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Study of the structure of $e^+ e^- \rightarrow b \bar{b}g$ events and first limits on the anomalous chromomagnetic coupling of the $b$ quark


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The structure of $e^+e^- \rightarrow b\bar{b}g$ events was studied using $Z^0$ decays recorded in the SLC Large Detector experiment at SLAC. Three-jet final states were selected and the charge-coupled device-based vertex detector was used to identify two of the jets as $b$ or $\bar{b}$. Distributions of the gluon energy and polar angle were measured over the full kinematic range for the first time, and compared with perturbative QCD predictions. The energy distribution is potentially sensitive to an anomalous $b$ chromomagnetic moment $\kappa$. We measured $\kappa$ to be consistent with zero and set the first limits on its value: $-0.17 < \kappa < 0.11$ at 95% C.L.

[Received 3 March 1999; published 6 October 1999]

PACS number(s): 13.65.+i, 12.38.Qk, 14.65.Fy

The observation of $e^+e^-$ annihilation into final states containing three hadronic jets, and their interpretation in terms of the process $e^+e^- \rightarrow q\bar{q}g$ [1], provided the first direct evidence for the existence of the gluon, the gauge boson of the theory of strong interactions, quantum chromodynamics (QCD). In subsequent studies the jets were usually energy ordered, and the lowest-energy jet was assigned as the gluon; this is correct roughly 80% of the time, but preferentially selects low-energy gluons. If the gluon jet could be tagged explicitly, event-by-event, the full kinematic range of gluon was reached. If the gluon jet could be tagged this is possible using $Z^0$ decays recorded in the SLC Large Detector experiment at SLAC. Three-jet final states were selected and the charge-coupled device-based vertex detector was used to identify two of the jets as $b$ or $\bar{b}$. Distributions of the gluon energy and polar angle were measured over the full kinematic range for the first time, and compared with perturbative QCD predictions. The energy distribution is potentially sensitive to an anomalous $b$ chromomagnetic moment $\kappa$. We measured $\kappa$ to be consistent with zero and set the first limits on its value: $-0.17 < \kappa < 0.11$ at 95% C.L.

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$$\mathcal{L}^{b\bar{b}g} = g_s b\bar{b} T_a \left( \gamma_\mu + \frac{i\sigma_{\mu\nu} k_\nu}{2m_b} (\kappa - i\bar{\kappa} \gamma_5) \right) b G_a^\mu, \quad (1)$$

where $\kappa$ and $\bar{\kappa}$ parametrize the anomalous chromomagnetic and chromoelectric moments, respectively, which might arise from physics beyond the SM. The effects of the chromoelectric moment are sub-leading with respect to those of...
jets are sometimes merged with the parent $b$-jet by the jetfinder. At higher gluon energies the correspondingly lower-energy $b$-jets are harder to tag, and there is also a higher probability of losing a jet outside the detector acceptance.

For the selected event sample, Fig. 1 shows the $N_{\text{jet}}^{\text{sig}}$ distributions separately for jets 1, 2 and 3. In about 15% of cases the gluon-tagged jet is not the lowest-energy jet (jet 3). The simulated contributions from true gluons are indicated, and the estimated gluon purities [16] are listed in Table I. The inclusive gluon purity of the tagged-jet sample is 95%. With this sample we formed the distributions of two gluon-jet observables, the scaled energy $x_g = 2E_{\text{gluon}}/\sqrt{s}$, and the polar angle with respect to the beamline, $\theta_g$. The distributions are shown in Fig. 2. The simulation is also shown; it reproduces the data.

The backgrounds were estimated using the simulation and are of three types: non-$b\bar{b}$ events, $b\bar{b}$ but non-$b\bar{b}g$ events, and true $b\bar{b}g$ events in which the gluon jet was mistagged as a $b$-jet. These are shown in Fig. 2. The non-$b\bar{b}$ events (~5% of the $b\bar{b}g$ sample) are mainly $c\bar{c}g$ events, 90% of which had the gluon correctly tagged. There is a small contribution (~0.1% of the $b\bar{b}g$ sample) from light-quark events. The dominant background is formed by $b\bar{b}$ but non-$b\bar{b}g$ events. These are true $b\bar{b}$ events which were not classified as 3-jet events at the parton level, but which were misreconstructed and tagged as 3-jet $b\bar{b}g$ events in the detector using the same jet algorithm and $y_{\text{cut}}$ value. This arises from the broadening of the particle flow around the original $b$ and $\bar{b}$ directions due

<table>
<thead>
<tr>
<th>Jet label</th>
<th>No. tagged gluon jets</th>
<th>Purity</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>1140</td>
<td>96.1%</td>
</tr>
<tr>
<td>2</td>
<td>155</td>
<td>90.2%</td>
</tr>
<tr>
<td>1</td>
<td>34</td>
<td>65.7%</td>
</tr>
</tbody>
</table>

FIG. 1. The $N_{\text{jet}}^{\text{sig}}$ distributions for jets in $b\bar{b}g$-tagged events, labeled according to jet energy (dots); errors are statistical. Histograms: simulated distributions showing jet flavor contributions.

FIG. 2. Raw measured distributions of (a) $x_g$ and (b) $\cos \theta_g$ (dots); errors are statistical. Histograms: simulated distributions including background contributions.
to hadronization and the high-transverse-momentum $B$-decay
products, causing the jet-finder to reconstruct a "fake" third
jet, which is almost always assigned as the gluon. The
population of such fake gluon jets peaks at low energy [Fig. 2(a)],
as expected. Mistagged events comprise less than 1% of the
$b\bar{b}g$ sample.

The distributions were corrected to obtain the true parton-
level gluon distributions $D^\text{true}(X)$ by applying a bin-by-bin
procedure: $D^\text{true}(X)=C(X)\left[D^\text{raw}(X)-B(X)\right]$, where $X$
$=x_g$ or $\cos \theta_g$. $D^\text{raw}(X)$ is the raw distribution, $B(X)$ is the
background contribution, and $C(X)=D^\text{MC}(X)/D^\text{MC}_{\text{rec}}(X)$ is a
correction that accounts for the efficiency for accepting true
$b\bar{b}g$ events into the tagged sample, as well as for bin-to-bin
migrations caused by hadronization, the resolution of the
detector, and bias of the jet-tagging technique. Here $D^\text{true}_{\text{MC}}(X)$ is
the true distribution for Monte Carlo (MC)-generated $b\bar{b}g$
events, and $D^\text{MC}_{\text{rec}}(X)$ is the resulting distribution after full
simulation of the detector and application of the same analy-
sis procedure as applied to the data. The shape-dependent
part of the bin-by-bin correction varies slowly and smoothly
between roughly 0.8 and 1.2 [11].

As a cross-check, an alternative correction procedure
was employed in which bin-to-bin migrations, which can be
as large as 20%, were explicitly taken into account: $D^\text{true}(X_i)=M(X_i,X_j)\left[D^\text{raw}(X_j)-B(X_j)\right]e(X_i)$, with
the unfolding matrix $M(X_i,X_j)$ defined by $D^\text{true}_{\text{MC}}(X_i)$
$=M(X_i,X_j)D^\text{MC}_{\text{rec}}(X_j)$, where true $b\bar{b}g$ events generated in
bin $i$ may, after reconstruction, be accepted into the tagged
sample in bin $j$. $e(X)$ is the efficiency for accepting $b\bar{b}g$
events in bin $i$ into the tagged sample. The resulting distribu-
tions of $x_g$ and $\cos \theta_g$ are within the error bands of the
respective distributions yielded by the bin-by-bin method.

The fully-corrected distributions are shown in Fig. 3. Since,
in an earlier study [6], we verified that the overall rate
of $b\bar{b}g$-event production is consistent with QCD expecta-
tions, we normalized the gluon distributions to unit area and

![FIG. 3. Corrected distributions of (a) $x_g$ and (b) $\cos \theta_g$ (dots); errors are statistical. Perturbative QCD predictions (see text) are shown as lines joining entries plotted at the respective bin centers.](image)

we study further the distribution shapes. The $x_g$ distribution
rises, peaks around $x_g \sim 0.15$, and decreases towards zero as
$x_g \sim 1$. The peak is a kinematic artifact of the jet algorithm,
which ensures that gluon jets are reconstructed with a non-
zero energy which depends on the $y_c$ value. The $\cos \theta_g$ dis-
tribution is flat.

We have considered sources of systematic uncertainty that
potentially affect our results. These may be divided into
uncertainties in modeling the detector and uncertainties in
the underlying physics modeling. To estimate the first case
we systematically varied the track and event selection
requirements, as well as the tracking efficiency [6,11]. In the
second case parameters used in our simulation, relating
mainly to the production and decay of charm and bottom
hadrons, as well as hadronization, were varied within their
measurement errors [11]. For each variation the data were
reconstructed to derive new $x_g$ and $\cos \theta_g$ distributions, and
the deviation with respect to the standard case was assigned as a
systematic uncertainty. None of the variations affects our
conclusions. All uncertainties were assumed to be uncorre-
lated and were added in quadrature in each bin of $x_g$ and
$\cos \theta_g$. The systematic error in each bin is smaller than the
corresponding statistical error.

We compared the data with perturbative QCD predictions
for the same jet algorithm and $y_c$ value. We used leading-
order (LO) and NLO results based on recent calculations [8]
in which quark mass effects were explicitly taken into ac-
count; a $b$-mass value of $m_b(m_Z)=3$ GeV/$c^2$ was used [17].
We also derived these distributions using the "parton shower" (PS) implemented in JETSET. This is equivalent to a
calculation in which all leading, and a subset of next-to-
leading, $\ln y_c$ terms are resummed to all orders in $\alpha_s$. In
physical terms this allows events to be generated with mul-
tiple orders of parton radiation, in contrast to the maximum
number of 3 (4) partons allowed in the LO (NLO) calcula-
tions, respectively. Configurations with $\geq 3$ partons are rel-
vant to the observables considered here since they may be
resolved as 3-jet events by the jet-finding algorithm.

These predictions are shown in Fig. 3. The calculations
reproduce the measured $\cos \theta_g$ distribution, which is clearly
insensitive to the details of higher-order soft parton emission.
For $x_g$, although the LO calculation reproduces the main
features of the shape of the distribution, it yields too few
events in the region $0.2<x_g<0.5$, and too many events for
$x_g<0.1$ and $x_g>0.5$. The NLO calculation is noticeably
better, but also shows a deficit for $0.2<x_g<0.4$. The PS calcu-
lation describes the data across the full $x_g$ range. The $\chi^2$
for the comparison of each calculation with the data is given in
Table II. These results suggest that multiple orders of parton
radiation need to be included, in agreement with our earlier

<table>
<thead>
<tr>
<th>QCD calculation</th>
<th>$\chi^2$: $x_g$ (10 bins)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LO $m_b(m_Z)=3$ GeV/$c^2$</td>
<td>73.6</td>
</tr>
<tr>
<td>NLO $m_b(m_Z)=3$ GeV/$c^2$</td>
<td>24.3</td>
</tr>
<tr>
<td>PS $M_b=5$ GeV/$c^2$</td>
<td>9.5</td>
</tr>
</tbody>
</table>
measurements of jet energy distributions using flavor-inclusive $Z^0$ decays [18]. We also investigated LO and NLO predictions based on matrix elements implemented in JETSET which assume massless quarks. The resulting distributions are practically indistinguishable from the massive ones, even though the large $b$-mass has been seen [17] to affect the $b\bar{b}g$ event rate at the level of 5%. The effect of varying $\alpha_s$ within the world-average range is similarly small.

We conclude that perturbative QCD in the PS approximation accurately reproduces the gluon distributions in $b\bar{b}g$ events. However, it is interesting to consider the extent to which anomalous chromomagnetic contributions are allowed. The Lagrangian represented by Eq. (1) yields a model that is non-renormalizable. Nevertheless tree-level predictions can be derived [9] and used for a “straw man” comparison with QCD. For illustration, the effect of a large anomalous moment, $\kappa=0.75$, on the shape of the $x_g$ distribution is shown in Fig. 3(a); there is a clear depletion of events in the region $x_g<0.5$ and a corresponding enhancement for $x_g\geq0.5$. By contrast the shape of the $\cos \theta_g$ distribution is relatively unchanged (not shown), even by such a large $\kappa$ value. In each bin of the $x_g$ distribution, we parametrized the leading-order effect of an anomalous chromomagnetic moment and added it to the PS calculation to arrive at an effective QCD prediction including the anomalous moment at leading-order. A $\chi^2$ minimization fit was performed to the data with $\kappa$ as a free parameter, yielding $\kappa = -0.029\pm0.070$(stat.$)^{+0.013}_{-0.003}$(syst.), which is consistent with zero within the errors, with a $\chi^2$ of 9.3 for 9 degrees of freedom. The distribution corresponding to this fit is indistinguishable from the PS prediction [Fig. 3(a)] and is not shown. Our result corresponds to 95% confidence-level (C.L.) upper limits of $-0.17<\kappa<0.11$.

In conclusion, we used the precise SLD tracking system to tag the gluon in 3-jet $e^+e^-\rightarrow Z^0\rightarrow b\bar{b}g$ events. We studied the structure of these events in terms of the scaled gluon energy and polar angle, measured for the first time across the full kinematic range. We compared our data with perturbative QCD predictions, and found that the effect of the $b$-mass on the shapes of the distributions is small, that beyond-LO QCD contributions are needed to describe the energy distribution, and that the parton shower prediction agrees best with the data. We also investigated an anomalous $b$-quark chromomagnetic moment, $\kappa$, which would affect the shape of the energy distribution. We set 95% C.L. limits of $-0.17<\kappa<0.11$. As far as we are aware, these are the first such limits on an anomalous quark chromomagnetic coupling.

We thank the personnel of the SLAC accelerator department and the technical staffs of our collaborating institutions for their outstanding efforts on our behalf. We thank A. Brandenburg, P. Uwer, and T. Rizzo for many helpful discussions and for their calculational efforts on our behalf.


[12] JADE Collaboration, W. Bartel et al., Z. Phys. C 33, 23 (1986). This algorithm has been used extensively in $e^+e^-$ annihilation studies for many years. In detailed simulation studies including other jet algorithms we found that it, with $y_c = 0.02$, yields the optimal performance of our impact-parameter-based flavor-tagging procedure.


[16] We expect less than 0.4% of the selected sample to comprise events of the type $e^+e^-\rightarrow q\bar{q}g$, with $g\rightarrow b\bar{b}$. We expect no events to have been selected in which a tagged jet contains both true $b$-quarks. In the evaluation of the purity only true $b\bar{b}$ events were considered as signal $b\bar{b}g$ events; $q\bar{q}$ $b\bar{b}$ events ($q\neq b$) were considered as backgrounds.
