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QCD with SLD*

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Abstract

We present selected new results on strong interaction physics from the SLD experiment at the SLAC Linear Collider (SLC), symmetry tests of $b\bar{b}g$ vertex, the rate of secondary $b\bar{b}$ production via gluon splitting, the B hadron energy spectrum and rapidity correlations between identified charged hadrons. The parity violation in $Z^0 \to b\bar{b}g$ decays is consistent with electroweak theory plus QCD. New tests of T- and CP-conservation at the bbg vertex are performed. A new measurement of the rate of gluon splitting into $b\bar{b}$ pairs yields $g_{b\bar{b}} = 0.00307 \pm 0.00071(stat.) \pm 0.00066(syst.)$ (Preliminary). The B hadron energy spectrum is measured using a new inclusive technique, allowing tests of predictions for its shape and a measurement of $\langle x_B \rangle = 0.714 \pm 0.005(stat.) \pm 0.007(syst.)$ (Preliminary). A study of correlations in rapidity between pairs of identified $\pi^{\pm}$, $K^{\pm}$ and p/p̄ confirms that strangeness and baryon number are conserved locally, and shows local charge conservation between meson-baryon and strange-nonstrange pairs. Flavor-dependent long-range correlations are observed for all combinations of these hadron species. The first study of correlations using signed rapidities is done and find the first direct observation of baryon number ordering along the $q\bar{q}$ axis.

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1 Introduction

The QCD physics at SLD experiment are characterized with very excellent features of SLC/SLD.

The SLC is the only single pass e^+e^- collider in the world, running on Z^0 pole with highly longitudinally polarized electron beam and small and stable interaction point (IP). The magnitude of the beam polarization averaged 73%, providing high sensitivity to parity violating observables and a quark hemisphere tag of 73% purity. The IP can be measured to a resolution of about 4μm in the plane transverse to the beam axis, allowing clean uds, c and b-quark event separation with our vertex detector (VXD3) [1, 2], which gives remarkable impact parameter resolutions of $\sigma_{xy} = 7.8 \oplus 33/p\sin^{3/2}\theta$ μm and $\sigma_{rz} = 9.7 \oplus 33/p\sin^{3/2}\theta$ μm. With topological vertex reconstruction algorithm [3], our study put enhance on strong interaction dynamics of b quark. Efficient π, K and p particle identifications for wide momentum rage are provided by the SLD Cherenkov Ring Imaging Detector (CRID) [4], which leads us a study of fragmentation process with clean e^+e^- environment.

In this paper, we report on selected new QCD results at SLD experiment, symmetry tests of $b\bar{b}g$ vertex [5], the rate of secondary $b\bar{b}$ production via gluon splitting [6], the B hadron energy spectrum [7] and rapidity correlations between identified charged hadrons [8].

2 SYMMETRY TESTS IN $Z^0 \to b\bar{b}g$

In recent years, there are excitement in $Z^0 \to b\bar{b}$ sector such as A_b and R_b measurements [9]. It is very important to make cross check on strong interaction dynamics of b quark and through test of $b\bar{b}g$ vertex. New tests of parity-violation in strong interactions have recently been proposed using angular distributions in polarized $e^+e^- \to q\bar{q}g$ events [10]. In this study, we consider two angles, the polar angle of the quark with respect to the electron beam direction θ_q, and the angle between the quark-gluon and quark-electron beam planes $\chi = \cos^{-1}(\hat{p}_q \times \hat{p}_g) \cdot (\hat{p}_q \times \hat{p}_e)$. The cosine x of each of these angles should be distributed as $1 + x^2 + 2A_P A_Z x$, where the Z^0 polarization $A_Z = (P_e - A_e)/(1 - P_e A_e)$ depends on the e^- beam polarization P_e, and A_e and $A_P = A_0 A_q$ are predicted by QCD plus electroweak theory.

Three-jet events (Durham algorithm, $y_{cut} = 0.005$) are selected and energy ordered. Using 550k hadronic event sample, the 14,658 events containing a secondary vertex with P_T corrected mass (M_{P_T}) above 1.5 GeV/c^2 in any jet are kept, having an estimated $b\bar{b}g$ purity of 85%. We calculate the momentum-weighted charge of each jet j, $Q_j = \Sigma_i q_i |\vec{p}_i \cdot \hat{p}_j|^{0.5}$, using the charge q_i and momentum $\vec{p}_i$ of each track i in the jet. We assume that the highest-energy jet is not the gluon, and tag it as the b ($\bar{b}$) if $Q = Q_1 - Q_2 - Q_3$ is negative (positive). We define the b-quark polar angle by $\cos\theta_b = -\text{sign}(Q)(\hat{p}_e \cdot \hat{p}_1)$.

The left-right-forward-backward asymmetry A^b_{LRFB} is shown as a function of $|\cos\theta_b|$ in Fig. 1. A maximum-likelihood fit to the data yields an asymmetry parameter of $A_P =$

$0.91 \pm 0.05(stat.) \pm 0.06(syst.)$ (Preliminary), consistent with the QCD prediction of $A_P = 0.93 A_b = 0.87$.

We then tag one of the two lower energy jets as the gluon jet: if jet 2 has $n_{sig} = 0$ and jet 3 has $n_{sig} > 0$, where n_{sig} is the number of significant tracks with normalized impact parameter with respect to the IP $d/\sigma_d > 3$, then jet 2 is tagged as the gluon; otherwise jet 3 is tagged as the gluon. The obtained result by a maximum-likelihood fit is $A_\chi = -0.014 \pm 0.035 \pm 0.002$ (Preliminary), to be compared with an expectation of -0.064.

Using these fully tagged events, we can construct observables that are formally odd under time reversal and/or CP reversal. For example, the triple product $\cos\omega^+ = \vec{\sigma}_Z \cdot (\hat{p}_1 \times \hat{p}_2)$, formed from the directions of the Z^0 polarization $\vec{\sigma}_Z$ and the highest- and second highest-energy jets, is T_N-odd and CP-even. Since the true time reversed experiment is not performed, this quantity could have a nonzero A_{LRFB}. A calculation [11] including Standard Model final state interactions predicts that $A^{\omega^+}_{LRFB}$ is largest for $b\bar{b}g$ events, but is only $\sim 10^{-5}$. The fully flavor-ordered triple product $\cos\omega^- = \vec{\sigma}_Z \cdot (\hat{p}_q \times \hat{p}_{\bar{q}})$ is both T_N-odd and CP-odd. Obtained $A^{\omega^+}_{LRFB}$ and $A^{\omega^-}_{LRFB}$ are consistent with zero at all $|\cos\omega|$. Fits to the data yield 95% C.L. limits on any T_N-violating and CP-conserving or CP-violating asymmetries of $-0.038 < A^+_T < 0.014$ or $-0.077 < A^-_T < 0.011$, respectively.

3 The Rate of Secondary $b\bar{b}$ Production via $g \to b\bar{b}$

The rate of secondary b-quark pair production via gluon splitting, $g \to b\bar{b}$, is also important input for R_b measurement in Z^0 decays and b-quark production in hadron-hadron collisions. However the rate is poorly known, both theoretically and experimentally, despite the fact that this is one of the elementary processes in QCD. The rate can be calculated using pQCD [12], however it is sensitive to both the $\Lambda^5_{\overline{MS}}$ parameter and the b-quark mass, which results in a substantial uncertainty in the calculation of the rate. And the measurement is experimentally difficult due to difficulty of B jet tag from $g \to b\bar{b}$ and large background. Here we present a new measurement of the $g \to b\bar{b}$ rate which takes our excellent B tagging performance.

In this analysis, we use 400k hadronic event sample. Candidate events containing a gluon splitting into a $b\bar{b}$ pair, $Z^0 \to q\bar{q}g \to q\bar{q}b\bar{b}$, where the initial $q\bar{q}$ can be any flavor, are required to have 4 jets (Durham algorithm, $y_{cut} = 0.008$). A secondary vertex is required in each of the two jets with the smallest opening angle in the event, yielding 314 events. This sample is dominated by background, primarily from $Z^0 \to b\bar{b}g(g)$ events and events with a gluon splitting into a $c\bar{c}$ pair.

A large component of the former background is $Z^0 \to b\bar{b}g$ events in which the b or $\bar{b}$ jet is split into two jets by the jet finder, and two distinct vertices from the *same* B-hadron decay are found. Since the small beam spot allows the vertex flight directions to be measured precisely, and the angle between the two flight directions from this background source tends to be small, it is suppressed by a cut on this angle.

Cuts are also made on the sum of the energies of the two jets, the angle between the plane formed by the two selected jets and that formed by the other two jets in the event, and the larger of the vertex masses (M_{P_T}s). The distribution of the latter quantity is shown in Fig. 2 after all other cuts. A clear excess of events is visible over the expected background for masses above 2 GeV/c^2. A cut at this value keeps 62 events, with an estimated background of 27.6±1.2 events. Using this and the estimated efficiency for selecting $g \rightarrow b\bar{b}$ splittings of 3.9% yields a measured fraction of hadronic events containing such a splitting of

$$g_{b\bar{b}} = 0.0031 \pm 0.0007\ (stat.) \pm 0.0006\ (syst.)\ \text{(Preliminary)}.$$

The systematic error is dominated by Monte Carlo statistics. The result is consistent with and complementary to previous measurements [13, 14, 15, 16] ; in particular it is relatively insensitive to the modeling of the gluon splitting process, due to the excellent efficiency for finding vertices from low-energy B hadrons.

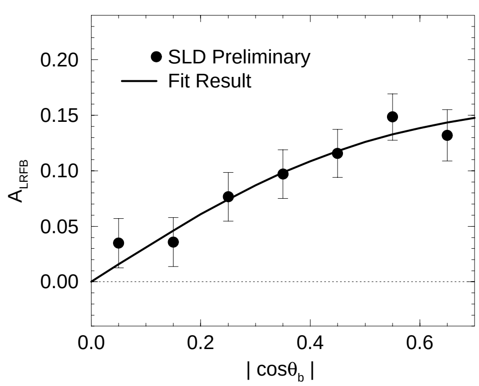

Figure 1: Left-right-forward-backward asymmetry of the b-quark polar angle in 3-jet Z^0 decays. The line is the result of a fit.

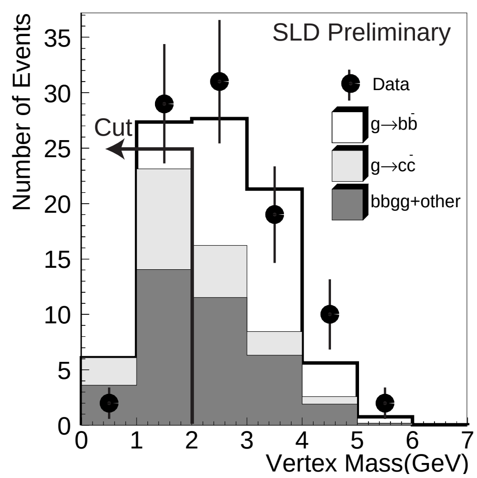

Figure 2: Distribution of the larger of the two vertex masses in candidate gluon splitting events after all other cuts (dots). The backgrounds expected from the simulation are indicated.

4 The B Hadron Energy Spectrum

Experimental studies of the B-hadron spectrum have been limited by the efficiency for reconstructing the energies E_B of individual B hadrons with good resolution, especially for low-energy B hadrons. Here we present a new study of the E_B distribution using a novel kinematic technique and only charged tracks. The high efficiency and good resolution for all E_B, results in a measurement covering the full kinematic range.

In this analysis, any secondary vertex in either thrust hemisphere of an event that has $M_{p_t} > 2$ GeV/c^2 is considered as a candidate B-hadron vertex. Its flight direction is taken to be along the line joining the IP and the vertex position. The four-vector sum of the tracks in the vertex (assigned the charged pion mass) is calculated, and the momentum component P_t transverse to the flight direction is equated with the transverse component of the "missing" momentum. At this point the missing mass M_0 and momentum along the flight direction are still needed to determine the energy E_B. Assuming a B hadron mass of M_B eliminates one of these unknowns, and also allows an upper limit to be calculated on M_0:

$$M_{0max}^2 = M_B^2 - 2M_B\sqrt{M_{chg}^2 + P_t^2} + M_{chg}^2,$$

where M_{chg} is the mass of the set of tracks in the vertex. True M_0 strongly tends to cluster near the M_{0max}. Using $M_B = 5.28$ GeV/c^2, equating M_0^2 with M_{0max}^2 and solving for E_B provides a good estimate of the true E_B. A sample of 1938 vertices is selected from 150k hadronic event sample, with an estimated B-hadron purity of 99.5%. The simulated energy resolution is 10% on average, roughly independent of E_B.

Using the obtained data distribution of the scaled energy $x_B = E_B/E_{beam}$, we test several fragmentation models at detector level using binned χ^2. Within the context of the JETSET [17] simulation, we exclude the models of Peterson et. al [18] Braaten et. al [19], and Collins and Spiller [20], whereas those of the Lund group [21], Bowler [22], and Kartvelishvili [23] are able to describe the data. In addition, we test the UCLA [24] and HERWIG [25] fragmentation models. The UCLA model is consistent with the data, but that of the HERWIG model is not.

Using four fragmentation models and four functional forms [26] that are consistent with the data, we unfold the data to obtain the true distribution, concerning migration between bins. Fig. 3 shows the unfolded x_B distribution, where in each bin i the average of the eight forms and the error bar includes their rms deviation due to strong simulation dependence of the unfolding. From these eight forms we extract a measurement of the mean value of the scaled energy,

$$\langle x_B \rangle = 0.714 \pm 0.005(stat.) \pm 0.007(syst.) \pm 0.002(rms) \text{ (Preliminary)}.$$

This is the most precise of the world's measurements that take the shape dependence into account, and this uncertainty is small since we are able to exclude a wide range of shapes.

5 Rapidity Correlations

Lighter identified particles are also an active field of study. The production of strange particles and baryons is of particular interest as they must be produced in strange-antistrange or baryon-antibaryon pairs, and the mechanism of their pair production can yield insights into the fragmentation process.

Here we present detailed studies of short- and long-range correlations between identified $\pi^\pm$, $K^\pm$ and p/$\bar{\text{p}}$. In addition, we use the SLC beam polarization to tag the quark hemisphere in each event and study for the first time rapidities signed such that positive (negative) rapidity corresponds to the (anti)quark hemisphere.

For this study we use the entire sample of hadronic events, as well as subsamples tagged as primary light-(uds), c-, and b-flavor, having purities of 88%, 39%, and 93%, respectively. Charged tracks identified as $\pi^{\pm}$, $K^{\pm}$ or p/p̄ in the CRID are considered, and their rapidities $y = 0.5\ln((E + p_{\|})/(E - p_{\|}))$ are calculated using their measured energies and components of momentum along the event thrust axis $p_{\|}$. For each pair of identified tracks in an event the absolute value of the difference between their rapidities $|\Delta y| = |y_1 - y_2|$ is considered. Fig. 4 shows the difference between the opposite-charge and same-charge distributions for all six pair combinations of identified π, K and p. The excesses of the $\pi\pi$, KK and pp at low $|\Delta y|$ indicate that strangeness, baryon number and electric charge conservation is local in the jet fragmentation process.

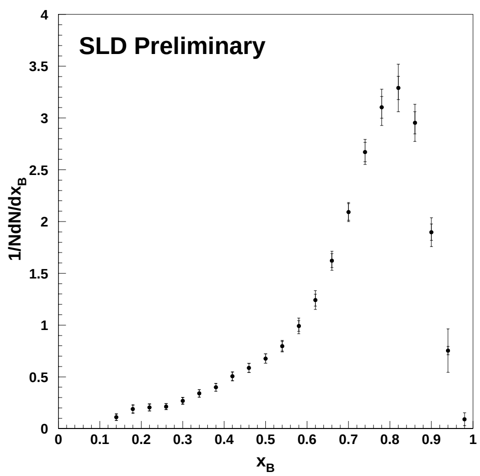

Figure 3: Corrected distribution of B-hadron energies averaged over the eight acceptable shapes. The outer error bars include the rms deviation among these shapes and provide an envelope for the true shape of the distribution.

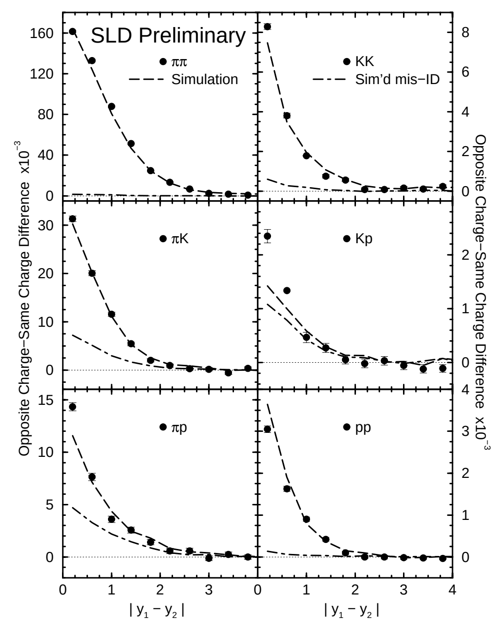

Figure 4: Differences between the $|\Delta y|$ distributions for opposite- and same-charge pairs of identified $\pi^{\pm}$, $K^{\pm}$, p/p̄ in hadronic Z^0 decays (dots). The dashed (dot-dashed) lines indicate the simulated differences (contributions from pairs with a misidentified track).

Also short-range correlations for all three unlike pair combinations are shown in Fig. 4. Excellent particle identification is required to observe these over the background from $\pi\pi$ pairs in which one of the pions is misidentified. This is the first direct observation of a fundamental feature of the jet fragmentation process, that electric charge can be conserved locally between a meson and a baryon, or between a strange particle and a nonstrange particle, and suggests charge ordering along the entire fragmentation chain.

To study long-range correlations, which are expected from leading particle production, it is necessary to consider high momentum tracks. The differences between the opposite- and same-charge $|\Delta y|$ distributions for pairs of tracks in which both have $p > 9$ GeV/c are studied. Significant correlations are observed for all pair combinations in light flavor events (see Fig. 5). The JETSET model predictions are consistent with these data, except that no πK correlation is predicted.

We now give the rapidity a meaningful sign by using the beam polarization to tag the quark hemisphere in each event, with a purity of 73%. The thrust axis is signed to point into this hemisphere, thus signing the rapidity such that $y > 0$ ($y < 0$) in the (anti)quark hemisphere. For pairs of hadrons one can define an ordered rapidity difference; for hadron-antihadron pairs we define $\Delta y^{+-} = y_+ - y_-$.

Fig. 6 shows the results for $\pi^+\pi-$, K^+K^- and $p\bar{p}$ pair combinations. The large positive difference observed for pp̄ pairs at low $|\Delta y^{+-}|$ is the first direct observation of another fundamental feature of jet fragmentation, namely the ordering of baryon number along the quark-antiquark axis. That is, the proton in a correlated proton-antiproton pair 'knows' and prefers the quark direction over the antiquark direction. This excess is observed at all proton momenta so cannot be attributed simply to leading baryons. We have searched for similar signals for strangeness and charge ordering in the K^+K^- and $\pi^+\pi^-$ samples, respectively, by isolating the light flavors and considering a variety of momentum bins. However no significant effects are observed.

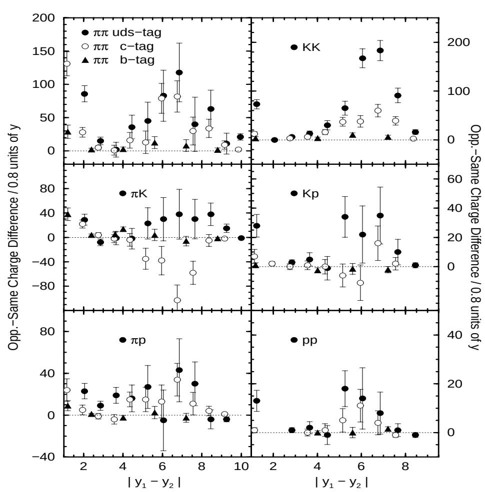

Figure 5: Differences between the $|\Delta y|$ distributions for opposite-charge and same-charge pairs in which both tracks have $p > 9$ GeV/c, for the light-(dots), c-(open circles), and b-tagged (triangles) samples.

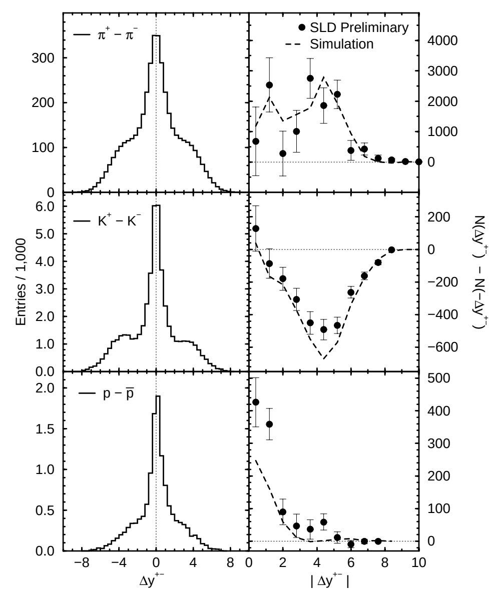

Figure 6: Distributions (left) of the ordered signed rapidity difference Δy^{+-}, and differences (right) between the positive and negative sides of each distribution. The dashed lines indicate the predictions of the JETSET simulation.

6 Summary

We use the excellent SLD vertexing and particle identification, and the high SLC e^- beam polarization to make several new tests of QCD. Using 3-jet final states in which jets are tagged as b, $\bar{b}$ or gluon jets: we find the parity violation in $Z^0 \to b\bar{b}g$ decays to be consistent with electroweak theory plus QCD; and we perform new tests of T- and CP-conservation in strong interactions. Using 4-jet final states in which the two most collinear jets are tagged as $b/\bar{b}$, we measure the rate of gluon splitting into a $b\bar{b}$ pair in hadronic Z^0 decays, $g_{b\bar{b}} = 0.00307 \pm 0.00071(stat.) \pm 0.00066(syst.)$ (Preliminary).

A new inclusive technique for measuring the energies of individual B hadrons is studied. We exclude several fragmentation functions, constrain the shape, and obtain an averaged scaled energy of $\langle x_B \rangle = 0.714 \pm 0.005(stat.) \pm 0.007(syst.) \pm 0.002(shape)$ (Preliminary).

Considering pairs of identified $\pi^\pm$, $K^\pm$ and p/p̄, we confirm that the conservation of strangeness, baryon number and electric charge quantum numbers is local in the jet fragmentation process, and observe local charge conservation between mesons and baryons and between strange and nonstrange particles. Long range correlations are also observed between all these pair combinations. The first study of ordered correlations in signed rapidity provides additional new information on fragmentation, including the first direct observation of baryon number ordering along the quark-antiquark axis.

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[26] We also test several ad hoc functional forms $f(x_B, \vec{\lambda})$ of the observable x_B itself, by minimizing χ^2 with respect to the parameter(s) $\vec{\lambda}$. Four functions, the Peterson function, two generalizations thereof, and a sixth order polynomial, are found to describe the data.

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