EXPERIMENTAL TEST OF THE FLAVOR INDEPENDENCE OF THE QUARK–GLUON COUPLING CONSTANT

TASSO Collaboration

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Reconstruction of charged D*'s produced inclusively in e^+e^- annihilations at CM energies near 34.4 GeV is accomplished in the decay modes $D^{*+} \to D^0\pi^+ \to K^-\pi^+\pi^0\pi^+$ and $D^{*+} \to D^0\pi^+ \to K^-\pi^+\pi^-\pi^+\pi^+$ and their charge conjugates. Using these and previously reported $D^{*+} \to D^0\pi^+ \to K^-\pi^+\pi^+$ and $D^{*+} \to D^0\pi^+ \to K^-\pi^+\pi^+$ + missing π^0 channels we present evidence for hard gluon bremsstrahlung from charm quarks and show that the ratio of the quark–gluon coupling constant of charm quarks to the coupling constant obtained in the average hadronic event, $\alpha_s^c/\alpha_s = 1.00 \pm 0.20 \pm 0.20$. Our result provides evidence that the quark–gluon coupling constant is independent of flavor.

One of the profound consequences of the gauge theory of strong interactions is the universality of the quark–gluon coupling constant, i.e. that the quark–gluon coupling is independent of the flavor of the quark [‡1]. It is the purpose of this paper to present a test of this universality by studying gluon emission in e^+e^- annihilation events originating from quarks of known flavor. Flavor tagging is achieved by selecting events where a $D^{*\pm}$ with a high $x = E_{D^*}/E_{beam}$ is reconstructed. We identify these events as having originated from a $c\bar{c}$ pair. These flavor-tagged events show evidence of the presence of hard gluon bremsstrahlung and are used to determine the coupling constant α_s^c between charm quarks and gluons. This is to be contrasted with previous determinations of the quark–gluon coupling constant α_s from three-jet events, i.e. $e^+e^- \to q\bar{q}g$, where flavor independence has been assumed [2]. The ratio α_s^c/α_s is presented as a sensitive measure of this universality since many of the systematic errors cancel. In the course of this analysis we also obtain an upper limit on D^0–$\overline{D^0}$ mixing.

Several experiments [3], including our own [4] have detected D* production at high energies via the decay chain $D^{*+} \to D^0\pi^+_{tr}$ and subsequently $D^0 \to K^-\pi^+$ or $D^0 \to K^-\pi^+$ + missing π^0 (charge conjugate modes are omitted for brevity; π_{tr} denotes the pion emitted in the D*–D transition). In order to increase the data sample for the purpose of the present test, we extract additional D* signals using the decay modes $D^0 \to K^-\pi^+\pi^0$ (π^0 identified) and $D^0 \to K^-\pi^+\pi^-\pi^+$. All four samples are combined to measure the strong quark–gluon coupling constant α_s^c of charm quarks.

Our data sample consists of 22 356 hadronic events produced at the DESY storage ring PETRA and observed with the TASSO detector. The criteria for the selection of hadronic events are as described in ref. [5]. The center of mass energy W, ranges between 30.0 and 36.7 GeV, the mean being 34.4 GeV.

Charged tracks are reconstructed with a momentum resolution given by $\Delta p/p = 0.010(2.9 + p^2)^{1/2}$ (p in GeV/c) as determined from μ pairs when the beam crossing point is used in the track fit [4]. Photons from the decay of neutral pions are detected in eight liquid argon shower counters with an energy resolution $\Delta E/E = 0.136/\sqrt{E} + 0.031$ (E in GeV) [6]. Neutral pion candidates are formed from pairs of photons, each having an energy greater than 0.150 GeV. Pairs with an invariant mass between 0.07 and 0.20 GeV are constrained to the π^0 mass, and those pairs which have a χ^2 probability greater than 0.2 are considered as candidate π^0's. Additionally, single showers with energies greater than 4.0 GeV are treated as unresolved π^0's.

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[‡1] See for example, the review article in ref. [1].

For reconstruction of the $D^0 \to K^-\pi^+\pi^0$ mode an event is split into two jets (hemispheres) with respect to the sphericity axis as determined by charged tracks. D*'s are reconstructed from combinations of particles within the same hemisphere, and a minimum momentum of 0.3 GeV/c is required for both charged tracks and π^0's. Oppositely charged tracks are paired, and each particle in turn is considered as a kaon and a pion. The lab frame angle between the momentum of the $K^-(\pi^+, \pi^0)$ and that of the D^0 is required to be less than 26.4° (42.4°, 45.0°). These cuts are satisied by ≈98% of all decays of $D^{*+} \to D^0\pi^+_{tr} \to K^-\pi^+\pi^0\pi^+_{tr}$ where $x(D^*) > 0.6$. For each $K^-\pi^+$ combination, the π^0 that would give the triplet an invariant mass closest to the D^0 mass of 1.865 GeV is selected. A two constraint kinematic fit is performed to the hypothesis that the two charged tracks and the two photons result from a D^0 decaying in this mode (for D^0's with unresolved π^0's a one-constraint fit is used), and a cut of 18.4 (15.1 for D^0's with unresolved π^0's) is made on the χ^2 given by this fit. The data indicate that a sizeable background exists in events where in the D^0 rest system, the kaon goes backward with respect to the D^0's lab frame momentum vector. Therefore, a maximum of 124° is allowed for this angle. The constrained D^0's are paired with remaining charged tracks to form D* candidates. D* candidates with $x > 0.6$ are considered. The D^*-D^0 invariant mass difference is a particularly sensitive indicator of a charm signal because of the low Q value of the $D^{*+} \to D^0\pi^+_{tr}$ decay. An enhancement near the expected value of 0.145 GeV is seen (fig. 1a), and the width of the peak is consistent with our resolution. The enhancement is also seen in the unconstrained mass difference distribution. If the same analysis is carried out on $K^-\pi^+\pi^0$ combinations with invariant masses

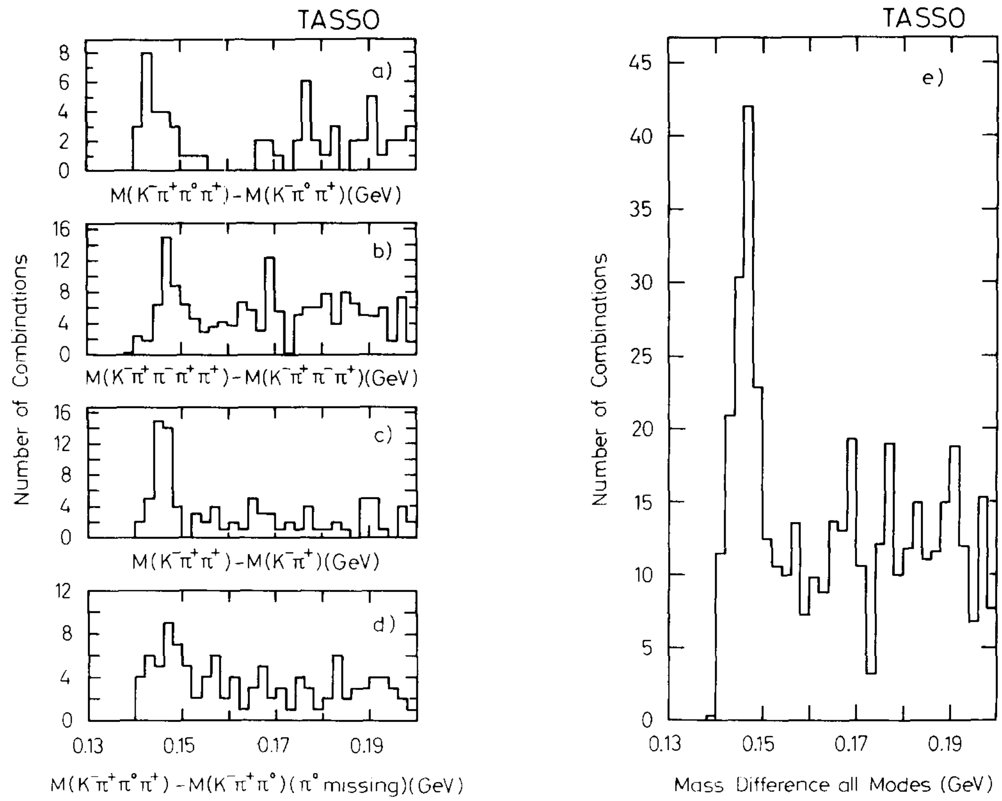

Fig. 1. (a) Mass difference spectrum $\Delta M = M(K^-\pi^+\pi^0\pi^+) - M(K^-\pi^+\pi^0)$ for $x > 0.6$. (b) Mass difference spectrum $\Delta M = M(K^-\pi^+\pi^-\pi^+\pi^+) - M(K^-\pi^+\pi^-\pi^+)$ for $x > 0.5$. (c) Mass difference spectrum $\Delta M = M(K^-\pi^+\pi^+) - M(K^-\pi^+)$ for $x > 0.5$. (d) Mass difference spectrum $\Delta M = M(K^-\pi^+\pi^0\pi^+) - M(K^-\pi^+\pi^0)$ for $x > 0.5$ where the π^0 has not been found. (e) Sum of plots (a)–(d).

in the "control region" between 2.1 and 2.5 GeV (in this region the pseudo-D^0 is unconstrained) a flat mass difference distribution results. The 20 events having 22 combinations with a mass difference below 0.150 GeV are taken as the D* candidates, and there is an estimated background of 3 events in this sample. A signal of this size is consistent with what is expected given the number of observed $D^{*+} \to D^0\pi^+_{tr} \to K^-\pi^+\pi^+_{tr}$ events and using our reconstruction efficiency and the published branching ratios [7].

The method used for reconstructing $D^{*+} \to D^0\pi^+_{tr} \to K^-\pi^+\pi^-\pi^+\pi^+_{tr}$ requires that the decay particles of the D* be completely contained within a hemisphere detimed by the sphericity axis of the event. All charged tracks are considered as both pions and kaons. Two of the oppositely charged pions are required to have an invariant mass of 0.770±0.150 GeV, i.e. close to the mass of the ρ^0. This is motivated by the result of ref. [8] that this decay proceeds mostly via $D^0 \to K^-\rho^0\pi^+$. In order to enhance the number of D^0's relative to the combinatorial background a set of kinematic cuts is placed on the momenta of the D^0 decay products and their angles relative to the original D^0 direction. The K^- (ρ^0, π^+, more energetic π from the ρ^0, less energetic π from the ρ^0) is required to have a momentum greater than 1.4 (2.5, 0.2, 1.3, 0.2) GeV/c and a maximum laboratory frame angle of 18° (10°, 25°, 18°, 35°) with respect to the D^0 direction. These cuts are satisfied by ≈75% of all decays of $D^{*+} \to D^0\pi^+_{tr} \to K^-\rho^0\pi^+\pi^+_{tr} \to K^-\pi^+\pi^-\pi^+\pi^+_{tr}$ where $x(D^*) > 0.5$. We take as D^0 candidates those four particle combinations which have invariant masses between 1.78 and 1.94 GeV. Their mass is kinematically constrained to 1.865 GeV, the mass of D^0. The remaining particles in the jet with momenta greater than 0.450 GeV/c are considered as π_{tr} candidates. The $D^0\pi^+_{tr}$ system is required to have $x > 0.5$. Often more than one combination passing the D^0 cuts is present in a jet. This can come about either through the assignment of the kaon identity to different members of the same set of four particles or by the inclusion of at least one different track. Since the correct combination is not known a priori, all the D^0 candidates associated with a particular transition pion are weighted according to their mass resolution function. A gaussian with $\sigma = 0.055$ GeV as determined by a Monte Carlo is used. The weights of all the D^0 candidates that are associated with a particular transition pion are normalized so that their sum equals one. The resulting D^*-D^0 mass difference distribution is shown in fig. 1b. The enhancement near the expected mass difference of 0.145 GeV indicates a charm signal. The corresponding distributions from the D^0 sideband region of 1.4–1.7 GeV and 2.1–2.5 GeV show no such enhancement. In principle multiple counting could occur if one or more D^0 candidates in a single jet pair off with different transition pions. This happens in only one event in the signal region defined by a mass difference between 0.141 and 0.150 GeV. The weighted number of D* candidates in the signal region is 32.8, coming from 35 different events. The estimated background is 11 events. A signal of this size is consistent with what is expected given the number of observed $D^{*+} \to D^0\pi^+_{tr} \to K^-\pi^+\pi^+_{tr}$ events and using our reconstruction efficiency and the published branching ratios [7].

Our previously reported D* signals in the modes $D^{*+} \to D^0\pi^+_{tr} \to K^-\pi^+\pi^+_{tr}$ and $D^{*+} \to D^0\pi^+_{tr} \to K^-\pi^+\pi^0\pi^+_{tr}$ (π^0 undetected) are shown in figs. 1c and 1d respectively. The combined mass difference distribution for all modes is shown in fig. 1e (note that there is multiple counting in this figure). Allowing no event to be counted more than once we find 119 charm candidates in the signal region, 26 of which are expected to be background. The contribution to this sample from primary bottom quarks is estimated to be less than 4% [9].

In a fraction of the $D^{*+} \to D^0\pi^+_{tr} \to K^-\pi^+\pi^+_{tr}$ candidates at least one of the D^0 decay particles enters the Cherenkov counter system in the TASSO hadron arms [10] (covering a solid angle of 19% of 4π) and can be identified. This permits a search for $D^0-\overline{D^0}$ mixing. Note that the charge of the π_{tr} determines whether th D* carries a c or $\bar{c}$ quark. Each arm contains silica aerogel, Freon 114 and CO_2 Čerenkov counters with threshold momenta of 0.7, 2.7 and 4.8 GeV/c for pions and 2.3, 9.5 and 17 GeV/c for kaons, respectively. Using the kinematic cuts of ref. [4] but including all CM energies from 14.0–36.7 GeV (27 530 events) we find 43 (35) candidate events for $D^0 \to K^-\pi^+$ ($D^0 \to K^+\pi^-$). By requiring the identification of at least one D^0 decay particle, 11 candidates of the type $D^0 \to K^-\pi^+$ are found with an estimated background of 1, and no decays of the type $D^0 \to K^+\pi^-$ are found. From this we obtain a 90% confidence level upper limit of 0.23 on the fraction of D^0's that decay hadronically as if they were $\overline{D^0}$'s. This complements the upper limit of 0.16 reported in ref. [11].

Having obtained a sample of events originating from quarks of known flavor, we proceed to the test of the flavor independence of the quark–gluon coupling constant. Three-jet events were first observed at PETRA. They were interpreted as evidence of hard gluon bremsstrahlung, i.e. $e^+e^- \to q\bar{q}g$ [12], and enabled the measurement of the quark–gluon coupling constant [2]. In these analyses, it was assumed that the quark–gluon coupling was independent of the quark flavors and hence described by a single parameter, α_s. Our purpose here is to show evidence for hard gluon bremsstrahlung from charm quarks and to test the universality of the quark–gluon coupling constant using the flavor-tagged D* events. Previously, we showed that the $p_\perp^2$ distribution of particles in charm jets and the sphericity and thrust distributions of charm jets are similar to those found in the total hadronic sample [9]. The observed agreement was indicative of gluon bremsstrahlung being also present in charm events. We demonstrated that in the context of a fragmentation scheme such as that of Field and Feynman [13], the transverse momentum distribution resulting from first rank charm fragmentation, i.e. $c \to D^{*+}d$ is, within error, the same as that obtained by averaging over rank and flavor [9]. It was also shown that there is little difference between the distributions of particles from charm jets and from jets of the overall hadronic sample. Therefore, for the purpose of determining the ratio α_s^c/α_s, we assume that the fragmentation process (apart from the longitudinal fragmentation of primary charm quarks) is identical for charm and average jets thus taking advantage of the much larger overall hadronic sample to deterine fragmentation parameters.

In our analysis we use a Monte Carlo simulation which includes second order QCD effects [14] and which fragments quarks and gluons independently [15]. The fragmentation parameters as determined in ref. [16] from the total hadronic sample are σ_q = 0.35 GeV/c and a_L = 0.66 where σ_q controls the transverse momentum distribution of quarks in the jet cascade,

$$\mathrm{d}\sigma/\mathrm{d}p_\perp^2 \propto \exp(-p_\perp^2/2\sigma_q^2)\ ,$$

and a_L is the parameter of the longitudinal fragmentation function

$$f(z) \propto (1-z)^{a_L}\ ,$$

of light quarks. The variable $z = (E+p_1)_{\mathrm{hadron}}/(E+p)_{\mathrm{quark}}$ where p_1 is the momentum component of the hadron along the quark direction. We take $\epsilon_c = 0.2$ [3,4] where ϵ_c is the parameter of the fragmentation function [17]

$$f(z) = 1/\{z[1 - 1/z - \epsilon_c/(1-z)]^2\}\ ,$$

used for charm quarks. Monte Carlo generated $c\bar{c}$, $c\bar{c}g$ and $c\bar{c}gg$ events are subjected to the detector simulation and to the same selection routines as used to find $D^{*+} \to D^0\pi_{tr}^+ \to K^-\pi^+\pi_{tr}^+$ in the data. This decay mode is used as representative of all modes observed. The systematic error introduced by this procedure is small compared to the statistical uncertainty of the data. For the purpose of calculating event shape distributions, we treat the D* as a single particle both in the data and in the Monte Carlo.

We have chosen to determine α_s^c by fitting the high momentum tail of the $p_{\perp\mathrm{in}}$ distribution ($p_{\perp\mathrm{in}} > 0.7$ GeV/c) of all charged particles in charm jets because this kinematic region is particularly sensitive to α_s^c through hard gluon bremsstrahlung. $p_{\perp\mathrm{in}}$ and $p_{\perp\mathrm{out}}$ are defined with respect to a coordinate system determined by the tensor

$$T_{ij}^{(\gamma)} = \sum_{n=1}^{N} \frac{p_{n_i}p_{n_j}}{|p_n|^{2-\gamma}} \Big/ \sum_{n=1}^{N} |p_n|^\gamma\ .$$

The indices i and j denote the spatial components of the momentum of particle n. For $\gamma = 2$, T represents the familiar momentum tensor of ref. [18]. The eigenvalues of T are ordered such that $Q_1 < Q_2 < Q_3$, and their corresponding eigenvectors are called $\hat{\boldsymbol{n}}_1$, $\hat{\boldsymbol{n}}_2$ and $\hat{\boldsymbol{n}}_3$. The event plane is spanned by $\hat{\boldsymbol{n}}_2$ and $\hat{\boldsymbol{n}}_3$, and $\hat{\boldsymbol{n}}_3$ is called the jet axis. The transverse momentum components of a particle with momentum $\boldsymbol{p}$ are defined by $p_{\perp\mathrm{out}} = |\boldsymbol{p}\cdot\hat{\boldsymbol{n}}_1|$ and $p_{\perp\mathrm{in}} = |\boldsymbol{p}\cdot\hat{\boldsymbol{n}}_2|$. Figs. 2a–2d exhibit the data and the $p_{\perp\mathrm{in}}$ and $p_{\perp\mathrm{out}}$ distributions given by the fit based on the $p_{\perp\mathrm{in}}$ distribution for $p_{\perp\mathrm{in}} > 0.7$ GeV/c, taking γ in the momentum tensor equal to 1 or 2 respectively. The fits yield for $\gamma = 1$, $\alpha_s^c = 0.150 \pm 0.029$ with $\chi^2 = 3.0$ for 1 DOF and for $\gamma = 2$, $\alpha_s^c = 0.155 \pm 0.032$ with $\chi^2 = 0.001$ for 1 DOF. The fits (represented by the solid histograms) describe the data well over the entire range of $p_{\perp\mathrm{in}}$ and $p_{\perp\mathrm{out}}$. The dashed histograms represent the Monte Carlo predictions with the same fragmentation parameters, but with $\alpha_s^c = 0$. They represent the data poorly.

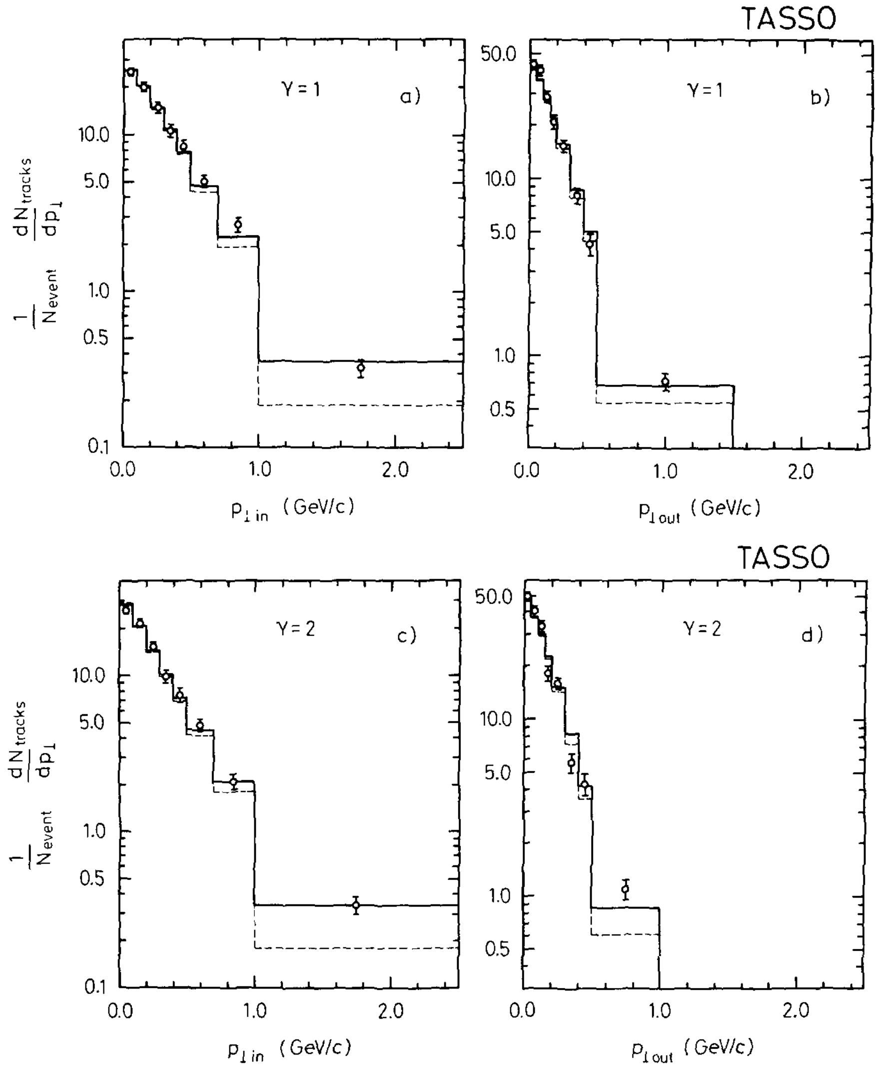

Fig. 2. Normalized transverse momentum distributions $(1/N_{event})dN/dp_\perp$ of the data (ϕ) and the Monte Carlo prediction obtained from the fit (solid histogram). The broken line is the Monte Carlo prediction for $\alpha_s^c = 0$. The exponent γ in the definition of the momentum tensor is equal to 1 for (2a), (2b) and equal to 2 for (2c), (2d).

In the region $p_{\perp in} > 0.7$ GeV/c, the data are 4.3 (3.5) SD above the Monte Carlo prediction for $\gamma = 1$ ($\gamma = 2$). Our data show evidence for the presence of hard gluon bremsstrahlung from charm quarks and are inconsistent with a zero charm–gluon coupling. The corresponding fits to the same variables for the overall hadronic sample give $\alpha_s = 0.153 \pm 0.0025$ for $\gamma = 1$ and $\alpha_s = 0.152 \pm 0.0025$ for $\gamma = 2$. A more detailed discussion of the α_s analysis for the overall hadronic sample will be given in ref. [16].

In principle, σ_q and α_s^c are correlated quantities. As a check we fit both parameters simultaneously to the full $p_{\perp in}$ and $p_{\perp out}$ distributions and find $\alpha_s^c = 0.138 \pm 0.029$, $\sigma_q = 0.371 \pm 0.021$ GeV/c. The value of α_s^c agrees with the value obtained before. Much of the systematic error that could be introduced by our analysis method (e.g. for use of a particular fragmentation scheme and a particular implementation of perturbative QCD and our choice of a particular distribution to fit) cancels in the ratio α_s^c/α_s. We find $\alpha_s^c/\alpha_s = 1.00 \pm 0.20$; statistically, the ratio is 3.9 SD away from zero. We note that in an analysis using first order QCD [19], we obtain $\alpha_s^c/\alpha_s = 0.91 \pm 0.23$.

We now estimate the systematic uncertainty in α_s^c/α_s introduced by our assumptions and by our method of fitting the data. We explore the effect of a first rank σ_q^c different from that of the average σ_q. If the first rank σ_q^c used in the Monte Carlo (measured to be $0.36 \pm 0.02 \pm 0.04$ in ref. (9)) is changed from 0.35 to 0.42, the ratio α_s^c/α_s decreases by 12%. We find only a weak dependence on our choice of the charm fragmentation parameter ϵ_c. If the ϵ_c used in the Monte Carlo is changed from 0.2 to 0.3, the ratio α_s^c/α_s increases by 13%. Within the context of the model used the value of α_s^c is $0.153 \pm 0.031 \pm 0.030$. We give as our final result $\alpha_s^c/\alpha_s = 1.00 \pm 0.20 \pm 0.20$.

In conclusion, we use reconstructed $D^{*\pm}$'s as a flavor tag. We find evidence for hard gluon bremsstrahlung from charm quarks. A comparison of α_s^c deduced from charm tagged events with α_s determined from all events gives for their ratio, $\alpha_s^c/\alpha_s = 1.00 \pm 0.20 \pm 0.20$. This provides experimental evidence for the universality of the quark–gluon coupling constant. Attempts to extract α_s^c from charmonium decays and to compare it with α_s^b deduced for the b quark from bottomonium decays support the flavor independence of α_s but have been hampered by theoretical uncertainties in the treatment of quarkonium decays [20]. Using particle identification, we are able to place a 90% confidence upper limit of 0.23 on the fraction of D^0 mesons decaying hadronically as if they were $\overline{D^0}$ mesons.

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References

[1] W. Marciano and H. Pagels, Phys. Rep. 36C (1978) 146.

[2] MARK J Collab., D.P. Barber et al., Phys. Lett. 89B (1979) 139;
TASSO Collab., R. Brandelik et al., Phys. Lett. 94B (1980) 437;
PLUTO Collab., Ch. Berger et al., Phys. Lett. 97B (1980) 459;
JADE Collab., W. Bartel et al., Phys. Lett. 119B (1982) 239;
CELLO Collab., H.J. Behrend et al., Nucl. Phys. B218 (1983) 269;
MARK J. Collab., B. Adeva et al., Phys. Rev. Lett. 50 (1983) 2051.

[3] MARK II Collab., J.M. Yelton et al., Phys. Rev. Lett. 49 (1982) 430;
CLEO Collab., C. Bebek et al., Phys. Rev. Lett. 49 (1982) 610;
CLEO Collab., P. Avery et al., Phys. Rev. Lett. 51 (1983) 1139;
HRS Collab., S. Ahlen et al., Phys. Rev. Lett. 51 (1983) 1147.

[4] TASSO Collab., M. Althoff et al., Phys. Lett. 126B (1983) 493.

[5] TASSO Collab., R. Brandelik et al., Phys. Lett. 113B (1982) 499.

[6] TASSO Collab., R. Brandelik et al., Phys. Lett. 108B (1982) 71;
A. Ladage, Proc. Intern. Conf. on Instrumentation for colliding beam physics (SLAC, 1982) SLAC-Report 250, p. 180;
TASSO Collab., to be published.

[7] Particle Data Group, Phys. Lett. 111B (1982) 1.

[8] MARK I Collab., M. Piccolo et al., Phys. Lett. 70B (1977) 260.

[9] TASSO Collab., M. Althoff et al., Phys. Lett. 135B (1984) 244.

[10] TASSO Collab., M. Althoff et al., Z. Phys. C17 (1983) 5.

[11] MARK I Collab., G.J. Feldman et al., Phys. Rev. Lett. 38 (1977) 1313;
MARK I Collab., G. Goldhaber et al., Phys. Lett. 69B (1977) 503.

[12] B.H. Wiik, Proc. Intern. Neutrino Conf. (Bergen, Norway, June 1979) p. 113;
P. Söding, Proc. European Physical Society Intern. Conf. on High energy physics (Geneva, Switzerland, June 1979) p. 271;
TASSO Collab., R. Brandelik et al., Phys. Lett. 86B (1979) 243;
MARK J. Collab., D.P. Barber et al., Phys. Rev. Lett. 43 (1979) 830;
PLUTO Collab., Ch. Berger et al., Phys. Lett. 86B (1979) 418;
JADE Collab., W. Bartel et al., Phys. Lett. 91B (1980) 142.

[13] R.D. Field and R.P. Feynman, Nucl. Phys. B136 (1978) 1.

[14] K. Fabricus, G. Kramer, G. Schierholz and I. Schmitt, Phys. Lett. 97B (1981) 431; Z. Phys. C, Particles and Fields 11 (1982) 315;

A. Ali et al., Phys. Lett. 82B (1979) 285; Nucl. Phys. B167 (1980) 454.
[15] P. Hoyer et al., Nucl. Phys. B161 (1979) 349;
A. Ali et al., Phys. Lett. 93B (1980) 155.
[16] TASSO Collab., to be published in Z. Phys. C, Particles and Fields (1984).
[17] C. Peterson et al., Phys. Rev. D27 (1983) 105.
[18] J.D. Bjorken and S.J. Brodsky, Phys. Rev. D1 (1970) 1416.
[19] J. Ellis, M.K. Gaillard and G.G. Ross, Nucl. Phys. B111 (1976) 253;
T.A. DeGrand, Y.T. Ng and S.H. Tye, Phys. Rev. D16 (1977) 3251;
A. De Rújila, J. Ellis, E. Floratos and M.K. Gaillard, Nucl. Phys. B138 (1978) 387;
G. Kramer, G. Schierholz and J. Willrodt, Phys. Lett. 79B (1978) 249.
[20] P. Mackenzie and G.P. Lepage, Phys. Rev. Lett. 47 (1981) 1244.