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HEAVY QUARK PRODUCTION IN Z^0 DECAYS*

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Abstract

We present studies of 3-jet final states from hadronic Z^0 decays recorded by the SLD experiment. A comparison of the strong couplings of light, c, and b quarks is made using 3-jet rates. We have performed a detailed study of $e^+e^- \to b\bar{b}g$ final states, in which the quark, antiquark, and gluon jets are identified. The gluon energy spectrum, measured over the full kinematic range, is consistent with the predictions of QCD, and we derive a limit on an anomalous chromomagnetic bbg coupling. We measure the parity violation in Z^0 decays into $b\bar{b}g$ to be consistent with the predictions of electroweak theory and QCD, and perform new tests of T- and CP-conservation at the bbg vertex.

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1. Introduction

Experimental studies of the structure of events containing three hadronic jets in e^+e^- annihilation have been limited by difficulties in identifying which jet is due to the quark, which to the antiquark and which to the gluon. Tagging of the origin of any two of the three jets in such events would allow more complete tests of QCD predictions. Here we present a study of 3-jet final states in which two of the jets have been tagged as b or $\bar{b}$ jets using the long lifetime of the B-hadrons in the jets and the precision vertexing system of the SLD. The remaining jet is tagged as the gluon jet, and its energy spectrum is studied over its full kinematic range. Adding a tag of the charge of one of the $b/\bar{b}$ jets, and exploiting the high electron beam polarization of the SLC, we measure two angular asymmetries sensitive to parity violation in the Z^0 decay, and also construct new tests of T- and CP-conservation at the bbg vertex.

2. A Test of the Flavor-Independence of Strong Interaction

In order for QCD to be a gauge-invariant renormalisable field theory it is required that the strong coupling α_s be independent of quark flavor. This basic *ansatz* can be tested directly in e^+e^- annihilation by measuring the strong coupling in events of the type $e^+e^- \to q\bar{q}g$ for specific quark flavors. Furthermore, a much more precise test of the flavor-independence can be made from the ratio of the couplings for different quark flavors, in which most experimental errors and theoretical uncertainties cancel [1].

Separation of the event sample into tagged flavor subsamples was based on the invariant mass, M_{vtx}, of topologically-reconstructed long-lived heavy-hadron decay vertices [2], and the vertex momentum, P_{vtx}, as well as on charged-track impact parameters in the plane normal to the beamline. The b-tagged sample was defined to comprise those events containing any vertex in region $M_{vtx} > 1.8 \oplus P_{vtx} + 10 < 15 M_{vtx}$, where M_{vtx} (P_{vtx}) is in units of GeV/c^2 (GeV/c). For the remaining events containing any vertex in region $M_{vtx} < 1.8 \oplus P_{vtx} > 5 \oplus P_{vtx} + 10 \geq 15 M_{vtx}$ we examined the distribution of the impact parameter of the vector $\vec{P_{vtx}}$ w.r.t. the IP, δ_{vtx}. We defined the c-tagged sample to comprise those events in this region with $\delta_{vtx} < 0.02$ cm. For the remaining events containing no selected secondary vertex the number of tracks per event that miss the IP by $d > 2\sigma_d$, N_{sig}, was examined. The uds-tagged sample was defined to comprise those events with $N_{sig} = 0$.

The jet structure of events was reconstructed in turn using six 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. For each algorithm and y_c value the 3-jet rate R_3^i for each of the i quark types ($i = b$, c, uds) was extracted from a simultaneous maximum likelihood fit to n_2^j and n_3^j, the number of 2-jet and 3-jet events, respectively, in the flavor-tagged subsample ($1 \leq j \leq 3$), using the relations:

$$n_2^j = \sum_{i=uds,c,b} \left(\varepsilon^{ji}_{(2\to2)}(1 - R_3^i) + \varepsilon^{ji}_{(3\to2)} R_3^i\right) f^i N$$

$$n_3^j = \sum_{i=uds,c,b} \left(\varepsilon^{ji}_{(3\to3)} R_3^i + \varepsilon^{ji}_{(2\to3)}(1 - R_3^i)\right) f^i N \ .$$

Here N is the total number of events after correction for the event selection efficiency, and f^i is the Standard Model fractional hadronic width for Z^0 decays to quark type i. The 3×3 matrices $\varepsilon^{ji}_{(2\to 2)}$ and $\varepsilon^{ji}_{(3\to 3)}$ are the efficiencies for an event of type i, with 2- or 3-jets at the parton level, to pass all cuts and enter subsample j as a 2- or 3-jet event, respectively. These matrices were calculated from the Monte Carlo simulation,

For the test of the flavor-independence of strong interactions it is more convenient to consider the ratios of the 3-jet rates in heavy- and light-quark events, namely R_3^c/R_3^{uds} and R_3^b/R_3^{uds}. These ratios were derived from the unfolded R_3^{uds}, R_3^c and R_3^b values. The measured ratios R_3^c/R_3^{uds} and R_3^b/R_3^{uds}, are shown in Fig. 1(a). R_3^b/R_3^{uds} lies above unity for the E, E0, P and P0 algorithms, and below unity for the D and G algorithms; note that all six data points are highly correlated with each other. For comparison, the corresponding QCD calculations of R_3^b/R_3^{uds} [3] are also shown with the arrows in Fig. 1(a), under the *assumption* of a flavor-independent strong coupling with an input value of $\alpha_s(M_Z^2) = 0.118$. The variation of the prediction corresponds to the b-quark mass range of $2.5 \leq m_b(M_{Z^0}) \leq 3.5$ GeV/c^2 with the arrow pointing towards the lower mass value. The calculations are in good agreement with the data, and the data clearly demonstrate the effects of the non-zero b-quark mass, which are larger than the statistical error. For the translation from R_3^b/R_3^{uds} to $\alpha_s^b/\alpha_s^{uds}$ we used a value of the running b-quark mass $m_b(M_{Z^0}) = 3.0$ GeV/c^2. The $\alpha_s^c/\alpha_s^{uds}$ and $\alpha_s^b/\alpha_s^{uds}$ ratios are summarised in Fig. 1(b). We obtained:

$$\begin{aligned}
\alpha_s^c/\alpha_s^{uds} &= 1.036 \pm 0.043(stat.)^{+0.041}_{-0.045}(syst.)^{+0.020}_{-0.018}(theory) \\
\alpha_s^b/\alpha_s^{uds} &= 1.004 \pm 0.018(stat.)^{+0.026}_{-0.031}(syst.)^{+0.018}_{-0.029}(theory).
\end{aligned}$$

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

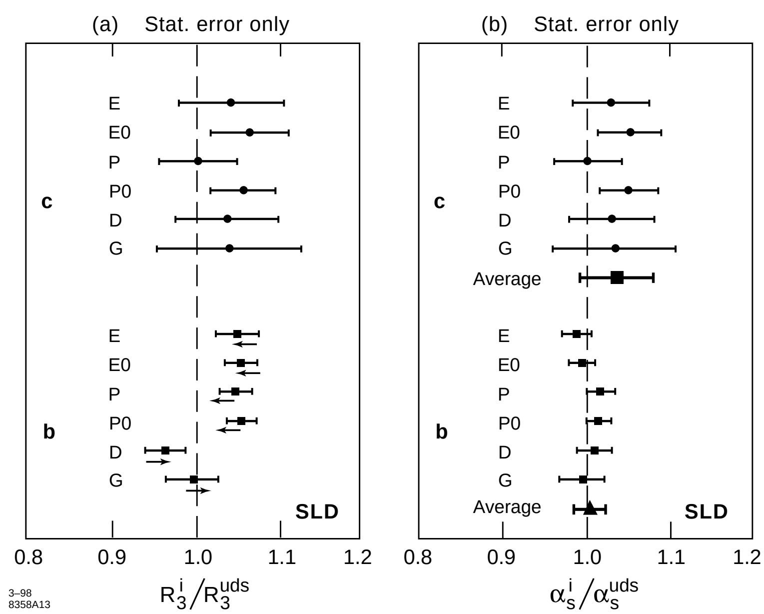

Figure 1: (a) The measured ratios R_3^i/R_3^{uds}, and (b) the strong coupling ratios α_s^i/α^{uds} ($i = c, b$).

3. The Gluon Energy Spectrum in $b\bar{b}g$ Events

In addition to the overall probability for gluon emission in $b\bar{b}$ events, one can study the structure of such emission. Well contained hadronic events in which exactly 3 jets are found using the JADE algorithm at $y_{cut} = 0.02$ are selected. The jet energies are calculated from the angles between them and the jets are energy ordered such that $E_1 > E_2 > E_3$. In each jet we count the number N_{sig} of 'significant' tracks, i.e. those with normalized transverse impact parameter with respect to the primary interaction point $d/\sigma_d > 3$. We require exactly two of the three jets to have $N_{sig} > 1$, and the remaining jet is tagged as the gluon jet. This yields 1533 events with an estimated purity of correctly tagged gluon jets of 91%. In 2.5% (12.5%) of these events, jet 1(2), the (second) highest energy jet, is tagged as the gluon jet, giving coverage over the full kinematic range.

The background from non-$b\bar{b}g$ events and events with an incorrect gluon tag is subtracted, and the resulting distribution of scaled gluon energy $z = 2E_g/\sqrt{s}$ is corrected for the effects of selection efficiency and resolution. The fully corrected spectrum is shown in Fig. 2, and shows the expected falling behaviour with increasing z. The distribution is cut off at low z by the finite y_{cut} value used for jet finding. Also shown are the predictions of first and second order QCD. Both reproduce the general behaviour, but fail to describe the data in detail. The prediction of the JETSET [4] parton shower simulation is also shown and reproduces the data. Our data thus confirm the predictions of QCD, although higher order effects are clearly important in the intermediate gluon energy range, $0.2 < z < 0.4$.

The gluon energy spectrum is particularly sensitive to the presence of an anomalous chromomagnetic term in the QCD Lagrangian. A fit of the theoretical prediction including an anomalous term parametrized by a relative coupling κ [5], yields a value of $\kappa = -0.03 \pm 0.06$ (*preliminary*), consistent with zero, and corresponding to limits on such contributions to the bbg coupling of $-0.15 < \kappa < 0.09$ at the 95% confidence level.

4. Parity Violation in Polarized $\mathbf{Z^0}$ Decays to $b\bar{b}g$

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 [6]. Consider the polar-angle distribution of the quark direction w.r.t. the electron beam:

$$\frac{d\sigma}{d\cos\theta} \propto (1 - P_{e^-} \cdot A_e)(1 + \alpha\cos^2\theta) + 2A_P(P_{e^-} - A_e)\cos\theta, \qquad (1)$$

where P_{e^-} is the electron beam polarization, A_e (A_f) is the parity-violating electroweak coupling of the Z^0 to the initial (final) state, given by $A_i = 2v_i a_i/(v_i^2 + a_i^2)$ in terms of the vector v_i and axial-vector a_i couplings, and A_P characterizes the degree of parity violation. One can write $A_P = A_f \cdot A_\theta^{QCD}$, where the second factor modulates the tree-level electroweak parity violation and can be calculated in QCD. Similarly, one can consider the distribution of the azimuthal-angle χ between the event plane and the quark-electron beam plane:

$$2\pi\frac{d\sigma}{d\chi} \propto (1 - P_{e^-} \cdot A_e)(1 + \beta\cos 2\chi) - \frac{\pi}{2}A'_P(P_{e^-} - A_e)\cos\chi, \qquad (2)$$

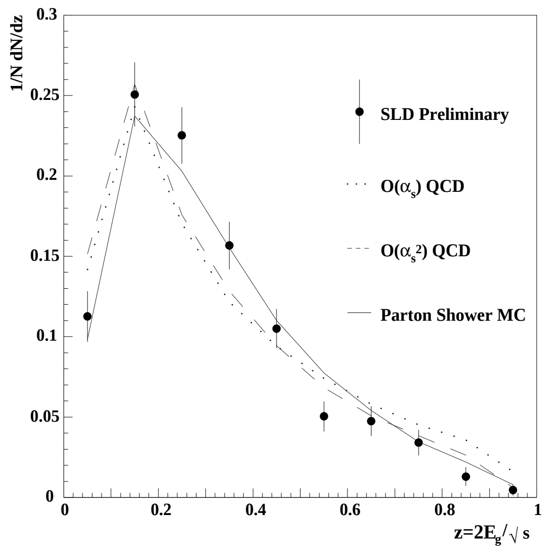

Figure 2: The measured scaled gluon energy distribution (dots), compared with the predictions of first and second order OCD, and of a parton shower calculation.

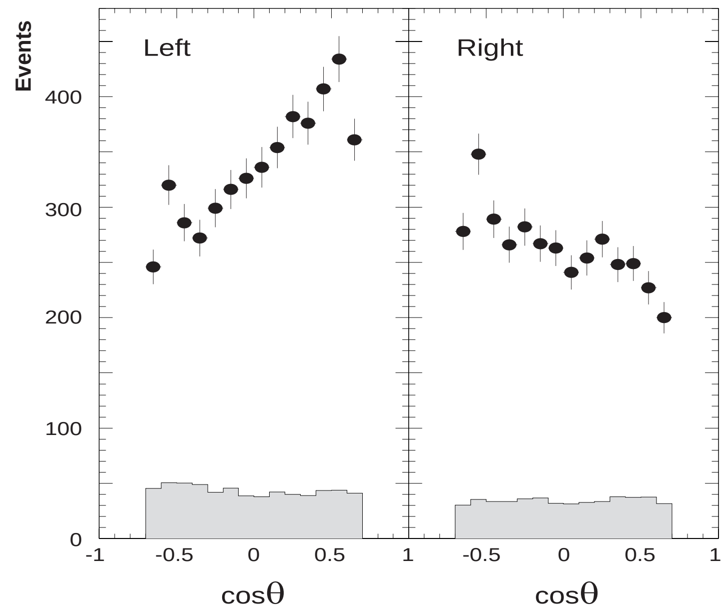

Figure 3: The polar angle distribution of the signed-thrust axis in $b\bar{b}g$ events

and $A'_P = A_f \cdot A_\chi^{QCD}$. Given the value of the electroweak parameter A_f, measurement of the angular asymmetry parameters A_P and A'_P in $Z^0 \rightarrow q\bar{q}g$ events allows one to test the QCD prediction for A_θ^{QCD} and A_χ^{QCD}, as well as set limits on parity-violation at the $q\bar{q}g$ vertex.

Three-jet events (Durham algorithm, $y_{cut} = 0.005$) are selected and energy ordered, and a topological vertex finder is applied to the tracks in each jet. The 8510 events containing any vertex with mass above 1.5 GeV/c^2 are kept, having an estimated $b\bar{b}g$ purity of 87%. 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 tag the highest-energy jet as the b ($\bar{b}$) jet if $Q = Q_1 - Q_2 - Q_3$ is negative (positive). We then define the polar angle of the thrust axis $\cos\theta = -\text{sign}(Q)(\hat{p}_e \cdot \hat{p}_1)$.

Figures 3(a) and (b) show the observed $\cos\theta$ distributions for event samples collected with left- and right-handed electron beam, respectively. The shaded histograms show the estimated backgrounds, which are mostly $c\bar{c}g$ events. A maximum likelihood fit yields an asymmetry parameter of $A_P = 0.89 \pm 0.06$. Assuming the electroweak parameter $A_b = 0.94$, the QCD asymmetry parameter is measured to be $A_\theta^{QCD} = 0.95 \pm 0.06 \pm 0.07$, consistent with the QCD prediction of 0.93, evaluated using the JETSET simulation.

We then tag one of the two lower energy jets as the gluon jet, using the impact parameters of their tracks, and construct the angle χ. Our measurement is consistent with the prediction, as well as with zero. A fit yields $A_\chi = -0.02 \pm 0.04$ and $A_\chi^{QCD} = -0.02 \pm 0.05$, to be compared with the QCD expectation of -0.06.

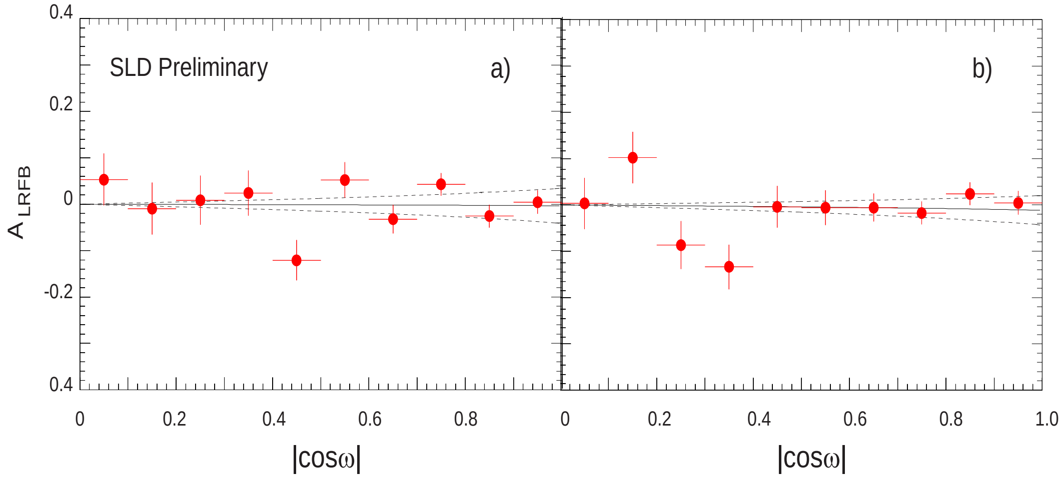

Figure 4: Left-right-forward-backward asymmetries of the a) energy- and b) flavor-ordered triple product. The solid (dotted) lines represent results of fits to the data (95% C.L. limits on the fitted parameters).

5. Symmetry Tests in Polarized Z^0 Decays to $b\bar{b}g$

Using these fully tagged events, we can construct observables that are formally odd under time and/or CP reversal. For example, the energy-ordered triple product $\cos\omega^+ = \vec{\sigma}_Z \cdot (\hat{p}_1 \times \hat{p}_2)$, where $\vec{\sigma}_Z$ is the Z^0 polarization vector, is T_N-odd and CP-even. Since the true time reversed experiment is not performed, this quantity could have a nonzero Forward-Backward asymmetry $\tilde{A}_{FB}$, and we have previously set a limit using events of all flavors[7]. A calculation [8] predicts that $\tilde{A}^{\omega^+}_{FB}$ 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.

Our measured $\tilde{A}^{\omega^+}_{FB}$ and $\tilde{A}^{\omega^-}_{FB}$ are shown in Fig. 4(a) and (b) respectively. They are consistent with zero and we set limits on possible T_N- and CP-violating asymmetries of $-0.039 < A^+_T < 0.035$ and $-0.086 < A^-_T < 0.040$, respectively at the 95% C.L.

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