EVIDENCE FOR THE NONABELIAN STRUCTURE OF QCD FROM $p\bar{p}$ COLLIDER DATA

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Received 22 May 1984

We analyse in detail the QCD predictions for the shape of the single inclusive jet p_T distribution measured at the $p\bar{p}$ collider. The measured shape cannot be described without the three-gluon vertex contribution to parton–parton scattering.

A nonabelian gauge theory, QCD [1], is presently accepted as the most likely candidate to explain the strong interactions of elementary particles. However, the most striking characteristic of this theory, i.e. the trilinear gauge coupling, has not yet been experimentally tested in a direct way [2]. In this paper we investigate this coupling by showing that the shape of the inclusive jet p_T cross section measured at the $p\bar{p}$ collider [3] is substantially influenced by the three-gluon vertex of QCD.

The QCD predictions for the inclusive jet p_T distribution at SPS collider energies have been computed to $O(\alpha_s)$ by several authors [4–7]. They are in general agreement with each other. The relatively small discrepancies that exist can be traced back to a different choice of the interaction scale and the use of different sets of parton structure functions. In this paper we first discuss the sensitivity of the QCD predictions to the choice of Q^2 scale and the uncertainties in the structure function determination. Finally, we investigate the effects of the three-gluon vertex.

For the purpose of this paper we use the shape of the parton structure functions as determined by the CDHS collaboration [8]. To take into account the EMC effect when scaling from iron nuclei to single protons, we normalized the quark structure functions in agreement with ref. [9]. As a characteristic Q^2 scale for the evaluation of α_s we took $Q^2 = \frac{1}{2}(p_T^{\mathrm{jet}})^2$ [10]. For α_s we assumed

$$\alpha_s = 4\pi/\beta_0 \ln(Q^2/\Lambda^2)\,, \tag{1}$$

where $\beta_0 = \frac{11}{3}N_c - \frac{2}{3}N_f$, N_c = number of colours and N_f = number of flavours. We assumed $N_c = 3$, $N_f = 5$ and, unless otherwise specified, $\Lambda = 0.7$ GeV. The rationale for this assumption will be discussed below.

For the elementary parton–parton subprocesses we took the cross sections of ref. [11]. The Altarelli–Parisi evolution equations for the structure functions were solved exactly and the integration was carried out using Monte Carlo techniques as described in ref. [5].

The inclusive jet p_T cross sections have been measured at the SPS collider by the UA1 and UA2 experiments. They agree well with each other within their systematic errors. However, the two groups do not apply the systematic corrections in the same way [3]. For this reason we limit ourselves in this paper to the comparison of our QCD predictions with the recently published UA2 [12] data. We chose the UA2 cross section because it is given in the form of an inclusive quark p_T distribution, which can therefore be compared to the QCD predictions at the parton level. At the end of the paper we show that our conclusions are also in full agreement with UA1 data.

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The systematic experimental errors of the UA2 measurement are of two types; the overall normalization error of ±45%[‡1] and the point-to-point systematic error, which is included in the error bars. The QCD predictions were compared to the data by varying an arbitrary normalization constant, A. A absorbs not only the error in the experimental normalization but also the unknown higher order corrections to the $O(\alpha_s)$ QCD predictions (K-factor) which are assumed to be independent of p_T. The experimental normalization error is around a factor 2 and the magnitude of the K-factor can also reach 2, so we would expect A to be somewhere between 1 and 4. From the fit to the data we obtained $A = 2.3$ and $\chi^2 = 24.4$ for 29 dof. Our normalized QCD prediction is compared to the data in fig. 1. To present more precisely this comparison we divided the data by the normalized QCD prediction as shown in fig. 2. From this figure we see that our standard QCD prediction (represented by the straight line with unit height) agrees well with the shape of the data.

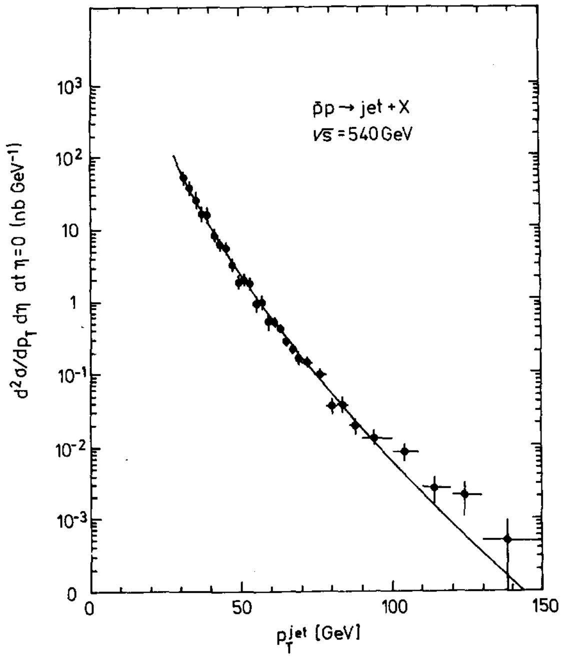

Fig. 1. Comparison of the inclusive p_T jet cross section from ref. [12] with out standard normalized QCD prediction.

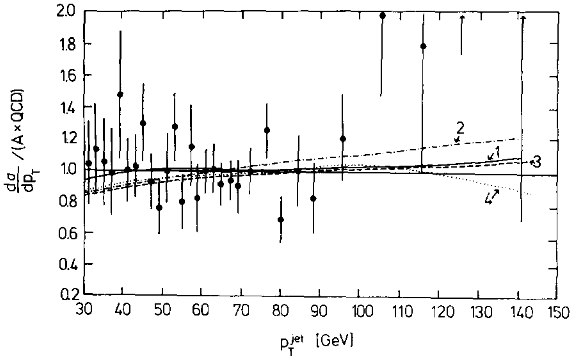

Fig. 2. Inclusive p_T jet cross section divided by the standard normalized QCD prediction. The solid points show the data of ref. [12]. The error bars contain the statistical and the systematical point to point errors. The curves 1–4 show the QCD predictions made with four extreme choices of gluon structure functions, see text.

To investigate the dependence on the uncertainties in the determination of the parton structure functions we varied the shape of the poorly known gluon structure function considerably. The gluon structure function was assumed to be of the form

$$xG(x) = a(1 + bx)(1 - x)^c \,. \qquad (2)$$

For our standard prediction we took $b = 8.9, c = 6.03$ and $\int xG(x)\,dx = 0.49$ [9]. To illustrate the influence of the uncertainties in the determination of the gluon structure function on the QCD prediction we computed the QCD prediction in four extreme cases: (1) $b = 9, c = 8$; (2) $b = 0, c = 8$; (3) $b = 0, c = 3$ and (4) $b = 9, c = 3$. In all cases we took $\int G(x)x\,dx = 0.49$. We consider these cases as extreme because the power c has to lie between that of the sea and of the valence quark distributions [13]. For each case we computed the QCD prediction and compared it with the data, fitting the normalization constant A. We obtained the following results for the fits: (1) χ^2/dof = 0.9, A = 2.7; (2) χ^2/dof = 0.95, A = 3; (3) χ^2/dof = 0.95, A = 2 and (4) χ^2/dof = 0.9, A = 1.5. The results of the QCD prediction in all four cases are plotted in fig. 2 divided by our standard QCD prediction. We see that the differences between these gluon distributions

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[‡1] The overall normalization error is mainly built up from the luminosity error and the error in the determination of the experimental energy scale. Due to the power-law behaviour of the inclusive jet cross section the uncertainty of the energy scale corresponds to a normalization error.

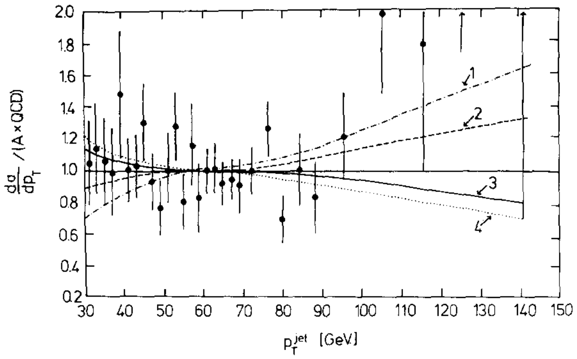

Fig. 3. Ratios of normalized QCD predictions with different choices of the Λ parameter and the normalized standard QCD prediction: (1) $\Lambda = 0.2, \chi^2/\mathrm{dof} = 1.15, A = 1.5$, (2) $\Lambda = 0.5$, $\chi^2/\mathrm{dof} = 0.9, A = 1.9$, (3) $\Lambda = 0.9, \chi^2/\mathrm{dof} = 0.9, A = 2.9$, (4) $\Lambda = 1.1, \chi^2/\mathrm{dof} = 0.92, A = 3.6$. The solid points show the data of ref. [12]. The error bars contain the statistical and the systematical point to point errors.

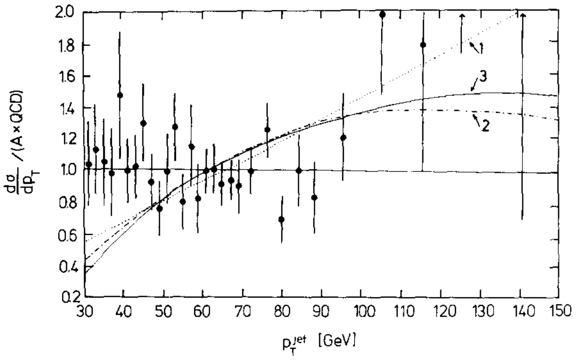

Fig. 4. Ratios of normalized QCD predictions where the contribution from the three-gluon vertex has been removed and the normalized standard QCD prediction: (1) no three-gluon vertex in elementary parton–parton scattering; $\chi^2/\mathrm{dof} = 1.8$, $A = 1.6$, (2) three-gluon vertex removed in elementary cross section and evolution equations; $\chi^2/\mathrm{dof} = 2.1, A = 1.8$, (3) in addition α_s = constant; $\chi^2/\mathrm{dof} = 2.5, A = 3.5$. The solid points show the data of ref. [12]. The error bars contain the statistical and the systematical point to point errors.

change the normalization constant A considerably; however, they have little effect on the shape. We also varied the normalization of the gluon structure function by ±5% as suggested by the experimental errors given in ref. [9]. The changes in the normalization led to changes in χ^2/dof which were smaller than 0.1 and which therefore are not displayed here.

In fig. 3 we present the effect on the shape of the p_T distribution of varying the Λ. Since Λ enters the computation only in conjunction with Q^2, see (1), the variation of Λ is equivalent to a variation of the interaction scale. The χ^2/dof of different fits varies by no more than 0.2. We obtained the best fit with $\Lambda = 0.7$ which we took as our standard Λ value. We interpret this relatively high Λ value as an indication that the appropriate Q^2 scale is even smaller than our assumption $\frac{1}{2}p_T^2$.

From the above investigation we conclude that the QCD prediction for the shape of the p_T distributions does not show any strong dependence on uncertainties in our knowledge of the parton structure functions or the Q^2 scale.

The shape of the inclusive jet p_T spectrum is, however, very dependent on the contribution of the three-gluon vertex. The three-gluon vertex enters into the QCD computation in three different ways: in the elementary parton–parton subprocesses through the Feynman diagrams containing this vertex, in the evolution equations through the splitting function P_{gg} and it determines the variation of α_s as a function of Q^2. To show the dependence of the QCD predictions on the three-gluon vertex we first removed its contribution from the elementary parton–parton cross section. The resulting normalized prediction, again divided by our standard QCD prediction, is displayed in fig. 4 (curve 1). We see that the shape of the prediction in this case differs considerably from the data ($\chi^2/\mathrm{dof} = 1.8$). Next we removed the three-gluon vertex in the QCD evolution formulae ($p_{gg} = 0$). This leads to an even greater disagreement, see curve 2 in fig. 4. Finally to show the effects of α_s variation we assumed α_s = constant [‡2]. We obtained then for the best fit $\chi^2/\mathrm{dof} = 2.5$ with $\alpha_s = 0.15$ and $A = 2.0$. The corresponding shape is displayed as curve 3 in fig. 4. All three curves in fig. 4 are in considerable disagreement with the data.

This disagreement cannot be explained by a different choice of the gluon structure function since, as has been shown above, the gluon structure functions have only a small influence on the shape of the p_T spectrum. In particular the choice of the softer gluon distribution ($b = 9, c = 8$), which would be necessary to improve

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[‡2] The assumption of growing α_s would give an even worse fit.

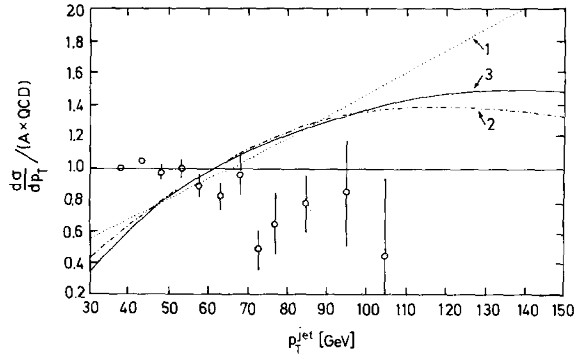

Fig. 5. The curves of fig. 4 compared to the data of ref. [14] divided by our standard QCD predictions. The error bars contain the statistical errors *only*.

the fit, is barely distinguishable from our standard choice[‡3].

Our investigation was based on the UA2 data of ref. [12]. The main result, however, does not depend on the particular choice of data set. To show this we plot in fig. 5 the UA1 data of ref. [14] divided by our standard normalized QCD prediction and compare the data to the same QCD prediction with the three-gluon vertex as shown in fig. 4.

In conclusion, we have shown that the QCD prediction for the shape of the inclusive p_T distribution is largely insensitive to the particular choice of quark and gluon structure functions and the Q^2 scale. The shape is, however, strongly sensitive to the three-gluon coupling taken with its usual QCD strength and, moreover, cannot be properly described without it.

We would like to thank F. Eisele and J. Ellis for discussions and B. Foster and G. Wolf for useful comments on the manuscript.

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[‡3] We checked also that this statement is true with our truncated, $P_{gg} = 0$, evolution