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# MINIJETS: ORIGIN AND USEFULNESS

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## ABSTRACT

As the energy is increased, minijet production provides a steadily-increasing fraction of the total cross-section in hadron-hadron collisions. We argue that, rather than being a new phenomenon, this is the result of the hard tail of soft diffractive events becoming increasingly prominent. We discuss the production of multiple minijets, and point out the interest of searching for minijet events in deep inelastic lepton scattering at HERA. Consequences for charm production are considered.

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The UA1 Collaboration at the SPS Collider has recently reported$^{1)}$ that at high energies events with minijets form a substantial fraction of the total cross-section. These events are interesting because they lie on the frontier between "soft" and "hard" physics. Hard physics is by now well understood in terms of perturbative QCD, while for the soft events we have a successful phenomenological framework$^{2)}$ but little fundamental understanding. We cannot claim to understand strong interaction physics until this is remedied, and a natural question is whether the study of minijet physics will help here.

For the sake of completeness, the UA1 measurements are plotted in Fig. 1. Here the minijets are defined to have transverse momentum of at least 5 GeV/c and are observed in the central rapidity region, $|\eta| < 1.5$. At Collider energy this corresponds to a kinematical domain where perturbation-theory calculations should still be reliable, and it also corresponds to the lowest practical limit for the UA1 jet-finding algorithm. The $P_T$-cut is low enough for the yield to be large (one minijet in four events!) and yet large enough for perturbative QCD to apply. These two conditions indeed define what a minijet is.

We remark that we reject at the outset the suggestion$^{3)}$ that minijets are a new phenomenon which is <u>responsible</u> for the rise in the total cross-section. We have two reasons for this. One is the obvious point that, although the suggestion might seem to be supported by the similar rises of the two data plots in Fig. 1, this similarity is surely spurious because the minijet cross-section depends sensitively on the rather arbitrary choice of the minimum $P_T$ required for the minijets. (It depends also on the rapidity acceptance.) The second point is that when the contributions from $\rho$, $\omega$, f and $A_2$ exchange are subtracted from the total cross-section, what is left rises at the same uniform rate [approximately $(\sqrt{s})^{0.16}$] all the way$^{4),5)}$ from $\sqrt{s}$ = 5 GeV to $\sqrt{s}$ = 900 GeV. Nobody would suggest that minijet production has any relevance at $\sqrt{s}$ = 5 GeV.

The steadily-rising component of the total cross-section is said to correspond to diffractive (or pomeron) exchange. Its phenomenology is now rather well known, but there is as yet no fundamental explanation of it. Presumably such an explanation will come when we are better able to undertake non-perturbative calculations of QCD. However, the UA1 measurements demonstrate that a steadily-increasing part of diffractive exchange results in minijet production, and this part is surely calculable from perturbative QCD.

The increase in the yield of minijets was predicted$^{6)}$ to be at the origin of an important change in the structure of the typical event between SPS fixed-target and SPS Collider energies. To produce a jet of transverse momentum $P_T$ emerging at 90° in the centre-of-mass frame, one needs a parton of that momentum in each of the colliding hadrons. At $\sqrt{s}$ = 20 GeV, the probability of finding a parton of momentum, say, 5 GeV in both hadrons is quite small, but at $\sqrt{s}$ = 600 GeV, it is some two orders of magnitude larger.

One has to confess, however, that there is no good theoretical understanding of just what are the conditions for a standard incoherent hard-scattering calculation, using parton densities, to be valid. At each energy it must break down when $P_T$ is small enough, if only because we know that coherent effects must eventually become dominant. Even if one neglects the possible importance of incoherent higher-twist contributions$^{7)}$, which played such a large role in discussions of the ISR data in the 1970's, there are two distinct possibilities. One is that the minimum value $P_T^{min}$ for the validity of the incoherence assumption remains fixed as $\sqrt{s}$ increases, and the other is that instead $P_T^{min}$ rises with $\sqrt{s}$. Certainly, if one wants to be able to calculate the relevant parton densities from an evolution equation, it is the latter which is true. At very small x, there are so many partons that they screen one another$^{8)}$, and so for 90° production one has to require some condition like

$$\alpha_s(P_T^2)\left|\log\frac{P_T}{\sqrt{s}}\right| \ll 1 \qquad (1)$$

in order to use the standard leading-log approximation. However, if one is instead content to take the small x behaviour of the parton densities from experiment, it could be that it is still valid to use the perturbation-theory hard-scattering calculation for the production of the jets if only

$$P_T \gg m_{nucleon} \qquad (2)$$

If it is (1) rather than (2) that is appropriate, one can to some extent overcome the constraint by focusing on more and more forward minijets as $\sqrt{s}$ increases, so as to keep the parton fractional momenta x at high enough values with $P_T$ remaining relatively small. If it is (2) that is applicable, minijet production can be used to get information about the behaviour of parton densities at very small x. It is conventional to assume a behaviour $x^{-1}$. However, the small x behaviour of parton densities is determined by Regge theory$^{9)}$, and the diffractive exchange that is responsible for the steadily-rising component of total hadron-hadron cross-sections reflects itself in a behaviour more like $x^{-1.08}$. [Collins$^{10)}$ has even argued that it should be something like $x^{-1.5}$, but it is not clear how this relates to existing data.] Such a power behaviour cannot be valid all the way down to x = 0, but it is likely to be good down to quite small values - unitarity demands that when $s \rightarrow \infty$, total cross-sections are bounded by $(\log s)^2$, but the multiple pomeron exchanges that guarantee this are small even at SPS Collider energy, and $s^{0.08}$ still describes the rise well at this energy. What is not well understood is how the Regge behaviour of the structure function is modified by scaling violation. However, in minijet production the scale at which the structure of the colliding hadrons is probed is presumably only of the order of $P_T^2$, and so scaling violation will be small.

If one integrates the differential yield of minijets, one has

$$\int_{P_T > P_T^{min}} \frac{d\sigma}{dP_T} dP_T = \langle n \rangle \sigma(P_T^{min}) \qquad (3)$$

where $\sigma(P_T^{min})$ is the total cross-section for minijet production and $\langle n \rangle$ is the average number of minijets per event. At very high $\sqrt{s}$, $\langle n \rangle$ could well be rather large, so that (3) exceeds the total cross-section. This is easy to understand in the usual hard-scattering model (Fig. 2). As the parton fractional momenta decrease, the invariant masses of the two sets of residual fragments of the initial hadrons increase. This is why the small x behaviour of the parton distributions is determined by Regge theory[9]. So it becomes more and more likely that they also include minijets. This does not mean that it is wrong to use Fig. 2 to calculate $d\sigma/dP_T$, but it does mean that $\langle n \rangle$ in (3) is greater than 2. The implication of this is that minijets will appear also at high W and small x among the target fragments in deep inelastic lepton scattering. It will be interesting to look for them at HERA.

An obvious remark is that the transverse momentum of a minijet is not straightforward to measure. As is well familiar[7] from the days of the ISR experiments, when the total $P_T$ of a jet is not very large, there are serious problems in separating the particles that make up the jet from those that form the "background" in the event. To some extent this is also a theoretical problem, as the two components of the event will interfere with one another. The practical consequences of this problem are serious because, with $d\sigma/dP_T$ a sharply-falling function of $P_T$, any overestimate of $P_T$ causes a rather large error in the measurement of the cross-section.

Although we have argued that minijet events are merely a part of what has long been called diffractive or pomeron exchange, this does not exclude the possibility that the presence of minijets is correlated with other unusual features. Indeed, there is quite a lot of evidence that this is true. Up to FNAL/SPS energies, the average transverse momentum $\langle p_T \rangle$ per particle is rather independent of energy and multiplicity. But it has been known for several years that in cosmic ray events at what we now call collider energy, $\langle p_T \rangle$ is larger when the central multiplicity is large11). This led to a separation between so-called Mirin and Açu events in the Emulsion Chamber data11), and this was interpreted as a correlation resulting from there being a sizeable number of minijets6). A continuous rise of $\langle p_T \rangle$ with central multiplicity has indeed been reported by the R420 experiment12) at the ISR and at the Collider by UA113). The effect is modest at the ISR, but well developed at the Collider, and there is now little doubt that it is correlated with the emergence of minijets14). It is possible also15) that the same can be said about the violation of KNO scaling in multiplicity distributions16).

Let us now return to the question of the production of more than one pair of minijets. We have said that this can be obtained from Fig. 2, and that Fig. 2 also represents a part of diffractive exchange. More specifically, it represents a part of single-pomeron exchange. There is also a non-negligible contribution to the total cross-section from double-pomeron exchange; it is at the 10% level4) at Collider energies, and its proportion rises with energy, so helping ultimately to yield the $(\log s)^2$ unitarity bound. Just as Fig. 2, with a central hard scattering, represents a part of single-pomeron exchange, Fig. 3 with two central hard scatterings is a part of two-pomeron exchange. It leads to two (or more) pairs of high-$p_T$ jets or minijets.

The analysis of minijets leads naturally to the study of events with four or more jets at wide angle, even if for practical reasons present information is confined to jets of relatively large $p_T$ value. There has been a lot of work17) on multiple parton scattering mechanisms such as depicted in Fig. 3. They provide the method to study parton-parton correlations and it seems that they have now been detected in the AFS experiment at the ISR18), though the recent UA2 four-jet analysis19) finds no trace of them at the Collider, but not surprisingly, as later agreed. At the small values of x appropriate for minijet production, the x distributions of pairs of partons in the incident hadrons are presumably uncorrelated, but there could be special radial correlations. Hence it should be a good approximation to write17) the cross-section $\sigma(2)$ for producing two pairs of minijets as

$$\sigma(2) = \frac{(\sigma(1))^2}{\sigma_0} \tag{4}$$

Here $\sigma(1)$ is the cross-section for producing one pair, and $\sigma_0$ is the geometric cross-section (whose exact value is uncertain). $\sigma_0$ corresponds to a parton flux factor and is therefore sensitive to any radial correlation among partons. Calculation[1),6)] of $\sigma(1)$ finds, for $\sqrt{s}$ = 630 GeV, $p_T^{min}$ = 5 GeV/c and integrating over pseudorapidity $|\eta| < 1.5$, a value of about 7mb. If one allows for uncertainties in the determination of the jet momentum, this is in line with the data point in Fig. 1. From (4) we conclude that $\sigma(2)$ is about 1mb.

Such a four-jet event would deposit more than 20 GeV of central transverse energy $E_T$. Collecting the same $E_T$ with only two jets, each having $p_T$ > 10 GeV/c, has about the same probability at Collider energy, but this is no longer true if we require larger $E_T$. This is in agreement with the findings[19)] of UA2. Four-jet events at large $E_T$, when they are seen, are then more likely to correspond to the radiation of two extra gluons from the central hard-scattering in Fig. 2. For mere dimensional agreement, the cross-section for double-parton collisions, as given by (4), should decrease as $E_T^2$ as compared with that for single collision where $E_T$ is the global transverse energy associated with the jet system. One can estimate that at collider energy it is for a global $E_T$ value of the order of 60 GeV over two units of central rapidity that double bremsstrahlung should begin to become dominant over double parton scattering for four-jet events. The transverse energy value at which this occurs increases with centre-of-mass energy because the inclusive jet yield falls less sharply with $P_T$[6)]. It is much less at ISR energies[18)] than at Collider energies.

Mueller and Navelet[20)] have emphasized the interest of the latter mechanism, with fixed fractional momenta with increasing centre-of-mass energy, for minijet production as a new testing ground for perturbative QCD. If one triggers on two minijets well separated in rapidity, produced by a gluon exchange in the central hard scattering of Fig. 2, that gluon can radiated extra gluon minijets. This is like the multiperipheral model studied many years ago[21)], except that here the use of perturbation theory is justified with known structure functions. Notice that there is no clear separation between this mechanism and the one we mentioned earlier, where the residual-fragment systems of hadrons contain minijets. It is found[20)] that the cross-section with such a trigger (two jets at fixed rapidities) rises sharply with energy, before eventually saturating to a $(\log s)^2$ behaviour.

To summarize what we have said, the study of minijets looks promising as a further source of QCD tests. Specific constraints must be put on $P_T$ and x, according to the question asked. It will be interesting to separate the three mechanisms for the production of four minijets: double-parton scattering, multiple jet production in a single hard scattering, and minijets produced among the beam fragments. In the second test, one has a clear check of QCD with a measurement of $\alpha_s$. In the third case, one has an interesting new test of QCD with a predicted energy dependence as pointed out Mueller and Navelet$^{20)}$. In the first case, once isolated, one has access to parton-parton correlations. The third of these mechanisms can also be looked for in deep inelastic lepton scattering at large W, and its presence is a consequence of the observation that minijet production becomes an increasingly important part of pomeron exchange as the energy increases, rather than being a new and distinct part of the cross-section.

Finally, we remark that minijets may be interesting in two other ways. First, they could be an ideal means for creating a quark-gluon plasma in heavy ion collisions at very high energy. They efficiently distribute incident energy over transverse degrees of freedom: the multiple scattering of medium-$P_T$ gluons in nuclear matter should be a good way to obtain the high temperature needed for plasma formation. Secondly, when the $P_T$ of the gluon associated with the minijet comfortably exceeds twice the charmed-quark mass, and 5 GeV is already high enough for that, the gluon may fragment instead into a $c\bar{c}$ pair. The yield will be two or three orders of magnitude less than the minijet yield, which is comparable to that expected from direct $c\bar{c}$ formation. At very high energy, events with several $c\bar{c}$ pairs should become common, just as events with several minijets will become common. The relation between $D^*$ production at large $P_T$ as reported by UA1$^{22)}$ and its interpretation as gluon fragmentation following gluon-gluon scattering$^{23)}$ now seem to be on solid ground. With upgraded detectors one could study such multicharm production. More generally speaking, our discussion of minijets led us to emphasize the hard component of pomeron exchange. This should also be at the origin of interesting findings in jet production in diffractive events$^{24)}$.

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## FIGURE CAPTIONS

Fig. 1 : Measurements1) by UA1 of the cross-section for events containing minijets with $p_T > 5$ GeV/c and $|\eta| < 1.5$, together with data for the total cross-section.

Fig. 2 : Hard-scattering model for high-$p_T$ jet production.

Fig. 3 : Double-scattering model for producing a pair of minijets.

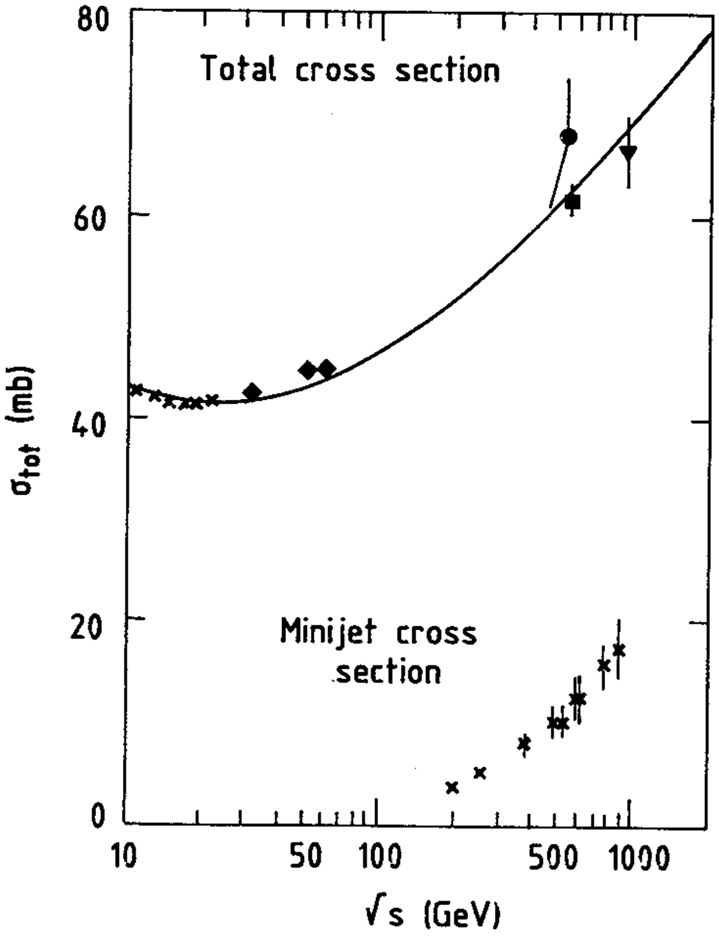

Fig. 1

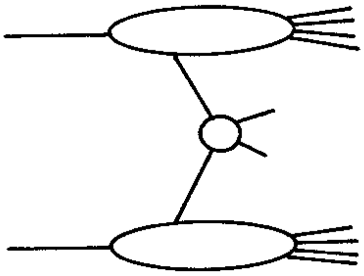

Fig. 2

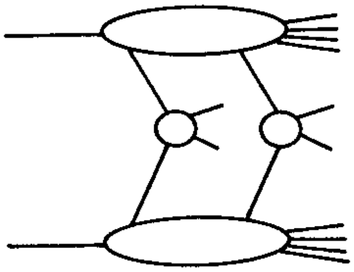

Fig. 3