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A PRELIMINARY STUDY OF THE STRUCTURE OF $b\bar{b}g$ EVENTS USING Z^0 DECAYS*

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ABSTRACT

The structure of three-jet $b\bar{b}g$ events has been studied using hadronic 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 a b or $\bar{b}$. The distributions of the gluon energy and polar angle with respect to the electron beam were examined and were compared with perturbative QCD predictions. These distributions are potentially sensitive to an anomalous b chromomagnetic moment κ. We measure κ consistent with zero and set limits on its value.

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1. Introduction

The observation of e^+e^- annihilation into final states containing three hadronic jets [1], and their interpretation in terms of the process $e^+e^- \rightarrow q\overline{q}g$ [2], provided the first direct evidence for the existence of the gluon, the gauge boson of the theory of strong interactions, quantum chromodynamics (QCD) [3]. Following these initial observations, studies of the partition of energy among the three jets were performed at the DESY e^+e^- collider PETRA and SLAC e^+e^- storage ring PEP. Comparison of the data with leading-order QCD predictions, and with a model incorporating the radiation of spin-0 (scalar) gluons, provided qualitative evidence [4] for the spin-1 (vector) nature of the gluon, which is a fundamental element of QCD. Similar studies have since been performed at the Z^0 resonance [5].

In these studies the gluon jet was not explicitly tagged. Instead the jets were energy ordered and the lowest-energy jet was assumed typically to be the gluon jet. If the gluon jet could be tagged event-by-event more detailed studies of the structure of QCD could be performed. Due to advances in vertexing this is now possible using three-jet $b\overline{b}g$ events. The large mass and long lifetime, ~ 1.5 ps, of B hadrons lead to decay signatures which uniquely distinguish them from charm and light quark decays. We have used the SLD CCD vertex detector to identify in each event the jets containing the B hadrons, and hence to tag the gluon jet. A similar technique has been used recently by the OPAL Collaboration, to investigate differences between quark and gluon jet properties [6].

The Standard Model has provided a remarkably successful description of almost all available data involving the electroweak interactions. Recently, however, some measurements of the quantities R_b and A_b have been reported [7] that are in mild disagreement, at the 2-3 standard deviation level, with Standard Model expectations. Since, on general grounds, one expects new high-mass scale dynamics to couple to the massive third-generation fermions, these measurements in the b-quark sector have aroused considerable interest and speculation. This provides additional motivation to study the strong-interaction dynamics of the b-quark via study of $Z^0 \to b\bar{b}g$ events.

The chromomagnetic moment of the bottom quark is induced at the one-loop level in QCD and is of the order α_s/π. One can also write down an *ad hoc* Lagrangian [8] with a $b\bar{b}g$ coupling modified via anomalous chromoelectric and chromomagnetic moments:

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

where g_s is the strong charge, T_a are the $SU(3)_c$ generators, m_b is the bottom quark mass, k is the outgoing gluon momentum, and κ and $\tilde{\kappa}$ parameterize the anomalous chromomagnetic and chromoelectric moments, respectively, which might arise from physics beyond the Standard Model. The effect of the former on three-jet observables has been calculated recently [8, 9]. The latter is CP-violating, and in this analysis we have not attempted to discriminate between the b and $\bar{b}$ jets and are hence insensitive to non-zero values of $\tilde{\kappa}$. Non-zero values of κ would modify the gluon energy distribution in $b\bar{b}g$ events (Section 5).

We present preliminary measurements of the distributions of the gluon jet energy and the gluon polar angle with respect to the electron beam direction from $b\bar{b}g$ decays of Z^0 bosons produced by e^+e^- annihilations at the SLAC Linear Collider (SLC) and recorded in the SLC Large Detector (SLD). We compare our measurements with the predictions of perturbative QCD and set limits on the anomalous chromomagnetic moment κ.

2. Apparatus and Hadronic Event Selection

The e^+e^- annihilation events produced at the Z^0 resonance by the SLAC Linear Collider (SLC) were recorded using the SLC Large Detector (SLD). A general description of the SLD can be found elsewhere [10]. This analysis used charged tracks measured in the Central Drift Chamber (CDC) [11] and in the Vertex Detector (VXD) [12], and energy clusters measured in the Liquid Argon Calorimeter (LAC) [13].

Momentum measurement is provided by a uniform axial magnetic field of 0.6T. The CDC and the VXD give a momentum resolution of $\sigma_{p_\perp}/p_\perp = 0.01 \oplus 0.0026 p_\perp$, where $p_\perp$ is the track momentum transverse to the beam axis in GeV/c. Including the uncertainty on the primary interaction point (IP), the resolution on the charged-track impact parameter (d) projected in the plane perpendicular to the beamline is $\sigma_d = 11 \oplus 70/(p_\perp \sqrt{\sin\theta})$ μm, where θ is the polar angle with respect to the beamline.

The trigger and initial selection of hadronic events are described in [14]. A set of cuts was applied to the data to select well-measured tracks and events well-contained within the detector acceptance. Well measured tracks were required to have $p_\perp \geq$ 0.15 GeV/c, a polar angle within $|\cos\theta| \leq 0.8$, and a distance of closest approach to the IP < 5 cm in the radial direction and < 10 cm along the beamline. Events well contained within the tracking volume were selected by requiring a minimum of five charged tracks, a thrust axis [15] direction, calculated using energy clusters measured in the LAC, satisfying $|\cos\theta_{Thrust}| \leq 0.71$, and a visible charged-track energy of at least 20 GeV, assuming all charged tracks are pions. We then applied the JADE algorithm [16] 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 $|\cos\theta_{Jet}| \leq 0.71$. From our 1993-95 data samples 33805 events were selected.

The energies of the jets were kinematically rescaled according to the angles between the jet axes, assuming energy and momentum conservation and massless kinematics. Labeling the jets arbitrarily 1,2 and 3, and the corresponding inter-jet angles θ_{23}, θ_{13} and θ_{12} respectively, the corrected energy of jet 1 is given by:

$$E_1 = \sqrt{s} \frac{\sin\theta_{23}}{\sin\theta_{12} + \sin\theta_{23} + \sin\theta_{31}} \tag{2}$$

where $\sqrt{s}$ is the c.m energy, with corresponding expressions for jets 2 and 3. This procedure resulted in improved jet energy resolution. The jets were then relabeled such that $E_1 > E_2 > E_3$.

The efficiency for flavour tagging, the background in the selected sample, and the resolution of the method were evaluated using a detailed Monte Carlo (MC) simulation. The JETSET 7.4 [17] event generator was used, with parameter values tuned to hadronic e^+e^- annihilation data [18], combined with a simulation of B-decays tuned to Υ(4S) data [19] and a simulation of the SLD based on GEANT 3.21 [20]

3. B Tagging

Tracks used for flavour tagging were required, in addition, to have at least one VXD hit, an error σ_d on the measured transverse impact parameter of $\sigma_d < 250$ μm, momentum $p \geq 0.5$ GeV/c, at least 40 CDC hits, with the first CDC hit on the track at a radius less than 39 cm, $\chi^2 < 5$ for the combined CDC and VXD track fit, and a distance of closest approach to the interaction point < 0.3 cm in the radial direction and < 1.5 cm along the beamline. Tracks from identified K_s^0 and Λ decays, as well as γ conversions, were removed [21].

Charged tracks with large transverse impact parameters were used to tag $b\bar{b}$ events. Figure 1 shows the distribution of N_{sig}^{evt}, the number of tracks per event with $d/\sigma_d \geq 3$. Events with $N_{sig}^{evt} \geq 4$ were selected as $b\bar{b}$ events. This gave a $b\bar{b}$ sample with an estimated purity of 94.7%. Events were retained in which two jets were tagged as b or $\bar{b}$ by requiring them to have a number of significant tracks per jet $N_{sig}^{jet} \geq 2$. The remaining jet in each event was tagged as the gluon. Figure 2 shows the N_{sig}^{jet} distributions separately for jets 1, 2 and 3 in the selected $b\bar{b}g$ event sample. The gluon-tagged jets, with $N_{sig}^{jet} < 2$, are predominantly in the lowest energy jet sample, but there are a substantial number of gluon-tagged jets in the two higher energy jet samples. It can be seen from Figure 2 that the simulation describes the data well. The purity of the gluon-jet tag was estimated from the simulation and is shown in Table 1. We estimate that the overall efficiency for correctly tagging a true $b\bar{b}g$ event is 8.25% and the overall purity of the tagged gluon-jet sample is 91%.

4. Gluon Jet Observables

We studied two gluon-jet observables in the tagged $b\bar{b}g$ events. The first is the distribution of scaled gluon energy z, where:

$$z = \frac{2E_{\rm gluon}}{\sqrt{s}} \tag{3}$$

The second is the distribution of the gluon polar angle with respect to the electron beam direction, θ_g. The raw data distributions of z and $\cos\theta_g$ are shown in Figure 3. The simulation is also shown and reproduces the data well. We corrected these distributions to obtain the true distributions:

$$D^{true}(X) = M(X)(D^{raw}(X) - B(X)) \tag{4}$$

where X represents z or $\cos\theta_g$, $D^{raw}(X)$ is the raw measured distribution, $B(X)$ is the background contribution, and $M(X)$ is a correction factor that accounts for the effects of tagging bias, detector acceptance effects, event selection efficiency and hadronisation.

A. Backgrounds

The backgrounds may be divided into 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 wrong jet was tagged as the gluon. The backgrounds were determined from the simulation and are indicated in Figure 3. The non-$b\bar{b}$ backgrounds are mainly $c\bar{c}$ events ($\sim$ 5% of the sample), with a small contribution from light quark events ($\sim$ 0.1% of the sample). The non-$b\bar{b}g$ events are true $b\bar{b}$ events that were tagged as three-jet $b\bar{b}g$ events but were not classified as three-jet events at the parton level using the same jet algorithm and y_{cut} value. Finally the wrongly-tagged $b\bar{b}g$ events are considered to be background as the gluon jet misassignment will change the shape of the distributions. In the simulation the jets that contain the b or $\bar{b}$ were determined by taking the dot product of each jet momentum vector and the momentum vector of any B hadrons in the event. The two jets closest to the respective B hadrons were defined as the b or $\bar{b}$ jets. These three types of background were then subtracted from the data, bin-by-bin.

B. Correction for Detector and Hadronisation Effects

We applied a bin-by-bin correction for the effects of tagging bias, detector acceptance effects, event selection efficiency and hadronisation. We define the correction factor:

$$M(X) = \frac{D_{MC}^{true}(X)}{D_{MC}^{recon}(X)} \tag{5}$$

Where $D_{MC}^{true}(X)$ is the simulated distribution of X for true $b\bar{b}g$ events at the parton level, and $D_{MC}^{recon}(X)$ is the reconstructed distribution for $b\bar{b}g$ events in the tagged sample. This factor is shown in Figure 4.

C. Comparison with QCD Predictions.

The fully corrected distributions are shown in Figure 5, where they are compared with QCD predictions calculated using JETSET 7.4. We evaluated the O(α_s), O(α_s^2), and parton shower (PS) predictions. The O(α_s) and the O(α_s^2) predictions describe the data well except in the region $0.2 < z < 0.4$. The PS prediction describes the data well across the full z range, suggesting that multiple orders of parton radiation are required for a good description. The χ^2 for the comparison of each prediction with the data is given in Table 2.

5. Study of the Effects of an Anomalous Chromomagnetic Moment

The Lagrangian represented by Eq. 1 yields a model that is non-renormalisable. Nevertheless tree-level O(α_s) predictions can be derived [8, 9] and used for a 'straw man' comparison with QCD. In this context we illustrate in Figure 6 the effect of an anomalous b chromomagnetic moment on the z distribution. As the absolute value of κ is increased the gluon energy spectrum gets harder, producing an excess of gluon jets with high scaled energy. A further difficulty arises in that the O(α_s) QCD calculation does not describe the data as well as the PS calculation, so that the higher-order QCD effects included in the PS prediction could be mimicked in the extended O(α_s) calculation by an artificially large anomalous moment κ. Therefore, in each bin i of the z distribution, we parametrised the leading-order effect of an anomalous chromomagnetic moment:

$$f_i(\kappa) = D^{O(\alpha_s)}(z_i, \kappa) - D^{O(\alpha_s)}(z_i, \kappa = 0) \tag{6}$$

and added it to the PS calculation to arrive at an effective parton shower QCD prediction including the anomalous moment at leading-order:

$$D^{eff}(z_i, \kappa) = D^{PS}(z_i) + f_i(\kappa) \tag{7}$$

A χ^2 minimisation fit of $D^{eff}(z_i, \kappa)$ was performed to the corrected z distribution with κ as the only free parameter. The result of the fit is shown in Figure 7. The χ^2 is 12.5 for 9 degrees of freedom. We find:

$$\kappa = -0.030^{+0.061}_{-0.062}(\mathrm{stat.}) \tag{8}$$

6. Systematic Errors

We have considered sources of systematic uncertainty that potentially affect our study of $b\bar{b}g$ events. These may be divided into uncertainties in modelling the detector and uncertainties on experimental measurements serving as input parameters to the underlying physics modelling. For the latter studies our simulation was used.

The uncertainties in modelling the detector were investigated by varying the event selection requirements. The thrust-axis containment cut was varied in the range $0.67 < |\cos\theta_{Thrust}| < 0.75$, the minimum number of charged tracks required was increased by 1 track, the total charged-track energy requirement was varied by $\pm$ 2 GeV and the tracking efficiency was varied by our estimated uncertainty of $+4.8\%$ [22].

A large number of measured quantities relating to the production and decay of charm and bottom hadrons are used as input to our simulation. For $b\bar{b}$ events we have considered the uncertainties on: the branching fraction for $Z^0 \rightarrow b\bar{b}$; the rate of production of B baryons; the lifetimes of B mesons and baryons; the branching ratios for $B \rightarrow D^+ + X$; the average charged multiplicity of B hadron decays; and the bottom fragmentation function. For $c\bar{c}$ events we have considered the uncertainties on: the branching fraction for $Z^0 \rightarrow c\bar{c}$; the charm fragmentation function; the charged multiplicity of charmed hadron decays; and the rates of production of D^+ mesons and charmed baryons. The uncertainty on gluon splitting into $b\bar{b}$ or $c\bar{c}$ was also considered. A list of quantities considered is shown is Table 3.

The variation of each quantity within its uncertainty was produced in turn in our simulated event sample using an event weighting technique [22]. The background contribution and correction factors were then recalculated, the data were recorrected, and the fit for κ was repeated. In each case the deviation with respect to the standard value was taken as a separate systematic error. These are listed in Table 3. These uncertainties were conservatively assumed to be uncorrelated and were added in quadrature to obtain a total systematic uncertainty on κ of $^{+0.012}_{-0.003}$.

7. Summary

We have used the precise SLD tracking system to tag $e^+e^- \rightarrow Z^0 \rightarrow b\bar{b}g$ events. We have studied the structure of $b\bar{b}g$ events in terms of the distributions of the scaled gluon energy and the gluon polar angle with respect to the electron beam direction, and found that the QCD parton shower predictions agree well with the data. We investigated the effects of an anomalous chromomagnetic moment, κ, and measured $\kappa = -0.030^{+0.061}_{-0.062}$ (stat) $^{+0.012}_{-0.003}$ (syst). We set 95% confidence-level upper limits of $-0.15 < \kappa < 0.09$.

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[†] *Deceased*

[a] *Also at the Università di Genova*

[b] *Also at the Università di Perugia*

Jet Label	Number of Tagged Gluon-Jets	Purity
3	1344	94.6 %
2	155	83.7 %
1	34	51.8 %

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

	χ^2	
QCD Calculation	z (10 bins)	Cos θ_g (10 bins)
O(α_s)	54.5	7.6
O(α_s^2)	27.7	5.8
PS	15.0	6.8

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

Source	Center Value	Variation	$\Delta\kappa$
B PHYSICS			
B decay multiplicity	$<n_{ch}> = 5.39$	±0.2 trks	${}^{+0.0005}_{-0.0007}$
B fragmentation	$<x_b> = 0.702$	∓0.008	${}^{+0.0015}_{-0.0024}$
B meson lifetime	$\tau_B = 1.55$ps	±0.05ps	${}^{+0.0001}_{-0.0002}$
B baryon lifetime	$\tau_B = 1.10$ps	±0.08ps	${}^{+0.0002}_{-0.0001}$
B baryon prod. rate	$f_{\lambda_b} = 7\,\%$	$\pm4\%$	${}^{+0.0002}_{-0.0002}$
$B \longrightarrow D^+ +$ X fraction	0.15	∓0.05	${}^{+0.0000}_{-0.0007}$
R_b	0.2216	∓0.0017	${}^{+0.0001}_{-0.0000}$
C PHYSICS			
R_c	0.16	∓0.01	${}^{+0.0001}_{-0.0002}$
c fragmentation	$<x_c> = 0.484$	±0.008	${}^{+0.0008}_{-0.0005}$
$c\overline{c} \longrightarrow D^+ +$ X fraction	0.231	∓0.026	${}^{+0.0002}_{-0.0002}$
D decay multiplicity	$<n_{ch}> = 2.39$	±0.14trks	${}^{+0.0002}_{-0.0002}$
g $\longrightarrow c\overline{c}$	2.4	$\mp$ 0.5	${}^{+0.0008}_{-0.0007}$
g $\longrightarrow b\overline{b}$	0.13	$\mp$ 0.04	${}^{+0.0002}_{-0.0004}$
DETECTOR			
E_{vis}	$E_{vis} > 20$GeV	±2GeV	${}^{+0.0000}_{-0.0008}$
cos θ_T	$\lvert\cos\theta_T\rvert < 0.71$	±0.04	${}^{+0.0013}_{-0.0000}$
n_{trk}	$n_{trk} \geq 5$	${}^{+1}_{-0}$trk	${}^{+0.0000}_{-0.0000}$
Tracking efficiency	$--$	${}^{+4.8}_{-0.0}\%$	${}^{+0.0114}_{-0.0000}$
TOTAL			${}^{+0.012}_{-0.003}$

Table 3: Table of systematic errors.

Figure Captions

Figure 1. The N_{sig}^{evt} distribution. The histogram shows the simulated distribution in which the event flavour contributions are indicated.

Figure 2. The N_{sig}^{jet} distributions for the jets in b-tagged events defined by $N_{sig}^{evt} \geq 4$ and two jets with $N_{sig}^{jet} \geq 2$. The histogram shows the simulated distribution in which the event flavour contributions are indicated.

Figure 3. Comparison of data and simulation; the background contributions are indicated in the simulated distributions.

Figure 4. The total correction factor (see text) for tagging bias, detector effects, event selection and hadronisation effects.

Figure 5. A comparison of the corrected distributions with QCD predictions.

Figure 6. Effect of an anomalous chromomagnetic moment on the scaled gluon energy spectrum.

Figure 7. Result of the fit of the parton shower calculation including a leading-order anomalous chromomagnetic moment contribution.

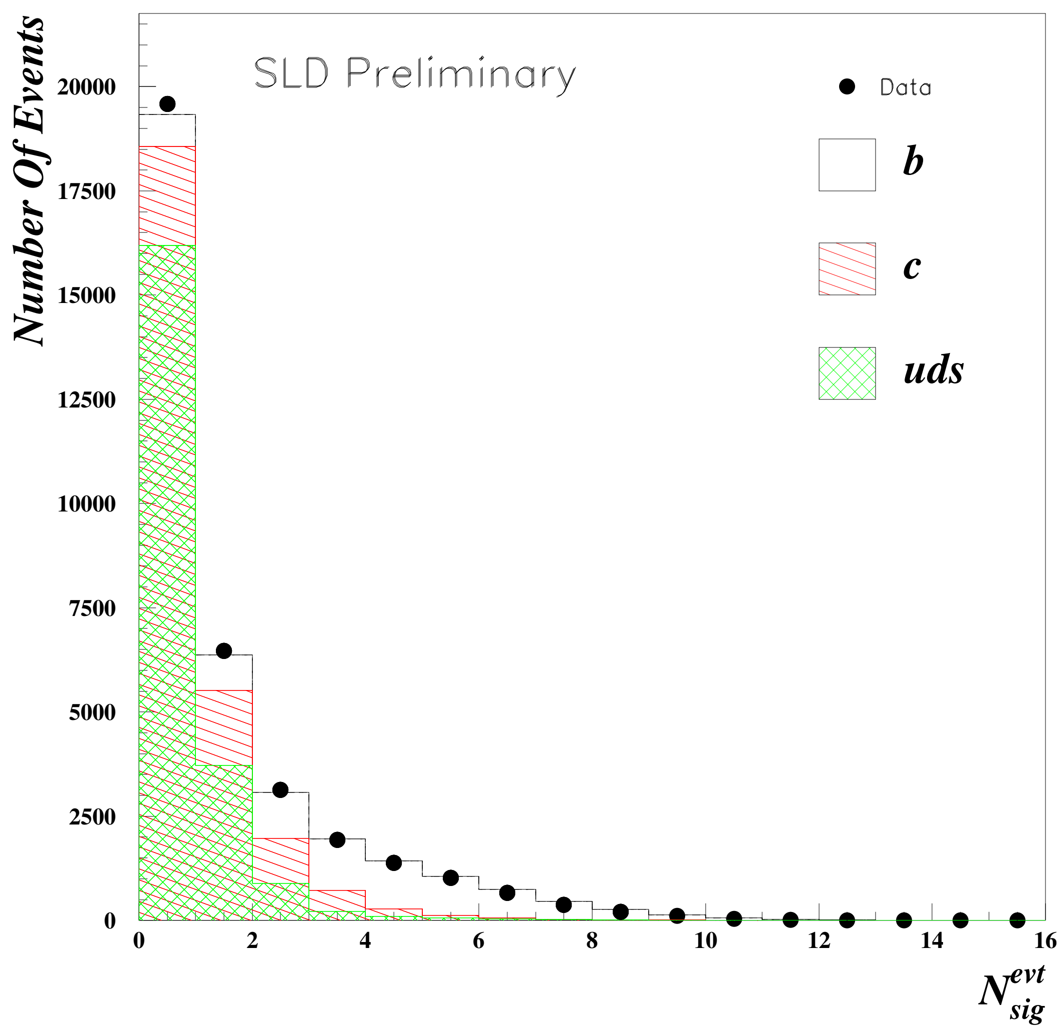
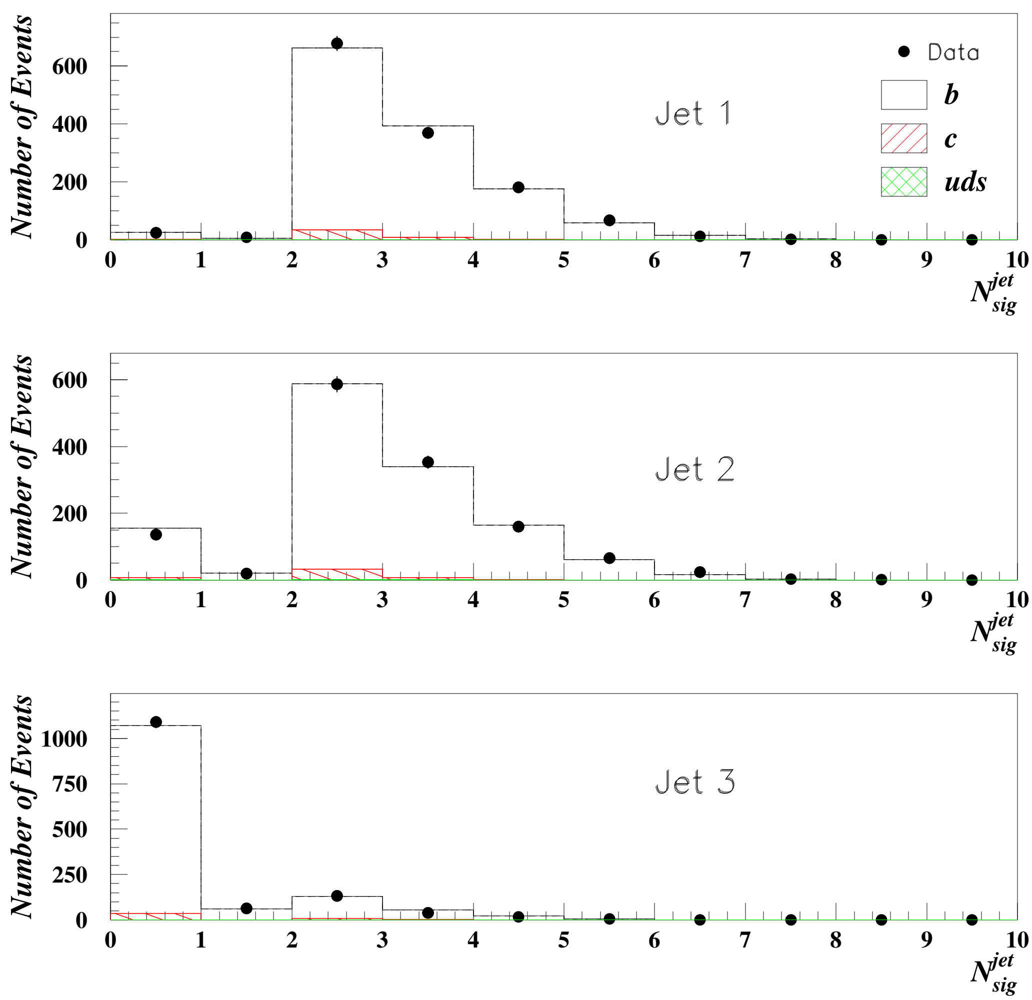

SLD Preliminary
Data
b
c
uds
Number Of Events
20000
17500
15000
12500
10000
7500
5000
2500
0
0
2
4
6
8
10
12
14
16
N_{sig}^{evt}

Figure 1:


Number of Events
600
400
200
0
0 1 2 3 4 5 6 7 8 9 10
N_{sig}^{jet}
Data
b
c
uds
Jet 1
Number of Events
600
400
200
0
0 1 2 3 4 5 6 7 8 9 10
N_{sig}^{jet}
Jet 2
Number of Events
1000
750
500
250
0
0 1 2 3 4 5 6 7 8 9 10
N_{sig}^{jet}
Jet 3

.

Figure 2:

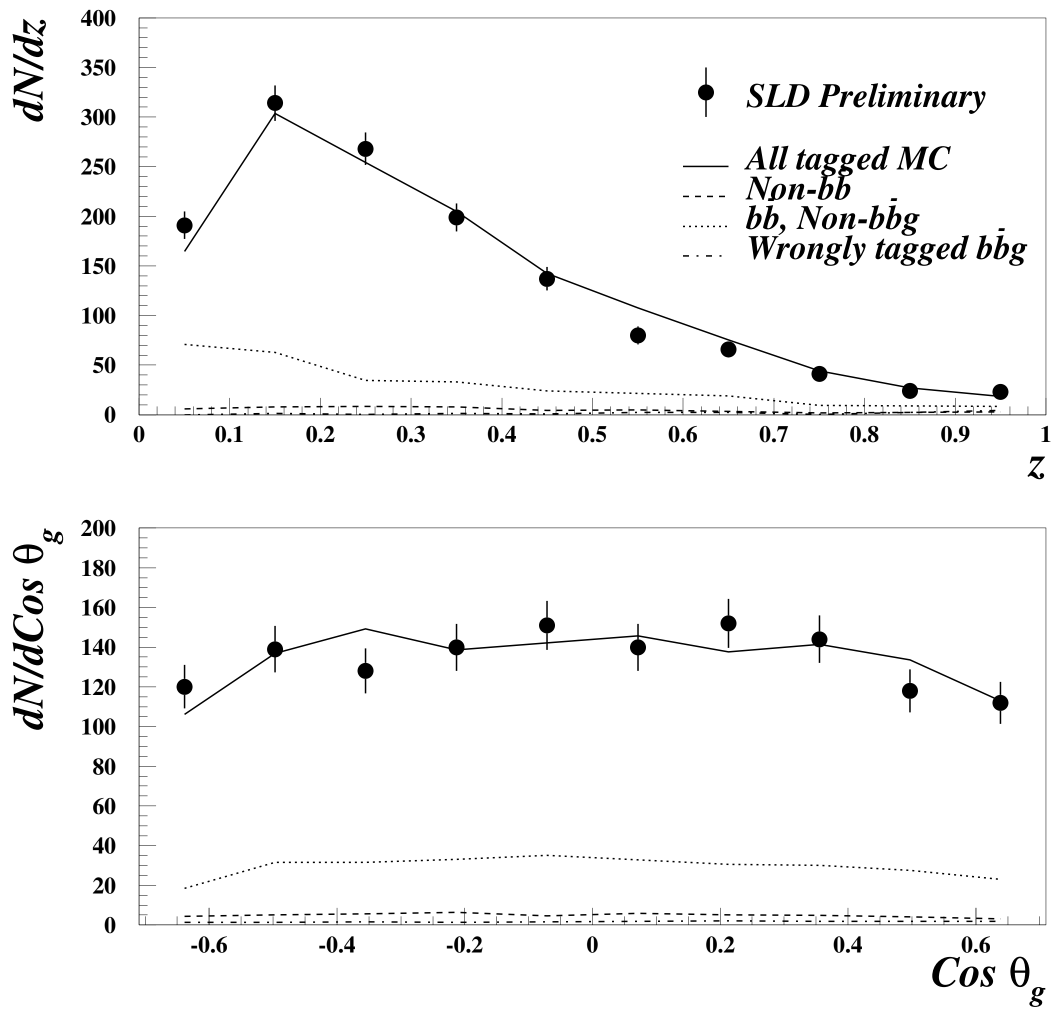
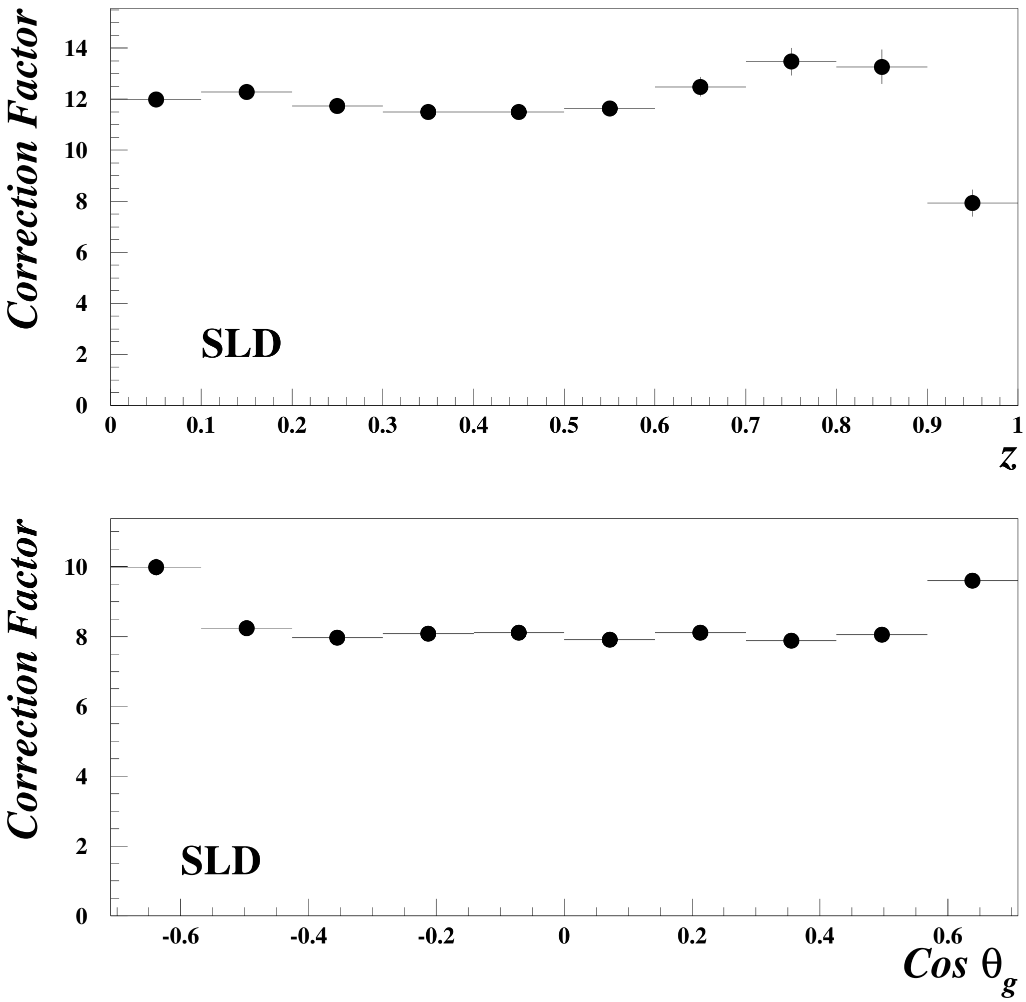
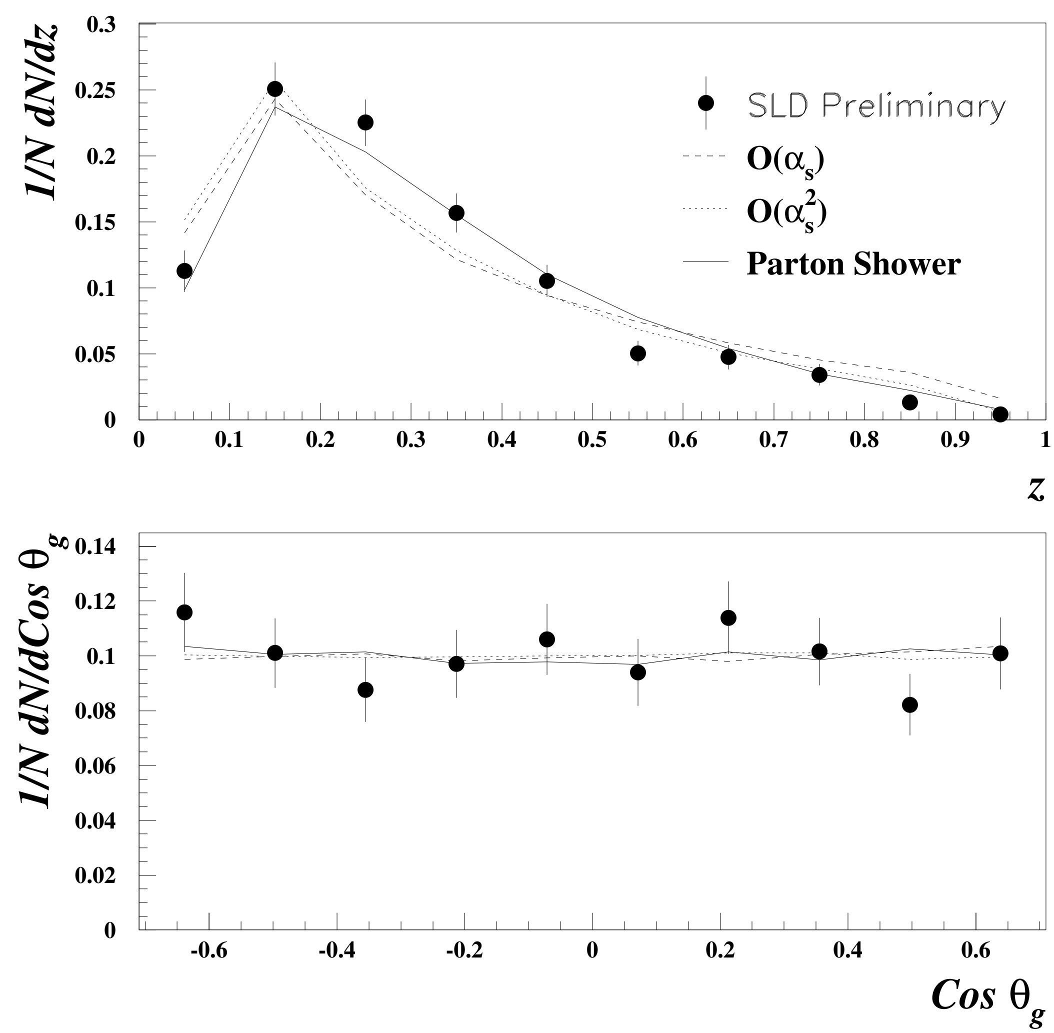

dN/dz
SLD Preliminary
All tagged MC
Non-bb̄
bb̄, Non-bb̄g
Wrongly tagged bb̄g
z
dN/dCos θg
Cos θg

Figure 3:


Correction Factor
14
12
10
8
6
4
2
0
SLD
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
z
Correction Factor
10
8
6
4
2
0
SLD
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
Cos θ_g

.

Figure 4:



1/N dN/dz
SLD Preliminary
O(αs)
O(αs2)
Parton Shower
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
0 0.05 0.1 0.15 0.2 0.25 0.3
z
1/N dN/dCos θg
0 0.02 0.04 0.06 0.08 0.1 0.12 0.14
-0.6 -0.4 -0.2 0 0.2 0.4 0.6
Cos θg

Figure 5:

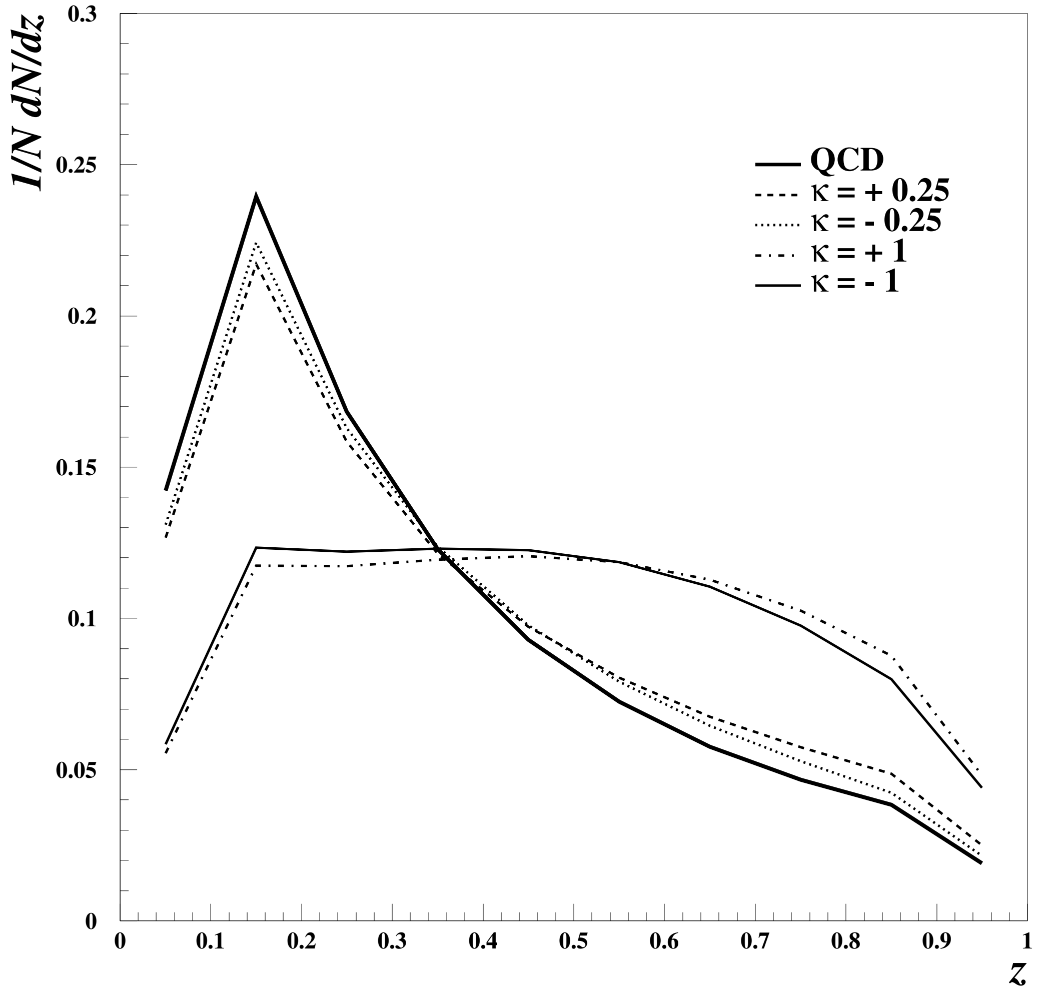
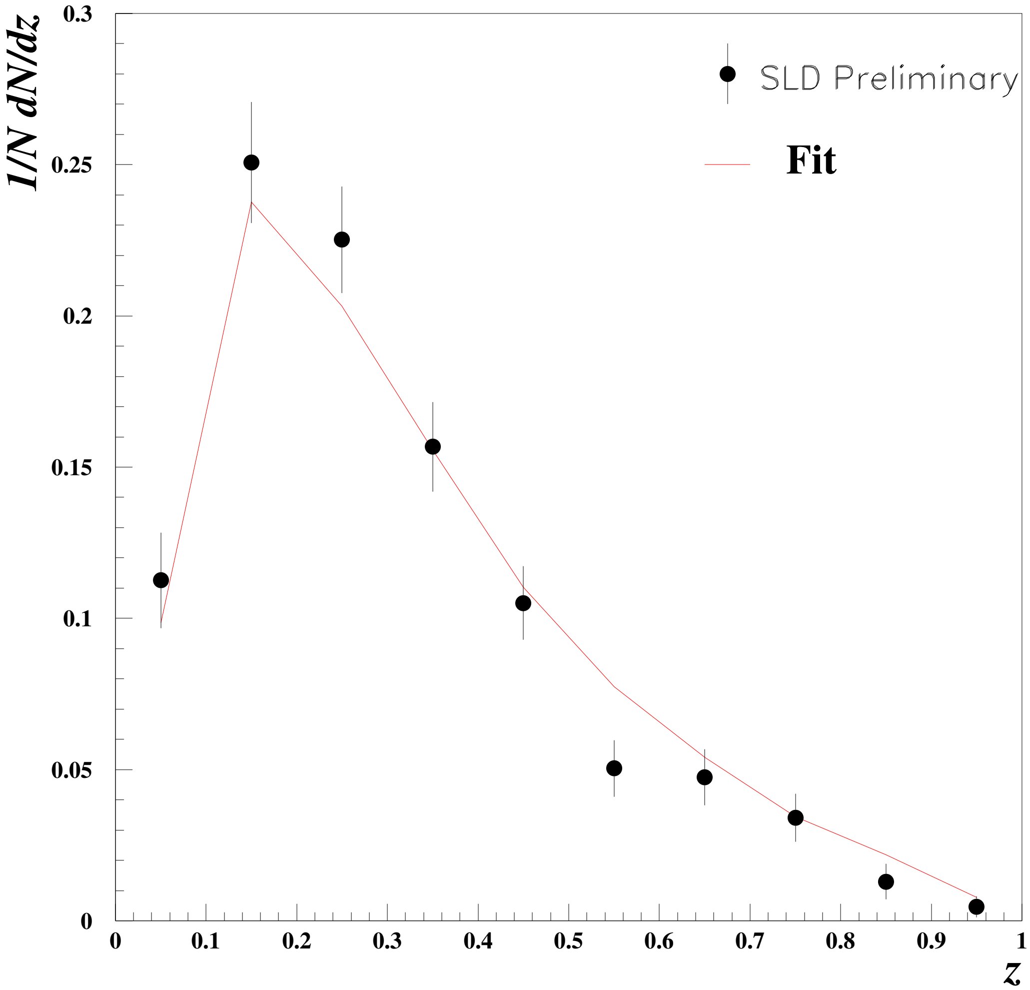

1/N dN/dz
QCD
κ = + 0.25
κ = - 0.25
κ = + 1
κ = - 1
z
0
0.05
0.1
0.15
0.2
0.25
0.3
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

Figure 6:


1/N dN/dz
0.3
0.25
0.2
0.15
0.1
0.05
0
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
z
SLD Preliminary
Fit

.

Figure 7: