# A Polarized Electron Beam Upgrade to SuperKEKB Enabling Precision Electroweak Measurements


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Consideration is being given to upgrading the SuperKEKB $e^+e^-$ collider with polarized electron beams, which would open a new program of precision electroweak physics at a centre-of-mass energy of 10.58GeV, the mass of the $\Upsilon(4S)$. These measurements include $\sin^2\theta_W$ obtained via left-right asymmetry ($A_{LR}$) measurements in $e^+e^-$ annihilations to pairs of electrons, muons, taus, charm and b-quarks. The precision obtainable at SuperKEKB will match that of the LEP/SLC world average and will thereby probe the neutral current couplings with unprecedented precision at a new energy scale sensitive to the running of the couplings. At SuperKEKB the measurements of the individual neutral current vector coupling constants to b-quarks and c-quarks and muons in particular will be substantially more precise than current world averages and the current $3\sigma$ discrepancy between the SLC $A_{LR}$ measurements and LEP $A^b_{FB}$ measurements of $\sin^2\theta_W^{eff}$ can be addressed. Having a polarized electron beam also enables measurements of tau lepton properties with unrivaled precision. This paper describes the measurements and includes a discussion of the necessary upgrades to SuperKEKB to achieve and measure the polarization in the SuperKEKB electron beam.



**KEYWORDS:** SuperKEKB, Polarization, Precision Electroweak


The SuperKEKB e$^+$e$^-$ collider, which operates at a centre-of-mass energy of 10.58 GeV and has a design luminosity of $8 \times 10^{35}$ cm$^{-2}$ s$^{-1}$, would broaden the Belle II physics program significantly if were upgraded with a longitudinally polarized electron beam. The target integrated luminosity for SuperKEKB/Belle II is 50 ab$^{-1}$ [1] and currently is projected to reach that goal by in the early 2030's. If SuperKEKB is upgraded to have electron beams with left and right longitudinal polarization of approximately 70% at the Belle II interaction point, whilst maintaining its high luminosity, it becomes a versatile - and unique - facility for probing new physics with precision electroweak measurements that no other experiments, current or planned, can achieve.

Initally considered for the SuperB project, as described in Reference [2], with polarized electron beams e$^+$e$^-$ $\rightarrow f\bar{f}$ processes at 10.58 GeV have left-right cross-section asymmetries arising from $\gamma - Z$ interference, which are sensitive to the product of the neutral current vector coupling constant, $g_V^f$, of the final-state fermion, $f$, and the neutral current axial-vector coupling constant of the initial state fermion, the electron, $g_A^e$. In the Standard Model (SM) $g_V^f$ is related to the weak mixing angle, $\theta_W$, through the relation $g_V^f = T_3^f - 2Q_f \sin^2\theta_W$, where $T_3^f$ is the 3rd component of weak isospin of $f$, $Q_f$ is its electric charge in units of electron charge and the notational conventions of Reference [3] are used.

Belle II accesses $g_V^f$ by measuring the left-right asymmetry, $A_{LR}^f$, for each identified final-state fermion-pair. At lowest order, for s-channel processes,

$$A_{LR}^{f}(Pol) = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \frac{sG_F}{\sqrt{2}\pi\alpha Q_f} g_A^e g_V^f \langle Pol \rangle \tag{1}$$

where $g_A^e = T_3^e = -\frac{1}{2}$, $G_F$ is the Fermi coupling constant, $s$ is the square of the centre-of-mass energy, and

$$\langle Pol \rangle = \frac{1}{2}\left[\left(\frac{N_{eR} - N_{eL}}{N_{eR} + N_{eL}}\right)_{\mathbf{R}} - \left(\frac{N_{eR} - N_{eL}}{N_{eR} + N_{eL}}\right)_{\mathbf{L}}\right] \tag{2}$$

is the average electron beam polarization, where $N_{eR}$ is the number of right-handed electrons and $N_{eL}$ the number of left-handed electrons in the event samples where the electron beam bunch is left polarized or right polarized, as indicated by the '**L**' and '**R**' subscripts. Calculations at next-to-leading-order have recently been published for muon-pair [4] and electron-pair [5] final states. The muon-pair asymmetry calculation has been cross-checked with the KKMC Monte Carlo [6] and a recently released version of the Bhabha Monte Carlo generator, ReneSANCe [7] has been used to independently validate the electron-pair calculations.

Even though the SM asymmetries are small ($-6\times10^{-4}$ for muons and taus, $+2\times10^{-4}$ for electrons, $-5\times10^{-3}$ for charm and $-2\%$ for the $b$-quarks), we can expect unprecedented precision to be achieved because of the combination of both a 70% beam polarization measured with a relative precision of better than ±0.5%. and high luminosity of SuperKEKB.

With a 20 ab$^{-1}$ data sample and 70% polarized electron beam the weak neutral current vector coupling constants of the $b$-quark, $c$-quark and muon can be determined with unprecedentedly high precision. The ratios of all pairings of vector couplings are precisely predicted in the SM assuming universality, which can be probed with high precision. In particular, the $b$-quark and $c$-quark measurements will likely be limited by the beam polarization uncertainty, determined with tau-pair events (see C. Miller contribution to this conference), however, their ratio, $g_V^b/g_V^c$, can be expected to be measured to 0.3%, more than an order-of-magnitude higher precision than currently exists.

The Belle II collaboration has published a luminosity paper [8] with Bhabha acceptance in the central part of the Belle II detector reporting a cross section of 17.4 nb and efficiency of 36% with high purity. From this information one can expect a measured value of $A_{LR}^e = +1.5 \times 10^{-4}$ and for 40ab$^{-1}$ of Bhabha data with 70% polarization a relative of uncertainty of 2%, which is dominated by statistics. This would translate into a uncertainty on $\sin^2\theta_W$ of 0.0003 using only electrons. With a data sample of 40 ab$^{-1}$, combining the three leptonic final state measurements enables Belle II to measure $\sin^2\theta_W$ with a statistics-dominated uncertainty of less than 0.0002, roughly equivalent to the uncertainty on the world average from the five LEP+SLD experiments at the $Z^0$-pole [3] and more than twice as precise as the current world average from LHC [9]. Because this will be measured at a much lower energy, it is sensitive to the running of $\sin^2\theta_W$ and new physics processes that might shift that running from that of the SM. Figure 1(left) presents the values of $\sin^2\theta_W$ as a function of energy scale at present and future experimental facilities including SuperKEKB upgraded with a polarized electron beam. With 40 ab$^{-1}$ of polarized electron beams in SuperKEKB, the neutral current electroweak program would provide the highest precision studies of neutral current vector coupling universality for all available final-state fermions with an error dominated by statistics, since the measured polarization, the dominant systematic error source, cancels in the ratio of the couplings. Further, we note that the right-handed $b$-quark couplings to the $Z$, which are currently in tension with the SM expectation by nearly $3\sigma$, can be experimentally probed with high precision at Belle II with polarized beams.

This level of precision allows Belle II to measure parity violation induced by the exchange of heavy particles such as a hypothetical TeV-scale $Z'$ boson(s). If such bosons only couple to leptons, they would not be produced at the LHC. Moreover, this upgrade renders SuperKEKB/Belle II unique in the ability to probe parity violation in the lepton sector mediated by light and very weakly coupled particles often referred to as “Dark Forces”. Such forces have been proposed as a possible connecting link between normal and dark matter [10, 11]. SuperKEKB upgraded with a polarized electron beam would be uniquely sensitivity to “Dark Sector” parity-violating light neutral gauge bosons, particularly if $Z_{\text{dark}}$ is off-shell having a mass between $\sim$10 and 35 GeV [12] or even up to the $Z^0$ pole, or if it couples more to the 3rd generation. (see Figure 1(right)).

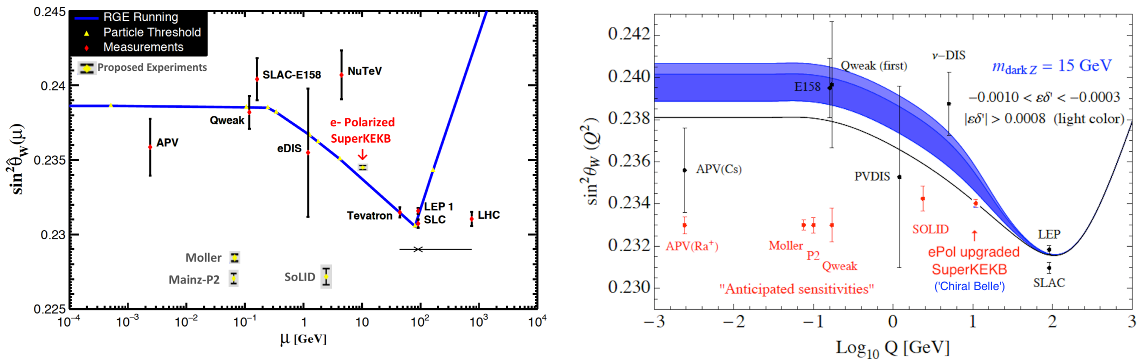


**Fig. 1.** Left: Measurements of $\sin^2\theta_W$ and uncertainties on measurements at future experimental facilities as a function of energy scale, adapted from [13]. Right: The $Q^2$-dependent shift in $\sin^2\theta_W$ caused by a 15 GeV mass dark Z is shown by the dark blue band, adapted from [12].

Such high precision measurements are possible because with 20 ab$^{-1}$ Belle II can identify between $10^9$ and $10^{10}$ final-state pairs of b-quarks, c-quarks, taus, muons and electrons with reasonable signal efficiency and high purity. It also relies on having all detector-related systematic errors made to cancel by flipping the laser polarization from **R** to **L** in a random, but known, pattern as collisions occur, as was done at SLC. The $\langle Pol \rangle$ would be measured in two ways. The first method, using a Compton polarimeter, can be expected to have an absolute uncertainty at the Belle II interaction point of less than 1% and provides a ‘bunch-by-bunch’ measurement of $\left(\frac{N_{eR}-N_{eL}}{N_{eR}+N_{eL}}\right)_{\mathbf{R}}$ and $\left(\frac{N_{eR}-N_{eL}}{N_{eR}+N_{eL}}\right)_{\mathbf{L}}$. The uncertainty is likely to be dominated by the need to predict the change in polarization between where it is measured, at the Compton polarimeter, and the interaction point. However, that effect is not present in the second method, which effectively measures the polar angle dependence of the polarization of $\tau$-leptons produced in $e^+e^- \to \tau^+\tau^-$ events using the kinematic distributions of the decay products of the $\tau$ separately for the **R** and **L** data samples. The tau-pair polarization distributions depend on $\langle Pol \rangle$ and therefore can be used to determine $\langle Pol \rangle$ to 0.5% at the Belle II interaction point in a manner entirely independent of the Compton polarimeter. For details on this, see C. Miller’s contribution to this conference with a paper entitled ”Measurement of Beam Polarization with Tau Polarimetry for a Potential SuperKEKB Upgrade”. This $\tau$ polarization method avoids the uncertainties associated with tracking the polarization losses to the interaction point and also automatically accounts for any residual positron polarization that might be present. It also automatically provides a luminosity-weighted beam polarization measurement.

Beyond the $A_{LR}$ measurements, a polarized beam at SuperKEKB will enable Belle II to measure $\tau$ lepton Michel parameters, $\tau$ electron dipole moment [14] and the $\tau$ anomalous magnetic moment form-factor, $Re(F_2(10\,GeV))$ [15, 16], with unrivaled precision. $Re(F_2(10GeV))$ provides a measurement analogous to that of the $(g-2)$ of the muon where there is currently a $4\sigma$ tension with the SM, but in the third generation.

A polarized beam can also be used to reduce backgrounds in searches for $\tau \to \mu\gamma$ and $\tau \to e\gamma$, leading to improved sensitivities and can be used to distinguish left and right handed new physics currents [2]. In addition, polarized $e^+e^-$ annihilation into a polarized $\Lambda$ or a hadron pair experimentally probes dynamical mass generation in QCD.

Such an upgrade to SuperKEKB involves three hardware projects:

(1) A low-emittance polarized electron source in which electron beams are produced via a polarized laser illuminating a "strained lattice" GaAs photocathode as was done for SLD [3]. The source would produce longitudinally polarized electron bunches whose spin would be rotated to be transversely polarized before they encounter any dipole fields. The source would have ~4 nC/bunch with 20 mm-mrad vertical emittance and 50 mm-mrad horizontal emittance. The current focus is on a GaAs cathode with a thin Negative Electron Affinity (NEA) surface.

(2) A pair of spin-rotators, one positioned before and the other after the interaction region, to rotate the spin to longitudinal prior to collisions and back to transverse following collisions. The challenge is to design rotators having minimal couplings between vertical and horizontal planes and to address higher order and chromatic effects in the design to ensure the luminosity is not degraded. One configuration under consideration for the spin-rotator system [17] is a set of four combined function magnets (two on each side of the IP), with each magnet replacing an existing dipole in the SuperKEKB electron beam lattice with a superconducting magnet that has both a dipole and solenoid as well as six skew quads used to minimize couplings between vertical and horizontal planes. Using the Bmad [18] software package with the SuperKEKB lattice for the electron ring, this approach has been shown to work at lowest order in having a spin-rotator system which is transparent to the rest of the lattice [19]. Another concept is to install spin-rotator magnets in the existing SuperKEKB drift regions [20].

(3) A Compton polarimeter that measures the beam polarization before the beam enters the interaction region in real-time. Experience from Compton polarimeter designs at HERA at DESY and the QWeak experiment at Jefferson Lab is being deployed in the design of a SuperKEKB polarimeter, which will be installed outside the interaction region.

It is also required that the beam has a reasonable de-polarization lifetime and it has been shown [20] that the depolarization lifetime for electrons with an energy of 7.15 GeV in the SuperKEKB electron ring is approximately 2 hours, which is twice the present beam lifetime. Also, the electron beam bunches are continuously topped-up at 50 Hz. These initial studies are encouraging and more detailed conceptual design work is currently underway.

An electron beam polarization upgrade at SuperKEKB opens a unique and exciting new window for discovery with precision electroweak physics and precision measurements of tau lepton decay properties. Current feasibility studies are encouraging and are continuing, as discussed in the KEK Roadmap 2021-2026 submission to the Japanese MEXT ministry. A growing international team is working on developing a conceptual design with a goal to realize the upgrade in order to begin taking Belle II data with polarized SuperKEKB electron beams as soon as possible after a long shutdown scheduled for an upgrade of the Interaction Region in second half of this decade.

## References


[1] T. Abe *et al.* Belle II Technical Design Report, KEK Report 2010-1, Edited by Z. Dolezal and S. Uno, arXiv:1011.0352 (2010).

[2] M. Baszczyk *et al.* (SuperB Collaboration), "SuperB Technical Design Report", INFN-13-01/PI, LAL 13-01, SLAC-R-1003, arXiv:1306.5655.

[3] ALEPH and DELPHI and L3 and OPAL and SLD Collaborations and LEP Electroweak Working Group and SLD Electroweak Group and SLD Heavy Flavour Group (S. Schael *et al.*), "Precision electroweak measurements on the $Z^0$ resonance", Phys. Rept. 427 (2006) 257-454.

[4] A. Aleksejevs, S. Barkanova, C. Miller, J.M. Roney and V. Zykunov, "NLO Radiative Corrections for Forward-Backward and Left-Right Asymmetries at a B-Factory", Phys. Rev. D 101 (2020) 5, 053003 (arXiv:1801.08510).

[5] A. Aleksejevs, S. Barkanova, Yu. M. Bystritskiy and V. Zykunov, “Application of Asymptotic Methods to Calculating Electroweak Corrections in Polarized Bhabha Scattering”, Phys. Atom. Nucl. 83 (2020) 2, 307-333, Yad. Fiz. 83 (2020) 2, 157-184.

[6] S. Jadach, B.F.L. Ward, Z. Was, “The Precision Monte Carlo event generator KKfor two fermion final states ine+ecollisions”, Comput. Phys. Commun. 130 (2000)260–325 (2000).

[7] R. Sadykov and V. Yermolchyk, “Polarized NLO EW $e + e \rightarrow e^{+}e$ cross section calculations with ReneSANCe-v1.0.0”, Comput.Phys.Commun. 256 (2020).

[8] F. Abudinén *et al.*, Belle II Collaboration, Chin.Phys.C 44 (2020) 2, 021001.

[9] P. A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020).

[10] M. Pospelov and A. Ritz, “Astrophysical Signatures of Secluded Dark Matter”, Phys. Lett. B671:391–397, 2009.

[11] N. Arkani-Hamed, D. P. Finkbeiner, T. R. Slatyer, and N. Weiner, “A Theory of Dark Matter”, Phys. Rev. D 79:015014, 2009.

[12] H. Davoudiasl, H. S. Lee and W. J. Marciano, Phys. Rev. D 92, no. 5, 055005 (2015).

[13] J. Erler and A. Freitas “ElectroweakModel and Constraints on New Physics” in M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D 98, 030001 (2018); J. Benesch *et al.* (Moller Collaboration), “The MOLLER Experiment: An Ultra-Precise Measurement of the Weak Mixing Angle Using Møller Scattering”, JLAB-PHY-14-1986, arXiv:1411.4088v2 [nucl-ex] 2014; D. Becker *et al.* “The P2 experiment”, arXiv:1802.04759 [nucl-ex] 2018.

[14] J. Bernabéu, G. A. Gonzalez-Sprinberg, and J. Vidal, “CP violation and electric dipole moment at low energy tau production with polarized electrons”, Nucl. Phys. B 763: 283–292, 2007, hep-ph/0610135.

[15] J. Bernabeu, G. A. Gonzalez-Sprinberg, J. Papavassiliou and J. Vidal, “Tau anomalous magnetic moment form-factor at super B/flavor factories,” Nucl. Phys. B **790**, 160-174 (2008).

[16] A. Crivellin, M. Hoferichter and J. M. Roney, “Towards testing the magnetic moment of the tau at one part per million,” [arXiv:2111.10378 [hep-ph]].

[17] U. Wienands (ANL), internal SuperKEKB $e^{-}$ Pol. Upgrade Working Group communication.

[18] D. Sagan, ”Bmad: A relativistic charged particle simulation library”, Nucl. Instrum. Meth. A558, (2006) 356-359; D. Sagan and J. Smith, “The TAO accelerator simulation program,” Conf. Proc. C **0505161**, 4159 (2005) PAC-2005-FPAT085.

[19] Y. Peng,“Conceptual Design of the Spin Rotator for the SuperKEKB High Energy Ring”, University of Victoria MSc Thesis 2021.

[20] I. Koop, A. Otboev and Yu. Shatunov (BINP), internal SuperKEKB $e^{-}$ Pol. Upgrade Working Group communication.