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QCD OF DIFFERENT QUARK FLAVORS WITH THE SLD DETECTOR

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Abstract

We have exploited the unique capabilities of the SLD detector at the SLC to tag very pure samples of heavy and light quarks in Z^0 decays with high efficiency in order to study the QCD of different quark flavors. Here, we present two measurements. First, we find the difference between the average charged multiplicity of $Z^0 \to b\bar{b}$ and $Z^0 \to$ hadrons to be $\overline{n}_b - \overline{n}_{\mathrm{had}} = 2.24 \pm 0.30(\mathrm{stat}) \pm 0.33(\mathrm{syst})$ tracks per event. From this, we have derived $\overline{n}_b - \overline{n}_{uds} = 3.31 \pm 0.41 \pm 0.79$. Comparing this measurement with those at lower center-of-mass energies, we find no evidence that $\overline{n}_b - \overline{n}_{uds}$ depends on energy. This result is in agreement with a precise prediction of perturbative QCD, and supports the notion that QCD remains asymptotically free down to the scale M_b^2. Second, by comparing the jet rates in flavor-tagged samples of uds, c, and b quarks, we find $\alpha_s(uds)/\alpha_s(\mathrm{all}) = 0.99 \pm 0.03(\mathrm{stat}) \pm 0.05(\mathrm{syst})$, $\alpha_s(c)/\alpha_s(\mathrm{all}) = 1.05 \pm 0.11(\mathrm{stat}) \pm 0.21(\mathrm{syst})$, and $\alpha_s(b)/\alpha_s(\mathrm{all}) = 1.02 \pm 0.04(\mathrm{stat}) \pm 0.07(\mathrm{syst})$.

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Flavor Tagging with SLD

Recent work in Perturbative QCD has produced a number of predictions that depend on quark mass. In particular, heavy quark systems are a good laboratory for detailed studies of the strong interaction and tests of the theory of Quantum Chromodynamics (QCD) as the large quark mass $M_Q \gg \Lambda_{QCD}$, where Λ_{QCD} is the QCD interaction scale, provides a natural cutoff in the parton shower evolution. Also, as formulated, QCD interatctions are independent of quark flavor. In order to study these effects, it is useful to extract pure samples of events of different quark flavors in a way that is relatively independent of the QCD effects to be measured.

The SLC Large Detector (SLD) at the SLAC Linear Collider (SLC) offers a unique laboratory to carry out this investigation. Its precision CCD vertex detector and small, stable, micron-sized beam interaction point (IP) greatly simplifies the task of separating quark flavors using lifetime information. A pure sample of $Z^0 \rightarrow b\bar{b}$ events can be selected by requiring many tracks per event to miss the IP with some significance. Conversely, the requirement that all tracks in an event originate from the IP can be used to isolate a pure sample of $Z^0 \rightarrow u\bar{u}$, $Z^0 \rightarrow d\bar{d}$, and $Z^0 \rightarrow s\bar{s}$ events.

The SLD is a multipurpose particle detector and is described elsewhere [1]. Charged particles are tracked and momentum analyzed in the Central Drift Chamber (CDC), which consists of 80 layers of axial or stereo sense wires in a uniform axial magnetic field of 0.6 T. In addition, a CCD vertex detector (VXD) [2] provides an accurate measure of particle trajectories close to the beam axis. An impact parameter resolution of $10.8\,\mu$m in the plane transverse to the beam has been measured using high-energy muons in $Z^0 \rightarrow \mu^+\mu^-$ decays, and the spatial resolution on the average transverse IP position is found from neighboring hadronic events to be $6\,\mu$m. The detailed shapes of the distributions of track impact parameters d in hadronic events and the normalized impact parameters d/σ_d are modeled extremely well by the SLD detector simulation with *no* additional smearing. Figure 1 shows the MC and data distributions for the number of tracks per event, with $d/\sigma_d \geq 3$ [3]. With such a high level of detector performance and understanding, we can proceed confidently to

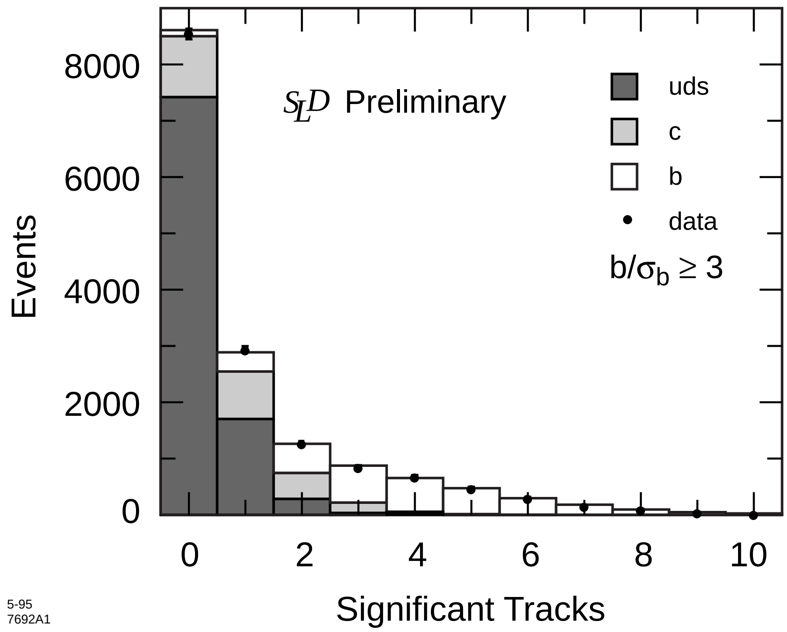

Figure 1. The flavor composition of the number of tracks per event with $d/\sigma_d \geq 3.0$. The points represent the data from the 1993 SLD run. Note that events with four or more such tracks are almost purely b events, and those with none are predominantly *uds* events.

a study of the properties of heavy and light quark decays, using the measurements provided by the tracking system as a tool to separate the different quark flavors.

Events were classified as hadronic decays of the Z^0 provided that they contained at least seven tracks which intersected a cylinder of radius $r_0 = 5$ cm and half-length $z_0 = 10$ cm surrounding the average IP, a visible charged energy of least 20 GeV, and a thrust axis satisfying $|\cos\theta_{\rm thrust}| < 0.7$. For the purpose of multiplicity counting, a loose set of requirements was placed on reconstructed tracks, while stricter requirements were placed on tracks used to measure impact parameters.

Multiplicity quality tracks were required to have:

(i) $p_\perp \geq 0.12$ GeV/c

(ii) $|\cos\theta| \leq 0.8$

(iii) to intersect a cylinder of $(r_0, z_0) = (1.5, 5.0)$ cm

Tagging quality tracks were required to have:

(i) $|\cos\theta| \leq 0.8$

(ii) at least one VXD hit

(iii) $\sigma_d < 250 \mu m$

(iv) $\chi^2/d.o.f.$ for the CDC-only and combined CDC/VXD fits of less than 5.0 and 10.0, respectively

(v) to intersect a cylinder of $(r_0, z_0) = (0.3, 1.5)$ cm.

In the α_s analysis described below, tracks from identified K^0's and Λ's have also been removed from the tracks used to tag the event.

Measurement of the Charged Multiplicity in $Z^0 \to b\bar{b}$ Events

Recently it has been recognized that, within the context of perturbative QCD, the high M_Q cutoff in the parton shower allows a stringent constraint to be placed on the difference in light hadron production between e^+e^- annihilation into heavy and light quarks [4]. In particular, it is expected that to $O\big([\alpha_s(W^2)]^{1/2}(M_Q^2/W^2)\big)$ ($\simeq 0.1$ track at $W = M_Z$), the difference between the total mean charged multiplicity in light quark ($q = u, d, s$) events and the mean charged multiplicity of radiated *nonleading* hadrons in heavy quark ($Q = b, c$) events—excluding the decay products of the *leading* long-lived heavy hadrons, should be *independent* of center-of-mass (cms) energy W. Furthermore, to $O\big(\alpha_s(M_Q^2)\overline{n}_{uds}(M_Q)\big)$ ($\simeq 1.2$ tracks for $Q = b$), this multiplicity difference should be equal to $\overline{n}_{uds}(\sqrt{e}M_Q)$, the mean charged multiplicity for e^+e^- annihilation to light quarks at the reduced cms energy $\sqrt{e}M_Q$, where $\ln e = 1$. A test of this hypothesis provides the opportunity to verify an accurate prediction of perturbative QCD, and to probe the validity of perturbative calculations down to the scale M_Q^2. Previous tests of these hypotheses [4,5] have been statistically-limited. Here, we present a more accurate measurement [6] based on the 1992 run of the SLD experiment.

A $Z^0 \to b\bar{b}$ enriched sample was selected by dividing each event into two hemispheres, separated by the plane perpendicular to the thrust axis, and requiring two or more impact parameter quality tracks in one hemisphere with normalized impact parameter $d/\sigma_d > 3$. Restricting the tag to tracks from a single hemisphere allowed any potential tagging bias to be reduced by measuring the multiplicity in the hemisphere opposite to the tag. Monte Carlo studies indicate that this tag is 50% efficient at identifying hemispheres containing B hadrons in selected hadronic events, while providing an enriched sample of 72% purity.

In determining the total charged $Z^0 \to b\bar{b}$ multiplicity $\overline{n}_b$, we minimized systematic errors by measuring $\delta\overline{n}_b \equiv \overline{n}_b - \overline{n}_{\rm had}$, and then adding back in the total hadronic charged multiplicity $\overline{n}_{\rm had}$, which has been accurately determined by other experiments [7].

The uncorrected mean charged multiplicity for all hadronic events was found to be $\overline{m}_h = 17.29 \pm 0.07$ tracks, while the mean charged multiplicity opposite tagged hemispheres was found to be $\overline{m}_t = 9.28 \pm 0.09$ tracks. Unfolding the underlying distributions of all hadrons and those containing b hadrons, using Monte Carlo results for the tag purities, yields $\delta\overline{n}_b = 1.94 \pm 0.30({\rm stat})$ tracks.

Combining these uncertainties in quadrature, and applying corrections for detector acceptance and modelling uncertainty, we find

$$\delta\overline{n}_b = 2.24 \pm 0.30({\rm stat}) \pm 0.33({\rm syst})\ {\rm tracks}\ . \tag{1}$$

Adding back in the world-average total hadronic multiplicity [7] at the Z^0 peak, $\overline{n}_{\rm had} = 20.95 \pm 0.20$, then yields

$$\overline{n}_b = 23.19 \pm 0.30({\rm stat}) \pm 0.37({\rm syst})\ {\rm tracks}\ . \tag{2}$$

The systematic error contains contributions from uncertainties in detector modeling and tracking efficiency, the largest of which is from discrepancies in the modeled charged-particle momentum spectrum.

To test the energy independence of the difference between the total multiplicity in light quark events and the nonleading multiplicity in $Z^0 \to b\bar{b}$ events, we make use of lower cms energy measurements of the $e^+e^- \rightarrow b\bar{b}$ multiplicity from the PEP and PETRA storage rings. Assuming the energy independence of the decay multiplicity of B hadrons produced in e^+e^- annihilation, it is equivalent to test the quantity $\Delta\overline{n}_b \equiv \overline{n}_b - \overline{n}_{uds}$. Results for this quantity for the various lower cms energy experiments are summarized in Ref. [4]. Applying the procedure presented in Ref. [4] to the SLD measurement to remove the contribution from $Z^0 \rightarrow c\bar{c}$, we arrive at the result

$$\Delta\overline{n}_b = 3.31 \pm 0.41(\mathrm{stat}) \pm 0.53(\mathrm{syst}) \pm 0.58(\overline{\mathrm{n}}_\mathrm{c}) \text{ tracks} , \tag{3}$$

where we have constrained $\overline{n}_c$ to lie between $\overline{n}_{uds}$ and $\overline{n}_b$, yielding $\overline{n}_c = 21.9 \pm 2.0$ tracks.

Figure 2 shows $\overline{n}_{\mathrm{had}}$ and $\Delta\overline{n}_b$ as functions of cms energy [8]. The $\Delta\overline{n}_b$ data, with the additional lever arm provided by the SLD measurement, are seen to be consistent with the hypothesis of energy independence, in marked contrast to the steeply rising total multiplicity data. Due to differing measurement techniques, results for $\Delta\overline{n}_b$ at PEP/PETRA energies are largely uncorrelated with those at the Z^0 peak. A linear fit to the $\Delta\overline{n}_b$ data yields a slope of -1.0 ± 1.1 tracks/ln(GeV), consistent with zero. Also shown is the perturbative QCD expectation for the value of $\Delta\overline{n}_b$. Averaging the SLD result with the previous measurements, we find that $\Delta\overline{n}_b^{\mathrm{comb}} = 3.83 \pm 0.63$, within 1.1 standard deviations of the perturbative QCD expectation of $5.5 \pm 0.8 \pm 1.2$(theory) [4]. A recent result from the OPAL collaboration [9] is consistent with this result.

A Test of the Flavor–Independence of α_s

One of the fundamental assumptions of QCD is that the strong-coupling α_s is independent of quark flavor. This assertion has been tested previously [10], but only to a precision of at best a few percent for b events, and not better than 30% for other flavors. Recently, with the advent of precision vertex detectors at e^+e^- colliders, it has become possible to test this fundamental assumption of QCD with previously unattainable accuracy.

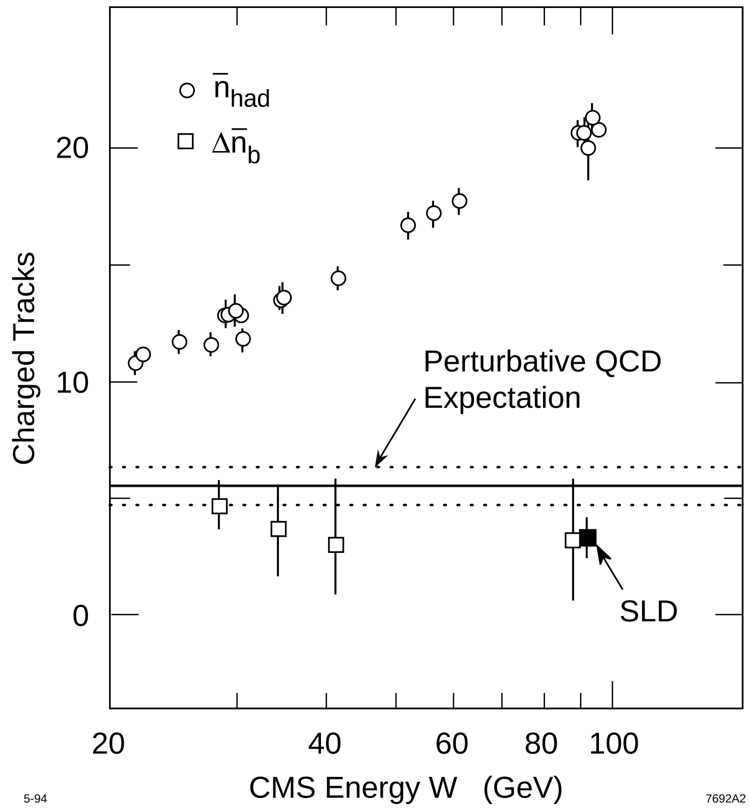

Figure 2. Energy dependence of the total multiplicity [8] and the multiplicity difference $\Delta\overline{n}_b$ [4,8] between $e^+e^- \to b\overline{b}$ and $e^+e^- \to uds$ events. The horizontal lines are the expected value and 1σ range for $\Delta\overline{n}_b$ given by lower-energy total multiplicity data in accordance with perturbative QCD (see text).

The principle of the analysis technique used here is as follows: given a sample of events tagged with the impact parameter method, we obtain the ratio of α_s in this tagged sample to that in all Z^0 decays by measuring the ratio of the 3-jet to 2-jet fractions for each sample. The ratio of the jet rates then, to first order, gives the ratio of the strong couplings in the two data samples:

$$\frac{\alpha_s(\mathrm{tag})}{\alpha_s(\mathrm{all})} = \frac{3-\mathrm{jet\ rate\ in\ tagged\ sample}}{\mathrm{total\ }3-\mathrm{jet\ rate}}\ . \tag{4}$$

This manner of determining the ratio of the couplings is relatively insensitive to most of the experimental and theoretical errors which plague an absolute determination of α_s. This method is applied to the 1993 SLD event sample, consisting of approximately 50 K Z^0 events before selection cuts. After hadronic event selection cuts, the entire event sample is divided inclusively into three parts: those events with *no* tracks with a normalized impact parameter $d/\sigma_d \geq 3.0$, defined as the *uds*-tagged sample$\big($efficiency (ε) = 77%, purity (Π) = 86%$\big)$; those events with between one and three tracks with $d/\sigma_d \geq 3.0$, defined as the c-tagged sample ($\varepsilon = 59\%$, $\Pi = 38\%$); and those events with four or more tracks with $d/\sigma_d \geq 3.0$, defined as the b-tagged sample ($\varepsilon = 46\%$, $\Pi = 94\%$). Each of these will be refered to as the i^{th} tag, where the correspondence is $i = 1 : uds$, $i = 2 : c$, $i = 3 : b$. Jets are found using the JADE algorithm [11], with $y_{\rm cut} = 0.05$. Defining the three-jet rate $R \equiv 1 - R_2$, where R_2 is the two-jet rate, the three-jet rate R_j for each of the j quark types (uds, c, and b) can be extracted from a maximum likelihood fit to the following relations:

$$\begin{aligned} n_i^{(2)} &= \sum_{j=1}^{3} \varepsilon_{ij}^{(2)} f_j N (1 - R_j) \ , \\ n_i^{(3)} &= \sum_{j=1}^{3} \varepsilon_{ij}^{(3)} f_j N R_j \ . \end{aligned} \tag{5}$$

Here, N is the total number of selected events, f_j is the Standard Model branching fraction of the Z^0 to the j^{th} quark type, $n_i^{(2)}$ and $n_i^{(3)}$ are the number of 2- and 3-jet events present in the i^{th} tagged sample, and the matrices $\varepsilon_{ij}^{(2)}$ and $\varepsilon_{ij}^{(3)}$ are the efficiencies for the i^{th} tag to select a 2- or 3-jet event of type j, respectively. These matrices must be calculated using Monte Carlo simulations.

After the fitting procedure, the PRELIMINARY results are as follows:

$$\begin{aligned} \frac{\alpha_s(uds)}{\alpha_s(\rm all)} &= 0.99 \pm 0.03({\rm stat}) \pm 0.05({\rm syst}) \ , \\ \frac{\alpha_s(c)}{\alpha_s(\rm all)} &= 1.05 \pm 0.11({\rm stat}) \pm 0.21({\rm syst}) \ , \\ \frac{\alpha_s(b)}{\alpha_s(\rm all)} &= 1.02 \pm 0.04({\rm stat}) \pm 0.07({\rm syst}) \ . \end{aligned} \tag{6}$$

A 5% correction [12] has been applied to $\alpha_s(b)$ to properly account for b quark mass effects. Since we use the entire event sample, the results of the fit for the three quark types are correlated. The correlation coefficients from the fit are: $uds - c : -0.79$, $uds - b : 0.26$, $c - b : -0.51$. The largest contributions to the systematic errors are from the uncertainty in tag efficiencies resulting from our limited knowledge of the heavy quark fragmentation functions and from uncertainties in the tracking efficiency.

In conclusion, we have presented two precise tests of perturbative QCD that exploit the unique capabilities of the SLD detector at SLC. We have measured the difference in the mean charged multiplicity between $Z^0 \to b\bar{b}$ and $Z^0 \to$ hadrons to be $\delta\overline{n}_b = 2.24 \pm 0.30(\text{stat}) \pm 0.33(\text{syst})$ tracks per event, from which we calculate the multiplicity difference between $Z^0 \to b\bar{b}$ and $Z^0 \to uds$ to be $\Delta\overline{n}_b = 3.31 \pm 0.41(\text{stat}) \pm 0.53(\text{syst}) \pm 0.58(\overline{\text{n}}_\text{c})$ tracks. Comparing our measurement with similar results from lower energy e^+e^- annihilation data, we find no evidence that $\Delta\overline{n}_b$ depends on cms energy. This energy independence is in agreement with the precise perturbative QCD expectation, and indicates that QCD remains asymptotically free down to the scale M_b^2. By comparing the rates of 3-jet events in flavor-tagged samples, we have also measured the ratios $\alpha_s(uds)/\alpha_s(\text{all}) = 0.99 \pm 0.03(\text{stat}) \pm 0.05(\text{syst})$, $\alpha_s(c)/\alpha_s(all) = 1.05 \pm 0.11(\text{sta.}) \pm 0.21(\text{syst})$, $\alpha_s(b)/\alpha_s(all) = 1.02 \pm 0.04(\text{stat}) \pm 0.07(\text{sys.})$, indicating that the strong coupling α_s is independent of quark flavor within present experimental sensitivity.

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