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Electroweak Physics with Polarized Electron Beams in a SuperKEKB Upgrade

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A potential upgrade of the SuperKEKB e^+e^- collider with a polarized electron beam will open a new program of precision electroweak physics at the centre-of-mass energy of the $\Upsilon(4S)$ and is currently being considered. These measurements include $\sin^2\theta_W$ obtained via left-right asymmetry measurements of e^+e^- transitions to pairs of electrons, muons, taus, charm and b-quarks. The precision obtainable at SuperKEKB will match that of the LEP/SLC world average but at the centre-of-mass energy of 10.58 GeV, thereby probing the neutral current couplings with unprecedented precision at a new energy scale sensitive to the running of the couplings. World average measurements of the individual neutral current vector coupling constants to b- and c-quarks and muons in particular will be substantially improved and the residual 3σ discrepancy between the SLC A_{LR} and LEP A_{FB}^b measurements will be addressed. This paper will include a discussion of the necessary upgrades to SuperKEKB. This program opens an exciting new window in searches for physics beyond the standard model.

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The SuperKEKB e^+e^- collider operating at a centre-of-mass energy of 10.58 GeV, with its high design luminosity of 8×10^{35} cm^{-2} s^{-1}, can access new windows for discovery with the Belle II experiment if it is upgraded to have a longitudinally polarized electron beam. The target integrated luminosity for SuperKEKB/Belle II is 50 ab^{-1}[1] and currently Belle II is projected to collect that amount of data, which will not have beam polarization without an upgrade to SuperKEKB, by 2027. Upgrading SuperKEKB to have electron beams with left and right longitudinal polarization of approximately 70% at the Belle II interaction point creates a unique and versatile facility for probing new physics with precision electroweak measurements that no other experiments, current or planned, can achieve.

In particular, a data sample of 20 ab^{-1} with a 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 any previous experiment. With 40 ab^{-1} of polarized beam data, the precision of the vector couplings to the tau and electron can be measured at a level comparable to current world averages, which are dominated by LEP and SLD measurements at the Z^0-pole.

Within the framework of the Standard Model (SM) these measurements of g_V^f, the neutral current vector coupling for fermion f, can be used to determine the weak mixing angle, θ_W, through the relation: $g_V^f = T_3^f - 2Q_f \sin^2\theta_W$, where T_3^f is the 3^{rd} component of weak isospin of fermion f, Q_f is its electric charge in units of electron charge and the notational conventions of Reference [2] are used.

As described in Reference [3], with polarized electron beams an e^+e^- collider at 10.58 GeV can determine g_V^f by measuring the left-right asymmetry, A_{LR}^f, for each identified final-state fermion-pair in the process $e^+e^- \to f\overline{f}$:

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

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

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

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. These asymmetries arise from $\gamma - Z$ interference and although the SM asymmetries are small (-6×10^{-4} for the leptons, -5×10^{-3} for charm and -2% for the b-quarks), unprecedented precisions can be achieved because of the combination of both the high luminosity of SuperKEKB and a 70% beam polarization measured with a precision of better than $\pm 0.5\%$. Note that higher order corrections are ignored here for simplicity, although studies at higher orders have recently begun [4].

The upgrade to SuperKEKB involves three hardware projects:

1) A low-emittance polarized electron source in which the electron beams would be produced via a polarized laser illuminating a "strained lattice" GaAs photocathode as was done for SLD [2]. The source would produce longitudinally polarized electron bunches whose spin would be rotated to be transversely polarized before it enters the SuperKEKB electron storage ring;

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. One configuration under consideration for the spin-rotator is a combined function magnet that replaces an existing dipole in the SuperKEKB electron beam lattice with a superconducting magnet that has both a dipole and solenoid [6] as well as six skew quads. The challenge is to design the rotators to minimize couplings between vertical and horizontal planes and to address higher order and chromatic effects in the design to ensure the luminosity is not degraded;
3) A Compton polarimeter that measures the beam polarization before the beam enters the interaction region.

The high precisions are possible at such an upgraded SuperKEKB because with 20 ab^{-1} of data Belle II can identify between 10^9 and 10^{10} final-state pairs of b-quarks, c-quarks, taus, muons and electrons with high purity and reasonable signal efficiency, and because all detector-related systematic errors can be made to cancel by flipping the laser polarization from **R** to **L** in a random, but known, pattern as collisions occur. $\langle Pol \rangle$ would be measured in two ways. The first method uses a Compton polarimeter, which 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 will be dominated by the need to predict the polarizatoin loss from the Compton polarimeter to the interaction point. The second method measures the polar angle dependence of the polarization of τ-leptons produced in $e^+e^- \to \tau^+\tau^-$ events using the kinematic distributions of the decay products of the τ separately for the **R** and **L** data samples. The forward-backward asymmetry of the tau-pair polarization is linearly dependent 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. The τ polarization forward-backward asymmetry 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. In addition, it automatically provides a luminosity-weighted beam polarization measurement.

Table 1 provides the sensitivities to electroweak parameters expected with polarized electron beams in an upgraded SuperKEKB from $e^+e^- \to b\bar{b}$, $e^+e^- \to c\bar{c}$, $e^+e^- \to \tau^+\tau^-$, $e^+e^- \to \mu^+\mu^-$, and $e^+e^- \to e^+e^-$ events selected by Belle II. From this information the precision on the b-quark, c-quark and muon neutral current vector couplings will improve by a factor of four, seven and five, respectively, over the current world average values[2] with 20 ab^{-1} of polarized data.

This is of particular importance for g_V^b, where the measurement of -0.3220±0.0077 is 2.8σ higher than the SM value of -0.3437 [2]. That discrepancy arises from the 3σ difference between the SLC A_{LR} measurements and LEP A_{FB}^b measurements of $\sin^2\theta_W^{eff}$. A measurement of g_V^b at an upgraded SuperKEKB that is four times more precise and which avoids the hadronization uncertainties that are a significant component of the uncertainties of the measurement of the forward-backward asymmetry at LEP, or any other forward-backward asymmetry measurement using on-shell Z^0 bosons, will be able to definitively resolve whether or not this is a statistical fluctuation or a first hint of a genuine breakdown of the SM.

Table 1 also indicates the uncertainties on $\sin^2\theta_W^{eff}$ that can be achieved with 40 ab^{-1} of polarized beam data - the combined uncertainty at Belle II would be comparable to the Z^0 world average measured uncertainty of ±0.00016 from LEP and SLD[2] but made at a significanlty lower

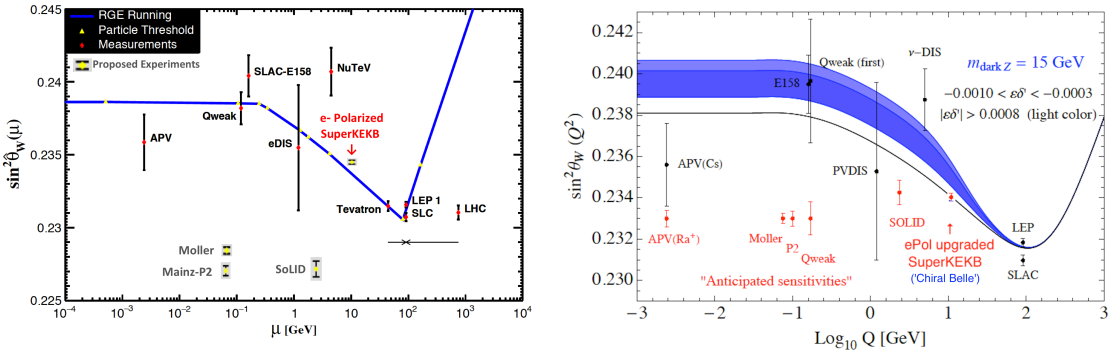

Figure 1: Left: Determination of $\sin^2\theta_W$ at present and future experimental facilities as a function of energy scale, adapted from [5]. Right: Dark blue band shows Q^2-dependent shift in $\sin^2\theta_W$ caused by a 15 GeV mass dark Z, adapted from [11].

Final State Fermion	A_{LR}^{SM}	Relative A_{LR} Error (%)	g_V^f W.A.[2]	$\sigma(g_V^f)$ (20 ab^{-1})	$\sigma(g_V^f)$ (40 ab^{-1})	$\sigma(s^2\theta_W)$ (40 ab^{-1})
b-quark (eff.=0.3)	-0.020	0.5	-0.3220 $\pm$0.0077	0.002 improves x4	0.002	0.003
c-quark (eff.=0.3)	-0.005	0.5	+0.1873 $\pm$0.0070	0.001 improves x7	0.001	0.0007
tau (eff.=0.25)	-0.0006	2.3	-0.0366 $\pm$0.0010	0.0008	0.0006	0.0003
muon (eff.=0.5)	-0.0006	1.5	-0.03667 $\pm$0.0023	0.0005 improves x5	0.0004	0.0002
electron (1 nb acceptance)	-0.0006	1.2	-0.3816 $\pm$0.00047	0.0004	0.0003	0.0002

Table 1: For each fermion pair cleanly identifiable in Belle II for the given efficiency in column 1: column 2 gives the SM value of A_{LR}; column 3, the expected relative error on A_{LR} based on based on 20 ab^{-1} and a beam polarization at Belle II of 70% with an error of $\pm$0.5%; column 4, the current world average value of its neutral current vector coupling; column 5, the projected error on g_V^f with 20 ab^{-1} of data; column 6, the projected error on g_V^f with 40 ab^{-1} of data; and column 7, the projected SuperKEKB/Belle II error on $\sin^2\theta_W^{eff}$ with 40 ab^{-1} of polarized e$^-$ beam data.

energy scale. Figure 1(left) shows the determinations 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 delivering 40 ab^{-1} of data to Belle II.

This electroweak program with polarized electron beams in SuperKEKB would provide the highest precision tests of neutral current vector coupling universality. In addition, right-handed b-quark couplings to the Z can be experimentally probed with high precision at Belle II with polarized beams. Also, measurements with the projected precision will enable Belle II to probe 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 will not be produced at the LHC. Moreover, the SuperKEKB machine will have a unique possibility 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 entertained as a possible connecting link between normal and dark matter [7, 8]. SuperKEKB with polarization would be uniquely sensitivity to "Dark Sector" parity violating light neutral gauge bosons,especially when Z_{dark} is off-shell and with a mass between roughly 10 and 35 GeV [11] or even up to the Z^0 pole, or couples more to the 3rd generation (see Figure 1(right)).

The enhancement of parity violation in the muon sector has been an automatic consequence of some models [9] that aim at explaining the unexpected result for the recent Lamb shift measurement in muonic hydrogen [10]. The left-right asymmetry of the $e^-e^+ \to \mu^-\mu^+$ in such models is expected to be enhanced at low-to-intermediate energies, and SuperKEKB with polarized beams may provide a conclusive test of such models, as well as impose new constraints on a parity-violating dark sector.

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