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LOW-p_t JETS AND THE RISE WITH ENERGY OF THE INELASTIC CROSS SECTION ☆

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The contribution of QCD jets to the rise with energy of the inelastic cross section is discussed quantitatively and found to be large. It is seen that the inclusive jet yield is the fastest growing component of the total cross section. The dependence of this yield upon the rapidity cuts, the choice of parton densities, the QCD scale Q^2 and the transverse momentum cutoff p_{cut} are examined. At higher energies, multiple parton scattering processes are seen to be non-negligible. Extrapolations of the low-p_t jet yield to the Tevatron are presented also.

1. Introduction. Perturbative quantum chromodynamics (QCD) has been very successful in predicting the general features of hadronic events initiated by high-energy e^+e^- collisions and in particular e^+e^- total hadronic cross section. Instead a much slower progress has characterized the more complicated hadron-initiated phenomena. A major breakthrough has taken place with the observation of spectacular large-p_t jets at the CERN Collider [1], which can be satisfactorily described in terms of lowest-order QCD [2], using elsewhere measured parton densities. Also, more complicated phenomena, involving three and four jets in the final state have been observed and discussed at high p_t [3]. Similarly, production of new flavours, charm and beauty, as well as the production of -onia, direct photons and W's and Z's are reasonably well accounted for by QCD calculations.

All these phenomena however represent only a *tiny* component of the total cross section, σ_{tot}. This paper addresses the question of how large a fraction of σ_{tot} can be derived meaningfully from an application of QCD. In contrast to e^+e^-, where – as pointed out – σ_{tot} can be derived perturbatively over the entire experimentally explored range, even in the best circumstances this program must be less ambitious, principally due to our lack of understanding of the very low p_t physics in the confinement region, $p_t \leqslant \Lambda_{\mathrm{QCD}}$. A high-energy hadron–hadron collision is an extremely complicated, simultaneous interaction between a very large number of different energy partons participating in the event. Therefore, in addition to hard parton–parton scattering, there are additional processes which take place simultaneously and which produce particles associated with the so-called *underlying event.* Note that the structure of the underlying event may be affected by the dynamics of the hard scattering. Notwithstanding these difficulties, as a first step, one can try to separate σ_{tot} into two terms, $\sigma_{\mathrm{tot}} \approx \sigma^{\mathrm{QCD}} + \sigma^{\mathrm{NP}}$ where the first term receives a contribution from processes which can be satisfactorily described by per-

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turbative QCD, while the second contains all remaining, non-perturbative contributions.

How large can σ^{QCD} be? In the present paper we shall examine the possibility that σ^{QCD} may be an important fast-rising part of σ_{tot} already at the CERN Collider. Indeed it is possible that if not the totality [4], at least a major fraction of the rise of σ_{tor} – which from ≈39 mb at $\sqrt{s} = 22$ GeV is now ≈60 mb at $\sqrt{s} = 630$ GeV (and it is commonly presumed to reach even larger values at very high energies from cosmic rays [5]) can be calculated from $\sigma^{(\mathrm{QCD})}$.

Perturbative QCD is in many ways indivisibly related to the experimental observation of jets. In order to establish a $\sigma^{(\mathrm{QCD})}$ which could give a significant contribution to σ_{tot} the observable jet phenomenon must be greatly enhanced (many orders of magnitude) and extended to transverse energies E_{T} which are much smaller than that reported by the already classic experiments at the CERN Collider. Some indications that this is indeed the case have been pointed out by us in previous publications [6], where we have put forward the hypothesis that such low-energy jets may be the cause of the observed KNO scaling violations [7] as well as the rise with multiplicity in the $\langle p_{\mathrm{t}}\rangle$ of charged particles at the CERN Collider [8], ISR [9] and in cosmic rays experiments [10]. To make this interpretation viable it is necessary that such a fraction becomes as much as 10–20% of the inelastic cross section and grow with energy from the very small value recorded at the ISR. It is then predicted [11,12] that the jet phenomenon at the collider will become a significant fraction of all events rather than a very specialized effect with tiny cross section. This can be formally achieved since the lowest-order cross section becomes arbitrarily large if extended to lower and lower p_{t} values. Therefore there must be a minimum transverse momentum p_{cut} above which perturbative QCD can be safely applied. The value of such a parameter is related to the experimental jet resolution threshold and it is expected to be a slowly varying function of the collider energy. Note that this cut-off may be lower than the energy at which jets are still experimentally observable, since the detection of low-energy "jets" in a hadronic background coming from the underlying event is not easy and it may depend on its choice of definition.

The UA1 Collaboration [13,14] has indeed reported the direct observation of such low-E_{T} jets. It becomes therefore possible for the first time to have a direct experimental clue about how large can $\sigma^{(\mathrm{QCD})}$ be and on the value of the lowest transverse momentum cut-off p_{cut}. The aim of this paper is to show that (1) the experimental data provide the right amount of jet cross section to explain KNO scaling violation and the increase of p_{t} with multiplicity and that (2) they can be well understood in terms of simple QCD calculations accounting for as much as ≈20% of the total inelastic cross section.

If such low-x parton–parton collisions become relevant it is eventually necessary to take into account also cases in which multiple, independent parton scattering becomes observable in the same event. As we shall see, at yet higher energies this phenomenon is expected to play a non-negligible role and must be included in the estimate of $\sigma^{(\mathrm{QCD})}$.

2. *The jet cross section at small E_{T}.* For very large transverse energies the jet phenomenon is rather striking. Its kinematics is well understood by QCD predictions, as reflected in the two-jet angular distribution [15]. Cross sections are well described by QCD calculations and structure functions which are extrapolated in Q^2 from neutrino scattering data. In these calculations the energy range is artificially limited by the experimental cuts to a domain in which a number af approximations are valid and which is very far from the minimum transverse momentum p_{cut} above which perturbative QCD can be applied.

Recently the UA1 Collaboration has reported new observations of inclusive jet production down to transverse energies of a few GeV, at $\sqrt{s} = 540$ GeV and 630 GeV [13] and through the energy range $\sqrt{s} = 200$–900 GeV [14]. These events have typical energies of the jets once recorded at the ISR and E_{T} as much as ten times smaller than the jets previously reported at the Collider. Therefore they are more difficult to study experimentally. With these measurements the jet cross section now spans an interval of almost 10 orders of magnitude, from ≈1 mb at $E_{\mathrm{T}} = 5$ GeV down to less than 10^{-9} mb at $E_{\mathrm{T}} \approx 150$ GeV. New problems also rise in comparing these results with theory since it is not known how low in E_{T} one can go before perturbative QCD becomes too rough an approximation and because differences in the choice of scale are more evident in the low-E_{T} region.

With these questions in mind we repeat the by now classic calculation of the jet cross section in lowest order QCD given by the expression

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\eta\,\mathrm{d}p_{\mathrm t}} = \frac{\pi}{2p_{\mathrm t}^3}\int_{x_0}^{1} \frac{F(x_1)}{x_1^2}\,\frac{F(x_2)}{x_2^2}\,\alpha_{\mathrm s}(Q^2)^2\,\frac{x_{\mathrm T}^4}{(2x_1 - x_{\mathrm T}\mathrm{e}^{\eta})}\,|A|^2\,, \tag{1a}$$

where

$$x_2 = x_1 x^{\mathrm T}\mathrm{e}^{-\eta}/(2x_1 - x_{\mathrm T}\mathrm{e}^{\eta})\,,\quad x_0 = x_{\mathrm T}\mathrm{e}^{\eta}/(2 - x_{\mathrm T}\mathrm{e}^{-\eta})\,,\quad x_{\mathrm T} = 2p_{\mathrm t}/\sqrt{s} = \sqrt{x_1x_2}\,\sin\theta^*\,,$$

and the CM scattering angle θ^* satisfies

$$z^* = \cos\theta^* = (x_1\mathrm{e}^{-\eta} - x_2\mathrm{e}^{\eta})/(x_1\mathrm{e}^{-\eta} + x_2\mathrm{e}^{\eta})\,.$$

Because of the similarity in the angular behaviour, all amplitudes can be approximated by the same term, viz.

$$|A|^2 = \tfrac{9}{8}(3 + z^{*2})^3/(1 - z^{*2})^2\,. \tag{1b}$$

In eq. (1) the non-singular proton structure function $F(x)$ is defined as

$$F(x) = G(x) + \tfrac{4}{9}[Q(x) + \bar{Q}(x)]\,,$$

with $G(x)$, $Q(x)$ and $\bar{Q}(x)$ representing the density of gluons, quarks and antiquarks, respectively. In figs. 1a and 1b we show the calculation for two different choices of parton densities, Duke and Owens in mode 1 [16] and EHLQ in mode 2 [17] and compare it with experimental data. The following remarks about the minimum-bias jet cross section can be made:

(i) The distribution of minimum-bias jets appears to join in smoothly with that at high $E_{\mathrm T}$ from the jet trigger.

(ii) The agreement with the QCD curve is reasonable, and within the various uncertainties discussed previously.

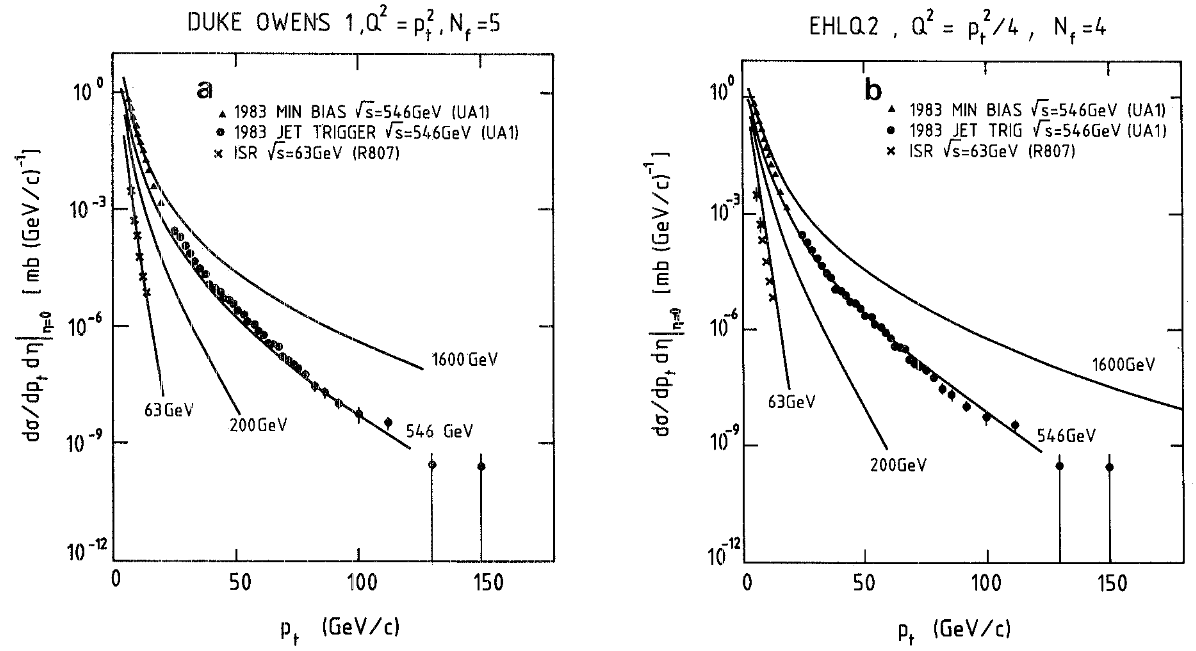

Fig. 1. Theoretical curves for $\mathrm{d}\sigma/\mathrm{d}p_{\mathrm t}\mathrm{d}\eta|_{\eta=0}$ versus $p_{\mathrm t}$ obtained through eq. (1) for $\sqrt{s}$ = 63, 200, 546 and 1600 GeV using Duke and Owens densities with $Q^2 = p_{\mathrm t}^2, N_{\mathrm f} = 5$, mode 1 (ref. [16]) in (a) and EHLQ densities with $Q^2 = \frac{1}{4}p_{\mathrm t}^2 N_{\mathrm f} = 4$, mode 2 (ref. [17]) in (b). 63 GeV data are from ref. [18], experiment R807. 546 GeV data are from ref. [19] (● UA1 1983 data from jet trigger) and ref. [14] (▲ UA1 1983 data from minimum bias).

(iii) The newly measured UA1 jet cross section from minimum-bias follow the general behaviour of the high-E_T jets and can safely be considered an almost straightforward extension of the high-E_T jet phenomenon.

A closer look at the data and to the QCD curve shows, however, the presence of some problems. ISR [18] and S$\bar{p}$pS data [14,19] shown in fig. 1 indicate that, while the agreement with experiments is good at $\sqrt{s} = 63$ GeV, a multiplicative, energy-dependent K-factor is needed at the Collider. As well known, such a factor is attributed to the presence of higher-order QCD corrections. Following the suggestion by EHLQ, one can try to minimize these corrections by an appropriate choice of the scale, for instance $Q^2 = \frac{1}{4}p_t^2$. This is shown in fig. 1b where the QCD prediction is obtained using their parton densities. Unfortunately (fig. 1b) one notices that while the agreement with high-energy data has improved at high p_t, this choice of scale does not reproduce the ISR data as well as the previous choice. Under all circumstances the low-E_T jet cross section at the collider lies higher than the QCD curve. We remark the need for more precise corrections in the region of lower energies where α_s is large. A likely source of corrections is initial state radiation which shifts the energy scale to a region where the cross section is rapidly varying. While this problem will require a complete investigation, in the following we shall concentrate on the first-order QCD calculation of integrated jet yields.

3. Integrated jet cross section. The UA1 Collaboration has given the inclusive jet cross section over the range $\sqrt{s} = 200$–900 GeV with a nominal "jet" threshold $E_T > 5$ GeV and in the central region $|\eta| < 1.5$. After elaborate corrections for detection efficiency and for events leading to jets outside the acceptance they give a total jet cross section, shown in fig. 2. The cross section is rapidly rising and it is quite large. It is instructive to compare these rates with the rate of increase of the inelastic cross section, which we take to be $\frac{2}{3}\sigma_{\rm tot}$ where for $\sigma_{\rm tot}$ we use the parametrization given by Amaldi et al. [20]. In the same figure we also show the experimental points [‡2] [22] for the quantity $\sigma_{\rm nsd} = \sigma_{\rm tot} - \sigma_{\rm el} - \sigma_{\rm sd}$. Notice that through the energy range of interest in this paper, they all appear to fall on the curve $\frac{2}{3}\sigma_{\rm tot}$.

One can numerically integrate eq. (1) or use an alternative expression, which gives the two-jet differential cross section through the parton–parton center of mass scattering angle,

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[‡2] For a recent review of elastic and total cross section data, see ref. [21].

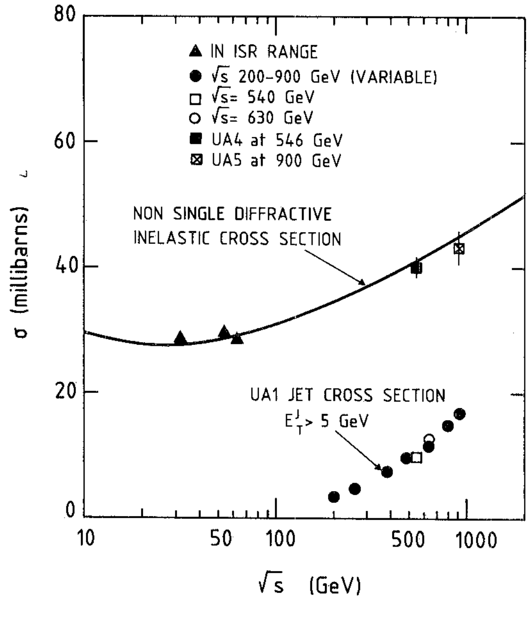

Fig. 2. Experimental data (from the review in ref. [21]) for $\sigma_{\rm nsd} = (\sigma_{\rm tot} - \sigma_{\rm el} - \sigma_{\rm sd})$ versus $\sqrt{s}$ is shown alongwith the continuous curve for $\frac{2}{3}\sigma_{\rm tot}$ obtained from ref. [20]. Also shown are the preliminary UA1 data for the inclusive jet yield from ref. [14].

$$\sigma_{\text{jet}}(s) = \frac{1}{2} \int \mathrm{d}x_1 \int \mathrm{d}x_2 \int \mathrm{d}\cos\theta^* \, \frac{\mathrm{d}\sigma}{\mathrm{d}x_1\,\mathrm{d}x_2\,\mathrm{d}\cos\theta^*} \,,$$

with

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x_1\,\mathrm{d}x_2\,\mathrm{d}\cos\theta^*} = \frac{9\pi[\alpha_s(Q^2)]^2}{32s} \, \frac{F(x_1, Q^2)}{x_1^2} \, \frac{F(x_2, Q^2)}{x_2^2} \, \frac{(3+\cos\theta^{*2})^3}{(1-\cos\theta^{*2})^2} \,, \tag{2}$$

where θ^* is the scattering angle in the center of mass of the parton–parton system and the integration in $\cos\theta^*$ extends between $-z_0$ and $+z_0$ with

$$z_0 = (1 - 4p_{\text{cut}}^2/sx_1x_2)^{1/2} \,,$$

The calculation of the jet yield is numerically simplified if one neglects the angular dependence in $\alpha_s(Q^2)$. Then the integration in $\cos\theta^*$ is straightforward and gives

$$\int \mathrm{d}\cos\theta^* \, \frac{\mathrm{d}\sigma}{\mathrm{d}x_1\,\mathrm{d}x_2\,\mathrm{d}\cos\theta^*} = \frac{9\pi}{16s} \, \frac{F(x_1, Q^2)}{x_1^2} \, \frac{F(x_2, Q^2)}{x_2^2} \, [\alpha_s(Q^2)]^2 I(p_{\text{cut}}) \,, \tag{3}$$

with

$$I(p_{\text{cut}}) = (8sx_1x_2/p_{\text{cut}}^2)(1 - 4p_{\text{cut}}^2/sx_1x_2)^{1/2} - 16\ln\frac{1 + (1 - 4p_{\text{cut}}^2/sx_1x_2)^{1/2}}{1 - (1 - 4p_{\text{cut}}^2/sx_1x_2)^{1/2}}$$

$$+ (1 - 4p_{\text{cut}}^2/sx_1x_2)^{1/2} \left(\tfrac{34}{3} - \tfrac{4}{3}p_{\text{cut}}^2/sx_1x_2\right) . \tag{4}$$

A further simplification is obtained if one neglects, in eq. (4), terms of higher order in $4p_{\text{cut}}^2/sx_1x_2$. One can then write [23]

$$\sigma_{2\text{-jets}}(s) = \frac{9\pi}{2p_{\text{cut}}^2} \int_{\epsilon}^{1} \frac{\mathrm{d}z}{z} F(\epsilon/z, Q^2) \int_{z}^{1} \frac{\mathrm{d}x}{x} \, F(x, Q^2)[\alpha_s(Q^2)]^2 \,, \tag{5}$$

with $\epsilon = 4p_{\text{cut}}^2/s$. In order to assess how reliable this approximation is at present energies, we have compared the total two-jet yield obtained using the complete expression, eqs. (3) and (4), with the approximate form given by eq. (5) for a variety of different values for p_{cut} in the energy range $\sqrt{s} = 100$–1000 GeV and found agreement within $\leqslant 10\%$, becoming better at higher energies.

We can now compare the size of the effect with UA1 observations. We have used UA1 parametrization for parton densities i.e.

$$F(x) = 6.2\exp(-9.5x) \,, \tag{6}$$

and we have chosen for the argument of α_s the quantity $Q^2 = \frac{1}{4}p_{\text{cut}}^2$. Using the approximate expression eq. (5) one gets $\sigma = 3.52$ mb at $\sqrt{s} = 540$ GeV and for $p_{\text{cut}} = 5$ GeV, to be compared with the experimental value $\sigma = 10.3$ mb. The origin of this large disagreement has to be further investigated. We make the reasonable hypothesis that somehow the effective cut-off must be lower than the "declared" value. This may indeed be due to the presence of the underlying event which contributes more or less isotropically to the measurement of all the transverse energy deposited in the calorimeters. In our calculation we shift the energy scale by 1.5 ± 0.5 GeV relative to the value given by UA1 in order to accommodate the effects of the underlying event. Thus a jet event assigned by the UA1 algorithm to 5 GeV can be produced by the overlap of a 3.5 GeV parton together with 1.5 GeV of soft debris from the underlying event. Above considerations make evident the large degree of arbitrariness in the determination of the jet yield.

We now try to estimate the dependence of the predictions on the assumptions on the input parameters in the

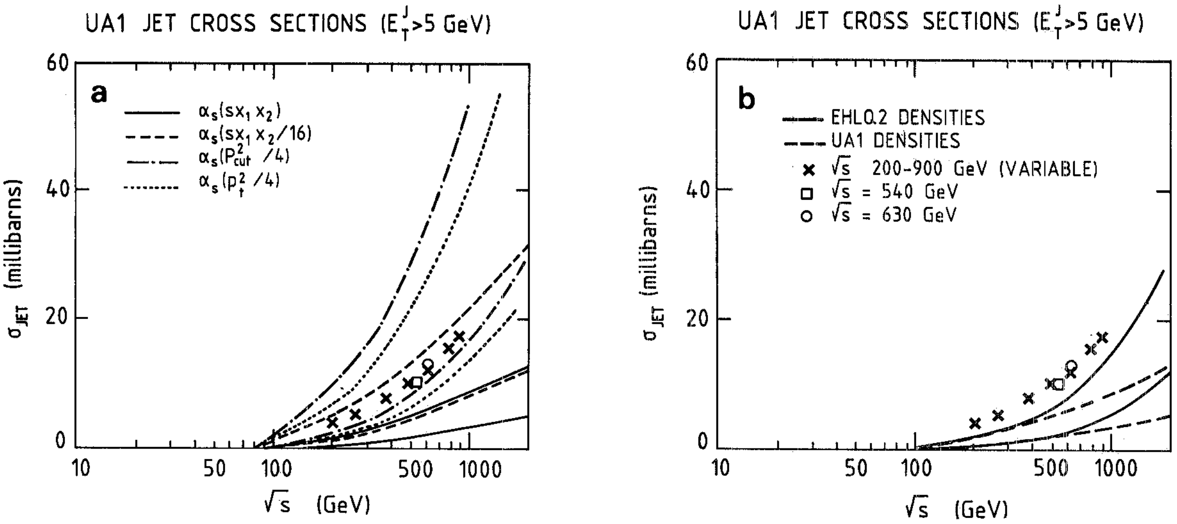

Fig. 3. (a) σ_{jet} versus $\sqrt{s}$ using UA1 densities, for various $\alpha_s(Q^2)$: $Q^2 = sx_1x_2$, continuous line; $Q^2 = \frac{1}{16}sx_1x_2$, dashed line; $Q^2 = \frac{1}{4}p_t$, dotted line; $Q^2 = \frac{1}{4}p_{cut}$, dash-dotted line. For each type of line, the upper and lower curves refer to $p_{cut} = 3$ and 4 GeV, respectively. Data shown are from ref. [14] as in fig. 2. (b) σ_{jet} versus $\sqrt{s}$ using EHLQ densities, mode 2 (continuous line) and UA1 densities (dashed lines). The upper two curves are for $p_{cut} = 3$ GeV and the lower two for $p_{cut} = 4$ GeV, $\alpha_s(sx_1x_2)$. Data are as in figs. 2 and 3a.

QCD calculation. To this effect we have investigated several choices of densities and parameters. In fig. 3a we show the comparative cross sections using UA1 parton densities, $p_{cut} = 3$ GeV and 4 GeV (in order to take into account the effect of the underlying event) and four different choices of the QCD scale: (a) $Q^2 = \frac{1}{4}p_{cut}^2$, (b) $Q^2 = \frac{1}{4}p_t^2$, (c) $Q^2 = \frac{1}{16}sx_1x_2$, (d) $Q^2 = sx_1x_2$. One notices that alternatives (a) and (b) give similar results and that the cross section grows less rapidly with energy if the scale is proportional to s as in cases (c) and (d). The above calculations are based on densities as directly measured by the UA1 group. The use of this set is numerically convenient but not justified outside the energy range of the CERN Collider. To study the effect of the evolution of the parton densities on the calculation of the jet yield, we show in fig. 3b the cross section with UA1 densities and with EHLQ parametrization, mode 2, $Q^2 = sx_1x_2$. As expected, at higher energies, the densities from ref. [17], being more peaked at smaller x values, give a larger contribution. On the basis of these considerations we can see that the "theoretical error" is quite large and that factors of order 2 can be easily accommodated by appropriate choice of the parameters. These uncertainties in the future may be reduced by more complete calculations which would settle the question of the correct QCD scale. Finally values of p_{cut} in the order of a few GeV appear to saturate the experimentally observed rise of the total cross section.

4. Multiple parton collisions. Our analysis of low E_T jets in minimum bias events shows a sharply rising contribution to the inelastic cross section. At even higher energies to be reached by TeV I, LHC and SSC, values of x as small as $\approx 10^{-4}$ contribute significantly to the cross section with $p_{cut} \approx 5$–10 GeV. For such small x values, the parton densities would become large enough to add a sizeable contribution to the inelastic cross section from multiple, independent parton–parton collisions (which are of higher order in α_s). Some evidence for multiple jet production may already be available at the CERN S$\bar{\text{p}}$pS from both UA1 and UA2 groups.

The four-jet yield due to 2 independent parton–parton scattering processes is approximately given by the expression [17,14,25]

Table 1

$\sqrt{s}$ (GeV)	σ_j/σ_t	σ_2/σ_t	σ_4/σ_2	σ_4/σ_t
200	0.076	0.074	0.037	0.0027
500	0.166	0.154	0.077	0.012
900	0.254	0.228	0.114	0 025

$$\frac{d\sigma_4}{dE_T} \approx \int_{p_{\text{cut}}}^{E_T - E_{\text{cut}}} dE_1 \int_{p_{\text{cut}}}^{E_T - p_{\text{cut}}} dE_2 \frac{d\sigma_2}{dE_1} \frac{d\sigma_2}{dE_2} \frac{1}{\sigma_{\text{tot}}} \delta(E_T - E_1 - E_2) , \tag{7}$$

where $d\sigma_2/dE$ is the 2–2 parton cross section folded with the parton densities and integrated over the rapidity variable. Upon integration over the transverse energy variable, eq. (7) can be further simplified to read [24]

$$\sigma_4/\sigma_{\text{tot}} \approx \tfrac{1}{2}(\sigma_2/\sigma_{\text{tot}})^2 . \tag{8}$$

We have seen that the ratio $\sigma_2/\sigma_{\text{tot}}$ increases with energy in the present energy range. Eq. (8) then indicates that also the ratio σ_4/σ_2 would increase. This implies the presence of a small, but finite fraction of multiple parton scattering events already at the CERN Collider. From the measured jet fraction as reported by UA1 [14], we can obtain the numbers shown in table 1.

An extrapolation of the above calculation to $\sqrt{s} = 2$ TeV gives for $\sigma_4 \approx 3$–4 mb, for a nominal jet detection threshold at 5 GeV. This is probably an overestimate, but it reflects the general problem of properly taking into account the contribution coming from multiple parton scattering. In general, for a process where n pairs of partons submit to independent parton–parton scattering, one can write

$$\sigma_{2n}/\sigma_{\text{tot}} \approx (1/n!)(\sigma_2/\sigma_{\text{tot}})^n , \tag{9}$$

Summing over all n, the inclusive one-jet production cross section due to independent multiple parton scattering may be written as

$$\sigma^{\text{inc}}_{1\text{-jet}} = 2 \sum_1 n\sigma_{2n} = 2\sigma_2 \exp(\sigma_2/\sigma_{\text{tot}}) . \tag{10}$$

The above expression is obtained in the limit in which one neglects all the correlations between partons emitted by the same hadron. An improved formula would take into account longitudinal and transverse momentum constraints.

Such independent multiple scattering will also manifest themselves in the KNO function at higher energies. Just like violations of KNO scaling at the Collider have revealed the presence of a large number of hard scattering events in the inelastic cross section, similarly a further widening of the distribution may signal the presence of a rising contribution from multiple parton processes. Indeed, if $\Psi(n/\langle n\rangle)$ keeps flattening as presently indicated by UA5 results [26] through the Tevatron and beyond, multiple parton collisions may be the reason. In this respect, our two-component model for KNO scaling violations

$$\sigma_{n\,\text{ch}} = \sigma^{(0)}_{n\,\text{ch}} + \sigma^{(1)}_{n\,\text{ch}} , \tag{11}$$

was only a first step. With $\langle n\rangle_0/\langle n\rangle_1$ fixed and Ψ_0 and Ψ_1 scaling, one does not obtain an indefinite flattening of the total KNO function. On the other hand this is precisely what would happen in the limit of an indefinite number of independent particle production processes, each of them characterized by an increasing average charged multiplicity. This problem is at present under investigation and the results will be presented elsewhere.

5. Conclusions. To summarize, we have analyzed in some detail the production of low-E_T jets in minimum-bias events at present energies (60–1600 GeV), to probe the uncertainties introduced by the choice of Q^2, the K-factor, parton densities at small x and a rather crucial critical dependence on p_{cut}. Despite these difficulties, it seems safe to conclude that a large fraction of the inelastic data at high energies can indeed be understood in terms of low-p_T jets. Beyond present energies, hard multiple collisions begin to play a non-negligible role and must be included in any quantitative estimate of the inelastic cross section as well as the KNO function. If these phenomenological observations are borne out at the Tevatron, an important theoretical effort should be done to understand the dynamical mechanism which would free a calculation of σ_{tot} from p_{cut} and yet not significantly alter the differential transverse-momentum distributions. On the basis of these considerations we can see that the "theoretical error" is still quite large and that factors of order 2 can be easily accomodated by appropriate choices of the parameters. These undertainties in the future may be reduced by more complete calculations which would settle the question of the correct QCD scale. Finally values of p_{cut} in the order of a few GeV appear to saturate the experimentally observed rise of the inelastic cross section.

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