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Studies of $b\bar{b}$ gluon and $c\bar{c}$ vertices*

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Abstract

We report on several new studies of $b\bar{b}g$ and $c\bar{c}g$ vertices using 3- and 4-jet hadronic Z^0 decays by e^+e^- collision. The gluon energy spectrum is measured over the full kinematic range, providing an improved test of QCD and limits on anomalous bbg couplings. 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 measurement of the probability of gluon splitting into $c\bar{c}$ pairs finds $g_{c\bar{c}} = (2.45 \pm 0.29 \pm 0.53)\%$. A new measurement of the rate of gluon splitting into bb pairs yields $g_{b\bar{b}} = (2.84 \pm 0.61(stat.) \pm 0.59(syst.)) \times 10^{-3}$ (Preliminary).

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1 Introduction

We present a number of precision tests of QCD in the perturbative regime using 3- and 4-jet final states from L3 and SLD collaborations.

Experimental studies of the structure of 3-jet events have typically used energy and angle distributions of energy-ordered jets. Since the gluon is expected to be the lowest-energy jet in most events, this suffices to confirm the $q\bar{q}g$ origin of such events and to determine the gluon spin. The identification of the three jets in such events would allow more complete and stringent tests of QCD. Here we present a study [1] of 3-jet final states in which two of the jets are tagged as b or $\bar{b}$ jets by the SLD collaboration. The remaining jet is tagged as the gluon jet and its energy spectrum studied over the full kinematic range. Adding a tag of the charge of the b or $\bar{b}$ jet, and exploiting the high electron beam polarization of the SLAC Linear Collider, the SLD collaboration measures [2] 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 rate of secondary heavy flavor production via gluon splitting, $g \to c\bar{c}$, $g \to b\bar{b}$ is a sensitive test of QCD, as it is suppressed strongly by the mass of the heavy quark, but is still expected to be the dominant source of secondary heavy hadrons. Here we present a measurement of the $g \to c\bar{c}$ rate [3] by the L3 collaboration and $g \to b\bar{b}$ rate [4] by the SLD collaboration. The study of events containing $b/\bar{b}$ quarks is especially useful, both as important input into measurements such as electroweak parameters [5] (R_b and A_b) in Z^0 decays and bottom production in hadron-hadron collisions, and also as a sensitive probe of any new physics that couples more strongly to heavier quarks.

2 The Gluon Energy Spectrum

Hadronic events with exactly 3 jets (JADE algorithm, $y_{cut} = 0.02$) are selected. Jet energies E_i are calculated from the inter-jet angles, and the jets are energy ordered: $E_1 > E_2 > E_3$. A cut ($n_{sig}^{(3)} \geq 2$) in exactly two of the three jets is required, and the remaining jet is tagged as the gluon jet. This yields 8196 events with an estimated purity of correctly tagged gluon jets of 91%. In 3.0% (12.9%) 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 distribution of the scaled gluon energy $x_g = 2E_g/\sqrt{s}$ is corrected for non-$b\bar{b}g$ and mistag backgrounds, selection efficiency and resolution. The prediction of the JETSET parton shower simulation reproduces the data well.

The x_g spectrum is particularly sensitive to the presence of an anomalous chromomagnetic term in the strong interaction Lagrangian. A fit of the theoretical prediction including an anomalous term parametrized by a relative coupling κ, yields a value of $\kappa = -0.01 \pm 0.05$ (Preliminary), consistent with zero, and corresponding to 95% C.L. limits on such contributions to the bbg coupling of $-0.11 < \kappa < 0.08$.

3 Symmetry tests in polarized Z^0 decays to $b\bar{b}g$

Now 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 $\chi = \cos^{-1}(\hat{p}_q \times \hat{p}_g) \cdot (\hat{p}_q \times \hat{p}_e)$ are considered. 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 that of the e^- beam P_e, and A_e and $A_P = A_{QCD} A_q$ are predicted by QCD plus electroweak theory.

Three-jet events (Durham algorithm, $y_{cut} = 0.005$) are selected and energy ordered. The 14,658 events containing a secondary vertex with mass above 1.5 GeV/c^2 in any jet are kept, having an estimated $b\bar{b}g$ purity of 84%. 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} in $\cos\theta_b$ is reconstructed. A fit to the data yields an asymmetry parameter of $A_P/A_b = 0.914 \pm 0.053(stat.) \pm 0.063(syst.)$, consistent with the QCD prediction of $A_P/A_b = 0.93$.

Then tag one of the two lower energy jets is tagged as the gluon jet: if jet 2 has $n^{(3)}_{sig} = 0$ and jet 3 has $n^{(3)}_{sig} > 0$, then jet 2 is tagged as the gluon; otherwise jet 3 is tagged as the gluon. We construct the angle χ and A^{χ}_{LRFB}. Our measurement is consistent with the prediction, as well as with zero. A fit yields $A_\chi/A_b = -0.014 \pm 0.035 \pm 0.002$, to be compared with an expectation of -0.064.

Using these fully tagged events, observables that are formally odd under time reversal and/or CP reversal can be constructed. 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}, and a limit using events of all flavors has been previously set. A calculation 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.

Measured $A^{\omega^+}_{LRFB}$ 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 $-0.045 < A^+_T < 0.016$ or $-0.082 < A^-_T < 0.012$, respectively.

4 Gluon splitting into a $c\bar{c}$ pair

L3 has reported measurements of the probability of gluon splitting into charmed quarks in hadronic Z decays using the following methods, (1) search for leptons in three jet events (2) use of neural networks and event shape variables.

Events are clustered in 3 jets (JADE algorithm, $Y_{cut} = 0.03$), with the assumption that the two charm quarks from splitting are close enough in angle to generate a single jet. Moreover, the jet from splitting is likely to be the least energetic one, due to the energy spectrum of the gluon. Signal selection is thus obtained by requesting a lepton (e or μ) in the least energetic jet in 3-jet events. The main background comes from leptons from b quarks decays. Those events are rejected using

b anti-tag and a cut on the mass of the third jet. The 360 electron and 450 muon candidate events are selected. The backgrounds are estimated to be 285 ± 10 and 399 ± 11 for electron and muon sample, respectively. The estimated $g \to c\bar{c}$ efficiency is 0.40% for electron and 0.54% for muon.

For neural network analysis, events with 3 jets are initially selected, and jets are order in energy; in this way, gluon splitting generated jets should be the second or the third.

The variables chosen for the input to the neural network are: (1) $M_{jet2} + M_{jet3} - M_{jet1}$; (2) 3 different Fox-Wolfram momenta; and (3) the fraction of the energy of the second jet within a cone of 8° around its axis. The additional cut requests the presence of a minimum number of tracks displaced from the primary vertex; this is done to enrich the sample in events with gluon splitting to heavy flavors. The selection efficiency is 4.4% and the purity is 4.5%.

Combining the results from the lepton and the neural network analyses, L3 obtains $g_{c\bar{c}} = (2.45 \pm 0.29 \pm 0.53)\%$, which is consistent with the QCD prediction of 2.0007% [6].

5 Gluon splitting into a $b\bar{b}$ pair

A new measurement of the rate of gluon splitting into $b\bar{b}$ pair has been reported from the SLD collaboration. 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, $y_{cut} = 0.009$). A secondary vertex is required in each of the two jets (jet1 and jet2) with the smallest opening angle in the event, yielding 547 events. This sample is dominated by background ($S/N \sim 1/5$), primarily from $Z^0 \to b\bar{b}g(g)$ events and events with a gluon splitting into a $c\bar{c}$ pair.

In order to improve the signal/background ratio, a neural network technique is used. Nine observables are chosen for inputs to the neural network. The inputs include the the P_T-corrected mass of the vertices and the angle between the vertex axes. b jets have higher P_T-corrected mass than c/uds jets, hence it is useful to separate b jets from c/uds jets. Many $Z^0 \to b\bar{b}$ background events have one b-jet which was split by the jet-finder into 2 jets so that the two found vertices are from different decay products from the same B decay. The two vertex axes tend to be collinear. The neural network is trained using Monte Carlo samples of 1800k $Z \to q\bar{q}$ events, 1200k $Z \to b\bar{b}$ events, 780k $Z \to c\bar{c}$ events and 50k $g \to b\bar{b}$ events. A cut (neural network output > 0.6) keeps 79 events, with an estimated background of 37.8 events. Using this and the estimated efficiency for selecting $g \to b\bar{b}$ splittings of 4.99% yields a measured fraction of hadronic events containing such a splitting of $g_{b\bar{b}} = (2.84 \pm 0.61(stat.) \pm 0.59(syst.)) \times 10^{-3}$ (Preliminary). The result is consistent with the QCD prediction of 1.75×10^{-3} [6].

6 summary

Several new studies of $b\bar{b}g$ and $c\bar{c}g$ vertices using 3- and 4-jet hadronic Z^0 decays by e^+e^- collision has reported in this proceeding. The results are in good agreement with the predictions of perturbative QCD.

References

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