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A STUDY OF THE STRUCTURE OF $e^+e^- \to b\bar{b}g$ EVENTS AND IMPROVED LIMITS ON THE ANOMALOUS CHROMOMAGNETIC COUPLING OF THE b-QUARK*

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ABSTRACT

The structure of $e^+e^- \to b\bar{b}g$ events was studied using Z^0 decays recorded in the SLD experiment at SLAC. Three-jet final states were selected and the CCD-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, and compared with perturbative QCD predictions. The energy distribution is potentially sensitive to an anomalous b chromomagnetic moment κ. We measured κ to be consistent with zero and set limits on its value, $-0.11 < \kappa < 0.08$ at 95% c.l. (preliminary).

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1 Introduction

The observation of e^+e^- annihilation into final states containing three hadronic jets, and their interpretation in terms of the process $e^+e^- \to q\bar{q}g$ [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 energies could be explored, and more detailed tests of QCD could be performed [2]. Due to advances in vertex-detection this is now possible using $\mathrm{e^+e^-} \to b\bar{b}g$ events. The large mass and relatively long lifetime, ~ 1.5 ps, of the leading B hadron in b-quark jets [3] lead to decay signatures which distinguish them from lighter-quark (u, d, s or c) and gluon jets. We used our original (1992-5) and upgraded (1996-8) CCD vertex detectors [4, 5] to identify in each event the two jets that contain the B hadrons, and hence to tag the gluon jet. This allowed us to measure the gluon energy and polar-angle distributions over the full kinematic range.

Additional motivation to study the $b\bar{b}g$ system has been provided by measurements involving inclusive $Z^0 \to b\bar{b}$ decays. Several reported determinations [6] of $R_b = \Gamma(Z^0 \to b\bar{b})/\Gamma(Z^0 \to q\bar{q})$ and the Z^0-b parity-violating coupling parameter, A_b, differed from Standard Model (SM) expectations at the few standard deviation level. Since one expects new high-mass-scale dynamics to couple to the massive third-generation fermions, these measurements aroused considerable interest and speculation. We have therefore investigated in detail the strong-interaction dynamics of the b-quark. We have compared the strong coupling of the gluon to b-quarks with that to light- and charm-quarks [7], as well as tested parity (P) and charge$\oplus$parity (CP) conservation at the $b\bar{b}g$ vertex [8]. We have also studied the structure of $b\bar{b}g$ events via the distributions of the gluon energy and polar angle with respect to (w.r.t.) the beamline [9]; here we present a preliminary update of these measurements using a data sample more than 3 times larger than in our earlier study. We compare these results with perturbative QCD predictions, including a recent calculation at next-to-leading order (NLO) which takes quark mass effects into account [10].

In QCD the chromomagnetic moment of the b quark is induced at the one-loop level and is of order α_s/π. A more general $b\bar{b}g$ Lagrangian term with a modified coupling [11] may be written:

$$\mathcal{L}^{b\bar{b}g} = g_s \bar{b} T_a \{\gamma_\mu + \frac{i\sigma_{\mu\nu}k^\nu}{2m_b}(\kappa - i\tilde{\kappa}\gamma_5)\} b G^\mu_a, \quad (1)$$

where κ and $\tilde{\kappa}$ parameterize the anomalous chromomagnetic and chromoelectric moments, respectively, which might arise from physics beyond the SM. The effects of the chromoelectric moment are sub-leading w.r.t. those of the chromomagentic moment, so for convenience we set $\tilde{\kappa}$ to zero. A non-zero κ would modify [11] the gluon energy distribution in $b\bar{b}g$ events relative to the standard QCD case. Hence we have used our larger data sample to set improved limits on κ.

2 $b\bar{b}g$ Event Selection

We used hadronic decays of Z^0 bosons produced by e^+e^- annihilations at the SLAC Linear Collider (SLC) which were recorded in the SLC Large Detector (SLD) [12]. The criteria for selecting Z^0 decays, and the charged tracks used for flavor-tagging, are described in [7, 13]. We applied the JADE algorithm [14] to define jets, using a scaled-invariant-mass criterion $y_{cut} = 0.02$. Events classified as 3-jet states were retained if all three jets were well contained within the barrel tracking system, with polar angle $|\cos\theta_{jet}| \leq 0.71$. From our 1993-98 data samples, comprising roughly 500,000 hadronic Z^0 decays, 126,871 events were selected. In order to improve the energy resolution the jet energies were rescaled kinematically according to the angles between the jet axes, assuming energy and momentum conservation and massless kinematics. The jets were then labelled in order of energy such that $E_1 > E_2 > E_3$.

Charged tracks with a large transverse impact parameter w.r.t. the measured interaction point (IP) were used to tag $b\bar{b}g$ events [7]. The resolution on the impact parameter, projected in the plane normal to the beamline, d, is $\sigma_d = 11 \oplus 70/(p_\perp\sqrt{\sin\theta})$ (1993-5) and $8 \oplus 33/(p_\perp\sqrt{\sin\theta})$ (1996-8) μm, where $p_\perp$ is the track transverse momentum in GeV/c, and θ the polar angle, w.r.t. the beamline. The jet flavor tag was based on the number of tracks per jet, N^{jet}_{sig}, with $d/\sigma_d \geq 3$ [9]. Events were retained in which exactly two jets were b-tagged by requiring each to have $N^{jet}_{sig} \geq 2$, and in which the remaining jet had $N^{jet}_{sig} < 2$ and was hence tagged as the gluon; 8196 events were selected. The efficiency for selecting true $b\bar{b}g$ events is 12%. This was estimated using a

Jet label	# Tagged gluon jets	Purity
3	1140	94.4 %
2	155	90.1 %
1	34	73.1 %

Table 1: Estimated purities of the tagged gluon-jet samples.

simulated event sample generated with JETSET 7.4 [15], with parameter values tuned to hadronic e^+e^- annihilation data [16], combined with a simulation of B-decays tuned to $\Upsilon(4S)$ data [17] and a simulation of the detector. The efficiency peaks at about 15% for 15 GeV gluons. Lower-energy gluon jets are sometimes merged with the parent b-jet by the jet-finder. At higher gluon energies the 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_{sig}^{jet} distributions separately for jets 1, 2 and 3. In about 16% of cases the gluon-tagged jet is not the lowest-energy jet (jet 3). The simulated contributions from true gluons are indicated [18] and the estimated gluon purities [18] are listed in Table 1. The inclusive gluon purity of the tagged-jet sample is 93%. With this sample we formed the distributions of two gluon-jet observables, the scaled energy $x_g = 2E_{\rm gluon}/\sqrt{s}$, and the polar angle w.r.t. the beamline, θ_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 mis-tagged events. These are shown in Fig. 2. The non-$b\bar{b}$ events ($\sim$5% of the selected sample) are mainly $c\bar{c}g$ events, 92% of which had the gluon jet correctly tagged. There is a small contribution ($\sim$0.1% of the 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 that were not classified as 3-jet events at the parton level, but were poorly reconstructed and tagged as 3-jet $b\bar{b}g$ events in the detector using the same jet algorithm and y_{cut} value. This arises from the broadening of the particle flow around the original b and $\bar{b}$ directions due to hadronization, especially the relatively high-transverse-momentum B-decay products, which causes the jet-finder to reconstruct a

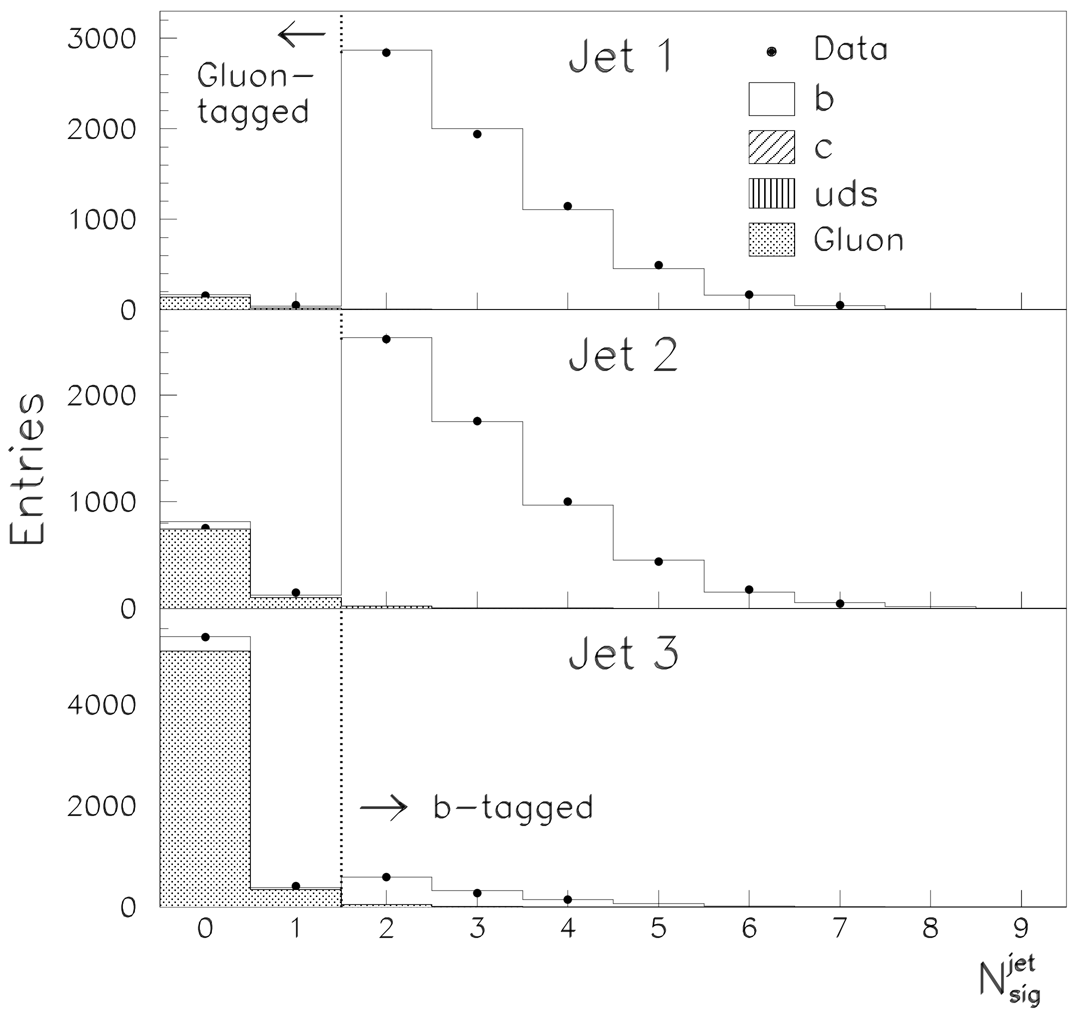

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Figure 1: The N_{sig}^{jet} distributions for jets in $b\bar{b}g$-tagged events, labelled according to jet energy (dots); errors are statistical. Histograms: simulated distributions showing jet flavor contributions.

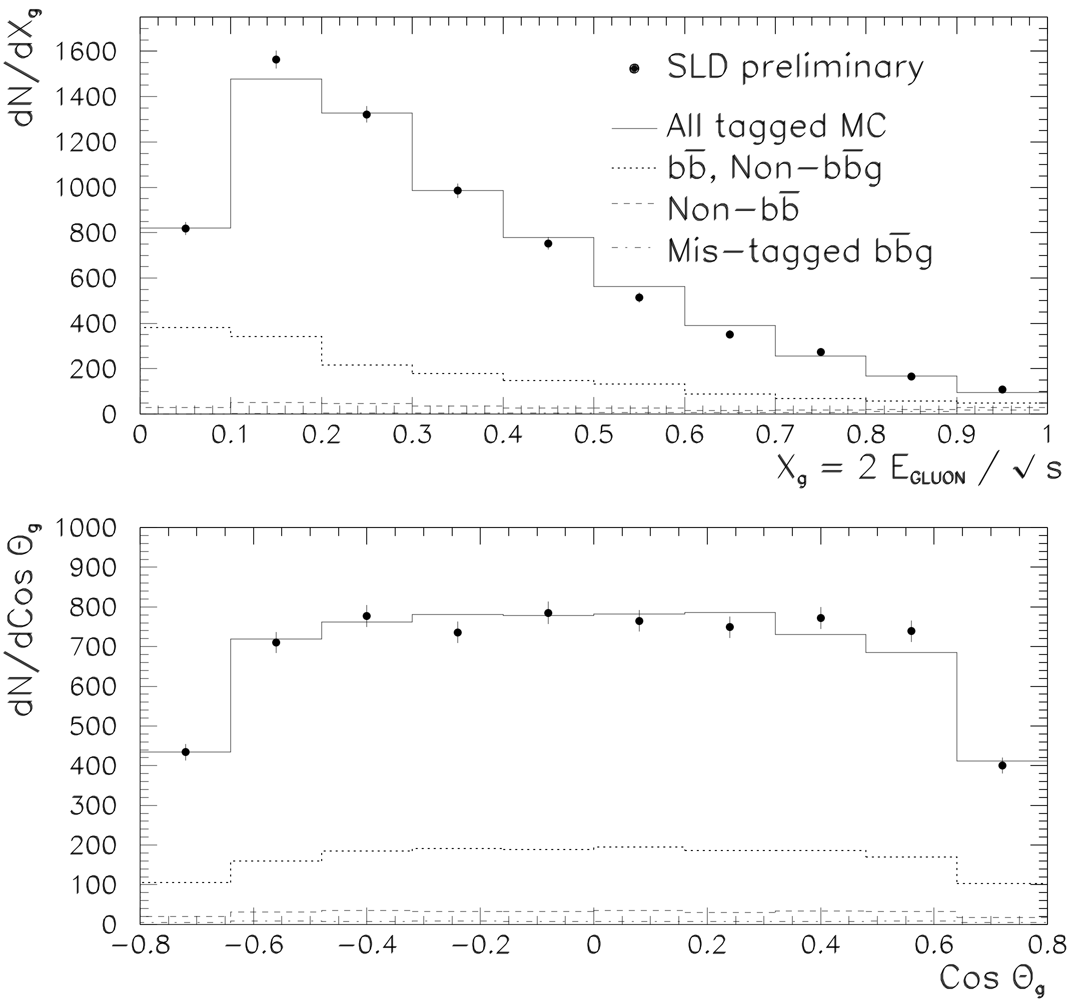

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Figure 2: Raw measured distributions of (a) x_g and (b) $\cos\theta_g$ (dots); errors are statistical. Histograms: simulated distributions including background contributions.

'fake' third jet, almost always assigned as the gluon. The population of such fake gluon jets peaks at low energy (Fig. 2(a)). Mis-tagged events, in which the gluon jet was mis-tagged as a $b/\bar{b}$-jet and the b or $\bar{b}$ jet enters into the measured distributions, comprise less than 1% of the total sample, but make a substantial contribution in the highest x_g bin.

The distributions were corrected to obtain the true gluon distributions $D^{true}(X)$ by applying a bin-by-bin procedure: $D^{true}(X) = C(X)\ (D^{raw}(X) - B(X))$, where $X = x_g$ or $\cos\theta_g$, $D^{raw}(X)$ is the raw distribution, $B(X)$ is the background contribution, and $C(X) \equiv D^{true}_{MC}(X)/D^{recon}_{MC}(X)$ 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 $D^{true}_{MC}(X)$ is the true distribution for MC-generated $b\bar{b}g$ events, and $D^{recon}_{MC}(X)$ is the resulting distribution after full simulation of the detector and application of the same analysis procedure as applied to the data.

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: $D^{true}(X_i) = M(X_i, X_j)(D^{raw}(X_j) - B(X_j))/\epsilon(X_i)$, with the unfolding matrix $M(X_i, X_j)$ defined by $D^{true}_{MC}(X_i) = M(X_i, X_j)D^{recon}_{MC}(X_j)$, where true $b\bar{b}g$ events generated in bin i may, after reconstruction, be accepted into the tagged sample in bin j. $\epsilon(X)$ is the efficiency for accepting $b\bar{b}g$ events in bin i into the tagged sample. The resulting distributions of x_g and $\cos\theta_g$ are statistically indistinguishable from the respective distributions yielded by the bin-by-bin method.

The fully-corrected distributions are shown in Fig. 3. Since, in an earlier study [7], we verified that the overall rate of $b\bar{b}g$-event production is consistent with QCD expectations, we normalised the gluon distributions to unit area and we study further the distribution shapes. The x_g distribution rises, peaks around $x_g \sim 0.15$, and decreases towards zero as $x_g \to 1$. 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 $\cos\theta_g$ distribution is flat.

We have considered sources of systematic uncertainty that potentially affect our results. These may be divided into uncertainties in modelling the detector and uncertainties in the underlying physics modelling. To estimate the first case we systematically varied the track and event selection requirements, as well as the tracking

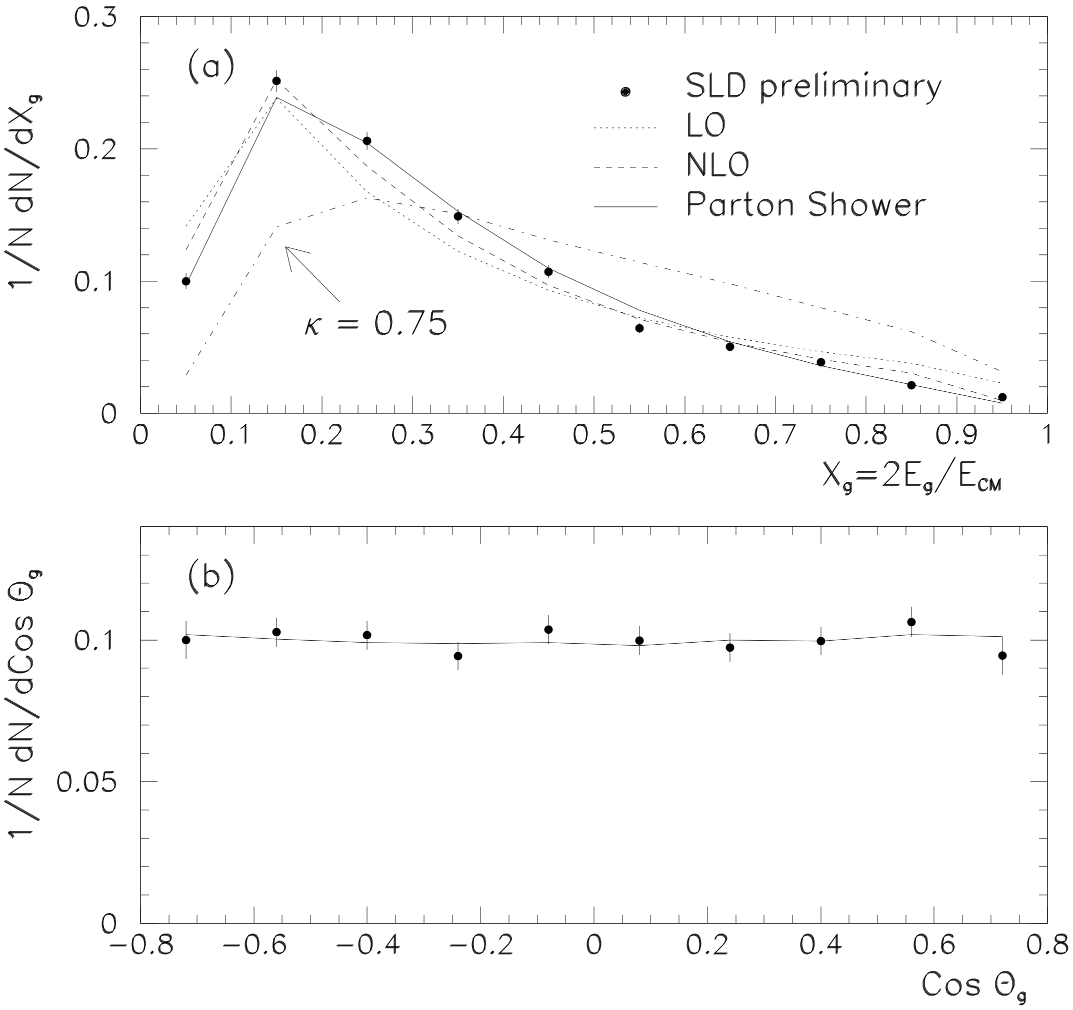

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Figure 3: Corrected distributions of (a) x_g and (b) $\cos\theta_g$ (dots); errors are statistical. Perturbative QCD predictions (see text) are shown as lines joining entries plotted at the respective bin centers.

efficiency [7, 13]. In the second case parameters used in our simulation, relating mainly to the production and decay of charm and bottom hadrons, were varied within their measurement errors [13]. For each variation the data were recorrected to derive new x_g and $\cos\theta_g$ distributions, and the deviation w.r.t. the standard case was assigned as a systematic uncertainty. None of the variations affects our conclusions. All uncertainties were conservatively assumed to be uncorrelated and were added in quadrature in each bin of x_g and $\cos\theta_g$. Since we are considering only the shapes of the distributions, the systemtic errors are much smaller than the statistical errors, except in the highest x_g bin.

3 Comparison with QCD Predictions

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 [10] in which quark mass effects were explicitly taken into account; a b-mass value of $m_b(m_Z) = 3$ GeV/c^2 was used [19]. 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 α_s. In physical terms this allows events to be generated with multiple orders of parton radiation, in contrast to the maximum number of 3 (4) partons allowed in the LO (NLO) calculations, respectively. Configurations with ≥ 3 partons are relevant 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 three calculations are indistinguishable for the $\cos\theta_g$ distribution and reproduce the measured distribution, which is almost flat in contrast to the $1+\cos^2\theta_q$ distribution for quark jets. 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 calculation describes the data across the full x_g range. These results suggest that multiple orders of parton radiation need to be included, in agreement with our earlier measurements of jet energy distributions using flavor-inclusive Z^0 decays [20]. We also investigated LO and NLO predictions based on matrix elements implemented

QCD Calculation	χ^2: x_g (10 bins)
LO $m_b(m_Z) = 3$ GeV/c^2	170
NLO $m_b(m_Z) = 3$ GeV/c^2	51
PS $M_b = 5$ GeV/c^2	18

Table 2: χ^2 for the comparison of the QCD predictions with the corrected data.

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 [19] to affect the $b\bar{b}g$ event rate at the level of 5%. The effect of varying α_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 [11] 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 $x_g \geq 0.5$. By contrast the shape of the $\cos\theta_g$ distribution is relatively unchanged (not shown), even by such a large κ value. In each bin of the x_g distribution, we parametrised 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 χ^2 minimization fit was performed to the data with κ as a free parameter, yielding $\kappa = -0.011 \pm 0.048(\text{stat.})^{+0.013}_{-0.003}(\text{syst.})$, which is consistent with zero within the errors, with a χ^2 of 17.8 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 $-0.11 < \kappa < 0.08$ (preliminary).

4 Conclusion

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 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 with the data. We also investigated an anomalous b-quark chromomagnetic moment, κ, which would affect the shape of the energy distribution. We set preliminary 95% c.l. limits of $-0.11 < \kappa < 0.08$.

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