"Soft" Hard Scattering in the Teraelectronvolt Range

T. K. Gaisser[(a)] and F. Halzen
Physics Department, University of Wisconsin, Madison, Wisconsin 53706
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Cross sections for the production of secondaries with large transverse momentum can become comparable to the total cross section in the teraelectronvolt energy range. We argue that the onset of this effect is observed at subteraelectronvolt energies via (i) an increase in the rapidity distribution near $y=0$, (ii) an increase of $\langle p_T \rangle$ with energy, and (iii) a correlation between $\langle p_T \rangle$ and multiplicity. We discuss the implications for future hadron colliders and cosmic-ray experiments in the corresponding energy range.

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Recent experiments[1] at the CERN $p\bar{p}$ collider have verified the existence of hard scattering processes between constituents leading to jet production at high p_T. The angular distributions of the jets agree in detail with calculations based on perturbative QCD.[2] Schematically,

$$\frac{d\sigma^{p\bar{p}}}{dx_1\, dx_2\, d\theta} = F_1(x_1) F_2(x_2) \sigma(\theta), \qquad (1)$$

where $F_1(x_1)$ and $F_2(x_2)$ are the probabilities for finding constituents with fractional momenta x_i in the incident hadrons and $\sigma(\theta)$ is the elementary cross section for scattering of the constituents to angle θ defined in the parton-parton c.m. system. The factorization displayed in Eq. (1) is an approximate result suitable for practical calculations.[2]

Equation (1) is normally applied to hard scattering at large angles to produce jets of high p_T. Because of the Rutherford form of $\sigma(\theta) \sim \sin^{-4}\theta/2$, however, the total jet cross section is dominated by scattering at small angles and grows rapidly as energy increases at fixed p_T. Indeed, there is some minimum jet p_T, which we call $p_{T\,\min}$, below which the perturbative calculations fail altogether. This transition region between hard and soft processes is not well defined. The breakdown of perturbation theory is associated with large logarithms of the form $\log(\sqrt{s}/p_{T\,\min})$ which have to be resummed. This is a formidable theoretical problem. Also, as Durand has shown,[3] the integrated hard-scattering cross section will eventually exceed the total cross section as s increases for fixed $p_{T\,\min}$. Presumably, multiple-scattering effects will take over to restore unitarity and prevent such an inconsistency.

We propose therefore to finesse these theoretical problems by taking a phenomenological approach and defining $p_{T\,\min}(\sqrt{s}\,)$ at each energy so that

$$\sigma_{\text{tot}} = \sigma_0 + \sigma_{\text{jet}}(p_{T\,\min}) \qquad (2)$$

gives the observed total cross section.[4] We take σ_0=const to be the pp cross section at low energy. Using explicit expressions[5] for $\sigma(\theta)$ in Eq. (1), one can carry out the angular integral explicitly, with the result

$$\frac{d\sigma}{dx_1} = \frac{\pi}{18 p_{T\,\min}^2} \int_{\xi/x_1}^{1} dx_2\, F(x_1,Q^2) F(x_2,Q^2) [\alpha_s(Q^2)]^2 H; \quad H(x_1,x_2,\xi) = 16T + \frac{4\xi}{x_1 x_2} \ln\left|\frac{1-T}{1+T}\right| + \frac{2\xi}{x_1 x_2} T, \qquad (3)$$

where $T=(1-\xi/x_1x_2)^{1/2}$, $\xi=(4p_{T\,\min}^2)/s$, and $Q^2=\hat{s}=x_1x_2s$. The jet total cross section is given by

$$\sigma_{\text{jet}}(p_{T\,\min}) = \int_{\xi}^{1} (d\sigma/dx_1)\, dx_1. \qquad (4)$$

Table I shows values of σ_{jet}, $p_{T\,\min}$, and mean values of Feynman x and rapidity of the scattered jet obtained from these integrals with use of the structure functions of Baier, Engels, and Petterson.[6] The values of $p_{T\,\min}$ have been

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)	$\langle x \rangle_{\text{jet}}$	$\langle y \rangle_{\text{jet}}$
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	43 300	6	127	0.05	5.9

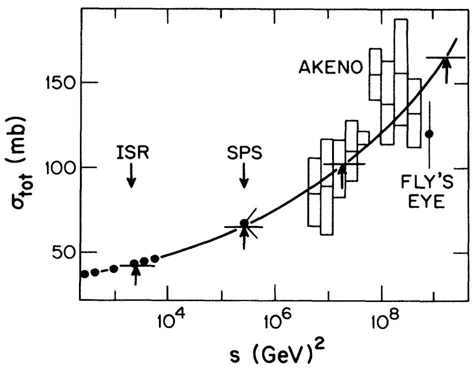

FIG. 1. The increasing cross section associated with jets of moderate transverse momentum (see Table I) superimposed on a constant total cross section of 38 mb. The result is compared to data (Ref. 7) for different center-of-mass energies.

chosen so that Eq. (2) reproduces the total cross sections shown in Fig. 1. It has been shown[8] that this value of $\sigma_{\rm jet}$ reproduces the transverse momentum distribution observed at the $p\bar{p}$ collider (see Fig. 2). Moreover, the observed[9] correlation between multiplicity and mean p_T per event (Fig. 3) is in qualitative agreement[10] with this picture since gluon radiation from jets produces high-multiplicity events.

Because of the large cross sections involved, such semihard processes can be expected to produce

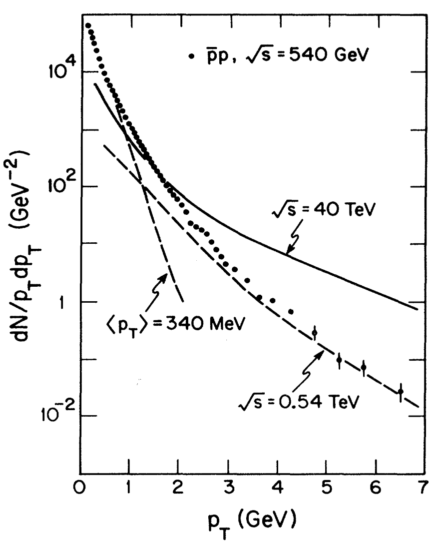

FIG. 2. Two-component description of the charged-particle transverse momentum distribution (Ref. 8). The low-p_T component is described by an exponential falloff with $\langle p_T \rangle = 340$ MeV. The "high"-p_T component corresponds to hadrons which are the fragments of parton jets with $p_T > p_{T\,\rm min}$ chosen as in Table I. The jets have been fragmented according to the distribution of Ref. 6. Data from the experiment of Arnison *et al.* (Ref. 9).

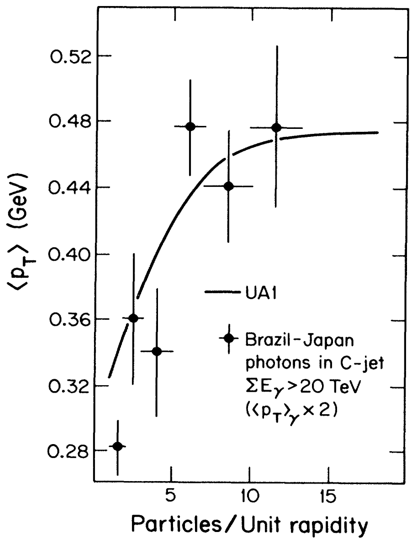

FIG. 3. Increase of $\langle p_T \rangle$ associated with increasing multiplicity. The data (Ref. 9) from Lattes, Fujimoto, and Hasegawa are compared with an interpolation of the data of Arnison *et al.* at $\sqrt{s} = 540$ GeV.

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 asymp-

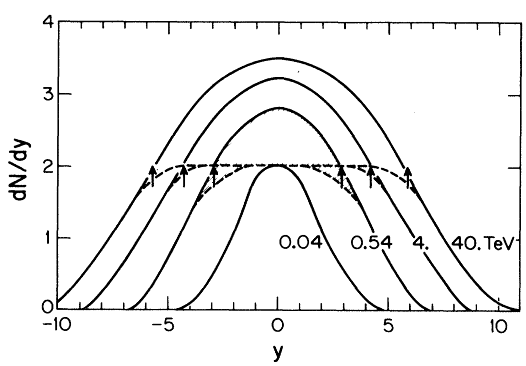

FIG. 4. Sketch of the two-component rapidity distribution corresponding to the two-component total cross section shown in Fig. 1. At each energy the rapidity distribution consists of a plateau on which is superimposed the excess of hadrons near $y = 0$ due to fragmentation of the scattered jets. Rapidities of the scattered jets are indicated by arrows. The excess is crosshatched for $\sqrt{s} = 0.54$ TeV.

totic 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.[11] The magnitude of this effect can be estimated from the values of $\langle x_{\rm jet}\rangle$ tabulated above. At high energies, where semihard scattering events represent a significant fraction of the cross section, $\langle x_{\rm jet}\rangle \simeq 0.05$, so that we expect fragmentation-region scaling violation only at the level of 5%.

We have thus reached the surprising conclusion that scaling-violation effects on total inclusive cross sections due to energy dependence of constituent interactions will be large in the central region (as already indicated by $p\bar{p}$ collider results) but fairly small in the fragmentation region. In particular, apart from the increase in the interaction cross section itself, scaling violations should have little effect on the behavior of cosmic-ray cascades because these depend primarily on the fragmentation region.[12]

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[a]On leave from Bartol Research Foundation, University of Delaware, Newark, Del. 19711.

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