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A TEST OF THE FLAVOR INDEPENDENCE OF STRONG INTERACTIONS

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Abstract

We present a comparison of the strong couplings of light (u, d, and s), c, and b quarks determined from multijet rates in flavor-tagged samples of hadronic Z^0 decays recorded with the SLC Large Detector at the SLAC Linear Collider. Flavor separation on the basis of lifetime and decay multiplicity differences among hadrons containing light, c, and b quarks was made using the SLD precision tracking system. We find: ${\alpha_s}^{uds}/{\alpha_s}^{\rm all} = 0.987 \pm 0.027({\rm stat}) \pm 0.022({\rm syst}) \pm 0.022({\rm theory})$, ${\alpha_s}^{c}/{\alpha_s}^{\rm all} = 1.012 \pm 0.104 \pm 0.102 \pm 0.096$, and ${\alpha_s}^{b}/{\alpha_s}^{\rm all} = 1.026 \pm 0.041 \pm 0.041 \pm 0.030$.

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A fundamental assumption of the theory of strong interactions, Quantum Chromodynamics (QCD), is that the strong coupling α_s is independent of quark flavor. This can be tested by measuring the strong coupling in events of the type $e^+e^- \to q\bar{q}(g)$ for specific quark flavors q. Although an absolute determination of α_s for each quark flavor would have large theoretical uncertainties [1], it is possible to test the flavor-independence of QCD precisely by measuring ratios of couplings in which most experimental errors and theoretical uncertainties are expected to cancel. Since it has recently been suggested [2] that a flavor-dependent anomalous quark chromomagnetic moment could modify the probability for the radiation of gluons, comparison of the strong coupling for different quark flavors may also provide information on physics beyond the Standard Model.

Comparisons of α_s for b or c quarks with α_s for all flavors made at PETRA [3] were limited in precision to ± 0.41 (c) and ± 0.57 (b) due to small data samples and limited heavy quark tagging capability. LEP measurements of $\alpha_s^b/{\alpha_s}^{udsc}$ have reached precisions between ± 0.06 and ± 0.02 [4] under the assumption that α_s is independent of flavor for all the non-b quarks. The OPAL Collaboration has measured $\alpha_s^f/{\alpha_s}^{\rm all}$ for all five flavors f with no assumption on the relative value of α_s for different flavors [5] to precisions of ± 0.026 for b and ± 0.09 to ± 0.20 for the other flavors. The kinematic signatures used to tag c and light quarks suffer from low efficiency and strong biases, due to preferential tagging of events without hard gluon radiation.

The SLC Large Detector (SLD) [6] at the SLAC Linear Collider (SLC) is an ideal environment in which to test the flavor independence of strong interactions. The tracking capability of the Central Drift Chamber (CDC) [7] and the precision CCD Vertex Detector (VXD) [8], combined with the stable, micron-sized beam interaction point (IP), allows us to select $Z^0 \to b\overline{b}(g)$ and $Z^0 \to q_l\bar{q}_l(g)$ ($q_l = u,\, d,\, s$) events using their quark decay lifetime signatures with high efficiency and purity and low bias. Here we present the first precise measurements of $\alpha_s^b/{\alpha_s}^{\rm all}$, $\alpha_s^c/{\alpha_s}^{\rm all}$, and $\alpha_s^{uds}/{\alpha_s}^{\rm all}$ using this technique, and making no assumptions about the relative values of α_s^b, α_s^c and α_s^{uds}.

This analysis is based on the 1.8 pb^{-1} of e^+e^- annihilation data collected during the 1993 run of the SLD at the SLC at a mean center-of-mass energy of $\sqrt{s} = 91.26$ GeV. The trigger and selection criteria for hadronic Z^0 decays are described in Ref. [1]. The efficiency for selecting a well-contained $Z^0 \to q\bar{q}(g)$ event was estimated to be above 96% independent of quark flavor. The estimated $0.10 \pm 0.05\%$ background was dominated by $Z^0 \to \tau^+\tau^-$ events. This analysis used charged tracks measured in the CDC and in the VXD [1].

We used normalized impact parameters d/σ_d as the basis for quark flavor tags, where d is the signed distance of closest approach of a charged track to the IP in the (x–y) plane transverse to the beam axis, and σ_d is the error on d. A resolution on d of 10.8 μm has been measured using $Z^0 \to \mu^+\mu^-$ decays, and the spatial resolution on the average transverse IP position has been measured to be 7 μm [9]. The distributions of d and d/σ_d are modeled well by the SLD simulation [9]. Tracks used for event flavor tagging were required to have: at least one VXD hit; at least 40 CDC hits, with the first hit at a radius less than 39 cm; a combined CDC+VXD fit quality $\sqrt{2\chi^2} - \sqrt{2n_{\mathrm{d.o.f.}} - 1} < 8.0$; momentum greater than 0.5 GeV/c; $\sigma_d < 250$ μm; and to miss the IP by less than 0.3 cm in the x–y plane and by less than 1.5 cm in z. Tracks from candidate K^0 and Λ decays and γ-conversions were removed.

Figure 1 shows the distribution of n_{sig}, the number of tagging tracks per event with $d/\sigma_d \geq 3$. The data are well described by a Monte Carlo simulation of hadronic Z^0 decays [10] with parameter values tuned [11] to hadronic e^+e^- annihilation data, combined with a simulation of the SLD. For the simulation, the contributions of events of different quark flavors are shown separately. The leftmost bin contains predominantly events containing primary u, d, or s quarks, while the rightmost bins contain a pure sample of events containing primary b quarks. The event sample was divided accordingly into three parts: those events with $n_{\mathrm{sig}} = 0$ were defined to be the uds-tagged sample; those with $1 \leq n_{\mathrm{sig}} \leq 3$ were the c-tagged sample; and those with $n_{\mathrm{sig}} \geq 4$ were the b-tagged sample. The efficiencies ε for selecting events (after cuts) of type i ($i = uds$, c, b) with tag i, and the fractions Π of events of type i in the i-tagged sample, were calculated from the Monte Carlo simulation to be: $(\varepsilon, \Pi)_{uds} = (77\%, 86\%)$; $(\varepsilon, \Pi)_c = (59\%, 38\%)$; and $(\varepsilon, \Pi)_b = (46\%, 94\%)$.

Jets were then reconstructed using iterative clustering algorithms. We used the 'E', 'E0', 'P', and 'P0' variations of the JADE algorithm, as well as the 'Durham' ('D') and 'Geneva' ('G') algorithms [12]. We divided events into two categories: those containing: (1) two jets, and (2) three or more jets. The fraction of the event sample in category 2 was defined as the 3-jet rate R_3. This quantity is infrared- and colinear-safe and has been calculated to $\mathcal{O}({\alpha_s}^2)$ in perturbative QCD [12,13]. For each algorithm, the jet resolution parameter y_c was chosen to be as small as possible subject to the requirement that $\mathcal{O}({\alpha_s}^2)$ QCD provides a good description of R_3 measured in our global sample of all flavors [1,14]. This choice maximizes R_3 while avoiding the 'Sudakov region' at low y_c where multiple gluon emission requires that large logarithmic terms of $1/y_c$ be resummed in order to describe the data [1]. The resulting y_c values are listed in Table 1.

The R_3^j for each of the j quark types ($j = uds$, c, b) was extracted from a maximum likelihood fit to n_2^i and n_3^i, the number of 2-jet and 3-jet events, respectively, in the i-tagged sample:

$$\begin{aligned} n_2^i &= \sum_{j=1}^{3} \left(\varepsilon_{(2\to 2)}^{ij}(1-R_3^j) + \varepsilon_{(3\to 2)}^{ij} R_3^j \right) f^j N \\ n_3^i &= \sum_{j=1}^{3} \left(\varepsilon_{(3\to 3)}^{ij} R_3^j + \varepsilon_{(2\to 3)}^{ij}(1-R_3^j) \right) f^j N \ . \end{aligned} \tag{1}$$

Here N is the total number of selected events corrected for the event selection efficiency, and f^j is the Standard Model fractional hadronic width for Z^0 decays to quark type j. The matrices $\varepsilon_{(2\to 2)}^{ij}$ and $\varepsilon_{(3\to 3)}^{ij}$ are the efficiencies for an event of type j, with 2- or 3-jets at the parton level, to pass all cuts and be tagged as a 2- or 3-jet event, respectively, of type i. Matrices $\varepsilon_{(2\to 3)}^{ij}$ and $\varepsilon_{(3\to 2)}^{ij}$ are the efficiencies for an event of type j, with 2- or 3-jets at the parton level, to pass all cuts and be tagged as a 3- or 2-jet event, respectively, of type i. This formalism explicitly accounts for modifications of the parton-level 3-jet rate due to hadronization, detector effects, and tagging bias. These matrices were calculated from the Monte Carlo simulation. The efficiencies for correctly tagging a 2-jet event and a 3-jet event differ by an average of 5.7%, 8.3%, and 30.3% for the uds, c, and b tags, respectively.

Equations 1 were solved using 3-jet events defined by each of the six algorithms. The ratios $R_3^j/R_3^{\rm all}$, where $R_3^{\rm all}$ is the 3-jet rate in the total event sample, are shown in Table 1. Averaged over all six algorithms the correlation coefficients from the fit are: uds-c : -0.76, uds-b : 0.30, c-b : -0.55. The statistical errors were calculated using the full covariance matrix.

The 3-jet rate in heavy quark (b, c) events is expected to be reduced relative to that in light quark events by the diminished phase-space for gluon emission due to the quark masses. We evaluated the suppression factors, R_3^c/R_3^u and R_3^b/R_3^d, for each jet algorithm and y_c value according to Ref. [15], assuming b (c) quark masses of 4.75 GeV/c^2 (1.50 GeV/c^2). These factors are listed in Table 1, and were used to correct the measured 3-jet rate ratios.

To $\mathcal{O}({\alpha_s}^2)$ in perturbative QCD, $R_3(y_c) = A(y_c)\alpha_s + (B(y_c) + C(y_c)){\alpha_s}^2$, where the $\mathcal{O}({\alpha_s}^2)$ coefficient includes a term $B(y_c)$ from 3-parton states calculated at next-to-leading order, and a term $C(y_c)$ from 4-parton states calculated at leading order. Hence, the ratio of the strong coupling of quark type j to the mean coupling in the sample of all flavors, ${\alpha_s}^j/{\alpha_s}^{\rm all}$, can be determined from:

$$\frac{R_3^j(y_c)}{R_3^{\rm all}(y_c)} \;=\; \frac{A(y_c)\,{\alpha_s}^j \;+\; [B(y_c)+C(y_c)]\;({\alpha_s}^j)^2}{A(y_c)\,{\alpha_s}^{\rm all} \;+\; [B(y_c)+C(y_c)]\;({\alpha_s}^{\rm all})^2}\;, \tag{2}$$

where $A(y_c)$, $B(y_c)$, and $C(y_c)$ for the different jet-finding algorithms were evaluated using Refs. [12,13]. Using our measured values of ${\alpha_s}^{\rm all}(M_Z^2)$ determined from jet rates [14], we found that for the E, E0, P, P0, and D algorithms, the leading-order QCD calculation $C(y_c){\alpha_s}^2$ lies below the experimental 4-jet rate by roughly a factor of two. We increased $C(y_c)$ *ad hoc* for these algorithms, so as to describe the data. Equation 2 was solved to obtain ${\alpha_s}^j/{\alpha_s}^{\rm all}$ for each jet algorithm; the results are shown in Fig. 2. The errors include contributions from the statistical error, as well as the experimental systematic errors and theoretical uncertainties.

We considered systematic effects that could modify the tagging efficiencies. In each case the error was evaluated by varying the appropriate parameter in the Monte Carlo simulation, recalculating the matrices ε, performing a new fit to Eq. 1, and rederiving ${\alpha_s}^j/{\alpha_s}^{\rm all}$. Suitable

variation about the world average value of each parameter was considered [9]. The errors are summarized in Table 2, where averages over the six algorithms are shown. The largest contributions result from limited knowledge of the heavy quark fragmentation functions and B decay multiplicity. The uncertainty in $BR(Z^0 \to c\bar{c})$ also produces large variations in ${\alpha_s}^c/{\alpha_s}^{\rm all}$ and ${\alpha_s}^{uds}/{\alpha_s}^{\rm all}$. Contributions from b hadron lifetimes, the fraction of D^+ in B meson decays, b baryon production rates, and the charm hadron decay multiplicity are small. The detector systematic error is dominated by the uncertainty in the charged track reconstruction efficiency. No systematic variation of the results was found when the event selection cuts, tag criteria, or y_c values were changed.

We considered sources of uncertainty in the QCD predictions that affect the values of ${\alpha_s}^j/{\alpha_s}^{\rm all}$ derived from Eq. 2. For each jet algorithm these include variation of the QCD renormalization scale within the range allowed by our measurements of jet rates in the global sample [14] and variation of the heavy quark masses used in the phase-space correction factors by ± 0.25 GeV/c^2. In addition, the shifts in ${\alpha_s}^j/{\alpha_s}^{\rm all}$ due to the *ad hoc* increase of the coefficient $C(y_c)$ were conservatively assigned as an uncertainty. The variation of the results due to uncertainties in parton production and hadronization were found to be small. These contributions were added in quadrature to yield the total QCD uncertainties listed in Table 2.

There is significant scatter among the ${\alpha_s}^j/{\alpha_s}^{\rm all}$ values derived from the different jet algorithms. In order to quote a single ${\alpha_s}^j/{\alpha_s}^{\rm all}$ value for each flavor j, we made the conservative assumption that the results are completely correlated, and we calculated the unweighted mean values and errors over all six algorithms. We obtained

$$\begin{aligned}
\frac{{\alpha_s}^{uds}}{{\alpha_s}^{\rm all}} &= 0.987 \pm 0.027\,({\rm stat}) \pm 0.022\,({\rm syst}) \pm 0.022\,({\rm theory})\ , \\
\frac{{\alpha_s}^{c}}{{\alpha_s}^{\rm all}} &= 1.012 \pm 0.104\,({\rm stat}) \pm 0.102\,({\rm syst}) \pm 0.096\,({\rm theory})\ , \\
\frac{{\alpha_s}^{b}}{{\alpha_s}^{\rm all}} &= 1.026 \pm 0.041\,({\rm stat}) \pm 0.041\,({\rm syst}) \pm 0.030\,({\rm theory})\ , \qquad (3)
\end{aligned}$$

where the theoretical uncertainty is the sum in quadrature of the QCD uncertainty from Table 2 and the rms of the results over the six algorithms. These averages are also shown in Fig. 2. The variation of results among jet algorithms, presumably due to different uncalculated $\mathcal{O}({\alpha_s}^3)$ QCD contributions, dominates the theoretical uncertainty, is not small compared with experimental errors, and has not been considered in previous analyses [4,5].

In conclusion, we have used hadron lifetime information to separate hadronic Z^0 decays into three flavor samples with high efficiency and purity, and small bias against events containing hard gluon radiation. From a comparison of the rates of multijet events in these samples, we find that the strong coupling is independent of quark flavor within our sensitivity. These are the first such results using a precision vertex detector for flavor separation at the Z^0. This represents the most precise test for *uds* events. Our findings are consistent with measurements performed at LEP using different flavor-tagging techniques [4,5].

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Table 1. Results for $R_3^j/R_3^{\rm all}$, derived from Eq. 1; see text. Errors shown are statistical.

Algorithm	y_c	R_3^{uds}/R_3^{all}	R_3^c/R_3^{all}	R_3^b/R_3^{all}	R_3^c/R_3^u factor	R_3^b/R_3^d factor
E	0.080	0.941±0.042	1.212±0.173	0.980±0.063	0.995	0.958
E0	0.050	0.975±0.036	1.113±0.145	0.981±0.053	0.994	0.945
P	0.030	1.001±0.027	0.985±0.109	1.007±0.041	0.992	0.929
P0	0.030	1.014±0.026	0.899±0.102	1.037±0.039	0.992	0.929
D	0.015	0.989±0.035	1.096±0.145	0.947±0.049	0.991	0.921
G	0.030	1.032±0.020	0.942±0.079	0.952±0.030	0.989	0.915

Table 2. Contributions to the systematic error on $\frac{{\alpha_s}^j}{{\alpha_s}^{\rm all}}$.

Source	$\Delta\left(\frac{{\alpha_s}^{uds}}{{\alpha_s}^{\rm all}}\right)$	$\Delta\left(\frac{{\alpha_s}^{c}}{{\alpha_s}^{\rm all}}\right)$	$\Delta\left(\frac{{\alpha_s}^{b}}{{\alpha_s}^{\rm all}}\right)$
b physics	0.008	0.060	0.033
c physics	0.017	0.060	0.011
Detector modeling	0.003	0.032	0.017
Monte Carlo statistics	0.011	0.048	0.014
QCD uncertainty	0.003	0.011	0.012

FIGURE CAPTIONS

1. The measured distribution of the number of tracks per event with $d/\sigma_d \geq 3.0$ (points). The histograms show the flavor composition estimated from a Monte Carlo simulation (see text).

2. Values of ${\alpha_s}^j/{\alpha_s}^{\rm all}$ derived for each of the six jet algorithms for each of the quark flavors j (see text). The error bars on the averages include the statistical and systematic errors and the total theoretical uncertainty.

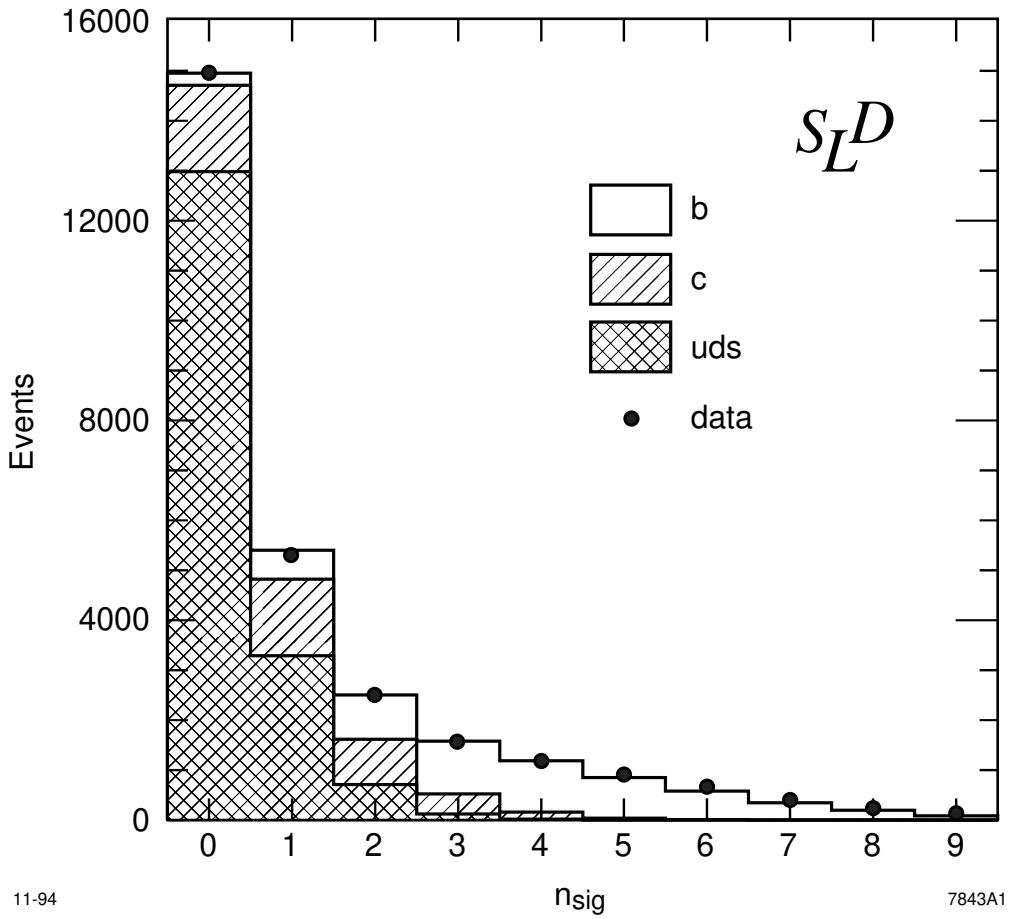
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Figure 1

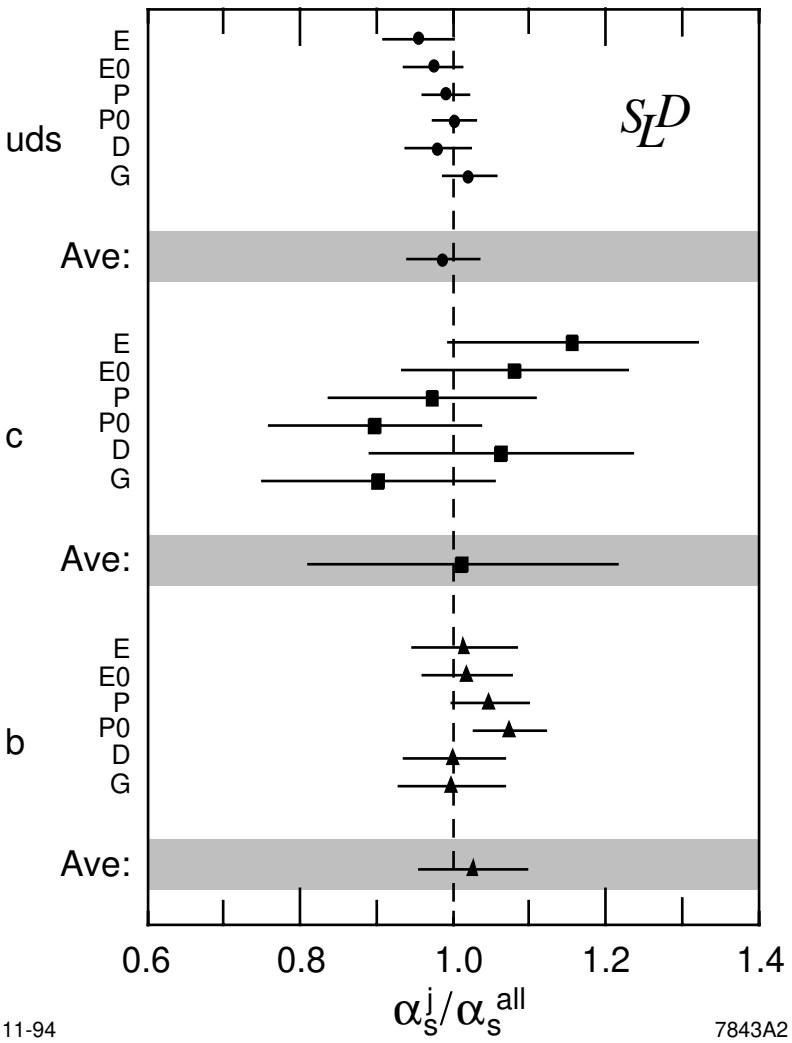
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Figure 2