B Physics with a Giga-Z Sample

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Abstract. Prospects for the study of B physics with a sample of 10^9 hadronic Z^0 decays, produced with a highly polarized electron beam, are discussed. The discussion is based on extrapolations made from current experience at LEP and the SLC, and includes both electroweak coupling measurements as well as the study of CKM parameters via exclusively reconstructed B hadron decays.

In this paper, the opportunities available to the study of B physics with a sample of 10^9 hadronic Z^0 decays at high electron beam polarization will be extrapolated from the results of current Z-pole measurements. The measurements include those from a sample of approximately 1.6×10^{10} unpolarized Z decays from LEP, and 5×10^5 decays from the SLC, produced with an electron beam polarization of approximately 75%.

In extrapolating experience gained from the recent Z^0 pole experiments, it is important to recognize that advances in technology, combined with the proposed pulse structure of the Linear Collider, should allow a substantial improvement of the tracking performance for a Linear Collider detector relative to its existing Z^0 pole counterparts. The discussion in this paper assumes a vertex detector composed of five layers of CCD pixel detectors evenly spaced in radius between 1.2 and 10 cm, with a point resolution of 5 μm. Central tracking is provided by 120 TPC measurements between 25 and 150 cm in radius. Double-sided disks of silicon strips provide forward tracking down to an angle of 110 mrad. With a magnetic field of 3 Tesla, this system provides momentum resolution 8-10 times better than that of the SLD detector. The improvement in r/ϕ impact parameter resolution (Fig. 1) varies from 50% ($|\cos\theta| \sim 0$; $p > 10$ GeV/c) to a factor of five ($|\cos\theta| \sim 0.8$; low momentum). In summary, it is expected that a Linear Collider detector will provide a substantial improvement in momentum and impact parameter resolution, as well as $|\cos\theta|$ coverage, relative to that of existing detectors.

B physics topics addressed in this brief paper fall into two categories: determi-

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nation of $Z - b$ coupling parameters and the use of B meson decays to constrain the properties of the CKM matrix. The b quark couplings can be constrained by two measurements: a measurement of the total strength of the coupling via R_b, the ratio of the $Z^0 \rightarrow b\bar{b}$ to the total hadronic decay width; and a measurement of the extent A_b of parity violation in the $Z - b$ coupling.

The current R_b measurement is essentially systematics limited at $\delta R_b/R_b \simeq 0.3\%$. The critical systematic issue is the determination of the efficiency of the $Z \rightarrow b\bar{b}$ tag, determined by comparing single- and double-hemisphere tag rates. Systematic issues concern correlations between hemispheres in the tag efficiency ($\pm 0.1\%$) as well as residual backgrounds in the $Z \rightarrow b\bar{b}$ sample ($\pm 0.2\%$). It is expected that the ultra-precise vertexing available for the Linear Collider detector will allow the backgrounds to be substantially reduced, while the excess of data in the Giga-Z sample will permit further reduction of the correlation systematic, resulting in an overall projection of $\delta R_b/R_b \simeq \pm 0.05\%$.

The combination of parity violation parameters $A_e A_b$ is measured via the angular dependence of b quark production. Measuring the angular distribution separately for left- and right-handed beam allows the direct extraction of A_b, while dramatically improving the statistical power of the measurement and reducing the sensitivity of the result to forward-backward acceptance asymmetry. A combination of LEP and SLC data, assuming the value of A_e measured from leptonic final states, yields $A_b = 0.892 \pm 0.015$, approximately 2.9σ from the Standard Model expectation of $A_b = 0.935$.

Rather than tag efficiency, the biggest systematic challenge in the A_b measurement is the separation of the b and $\bar{b}$ quark hemispheres, which can be calibrated by comparing the sign determination in opposing hemispheres. The most promising approach in use makes use of the precise SLD CCD vertex detector to reconstruct

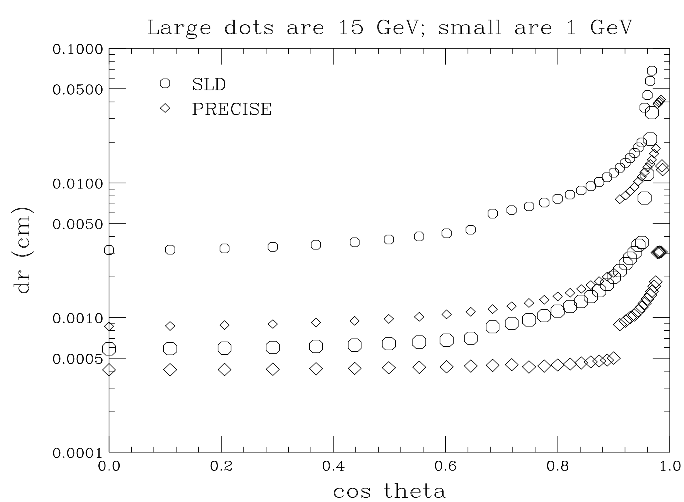

FIGURE 1. Comparison of impact parameter resolution between SLD and Linear Collider detectors.

the net charge of secondary vertices in $Z \to b\bar{b}$ events, which achieves a preliminary precision of $\pm 0.019(stat.) \pm 0.025(syst.)$. It is expected that dominant systematic uncertainties, due to hemisphere correlations and backgrounds, can be substantially reduced by considering only events with two charge-determining reconstructed secondary vertices. For the SLD, the restriction to double-tagged events results in an effective reduction in the sample size by a factor of three; presumably, this would be somewhat less with improved Linear Collider detector tracking. The resulting expectation for a Giga-Z run is $\delta A_b/A_b \sim 0.1\%$ (stat. and syst. combined). Both the projections for δR_b and δA_b confirm earlier projections from a study by Mönig and Hawkins [1].

Turning to the issue of constraining CKM parameters with a Giga-Z sample, we note that data from both upgraded B factories as well as dedicated hadronic B physics facilities (BTEV, LHCB) should be available by the time a Linear Collider Z factory would be running. In this paper, I have chosen to make comparisons to the projected performance of BTEV, which claims to be competitive with both LHCB as well as e^+e^- B factories running at upgraded luminosities of $10^{35} cm^{-2} s^{-1}$.

In terms of raw numbers, hadronic B factories enjoy a large advantage over a Giga-Z facility, with an expected rate of 2×10^{11} $b\bar{b}$ pairs per year, about 1,000 times greater than that available from a Giga-Z sample. However, the experimental environment is somewhat more challenging for the hadronic experiment, leading to a substantially lower reconstruction efficiency.

A good point of comparison, for which both BTEV and the SLD have reliable studies of reconstruction efficiencies, is the $B^0 \to \pi^+\pi^-$ signal. BTEV [2] cites an absolute efficiency of 3.7% for reconstructing this mode, with a resulting S:B of 3:1 for BR($B^0 \to \pi^+\pi^-$) = 4.3×10^{-6}. Much of the loss of efficiency comes from the tendency of the B sample to populate the central region, which BTEV does not instrument due to the relatively low energy of the B hadrons produced in this region. On the other hand, published SLD results [3] cite an efficiency of 34% for this mode, with a background rejection rate corresponding to a S:B of 5:1 for BR($B^0 \to \pi^+\pi^-$) = 4.3×10^{-6}. With the substantially improved Linear Collider momentum and intermediate energy impact parameter resolution, this would be expected to improve substantially. Additionally, efficiency of the SLD exclusive reconstruction is relatively insensitive to the number of decay prongs, while it tends to fall substantially in higher background environments.

In order to extract CKM information from a sample of exclusively reconstructed decays, it is necessary to 'tag' the initial state of the decaying B hadron to determine its original flavor. The figure of merit of the tagging algorithm is ϵD^2, where ϵ is the efficiency for the reconstructed event to satisfy the requirements of the tagging algorithm, while $D = (N_{right} - N_{wrong})/N_{tot}$ is the dilution of the resulting tag decision. Using the inclusively decaying recoil B, as well as particles produced in association with the reconstructed B during the fragmentation process, BTEV expects to achieve $\epsilon D^2 \simeq 0.1$. On the other hand, for an electron beam polarization of 85% and coverage to $|\cos\theta| \simeq 0.9$, the $Z \to b$ differential cross section alone provides $\epsilon D^2 \simeq 0.4$. Including additional tags similar to BTEV, once can reasonably expect $\epsilon D^2 \simeq 0.5\%$. Combined, the efficiency and tagging advantages account for about a factor of 100 in effective sample size.

For signals for which proper time resolution is critical (such as B_s mixing for large x_s), the Linear Collider is expected to hold an additional advantage due to its ultra-precise vertexing. For track momenta beyond the MCS regime (where the stated samples of both the LC and BTEV detectors lie), the proper time resolution σ_τ is independent of boost. From simple geometrical arguments, $\sigma_\tau \simeq \sigma_b/c$, where σ_b is the impact parameter resolution. From this estimate, $\sigma_\tau \simeq 15$ fs for the Giga-Z detector, 2-3 times as good as the BTEV value of 40 fs. Thus, at BTEV, the proper time resolution will begin to degrade statistical power for $x_s \sim 25$, while the Giga-Z measurement should maintain its full statistical power to $x_s \simeq 40$. This may well render a Giga-Z B_s mixing measurement competitive in reach or accuracy to that of the hadronic B factories.

In addition, there are types of rare B hadron decay modes that may be best accessible in a Giga-Z run. Modes with 0 or 1 charged prong, which are difficult to trigger on in a hadronic environment, might be accessible to a high statistics Z-pole run with a state-of-the-art Linear Collider detector. The inclusive charmless decay rate, which provides a relatively clean measure of $|V_{ub}|$, might be separable via its single-vertex topology. Furthermore, there is some possibility that further improvements in vertexing technology may be able to substantially improve the impact parameter resolution beyond the current Linear Collider Detector baseline, particularly at the intermediate momenta populated by tracks from low-multiplicity exclusive decays [4].

In conclusion, a sample of 10^9 hadronic Z^0 decays produced with a highly polarized electron beam, and analyzed with a state-of-the-art Linear Collider Detector, seems to provide an opportunity for roughly an order of magnitude improvement in out current knowledge of $Z-b$ coupling parameters. On the other hand, while the Linear Collider environment does seem to be a more natural setting for the study of B system CKM physics, the limited size of the sample relative to those of hadronic B factories will make it difficult to compete broadly with data from those other sources. There may, however, be some notable exceptions, including B_s physics (mixing and CP) if x_s is large, the extraction of V_{ub}, and the observation and study of rare high multiplicity fully-charged modes, or rare modes with neutrals and zero or one charged prong. It is these latter topics which probably best warrant further study.

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