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A PRELIMINARY IMPROVED TEST OF THE FLAVOR INDEPENDENCE OF STRONG INTERACTIONS*

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ABSTRACT

We present an improved comparison of the strong couplings of gluons to 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 between 1993 and 1995. 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, yielding tags with high purity and low bias against $\geq$ 3-jet final states. We find: $\alpha_s^{uds}/\alpha_s^{all} = 0.997 \pm 0.011(stat) \pm 0.011(syst) \pm 0.005(theory)$, $\alpha_s^{c}/\alpha_s^{all} = 0.984 \pm 0.042 \pm 0.053 \pm 0.022$, $\alpha_s^{b}/\alpha_s^{all} = 1.022 \pm 0.019 \pm 0.023 \pm 0.012$.

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1. Introduction

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 $e^+e^- \rightarrow q\bar{q}(g)$ 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. Measurements made at LEP of $\alpha_s^b/\alpha_s^{udsc}$ have reached precisions between ± 0.06 and ± 0.013 [4]. However, these tests make the simplifying assumption that α_s is independent of flavor for all the non-b quarks, and are insensitive to differences between α_s for these flavors, especially a different α_s for c quarks compared with either b or light quarks. The OPAL Collaboration has measured $\alpha_s^f/\alpha_s^{all}$ 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. In that analysis 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 precise CCD Vertex Detector (VXD) [8], combined with the stable, micron-sized beam interaction point (IP), allows us to select $Z^0 \to b\bar{b}(g)$ 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 with low bias against 3-jet events, an important advantage of this analysis. Our previous measurement [9], based on the sample of roughly 50,000 Z^0 decay events collected in 1993, reached precisions of ± 0.04 ($\alpha_s^{uds}/\alpha_s^{all}$), ± 0.17 ($\alpha_s^c/\alpha_s^{all}$), and ± 0.06 ($\alpha_s^b/\alpha_s^{all}$), and tested the flavor independence of the strong coupling making no assumptions about the relative values of α_s^b, α_s^c and α_s^{uds}. Here we present improved measurements of these quantities using the same technique, and based on the total sample of 150,000 Z^0 decay events collected by SLD between 1993 and 1995.

2. Event Selection and Flavor Tagging

This analysis is based on 5.4 pb^{-1} of e^+e^- annihilation data collected 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 selected sample comprised 78319 events, with an estimated $0.10 \pm 0.05\%$ background contribution 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. 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 CDC fit quality ${\chi^2}_{CDC}/d.o.f < 5$; a combined CDC+VXD fit quality ${\chi^2}_{CDC+VXD}/d.o.f < 5$; 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 [10]. For these selected tracks, $\sigma_d = 11 \oplus 70/(p_t(\mathrm{GeV}/c^2)\sqrt{\sin\theta})\mu$m has been measured using $Z^0 \to \mu^+\mu^-$ decays and hadronic events, where p_t is the track momentum transverse to the beam axis, and θ is the polar angle with respect to the beam axis. The spatial resolution on the average transverse IP position has been measured to be 7 μm [10]. The distributions of d and d/σ_d are modeled well by the SLD simulation [10].

Figure 1 shows the distribution of $N_{\rm sig}$, 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 [11] with parameter values tuned [12] 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 five subsamples: (1) $N_{sig} = 0$, (2) $N_{sig} = 1$, (3) $N_{sig} = 2$, (4) $N_{sig} = 3$, and (5) $N_{sig} \geq 4$. We refer to subsample 1 as the uds-tagged sample, the union of subsamples 2, 3 and 4 as the c-tagged sample, and subsample 5 as the b-tagged sample. The hard b tag yields a sample with very low contamination from charm events, maximizing the sensitivity of the three-flavor test. The light-quark tag does not change the relative flavor composition of the uds 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: $(\varepsilon, \Pi)_{uds} = (84.2 \pm 0.1\%,\ 86.2 \pm 0.1\%)$; $(\varepsilon,\ \Pi)_c = (57.0 \pm 0.2\%,\ 32.3 \pm 0.1\%)$; $(\varepsilon,\ \Pi)_b = (43.4 \pm 0.2\%, 95.2 \pm 0.1\%)$; the errors are discussed below.

3. Jet Finding

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 [13]. 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 collinear-safe and has been calculated to $\mathcal{O}(\alpha_s^2)$ in perturbative QCD [13, 14]. For each algorithm, the jet resolution parameter y_c was chosen so as to minimize the combined statistical and systematic errors on the α_s flavor ratios, as discussed below. This choice also avoids 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 chosen 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 simultaneous maximum likelihood fit to all n_2^i and n_3^i, the number of 2-jet and 3-jet events, respectively, in subsample i ($1 \leq i \leq 5$), using the relations:

$$\begin{aligned} n_2^i &= \sum_{j=1}^{3} \left(\varepsilon^{ij}_{(2\to2)}(1-R_3^j) + \varepsilon^{ij}_{(3\to2)}R_3^j\right) f^j N \\ n_3^i &= \sum_{j=1}^{3} \left(\varepsilon^{ij}_{(3\to3)}R_3^j + \varepsilon^{ij}_{(2\to3)}(1-R_3^j)\right) f^j N \;. \end{aligned} \tag{1}$$

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 5×3 matrices $\varepsilon^{ij}_{(2\to2)}$ and $\varepsilon^{ij}_{(3\to3)}$ are the efficiencies for an event of type j, with 2- or 3-jets at the parton level, to pass all cuts and enter subsample i as a 2- or 3-jet event, respectively. 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 over jet algorithms of 5.1%, 9.8%, and 19.6% for the uds, c, and b tags, respectively.

Equations 1 were solved using 2- and 3-jet events defined by each of the six algorithms. The ratios R_3^j/R_3^{all}, where R_3^{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 : -0.68, uds-b : 0.32, c-b : -0.57. The statistical errors were calculated using the full covariance matrix.

4. Comparison of α_s values

The 3-jet rate in heavy quark (b, c) events is expected to be modified relative to that in light quark events by the diminished phase-space for gluon emission due to the quark masses. We evaluated the correction factors, R_3^c/R_3^u and R_3^b/R_3^d, for each jet algorithm and y_c value according to the JETSET7.4 parton shower simulation. 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, $\alpha_s^j/\alpha_s^{all}$, can be determined from:

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

where $A(y_c)$, $B(y_c)$, and $C(y_c)$ for the different jet-finding algorithms were evaluated using Refs. [13, 14]. Equation 2 was solved to obtain $\alpha_s^j/\alpha_s^{all}$ for each jet algorithm. As an example, for the Geneva algorithm R_3^i/R_3^{all} for each subsample i ($1 \leq i \leq 5$) and the unfolded results $\alpha_s^j/\alpha_s^{all}$ ($j = uds$, c, b) are shown in Fig. 2 as a function of y_c. Fig. 3 summarises the results for all algorithms; the errors are statistical only.

We considered experimental 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 of Eq. 1, and rederiving $\alpha_s^j/\alpha_s^{all}$. Suitable variation about the world average value of each parameter was considered [10]. The errors are summarized in Table 2, where averages over the six algorithms are shown. The dominant physics contributions in $\alpha_s^b/\alpha_s^{all}$ result from limited knowledge of the average B decay multiplicity and the heavy quark fragmentation functions. The uncertainty in $BR(Z^0 \to c\bar{c})$ also produces variations in $\alpha_s^c/\alpha_s^{all}$ and $\alpha_s^{uds}/\alpha_s^{all}$. 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 $\alpha_s^j/\alpha_s^{all}$ 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 [15] and variation of the heavy quark masses used in the phase-space correction factors by ± 0.25 GeV/c^2. The rates of gluon splitting to heavy flavors were also considered. The variation of the results due to uncertainties in parton production and hadronization was investigated [1] by using JETSET [11] and was found to be small. These contributions are listed in Table 3.

There is some scatter among the $\alpha_s^j/\alpha_s^{all}$ values derived from the different jet algorithms. In order to quote a single $\alpha_s^j/\alpha_s^{all}$ 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

$$\begin{aligned}
\frac{\alpha_s^{uds}}{\alpha_s^{all}} &= 0.997 \pm 0.011\,(\mathrm{stat}) \pm 0.011\,(\mathrm{syst}) \pm 0.005\,(\mathrm{theory})\ , \\
\frac{\alpha_s^{c}}{\alpha_s^{all}} &= 0.984 \pm 0.042\,(\mathrm{stat}) \pm 0.053\,(\mathrm{syst}) \pm 0.022\,(\mathrm{theory})\ , \\
\frac{\alpha_s^{b}}{\alpha_s^{all}} &= 1.022 \pm 0.019\,(\mathrm{stat}) \pm 0.023\,(\mathrm{syst}) \pm 0.012\,(\mathrm{theory})\ , \qquad (3)
\end{aligned}$$

where the theoretical uncertainty is the sum in quadrature of the QCD uncertainty and the r.m.s. of the results over the six algorithms (Table 3). These average values are also shown in Fig. 3.

5. 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. Our results are consistent with our previous measurements [9], but are substantially more precise, as well as 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. The 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	0.030	0.996 ± 0.014	0.945 ± 0.055	1.056 ± 0.024	0.997	1.004
E0	0.020	0.993 ± 0.012	0.975 ± 0.046	1.039 ± 0.020	0.993	1.026
P	0.020	1.001 ± 0.012	0.930 ± 0.047	1.054 ± 0.021	0.992	1.024
P0	0.015	0.989 ± 0.010	0.999 ± 0.040	1.034 ± 0.018	0.992	1.031
D	0.010	1.006 ± 0.016	1.021 ± 0.062	0.966 ± 0.026	1.001	0.916
G	0.040	1.011 ± 0.014	0.999 ± 0.065	0.969 ± 0.024	0.998	0.944

Table 2. Systematic Erorrs

source	Center Value	Variation	$\Delta\left(\frac{\alpha_s^{uds}}{\alpha_s^{all}}\right)$	$\Delta\left(\frac{\alpha_s^{c}}{\alpha_s^{all}}\right)$	$\Delta\left(\frac{\alpha_s^{b}}{\alpha_s^{all}}\right)$
B decay multiplicity $< n_{ch} >$	5.39	± 0.2trks	0.001	0.022	0.014
B fragmentation $< x_b >$	0.700	± 0.008	0.002	0.008	0.012
B meson lifetime τ_B	$1.55ps$	$\pm 0.05ps$	0.001	0.008	0.003
B baryon lifetime τ_B	$1.10ps$	$\pm 0.08ps$	0.001	0.002	0.001
B baryon prod. rate f_{Λ_b}	7%	$\pm 4\%$	0.001	0.004	0.006
$B \to D^+ + X$ fraction	0.15	± 0.05	0.001	0.003	0.002
R_b	0.2216	± 0.0017	0.001	0.003	0.001
R_c	0.17	± 0.010	0.0008	0.037	0.005
C fragmentation $< x_c >$	0.484	± 0.008	0.003	0.011	0.002
$c\bar{c} \to D^+ + X$ fraction	0.20	± 0.04	0.001	0.003	0.001
C decay multiplicity $< n_{ch} >$	2.34	± 0.2trks	0.003	0.008	0.006
tracking efficiency	correction	on/off	0.002	0.013	0.005
impact parameter resolution	smear	on/off	0.001	0.005	0.001
MC statistics	0.8M events		0.005	0.020	0.008
Total			0.011	0.053	0.023

Table 3. Theoretical Uncertainties

α_s^{all}	0.120	± 0.01	0.001	0.001	0.002
m_b	5.0GeV$/c^2$	± 0.25GeV$/c^2$	0.001	0.002	0.003
m_c	1.35GeV$/c^2$	± 0.25GeV$/c^2$	0.001	0.002	0.003
$g \to cc$	1.7×10^{-2}	$\pm 50\%$	0.001	0.002	0.002
$g \to bb$	1.6×10^{-3}	$\pm 50\%$	0.001	0.001	0.003
Jet Algorithm	average	r.m.s	0.004	0.022	0.011
Total			0.005	0.022	0.012

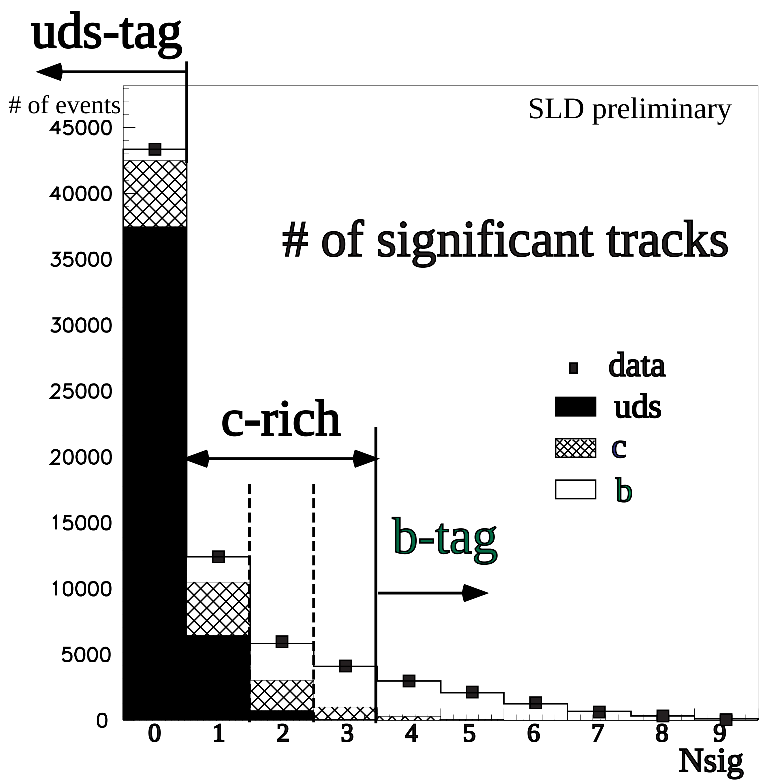

Figure 1: The distribution of the the number of tracks per event that miss the interaction point by $\geq 3\sigma$.

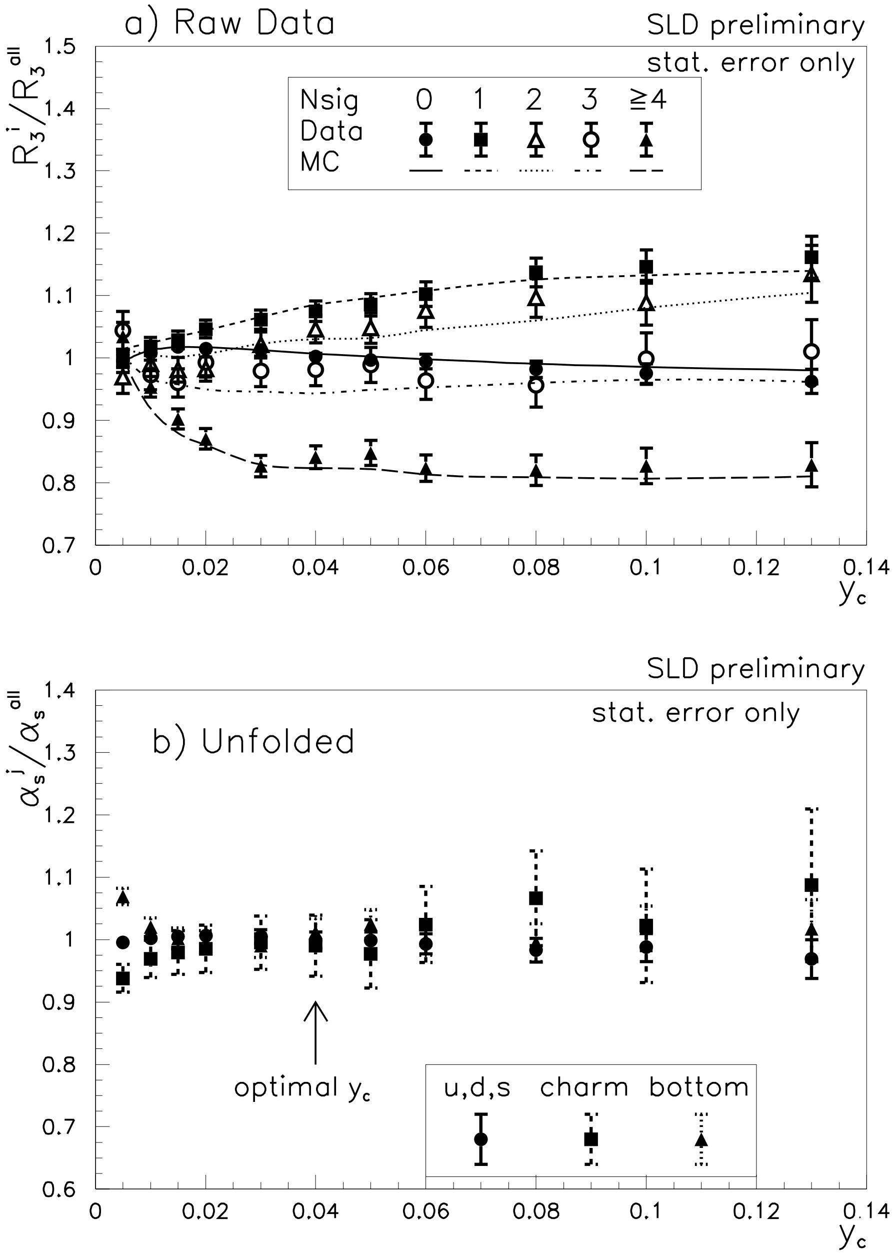

Figure 2: a) Detector level $R_3^{subsample}/R_3^{all}$. b) Unfolded $\alpha_s^{flavor}/\alpha_s^{all}$ (Geneva algorithm). The error bars are statistical only.

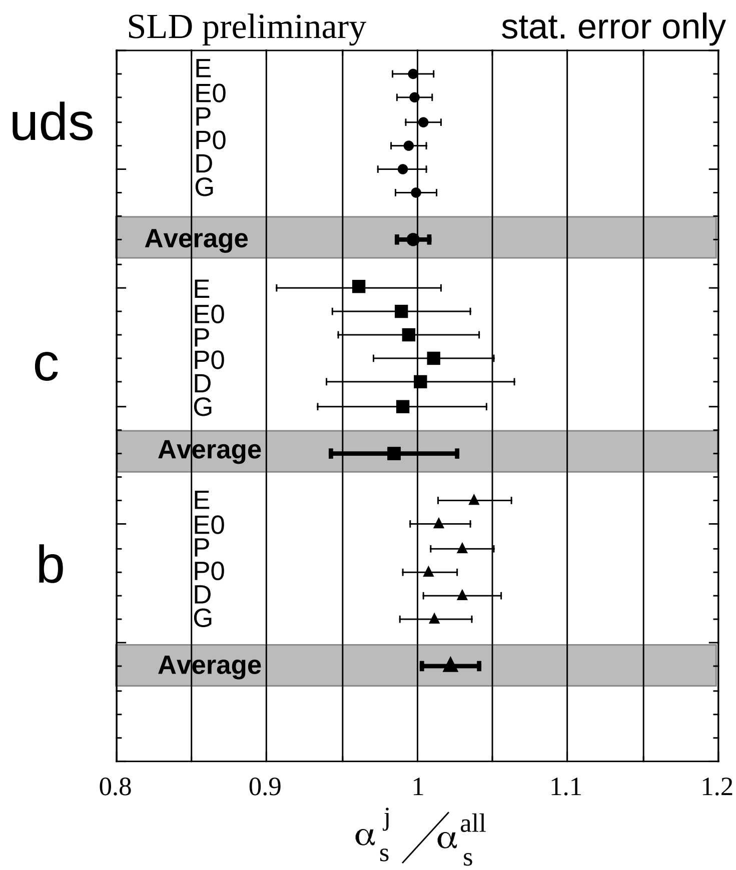

Figure 3: Values of $\alpha_s^j/\alpha_s^{all}$ derived for each of the six jet algorithms for each of the quark flavors j (see text). The error bars on the averages include only statistical errors.