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Sterman-Weinberg Jets and Energy Flow in e^+e^- Annihilation at CM Energies Between 9.4 and 35 GeV

PLUTO Collaboration

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Abstract. The Sterman-Weinberg 2-jet cross section is measured from the hadron energy flow using the thrust axis to define the axis of the jet cone. The results are compared with first order QCD predictions. Deviations due to fragmentation are observed which decrease with increasing center of mass energy. We obtain an upper limit of $\Lambda_{\max} \approx 523$ MeV for the QCD scale parameter using a method which is insensitive to the details of the fragmentation. Moments of energy flow are also studied.

1. Introduction

In a well-known paper [1] Sterman and Weinberg obtained for the first time a partial cross section for jet production in e^+e^- annihilation using perturbative QCD. They defined a 2-jet event produced in e^+e^- annihilation as an event in which not more than a fraction ε of the total centre of mass energy E_{CM} is emitted outside a double-cone of half opening angle δ. The orientation of the cone in space is chosen so as to maximize the energy inside it. Sterman and Weinberg computed $\sigma_2(\varepsilon, \delta)$, the partial cross section for the production of 2-jets. Later this original 2-jet definition was modified [2-6] so as to extend the region of appicability in ε and δ, but no comparison with experimental data has yet been reported.

In this publication we present data on 2-jet cross sections obtained with the PLUTO detector in the CM energy range from 9.4 to 35 GeV. Data were taken at energies 9.4, 12.0, 13, 17.0, 22.0, 27.0, 30.8 and 35.0 GeV with event numbers of 494, 193, 87, 77, 22, 160, 515 and 6955, respectively. In Sect. 2 we review briefly the experimental procedure and the data selection criteria. In Sect. 3 we present our result on the Sterman-Weinberg cross section, for which we have used yet another definition [7] which permits the calculation in the full ε, δ-range. This definition has the advantage of making the comparison with experiment particularly easy, since the cone axis is chosen to coincide with the thrust axis, as one assumes that the measured hadron energy flow follows the original parton energy flow. Thus it is not necessary to reconstruct all the partons or to apply topological selection criteria. Therefore the method is rather insensitive to details of fragmentation. We introduce our 2-jet definition and present the 2-jet cross section obtained in first order QCD. This is compared directly with the data. It is not surprising that for low energy, where the fragmentation effects are dominant, data and QCD predictions do not agree. With increasing energy, however, the data approach the predictions. We also present a method which suppresses in part the fragmentation effects. For high energies we fit the data to the QCD predictions and obtain an upper limit on the scaling parameter Λ.

We also determine the fraction $\eta = E(\delta)/E_{CM}$ of the total energy emitted within a double cone centred around the thrust axis. In first order QCD it is possible to calculate the expectation values of η or powers of η. In Sect. 4 we present the QCD prediction for these energy moments $M^{(n)} = \langle \eta^n \rangle$ as a function of δ and compare them with the experimental data. Again we observe a convergence of prediction and experiment as the energy increases.

2. Experimental Procedure and Data Selection

The data used in the present analysis have been obtained with the PLUTO detector at the storage rings DORIS and PETRA at DESY, Hamburg, for CM energies of 9.4, 12, 13, 17, 22, 27.6, 30.8 and 35 GeV. The main features of the detector at PETRA are as follows:

a) a magnetic field of 1.64 Tesla is provided by a superconducting solenoid,

b) charged particles are tracked in a central detector consisting of thirteen layers of cylindrical proportional chambers covering 87% of 4π,

c) photons are detected with the help of two sets of lead scintillator shower counters ("barrel" and "end cap") covering together 96% of 4π.

Full details of the apparatus have been published elsewhere [8].

The data selection criteria demanded that

a) the visible energy should be greater than half the nominal CM energy,

b) at least four charged tracks should have a common interaction vertex centered within ± 4 cm of the nominal interaction point,

c) the angle ϑ between the thrust axis and the e^+ beam direction should satisfy $|\cos \vartheta| < 0.75$.

Final states selected this way were visually inspected and found to contain a negligible contamination from showering cosmic ray particles, $\gamma\gamma$-events, QED events and from beam-gas interactions (<2% total).

3. The Sterman-Weinberg 2-Jet Cross Section

As in the original approach of Sterman and Weinberg we use a fractional energy ε and a half opening angle δ of a double cone to define a 2-jet event. But the cone is now centered around the thrust axis, i.e.

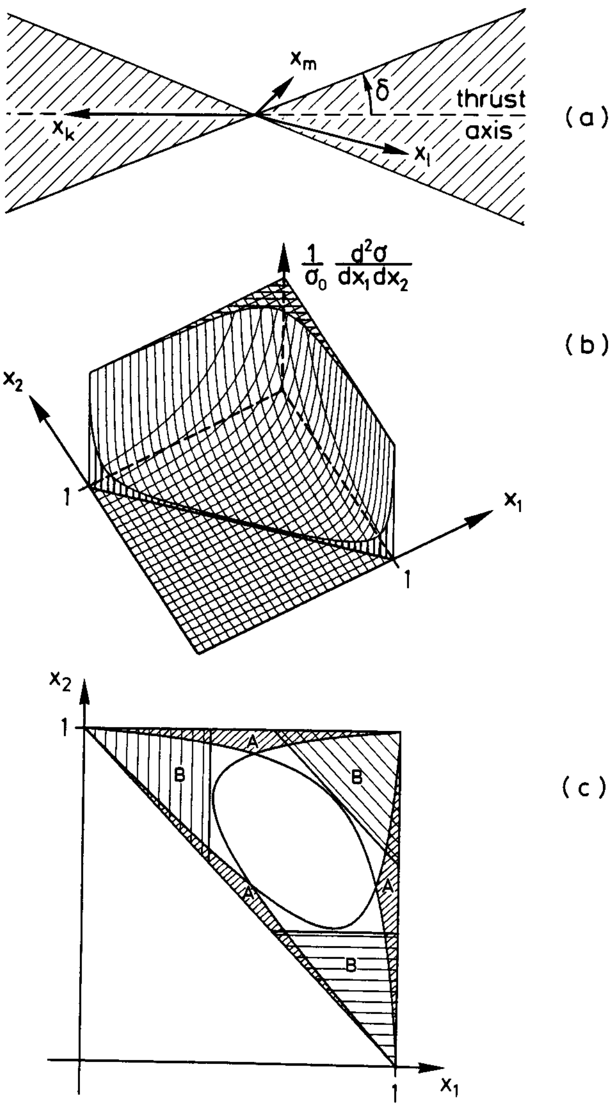

Fig. 1. a The thrust axis of an event $e^+e^- \to q\bar{q}g$ coincides with the direction of the most energetic parton which may be either $q, \bar{q}$ or g. A double cone of half opening angle δ is used in the 2-jet definition. **b** Differential cross section for the reaction $e^+e^- \to q\bar{q}g$ as a function of the fractional energies $x_{1,2} = 2E_{q,\bar{q}}/\sqrt{s}$. The kinematically allowed region is the triangle $x_1 \leqq 1$, $x_2 \leqq 1$, $x_1 + x_2 \geqq 1$. The cross section diverges for $x_1 \to 1$, $x_2 \to 1$ and for $x_3 = (2 - x_1 - x_2) \to 0$. In the figure this is made apparent by cutting the surface which describes the differential cross sections with a plane parallel to the (x_1, x_2)-plane. The resulting cut (at the top of the figure) is hatched horizontally. **c** The 2-jet region in the (x_1, x_2)-plane is hatched. In the subregions A all partons are inside the cone, in B less than a fraction of ε of energy is outside. For this figure $\varepsilon = 0.2$ and $\delta = 30°$ were chosen

around the direction of the most energetic parton labelled k in Fig. 1a. For given values of ε and δ, a 2-jet event is defined as one in which not more than a fraction ε of the total energy is outside the cone. Following the approach of Stevenson [2] the 2-jet cross section σ_2 in first order QCD is computed from the total hadronic cross section σ_{tot} and the 3-jet cross section σ_3, i.e.

$$\sigma_2 = \sigma_{\text{tot}} - \sigma_3, \qquad \sigma_{\text{tot}} = \sigma_0(1 + \alpha_s/\pi).$$

Here the 3-jet cross section

$$\sigma_3 = \int_{R_3} d\sigma_{q\bar{q}g}$$

is obtained by integrating the differential cross section for the quark-antiquark-gluon final state over the 3-jet region R_3. Denoting by $x_i = 2E_i/\sqrt{s}$ the fractional energies of the partons and identifying by the indices $i = 1, 2, 3$ the quark, antiquark and gluon, respectively, one has

$$\frac{1}{\sigma_0}\frac{d^2\sigma_{q\bar{q}g}}{dx_1 dx_2} = \frac{2\alpha_s}{3\pi}\frac{x_1^2 + x_2^2}{(1-x_1)(1-x_2)}.$$

Using the energy constraint $x_1 + x_2 + x_3 = 2$ one obtains the form

$$\frac{1}{\sigma_0}\frac{d^2_{q\bar{q}g}}{dx_1 dx_2} = \frac{2\alpha_s}{3\pi}(x_1^2 + x_2^2)\left(\frac{1}{x_3(1-x_1)} + \frac{1}{x_3(1-x_2)}\right),$$

which explicitly exhibits the "soft" singularity $(x_3 \to 0)$ and the "collinear" singularities $(x_1 \to 1, x_2 \to 1)$. The differential cross section is plotted in Fig. 1b over the x_1, x_2 plane. The cross section σ_3 stays finite only if the region R_3 of integration is free of singularities. We can think of the total triangular region Δ in the x_1, x_2 plane as composed of two non-overlapping regions: a 3-jet region R_3 and a 2-jet region R_2, i.e. $\Delta = R_3 \cup R_2$*. The 2-jet definition introduced at the beginning of this section yields a region $R_2 = A \cup B$ shown as the shaded area in Fig. 1c. (In subregions A all partons are inside the cone, in B less than the fraction ε of the total energy is outside). The complementary region R_3 is then free of singularities.

The fraction of 2-jet events is defined as

$$f_T(\varepsilon, \delta) = \sigma_2/\sigma_{\text{tot}} = 1 - \sigma_3/\sigma_{\text{tot}}.$$

(The subscript T denotes that the thrust direction was used as cone axis). Curves of $f_T(\varepsilon, \delta)$ as a function of δ with ε as a parameter are given in [7].

The Sterman-Weinberg approach to define the fraction of 2-jet events using simply a double cone cannot easily be generalized to 2nd order QCD [12]. Therefore we use first order calculations only.

Experimental values for $f_T(\varepsilon, \delta)$ were obtained by the following procedure.

* where the symbol $\cup$ defines the union of the two sets, without double counting

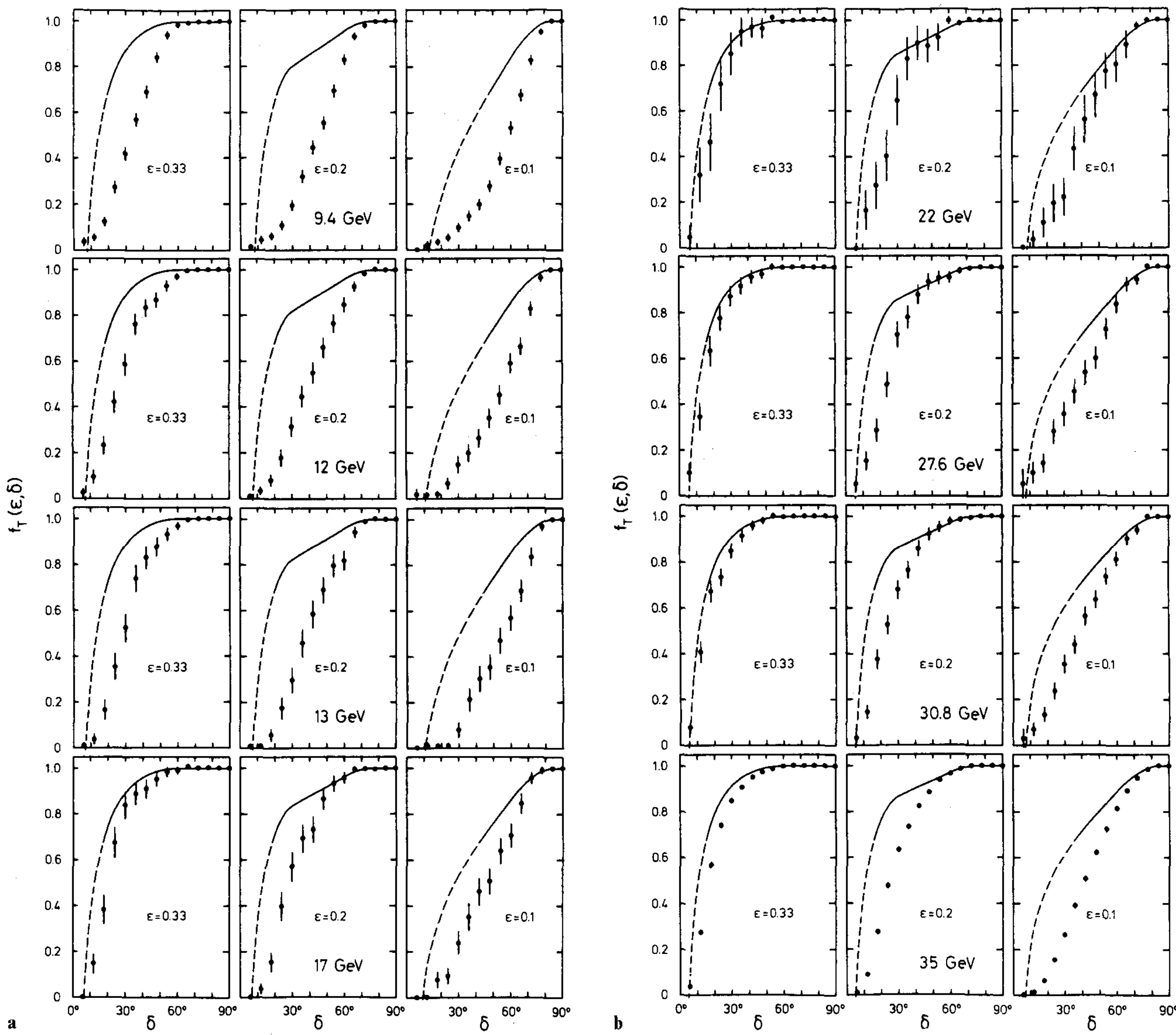

Fig. 2a and b. Measured fraction $f_T(\varepsilon, \delta)$ of 2-jet events compared to first order calculations computed for $\Lambda = 523$ MeV

(a) Charged and neutral particles were considered. All charged particles observed in the tracking chambers were assigned the pion mass. It was assumed that all neutral energy clusters seen in the shower originated from photons. Thus four-momenta for all final state particles were obtained.

(b) The thrust axis [9] was computed from the momentum vectors.

(c) For the half opening angle δ the values $6°, 12°, \ldots, 90°$ were chosen.

(d) Three ε-values (0.1, 0.2, 0.33) were considered in turn.

(e) For given ε and δ the number $N(\varepsilon, \delta)$ of events was determined in which more than the fraction $1-\varepsilon$ of the total visible energy is contained inside the double cone.

(f) The fraction $f_T(\varepsilon, \delta)$ of 2-jet events is the quotient $N(\varepsilon, \delta)/N_{\text{tot}}$ where N_{tot} is the total number of events at the CM energy considered.

(g) The statistical error $\Delta f_T(\varepsilon, \delta)$ was computed ignoring correlations

$$(\Delta f_T(\varepsilon, \delta))^2 = N(\varepsilon, \delta) \cdot (N_{\text{tot}} - N(\varepsilon, \delta))/N_{\text{tot}}^3.$$

(h) The numbers $f_T, \Delta f_T$ were then corrected for detector acceptance and resolution and for the effects of initial state radiation. (For the correction procedure the data points were assumed to be uncorrelated. Only in the 22 GeV data, which are based on very few events, does this approximation disturb the monotonous increase of f_T with δ. Even then this effect is within the computed errors.) The errors of the corrected fraction of 2-jet events also

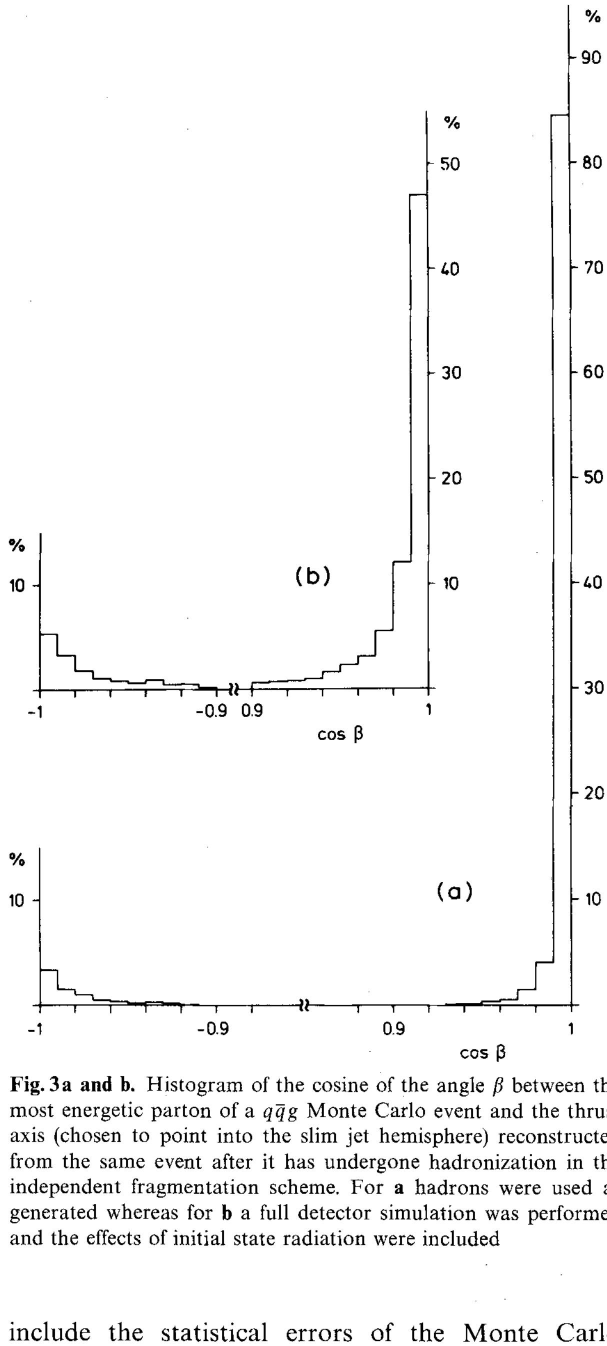

Fig. 3a and b. Histogram of the cosine of the angle β between the most energetic parton of a $q\bar{q}g$ Monte Carlo event and the thrust axis (chosen to point into the slim jet hemisphere) reconstructed from the same event after it has undergone hadronization in the independent fragmentation scheme. For **a** hadrons were used as generated whereas for **b** a full detector simulation was performed and the effects of initial state radiation were included

include the statistical errors of the Monte Carlo correction procedure.

In Fig. 2 we present $f_T(\varepsilon, \delta)$ as a function of δ. The lines represent the first order QCD predictions. Since the computation is done in finite order perturbation theory the 2-jet cross section, and hence $f_T(\varepsilon, \delta)$ becomes negative and diverges for too small δ and/or ε. The region of validity of the $O(\alpha_s)$ calculations is not precisely known. We have indicated this by drawing the computed function f_T as a broken line for $f_T < 2/3$. All lines were obtained with one common value of Λ, the QCD scaling parameter. We used $\Lambda = 523$ MeV. (The reason for the particular choice of Λ will be discussed at the end of this section.) It may be observed that there is a large discrepancy between the pure QCD predictions and the data for the lower CM energies. But as the energy increases the data approach the predictions, particularly for larger ε. However, the data points are always systematically lower than the predictions indicating the importance of non-perturbative effects which result in energy escaping from the cone.

In an attempt to reduce these effects of fragmentation we have tried the following procedure. A plane perpendicular to the thrust axis was used to separate the two jets. For each jet the sum of the absolute values of the momenta perpendicular to the thrust axis was computed. The jet yielding the smaller value was considered to be the "slim jet" originating from a single parton in both $q\bar{q}$ and $q\bar{q}g$ final states. The slim jet thus identified was then replaced by a single particle carrying the same energy as the jet and travelling along the thrust axis. In this way, at least in principle the fragmentation effects of the slim jet are eliminated. We have checked the method using Monte Carlo $q\bar{q}g$ events generated in the IFM (independent fragmentation) scheme at $E_{CM} = 35$ GeV. We found that the angle β between the direction of the most energetic parton and that of the thrust axis (chosen to point into the slim jet hemisphere) is reconstructed with high precision under the assumption of an ideal detector (Fig. 3a). The precision deteriorates when the detector effects and initial state radiation are included (Fig. 3b). However, we still find $\cos\beta > 0.95$ in 70% of all $q\bar{q}g$ events at 35 GeV. The errors in this reconstruction are globally accounted for in the Monte Carlo correction procedure. (The above procedure is based on the assumption that parton and jet direction coincide. This is the case in the independent fragmentation model (IFM) but not in the color string model. In the definition of a Sterman-Weinberg jet it is assumed that the hadronic energy observed in a certain cone corresponds to the parton energy emitted within this cone in complete analogy to the IFM. We have therefore not tried to connect the Sterman-Weinberg quantity $f(\varepsilon, \delta)$ with the picture of string fragmentation.)

In Fig. 4 we show the experimental data evaluated in this way. The errors are statistically only. The lines representing the first order QCD predictions are identical to those in Fig. 2. A fit* of the pre-

* The fraction of 2-jets introduced by Sterman and Weinberg is a cumulative distribution with respect to the opening angle δ. Thus the errors of the quantities $f(\varepsilon, \delta_1)$ and $f(\varepsilon, \delta_2)$ measured at two values of δ are in general correlated. In order to avoid this correlation the fit was actually performed using the differential distribution with respect to δ

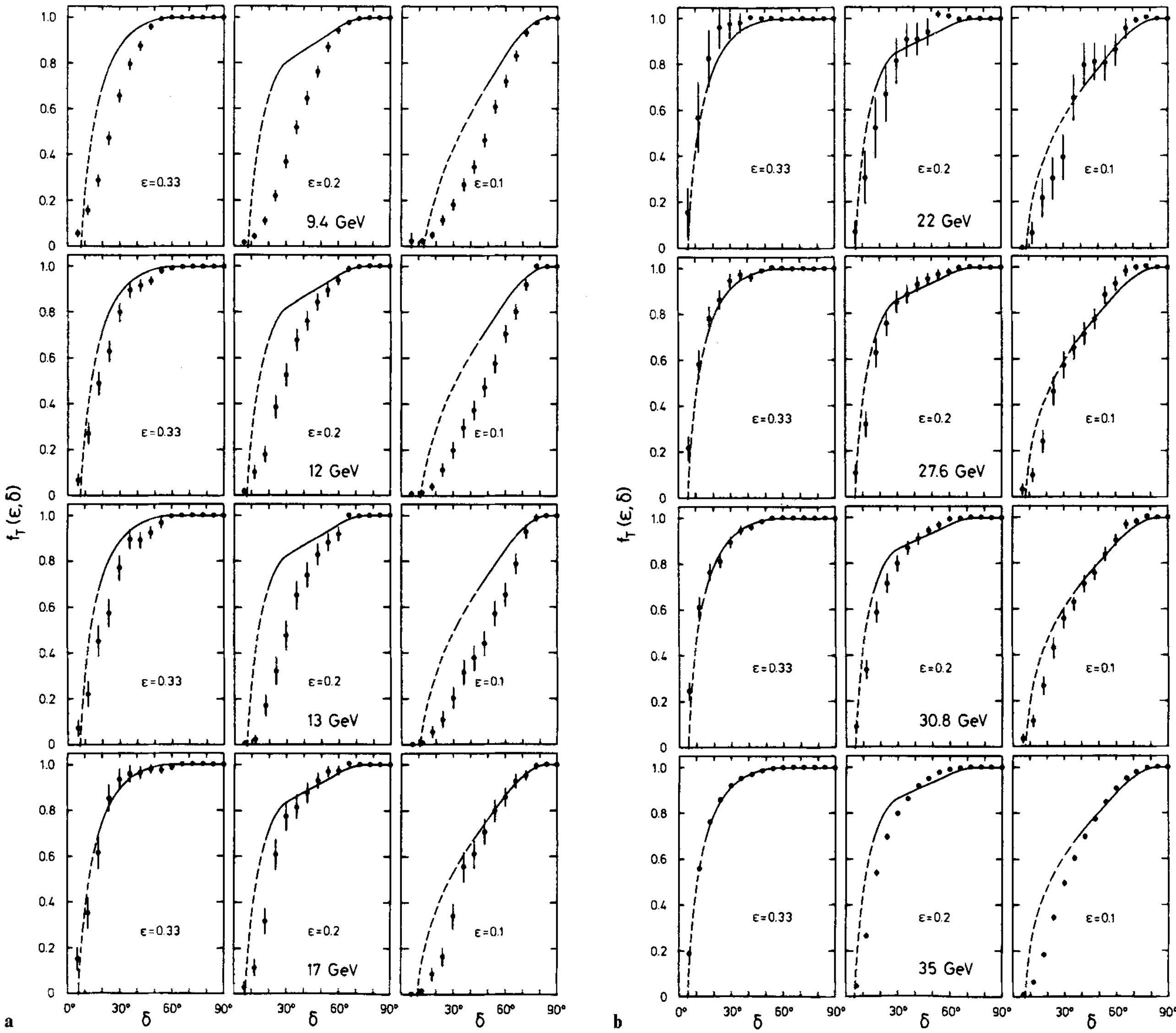

Fig. 4a and b. Fraction $f_T(\varepsilon, \delta)$ of 2-jet events obtained by replacing the slim jet by a single particle compared to first order calculations computed for $\Lambda = 523$ MeV

diction to the data for $\varepsilon = 0.33$ at the highest energy point, where we have good statistics, in the δ-range $18° \leqq \delta \leqq 54°$ yields $\Lambda = 523 {+87 \atop -72}$ MeV, which for 5 flavours corresponds to $\alpha_s = 0.19 \pm 0.01$ in first order QCD. This value of Λ is insensitive to changes in $\delta_{\min}$, the lower limit of the δ-range used in the fit as long as $\delta_{\min} \geqq 12°$. For lower δ non perturbative effects become important. The δ-range used for the fit was chosen on the following grounds. For $\delta > 54°$ the data points of the distribution are almost constant and thus provide no additional information for the fit. For too small values of δ the QCD predictions, as pointed out above, are not expected to be valid. The χ^2 of the fit is 3.1 for 5 degrees of freedom. All curves in Figs. 2 and 4 were computed for this common value of Λ. For $\varepsilon = 0.33$ there is reasonable agreement between data and prediction for $E_{CM} \geqq 17$ GeV. For smaller values of ε and lower energies the data lie systematically below the predicted curves. It is obvious that also the fragmentation of the two other partons influence the distributions $f_T(\varepsilon, \delta)$. Correction of this effect would shift the data points above the curve at high energies. Therefore we consider the Λ value obtained as an upper limit, $\Lambda_{\max} \approx 523$ MeV.

4. Moments of Energy Flow

The expected value of the fractional energy $\eta = E(\delta)/E_{CM}$ emitted inside a double cone of half

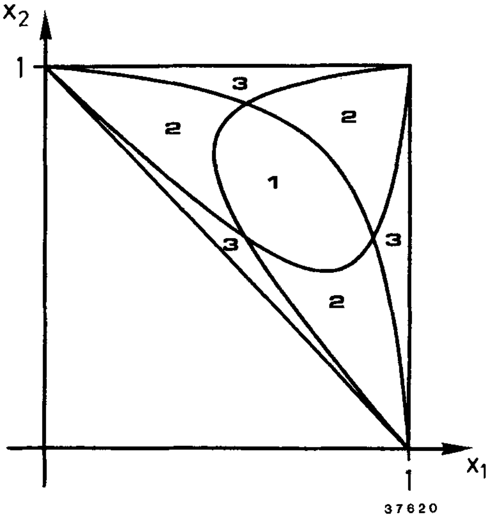

Fig. 5. The regions 1, 2 and 3 in the (x_1, x_2)-plane are those in which 1, 2 or all partons of a $q\bar{q}g$ final state are inside a cone of half opening angle δ (chosen to be 35° for this figure) around the thrust axis. The integration region $R(\delta)$ comprises the regions 1 and 2

opening angle δ centered around the thrust axis can also be computed exactly in first order QCD. The same is true for higher moments of η. The n-th moment can be written as

$$M^{(n)}(\delta) = \int \eta^n \rho(\eta)\, d\eta$$

where $\rho(\eta)$ is the probability density describing the emission of the fractional energy η inside the cone. Making use of the fact that $M^{(n)}(90°) = 1$ and dividing the region of integration into two parts (one in which all partons are inside the cone and another one in which at least one parton is outside) one can write the moment as [10]

$$M^{(n)}(\delta) = 1 - \int_{R(\delta)} (1 - \eta^n)\, \rho(\eta)\, d\eta,$$

$R(\delta)$ being the region where at least one of the final state partons is outside the cone, so that only the $q\bar{q}g$ final state has to be considered. Using again the fractional parton energies x_i as variables we have

$$M^{(n)}(\delta) = 1 - \frac{2\alpha_s}{3\pi} \int_{R(\delta)} (1 - \eta^n) \frac{x_1^2 + x_2^2}{(1 - x_1)(1 - x_2)}\, dx_1\, dx_2,$$

where η is now a function of x_1 and x_2.

The region $R(\delta)$ where at least one parton is outside the cone is indicated in Fig. 5. The singularities remaining in $R(\delta)$ are weighted by the factor $(1 - \eta^n)$ so that the integral is finite. The moments have a weak dependence on E_{CM}. They have been computed in [10].

Experimentally the first moment $M^{(1)}(\delta)$ was measured by the PLUTO collaboration in 1978 [11] at $E_{CM} = 9.4$ GeV. At that time no QCD prediction of $M^{(n)}(\delta)$ was available. The results presented here were obtained with the same data as in section 3 spanning the energy range from 9.4 to 35 GeV. The analysis proceeded as follows.

(a), (b), (c) As in Sect. 3.

(d) The values $n = 1$ and $n = 5$ were considered.

(e) For each event at a given CM energy the fraction $\eta(\delta)$ of the total visible energy deposited in

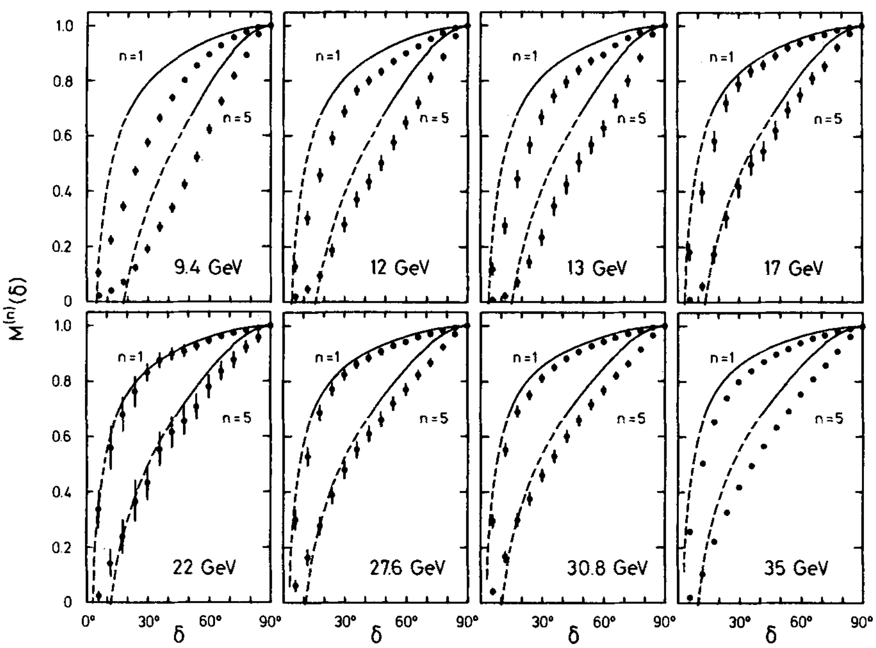

Fig. 6. Measured moments of energy flow $M^{(1)}$ and $M^{(5)}$ compared to first order predictions computed for $\Lambda = 523$ MeV

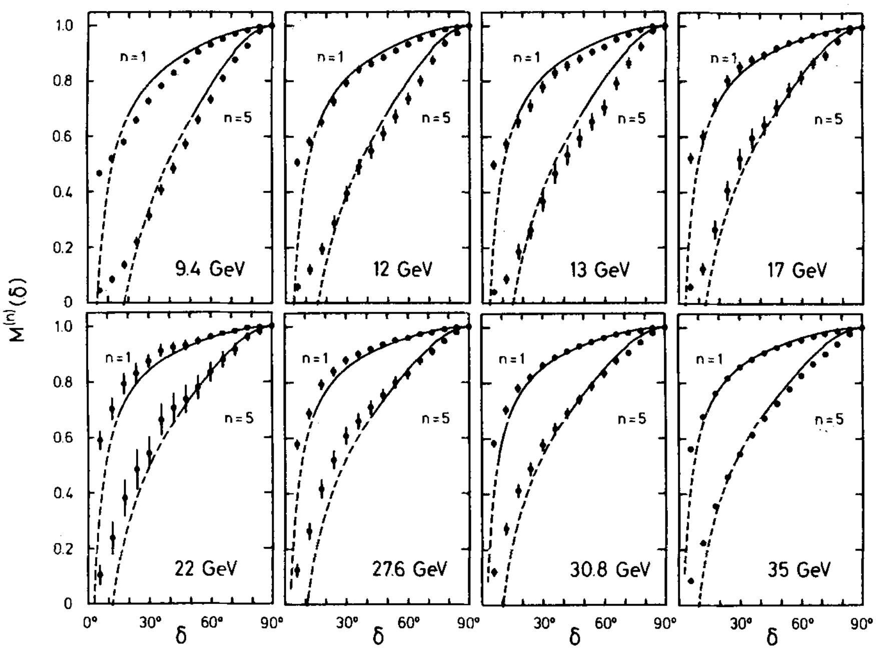

Fig. 7. Moments $M^{(1)}$ and $M^{(5)}$ obtained by replacing the slim jet by a single particle compared to first order prediction computed for $\Lambda = 523$ MeV

a double cone of half opening angle δ centered around the thrust axis was obtained.

(f) The moments $M^{(n)}(\delta)$ were computed by averaging $\eta^{(n)}(\delta)$ over all events observed at the same CM energy.

(g) The statistical errors $\Delta M^{(n)}(\delta)$ were calculated.

(h) Corrections as in Sect. 3.

The results of this analysis are shown in Fig. 6. The lines are the QCD prediction for the same value of $\Lambda = 523$ MeV used in Sect. 3. We again estimate the range of validity of the QCD prediction, indicated by full lines, by requiring that $M^{(n)}(\delta) > 2/3$. The data are systematically below the predictions, i.e. there is less energy emitted inside the cone than expected by perturbative QCD. However, the data come closer to expectation as the energy increases. In order to reduce non-perturbative effects we also applied the procedure (described at the end of Sect. 3) of replacing the slim jet by a single particle. These results are presented in Fig. 7. Now for $E_{CM} \geqq 17$ GeV and $n=1$ the data follow the QCD curves. Since fragmentation effects have been removed only partially we conclude again that the chosen Λ value is an upper limit. The remaining non-perturbative effects can also explain the discrepancies for energies below 17 GeV.

5. Summary and Conclusions

The Sterman-Weinberg cross section for 2-jet production in e^+e^- annihilation has not been measured previously probably because of difficulties in matching the theoretical and experimental jet definitions. Using the thrust axis as the jet axis for both hadron and parton events we can readily obtain the 2-jet cross section from the data and also compute it in first order QCD. Comparing the two results in the CM range between 9.4 and 35 GeV we have found that the experimental 2-jet cross section approaches the first order predictions from below, the discrepancy being smallest for large ε and high energies. We attribute the discrepancy to non-perturbative effects. They can be suppressed to some extent by replacing the slim jet by a single particle having the jet energy. After applying this procedure, the data for $E_{CM} \geqq 17$ GeV are fitted to the scale parameter Λ. Since there are remaining fragmentation effects from the low energy partons, we use the result of the fit as an upper limit which is rather independent of fragmentation models. The limit $\Lambda_{max} \approx 523$ MeV is in reasonable agreement with other first-order determinations of this QCD parameter.

We have also measured the average normalized energy flow $\langle\eta\rangle = \langle E(\delta)/E_{CM}\rangle$ within a double cone of half opening angle δ centered around the thrust axis as well as the fifth moment $\langle\eta^5\rangle$. The comparison with first order QCD revealed features similar to our results on the fraction of 2-jets. The data lie systematically below the prediction but approach it with increasing energy. After using our simple fragmentation suppression procedure we again find good agreement between experimental and theoretical values for $E_{CM} \geqq 17$ GeV, using the same value of Λ.

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