QCD-MOTIVATED DESCRIPTION OF VERY HIGH ENERGY*
PARTICLE INTERACTIONS

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ABSTRACT

Cross sections for the production of secondaries with large trans-
verse momentum can become comparable to the total cross section in the
TeV energy range. We argue that the onset of this effect is observed
at sub-TeV energies via (i) an increase of the rapidity distribution
near $y = 0$, (ii) an increase of $\langle p_T \rangle$ with energy and, most directly,
via (iii) a correlation between $\langle p_T \rangle$ and multiplicity. If indeed scal-
ing violations are associated with the hard scattering of partons, then
scaling violations are largely confined to the central region and have
little effect on cosmic ray data which are sensitive to the forward
fragmentation region.

Recent $p\bar{p}$-collider experiments confirmed the observation by the
Brazil-Japan emulsion group that the average transverse momentum of
secondaries is larger in events with high multiplicity,[1] see Fig. 1.
QCD allows for a straightforward interpretation[1] of this observa-
tion: large p_T results from hard scattering of partons, and hard
scattering is accompanied by abundant gluon radiation resulting in
an increased multiplicity. This effect is most dramatically observed
in hard quark + antiquark → weak boson events where the hadronic
activity accompanying W,Z is larger[2] than that in average minimum
bias events despite the fact that roughly 1/5 of the c.m. energy
$\sqrt{s} = 0.54$ TeV is taken away by the W or Z mass. This interpretation
of the $\langle p_T \rangle$-multiplicity correlation received further confirmation
by the recent observation[3] that high multiplicity events indeed show
jet-like final state structure. A large fraction of them contained
at least one identified jet with $p_T \geq 5$ GeV. Although the QCD origin
of large p_T jets has been quantatively verified we are here discussing
events where the "large" p_T is not much larger than $\langle p_T \rangle$ and perturba-
tive calculations are difficult. We discuss this next.

Perturbative calculations of jet cross sections are made possible
by the fact that hadrons interact over a distance scale $O(1/p_T)$ which
is small. The hadrons interact via a single quark or gluon in each
hadron. When p_T becomes small many relative soft constituents are
stacked in the interacting hadrons and therefore multiple parton-parton
interactions become likely in a single hadron-hadron collision. Per-
turbation theory breaks down; e.g. for the SSC energy $\sqrt{s} = 40$ TeV we
estimate following Ref. 4 that the cross section for double parton-
parton interactions is 100 ~ 200 mb for $p_T \geq 6$ GeV. This is roughly

equal to the conventional single hard scattering cross section for $p_T \geq 6$ GeV as we will see further on. Conversely one might actually hope that naive perturbation theory yields reliable results for p_T-values as low as $5 - 10$ GeV which corresponds to x (= $p_T/\sqrt{s}$) $\simeq 10^{-3}$ at $\sqrt{s} = 40$ TeV!

Using perturbative QCD jet calculations down to $x \simeq 10^{-3}$ we have made a toy model of hadronic interactions at all energies and all p_T. The basic idea is to integrate the perturbative QCD expressions for hard scattering of constituents down to an energy-dependent $p_{T\ min}$ defined by

$$\sigma_{tot} = \sigma_0 + \sigma_{jet} \, (p_{T\ min}) \ ,\tag{1}$$

where

$$\sigma_{jet}(p_{T\ min}) = \iiint_{p_{T\ min}} F(x_1) F(x_2) \sigma(\theta) \ .\tag{2}$$

$F(x_i)$ are the probabilities for finding constitutents with fractional momenta x_i in the incident hadrons and $\sigma(\theta)$ is the elementary cross section for scattering of constituents to angle θ defined in the parton-parton c.m. system. Unlike the calculation of Ding, et al.[5] we have no cutoff in θ except that required by $p_T > p_{T\ min}$. The factorization displayed in Eq. (2) is an approximate result suitable for practical calculations.[1] σ_0 represents the soft hadronic cross section and further results will depend on assumptions regarding its magnitude and energy dependence. For illustration we assume $\sigma_0 = 38$ mb at all energies. Table I shows values of σ_{jet}, $p_{T\ min}$ and mean values of Feynman x and rapidity of the scattered jet obtained from Eqs. (1, 2). For details of the calculation see Ref. 1. The values of $p_{T\ min}$ have been adjusted so that Eq. (1) reproduces the total cross section data shown in Fig. 2. Our calculation also reproduces the p_T-distribution measured at the $p\bar{p}$ collider, see Fig. 3.

Because of the large cross sections involved, such semihard processes can be expected to produce dramatic effects at high energy. Figure 4 illustrates the expected energy dependence of the rapidity distribution at various energies of interest. We have assumed that beam fragments in hard collisions produce rapidity distributions of secondary pions as in soft collisions, with two charged particles per unit of rapidity. The scattered jets are assumed to produce rapidity distributions of the same shape as beam fragments at the kinematic limits, and also with an asymptotic density of two charged particles per unit of rapidity. In the absence of significant scaling violation effects in the fragmentation functions, we would predict an asymptotic rapidity density of four charged particles.

By energy conservation one expects a violation of scaling in the fragmentation region as the central component grows with energy. The magnitude of this effect can be estimated from the values of $\langle x_{jet} \rangle$ tabulated above. At high energies, where semihard scattering events represent a significant fraction of the cross section, $\langle x_{jet} \rangle \simeq 0.05$ so we expect fragmentation region scaling violation only at the level of 5%. This is a smaller effect than suggested in Ref. 5.

We therefore conclude that if the association between hard scattering and increasing cross section described here is qualitatively correct, then scaling violations should have little effect on the behavior of the electromagnetic component of cosmic ray cascades because these depend primarily on the fragmentation region. In particular, use of scaling-type models to interpret the Fly's Eye experiment should be essentially correct. A non-trivial result of the calculation that increases our confidence in the correctness of the association between growing cross section and hard scattering is represented by the last column of Table I. The jet rapidities that come out of the QCD calculation are such that the excess rapidity density from the scattered jets joins smoothly onto the underlying rapidity plateau from beam fragments. The Gaussian-type rapidity distribution observed at $\sqrt{s} = 540$ GeV is thus naturally reproduced.

REFERENCES

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3. G. Ciapetti, Proceedings of the pp Collider Workshop, Aosta, Italy (1985).
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ACKNOWLEDGEMENTS

TABLE I. Properties of jet cross sections with $p_T > p_{T\ min}$ at different energies.

E (TeV)	$\sqrt{s}$ (GeV)	$p_{T\ min}$ (GeV)	σ_{jet} (mb)	$<x>_{jet}$	$<y>_{jet}$
1	43.	1.25	4	0.17	1.8
150	540.	2	26	0.07	2.9
10^4	4330.	3.2	63	0.05	4.2
10^6	43300.	6	127	0.05	5.9
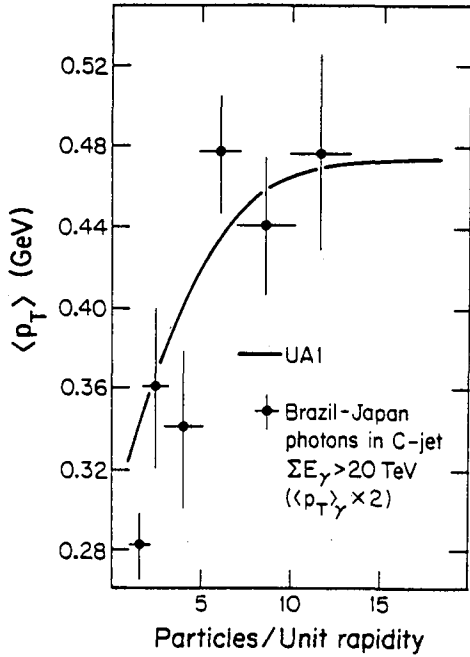
FIGURE 1. Increase of $\langle p_T \rangle$ associated with increasing multiplicity.

FIGURE 2. The increasing cross section associated with jets of moderate transverse momentum.
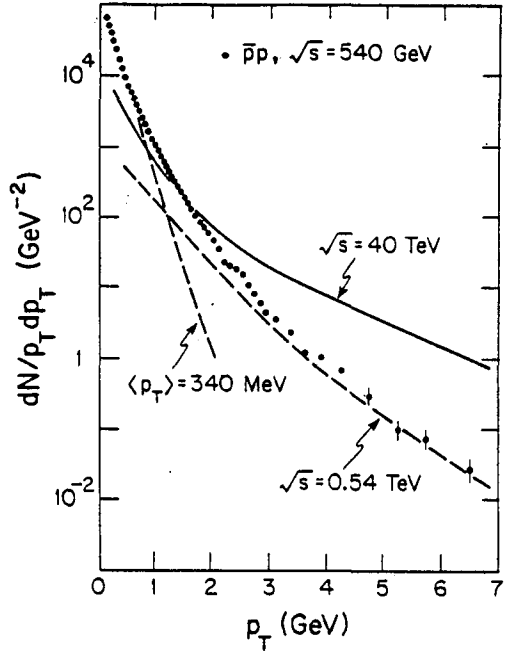

FIGURE 3. Two-component description of the charged particle transverse momentum distribution. The low-p_T component is described by an exponential fall-off with $\langle p_T \rangle$ = 340 MeV. The "high"-p_T component corresponds to hadrons which are the fragments of parton jets with $p_T > p_{T\ min}$ chosen as in Table I. Data from the UA1 experiment.
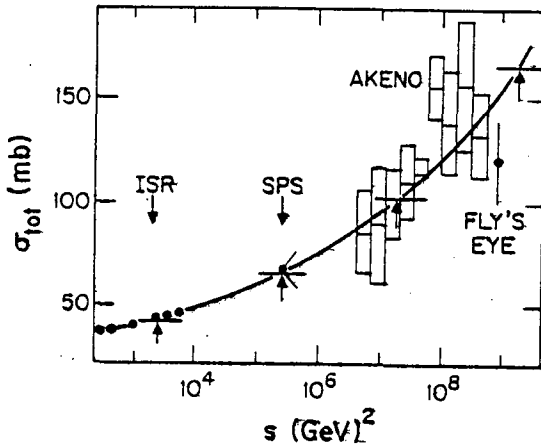
FIGURE 4. Sketch of the two-component rapidity distribution corresponding to the two-component total cross section shown in Fig. 2. At each energy the rapidity distribution consists of a plateau on which is superimposed the excess of hadrons near y = 0 due to fragmentation of the scattered jets. Rapidities of the scattered jets are indicated by arrows. The excess is cross-hatched for $\sqrt{s}$ = 0.54 TeV.