**ANGULAR DISTRIBUTIONS FOR HIGH-MASS JET PAIRS
AND A LIMIT ON THE ENERGY SCALE OF COMPOSITENESS FOR QUARKS
FROM THE CERN $p\bar{p}$ COLLIDER**

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ABSTRACT

Angular distributions of high-mass jet pairs ($180 < m_{2J} < 350$ GeV) have been measured in the UA1 experiment at the CERN $p\bar{p}$ Collider ($\sqrt{s} = 630$ GeV). We show that angular distributions are independent of the subprocess centre-of-mass (c.m.) energy over this range, and use the data to put constraints on the definition of the Q^2 scale. The distribution for the very high mass jet pairs ($240 < m_{2J} < 300$ GeV) has also been used to obtain a lower limit on the energy scale Λ_c of compositeness of quarks. We find $\Lambda_c > 415$ GeV at 95% confidence level.

1. INTRODUCTION

In this paper we present results based on measurements of angular distributions of high-mass jet pairs in the UA1 experiment at the CERN Super Proton Synchrotron (SPS) $p\bar{p}$ Collider. In quantum chromodynamics (QCD), parton-parton scattering produces jets with an angular distribution which is peaked strongly at a small centre-of-mass (c.m.) scattering angle. The theoretical prediction of the two-jet angular distribution in QCD is particularly straightforward. The shape of this angular distribution is almost independent of any knowledge of the proton structure functions, which enter only through their dependence on a momentum-transfer parameter Q^2 , which is logarithmic and theoretically relatively well understood. Beyond QCD, any modification to the parton-parton interaction—arising, for example, from a finite parton size implying substructure—will modify this angular distribution. Typically, such effects will lead to a more spherically symmetric angular distribution, i.e. more events at wide angles relative to the QCD prediction. Measurements of angular distributions have the important advantage of being relatively free from systematic errors, essentially because the c.m. scattering angle depends primarily on the measurement of jet directions, which are well determined in the UA1 detector.

In this analysis the angular distribution of high-mass jet pairs ($200 < m_{2J} < 240$ GeV) is compared with leading-order QCD predictions, including scale-breaking effects. The calculation of scale-breaking effects depends on the momentum-transfer parameter Q^2 , which appears as the argument of the QCD coupling constant $\alpha_s(Q^2)$ and the effective structure function $F(x, Q^2)$. At fixed c.m. scattering angle θ , Q^2 is proportional to the parton-parton c.m. energy squared, $\hat{s}$. However, the θ -dependence of Q^2 at fixed $\hat{s}$ is not known. Fitting the shape of the experimental angular distribution, we obtain information on the Q^2 scale which is related to the higher-order QCD corrections [1]. The angular distribution at very high masses ($240 < m_{2J} < 300$ GeV) is fitted within the context of a model by Eichten et al. [2] to obtain a limit on the energy scale of compositeness of quarks Λ_c .

2. DATA SAMPLE

The data sample corresponding to an integrated luminosity of $\approx 260 \text{ nb}^{-1}$ was obtained with the UA1 detector during the 1984 $p\bar{p}$ Collider run at $\sqrt{s} = 630$ GeV. Some details of the data selection and processing for this sample have been given previously [3]. The hardware jet trigger required a localized transverse energy E_T deposition anywhere in the central calorimetry (pseudorapidity $|\eta| < 3.0$) with thresholds $E_T > 25$ or 30 GeV depending on running conditions. In the off-line filter program, jets were defined using the UA1 jet algorithm [4]. The energy and momentum of a jet are obtained by forming scalar and vector sums of energies in all calorimeter cells within a cone of $\Delta R < 1$ with respect to the jet axis. The parameter ΔR is defined by $(\Delta R)^2 = (\Delta\eta)^2 + (\Delta\phi)^2$, where $\Delta\eta$ is the separation in pseudorapidity and $\Delta\phi$ is the separation in azimuthal angle (in radians) measured around the beam direction. Events with at least one jet of transverse momentum p_T larger than 40 GeV are retained by the filter program for further processing.

Corrections ($\approx +15\%$) are applied to the energy and momentum of each jet mainly to account for the energy loss outside the cone [5], on the basis of a Monte Carlo simulation using ISAJET [6]. Further corrections at the few percent level are applied to account for minor adjustments in the calibration constants since the time of the original filtering. Events with total energy E_{tot} greater than 700 GeV or with total missing transverse energy vector $|\vec{E}_T^{\text{miss}}|$ greater than 2.5σ (where $\sigma = 0.7\sqrt{\Sigma E_T}$ and ΣE_T is the total scalar transverse energy) are rejected from the sample. These cuts eliminate multiple interactions and events with associated beam-halo hits.

3. ANALYSIS OF ANGULAR DISTRIBUTIONS

For this analysis, events are selected with two or more jets of which one necessarily satisfies the filter threshold ($p_T > 40$ GeV). The procedures used to calculate kinematic variables are similar to those used in a previous publication [7]. For each event the two-jet mass m_{2J} was calculated using the fully corrected four-momenta of the two highest p_T jets. The c.m. scattering angle θ was calculated as the angle between the axis of the jet pair and the beam direction in the jet-jet rest frame [8]. In terms of $\cos\theta$, the variable χ is defined as

$$\chi \equiv (1 + \cos\theta)/(1 - \cos\theta). \quad (1)$$

In this variable, the event rate is expected to be approximately uniform [9].

In fig. 1 the angular distribution for events in the range $180 < m_{2J} < 240$ GeV is plotted as a function of $\cos\theta$. A small correction has been applied to the measured distribution to account for the inefficiency of the filter selection. This is necessary because the filter selection was made before all the jet-energy corrections were applied, and the effective p_T cut is no longer exactly the same for all events. The correction has been applied as a function of the corrected p_T 's of the two highest p_T jets and their pseudorapidities. The correction has the tendency to increase the event rate at the highest values of $\cos\theta$. For the $\cos\theta$ range plotted, this correction is everywhere less than 5%. A further correction has been made to the distribution to account for the angular dependence of the calorimeter resolution for jets. In particular the resolution deteriorates somewhat in the region of the overlap of barrel and end-cap calorimetry ($|\eta| \sim 1.5$). In the case of a falling mass spectrum, this leads to systematic effects in the $\cos\theta$ distribution which have been corrected for using the results from a Monte Carlo simulation. This correction has the tendency to reduce the event rate at large $\cos\theta$ values but is everywhere less than 5%. The solid curve in fig. 1 represents the theoretical prediction using EHLQ structure functions [10] with $\Lambda_{QCD} = 0.2$ GeV. For this calculation [11] it has been assumed that $Q^2 = p_T^2 [= (\hat{s}/4) \sin^2\theta]$. The theoretical curve provides a good description of the data.

In QCD we expect the shape of the angular distribution to be rather independent of the subprocesses c.m. energy $\sqrt{\hat{s}}$. To test this, we define a wide-angle to small-angle ratio $R(4, 9)$, such that

$$R(4, 9) = \sigma(1 < \chi < 4)/\sigma(4 < \chi < 9), \quad (2)$$

corresponding to the ratio of event rates between $0.0 < \cos\theta < 0.6$ ($90^\circ > \theta > 53^\circ$) and $0.6 < \cos\theta < 0.8$ ($53^\circ > \theta > 37^\circ$). In fig. 2 we plot the wide-angle to small-angle ratio as a function of the two-jet mass m_{2J} . We conclude that within the experimental errors the shape of the angular distribution does not depend on the subprocess c.m. energy. The mean value of $R(4, 9)$ for the data in the mass range $180 < m_{2J} < 240$ GeV is given by $R(4, 9) = 0.521 \pm 0.025$. The solid curve is the QCD prediction (for $Q^2 = p_T^2$). Over this large range in mass, the QCD prediction is almost constant and is given by $R(4, 9) \approx 0.55$, in reasonable agreement with the data.

Figure 3 shows the normalized χ -distribution, $(1/\sigma)(d\sigma/d\chi)$, in the range $200 < m_{2J} < 240$ GeV. We note that for a given mass m_{2J} the available range in χ is limited by the requirement that the events satisfy the filter threshold. Clearly, for a given filter threshold, the available range in χ increases with increasing mass m_{2J} , and the data are plotted over the range $1 < \chi < 13$. The χ -distribution has been corrected for the effects of filter inefficiencies and smearing, as discussed for the $\cos\theta$ distribution. The solid curve in fig. 3 represents the QCD prediction assuming $Q^2 = p_T^2$, and provides a good fit to the data [$\chi^2/\text{degree of freedom (DOF)} = 8.6/5$].

We have performed fits for other choices of the definition of the Q^2 scale. In particular we have set $Q^2 = p_T^2/A$ in the theoretical calculation discussed above, and fitted the data (rebinned in bins of $\Delta\chi = 2$) for the parameter A . Although this form ($Q^2 = p_T^2/A$) is not completely general, it is representative of most of the forms that have appeared in the literature [10, 12]. The results are shown in fig. 4, where the chi-squared is shown as a function of the choice of the Q^2 scale. From the data the preferred choice is given by $Q^2 \approx p_T^2$, although it is clear that the Q^2 scale is not very well constrained ($67p_T^2 > Q^2 > p_T^2/10$ at 90% CL). We have also tried to fit the data with $Q^2 = \hat{s}$, for which the scale-breaking effects are independent of the angle, and find that this choice is excluded by the data (chi-squared/DOF = 42.3/5).

In conclusion, although $Q^2 = \hat{s}$ is excluded by the data, it is clear that the data do not place strong constraints on the definition of an angle-dependent Q^2 scale. Thus in the analysis of the very high mass angular distribution which follows, we simply choose to define the Q^2 scale such that $Q^2 = p_T^2$, although we anticipate that the results will be rather insensitive to this choice.

4. A LIMIT ON QUARK SUBSTRUCTURE

In this section we analyse the angular distribution of very high mass jet pairs ($240 < m_{2J} < 300$ GeV) to obtain a limit on the energy scale of compositeness of quarks. According to QCD $\sim 50\%$ of the jet pairs in this mass region result from the quark-antiquark scattering. In composite models, quarks are considered to be bound states of more fundamental constituents, e.g. preons. These constituents are bound together in quarks by a new, very strong, metacolour interaction. At very high energies the metacolour forces lead to an effective four-fermion interaction between the quarks of strength $\pm g^2/\Lambda_c$, where Λ_c is the energy scale of compositeness. The effective coupling constant g is unknown, but by convention Λ_c is defined such that $g^2/4\pi = 1$.

In the model of Eichten et al. [2, 10] the quark-antiquark scattering ($u\bar{u}$) cross-section can be written

$$d\sigma/d\chi \approx 8/9 (\pi\alpha_s^2/\hat{s}) \left(1 \pm (1/\alpha_s)(\hat{s}/\Lambda_c^2)[\chi^3/(\chi+1)^4] + (3/\alpha_s^2)(\hat{s}/\Lambda_c^2)^2 [\chi^2/(\chi+1)^4] \right) \quad (3)$$

In eq. (3) the first term represents the normal QCD interaction neglecting all χ -dependent terms, the last term represents the direct effect of the contact interaction, and the middle term represents the interference. In the analysis which follows, complete leading-order formulae for all the subprocess scattering cross-sections have been used in the calculation of theoretical predictions.

Figure 5 shows the normalized angular distribution, $(1/\sigma)(d\sigma/d\chi)$, for the very high mass jet-pairs ($240 < m_{2J} < 300$ GeV). The data are plotted over the range $\chi = 1$ to 19 ($\cos\theta = 0.0$ to 0.9). The solid curve is the QCD prediction (using EHLQ structure functions [10] with a $\Lambda_{QCD} = 0.2$ GeV and assuming five quark flavours) for the choice of $Q^2 = p_T^2$. The QCD prediction corresponds to $\Lambda_c = \infty$ and is the best fit to the data (chi-squared per degree of freedom = 0.9). By varying the value of the parameter Λ_c in the fit and taking into account a $\pm 10\%$ error due to the systematic uncertainty on the jet-energy scale, we obtain the lower limit $\Lambda_c > 415$ GeV at 95% CL. This compares well with the limits of $\Lambda_c > 370$ GeV (at 95% CL) obtained by the UA2 Collaboration [13] and $\Lambda_c > 400$ GeV (at 95% CL) obtained by the UA1 Collaboration [3] from studies of inclusive cross-sections for high- p_T jet production at the CERN $p\bar{p}$ Collider.

Acknowledgements

We thank W. Buchmüller, D. Drijard and W.J. Stirling for informative discussions. We are grateful to the management and staff of CERN and of all participating Institutes for their vigorous support of the experiment.

The following funding agencies have contributed to this programme:

Fonds zur Förderung der Wissenschaftlichen Forschung, Austria.

Valtion luonnontieteellinen toimikunta Suomen Akatemia, Finland.

Institut National de Physique Nucléaire et de Physique des Particules and
Institut de Recherche Fondamentale (CEA), France.

Bundesministerium für Forschung und Technologie, Fed. Rep. Germany.

Istituto Nazionale di Fisica Nucleare, Italy.

Science and Engineering Research Council, United Kingdom.

Stichting Voor Fundamenteel Onderzoek der Materie, The Netherlands.

Department of Energy, USA.

The Natural Sciences and Engineering Council of Canada.

Thanks are also due to F. Bernasconi and L. Dumps, who have worked with the Collaboration in the preparations for the data collection on the runs described here.

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Figure captions

- Fig. 1. The two-jet angular distribution plotted as a function of $\cos\theta$, where θ is the scattering angle in the parton-parton rest frame. The solid curve is the QCD prediction taking account of scale-breaking effects.
- Fig. 2. The wide-angle to small-angle ratio (defined as events within $1 < \chi < 4$ to events within $4 < \chi < 9$) $R(4, 9)$ is shown as a function of two-jet mass m_{2J} . The QCD prediction for this ratio is represented by the solid curve.
- Fig. 3 The angular distribution $(1/\sigma)(d\sigma/d\chi)$ for the high-mass ($200 < m_{2J} < 240$ GeV) jet pairs is shown as a function of χ , where $\chi = (1 + \cos\theta)/(1 - \cos\theta)$. The solid curve represents the QCD prediction.
- Fig. 4 The chi-squared for the fit to the angular distribution (in bins of $\Delta\chi = 2$) for $200 < m_{2J} < 240$ GeV plotted as a function of the choice of the Q^2 scale.
- Fig. 5 The angular distribution $(1/\sigma)(d\sigma/d\chi)$ for the very high mass ($240 < m_{2J} < 300$ GeV) jet pairs shown as a function of χ , where $\chi = (1 + \cos\theta)/(1 - \cos\theta)$ and θ is the subprocess c.m. scattering angle. The solid curve represents the QCD prediction which corresponds to $\Lambda_c = \infty$, and is the best fit to the data. The dotted curve, which corresponds to $\Lambda_c = 300$ GeV, is clearly excluded by the data.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5