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A TEST OF THE FLAVOR INDEPENDENCE OF STRONG INTERACTIONS*

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We present a comparison of the strong couplings of *b*, *c*, and light (*u*, *d*, and *s*) quarks derived from multi-jet rates in flavor-tagged samples of hadronic Z^0 decays recorded with the SLC Large Detector at the SLAC Linear Collider. By comparing the rates of 3-jet events in these three samples we have extracted the Preliminary values of: $\alpha_s(uds)/\alpha_s(all)$ = 0.96±0.03(stat.)±0.04(syst.)±0.02(theory), $\alpha_s(c)/\alpha_s(all)$ = 1.16±0.11(stat.)± 0.10(syst.)±0.07(theory), $\alpha_s(b)/\alpha_s(all)$ = 0.98±0.04(stat.)±0.08(syst.)±0.02(theory).

1. INTRODUCTION

One of the fundamental assumptions of the theory of strong interactions, Quantum Chromodynamics (QCD), is that the strong coupling α_s is independent of quark flavor. This assertion can be tested precisely by selecting selecting events of the type $e^+e^- \to q\bar{q}(g)$ for specific quark flavors *q*, and measuring the strong coupling in these selected samples. Although an absolute determination of α_s for each quark flavor would have large errors, it is possible to test the flavor-independence of QCD precisely by measuring ratios of couplings in which most experimental and theoretical errors are expected to cancel. Previous measurements [[1]] using this technique have verified the flavor-independence of strong interactions to a precision of a few percent for *b* quarks, and to 15% for other flavors. It has recently been suggested [[2]] that an anomalous quark chromo-magnetic moment could modify the probability for the radiation of gluons, effectively changing the measured value of α_s for those quarks with anomalous couplings by as much as 10%. Thus, in addition to providing a test of the fundamental assumptions of QCD, the determination of the strong coupling for different quark flavors may also provide information on physics beyond the Standard Model.

Experimentally, various kinematic signatures can be used to obtain a pure sample of events containing quarks of a given flavor, such as requiring high-p_T leptons to select *b*-quark events, or fast protons and kaons to tag *uds*-quark events. Previous analyses[1] have used a variety of these techniques and typically suffer from large errors due to inefficient flavor tagging and large corrections for biases due to preferential selection of events without hard gluon radiation. However, with the advent of precision vertex detectors at e^+e^- colliders it has become possible to use the quark lifetime information contained in charged tracks to select pure samples of particular quark flavors with high efficiency in a relatively unbiased manner. Comparison of the rates of multi-jet production in these samples allows one to derive measurements of the ratio of the strong coupling α_s for the selected quark flavor relative to that for the global sample of all flavors.

2. ANALYSIS

The SLC Large Detector (SLD) [[3]] at the SLAC Linear Collider (SLC) is an ideal venue to test the flavor independence of strong interactions

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and to search for anomalous quark chromo-magnetic couplings. The excellent tracking provided by a central drift chamber (CDC) [4] and a precision CCD vertex detector (VXD) [5], combined with the stable, micron-sized beam interaction point (IP) allow us to select $Z^0 \to b\bar{b}$ and $Z^0 \to u\bar{u}$, $d\bar{d}$, and $s\bar{s}$ events with high efficiency and purity using their decay lifetime signatures. An impact parameter resolution of 10.8 μm in the plane transverse to the beam has been measured using high-energy muons in $Z^0 \to \mu^+\mu^-$ decays, and the spatial resolution on the average transverse IP position found from neighboring hadronic events is measured to be 6 μm [6]. The shapes of the distributions of track impact parameters *(d)* in hadronic events and the normalized impact parameters, d/σ_d, are modelled well by the SLD detector simulation [6] without any *ad hoc* smearing of track parameters.

In this paper, we present an analysis based on the 1993 run of the SLD at the SLC, during which approximately 2 pb^{-1} of electron-positron annihilation data were collected at a mean center-of-mass energy of $\sqrt{s}$=91.26 GeV. The triggers and selection for hadronic events are described in Ref.[7]. The analysis presented here used charged tracks measured in the CDC and in the VXD. Well-measured tracks were required to have: i) a momentum transverse to the beam axis $p_\perp \geq$ 0.10 GeV/c; ii) a polar angle of |cos θ| ≤ 0.8; and iii) were required to intersect a cylinder of radius r_0 = 5 cm and half-length z_0 = 10 cm surrounding the IP. Events well-contained within the detector were selected by requiring: i) a minimum of 7 such tracks; ii) a thrust axis [8] direction satisfying $|\cos \theta_{thrust}| < 0.71$; and iii) a visible charged-track energy of at least 20 GeV, assuming all charged tracks are pions. From our 1993 data sample, 28036 events remain after these cuts. The efficiency for a well-contained hadronic event to pass these cuts was estimated to be above 96%, with a background of 0.10 ± 0.05%, dominated by $Z^0 \to \tau^+\tau^-$ events.

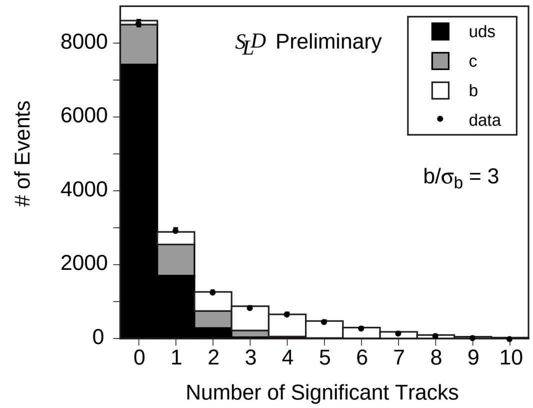

Figure 1. The flavor composition of the number of tracks per event with $d/\sigma_d \geq 3$. The points represent the data.

Tracks used for event flavor tagging were required in addition to have: i) at least one VXD hit; ii) an error σ_d on the measured impact parameter d in the plane perpendicular to the beam axis of σ_d < 250 µm; iii) $p_{tot} \geq$ 0.5 GeV/c; iv) at least 40 CDC hits, with the first CDC hit on the track at a radius less than 39 cm; v) $\sqrt{2\chi^2} - \sqrt{2n_{d.o.f.}-1} < 8.0$ for the combined CDC/VXD fit; and vi) to intersect a cylinder of (r_0, z_0) = (0.3,1.5) cm centered on the IP. Tracks from identified K^0's and Λ's were removed from this sample of tagging tracks.

The analysis presented below used the charged-track impact parameter measured in the plane transverse to the beam axis as a basis for the quark flavor tags. Figure 1 shows the distributions of n_{sig}, the number of tracks per event with $d/\sigma_d \geq 3$. Note the excellent agreement between the data and the simulation. The leftmost bin contains predominantly events produced by primary light (*uds*) quarks, while the rightmost bins contain an extrememly pure sample of events produced by primary b quarks. Accordingly, the event sample was divided into three parts, each refered to as the i^{th} tag: those events with n_{sig}=0 were defined as the *uds*-tagged sample (*i=1*); those with $1 \le n_{sig} \le 3$ were defined as the *c*-tagged sample (*i=2*); and those with $n_{sig} \ge 4$ were defined as the defined as the *b*-tagged sample (*i=3*). The efficiencies ε for selecting an event of the desired type after event cuts and the purities Π of the tagged samples relative to all events passing cuts are as follows: (ε,Π) = 77%,86% (*i=1*); (ε,Π) = 59%,38% (*i=2*); and (ε,Π) = 46%,94% (*i=3*).

Jets were then reconstructed using iterative clustering algorithms in which a measure y_{kl}, such as invariant mass-squared/*s*, is calculated for all pairs of particles *k* and *l*, and the pair with the smallest y_{kl} is combined into a single `pseudo-particle'. The process is repeated until all pairs have y_{kl} exceeding a value y_c, and the jet multiplicity of the event is defined as the number of particles remaining. Various recombination schemes and definitions of y_{kl} have been suggested [[9]]. We have used the JADE algorithm [[10]] and its `E',`E0',`P', and `P0' variations, as well as the `Durham' algorithm [[11]]. For each algorithm, y_c was chosen to maximize the rate of 3-jet event production R_3, subject to the constraint that the measured rate of 4-jet events R_4 was smaller than 1%. Systematic effects arising from the use of different jet algorithms will be discussed below.

The three-jet rate R_3^j for each of the quark types (*j=1:uds*, *j=2:c*, and *j=3:b*) can be extracted from a maximum likelihood fit to the following relations:

$$n^i_{(2)} = \sum_{j=1}^{3} (\varepsilon^{ij}_{(2\to2)}(1-R^j_3) + \varepsilon^{ij}_{(3\to2)}R^j_3)\, f^j N$$
$$n^i_{(3)} = \sum_{j=1}^{3} (\varepsilon^{ij}_{(3\to3)}R^j_3 + \varepsilon^{ij}_{(2\to3)}(1-R^j_3))\, f^j N \qquad (1)$$

where N is the total number of selected events corrected for the efficiency for a hadronic Z^0 decay to pass all event selection cuts, f^j is the Standard Model branching fraction for Z^0 decays to the j^{th} quark type, and $n^i_{(2)}$ and $n^i_{(3)}$ are the number of 2- and 3-jet events present in the i^{th} tagged sample. The matrices $\varepsilon^{ij}_{(2\to2)}$ and $\varepsilon^{ij}_{(3\to3)}$ are the efficiencies for a 2- or 3-jet event at the parton level to pass all cuts and be selected by the i^{th} tag as a 2- or 3-jet event of type *j*, respectively. The matrices $\varepsilon^{ij}_{(2\to3)}$ and $\varepsilon^{ij}_{(3\to2)}$ contain the efficiencies for a 2- or 3-jet event at the parton level to pass all cuts and be selected by the i^{th} tag as a 3- or 2-jet event of type *j*, respectively. Thus, this formalism explicitly accounts for all possible modifications of the parton-level 3-jet rate due to hadronization, detector effects, and tagging.

3. RESULTS

The efficiency matrices are calculated using Monte Carlo simulations of hadronic Z^0 decays [[12]] combined with the simulation of the SLD detector [6]. To demonstrate the unbiased nature of tagging algorithms using impact parameter information, we define the tag bias B^i as the ratio of the diagonal elements of the efficiency matrices: $B^i = \varepsilon^{ii}_{(2\to2)} / \varepsilon^{ii}_{(3\to3)}$. After correcting for the overall efficiency for passing event selection cuts, the values of the tag bias for the three tags are:

B^{uds} = 1.060, B^c = 1.032, B^b = 1.224. (2)

Solution of equation (1) for the JADE algorithm, for example, yielded:

$$\frac{R_3^{uds}}{R_3^{all}} = 0.98 \pm 0.04(stat.) \pm 0.05(syst.)$$

$$\frac{R_3^{c}}{R_3^{all}} = 1.13 \pm 0.15(stat.) \pm 0.15(syst.)$$

$$\frac{R_3^{b}}{R_3^{all}} = 0.90 \pm 0.05(stat.) \pm 0.09(syst.) \qquad (3)$$

Table 1 lists the various contributions to the systematic errors quoted above for each quark type. These errors are evaluated by varying the parameters in the Monte Carlo simulation, recalculating the matrices ε, and performing a new fit based on the same data sample. An event weighting scheme [6] was used to produce the proper distributions. The largest error contributions are from the uncertainty in tag efficiencies resulting from our limited knowledge of the heavy quark fragmentation functions. 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.

To $O(\alpha_s^2)$ in perturbative QCD, the three-jet rates R_3 have the general form: $R_3 = A(y_c)\alpha_s + B(y_c)\alpha_s^2$. Hence, the ratio of the strong coupling in a sample of quark type *j* to that of all hadronic Z^0 boson decays can be extracted from the ratio of the three-jet rates by inverting the following equation:

$$\frac{R_3^{j}}{R_3^{all}} = \frac{A\alpha_s(j) + B\alpha_s^2(j)}{A\alpha_s(all) + B\alpha_s^2(all)} \qquad (4)$$

where the values for the coefficients *A* and *B* for different jet-finding algorithms are tabulated in Ref [13] and Ref 11.

In order to obtain the proper value for α_s in heavy quark events, a correction to the three jet rate must be made to account for the reduced phase-space for gluon emission due to the heavy quark mass [[14]], [[15]]. This correction depends on y_c and is different for different jet-finding algorithms; for the JADE algorithm at y_c =0.05 a correction of 0.94 should be applied.

After applying the phase space correction, equation 4 was inverted for all jet algorithms and the results averaged to obtain the ratio of the strong couplings, giving (Preliminary) values of:

$\frac{\alpha_s(uds)}{\alpha_s(all)}$ =0.96±0.03(stat.)±0.04(syst.)±0.02(theory
)

Error:	Central Value	Variation	$\Delta\left(\frac{\alpha_s(uds)}{\alpha_s(\mathrm{all})}\right)$(%)	$\Delta\left(\frac{\alpha_s(c)}{\alpha_s(\mathrm{all})}\right)$(%)	$\Delta\left(\frac{\alpha_s(b)}{\alpha_s(\mathrm{all})}\right)$(%)
B meson lifetime	$\tau_B = 1.55$ ps	±0.1 ps	0.8	2.1	0.2
B baryon lifetime	$\tau_B = 1.10$ ps	±0.3 ps	1.0	2.7	0.3
B fragmentation	$\langle x_b \rangle = 0.700$	±0.021	2.9	1.1	7.1
B decay multiplicity	$\langle n_{ch} \rangle = 5.39$	±0.20 tracks	0.9	3.2	1.6
B decay model	LUND	Phase space	0.5	3.1	1.5
$B \to D^+ + X$ fraction	0.17	±0.07	1.3	4.0	0.5
R_b (bottom fraction)	0.220	±0.004	0.2	0.2	0.3
R_c (charm fraction)	0.170	±0.017	1.2	3.7	0.5
$c\bar{c} \to D^+ + X$ fraction	0.20	±0.04	1.0	3.4	0.4
Heavy Quark Modelling	–	–	3.8	8.6	7.5
M.C. statistics	–	–	1.5	5.6	1.5
tracking efficiency	$\langle n_{ch} \rangle = 11.5$	±0.05 tracks	0.1	0.5	0.3
Jet Algorithm	–	–	1.7	4.1	1.5
		TOTAL:	4.4	11.1	7.8

Table 1. Contributions to the systematic error on the values for α_s of different quark types.

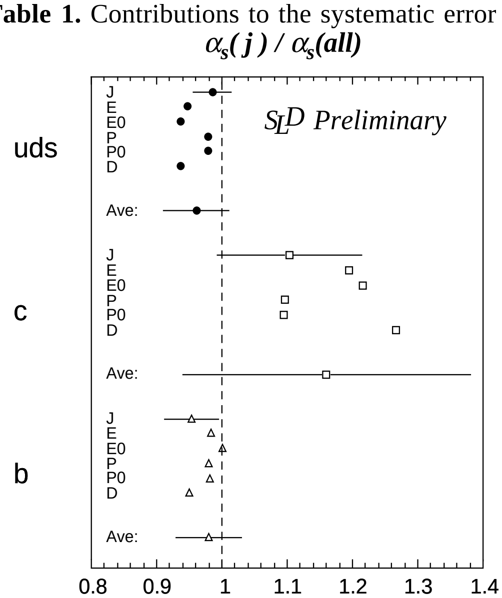

Figure 2. The results from correcting the R_3 values to obtain $\alpha_s(j)/\alpha_s(all)$, derived for each of the jet algorithms used in the analysis for each of the quark flavors. Typical statistical + systematic errors are shown on the points representing the JADE algorithm. The error bars on the average values include the r.m.s. variation of the values from the different algorithms and the statistical and systematic errors.

$$\frac{\alpha_s(c)}{\alpha_s(all)} = 1.16 \pm 0.11(\text{stat.}) \pm 0.10(\text{syst.}) \pm 0.07(\text{theory})$$

$$\frac{\alpha_s(b)}{\alpha_s(all)} = 0.98 \pm 0.04(\text{stat.}) \pm 0.08(\text{syst.}) \pm 0.02(\text{theory})$$

These results are summarized in Figure 2. The theory error includes an overall theoretical error on $\alpha_s(all)$ of 0.01 [9], and the r.m.s. of the spread in values when the analysis is repeated with each of the 6 jet algorithms, which dominates the error.

In conclusion, from a comparison of the rates of 3-jet events in flavor-tagged samples, we have measured the ratios $\alpha_s(uds)/\alpha_s(all)$, $\alpha_s(c)/\alpha_s(all)$, and $\alpha_s(b)/\alpha_s(all)$. Our measured values indicate that the strong coupling is independent of quark flavor within present experimental sensitivity.

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