OBSERVATION OF QCD EFFECTS IN TRANSVERSE MOMENTA OF e^+e^- JETS

PLUTO Collaboration

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Probability distributions of the total transverse momenta ($K_\perp$) of charged particles produced in hadronic jets in e^+e^- annihilations have been measured for center of mass energies in the range from 9.2 to 31.6 GeV. A linear increase of the average $K_\perp^2$ with Q^2 is observed. The data are successfully compared with high order QCD predictions (according to a simple $q\bar{q}$ picture supplemented by multiple emission of soft gluons). Deviations from this picture at the highest energies and large $K_\perp$ are then analyzed in terms of hard gluon bremsstrahlung and qualitative agreement is found with first order QCD predictions. Scaling "in the mean" is found to be valid both for jet and single particle transverse momenta.

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Hadron production in e^+e^- annihilation, above ≈ 5 GeV c.m. energy, is well described by the production of a quark–antiquark pair and its subsequent fragmentation into two hadron jets [1,2]. Quantum chromodynamics (QCD), the candidate theory of strong interactions, predicts that the pure $q\bar{q}$ topology will be altered significantly with increasing energy due to gluon emission. Deviations from the two-jet topology have in fact been observed at the highest energies of PETRA and have been interpreted as clear QCD effects (hard gluon bremsstrahlung [3], soft gluon effects observed in acollinearity distributions [4]).

The QCD prediction of hard gluon bremsstrahlung with its consequences such as events with planar three-jet configurations, has usually been tested by comparing experimental distributions of jet variables and of inclusive particle data with specific (partly phenomenological) models. These models consider first and occasionally second order QCD predictions for the production of partons and use empirically derived algorithms to describe the fragmentation of quarks and gluons into hadrons.

In order to provide quantitative and model independent tests of QCD at the parton level, the data must be compared to the theoretical predictions in variables which are insensitive to the details of the hadronization process of quarks and gluons. The total transverse jet momentum has been proposed as such a variable whose measured distribution would be a direct test of QCD beyond the leading order [5]. The theoretical prediction rests on exponentiated forms obtained upon summation of all orders in perturbation theory in the leading dilogarithmic approximation and includes the correlation imposed by transverse momentum conservation in a jet. Due to this conservation, the partonic distribution is expected not to be modified appreciably by the fragmentation of quarks and gluons into real hadrons.

In this letter we present measurements of distributions of the full transverse momentum ($K_\perp$) for the charged particles of hadronic jets produced in e^+e^- annihilations for c.m. energies in the range from 9.2 to 31.6 GeV and compare them to those predictions. Our data were taken with the magnetic detector PLUTO at the e^+e^- storage rings DORIS and PETRA. The detector and data reduction have been described elsewhere [6]. The results of the analysis of hadronic final states in terms of two- and three-jets have been published [2,4,6].

In the present analysis we determine for each event the direction of maximum thrust for all particles (charged and neutral). The full transverse momentum $K_\perp$ is defined by the following procedure. We first divide each event by a plane orthogonal to the thrust axis and treat the particles on each side separately (thus two $K_\perp$ entries per event are obtained). We then compute for each side $K_\perp = |\Sigma_i^N \boldsymbol{p}_{\perp i}|$, where $\boldsymbol{p}_{\perp i}$ is the transverse momentum vector of a particle relative to the thrust axis and the sum runs over the particles on one side of an arbitrary dividing plane containing that axis. This dividing plane is initially chosen to contain the beam axis, but in order to avoid dynamical biases the dividing plane is then rotated around the thrust axis by $\pm 120^\circ$ and $K_\perp$ is measured in each case. The average value of these three measurements is used to obtain the $K_\perp$ distributions.

Since particles travelling close to the beam axis escape the detector acceptance, we reduce the contribution of incompletely measured jets by considering only events with thrust axes inclined more than 45° to the beam axis. Constraints have been applied to the measured quantities to ensure that energy is conserved and that the missing mass is positive. Only charged particles, whose pattern recognition and momentum resolution is better than that of neutrals, have been used for computing the $K_\perp$'s and $p_\perp$'s. $K_\perp$ for charged particles is smaller than or equal to the total $K_\perp$. However, we can overcome this by exploiting a nice feature of the expected distribution, namely the "scaling in the mean" (see below): if we measure the reduced total transverse momentum $K_\perp/\langle K_\perp\rangle$, where $\langle K_\perp\rangle$ is the average observed $K_\perp$, the distributions for all particles or for a sample of them are expected to become identical.

All experimental distributions have been corrected for acceptance, detection efficiency, and resolution of our detector as well as for electromagnetic radiation using a Monte Carlo calculation. The hadron production model is based on that of Hoyer et al. [7] and includes hard gluon emission as well as 4 or 5 quark flavours in the final state (i.e. u, d, s, c quarks for 9.4 GeV data and u, d, s, c, b quarks for 12–31.6 GeV data). For our selected events, the correction is completely negligible at high $K_\perp$ values and amounts to an $\approx 8\%$ change at the most probable $K_\perp$ at each energy. We have checked that our corrections are practically model independent by comparison to a different Monte Carlo calculation based on a model by Ali et al. [8]. Both these models are partly phenomenological and reproduce the measured distributions quite well. In the final distributions some of the energy points (9.4, 27.5, 30.0, 31.05) are averages over energy intervals, typically of 1 GeV width.

Theoretically the probability distribution $(\mathrm{d}P/\mathrm{d}K_\perp)$ of the $\mathrm{q\bar{q}}$ jet transverse momentum is given by [5,9] [‡1]

$$\frac{\mathrm{d}P}{\mathrm{d}K_\perp} = K_\perp \int_0^\infty \xi \mathrm{d}\xi J_0(\xi K_\perp) \exp\Bigg(-\frac{16}{3\pi} \times \int_0^{\bar{k}_\perp} \frac{\mathrm{d}q_\perp}{q_\perp} \ln(Q/q_\perp)\,\alpha_\mathrm{s}(q_\perp)[1 - J_0(\xi q_\perp)]\Bigg), \tag{1}$$

where $\alpha_\mathrm{s}(q_\perp)$ is the running coupling constant and $\bar{k}_\perp$ is the effective phase space limit for the emitted gluons, which is proportional to Q. (Its actual determination for our analysis will be discussed below.) Eq. (1) has been derived [5] by an explicit sum of all orders in α_s, in the leading double logarithmic approximation and assuming massless quarks. Transverse momentum conservation is also explicitly taken into account. From eq. (1), which is properly normalized to unity, one also gets:

$$\langle K_\perp^2 \rangle = \frac{4}{3\pi} \int_0^{\bar{k}_\perp} \mathrm{d}(q_\perp^2) \ln(Q^2/q_\perp^2)\,\alpha_\mathrm{s}(q_\perp)\,, \tag{2}$$

which for large Q^2 leads to $\langle K_\perp^2 \rangle \propto Q^2$ + const., up to logarithmic terms.

To extend the distribution (1) to the region of small $K_\perp$, $\alpha_\mathrm{s}(k_\perp)$ is replaced by an effective coupling constant $\alpha_\mathrm{eff} \approx 0.48$. This value has been determined in a previous independent analysis [11], based on duality, which successfully compares all data for the ratio

$$R \equiv \sigma(\mathrm{e^+e^-} \to \mathrm{hadrons})/\sigma(\mathrm{e^+e^-} \to \mu^+\mu^-)\,,$$

with first order QCD predictions. Then the low energy domain ($Q \lesssim 3$ GeV) determines an effective value of α_s as given above, whereas at higher energies, the usual asymptotic freedom estimated $\alpha_\mathrm{s}(Q) = 1/[2b \ln(Q/\Lambda)]$ is used, with $b = 25/(12\pi)$ and $\Lambda \approx 0.7$ GeV. Then eq. (2) can be rewritten as

$$\langle K_\perp^2 \rangle_{\mathrm{q\bar{q}}} = \tfrac{1}{2}\beta \bar{k}_\perp^2\,, \tag{3}$$

with

$$\beta = \tfrac{8}{3}(\alpha_\mathrm{eff}/\pi)[\ln(Q^2/\bar{k}_\perp^2) + 1]\,. \tag{4}$$

In order to compare the predicted $(\mathrm{d}P/\mathrm{d}K_\perp)$ with the data at all energies, we shall make use of the observation [12,5] that this distribution is expected to approximately scale with Q^2 as a function of $K_\perp/\langle K_\perp \rangle$, where the average $\langle K_\perp \rangle_{\mathrm{q\bar{q}}}$ of (1) is given by

$$\langle K_\perp \rangle_{\mathrm{q\bar{q}}} \simeq \tfrac{1}{4}\sqrt{\pi}\,\beta \bar{k}_\perp \frac{\Gamma(1/2 + \beta/2)}{\Gamma(1 + \beta/2)}\,. \tag{5}$$

Then the distribution $\mathrm{d}P/\mathrm{d}(K_\perp/\langle K_\perp \rangle)$ depends only on β, and using eqs.(3)–(5) on α_eff, i.e. it is expected to be approximately independent of energy ("scaling in the mean").

We first show in fig. 1 (circles) the energy dependence of the experimental $\langle K_\perp^2 \rangle$ of all charged particles. The full line is a linear fit to our results. The almost linear increase of $\langle K_\perp^2 \rangle$ with Q^2 is much more pronounced than for the case of single particle inclusive production [3]. A linear rise is expected from multiple soft gluon radiation described by eq. (2) [see also eq. (3): the slope is not directly predicted]. Notice, however, that hard gluon bremsstrahlung would also produce a similar increase with Q^2 [13]. Therefore the observed feature should result from the two combined effects. The linear fit to the data (cir-

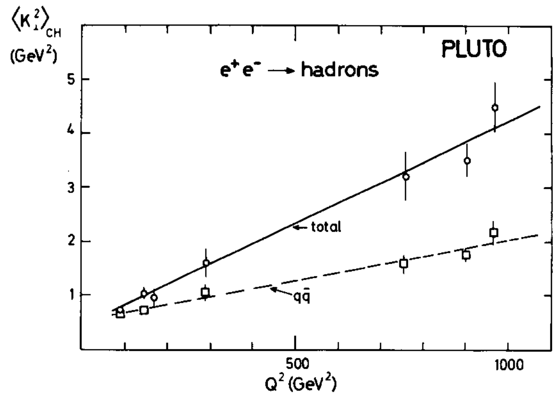

Fig. 1. Average squared transverse momentum relative to the thrust axis (from charged particles only) versus squared c.m. energy. Circles: directly measured values. Squares: fitted $\langle K_\perp^2 \rangle_\mathrm{ch}$ attributed to $\mathrm{q\bar{q}}$ jets (see text). Both full and dashed lines are linear fits to the data.

[‡1] For the Drell–Yan process the same formula has been proposed by Parisi and Petronzio [10].

cles) gives

$$\langle K_\perp^2\rangle_{\mathrm{ch}} = (0.54 \pm 0.01) + (3.84 \pm 0.01) 10^{-3} Q^2 (\mathrm{GeV}^2),$$

with negligible errors. The square points will be explained below.

Next we show in fig. 2 the experimental distribution $\mathrm{d}P/\mathrm{d}(K_\perp/\langle K_\perp\rangle)$ at several c.m. energies. The data are compared with the absolute prediction of eq. (1) in the reduced variable $K_\perp/\langle K_\perp\rangle$, computed for $Q = 9.4$ GeV and $\alpha_{\mathrm{eff}} = 0.48$ (full curve). In addition to the full transverse momentum data we also plot in fig. 2 the distribution of the single particle reduced transverse momentum $\mathrm{d}P/\mathrm{d}(p_\perp/\langle p_\perp\rangle)$ at 9.4 and 30.0 GeV. It has been observed [5,12] that in fact the extrapolation of the theoretical $K_\perp$ distributions at very low momenta describes very accurately the $p_\perp$ distributions.

As demonstrated in fig. 2, our results nicely overlap in a wide range of energies and agree also quantitatively with the theoretical prediction. It is rather striking that the same universal curve describes the $p_\perp$ and $K_\perp$ distributions in a wide range of transverse momenta ($p_\perp \lesssim 1.5$ GeV, $K_\perp \lesssim 4$ GeV). This scaling in the mean had been observed empirically for inclusive $p_\perp$ distributions in pp interactions [14], but only recently it was shown to be deducible from QCD [12] [‡2].

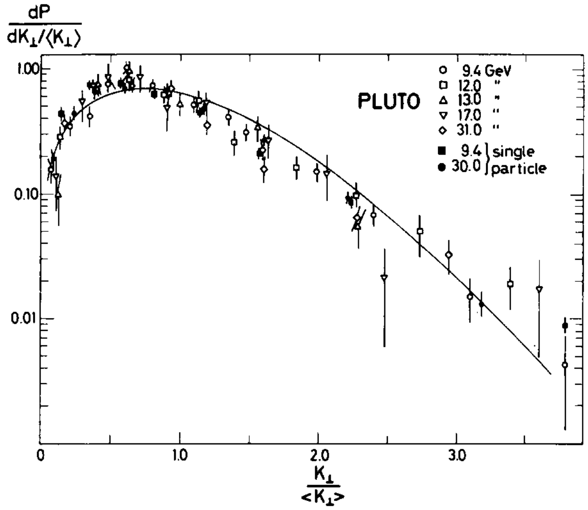

Fig. 2. Distributions of the reduced variable $K_\perp/\langle K_\perp\rangle$ at the quoted c.m. energies. The full line is the theoretical expectation computed at 9.4 GeV. Also shown (full points) are the experimental distributions of the corresponding single particle reduced variable $p_\perp/\langle p_\perp\rangle$ at 9.4 and 30 GeV. (In order not to overload the figure, we show here only one of our high energy distributions, which are reported in fig. 4.)

A more detailed analysis shows, however, that deviations occur from the simple $\mathrm{q\bar{q}}$ picture at high energies and large $K_\perp$, as is expected if hard gluon bremsstrahlung sets in. We therefore make a separate analysis of the $K_\perp$ distributions at each energy, assuming a mixture of $\mathrm{q\bar{q}}$ jets [eq. (1)] and $\mathrm{q\bar{q}g}$ jets. For the latter, the perturbative first order $K_\perp$ distribution with respect to the thrust axis is given by

$$\frac{1}{\sigma_0}\frac{\mathrm{d}\sigma(\mathrm{q\bar{q}g})}{\mathrm{d}x_\perp^2} = \frac{1}{\sigma_0}\int_{T_{\min}}^{1-x_\perp^2} \frac{\mathrm{d}\sigma(\mathrm{q\bar{q}g})}{\mathrm{d}T\,\mathrm{d}x_\perp^2}\,\mathrm{d}T, \qquad (6)$$

where

$$x_\perp^2 = (4K_\perp^2/Q^2) = (4/T^2)(1-x_{\mathrm{q}})(1-x_{\mathrm{\bar{q}}})(1-x_{\mathrm{g}}),$$

T is the thrust variable, σ_0 is the lowest order $\mathrm{q\bar{q}}$ cross section, $T_{\min}$ is the solution of

$$x_\perp^2 = (4/T_{\min}^2)(1-T_{\min})^2(2T_{\min})^{-1},$$

and the integrand of the rhs of eq. (6) is well known [13].

In figs. 3 and 4 we present our probability distributions for $K_\perp$ at various energies and compare them with the theoretical predictions. The full curves describing $\mathrm{q\bar{q}}$ jets have been obtained from eq. (1) for $\alpha_{\mathrm{eff}} = 0.48$,

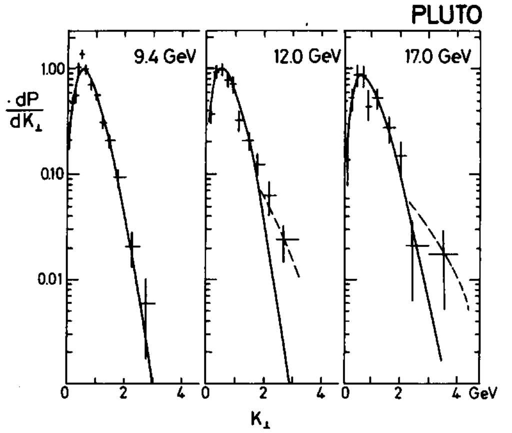

Fig. 3. Distributions of the jet transverse momentum $K_\perp$ at 9.4, 12.0, 17.0 GeV compared with QCD expectation (see text).

[‡2] The analogy between $\mathrm{e^+e^-}$ and pp jets is presently being exploited at CERN by the CERN–Bologna–Frascati–Bari Collaboration (see for instance Basile et al. [15]).

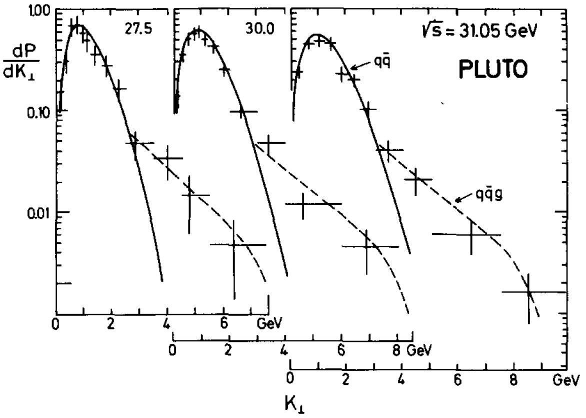

Fig. 4. Same as fig. 3 for 27.5, 30.0 and 31.05 GeV average c.m. energies. (The two last points for 30 GeV do not appear in fig. 2, being out of range.)

fitting $\langle K_\perp^2 \rangle_{q\bar{q}}$ at each energy to all but the highest $K_\perp$ points. [This, according to eq. (3), is equivalent to determining $\bar{k}_\perp^2$.] The resulting values for $\langle K_\perp^2 \rangle_{q\bar{q}}$ are plotted in fig. 1 (squares, broken line). We get a linear increase also in this case as expected, and it is clear that the broadening of a QCD $q\bar{q}$ jet with Q^2 accounts only for about a half of the actual increase of the measured $\langle K_\perp^2 \rangle_{ch}$.

The large $K_\perp$ tail in figs. 3, 4 (dashed curve) is obtained from eq. (6), which also scales with $\langle K_\perp \rangle$. Because only a fraction of the gluon's transverse momentum is retained in our averaging procedure, an appropriate rescaling factor has to be applied. This has been fixed by normalizing the full (soft + hard) $K_\perp$ distribution to the data. The stability and uniqueness of our procedure has been carefully checked. A value $\Lambda \simeq 0.7$ has been used for $\alpha_s(Q)$. Our results do not depend appreciably on $\alpha_s(Q)$ due to the lack of absolute normalization.

In fig. 3 we observe that the 9.4 GeV data are very well described by simply a $q\bar{q}$ jet, the hard gluon contribution being small. As Q increases the effect of hard gluon bremsstrahlung becomes more and more important, being essential to understand the data at large $K_\perp$ at the highest values of Q (fig. 4). It also accounts for the difference in the two lines in fig. 1.

We conclude that the $K_\perp$ distributions as well as the first observation of the linear increase of $\langle K_\perp^2 \rangle_{ch}$ with Q^2 give strong support to soft gluon resumming formulae in QCD and to the process of single hard gluon bremsstrahlung. We note that our analysis procedure makes no use of phenomenological models of the hadronization of quarks and gluons. We also find that scaling in the mean is valid for both the $K_\perp$ as well as the inclusive $p_\perp$ distributions (it is expected to set in more rapidly for $K_\perp$ than $p_\perp$ as a function of Q), perhaps indicating that hadronization retains in transverse momentum much of the primary parton properties. Moreover, a universal scaling curve approximately describes the relevant distributions at all energies suggesting a similar basic mechanism for different processes (e^+e^- and pp). The agreement of the data and the predictions also support the reliability of the parametrization of QCD at small Q^2 with an effective coupling constant.

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