Snowmass 2021 Letter of Interest: Tau Physics and Precision Electroweak Physics with Polarized Beams at SuperKEKB/Belle II

on behalf of the U.S. Belle II Collaboration

D. M. Asner[1], Sw. Banerjee[2], J. V. Bennett[3], G. Bonvicini[4], R. A. Briere[5], T. E. Browder[6], D. N. Brown[2], C. Chen[7], D. Cinabro[4], J. Cochran[7], L. M. Cremaldi[3], A. Di Canto[1], K. Flood[6], B. G. Fulsom[8], R. Godang[9], M. Hernández Villanueva[3], W. W. Jacobs[10], D. E. Jaffe[1], K. Kinoshita[11], R. Kroeger[3], R. Kulasiri[12], P. J. Laycock[1], K. A. Nishimura[6], B. Parker[1], T. K. Pedlar[13], L. E. Piilonen[14], S. Prell[7], J. M. Roney[15], C. Rosenfeld[16], A. Rostomyan[17], D. A. Sanders[3], V. Savinov[18], A. J. Schwartz[11], J. Strube[8], D. J. Summers[3], S. E. Vahsen[6], G. S. Varner[6], A. Vossen[19], U. Wienands[20], L. Wood[8], and J. Yelton[21]

[1]*Brookhaven National Laboratory, Upton, New York 11973*
[2]*University of Louisville, Louisville, Kentucky 40292*
[3]*University of Mississippi, University, Mississippi 38677*
[4]*Wayne State University, Detroit, Michigan 48202*
[5]*Carnegie Mellon University, Pittsburgh, Pennsylvania 15213*
[6]*University of Hawaii, Honolulu, Hawaii 96822*
[7]*Iowa State University, Ames, Iowa 50011*
[8]*Pacific Northwest National Laboratory, Richland, Washington 99352*
[9]*University of South Alabama, Mobile, Alabama 36688*
[10]*Indiana University, Bloomington, Indiana 47408*
[11]*University of Cincinnati, Cincinnati, Ohio 45221*
[12]*Kennesaw State University, Kennesaw, Georgia 30144*
[13]*Luther College, Decorah, Iowa 52101*
[14]*Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061*
[15]*University of Victoria, Victoria, British Columbia, V8W 3P6, Canada*
[16]*University of South Carolina, Columbia, South Carolina 29208*
[17]*Deutsches Elektronen–Synchrotron, 22607 Hamburg, Germany*
[18]*University of Pittsburgh, Pittsburgh, Pennsylvania 15260*
[19]*Duke University, Durham, North Carolina 27708*
[20]*Argonne National Laboratory, Lemont, Illinois 60439*
[21]*University of Florida, Gainesville, Florida 32611*

Corresponding Author(s):

Swagato Banerjee (University of Louisville), swagato.banerjee@louisville.edu
J. Micheal Roney (University of Victoria), mroney@uvic.ca

Thematic Area(s):

■ (RF01) Weak Decays of b and c
■ (RF02) Strange & Light Quarks
■ (RF03) Fundamental Physics in Small Experiments
■ (RF05) Charged Lepton Flavor Violation (electrons, muons and taus)
■ (RF06) Dark Sector at Low Energies
■ (AF05) Accelerators for rare processes and precision measurements
■ (EF04) EW Physics: EW Precision Physics and constraining new physics

Abstract:

The SuperKEKB e^+e^- collider operating at a centre-of-mass energy near 10.58 GeV, with its high design luminosity of 8×10^{35} cm^{-2} s^{-1}, enables the Belle II experiment to make new precision measurements of the tau lepton and its decays. The tau being the only lepton heavy enough to decay both into leptons and quarks, probes new physics contributions in mass dependent couplings sensitive to the third generation. If SuperKEKB is upgraded to have electron beams with longitudinal polarization, a unique precision electroweak physics program is enabled, which opens new windows for discovery with Belle II, including a probe of dark sector parity-violating processes. Polarized beams with the projected luminosity at SuperKEKB can probe parity violating components of neutral current couplings of both heavy and light quarks, as well as all leptons to new particles up to unprecedented precision. Tau polarization measurements in Belle II serve as a precision means of measuring the beam polarization at the interaction point, which is required for the precision electroweak program.

1 Searches for new physics with the τ lepton

The τ lepton decays through the weak interaction into leptons as well as hadrons: $\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau$, where $\ell =$ electron or muon, and $\tau^- \to \bar{u} d' \nu_\tau$, where $d' = V_{ud} d + V_{us} s$, V_{ud} and V_{us} being respectively the largest diagonal and off-diagnal elements of the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix[1]. The Belle II experiment provides a clean laboratory to study charged leptonic and hadronic currents using the world's largest sample of 10^{11} τ-pair events[2]. With upgraded calorimetry and muon detection, it would enable the world's most precise tests of the assumption that all three leptons have equal coupling strength (g_ℓ) to the charged gauge bosons of the electroweak interaction, known as charged current lepton universality[3].

The $|V_{us}|$ element can be measured from the ratio of strange to non-strange inclusive branching fractions of the τ lepton, interpreted in the framework of the Operator Product Expansion (OPE) and finite energy sum rules (FESR). The ratio $\frac{\mathcal{B}(\tau^- \to K^- \nu_\tau)}{\mathcal{B}(\tau^- \to \pi^- \nu_\tau)}$ of exclusive final states also provides an alternate measurement of $|V_{us}|$ from τ decays, which is independent of the convergence of the OPE. While the latter measurement of V_{us} agrees with the unitarity prediction to within 1σ[3], there is a 3σ discrepancy between the value of $|V_{us}|$ measured from the inclusive sum of strange decay modes and the unitarity prediction[4], which would be resolved by high precision Belle II data. The determination of spectral functions for the vector and axial-vector modes will allow precise determination of the strong coupling α_s, providing the most accurate test of asymptotic freedom[5].

The τ lepton provides a clean environment to search for second class currents whose branching fractions are suppressed to a few parts in 10^{-5} by isospin-violating effects[6;7]. This suppression makes an interesting case to search for new physics contributions, i.e., not induced by isospin-breaking terms, to the second class current dominated final states. For example, rates of $\tau^- \to \pi^- \eta^{(\prime)} \nu_\tau$ decays may be greatly enhanced by the extended Higgs sector[8] or leptoquark bosons[9].

New physics contributions to the anomalous magnetic moment of a lepton can be enhanced by powers of its mass. Present deviation of the measured magnetic moment of the muon from its prediction makes the study of such moments very exciting. Electric dipole moments are also interesting probes of the charge-parity symmetry. Measurements of Michel parameters in leptonic and radiative leptonic τ decays are very sensitive to new physics and will enable the world's best measurements of electric and magnetic moments of the τ with sensitivity of 10^{-6} and 10^{-20} $\mathrm{e} \cdot \mathrm{cm}$, respectively, which are several orders of magnitude below any other existing bounds[10;11].

Observation of lepton flavour violation (LFV) in the charged lepton sector would completely change our understanding of nature, and herald a new era of discovery in elementary particle physics. Now is a very interesting era in the searches for LFV, as the current limits will improve by an order of magnitude in the next decade at Belle II, which expects to probe LFV in τ decays down to few parts in $10^{-9} - 10^{-10}$ or discover unambiguous signatures of new physics[2].

Sensitivity to new physics exploited through τ polarization are enhanced by polarized beams. Beam polarization increases the sensitivity of LFV decays, since the dominant Standard Model backgrounds depend on the polarization of electron beams[12]. Beam polarization offers the possibility to disentangle new physics contributions to the helicity structure via precise measurements of the Michel parameters[13] as well as LFV couplings[14]. New methodologies sensitive to τ polarization lead to improved measurements of the electric and magnetic moments of the τ lepton[15].

2 Searches for new physics with precision electroweak measurements

Precision electroweak measurements are among the highest priority activities of the field and with polarized electron beams at SuperKEKB, a new discovery window opens with left-right asymmetry measurements of $\sin\theta_W^2$ at Belle II. At 10.58 GeV center-of-mass, the left-right asymmetry is linearly dependent on the product of the neutral axial-vector coupling of the electron and the vector coupling of the final state fermion via $Z-\gamma$ interference.

A data sample of 20 ab^{-1} with a 70% polarized electron beam enables Belle II to measure the weak neutral current vector coupling constants of the b-quark, c-quark and muon at significantly higher precision than current world averages[16]. With 40 ab^{-1} of polarized beam data, the precision of the vector couplings to the tau and electron can be measured with substantially higher precision than current world averages (currently dominated by measurements at the Z^0-pole) and beauty-charm neutral-current universality can be probed below 0.05%. No other experiment, currently running or planned, can perform such precision tests of vector coupling universality in neutral currents[17].

Moreover, the SuperKEKB machine will yield a unique possibility for discovering "Dark Forces" that can serve as portals between normal and dark matter. SuperKEKB with polarization complements other measurements as it is uniquely sensitive to a parity violating light neutral gauge boson in the "Dark Sector" (Z_{dark}) under various mass and coupling scenarios, including models where Z_{dark} couples more to the 3rd generation via mass-dependent couplings. For example, a 15 GeV Z_{dark} would cause a shift in the measurement of $\sin^2\theta_W$ in the energy region where SuperKEKB with polarized beams has one of the highest potentials for discovery[18]. With polarized beams SuperKEKB can also probe parity violating couplings of new heavy particles that couple only to leptons, complementing electroweak studies at the LHC.

A beam polarization upgrade to the SuperKEKB collider requires the development of a pair of spin-rotators, a polarized electron source and Compton polarimeter. There is excellent opportunity to exploit synergies with work done for the ILC and, now EIC. Important challenges are to design the spin-rotators to minimize couplings between vertical and horizontal planes, and to address higher order chromatic effects in the design to ensure the luminosity is not degraded. We propose to develop a smart system to keep track of the many complex coil configurations needed for field correction of the spin-rotators.

The Compton polarimeter will provide real-time measurements of the beam polarization with per mille level relative uncertainties. A precise absolute polarization is provided by the polar angle dependence of τ polarization measured in Belle II, and gives the beam polarization directly at the interaction point. The τ polarization method automatically provides a luminosity-weighted beam polarization measurement and accounts for any residual polarization of the positron beam. This dual approach will calibrate the beam polarization at the per mille level precision, as needed to disentangle contributions from new physics models, e.g., of the "Dark sector".

To summarize, polarized beams with the projected precision at SuperKEKB opens up unique windows of discovery by enabling precision electroweak measurements. With 40 ab^{-1} of polarized data, Belle II will substantially improve the precision and our knowledge of $\sin^2\theta_W$.

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