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TESTS OF QCD USING $Z^0 \rightarrow b\bar{b}g$ EVENTS*

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Abstract

We present new studies of 3-jet final states from hadronic Z^0 decays recorded by the SLD experiment, in which the quark, antiquark, and gluon jets are identified. Our 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. Since the gluon is expected to be the lowest-energy jet in most events, the predictions of QCD have been tested using energy and angle distributions of energy-ordered jets, and this is sufficient to confirm the $q\bar{q}g$ origin of such events and to determine the gluon spin [1]. Tagging of the origin of any two of the three jets in such events would allow more complete and stringent tests of QCD predictions.

Here we present a study [2] 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. The study of b-flavor events is especially useful as input to measurements of electroweak parameters such as R_b and A_b, and as a probe of new physics, which is expected in many cases to couple more strongly to heavier quarks.

2 The Gluon Energy Spectrum

Well contained hadronic events [3] 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 [3] 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. 1, 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, $0.2 < z < 0.4$.

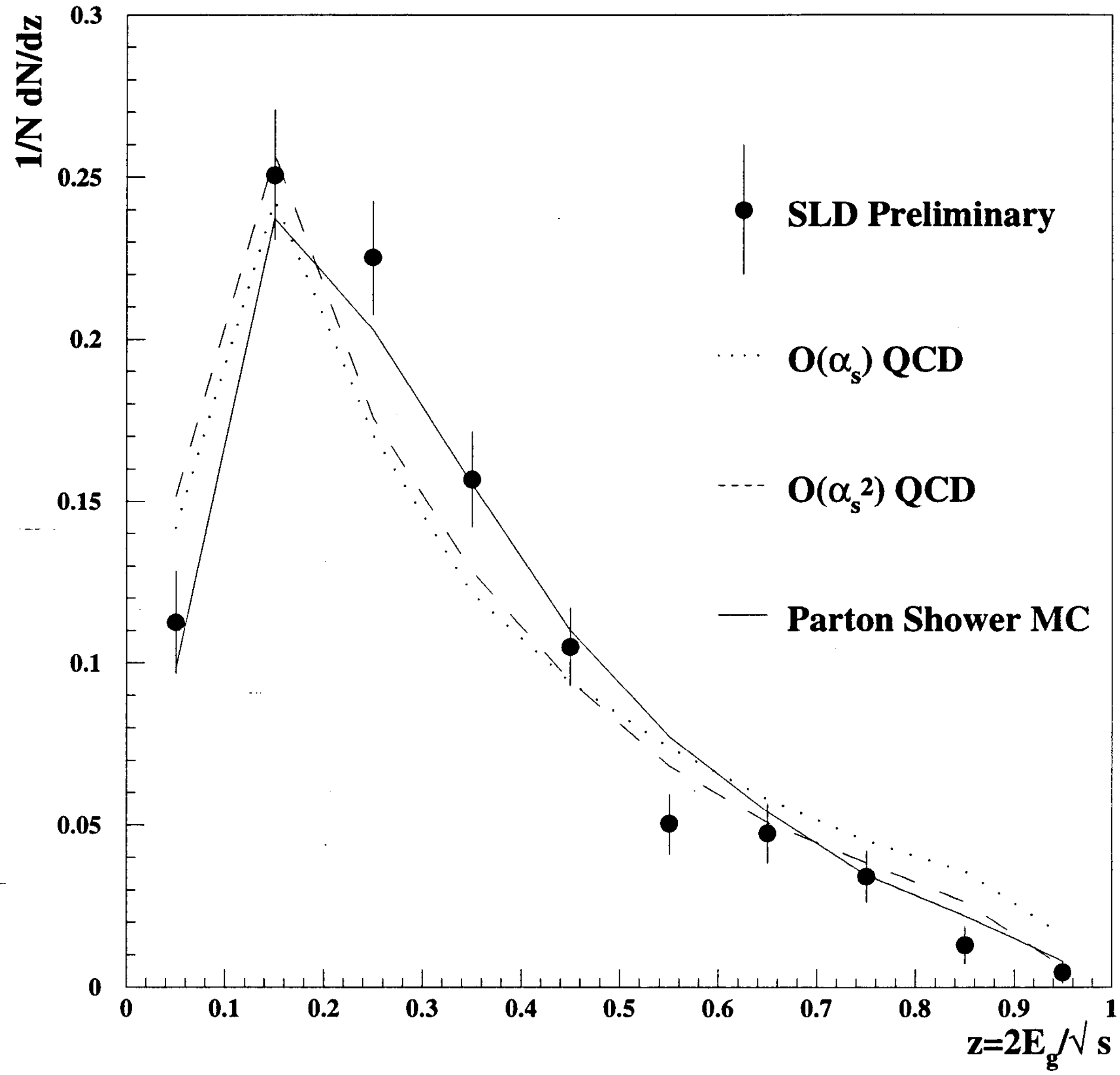

Figure 1: The measured scaled gluon energy distribution (dots), compared with the predictions of first and second order QCD, and of a parton shower calculation.

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 [5] including an anomalous term parametrized by a relative coupling κ, 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.

3 Parity Violation in 3-jet Z^0 Decays

We now consider two angles, the polar angle of the quark 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 is 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 electron beam polarization P_e, and each A_P is predicted by QCD.

Three-jet events (Durham algorithm, $y_{cut} = 0.005$) are selected and energy ordered, and a topological vertex finder [6] is applied to the tracks in each jet. The 3420 events containing any vertex with invariant 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. In this case we assume that the highest-energy jet is not the gluon, and tag it as the b ($\bar{b}$) jet if $Q = Q_1 - Q_2 - Q_3$ is negative (positive). We then define the b-quark polar angle $\cos\theta_b = -\text{sign}(Q)(\hat{p}_e \cdot \hat{p}_1)$.

We construct the left-right-forward-backward asymmetry $\tilde{A}^b_{FB}$ in this polar angle, which is shown as a function of $|\cos\theta_b|$ in fig. 2a. A clear asymmetry is seen, which increases with $|\cos\theta_b|$ in the expected way. A maximum likelihood fit yields an asymmetry parameter of $A_P = 0.99 \pm 0.09 \pm 0.07$ (*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, using the impact parameters of their tracks. If jet 2 has $n_{sig} = 0$ and jet 3 has $n_{sig} > 0$, then jet 2 is tagged as the gluon jet; otherwise jet 3 is tagged as the gluon jet. In each event we construct the angle χ, and A^χ_{LRFB} is shown as a function of χ in fig. 2b. Here we expect only a small deviation from zero as indicated by the line on fig. 2b. Our measurement is consistent with the prediction, as well as with zero. A fit yields $A_\chi = 0.01 \pm 0.05(stat.)$ (*preliminary*), to be compared with an expectation of 0.047.

4 Symmetry tests in 3-jet Z^0 Decays

Using these fully tagged events, we can construct observables that are 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 $\tilde{A}_{FB}$, and we

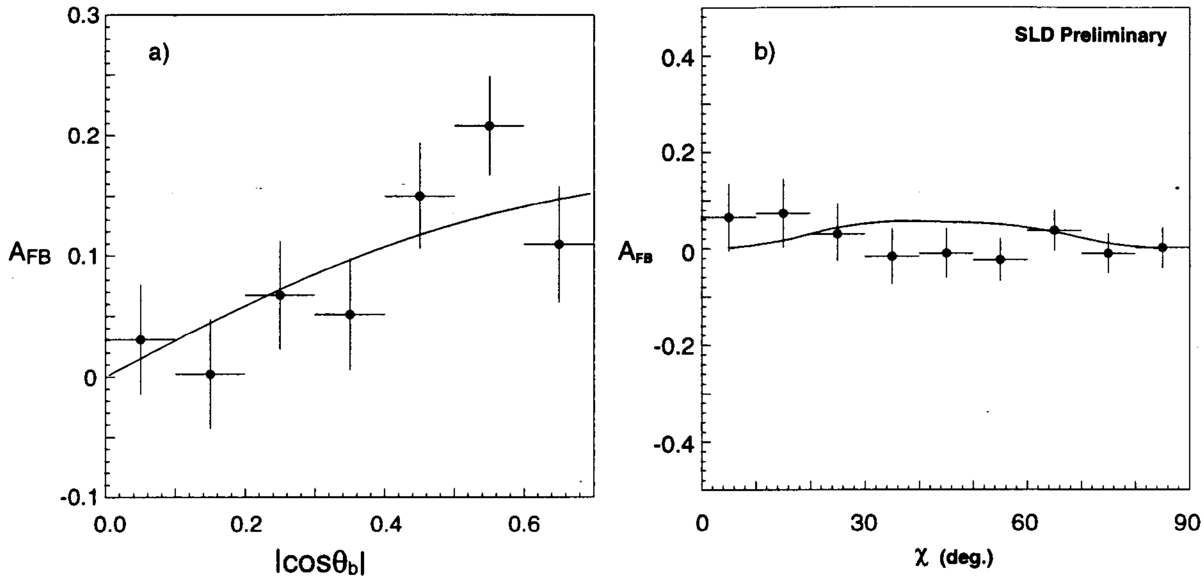

Figure 2: Left-right-forward-backward asymmetries of a) the b-quark polar angle and b) the angle χ in 3-jet Z^0 decays. The solid lines represent (a) the result of a fit to the data and (b) the QCD prediction.

have previously set a limit [3] using events of all flavors. A standard model calculation [7] 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. 3. They are consistent with zero and we set limits on possible T_N- and CP-violating asymmetries of $-0.056 < A^+_T < 0.051$ and $-0.056 < A^-_T < 0.051$, respectively.

5 Conclusion

In summary, we use the excellent vertexing capability of the SLD and the high electron beam polarization of the SLC to make several new tests of QCD, using 3-jet final states in which the quark, antiquark and gluon jets are identified. The gluon energy spectrum is measured over its full kinematic range; we confirm the prediction of QCD and set limits on anomalous chromomagnetic couplings. The parity violation in Z^0 decays to $b\bar{b}g$ is found to be consistent with the predictions of electroweak theory plus QCD, and new tests of T- and CP-conservation in strong interactions are performed.

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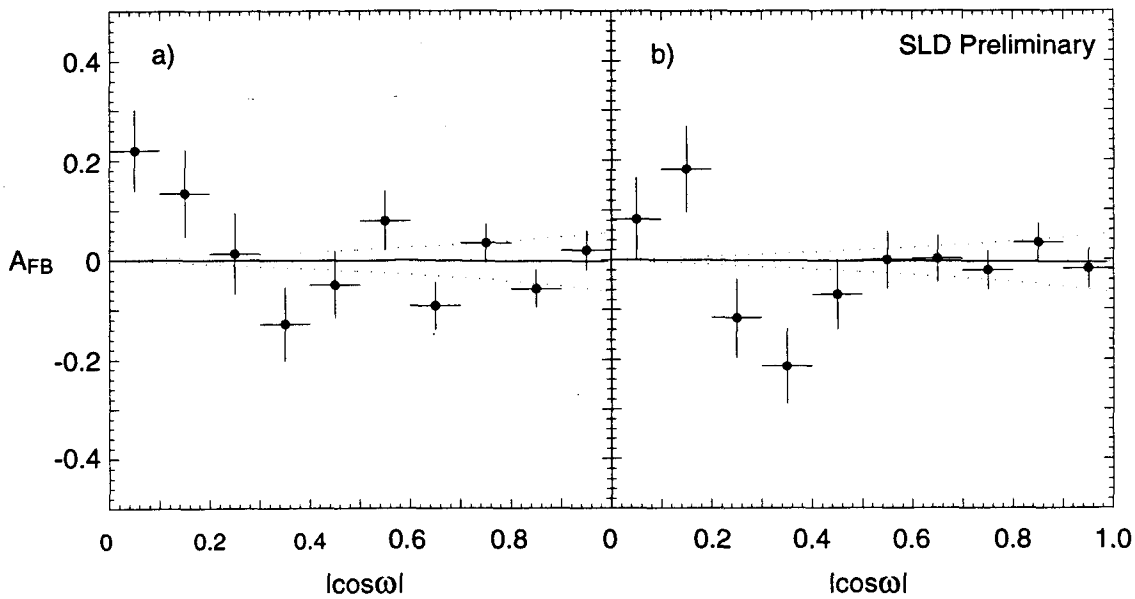

Figure 3: Left-right-forward-backward asymmetries of the a) energy- and b) flavor-ordered triple product. The solid (dotted) lines represent results of fits to the data (95% confidence limits on the fitted parameters).

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