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Tests of QCD using Heavy Flavors at SLD*

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Abstract

We present preliminary results on three SLD analyses: the gluon energy spectrum in 3-jet $b\bar{b}g$ events, the rate of $g \to b\bar{b}$, and the b fragmentation function in Z^0 decays. The gluon energy spectrum, measured over the full kinematic range, is compared with perturbative QCD predictions. We set new 95% C.L. limits on the anomalous chromomagnetic coupling of the b quark: $-0.09 < \kappa < 0.06$. $g_{b\bar{b}}$ is measured to be $(3.07 \pm 0.71\ (\text{stat}) \pm 0.66\ (\text{syst})) \times 10^{-3}$. The inclusive B hadron energy distribution is measured for the first time over the full kinematic range, using a novel B hadron energy reconstruction technique. Several models of b fragmentation including JETSET + Peterson are excluded by the data. The average scaled B hadron energy of the weakly decaying B hadron is measured to be $x_B = 0.713 \pm 0.005\ (\text{stat}) \pm 0.007\ (\text{syst}) \pm 0.002\ (\text{model})$. All three measurements take advantage of the small and stable SLC interaction point as well as the excellent vertexing and tracking capabilities of the upgraded CCD-pixel vertex detector.

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1. Introduction

One of the powerful aspects of QCD is that it provides a framework to understand the production of hadronic jets. Perturbative QCD (pQCD) in principle allows us to calculate infrared finite quantities as an expansion of the strong coupling α_s and its predictions are subject to precision experimental tests. The nonperturbative fragmentation process, which transforms quarks and gluons into hadrons, however, has not been well-understood theoretically, nor has it been well-measured experimentally. This limits the precision in our understanding of the production and structure of hadronic jets and will likely affect the precision of physics studies at future colliders, where large numbers of hadrons will be produced. In view of this, it is important both to test pQCD and to precisely measure quantities that will help extract the nonperturbative effects in the fragmentation process. Heavy flavors are especially well-suited for this purpose. The mass of the b quark provides a natural cutoff in pQCD calculations, a feature that allows a number of precise pQCD predictions to be made. Furthermore, $e^+e^- \to Z^0$ environment is a particularly clean. When a B hadron is highly boosted, its decay vertex is significantly displaced from the interaction point (IP), allowing high efficiency and purity B tagging.

Here we report three SLD [1] analyses involving heavy quark production. SLD's strength to study B physics largely resides in the upgraded CCD-pixel vertex detector (VXD3) [2]. Using VXD3, the impact parameter resolution is 11μm (23μm) transverse to (along) the beam axis for high momentum tracks. SLC's small and stable IP can be measured to a resolution of about 4.4μm in the plane transverse to the beam axis. This allows not only the selection of a high purity B sample, but also the precise measurement of kinematic quantities.

2. The Gluon Energy Spectrum in $Z^0 \to b\bar{b}g$

In studying $e^+e^- \to$ 3-jet events , the key is to know the origin of each jet. In previous studies, jets were usually energy-ordered and the lowest is assumed to be the gluon jet. This is correct about 80% of the time. However, the bias towards selecting low energy gluon jets makes this method undesirable for testing pQCD predictions of the gluon jet energy spectrum, to which high energy gluon jets are most sensitive.

In this analysis [3], the gluon jet is tagged explicitly by identifying the two jets that contain B hadrons. A 3-jet event (selected using the JADE algorithm at $y_{cut} = 0.02$) is tagged as a $b\bar{b}g$ event if exactly two of the three jets each contain two or more tracks with normalized transverse impact parameter $d/\sigma_d > 3$. The remaining jet, which does not satisfy this criterion, is tagged as the gluon jet. In 2.5% (12.5%) of the selected $b\bar{b}g$ events, the (second) highest energy jet is tagged as the gluon jet, covering the full kinematic range. Non-$b\bar{b}$ events (4%), non-$b\bar{b}g$ events (21%), and $b\bar{b}g$ events in which the gluon jet is wrongly tagged (1%) are treated as backgrounds and are subtracted from the data. The resulting distribution of the scaled gluon energy $x_g = 2E_g/E_{CM}$ is corrected for effects of efficiency and resolution. The fully corrected spectrum is shown in Figure 1. The cutoff at low x_g is caused by the finite y_{cut} value used in jetfinding. Leading order (LO) and next-to-leading order (NLO) QCD predictions [4] describe the general but not the detailed behavior of the spectrum. Higher order QCD effects are clearly important.

Parton shower Monte Carlo is able to describe the data.

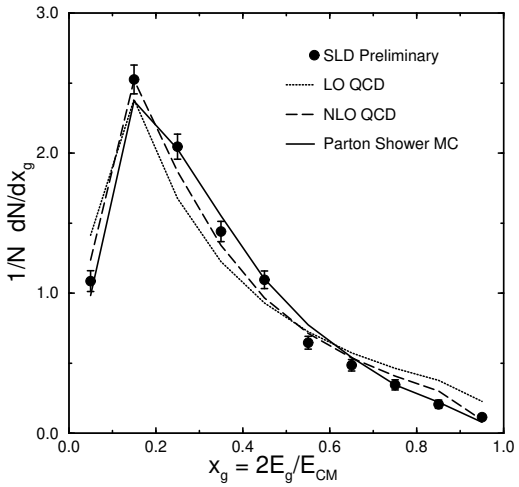

Figure 1. The measured scaled gluon energy spectrum.

The gluon energy spectrum is particularly sensitive to the presence of an anomalous chromomagnetic coupling of the b quark in the QCD Lagrangian [5],

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

where κ and $\tilde{\kappa}$ parameterize the anomalous chromomagnetic and chromoelectric moments, respectively, which might arise from physics beyond the SM. Setting $\tilde{\kappa}$ to zero, a fit of the theoretical prediction to the data yields $\kappa = -0.02 \pm 0.04$ (preliminary), which is consistent with zero. The 95% C.L. limits are $-0.09 < \kappa < 0.06$ (preliminary).

3. The Rate of Secondary $b\bar{b}$ Production via $g \to b\bar{b}$

The process of gluon splitting into a quark-antiquark pair is poorly known, both theoretically and experimentally, despite the fact that this is one of the elementary processes in QCD. The rate of $g \to b\bar{b}$, $g_{b\bar{b}}$, defined as the fraction of hadronic events in which a gluon splits into a $b\bar{b}$ pair, is an infrared finite quantity and can be calculated using pQCD because the mass of the b quark provides a natural cutoff [6]. However, $g_{b\bar{b}}$ is sensitive to both the $\Lambda^5_{\overline{MS}}$ parameter and the b quark mass, which results in a substantial theoretical uncertainty in the calculation of $g_{b\bar{b}}$. The limited accuracy of the $g \to b\bar{b}$ prediction is one of the main sources of uncertainty in the measurement of the partial decay width of the $Z^0 \to b\bar{b}$. In addition, about 50% of the B hadrons are produced via gluon splitting at Tevatron, and an even larger fraction is expected at the LHC. A better knowledge of this process will improve the theoretical modeling and predictions of heavy flavor production at such colliders.

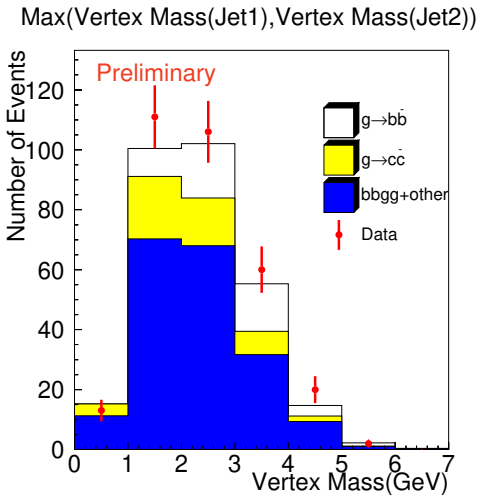

Figure 2. The larger of the two vertex masses.

Since the background in this analysis is very large, the main task is to enhance the signal to background ratio. The 4-parton final state of the signal, $q\bar{q}b\bar{b}$, suggests that we select 4-jet hadronic events. We used the Durham algorithm with $y_{cut} = 0.008$. Most $Z^0 \to q\bar{q}$ events and $Z^0 \to q\bar{q}g$ events in which the gluon does not split are rejected, but the majority of the selected events are still backgrounds from $q\bar{q}gg$ and $q\bar{q}c\bar{c}$. Back-

ground of the type $q\bar{q}gg$ where $q \neq b$ or c can be mostly removed by looking for heavy hadrons in the selected events. Using a topological vertexing algorithm [7], secondary vertices are searched for in the two jets forming the smallest angle. About 300 events in which both jets contain a secondary vertex are selected. Figure 2 shows the distribution of the larger of the two vertex masses, together with the breakdown of Monte Carlo events into the signal and the backgrounds.

We then focus on distinguishing the topology of $g \to b\bar{b}$ events from that of $b\bar{b}gg$ events. In many events, the two selected jets actually originate from the same b jet. Figure 3 shows the angular separation between the two vertices. The high IP and vertex resolutions give us a good discriminating power between the signal and the background, about half of which peak at $\cos\theta \sim 1$. In order to enhance the signal to background ratio, we require $-0.2 < \cos\theta < 0.96$. Since the radiated virtual gluon in $Z^0 \to q\bar{q}g$ is polarized in the plane of the three partons, the subsequent gluon splitting favors $g \to q\bar{q}$ emission out of this plane. We therefore consider a variable similar to the Bengtsson-Zerwas angle, which is the angle between the plane formed by the two jets containing secondary vertices and the plane formed by the other two jets. Figure 4 shows the distribution of $|\cos\alpha|$. Events with $|\cos\alpha| > 0.8$ are rejected. Finally, since b jets from the gluon splitting tend to be softer than other jets, we require the total energy of the two selected jets to be less than 36 GeV. After these cuts, the background consists of 49% $b\bar{b}gg$, 34% $g \to c\bar{c}$ and the remaining 17% $q\bar{q}gg$, where $q \neq b$ or c. To further reduce the $g \to c\bar{c}$ background, we require the maximum vertex mass to be greater than 2.0 GeV. 62 events in the data survived all these selection cuts. We subtract the expected background of 27.6±1.2 events and divide the selection efficiency of 3.86% to obtain the preliminary measured value of $g_{b\bar{b}}$

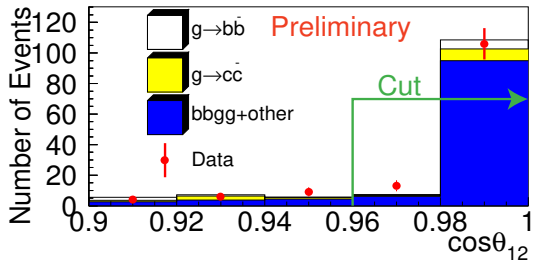

Figure 3. Distribution of the cosine of the angle between the two jets forming the smallest angle, for data (points) and in Monte Carlo (histogram).

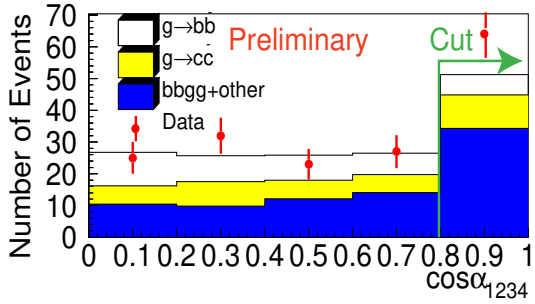

Figure 4. Distribution of the cosine of the angle between the two planes, for data (points) and in Monte Carlo (histogram).

$$g_{b\bar{b}} = (3.07 \pm 0.71(stat) \pm 0.66(syst)) \times 10^{-3}. \quad (2)$$

4. The b Quark Fragmentation Functions

According to the factorization theorem, the heavy quark fragmentation function can be described as a convolution of perturbative and non-perturbative effects. For the b quark, the perturbative calculation is in principle understood [8, 9]. Nonperturbative effects have

been parametrized in both model-dependent [10, 11, 12, 13, 14, 8] and model-independent approaches [9, 15, 16].

It is experimentally challenging to measure the b quark fragmentation function to a level of precision sufficient to distinguish among the various models. Since the b quark fragmentation function is the probability distribution of the fraction of the momentum of the b quark carried by the B hadron, the most sensitive experimental determination of the shape of the b fragmentation function is expected to come from a precise direct measurement of the B hadron energy (or momentum) distribution. The difficulty of such a measurement stems mostly from the fact that most of the B decays can only be partially reconstructed, causing a fraction of the B energy to be missing from the B decay vertex. Recent direct measurements at LEP [17, 18] and SLD [19] have used overall energy-momentum constraints and calorimetric information to extract this missing energy in a sample of semi-leptonic B decays. These measurements suffer from low statistics as well as poor B energy resolution at low energy, and hence have a relatively weak discriminating power between different shapes of the fragmentation function. Indirect measurements [20] such as the measurement of the lepton spectrum have been used to constrain the average B energy. These measurements, however, are not sensitive to the shape of the B hadron energy distribution.

Here we describe a new method for reconstructing individual B hadron energy with good resolution over the full kinematic range while achieving a much higher efficiency [21]. We reconstruct secondary B decay vertices inclusively with high efficiency using a topological vertexing algorithm [7]. At SLD, the B flight direction, pointing along the line joining the IP and the secondary vertex, is well-measured because of the very small IP error and the excellent vertex resolution. Therefore the transverse momentum P_t of tracks associated with the vertex relative to the B flight direction is also well-measured. We then obtain the invariant mass M_{ch} and the total energy E_{ch} of the associated tracks, assigning the pion mass to each charged track. Furthermore, we assume that the true mass of the B hadron decayed at the vertex is equal to the B^0 meson mass. An upper limit on the mass of the missing particles is then found to be $M^2_{0max} = M^2_B - 2M_B\sqrt{M^2_{ch} + P^2_t} + M^2_{ch}$. Since the true missing mass M_0^{true} is often rather close to M_{0max}, M_{0max} is subsequently used as an estimate of M_0^{true} to solve for the longitudinal momentum of the missing particles from kinematics, and hence the energy of missing particles E_0. The B hadron energy is then $E_B = E_{ch} + E_0$. Since $0 \leq M_0^{true} \leq M_{0max}$, the B energy is well-constrained when M_{0max} is small. In addition, most uds and c backgrounds are concentrated at large M_{0max}. We choose an *ad hoc* upper cut on the M^2_{0max} to achieve a nearly x_B-independent B selection efficiency of about 3.9%; the estimated purity is about 99.5%. A total of 1920 vertices in the 1996-97 data satisfy all selection cuts. Figure 5 shows the distribution of the reconstructed scaled weakly decaying B hadron energy for data and Monte Carlo.

We examine the normalized difference between the true and reconstructed B hadron energies for Monte Carlo events. The distribution is fitted by a double Gaussian, resulting in a core width (the width of the narrower Gaussian) of 10.4% and a tail width (the width of the wider Gaussian) of 23.6% with a core fraction of 83%. The core width is essentially independent of x_B, another feature that makes this method unique.

After background subtraction, the distribution of the reconstructed scaled B hadron energy is compared with a set of *ad hoc* functional forms of the x_B distribution in order

to estimate the variation in the shape of the x_B distribution. For each functional form, the default SLD Monte Carlo is re-weighted and then compared with the data bin-by-bin and a χ^2 is computed. The minimum χ^2 is found by varying the input parameter(s). The Peterson function [12], two *ad hoc* generalizations of the Peterson function [18], and an 8th-order polynomial are consistent with the data. We exclude the functional forms proposed by BCFY [16], Collins and Spiller [14], Kartvelishvili [10], Lund [13] and a power function of the form $f(x) = x^{\alpha}(1-x)^{\beta}$.

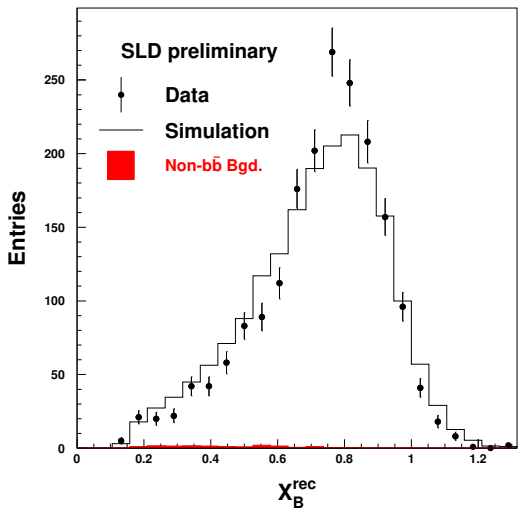

Figure 5. Distribution of the reconstructed scaled B hadron energy.

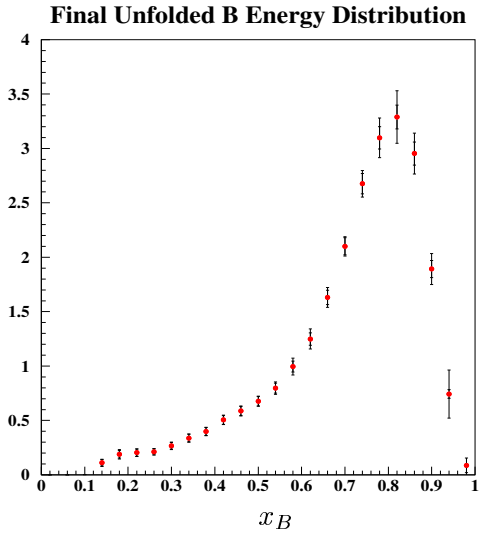

Figure 6. The binwise average of the seven unfolded distributions (Preliminary).

We then test several heavy quark fragmentation models. Since the fragmentation functions are usually functions of an experimentally inaccessible variable (e.g. $z = (E+p_{\parallel})_H/(E+p_{\parallel})_Q$), it is necessary to use a Monte Carlo generator such as JETSET [22] to generate events according to a given input heavy quark fragmentation function. The resulting B energy distribution is then used to re-weigh the Monte Carlo distribution before comparing with the data. The minimum χ^2 is found by varying the input parameter(s). Within the context of the JETSET Monte Carlo, Kartvelishvili [10], Bowler [11], and the Lund [13] models are consistent with the data, while BCFY [16], Collins and Spiller [14], and Peterson [12] models are found to be inconsistent with the data.

The four functional forms and the three fragmentation models consistent with the data are then used in turn to calculate a model-dependent unfolding matrix which is applied to the data to obtain the unfolded x_B distribution. The resulting seven unfolded x_B distributions show substantial model-variations. Figure 6 shows the binwise average of the seven unfolded distributions, where the inner error bar represents the statistical error and the outer error bar is the quadrature sum of the r.m.s. of the seven unfolded distributions and the statistical error within each bin. The outer error bars therefore provide an envelope within which the true x_B distribution is expected to vary. The mean of the scaled weakly decaying B hadron energy distribution is obtained by taking the average of the means of the seven functions. The r.m.s. of the seven means is regarded as

the error on model-dependence. The preliminary result is

$$< x_B >= 0.713 \pm 0.005(stat) \pm 0.007(syst) \pm 0.002(model) \quad (3)$$

where the small model-dependence error indicates that $< x_B >$ is relatively insensitive to the allowed forms of the shape of the fragmentation function.

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