ B-Factory with a new tau polarimetry technique

*Swagato Banerjee*

UNIVERSITY OF LOUISVILLE

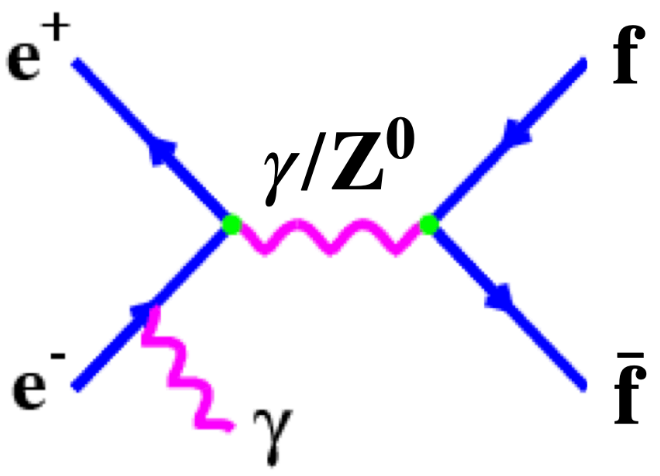
## Rich physics program via beam polarization upgrade of SuperKEKB


**Snowmass**
**WhitePaper**
**2205.12847**




- Goal is 70% longitudinal polarization of e$^-$ beam at interaction point (IP)
- Precise control of beam polarization:
  - Compton Polarimeter: Moller scattering
  - Tau Polarimetry: independent of spin and beam transport model

# Precision electroweak physics



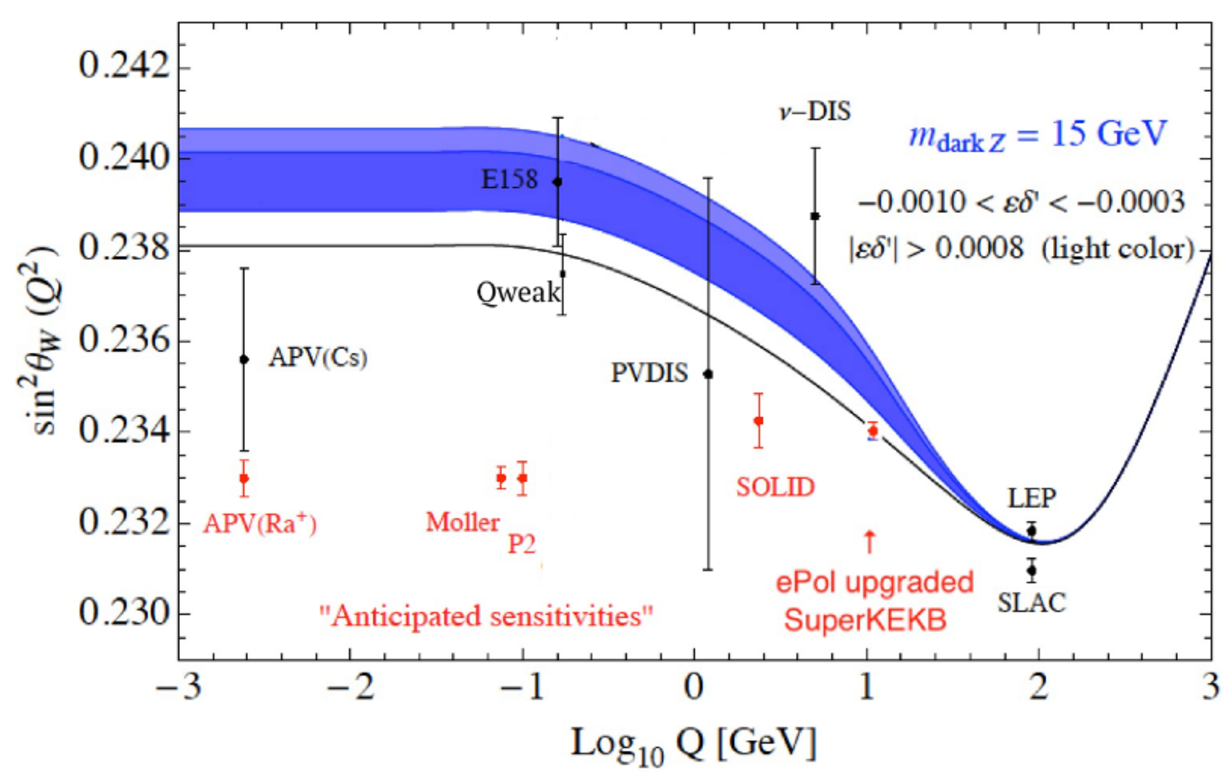

$\sigma_{L,R}$: cross-section of $e^-_{L,R} + e^+ \rightarrow X$

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




Dark blue band shows $Q^2$-dependent shift in $\sin^2\theta_W$ due to a 15 GeV parity-violating dark-Z

- Adapted from Fig. 3 of H. Davoudiasl, H.S. Lee and W.J. Marciano, Phys.Rev.D 92 (2015) 05505.
- Red bars shows expected ±1 sigma uncertainty = 0.0002 with 40 $\mathrm{ab}^{-1}$ at Chiral Belle [placed at arbitrary positions].
- Also sensitive to parity violation induced by exchange of heavy particles e.g. a hypothetical TeV-scale Z' boson, which couples only to lepton and are uniquely produced at e+e- colliders and not in pp collisions.

# Tau Polarimetry

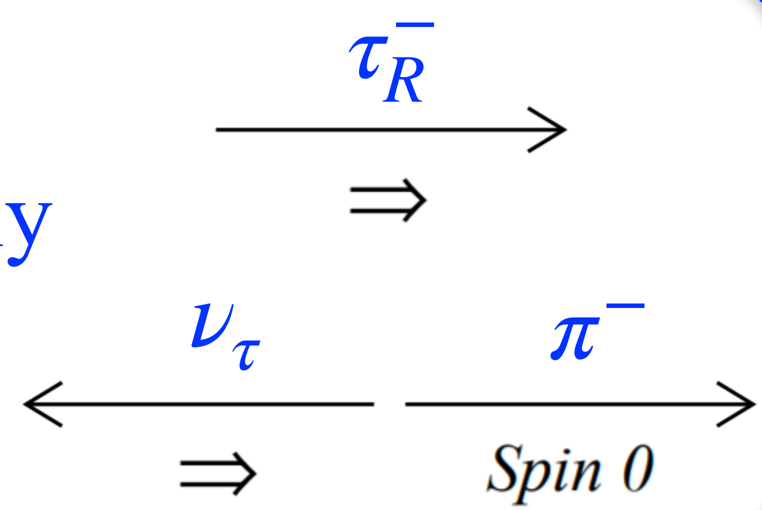
- Polarization of $\tau's$ ($P_\tau$) related to polarization of $e^-$ beam ($P_e$)

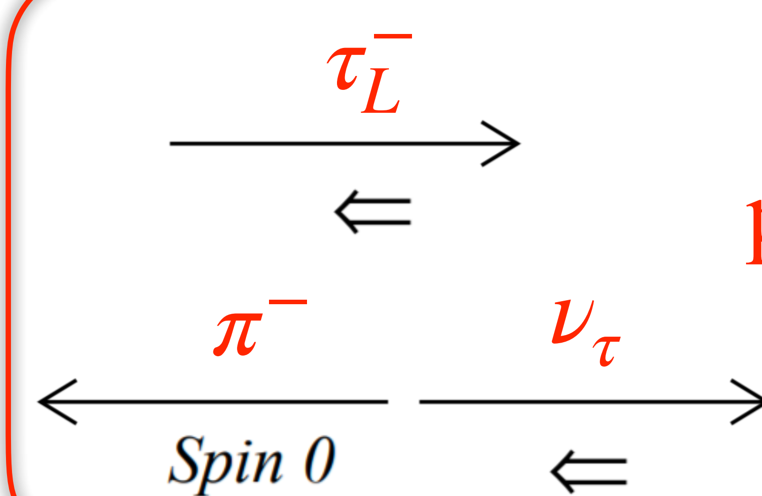
$$P_{\tau^-} = P_e \underbrace{\frac{\cos\theta}{1+\cos^2\theta}}_{\text{EM term}} - \underbrace{\frac{8G_F s g_V^\tau}{4\sqrt{2}\pi\alpha}\left(g_A^\tau \frac{|\vec{p}|}{p^0} + 2g_A^e \frac{\cos\theta}{1+\cos^2\theta}\right)}_{\substack{\text{Electroweak correction} \\ \sim 0.003}}$$

$\theta$ is the polar angle of $\tau^-$ with respect to the $e^-$ beam

- $\langle P_\tau \rangle$ from decay products in $\tau^- \to \pi^- \nu_\tau$ decays

$\pi^-$ from $\tau_R^-$ preferentially forward (fast)



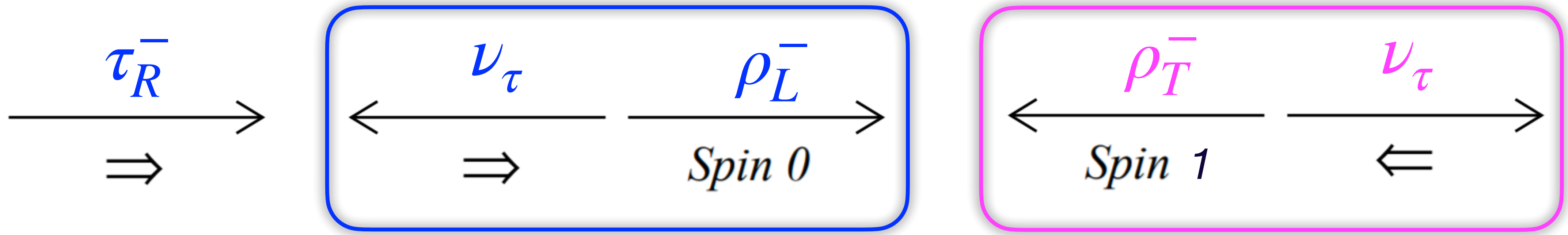

$\pi^-$ from $\tau_L^-$ preferentially backward (slow)

$\rightarrow$: Momentum
$\Rightarrow$: Spin ½

# Tau Polarimetry

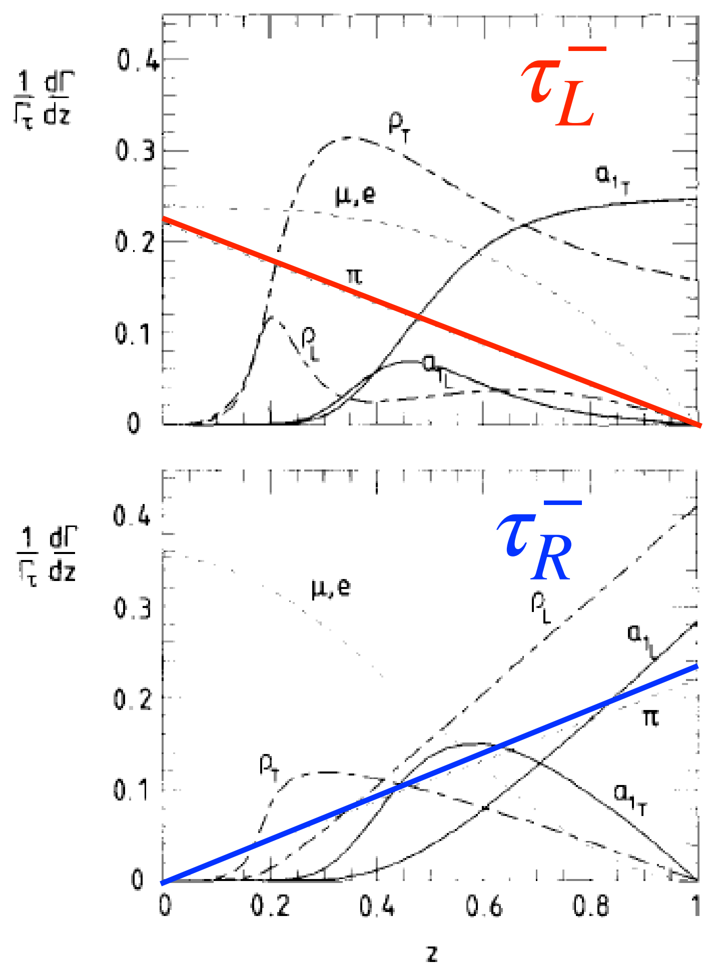
- Also for $\tau^- \to \nu_\tau \rho^-(\to \pi^- \pi^0)$, $\tau^- \to \nu_\tau a_1^-(\to \pi^- \pi^0 \pi^0)$ decays

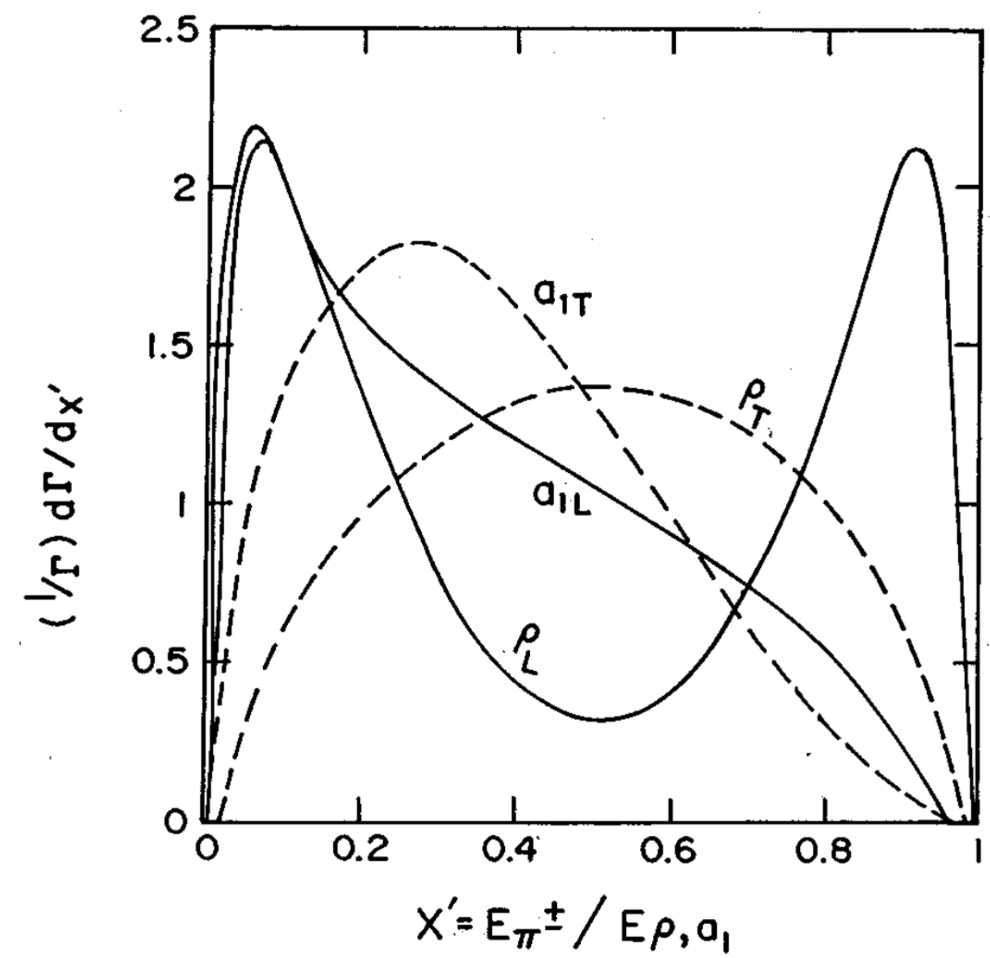
→: Momentum
⇒: Spin½




- $\langle P_\tau \rangle$ measured from kinematics of tau decay products

z: fraction of visible energy in $\tau$ decay



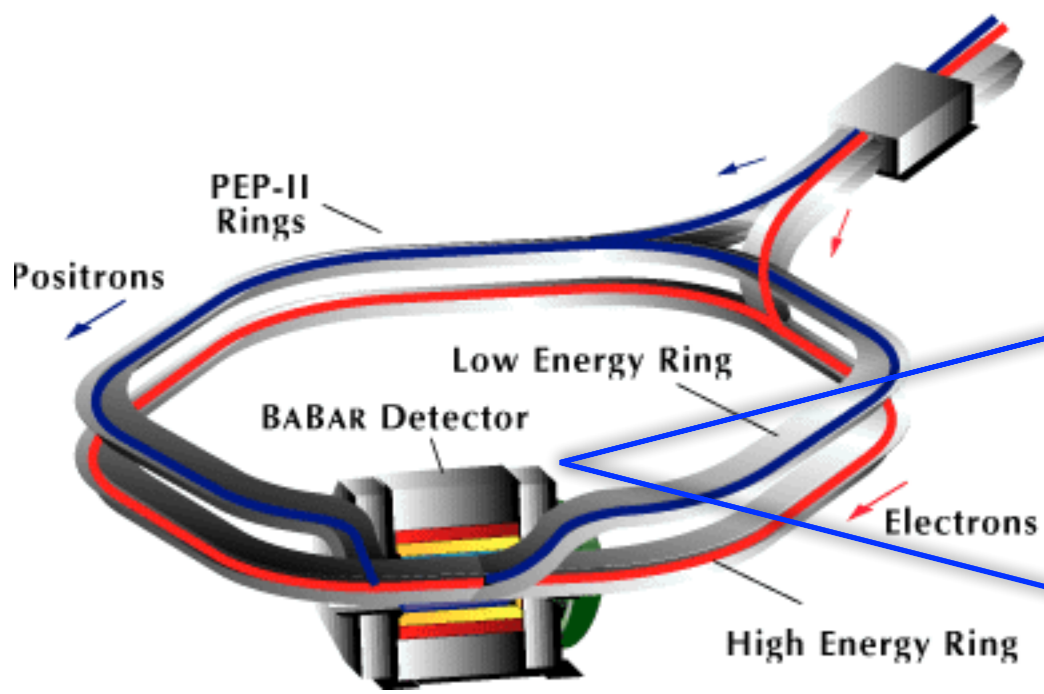




Bullock, Hagiwara, Martin Nucl. Phys. B395 (1993) 499

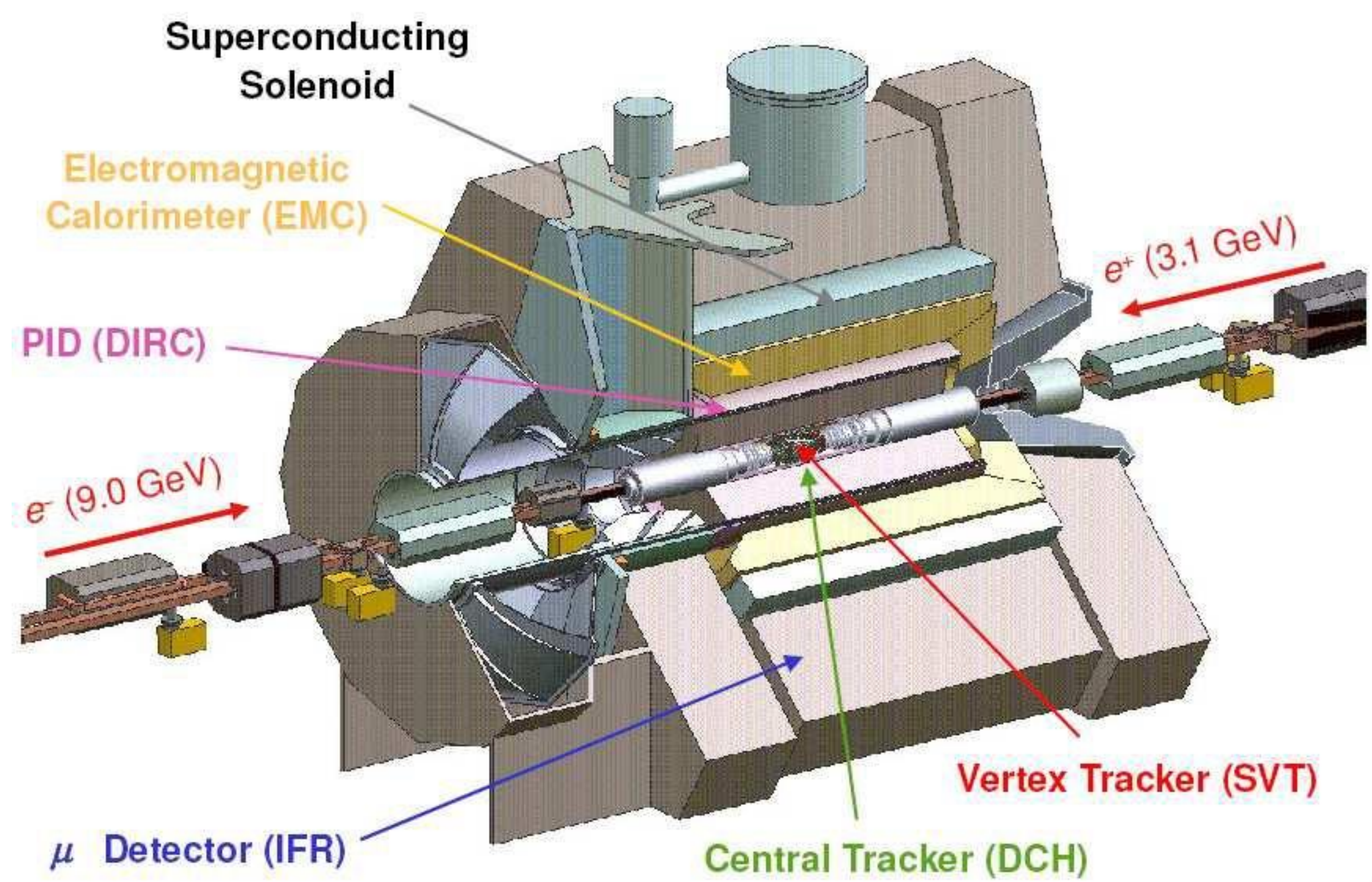
S.Raychaudhuri, D.P.Roy Phys. Rev. D53 (1996) 4902

# BaBar at PEP-II

- BaBar & PEP-II operated at SLAC between 1999 and 2008

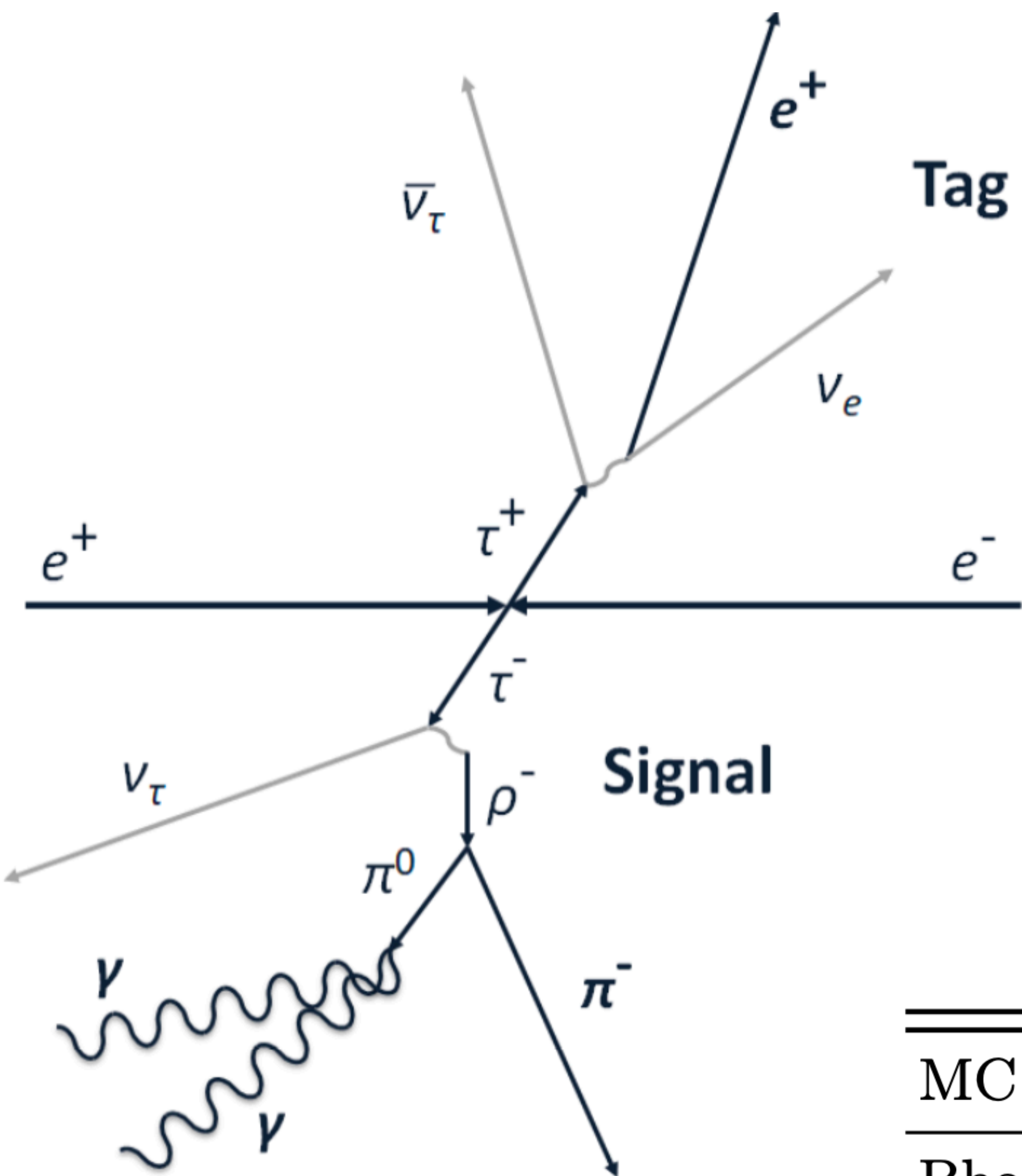



The BaBar detector




- This analysis uses 432 $fb^{-1}$ of data over 6 run periods at $\Upsilon(4S)$
- No beam polarization expected at PEP-II

# Event topology

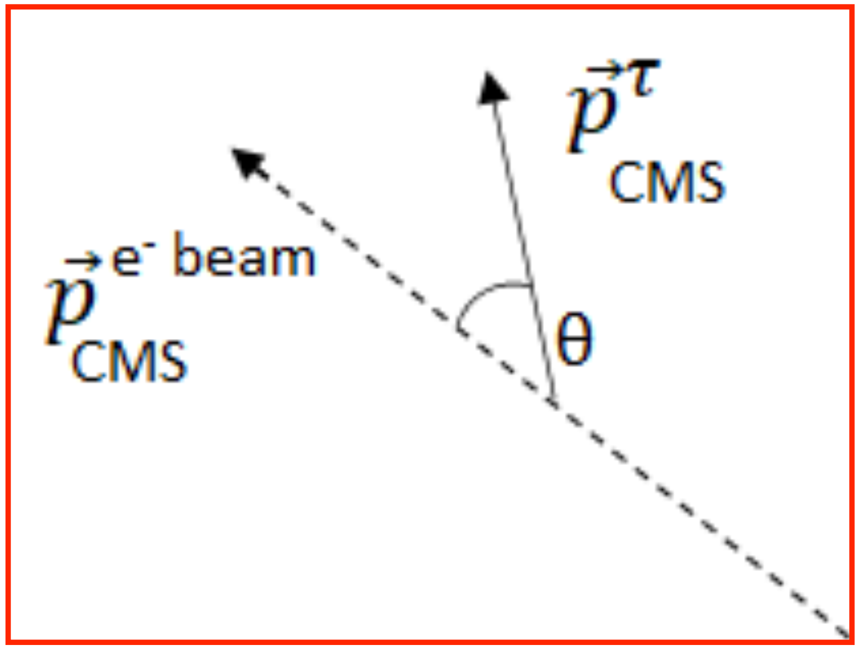



- Events selected in 1-vs-1 topology perpendicular to the thrust axis
- Tag-side: $\tau^+ \to \ell^+ \nu_\ell \bar{\nu}_\tau$ $(\ell = e, \mu)$
- Signal-side: $\tau^- \to \pi^- \pi^0 \nu_\tau$
- Charged tracks required to lie within acceptance of calorimeter
- Opening angle between charged and neutral pions satisfies $\cos\alpha < 0.9$
- 5.5 million $\tau$-pair events selected

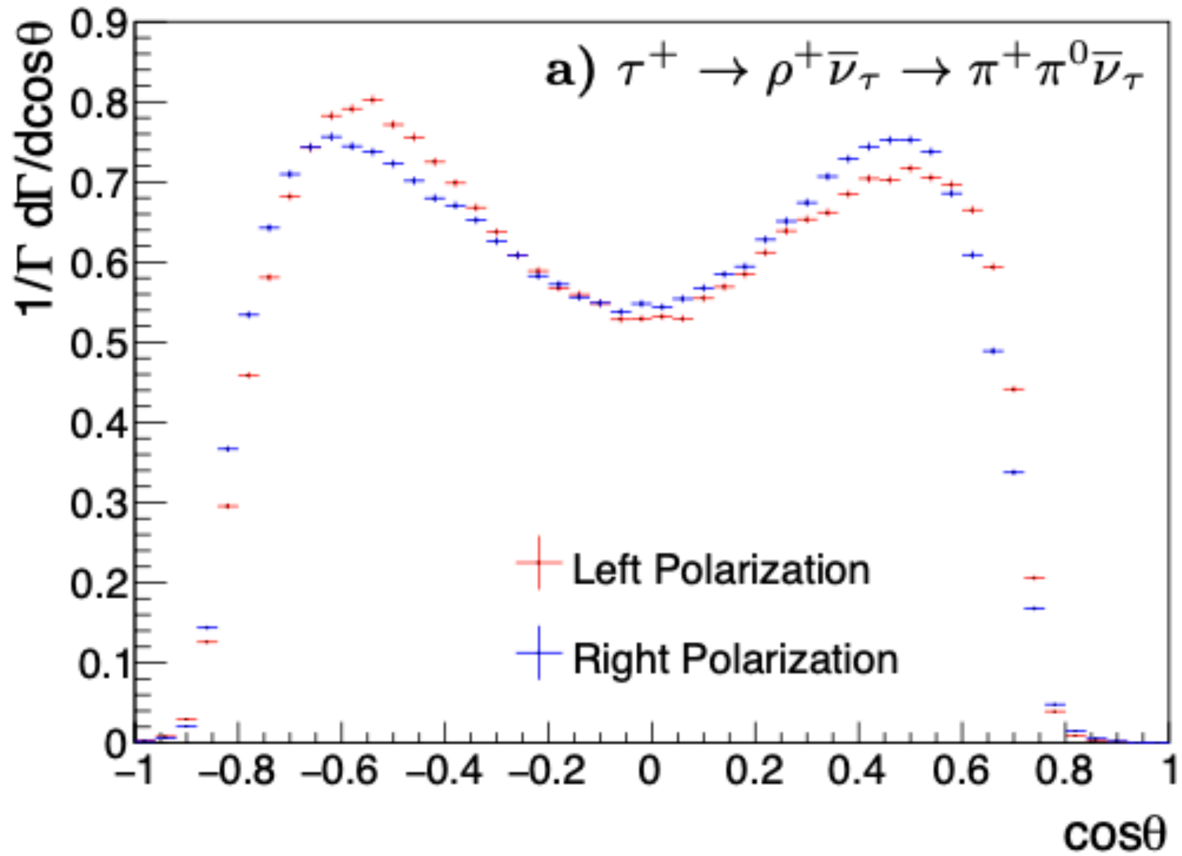
| MC source | Fraction |
|---|---|
| Bhabha | 0.046% |
| $\mu^+\mu^-$ | 0.046% |
| $u\bar{u}, d\bar{d}, s\bar{s}$ | 0.030% |
| $c\bar{c}$ | 0.006% |
| $b\bar{b}$ | 0.000% |
| $\tau^+\tau^-$ | 99.871% |

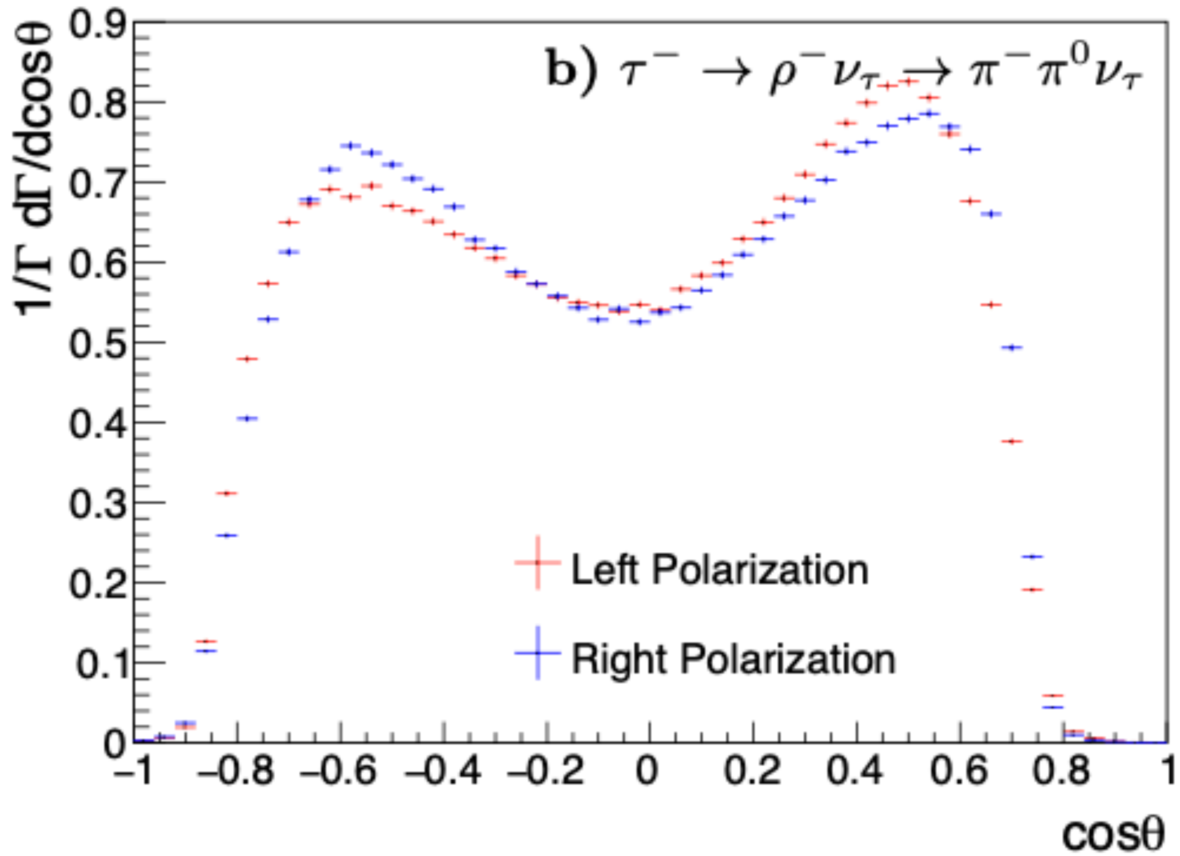
| Tau Signal | Fraction |
|---|---|
| $\tau^- \to e^- \overline{\nu}_e \nu_\tau$ | 0.018% |
| $\tau^- \to \mu^- \overline{\nu}_\mu \nu_\tau$ | 0.031% |
| $\tau^- \to \pi^- \nu_\tau$ | 0.035% |
| $\tau^- \to \rho^- \nu_\tau \to \pi^- \pi^0 \nu_\tau$ | 87.858% |
| $\tau \to (a_1 \to \pi^\pm \pi^0 \pi^0) \overline{\nu}_\tau$ | 9.785% |
| $\tau \to$ else | 2.145% |

# Polarization observables



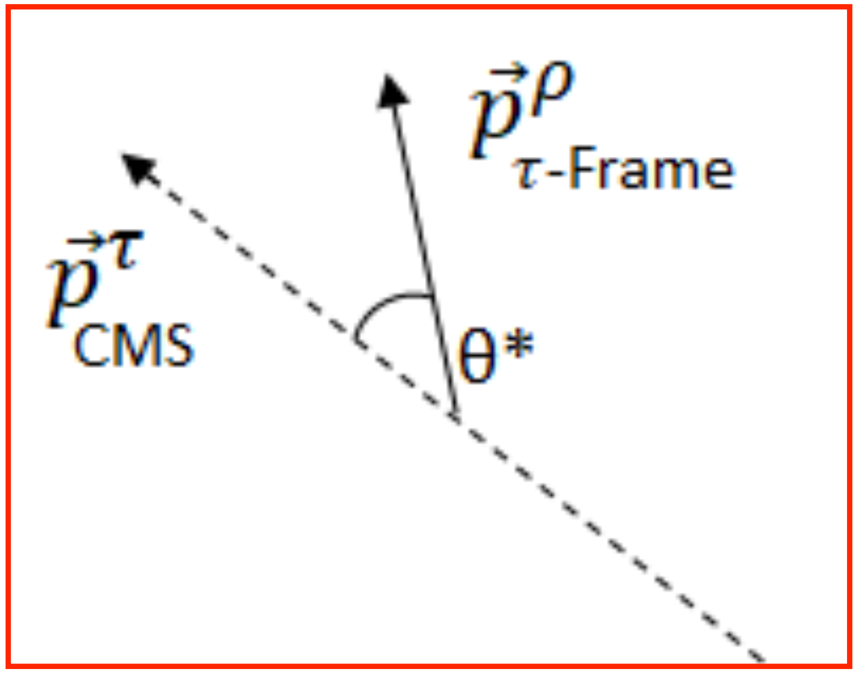

Angle between direction of $e^-$ beam and momentum of $\tau^-$in center-of-mass frame




Monte Carlo simulation plots showing sensitivity to polarization

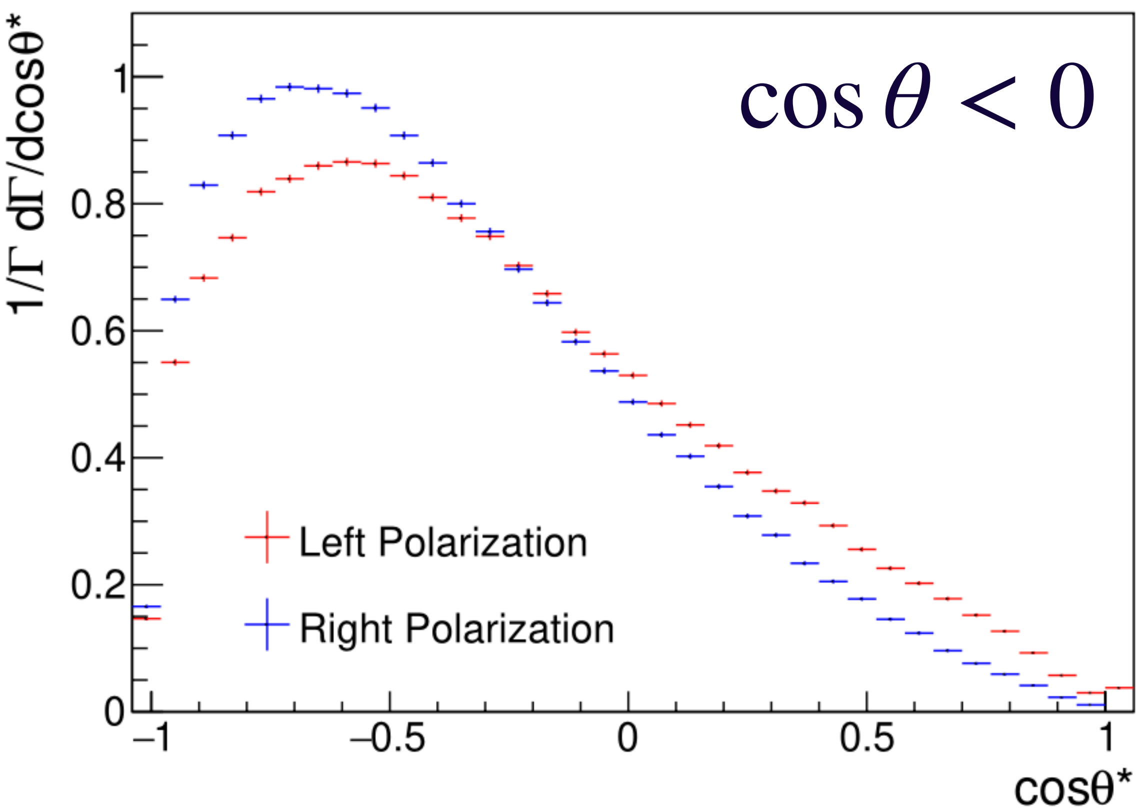
# Polarization observables

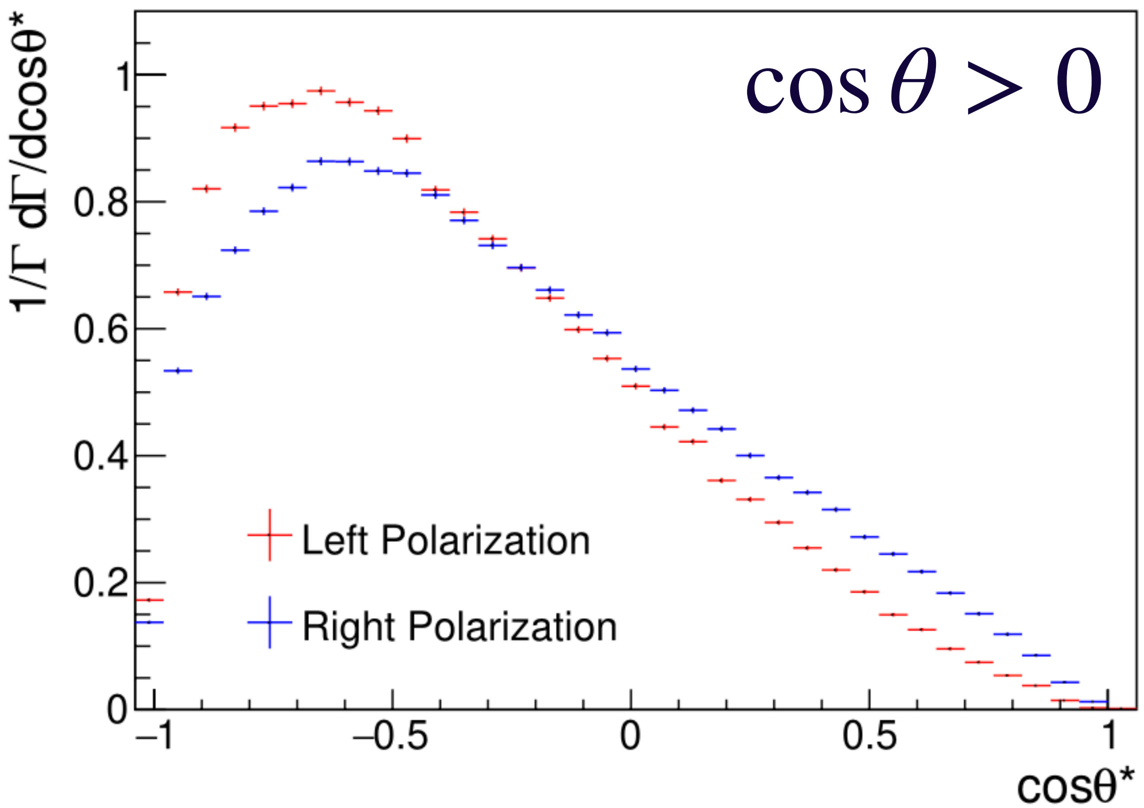



Angle between direction of $\tau^-$ and momentum of $\rho^-$in center-of-mass frame

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

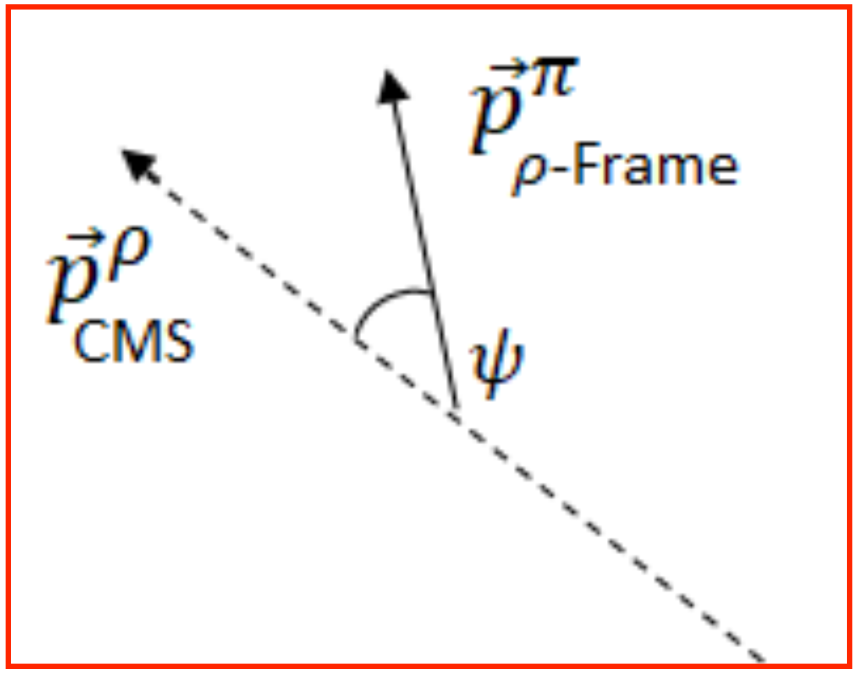
Hagiwara, Martin, Zeppenfeld Phys. Lett B235 (1990) 198




Monte Carlo simulation plots showing sensitivity to polarization

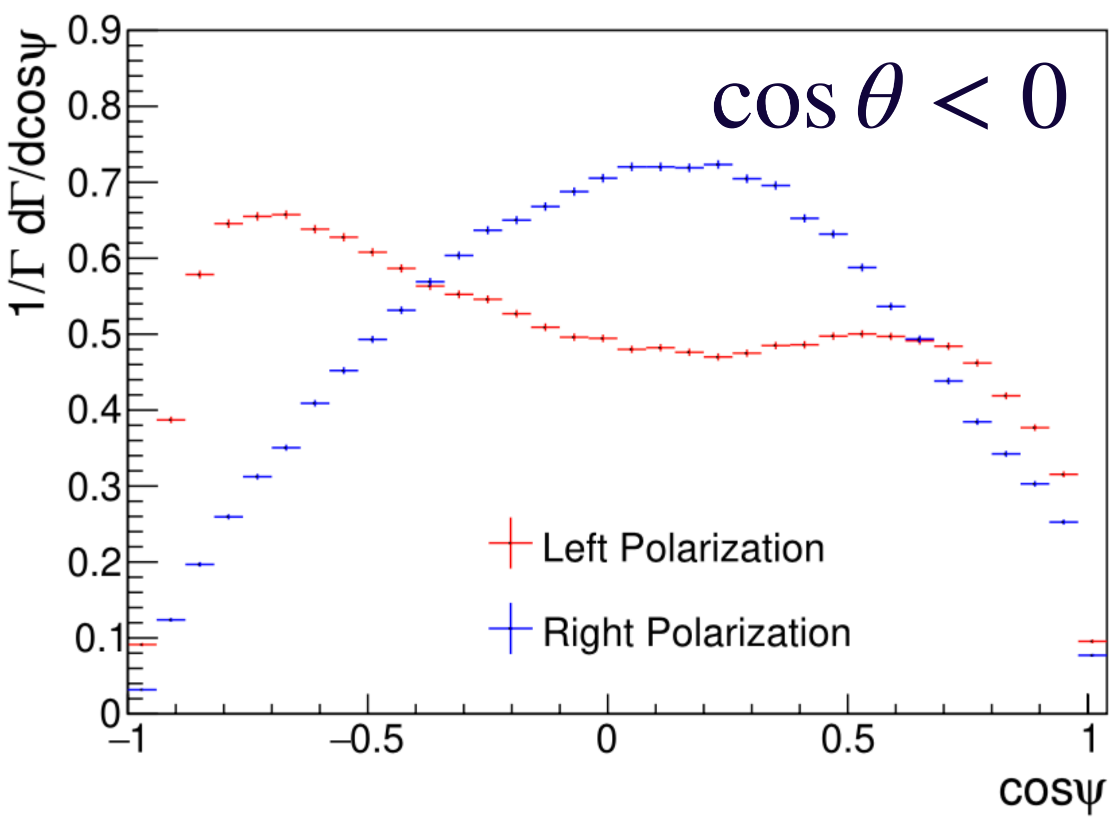
# Polarization observables

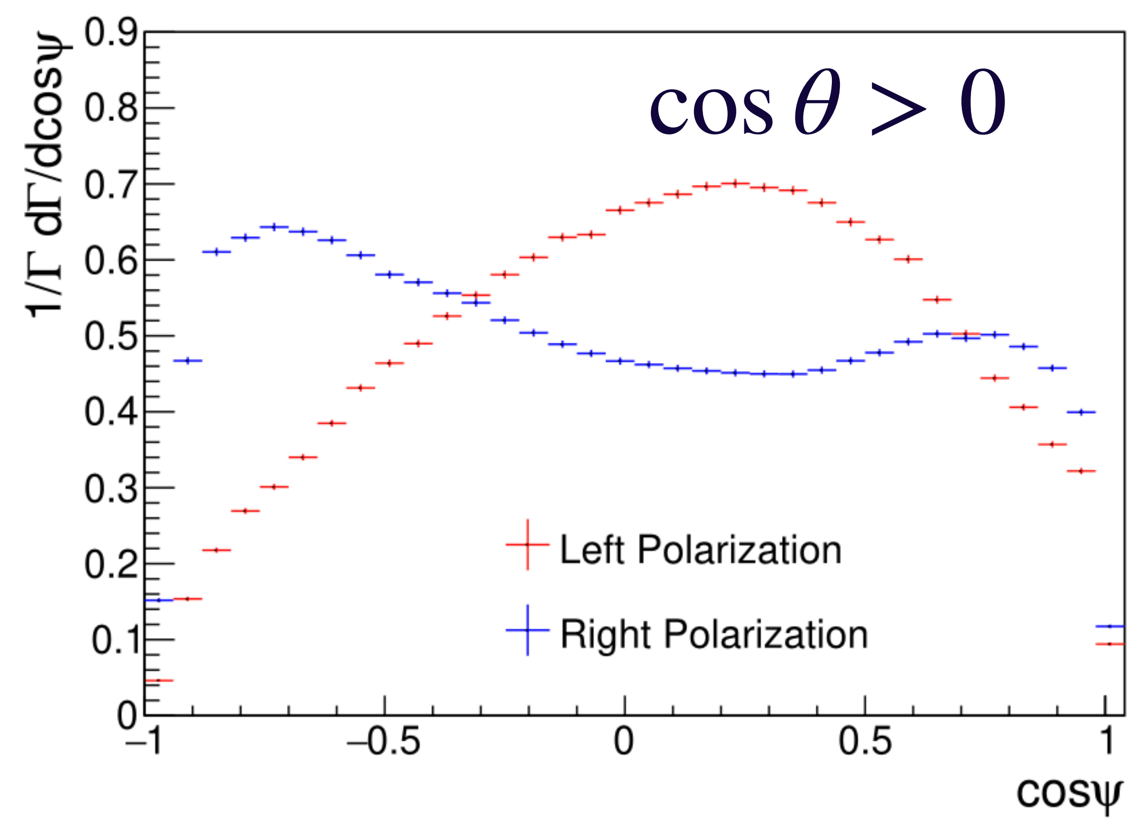



Angle between direction of $\rho^-$ and momentum of $\pi^-$ in center-of-mass frame

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

Hagiwara, Martin, Zeppenfeld Phys. Lett B235 (1990) 198




Monte Carlo simulation plots showing sensitivity to polarization

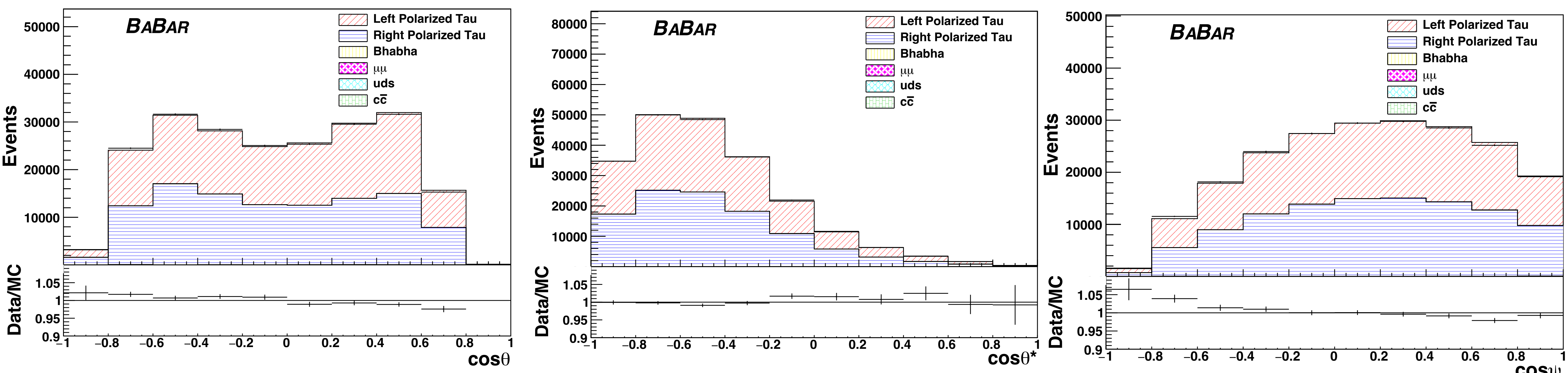
# Template fit

## 2-parameter $(a_l, a_r)$ fit to 3-dimensional histograms of $(\cos\theta, \cos\theta^\star, \cos\psi)$

Barlow, Beeston Comput.Phys.Commun. 77 (1993) 219-228

$$\overbrace{D}^{\text{Data / sample to be fit}} = \underbrace{a_l L + a_r R}_{\substack{\text{(L)eft and (R)ight polarized Tau MC} \\ \text{(floated in fit)}}} + \overbrace{a_b B + a_m M + a_u U + a_c C}^{\substack{\text{Backgrounds} \\ \text{B:Bhabha } (e^+e^-),\ \text{M:}\mu^+\mu^-,\ \text{U:}u\bar{u}, d\bar{d}, s\bar{s},\ \text{C:}c\bar{c} \\ \text{(fixed in fit)}}}$$

| | |
|---|---|
| $a_b$ | $3.8\times10^{-5}$ |
| $a_m$ | $1.4\times10^{-3}$ |
| $a_u$ | $3.8\times10^{-4}$ |
| $a_c$ | $4.8\times10^{-5}$ |

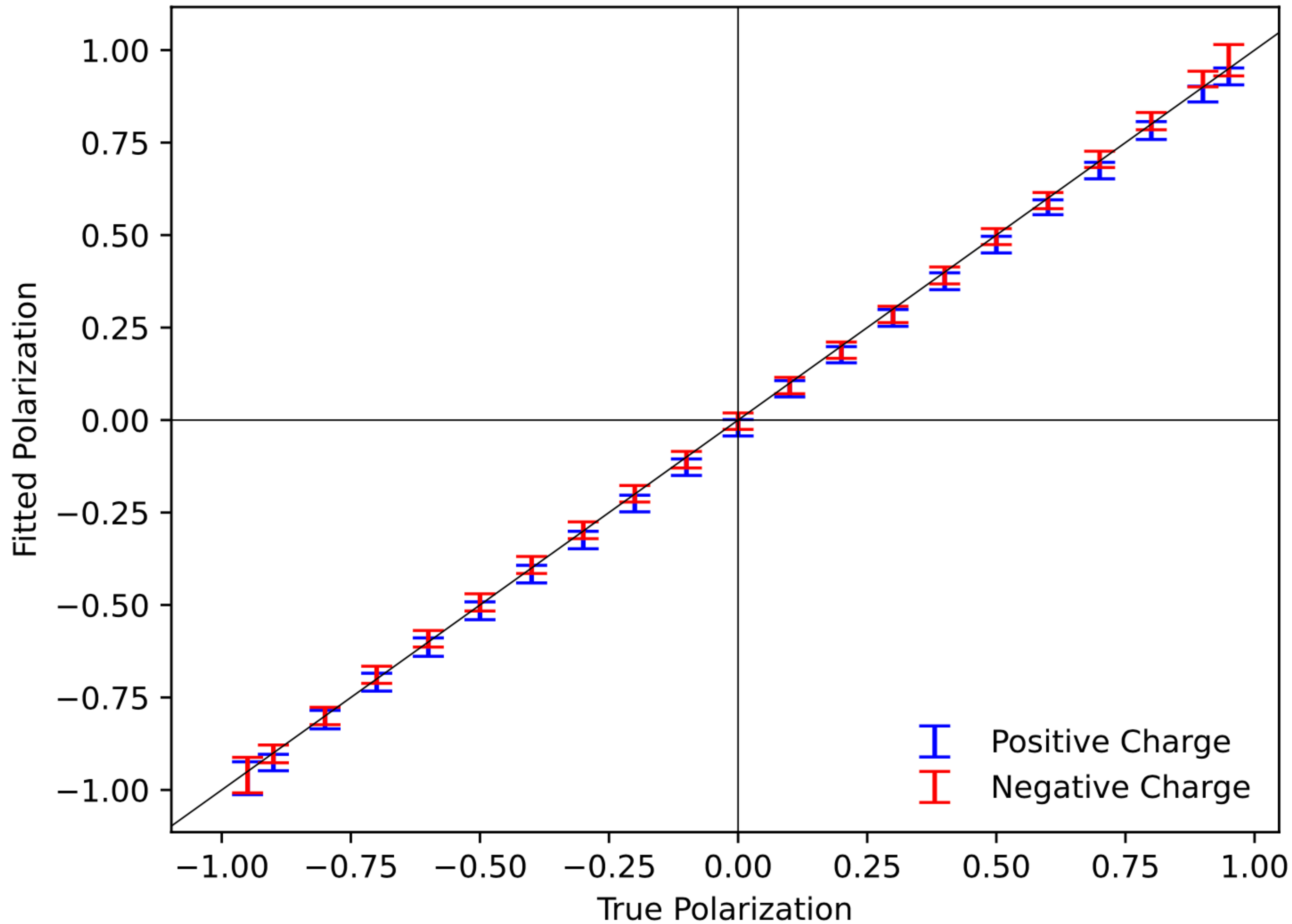



1-D projections from fit to $\tau^-$ decays from Run 3 (32.3 fb$^{-1}$) data

# Fit calibration

- Half of Monte Carlo used for templates, other half fitted
- Fit to polarization samples from −1 to 1 in steps of 0.1
- 70% polarization sample = 85% left-, 15% right-polarized
- Diagonal line shows optimal correlation in fit calibration

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



# Fit results

| Data Set ($fb^{-1}$) | Positive Charge | Negative Charge | Average Polarization |
|---|---|---|---|
| Run 1 (20.4) | 0.0018±0.014 | -0.0047±0.014 | -0.0014±0.010 |
| Run 2 (61.3) | 0.0075±0.0083 | 0.0007±0.0083 | 0.0041±0.0059 |
| Run 3 (32.3) | 0.0151±0.012 | -0.0047±0.012 | 0.0048±0.0083 |
| Run 4 (99.6) | -0.0035±0.0072 | 0.0010±0.0067 | -0.0011±0.0049 |
| Run 5 (132.3) | -0.0028±0.0062 | 0.0136±0.0064 | 0.0052±0.0045 |
| Run 6 (78.3) | 0.0036±0.0089 | 0.0133±0.0088 | 0.0084±0.0062 |
| 424.18±1.8 | 0.0015±0.0034 | 0.0055±0.0034 | 0.0035±0.0024 |

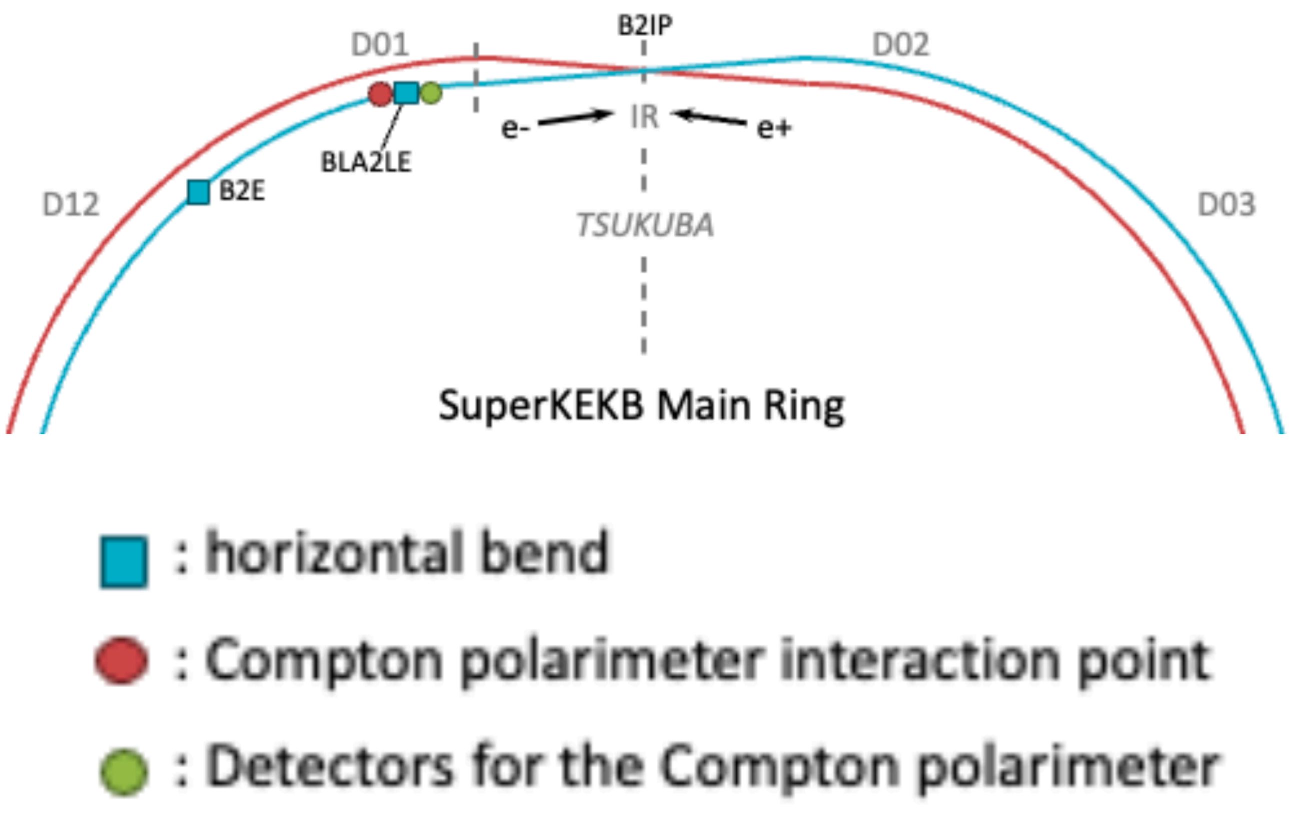
# Systematic uncertainties

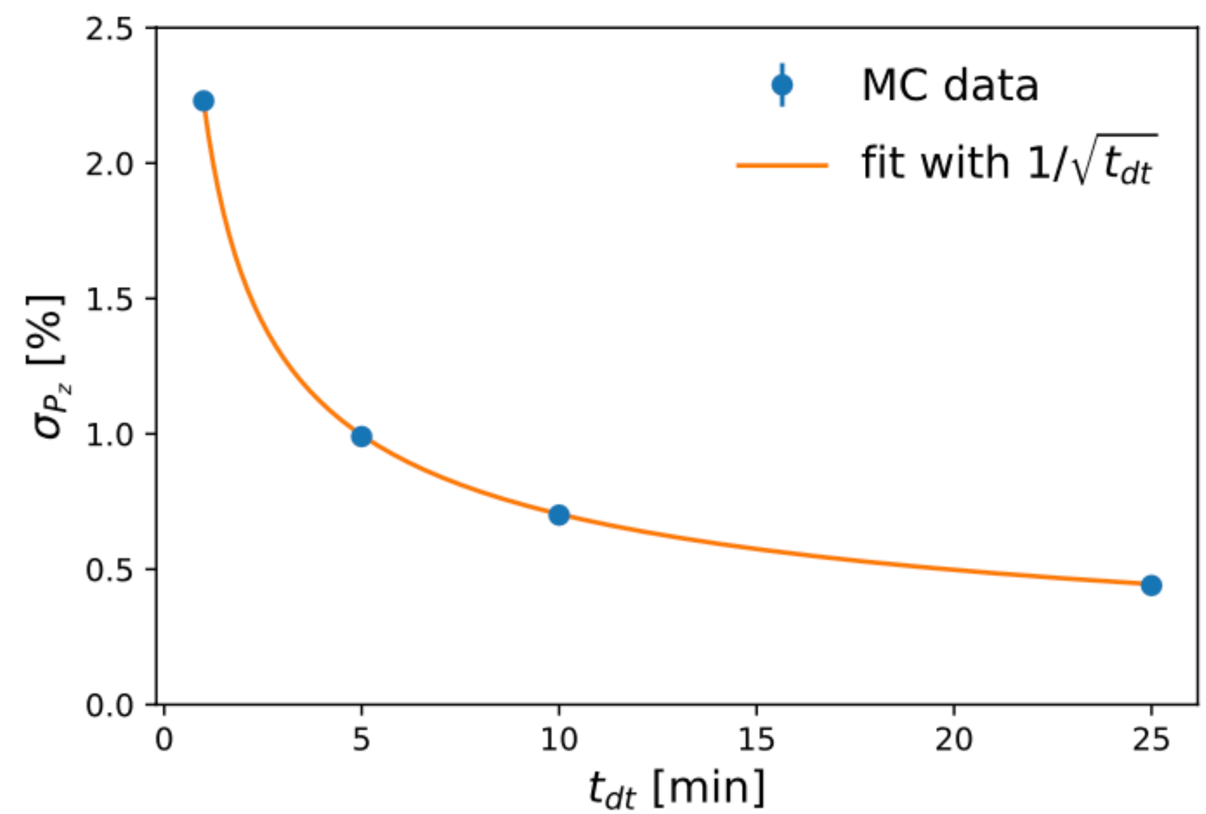
Neutral shower modeling dominated

| Source | Run 1 | Run 2 | Run 3 | Run 4 | Run 5 | Run 6 | Combined |
|---|---|---|---|---|---|---|---|
| $\pi^0$ efficiency (VII A 1) | 0.0025 | 0.0016 | 0.0013 | 0.0018 | 0.0006 | 0.0017 | **0.0013** |
| Muon PID (VII C) | 0.0018 | 0.0018 | 0.0029 | 0.0011 | 0.0006 | 0.0016 | **0.0012** |
| Split-off modeling (VII B 1) | 0.0015 | 0.0017 | 0.0016 | 0.0006 | 0.0016 | 0.0020 | **0.0011** |
| Neutral energy calibration (VII A 2) | 0.0027 | 0.0012 | 0.0023 | 0.0009 | 0.0014 | 0.0008 | **0.0010** |
| $\pi^0$ mass (VII B 2) | 0.0018 | 0.0028 | 0.0010 | 0.0005 | 0.0004 | 0.0004 | **0.0008** |
| $\cos\alpha$ (VII B 3) | 0.0015 | 0.0009 | 0.0016 | 0.0007 | 0.0005 | 0.0005 | **0.0007** |
| $\pi^0$ likelihood (VII B 4) | 0.0015 | 0.0009 | 0.0015 | 0.0006 | 0.0003 | 0.0010 | **0.0006** |
| Electron PID (VII C) | 0.0011 | 0.0020 | 0.0008 | 0.0006 | 0.0005 | 0.0001 | **0.0005** |
| Particle transverse momentum (VII B 5) | 0.0012 | 0.0007 | 0.0009 | 0.0002 | 0.0003 | 0.0006 | **0.0004** |
| Boost modeling (VII A 3) | 0.0004 | 0.0019 | 0.0003 | 0.0004 | 0.0004 | 0.0004 | **0.0004** |
| Momentum calibration (VII A 4) | 0.0001 | 0.0014 | 0.0005 | 0.0002 | 0.0001 | 0.0003 | **0.0004** |
| Max EMC acceptance (VII B 7) | 0.0001 | 0.0011 | 0.0008 | 0.0001 | 0.0002 | 0.0005 | **0.0003** |
| $\tau$ direction definition (VII A 5) | 0.0003 | 0.0007 | 0.0008 | 0.0003 | 0.0001 | 0.0004 | **0.0003** |
| Angular resolution (VII A 6) | 0.0003 | 0.0008 | 0.0003 | 0.0003 | 0.0002 | 0.0003 | **0.0003** |
| Background modeling (VII A 7) | 0.0005 | 0.0006 | 0.0010 | 0.0002 | 0.0003 | 0.0003 | **0.0003** |
| Event transverse momentum (VII B 6) | 0.0001 | 0.0013 | 0.0005 | 0.0002 | 0.0002 | 0.0004 | **0.0003** |
| Momentum resolution (VII A 4) | 0.0001 | 0.0012 | 0.0004 | 0.0002 | 0.0001 | 0.0005 | **0.0003** |
| $\rho$ mass acceptance (VII B 8) | 0.0000 | 0.0011 | 0.0003 | 0.0001 | 0.0002 | 0.0005 | **0.0003** |
| $\tau$ branching fraction (VII A 8) | 0.0001 | 0.0007 | 0.0004 | 0.0002 | 0.0002 | 0.0002 | **0.0002** |
| $\cos\theta^\star$ acceptance (VII B 9) | 0.0002 | 0.0006 | 0.0004 | 0.0001 | 0.0001 | 0.0004 | **0.0002** |
| $\cos\psi$ acceptance (VII B 9) | 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** |

# Compton Polarimeter

- Scattering of electron beam with a circular polarized laser
- Placed at 210 m upstream from interaction point
- Online measurement performed bunch-by-bunch
- Systematic uncertainty $\simeq$ 0.5 % & statistical uncertainty $\simeq$ 1 % in 5 minutes




Conceptual study of a Compton polarimeter for the upgrade of the SuperKEKB collider with a polarized electron beam

D. Charlet, T. Ishibashi, A. Martens, M. Masuzawa, F. Mawas, Y. Peinaud, D. Zhou and F. Zomer

Journal of Instrumentation, Volume 18, October 2023 P10014

# Summary & Outlook

- Proposed upgrade of SuperKEKB/Belle II
  - Chiral Belle with 70% polarized electron beams
  - $\tau$ decays complements Compton polarimeters to measure $\langle P_{beam} \rangle$

- Open up a unique window of Electroweak precision measurements
  - Neutral current vector coupling universality

- Chiral Belle probes parity violation both at low & high energy:
  - When Dark Z is off-shell and couples more to 3rd generation
  - TeV-scale Z' which couples only to leptons

- Tau polarimetry method demonstrated with 432 $fb^{-1}$ of BaBar data
  - $\langle P \rangle = 0.0035 \pm 0.0024\ (\text{stat}) \pm 0.0029\ (\text{syst})$
  - Dominant systematics related to modeling of neutral processes

Phys.Rev.D 108 (2023) 9, 092001 • e-Print: 2308.00774 [hep-ex]