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Properties of $Z^0 \rightarrow b\bar{b}g$ Events*

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Abstract

We present studies of $e^+e^- \rightarrow b\bar{b}g$ events recorded with the SLC Large Detector(SLD) at the SLAC Linear Collider. The SLD precision vertex detector was exploited to select light quarks- (u,d, and s), c- , and b-enriched event samples. A comparison of the strong couplings of light, c, and b quarks was made using jet rates in these samples. We find: ${\alpha_s}^{uds}/{\alpha_s}^{all} = 0.994 \pm 0.018(stat) \pm 0.025(syst)$, ${\alpha_s}^{c}/{\alpha_s}^{all} = 1.021 \pm 0.070 \pm 0.081$, and ${\alpha_s}^{b}/{\alpha_s}^{all} = 1.007 \pm 0.031 \pm 0.032$ (PRELIMINARY). We also investigated the structure of $b\bar{b}g$ events via the energy and polar-angle distributions of the gluon, and the forward-backward production asymmetry of the b-quark.

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1. Introduction

A complete study of $e^+e^- \rightarrow b\bar{b}g$ 3-jet final states provides an important test of QCD, since the b and $\bar{b}$ jets, and hence the gluon jet can be identified event-by-event. Furthermore a good understanding of this structure is essential for precision measurements of the electroweak dynamics, e.g. R_b and A_b. Here we present measurements of the rate of $b\bar{b}g$ vs. $q\bar{q}g$ events, and of the structure of $b\bar{b}g$ events.

The SLC Large Detector (SLD) [1] at the SLAC Linear Collider (SLC) provides an ideal environment in which to measure $b\bar{b}g$ final states. The tracking capability of the Central Drift Chamber (CDC) [2] and the precision CCD Vertex Detector (VXD) [3] , combined with the stable, micron-sized beam interaction point, allows us to select $Z^0 \rightarrow b\bar{b}(g)$ and $Z^0 \rightarrow q_l\bar{q}_l(g)$ ($q_l = u$, d, s) events using their quark decay lifetime signatures with high efficiency and purity. This analysis is based on 150,000 hadronic Z^0 decays produced by e^+e^- annihilation at a mean center-of-mass energy of $\sqrt{s}$ = 91.26 GeV collected during the 1993-1995 runs.

2. A Test of The Flavor-Independence of Strong Interactions

One of the fundamental assumptions of QCD is that the strong-coupling α_s is independent of quark flavor. Recently, with the advent of precision vertex detectors at e^+e^- colliders, it has become possible to test this fundamental assumption of QCD with previously unattainable accuracy. The assertion has been tested previously [6, 7, 8], to a precision of $\sim 1\%$ for b vs. any of the other flavors, $\sim 10\%$ for c, and $\sim 5\%$ for the light flavors.

Although an absolute determination of α_s for each quark flavor would have large theoretical uncertainties [4], it is possible to test the flavor–independence of QCD precisely by measuring ratios of couplings in which most experimental errors and theoretical uncertainties are expected to cancel. Here we present precise measurements of $\alpha_s^b/{\alpha_s}^{all}$, $\alpha_s^c/{\alpha_s}^{all}$, and $\alpha_s^{uds}/{\alpha_s}^{all}$ using this technique, and making no assumptions about the relative values of α_s^b, α_s^c and α_s^{uds}.

Lifetime-based flavor tagging has relatively low bias against 3-jet events, an important advantage of this analysis. Figure 1 shows the distribution of n_{sig}, the number of 'impact parameter quality tracks' in an event that are separated from the interaction point by more than 3σ in the plane perpendicular to the beam axis [5]. The data are well described by our Monte Carlo simulation of hadronic Z^0 decays [9]. The 78319 selected-event sample was divided into three parts: those events with $n_{sig} = 0$ were defined to be the uds-tagged sample; those with $1 \leq n_{sig} \leq 3$ were the c-rich sample; and those with $n_{sig} \geq 4$ were the b-tagged sample. The hard b tag yields a sample with very low contamination from charm events, maximizing the sensitivity of the three-flavor test. The efficiencies ε for selecting events (after cuts) of type i ($i = uds$, c, b) with tag i, and the fractions Π of events of type i in the i-tagged sample, were calculated from the Monte Carlo simulation to be: $(\varepsilon, \Pi)_{uds} = (85\%,\ 87\%)$; $(\varepsilon,\ \Pi)_c = (58\%,\ 33\%)$; $(\varepsilon,\ \Pi)_b = (45\%, 95\%)$ for 2-jet events, and $(\varepsilon, \Pi)_{uds} = (80\%,\ 83\%)$; $(\varepsilon,\ \Pi)_c = (53\%,\ 28\%)$; $(\varepsilon,\ \Pi)_b = (34\%, 95\%)$ for 3-jet events.

Jets were then reconstructed using iterative clustering algorithms. We used the 'E', 'E0', 'P', and 'P0' variations of the JADE algorithm, as well as the 'Durham' ('D') and 'Geneva' ('G') algorithms [4]. We divided events into two categories: those containing: (1) two jets, and (2) three or more jets. The fraction of the event sample in category 2 was defined as the 3-jet rate R_3. For each algorithm, the jet resolution parameter y_c was chosen to be as small as possible subject to the requirement that $\mathcal{O}({\alpha_s}^2)$ QCD provides a good description of R_3 measured in our global sample of all flavors [4]. This choice maximizes R_3 while avoiding the 'Sudakov region' at low y_c [8] .

The R_3^j for each of the j quark types ($j = uds$, c, b) was extracted from a maximum likelihood fit to n_2^i and n_3^i, the number of 2-jet and 3-jet events, respectively, in the i-tagged sample:

$$\begin{aligned} n_2^i &= \sum_{j=1}^{3} \left(\varepsilon^{ij}_{(2\to2)}(1-R_3^j) + \varepsilon^{ij}_{(3\to2)}R_3^j\right) f^j N \\ n_3^i &= \sum_{j=1}^{3} \left(\varepsilon^{ij}_{(3\to3)}R_3^j + \varepsilon^{ij}_{(2\to3)}(1-R_3^j)\right) f^j N \ . \end{aligned} \tag{1}$$

Here N is the total number of selected events corrected for the event selection efficiency, and f^j is the Standard Model fractional hadronic width for Z^0 decays to quark type j. The matrices $\varepsilon^{ij}_{(2\to2)}$ and $\varepsilon^{ij}_{(3\to3)}$ are the efficiencies for an event of type j, with 2- or 3-jets at the parton level, to pass all cuts and be tagged as a 2- or 3-jet event, respectively, of type i. This formalism explicitly accounts for modifications of the parton-level 3-jet rate due to hadronization, detector effects, and tagging bias. These matrices were calculated from the Monte Carlo simulation. Equations 1 were solved using 2- and 3-jet events defined by each of the six algorithms.

The 3-jet rate in heavy quark (b, c) events is expected to be reduced relative to that in light quark events by the diminished phase-space for gluon emission due to the quark masses. We calculated the suppression factors, R_3^c/R_3^u and R_3^b/R_3^d, for each jet algorithm and y_c value according to the JETSET7.4 Parton Shower simulation.

The ratio of the strong coupling of quark type j to the mean coupling in the sample of all flavors, ${\alpha_s}^j/{\alpha_s}^{all}$, was determined from:

$$\frac{R_3^j(y_c)}{R_3^{all}(y_c)} \quad = \quad \frac{A(y_c)\,{\alpha_s}^j \;+\; [B(y_c)+C(y_c)]\;({\alpha_s}^j)^2}{A(y_c)\,{\alpha_s}^{all} \;+\; [B(y_c)+C(y_c)]\;({\alpha_s}^{all})^2}\,, \tag{2}$$

where $A(y_c)$, $B(y_c)$, and $C(y_c)$ for the different jet-finding algorithms were evaluated using Refs. [11, 12].

In order to quote a single ${\alpha_s}^j/{\alpha_s}^{all}$ value for each flavor j, we made the conservative assumption that the results are completely correlated, and we calculated the unweighted mean values and errors over all six algorithms. We obtained the preliminary results:

$$\begin{aligned}
{\alpha_s}^{uds}/{\alpha_s}^{all} &= 0.994 \pm 0.018\,(stat) \pm 0.025\,(syst)\;, \\
{\alpha_s}^{c}/{\alpha_s}^{all} &= 1.021 \pm 0.070\,(stat) \pm 0.081\,(syst)\;, \\
{\alpha_s}^{b}/{\alpha_s}^{all} &= 1.007 \pm 0.031\,(stat) \pm 0.032\,(syst)
\end{aligned} \tag{3}$$

We find that the strong coupling is independent of quark flavor within our sensitivity.

3. Structure of $b\bar{b}g$ Events

• Gluon energy and polar-angle distributions

We selected 3-jet events for this analysis using the JADE algorithm with $y_c = 0.02$, and required the polar-angle of all jets with respect to the beam axis θ_{jet} to satisfy $|\cos\theta_{jet}| \leq 0.71$. The energies of the jets were kinematically rescaled and labeled such that $E_1 > E_2 > E_3$ in order to improve energy resolution [13]. Jets containing b or $\bar{b}$ quarks were tagged by requiring 2 or more significant tracks. The 1611 events with exactly 2 jets tagged were retained and the untagged jets were assigned as the gluon jets. The purities for correctly tagging two of the jets are 95%, 84%, and 52%, for (jet 1 and jet 2), (jet 1 and jet 3), and (jet 2 and jet 3), respectively. We obtained the parton-level distributions of gluon energy (fig. 2) and polar-angle (fig. 3) after background subtraction and efficiency and resolution correction. We find that the data are well described by the JETSET7.4 parton shower MC.

The existence of an anomalous coupling of quarks to gluons could manifest itself via a modification of the pattern of emitted gluon radiation [14]. A parametrization of anomalous couplings in the strong-interaction Lagrangian may be written:

$$L^{b\bar{b}g} = g_s \bar{q} T_a \left(\gamma_\mu + \frac{i\sigma_{\mu\nu} k^\nu}{2m_b} (\kappa - i\tilde{\kappa}\gamma_5) \right) q G_a{}^\mu ,$$

where κ and $\tilde{\kappa}$ represent anomalous 'chromomagnetic' and 'chromoelectric' dipole moments, respectively. We concentrated on the effect of κ, keeping $\tilde{\kappa} = 0$; $\tilde{\kappa}$ gives rise to CP-violating effects. Comparing with a calculation at leading order in perturbation theory, fig. 2 shows that our data exclude large non-zero κ values.

- **b-quark direction in polarized $Z^0 \rightarrow b\bar{b}g$ decays**

We studied the b-quark polar angle distribution in $b\bar{b}g$ events produced with longitudinally polarized electrons, which allows a new and more detailed test of QCD [15]. In this analysis, 3-jet events were selected using the Durham algorithm with $y_c = 0.005$, and b-events were tagged using 'topological vertex mass reconstruction' [16]. The secondary vertex mass distribution of the highest-energy jets is shown in fig. 4a. To separate b and $\bar{b}$ quark jets, the vertex charge at each reconstructed vertex was examined; this is shown in fig. 4b.

Requiring a non-zero vertex invariant mass and positive(negative) vertex charge to tag the highest-energy jet as a $\bar{b}$ (b) jet, we obtained 1914 events. The efficiency and purity for tagging $b\bar{b}g$ events are 55% and 79%, respectively, and the probability of correct charge assignment is 65%, estimated from the Monte Carlo. Fig. 5 shows the polar angle distribution of the b-quark jets. A large forward-backward asymmetry is observed as a result of the high electron beam polarization [17]. This measurement will provide an experimental constraint on the QCD correction to the electroweak asymmetry.

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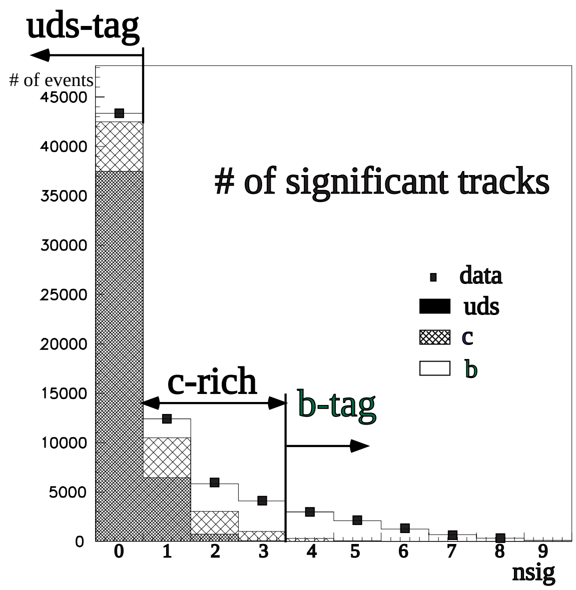

Figure 1: The distribution of the the number of tracks per event that miss the interaction point by $\geq 3\sigma$.

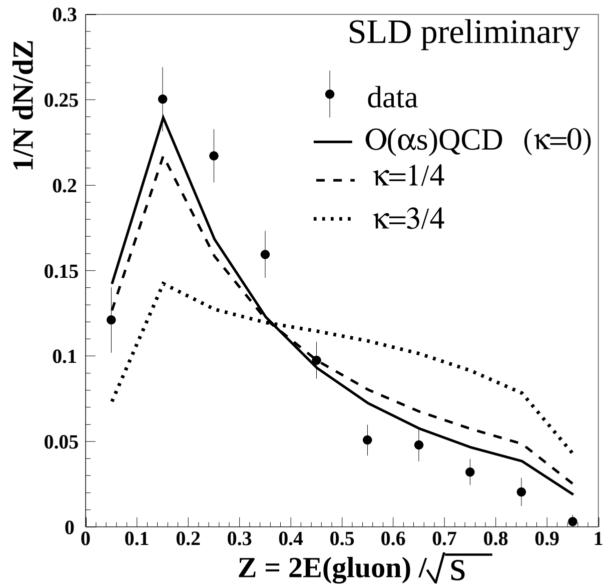

Figure 2: The gluon energy distribution normalized by center of mass energy in $b\bar{b}g$ events.

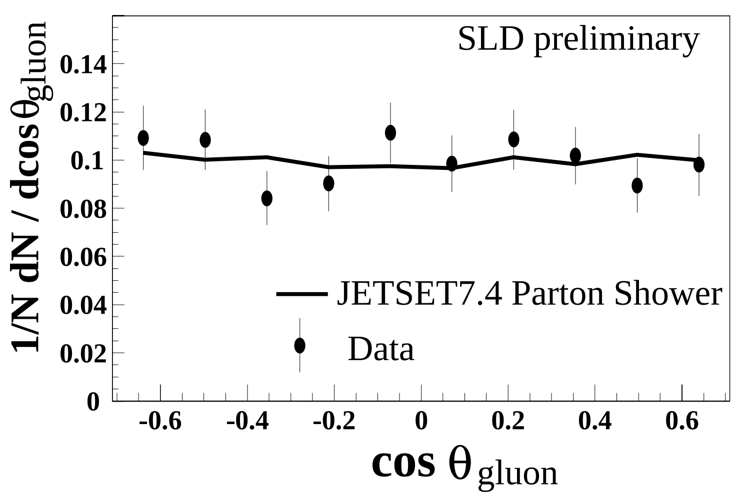

Figure 3: The gluon polar-angle distribution in $b\bar{b}g$ events.

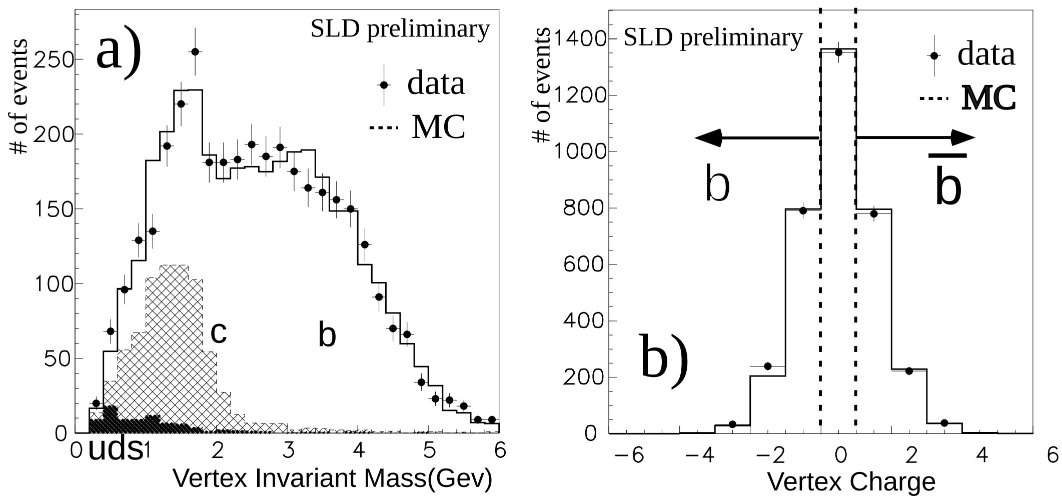

Figure 4: The distribution of topological vertex mass (a) and its charge (b)

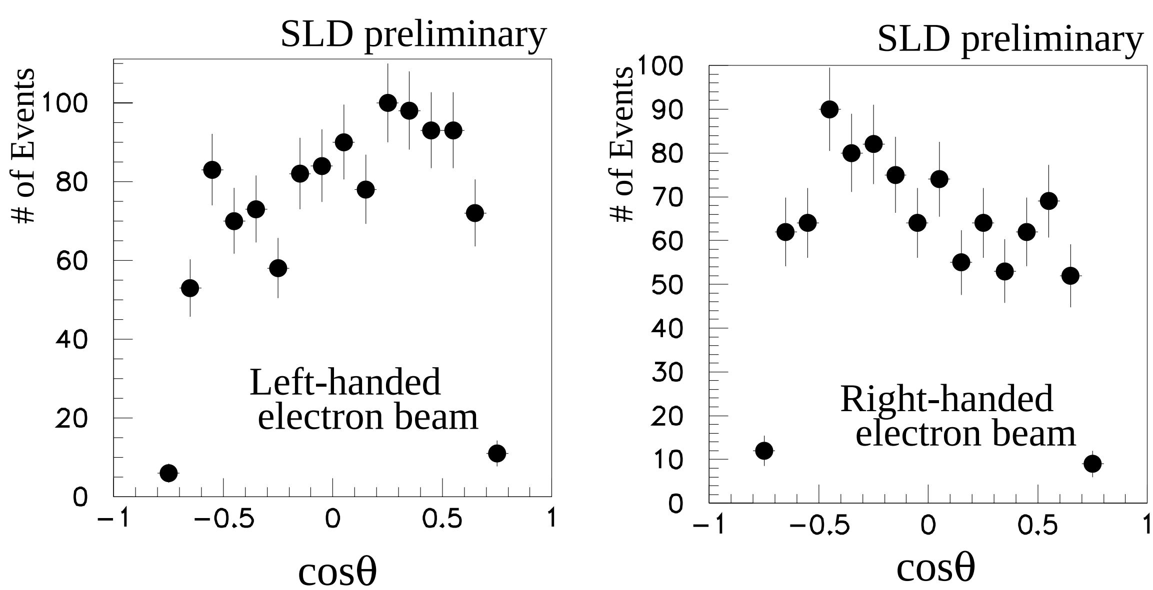

Figure 5: Polar-angle distribution of b-quark production in $b\bar{b}g$ events.