High-Transverse-Momentum Secondaries and Rising Total Cross Sections in Cosmic-Ray Interactions*

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We draw attention to hadron collisions from cosmic-ray data showing evidence for high-transverse-momentum secondaries in substantial excess of the celebrated exponential cutoff, analogous to recent observations at the CERN intersecting storage rings. The data support a composite (parton/quark) picture of the proton in which deep inelastic proton collisions at high energy ($\sim 10^3$ GeV) produce constituents, observed through hadron jets. This phenomenon is possibly connected to the rise of the total cross section observed in the same range of energy.

Recent observations[1-3] at the CERN intersecting storage rings (ISR) indicate unexpectedly large cross sections for the interactions

$$p + p \to \pi^0 + \text{all}, \tag{1}$$

$$p + p \to \pi^\pm + \text{all}, \tag{2}$$

in which the observed pion has high transverse momentum (p_T). The data are taken at $\theta = 90°$ in the center of mass. For $p_T > 3$ GeV/c the cross sections fall approximately as p_T^{-8} at fixed energy and are orders of magnitude in excess of the extrapolation of the $\exp(-6p_T)$ behavior observed for $p_T < 1$ GeV/c. Furthermore, the large-p_T tail of the distribution of Reaction (2) is observed to rise in energy (approximately like s at fixed p_T).

These features of the observed transverse-momentum distribution are generally consistent[4-6] with a composite model of the proton[7] (the constituents are pointlike and called partons or quarks). At small p_T the hadrons scatter "at the surface" (peripheral scattering of geometrical objects), resulting in an exponential cutoff in transverse momentum. This is, of course, related to the collective properties of the partons. In deep inelastic collisions, on the contrary, protons interact through individual constituents. Partons emerge with high transverse momentum and produce a jet of hadrons[7] (analogous to brehmsstrahlung) that populate the high-p_T part of the cross section. For the single-particle inclusive Reactions (1) and (2), parton models yield an invariant cross section

$$E\, d^3\sigma/d^3p = p_T^{-n} F(\sqrt{s}/p_T). \tag{3}$$

Using a specific parton model with gluon exchange[7] we obtain $n = 4$ and the form of F reproduces the qualitative features of the ISR data discussed above.[6] Hadrons with high transverse momentum are produced in hadron jets. The model has the very appealing property that an event where a parton decays into a jet of hadrons of total transverse momentum, say 5 GeV/c, is much more likely to happen than an event where the same transverse momentum is carried away by a single hadron. The cross section for the production of hadron jets is appreciable[8] and will affect the energy dependence of the proton-proton total cross section around 10^3 GeV.

For the past decade there have been a number of experimental hints that superhigh-energy ($E_0 \gtrsim 10^4$ GeV; $s \simeq 2mE_0$) collisions of cosmic-ray hadrons yield an anomalous number of particles at high p_T, either single particles or jetlike clusters. In view of the limited flux available in cosmic-ray studies, the mere observation of such events would indicate that high-transverse-momentum phenomena are an important characteristic of high-energy collisions.

The growth of the average transverse momentum $\langle p_T \rangle$ with primary energy is a well-established experimental fact both for charged particles and π^0's. Data[9,10] are shown in Fig. 1; they are primarily relevant to the pionization region,[11] or $x \equiv p_\parallel/(p_\parallel)_{\max} \sim 0$. The value of $\langle p_T \rangle$ grows at least as $\ln(s)$, but since 1967, data[12] on extensive air showers (EAS) have appeared suggesting a growth of $\langle p_T \rangle$ by at least an order of magnitude when E_0 reaches 10^7–10^9 GeV. The whole picture is very suggestive of the onset of a "parton component" of the cross section in the large-transverse-momentum region. However, a growth as slow as $\langle p_T \rangle \sim \ln(s)$ can be accommodated by other models[11] (e.g., the hydrodynamic model[13]).

A sample of a p_T distribution is shown in Fig. 2(a). This set of data[14] (and other in the literature[11]) suggests a break very reminiscent of the one observed at the ISR; the deviation from an exponential falloff of the cross section appears

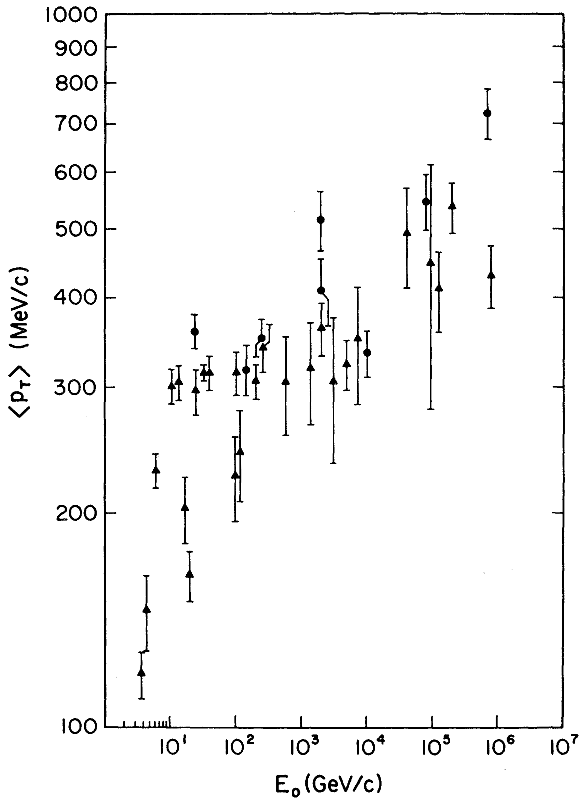

FIG. 1. Energy dependence ($E_0 \simeq s/2m$) of the average transverse momentum $\langle p_T \rangle$ as taken from Refs. 9 and 10; $s \sim 10^4$ GeV^2.

already for p_T values as low as 1 GeV/c. The number of events falls as p_T^{-2} to p_T^{-3}; and as they are mainly at $x \simeq 0$,[11] this yields

$$E\, d^3\sigma/d^3p \sim p_T^{-4}\text{–}p_T^{-5}, \tag{4}$$

as expected from (3) at large s where $F \to$ constant. Normalizing the cosmic-ray distribution with the assumption that at small p_T the cross section scales (is energy independent), we can make a direct comparison of (4) with the ISR observations. This is shown in Fig. 2(b).

It has been repeatedly reported[12,15] that the transverse-momentum distribution of secondaries in very high-energy EAS consists of two components, one component with $\langle p_T \rangle \sim 1$ GeV/c and a second with $\langle p_T \rangle \sim 5$ GeV/c. The relative frequen-

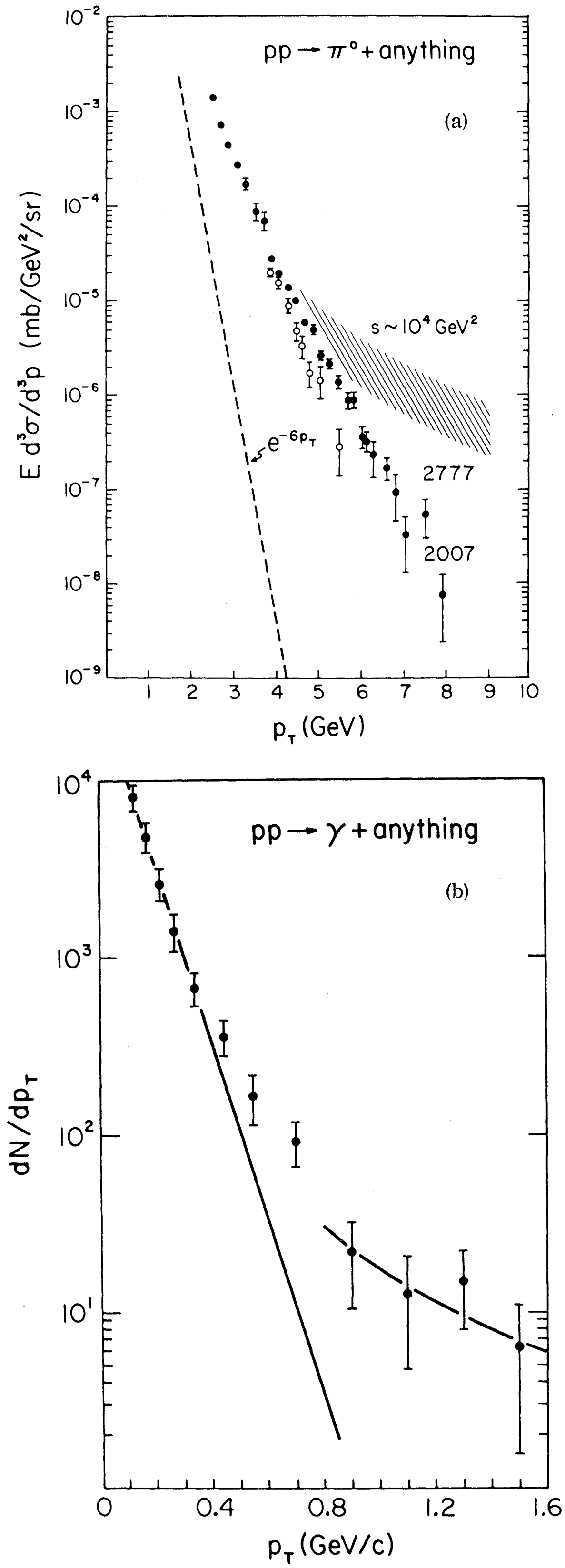

FIG. 2. (a) p_T distribution of photons from parent π^0's from a cosmic-ray experiment at $E_0 = 10^4$ GeV (Ref. 14). The curves represent an exponential falloff at small p_T and a power falloff at larger p_T. (b) Comparison of the trend of the cosmic-ray data of (a) with data obtained at the CERN intersecting storage rings (Ref. 1).

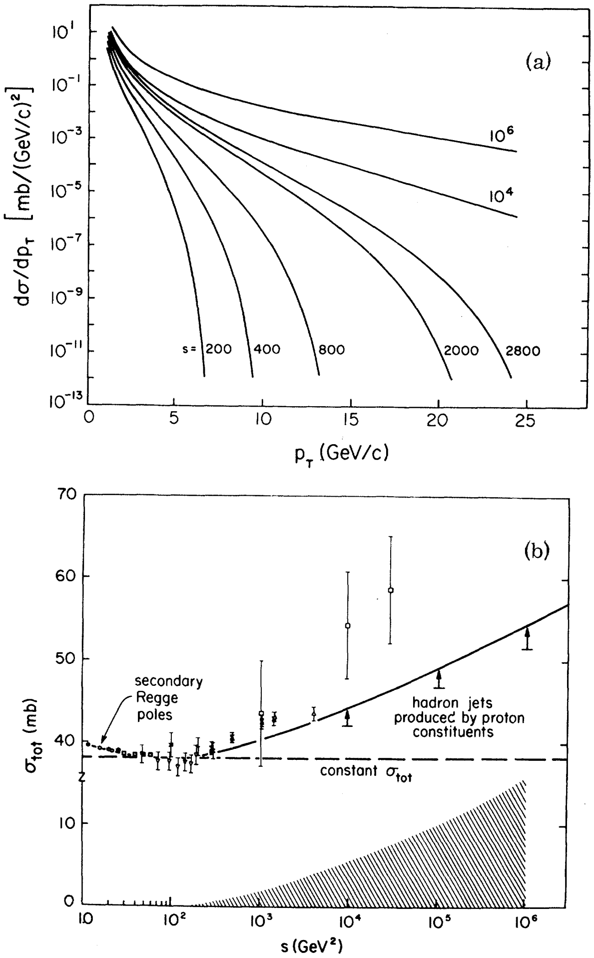

FIG. 3. (a) Inclusive cross sections for hadron jets from high-p_T partons, estimated in the quark-gluon model for different energies, versus the total p_T of the hadron jet at 90° in the c.m. system. (b) Contribution to the total proton-proton cross section from the production of inelastic partons (shaded region). The resulting rise in σ_{tot} (total p_T of the jet > 2 GeV/c) is illustrated by adding the parton contribution to a constant value of 38.5 mb and is shown along with high-energy data (Refs. 17, 19, and 20).

cy of the two components is a few times 10^{-4}. Furthermore, individual particles with $p_T = 50-100$ GeV/c have been observed both in EAS and from wide-angle muons.[16] It is very intriguing to associate this with the substantial appearance of particle jets produced by high-transverse-momentum partons. An estimate[8] of the jet at high p_T and high s in the quark-gluon model is shown in Fig. 3(a). We see that

$$\langle p_T \rangle = \frac{\int_3^{\sqrt{s}/2} (p_T \, d\sigma/dp_T) \, dp_T}{\int_3^{\sqrt{s}/2} (d\sigma/dp_T) \, dp_T} \simeq 4.5. \tag{5}$$

The cutoff $p_T = 3$ GeV/c is suggested by the ISR data, the result (5) is easy to understand since at fixed s ($\sim 10^6$ GeV^2)

$$d\sigma/dp_T \sim p_T^{-3.5}. \tag{6}$$

The relative frequency of this type of events to small-p_T events is $10^{-3}-10^{-4}$.

Although hadron jets have escaped direct observation in accelerator experiments, their effect might have been measured indirectly through the observed rise in the proton-proton total cross section at the CERN ISR.[17] The contribution of the sizable cross sections for hadron jets produced by deep inelastic partons to the proton-proton total cross section can be readily calculated; symbolically,

$$\sigma_{tot} = \int_{p_T = 2-3}^{p_T = \sqrt{s}/2} \frac{d\sigma}{dp_T} d(\text{phase space}). \tag{7}$$

Its contribution is negligible up to $s = 10^3$ GeV^2 but contributes roughly 7 mb at 10^4 GeV^2 (which could at least partly[18] explain the rise in σ_{tot} observed at the ISR) and would contribute ~15 mb at 10^6 GeV^2. The contribution of (7) to σ_{tot} is shown as a shaded area in Fig. 3(b). Adding this to a constant geometrical or diffractive contribution, we get the curve shown in Fig. 3(b) along with existing data.[17,19,20] It is interesting to speculate that the production of partons is primarily responsible for the rise in the total proton-proton cross section, analogous to the rise at lower energies near the pion production threshold.[21] Our choice of a cutoff of $p_T = 2-3$ GeV/c in Eq. (7) would be too conservative. Taking $p_T = 1$ GeV/c the rise in σ_{tot} would be much stronger as suggested by the lower bounds calculated from cosmic-ray data in Ref. 20, and our results would be very similar to the calculations of Kogut, Frye, and Susskind.[22]

We finish with a word of warning on cosmic-ray data. Every individual experimental observation of the type discussed in this paper is subject to ambiguities and in many cases the evidence has been challenged.[23,24] Taken in bulk, however, existing data suggest that large-transverse-momentum secondaries may be plentiful at cosmic-ray energies, as expected from composite-hadron models.

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Non-Abelian Gauge Theories of the Strong Interactions*

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A class of non-Abelian gauge theories of strong interactions is described, for which parity and strangeness are automatically conserved, and for which the nonconservations of parity and strangeness produced by weak interactions are automatically of order α/m_W^2 rather than of order α. When such theories are "asymptotically free," the order-α weak corrections to natural zeroth-order symmetries may be calculated ignoring all effects of strong interactions. Speculations are offered on a possible theory of quarks.

Recently Gross and Wilczek and Politzer have made the exciting observation that non-Abelian gauge theories can exhibit free-field asymptotic behavior at large Euclidean momenta.[1] However, the physical application of this discovery raises serious problems: (1) Why don't the weak interactions produce parity and stangeness nonconservations of order α? (This problem finds a natural solution when the strong interactions are described by *Abelian* gauge models,[2] but not, to the best of my knowledge, in non-Abelian models of the "Berkeley" type.[3]) (2) Even with asymptotic freedom, when can the strong interactions actually be neglected? (3) Even if asymptotic freedom explains the success of naive quark-model calculations, why don't we see physical quarks? This