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Variation of the Strong Coupling Constant from a Measurement of the Jet Energy Spread in e^+e^- Annihilation *

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ABSTRACT

A measurement of jet energy spread in the reaction $e^+e^- \to$ hadrons is presented. Using a jet calculus model for the jet development we determine the variation of the strong coupling constant with respect to momentum transfer. The observed variation is consistent with that expected for QCD over a wide range of momentum transfers. This method alone is not sufficient to distinguish QCD from simple limited transverse momentum models.

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In recent years the theory of the strong interaction, QCD, has been successful in explaining the characteristics of deep inelastic lepton-nucleon scattering and hadron production in $e^+ e^-$ annihilation. An important consequence of QCD is a decreasing coupling constant with increasing energy. The experimental verification of this fact is difficult, since the coupling constant α_s changes logarithmically with the energy. The value of α_s at fixed energy can be determined by the leptonic branching ratios of the Ψ, Ψ' and Υ resonances[1]. Measurements of α_s over a range of energies in deep inelastic lepton nucleon scattering have large statistical errors[2]. Konishi, Ukawa and Veneziano[3] have suggested a statistically powerful method which uses the angular energy spread inside a hadron jet to determine α_s. In jet development, the relevant mass scale in the succesive branching of partons varies from half the center-of-mass energy down to a few GeV, thus allowing the variation of the effective coupling constant to be determined over almost two orders of magnitude in q^2.

In this method, energy and momenta are measured using a set of fictitious calorimeters that completely cover a jet produced in the reaction $e^+e^- \rightarrow$ hadrons. Each calorimeter subtends an opening angle (2δ). If E_i is the energy measured in the i-th calorimeter, then the jet energy is given by

$$E_{jet} = \sum_{1}^{N} E_i(\delta) \quad , \text{N=number of calorimeters.}$$

and the jet energy spread of order n is defined as:

$$C^n(\delta) = \langle \Sigma\, x_i^n(\delta) \rangle \quad \text{with } x_i = \frac{E_i(\delta)}{\Sigma\, E_j(\delta)} \qquad (1)$$

The mean value is computed by averaging over all measured jets and energy conservation requires $C^1(\delta) = 1$. In QCD, δ is proportional to the internal momentum transfer in the parton cascade and allows the determination of $\alpha_s(q^2)$.

The jet energy spread was measured from data taken with the MARK II detector at the electron positron storage ring PEP at the Stanford Linear Accelerator Center. The data used in this analysis correspond to an integrated luminosity of approximately 14500 nb^{-1} accumulated at a center-of-mass energy of 29 GeV. The MARK II detector is composed of a large-volume solenoid magnet coaxial with the PEP beam line, a system of 16 layers of cylindrical drift chambers in the field to determine particle momenta, a set of liquid argon-and-lead shower counters outside the tracking region covering 2π in azimuth to detect photons and identify electrons, a time-of-flight system to measure particle velocities, and a set of steel absorbers and counters to identify μ mesons. The detector has been described in detail elsewhere[4].

Events for this analysis were selected by applying the following cuts. Charged and neutral tracks had to lie in the polar angle range $50° < \theta < 130°$ to stay safely within the region covered by the liquid argon shower counters. Charged tracks were required to have a minimum transverse momentum with respect to the beam axis of 100MeV/c and photons to have a measured energy of at least 300 MeV. The particle identification capabilities of the MARK II were used to assign masses to charged particles. If the mass was ambiguous a pion mass was assumed. Photons were rejected if their distance to any charged track was less than 15cm at the entrance of the liquid argon shower counters. All events were analysed as two-jet events. Selected events were required to have a measured thrust value greater than 0.85. This cut removed events with hard gluon radiation at large angles, and was made to justify the leading logarithm approximation[5] used in the jet calculus. The results are quite independent of the particular value of the thrust cut. The polar angle of the thrust axis had to be in the range between 65° and 115° to make sure that most of the energy flow of the jets went into the angular region where it could be measured. The measured energy of each of the two jets had to be at least 8GeV. Each jet was required to contain at least three detected particles with at least two of them being charged. In addition the detected charged multiplicity of the event had to exceed four to discriminate against τ-pair production. To remove showering Bhabha events, events were rejected if an electron with more than 8 GeV was identified. After applying the above cuts there remained 1866 jets with an average jet energy of 11 Gev.

For each opening angle δ, the total solid angle was divided into a set of calorimeters with approximately equal size. The number of calorimeters varied between 6 and 76, and the orientation of the calorimeters was chosen for each event such that the jet axis pointed into the center of a calorimeter. If E_i was the energy in the i-th calorimeter and M_i the number of calorimeters with assigned energies different from zero, then the following moments were calculated:

$$C^n(\delta) = \frac{1}{N} \sum_{j=1}^{N} \sum_{i=1}^{M_j} x_i^n \qquad \text{with } x_i = \frac{E_i}{\Sigma E_k} \tag{2a}$$

and

$$x(\delta) = \frac{1}{N} \sum_{j=1}^{N} 1/M_j \sum_{i=1}^{M_j} x_i = \left\langle \frac{1}{M_j} \right\rangle \tag{2b}$$

where N is the number of jets.

The measured values $x(\delta)$ and $C^n(\delta)$ had to be corrected by a Monte Carlo simulation of the data for track and event selection cuts, undetected energy, initial state radiation and weak decays of charmed and bottom mesons. This correction procedure depends only on the acceptance of the detector and is insensitive to changes in the parameters of the fragmentation model. The resulting corrections for $C^n(\delta)$ are typically a few percent and reach 15% for larger moments , for $x(\delta)$ they are about 35%. The corrections are given in detail in table 1.

The corrected values for the jet energy spread $C^n(\delta)$ and the average fractional energies $x(\delta)$ of the calorimeters are given in table 2. The quoted errors are the linear sums of the statistical and systematic error arising from uncertainties in the correction procedure. For small angles the systematic error dominates. We have checked that the result does not depend on the particular choice of the calorimeters by repeating the analysis with different grids.

The jet energy spread has been calculated by K.Konishi et al.[3] in the framework of perturbative QCD. This "jet calculus" is a probabilistic interpretation of jet development. In this picture a primary parton created in the process $e^+e^- \to q\bar{q}$ at a center-of-mass energy $\sqrt{s}$ develops into a parton shower by successive gluon radiation and quark-antiquark pair production. This leads to a tree-like structure where the virtual mass of the primary parton decreases successively along each branch. The shower evolution is calculated perturbatively until the virtual mass of the remaining partons are of the order of a typical hadronic mass. Then the partons turn non-perturbatively into hadrons. Since momentum transfers involved in this final hadronization process are small compared to the transverse momentum scale of the perturbative jet evolution, directional energy flow is approximately conserved. As assumed by ref. 3, these non-perturbative effects should not alter the result of the analysis, if the minimum momentum transfer observed (i.e. minimum δ) is not too small. As a result the measured hadronic energy E inside a cone of opening angle 2δ originates from the decay of a virtual parton in the shower with a virtual mass up to:

$$4\bar{q}^2 = \langle x\rangle^2 \, s \, \sin^2\delta \qquad (3)$$

where the average is to be taken over all sets of calorimeters of fixed opening angles 2δ and over all jets. Equation (3) is only an upper limit for the invariant mass, since angles smaller than the size of the calorimeter cannot be resolved.

In the theory the density of such virtual partons with fractional energy x in a shower of a primary parton i with mass up to $\sqrt{s}/4$ is given by a partonic fragmentation function[3,6] $D_i(x,s,\bar{q}^2)$, (i=quark,gluon). The jet energy spread is then given by the moments of the quark fragmentation function at that $\bar{q}^2$:

$$C^n_q(\bar{q}^2) = \langle \Sigma x_i^n \rangle_q = \int dx \, x^n \, D_q(x,s,\bar{q}^2) \qquad (4)$$

The q^2 evolution of these fragmentation functions is predicted by the well known Altarelli-Parisi equations[7] which can be solved for the moments C_q^n with the result[8]:

$$C_q^n(\bar{q}^2) = a_1^n \left(\frac{\alpha_s(4\bar{q}^2)}{\alpha_s(s)}\right)^{\frac{\lambda_+^n}{2\pi b}} + b_1^n \left(\frac{\alpha_s(4\bar{q}^2)}{\alpha_s(s)}\right)^{\frac{\lambda_-^n}{2\pi b}} \qquad (5)$$

Here, λ_+^n, λ_-^n and a_1^n, b_1^n are the eigenvalues and the first components of the corresponding eigenvectors of the matrix of anomalous dimensions as given by references 3 and 8, and $b = 33-2N_f$ for N_f quark flavors. The range of validity of this calculation is limited to $\alpha_s(4\bar{q}^2) \ll \pi$ and $\bar{q}^2 \gg m^2_{hadron}$. This is equivalent to the requirement that 2δ must not be taken too small.

In comparing the experimental results to eq. (5), one has to choose the number of quark flavors effective in the development of the parton cascade. Recently, Edwards and Gottschalk[9] have shown that the quark mass dependent effective QCD coupling constant can be approximated sufficiently well by the formula for massless quarks if one introduces thresholds for the production of new quark flavors at approximately twice the respective quark mass. Except for the highest value of $4\bar{q}^2$ in table 2 the invariant masses of the partons in the cascade are too low to permit production of charmed quarks in their decay, and at the highest value $4\bar{q}^2 = 79GeV^2$ eq. (5) gives results for $N_f = 3$ and $N_f = 4$ which are almost identical.

In fig. 1 we show the measurements of $C^2(4\bar{q}^2)$ and $C^6(4\bar{q}^2)$ as a function of the averaged values $4\bar{q}^2$ and compare them to the predictions of eq. 5 for $N_f=3$. We do not consider moments of order higher than 6 because the correction factors become large. The second order moment C^2 is well described by eq. 5 with an α_s of about 0.16 at $Q_0 = 29GeV$ even down to small values of $\bar{q}^2$, where perturbative methods may not be applicable. The prediction of the moments are very sensitive to α_s, however the momentum transfer scale is very approximate. For the sixth order moment C^6 the agreement is still good although the best fit value of

α_s(29Gev) is 0.18. The significance of the variation of α_s with the order of the moments is not clear to us. Higher order corrections to the jet calculus or residual non-perturbative effects can contribute to this difference.

Equation (5) can be solved numerically for the ratio $\alpha_s(4\bar{q}^2)/\alpha_s(s)$ which allows the variation of α_s with invariant mass to be determined from the experiment. In fig. 2 the ratios $\alpha_s(4\bar{q}^2)/\alpha_s(s)$ derived from C^2 and C^6, using N_f=3, are plotted against $4\bar{q}^2$. The data clearly show a decreasing ratio with increasing energy. The curves are the predictions from the first order calculation of α_s:

$$\frac{\alpha_s(4\bar{q}^2)}{\alpha_s(s)} = \frac{1}{1 + \alpha_s(s)\ b\ \ln(4\bar{q}^2/s)} \qquad (6)$$

with $\alpha_s(s)$ as a parameter. The agreement between data and the perturbative prediction is good for n=2 even down to very low values of $4\bar{q}^2$, where the application of the perturbative theory becomes doubtful. For n=6 the agreement is also qualitatively as stated above but, a higher value of $\alpha_s(s)$ is required. The ratios $\alpha_s(4\bar{q}^2)/\alpha_s(s)$ derived with the assumption of 4 flavors are slightly larger and would require a value of $\alpha_s(s)$ which is larger by a few percent.

We have also compared the data to the prediction of other completely ad hoc models of $e^+e^- \rightarrow$ hadrons in order to see if the jet energy moments are a sensitive discriminant among models. One simulation uses an implausible model that generates events looking nothing like the data (isotropic phase space) with the multiplicity adjusted to agree with the data. A jet axis can be determined because a finite number of particles in the final state can never give complete spherical symmetry. The moments determined from the simulation look nothing like the data in magnitude or in shape.

The second simulation generates hadrons in back-to-back jets with a transverse momentum distribution with respect to the jet axis that is gaussianly distributed and a longitudinal momentum distribution determined by phase space. Again, the mean multiplicity is adjusted to fit the real data. These events look, superficially, very much like real data, and this model as well as QCD fits the energy moments with $\langle p_{\perp} \rangle$ = 400 MeV for C^2 and $\langle p_{\perp} \rangle$ = 480 MeV for C^6. It is interesting to note that these values of $\langle p_{\perp} \rangle$ are similar to those determined at the SPEAR storage ring for jets produced at 7.4 GeV which give $\langle p_{\perp} \rangle = 364 \pm 2$ MeV[10].

Models for the jet development such as the one proposed by Feynman and Field[11], which are adjusted not only to fit $p_{\perp}$ but also $p_{\parallel}$ will naturally reproduce the energy moments.

In a third model we have tested the sensitivity of the jet calculus method and our experimental procedure by using a leading logarithm QCD-Monte Carlo[12]. The jet development in this model is determined by multiple gluon emission with a logarithmically changing coupling constant, $\alpha_s \propto 1/\ln(q^2/\Lambda^2)$. Since Λ is a parameter, we were able to examine the sensitivity of the experimental procedure to a variation of α_s.

In conclusion, this analysis shows that the perturbative QCD jet calculus gives a good description of the jet energy moments. In the framework of this model we have extracted α_s at different momentum transfers and we have demonstrated that the data require a decreasing value of α_s with increasing energy. This method alone is not sufficient to distinguish QCD from simple limited transverse momentum models.

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Table 1.

Correction factors for the moments $C^n(\delta)$ and for $x(\delta)$.

δ	n= 2	4	6	$\langle x(\delta)\rangle$
13.1	.992	1.017	1.002	.664
15.9	.993	.991	.966	.659
19.7	.973	.950	.918	.645
26.3	.952	.997	.865	.632
29.5	.940	.887	.840	.612
47.8	.938	.882	.835	.617

Table 2.

Energy spread moments and momentum transfer as a function of δ.

δ	C^2	C^4	C^6	$4\bar{q}^2(GeV^2)$
13.1	.500±.007	.280±.009	.191±.007	1.15±.28
15.9	.574±.007	.355±.009	.254±.010	2.18±.53
19.7	.637±.010	.429±.012	.322±.014	4.4 ±1.0
26.3	.718±.012	.531±.018	.420±.021	11.3 ±3.0
29.5	.745±.014	.575±.022	.466±.026	16.4 ±4.7
47.8	.864±.014	.751±.022	.667±.032	79.9 ±22.2

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FIGURE CAPTIONS

1. Measured second and sixth order moments of the jet energy spread as a function of the observed average $4\bar{q}^2$. The curves are the result of eq. 5 with different values of α_s(29 GeV).

2. Ratios $\alpha_s(4\bar{q}^2)/\alpha_s$ derived from the second and sixth order moments of the energy spread. The full and dashed lines are the perturbative QCD expectations for $\alpha_s(s) = 0.17$ (0.16 resp.).

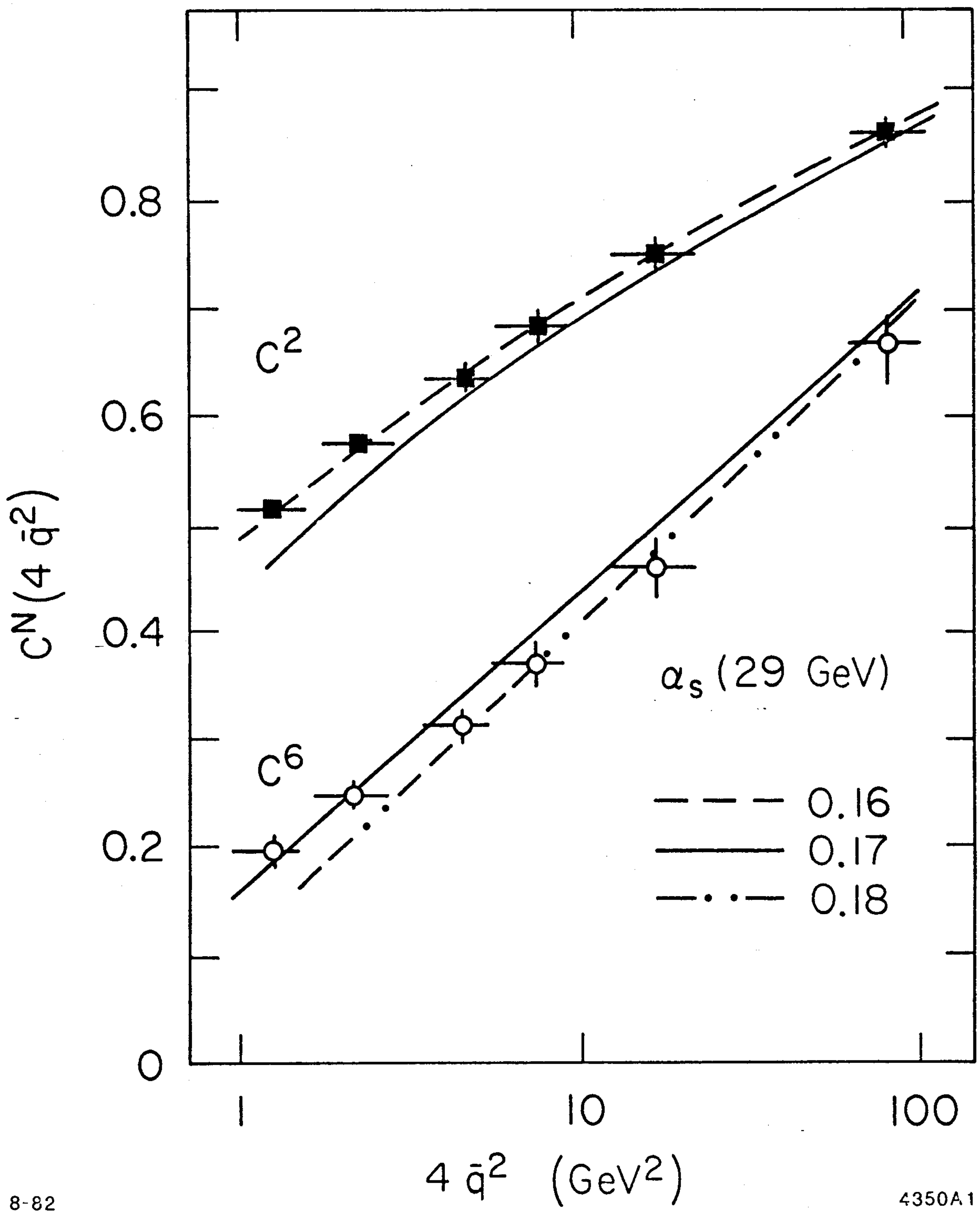
0.8
0.6
0.4
0.2
0
$C^N(4\bar{q}^2)$
C^2
C^6
α_s (29 GeV)
0.16
0.17
0.18
1
10
100
$4\bar{q}^2$ (GeV^2)
8-82
4350A1

Fig. 1

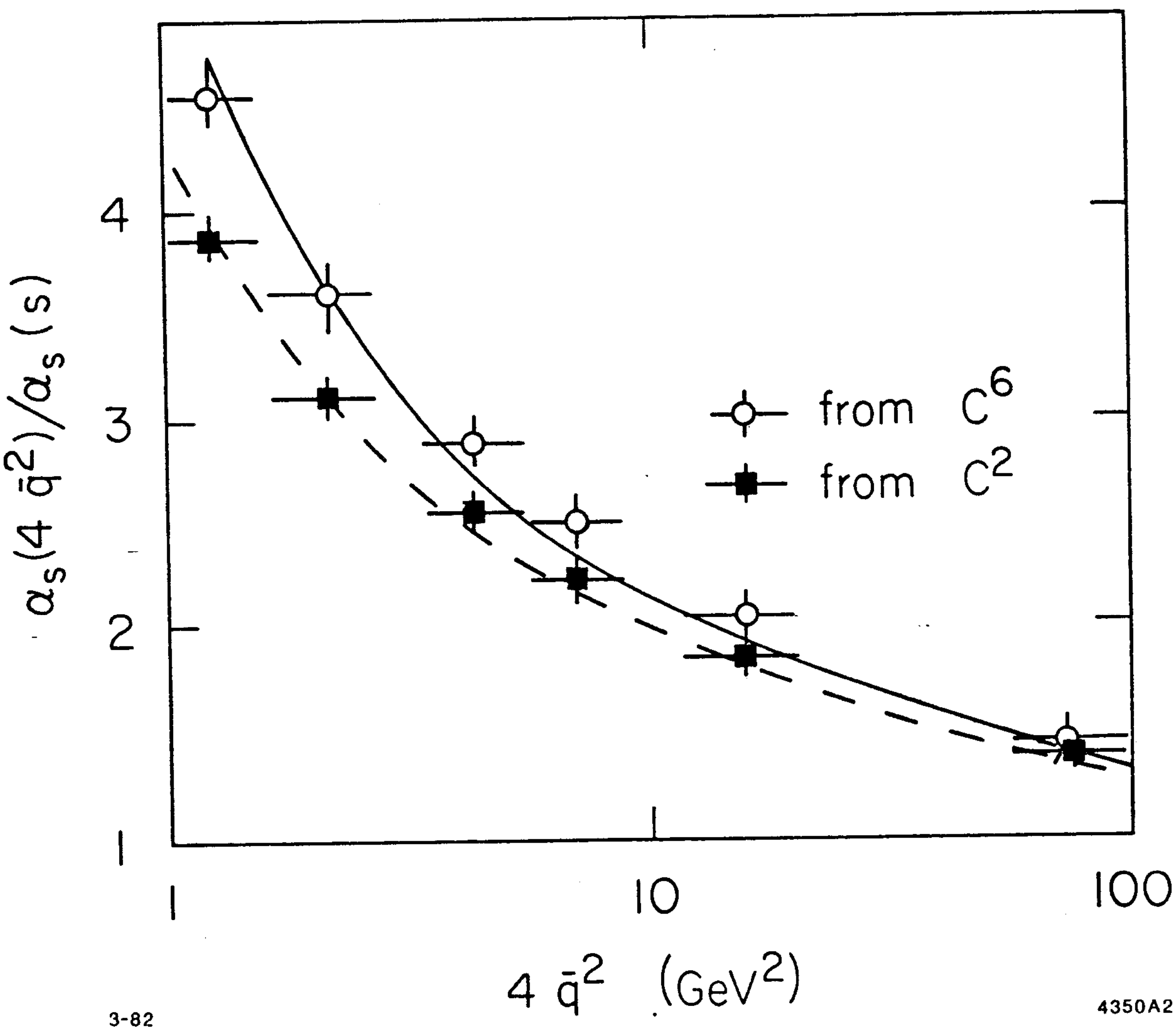
$\alpha_s(4\bar{q}^2)/\alpha_s(s)$
1
2
3
4
1
10
100
$4\bar{q}^2$ (GeV^2)
from C^6
from C^2
3-82
4350A2

Fig. 2