AN ANALYSIS OF THE CHARGED AND NEUTRAL ENERGY FLOW IN e^+e^- HADRONIC ANNIHILATION AT 34 GeV, AND A DETERMINATION OF THE QCD EFFECTIVE COUPLING CONSTANT

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Using both charged and neutral components, 2600 multihadronic e^+e^- annihilation events, recorded at 34 GeV by the CELLO detector at PETRA, have been analysed in a calorimetric approach. The fraction of energy carried by gamma rays is measured to be $f_\gamma = (26.0 \pm 0.4 \text{ (stat)} \pm 4.0 \text{ (syst)})\%$. The neutral energy flow is seen to follow closely the overall energy flow. From the corrected oblateness distribution, a first order determination of α_s is performed. The result is $\alpha_s = 0.16 \pm 0.01$ (stat) $\pm$ 0.03 (syst).

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In the framework of perturbative QCD, calculable quantities relevant to e^+e^- annihilation are of the "infrared stable" type. The experimental determination of such quantities relies essentially on a knowledge of the final-state energy flow. One way to achieve this is to measure the final charged particles, and to correct subsequently for the unseen neutrals using some fragmentation model. Or one can try to perform as complete as possible a measurement of the final-state energy flow.

In this paper, we present a calorimetric analysis of multihadronic e^+e^- annihilation events at high energy incorporating both charged and neutral particles. We measure the fraction of energy carried by γ rays, and show that the charged and neutral components are distributed in a very similar way. The simultaneous use of both components, together with severe cuts on the total energy and on the direction of the event thrust axis, allows us to obtain thrust and oblateness distributions for which the corrections are small. Comparing the corrected distributions with a QCD calculation, we then extract the value of α_s, the QCD effective coupling constant, in the first order of perturbation theory.

The data sample we used consists of 2600 multihadronic annihilation events recorded at PETRA by the CELLO detector [1], at an average center of mass energy of 34.3 GeV. The trigger conditions, the selection procedure, and the charged-particle reconstruction were those described in ref. [2]. Neutral particles were measured using the lead–liquid-argon electromagnetic calorimeter. In order to match the effective charged-particle acceptance, the end-cap calorimeters were not used in this analysis. This results in a polar angle acceptance $|\cos\theta| < 0.86$. To minimize the effect of hadrons interacting in the calorimeter, only the first 11 radiation lengths were used since they are enough to contain most of the electromagnetic origin while the showers coming from nuclear interactions of charged and neutral hadrons tend to originate and spread more deeply in the calorimeter. To estimate the neutral energy and its spatial distribution [‡1], each reconstructed charged track was extrapolated to the liquid-argon system, and the expectation value of its energy loss was locally subtracted. This energy loss was estimated, given the momentum and incidence angle of the particle, and assuming it to be a pion, from measurements made with prototype calorimeters exposed to pion beams of various energies [3]. The extrapolation to momenta lower than 1 GeV/c, the lowest available measurement, is the main source of systematic uncertainty attached to this procedure. Monte Carlo simulations incorporating the known features of low- and medium-energy hadron–nucleus scattering allowed us to cross-check this method. We call "converted neutral energy" (CNE) the energy which remains from that measured in the calorimeter, after this subtraction procedure has been applied.

To extract f_γ, the fraction of energy carried by gamma rays (not including those coming from $K^0_S \to 2\pi^0$ decays), the CNE fraction (35.2%) still has to be corrected for a number of much smaller effects. Together with acceptance and initial-state radiation [4], this was done, given the existing data on inclusive lepton, kaon, and baryon production [5], using a Monte Carlo model [6] and a detailed simulation of the detector. The effects considered were:

(i) Conversion of photons into e^+e^- pairs in the beam pipe (the electron energies should not have been subtracted) (+0.3%).

(ii) Direct electrons (since they were treated like hadrons, their energies were insufficiently subtracted) (−0.5%).

(iii) Charged hadrons not reconstructed because of detector or program inefficiencies, and therefore not subtracted (−4.3%).

(iv) K^0_L interactions and $K^0_S \to 2\pi^0 \to 4\gamma$ contamination (−3.3%).

(v) Error in the estimation of the energy deposition of $K^\pm$, p, $\bar{p}$ because of the π mass assumption; contri-

‡1 To obtain a spatial distribution of energy, a technical difficulty arises from the strip structure of the CELLO calorimeter modules. Charge measurements on parallel strips along three directions (longitudinal, transverse and crossed) provide independent projected energy distributions. These are transformed into a spatial distribution using the following procedure: in each module, the distribution of energy measured along the longitudinal projection is spread in the transverse direction, using as a weighting function the shape of the distribution of energy measured along the transverse projection. Similarly, the transverse and crossed projections are spread, using the shape of the longitudinal distribution of energy as a weighting function. The three spread distributions are then added. We checked by Monte Carlo simulations that the distortions introduced by this method for global quantities such as the ones presented in this paper are totally negligible.

butions from anti-baryon annihilations, n and Λ interactions; $\Lambda \to n\pi^0 \to n2\gamma$ contamination (−1.4%).

From this study, we could infer that more than 75% of the CNE is of photonic origin, that ~10% is due to other neutrals, and that the contamination due to unreconstructed charged tracks is ~15%.

The result of this analysis is f_γ = 26.0 ± 0.4 ± 4.0)% not including a fraction ~1.5% from $K^0_S \to 2\pi^0$. The first error is statistical, the second one represents the systematic uncertainties attached to this method. Using a different procedure, where individual showers are reconstructed in the calorimeter, a value f_γ = (25.1 ± 0.3 ± 4.0)% was obtained in the same experiment [7]. The natures of the systematic uncertainties attached to both methods are widely different. The average of the two determinations is f_γ = (25.5 ± 0.3 ± 3.5)%. This result is lower than, but not incompatible with the value of (30 ± 3)% obtained by the JADE collaboration [8] with a method similar to the one presented here. It is also compatible with lower-energy results [9].

We now compare the spatial distribution of the CNE to the overall (charged + neutral) energy distribution. On an event by event basis, these distributions may be distorted by fluctuations in the deposition of energy by the charged hadrons; but these fluctuations

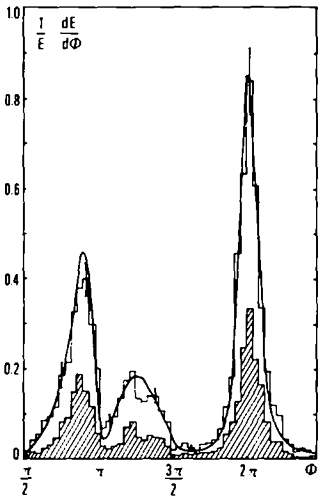

Fig. 1. Overall and neutral (hatched) energy flows projected onto the oriented event plane. Cuts (I), (II) were applied to select planar events. The curve is the expectation from QCD obtained by Monte Carlo simulation (α_s = 0.166, σ_q = 290 MeV).

tend to cancel, for quantities linear in the energy density, when the number of events becomes large. This is the case, for instance, for the projected angular energy flows displayed in fig. 1 for planar events. The following cuts were applied to the data entering this figure: (I) a total visible energy greater than 50% of the center of mass energy, and a thrust [10] axis more than 45° away from the beam axis; these cuts ensure that no appreciable fraction of the final state escaped in the forward direction; (II) a broad side oblateness [11] $O_B > 0.25$; this cut selects "planar" events. The event plane, defined by the thrust and major [11] axes with the origin of the angles along the thrust axis pointing towards the narrow side, is oriented in such a way that more energy rests between $\pi/2$ and π, the "quark quarter", than between π and $3\pi/2$, the "gluon quarter" [12]. A precise definition of the thrust and major axes, and of the oblateness will be given further down. It can be seen in fig. 1 that for the 305 events surviving cuts (I) + (II), the CNE follows closely the overall energy flow. In particular, the by now well-known three-bump structure, usually interpreted as evidence for hard-gluon bremsstrahlung at large angle in the planar events [13], is clearly visible also in the neutral component. The relevant CNE fractions are given in table 1, normalized to the overall visible energy in the same areas (the normalization to the visible energy induces an overestimation of the CNE fractions by ~3%). Within statistics, no difference can be told in this respect between planar and non-planar events, between narrow and broad sides, between "quark" and "gluon" quarters.

It can also be seen in fig. 1 that the observed overall energy flow is very well reproduced by a Monte Carlo model [6] incorporating first order QCD, quark and gluon fragmentation (with parameters adjusted as described further down), and a detailed simulation of the detector. We used this simulation to correct all measured distributions, always determined using both charged and neutral components, for acceptance, initial-state radiation [4], inefficiencies, and for smearing due to finite resolution.

From now on the analysis is restricted to the 1690 events surviving cuts (I). The corrected event thrust T, narrow side thrust T_N, and broad side oblateness O_B distributions for those events are presented in figs. 2, 3 and 4. To be more specific, these quantities are defined as follows. The event thrust axis $\boldsymbol{t}$ is that direction

Table 1
Converted neutral energy fractions (%) (statistical errors only).

Events	Cuts	Complete events	Narrow side	Broad side	Quark quarter	Gluon quarter
all	(I)	38.4 ± 0.5				
non-planar	(I) + $\overline{\text{(II)}}$	38.3 ± 0.5	37.7 ± 0.7	38.9 ± 0.8		
planar	(I) + (II)	39.0 ± 1.1	39.0 ± 1.6	38.9 ± 1.6	40.6 ± 2.1	36.2 ± 2.4

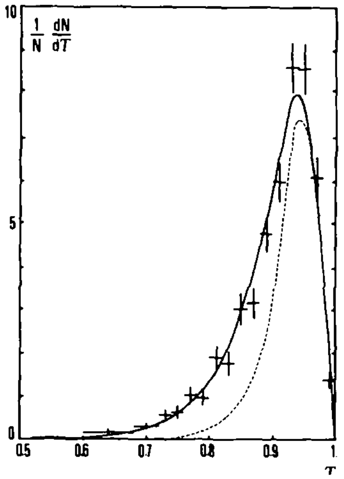

Fig. 2. Corrected event thrust distribution for events surviving cuts (I). The full curve is the QCD prediction ($\alpha_s = 0.166$, $\sigma_q = 290$ MeV). The dashed curve is the $q\bar{q}$ contribution.

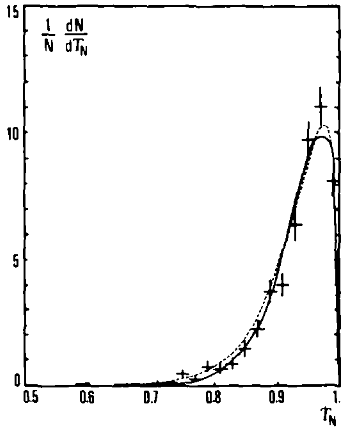

Fig. 3. Corrected narrow side thrust distribution for events surviving cuts (I). The full curve is the QCD prediction for $\alpha_s = 0.166$ with $\sigma_q = 290$ MeV. The dotted curve is the QCD prediction for $\alpha_s = 0.142$ with $\sigma_E = 400$ MeV.

which makes the thrust T,

$$T = \frac{1}{E} \int |\boldsymbol{t} \cdot \boldsymbol{u}(\Omega)| \frac{dE}{d\Omega} d\Omega ,$$

maximum, where $dE/d\Omega$ is the density of visible energy flowing along the direction $\boldsymbol{u}(\Omega)$, and E is the total visible energy in the event. The event major axis $\boldsymbol{m}$ is that direction, orthogonal to $\boldsymbol{t}$, which makes the major M,

$$M = \frac{1}{E} \int |\boldsymbol{m} \cdot \boldsymbol{u}(\Omega)| \frac{dE}{d\Omega} d\Omega ,$$

maximum. The event minor axis $\boldsymbol{n}$ is orthogonal to both $\boldsymbol{t}$ and $\boldsymbol{m}$, and we define the minor N,

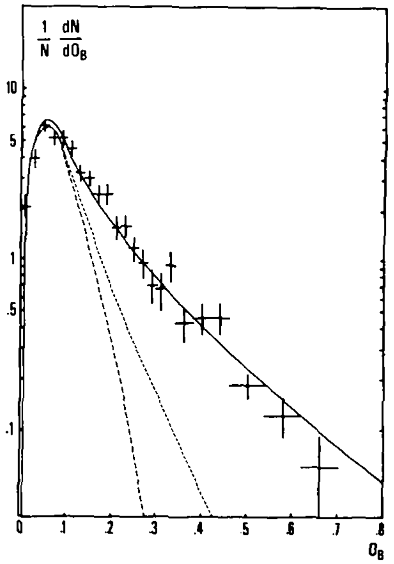

Fig. 4. Corrected broad side oblateness distribution for events surviving cuts (I). The full curve is the QCD prediction ($\alpha_s = 0.166$, $\sigma_q = 290$ MeV). The dashed curve is the $q\bar{q}$ contribution for $\alpha_s = 0.166$ with $\sigma_q = 290$ MeV, the dotted curve is the $q\bar{q}$ contribution for $\alpha_s \approx 0.142$ with $\sigma_E = 400$ MeV.

$$N = \frac{1}{E} \int |\boldsymbol{n} \cdot \boldsymbol{u}(\Omega)| \frac{dE}{d\Omega} d\Omega ,$$

and the oblateness $O = M - N$. The plane orthogonal to the thrust axis divides the event into two hemispheres. Within each of these hemispheres, jet axes and jet quantities (thrust, major, minor, oblateness) are determined by restricting to the considered hemisphere the domain of integration for T, M and N, and by normalizing the integrals to the energy visible in that hemisphere (jet visible energy). We define as the broad side the hemisphere with the bigger normalized energy transverse to the jet thrust axis $\boldsymbol{t}_j$:

$$t_j = \frac{1}{E_j} \int [1 - |\boldsymbol{t}_j \cdot \boldsymbol{u}(\Omega)|^2]^{1/2} \frac{dE}{d\Omega} d\Omega ,$$

with E_j the jet visible energy. The hemisphere opposite to the broad side B is called the narrow side N.

To determine the parameters entering our first order QCD Monte Carlo model [6], we proceeded in an iterative way:

(i) Pure $q\bar{q}$ production was first assumed and σ_q, the scale of the gaussian transverse momentum distribution in the fragmentation chain was adjusted so that the average $\langle T_N \rangle$ of the narrow side thrust be reproduced by the simulation.

(ii) Fixing σ_q to this value, α_s, the QCD effective coupling constant, was adjusted so that the fraction $f_O = (16.6 \pm 1.2)\%$ of events with $O_B > 0.25$ be reproduced (a high-O_B cut was chosen since it is expected that, for large enough O_B, the contribution from hard-gluon bremsstrahlung will dominate, with the remaining pure $q\bar{q}$ contamination resulting only from unexpectedly large fluctuations during the fragmentation process).

(iii) Fixing α_s to the value thus determined, σ_q was recalculated from $\langle T_N \rangle$; and then α_s again from f_O, etc...

The result of this rapidly converging procedure is $\sigma_q = (290 \pm 25)$ MeV and $\alpha_s = 0.166 \pm 0.011$, with very little correlation between the two quantities [‡2].

‡2 The other parameters entering the fragmentation model [6] were fixed. The quark fragmentation is parametrized by $f(z) = 1 - a + 3a(1 - z)^2$, with $a = 0.77$, except for heavy quarks where $a = 0$. The proportion P/(P + V) of primordial pseudoscalar mesons produced is set to 0.5. It has been shown [14] that α_s is not significantly correlated with these parameters.

It can be seen in figs. 1 to 4 that, with these parameters. the simulation reproduces the data very well. Still using σ_q = 290 MeV, an α_s value of 0.171 ± 0.013 can be obtained from the fraction $f_T = (16.1 \pm 1.2)\%$ of events with $T < 0.84$. This value, in good agreement with the one determined from f_O, is, however, much more correlated with σ_q. Indeed, it can be seen in figs. 2 and 4 that the $q\bar{q}$ contribution in the $T < 0.84$ sample is still ~17%, whereas it is <2% in the $O_B > 0.25$ sample, in spite of the practical equality between f_T and f_O. This difference is even higher (28% versus 9%) before MC correction between the raw f_T and f_O, due to the $q\bar{q}\gamma$ contamination where γ is an initial-state radiated photon. Finally we would also like to stress at this point that the corrections applied to the raw f_O and f_T were not bigger than 10%, whereas they would have been ~30% if only the charged particles had been used in the analysis.

The determination of α_s from f_O is subject to a number of systematic uncertainties:

(i) By varying the O_B cut from 0.3, where statistics become too poor, down to 0.2, where the pure $q\bar{q}$ contamination becomes significant, α_s changes by ±0.004.

(ii) By varying σ_q within the range allowed by $\langle T_N \rangle$, namely between 265 and 315 MeV, α_s changes by ±0.004.

(iii) The correction factor to the raw f_O is determined with an accuracy limited by the statistics of the Monte Carlo simulation. This introduces an uncertainty on α_s of ±0.009.

(iv) We changed the transverse-momentum distribution in the fragmentation chain to an exponential one [15], with slope $1/\sigma_E$. The same iterative procedure as described above was applied. The result for σ_E is 400 MeV, and 0.142 for α_s, still with little correlation between the two. It can be seen in fig. 4 that, though the $q\bar{q}$ contamination at high O_B is larger with a gaussian transverse-momentum distribution, it is far from being able to accomodate the whole of the high-O_B tail. Fig. 3 shows that the low-T_N region is now a little overestimated, whereas it used to be slightly underestimated in the gaussian case. Interpolating between the predictions of these two fragmentation models to reproduce the behavior of the data in the low-T_N region, we determine 0.16 as our best α_s value, with an additional systematic error of ±0.012.

Therefore, $\alpha_s = 0.16 \pm 0.01$ (stat) ± 0.03 (syst) where all systematic errors have been combined linearly. However, no uncertainty has been included which would reflect a change in the fragmentation scheme from a Feynman–Field type model [6] to the colored string model [16]. Studies of such effects are underway in our collaboration.

Our value of α_s is in good agreement with results obtained in the same experiment with different methods [17]. It is also well compatible with the values obtained by the other PETRA experiments [13,14,18].

In conclusion, we have measured the fraction of energy carried by gamma rays to be $f_\gamma = (26.0 \pm 0.4 \pm 4.0)\%$. We have shown that the neutral energy follows closely the overall energy flow. Using both charged and neutral components, we obtained corrected thrust and oblateness distributions from which we derived $\alpha_s = 0.16 \pm 0.01 \pm 0.03$ in first order of perturbation theory at $\sqrt{s} \sim 34$ GeV.

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