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Hadronic interactions around 50 TeV

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Monte Carlo simulations which incorporate experimental selection criteria show that many features of local interactions in the Brazil-Japan emulsion chamber at Mt. Chacaltaya can be understood in terms of conventional ideas extrapolated from accelerator energies. This experiment provides the most direct information that currently exists on strong interactions up to about 100 TeV. A feature without which the data cannot be understood is the inclusion of a large fraction of hard scattering.

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I. INTRODUCTION

Large emulsion chambers[1] have by now accumulated a significant number of cosmic-ray interactions with visible energies of twenty to several hundred TeV, corresponding to interaction energies of 50–1000 TeV. The interactions fall into two classes: (1) local interactions in the detector and (2) interactions in the atmosphere above the detector. The latter class contains the highest-energy events because it includes interactions that take place well above the detector where the flux is relatively high.[2] This class includes the anomalous Centauro events. Interpretation of atmospheric events is, however, correspondingly more complicated because of the large dimension of the effective target.

In this paper we concentrate on interpretation of local interactions in the detector, called carbon jets (C jets) by the Brazil-Japan group.[3] The existence of complicated scanning selection criteria, together with large fluctuations and the steep energy spectrum of the cosmic-ray beam, make it essential to carry out a detailed Monte Carlo simulation in order to interpret the data. In particular, the most important limitation of the technique is the fact that only energetic secondary γ rays (e.g., from decay of π^0's produced in the interaction) are detected. Charged hadrons typically escape the detector without further interaction.

We carried out such a simulation some time ago[4] in which we showed that the main features of the energy dependence and distributions of pseudorapidity of secondary photons could be understood as a consequence of the various selection effects superimposed on a straightforward (scaling) extrapolation of accelerator data. The large observed fraction of events with large masses (M_γ) of clusters of secondaries and with high P_T did not, however, emerge from the original simulation, in which all secondaries were chosen from ordinary P_T distributions without a high-P_T component.[5] A major result of the simulation that we report here is that inclusion of a hard-scattering component as suggested by parton models of hadronic processes may also account for this aspect of the data also. Indeed we find that the M_γ distribution is rather sensitive to details of the hard-scattering model.

The paper is organized as follows. In Sec. II we describe the interaction model and in Sec. III the details of the simulation of the experiment. Section IV contains results on distributions of energies and pseudorapidities of secondary photons. The subject of high transverse momentum and large cluster masses is discussed in Sec. V, which is followed by the concluding Sec. VI.

II. INTERACTION MODEL

In order to make use of the large amount of existing experimental data on inclusive single-particle production at high energies, we have adopted an independent-emission scaling model. Secondary-particle center-of-mass (c.m.) momenta are drawn at random from probability distributions which result from radial scaling[6] of the invariant inclusive cross sections. Thus the momentum of each secondary is uncorrelated with that of any other—there is no dynamical clustering. Secondary particles are created until the available c.m. energy is exhausted.

We have chosen to neglect, at this stage, any effects due to the nuclear composition of the target; the target is assumed to be a nucleon. Accelerator measurements[7] of forward secondaries produced on nuclear targets show a ~20% increase in multiplicity of minimum ionizing secondaries for $A \sim 14$ targets. For the energetic forward secondaries with which this simulation is most concerned, the difference is considerably smaller.

We have also included the observed[8] correlation between longitudinal and transverse secondary momenta. In creating a secondary, the simulation program first selects, at random, a value of $x_R = 2E^*/\sqrt{s}$ from an appropriate distribution, selects a value of $P_\perp$ from its x-dependent distribution, and then computes the c.m.-momentum vector.

More specifically, the following set of steps is executed for each interaction:

(1) The c.m. energy of the fragment nucleons from the projectile and target nucleons are chosen independently from a flat distribution.[9] In pion initiated interactions a single "fragment" pion is chosen from a distribution in x_R given by $dn/dx_R = 3.2 - 2.75\theta(x - 0.2)$. The mean inelasticity is thus 0.5 for NN and a 0.28 for πN collisions. The fragment pion is normally chosen to be charged.

(2) Secondary kaons and pions are created in the ratio $\pi/K = \frac{9}{1}$. Pions are randomly tagged as neutral with an average probability of $\frac{1}{3}$. The fraction of secondaries which are $\bar{N}$ (or associated nucleons) is extrapolated from accelerator data and is 5% at 50 TeV. Longitudinal momenta of mesons are found from the x_R distribution which would result from an invariant cross section of the form

$$E\frac{d^3\sigma}{dp^3} \propto e^{-Ax_R}\,. \qquad (1)$$

For incident protons, the value of A is randomly taken to be either 5.5 or 6.5 with 50% chance of each; for incident pions $A = 3.5$. In both cases $A = 11$ for $N\bar{N}$ production.

(3) Transverse momenta of all particles are chosen from transverse momentum distributions to be described below. Approximate momentum conservation is obtained by pointing the c.m. momentum vector of each particle into the octant opposite to that of the vector sum of momenta of all previously chosen particles in the event.

(4) After the momentum of each particle is determined the total amount of c.m. energy used so far is computed. If the most recently created particle makes the total energy greater than the actual c.m. energy, this particle is randomly included 50% of the time, and the momenta are Lorentz-transformed to the laboratory. If there is more energy available, more secondaries are produced until the available energy is used up.

Events simulated by this procedure are compared with experimental data[10,11] in Fig. 1. The procedure conserves momentum only approximately. One consequence of this is that the total energy of the outgoing particles is not exactly the same as the incident energy. Since the last particles produced are secondaries which are, for the most part, rather soft in the c.m. the energy imbalance is not very severe. The fractional c.m.-energy error is approximately 4%. The lack of exact transverse-momentum conservation is unimportant in the present context since the total transverse momentum of the detected subset of secondary photons is also nonzero.

The transverse-momentum distribution we use has the two-component form

$$\frac{dn}{P_T\,dP_T} \propto A e^{-B_i(x)P_T} + \frac{C}{(P_T{}^2+1)^2} e^{-(48x_\perp' + 38x_\perp'^3)}\,, \qquad (2)$$

where

$$B(x) = \begin{cases} 2/(0.25 + |x|), & |x| \leqslant 0.2 \\ 4.44, & |x| > 0.2 \end{cases}$$

for secondary mesons and $B = 6, 4, 4$ for fragment π, p, K. The second term in Eq. (1) is the high-P_T component, the form of which is taken from the work of Halzen and Luthe,[12] which gives an explicit parametrization of the energy dependence of the high-P_T component. The constant C/A is related to the fraction F of secondary pions which are chosen from a distribution proportional to the second term in Eq. (1), in which $x_\perp' \equiv 2(P_T + 1)/(s + 1156)^{1/2}$ (s in GeV^2, P_T in GeV/c). For each secondary meson a decision is made randomly

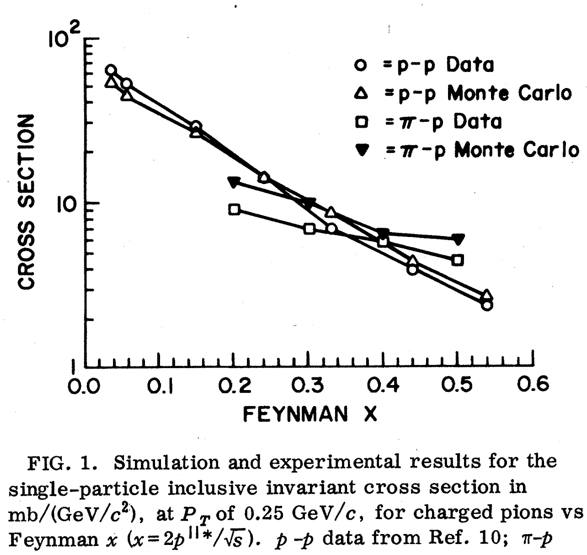

FIG. 1. Simulation and experimental results for the single-particle inclusive invariant cross section in mb/(GeV/c^2), at P_T of 0.25 GeV/c, for charged pions vs Feynman x ($x = 2p^{\parallel *}/\sqrt{s}$). p-p data from Ref. 10; π-p data from Ref. 11.

whether to choose from the low-P_T or high-P_T distribution. (The correct procedure would be to compute the parton-parton scattering first and then to choose individual pions from decay of the resulting jets.)

The energy dependence of F reflects the threshold behavior of the high-P_T process, which arises from the low probability of a parton-parton subenergy with a large fraction of $\sqrt{s}$. As energy increases a given subenergy, and hence a given P_T, corresponds to an ever smaller fraction of the total c.m. energy. Here we take

$$F=\begin{cases}(3.4\times10^{-4})s^{0.605}, & s<30\,000\ \mathrm{GeV}^2,\\ (1.4\times10^{-2})s^{0.254}, & 30\,000<s<400\,000,\\ 0.40, & s>400\,000.\end{cases}$$

Shibata[13] has recently made an extensive calculation of high-P_T processes at cosmic-ray energies which incorporates the full machinery of the modern parton model, including gluon scattering, scale breaking, and parton transverse momentum. He extended the hard scattering calculations, which are normally done for near 90° in the center of mass, to the forward fragmentation region, which is relevant for the cosmic-ray calculation in which only fast secondaries are visible. The inclusive distributions obtained from the simple parametrization described above are roughly in agreement with the parton-model calculation. The absolute magnitude of the high-P_T component we use is in good agreement with that of Shibata, but the shape is somewhat flatter. Accordingly, we have also tried a distribution with the exponent -2 in Eq. (2) replaced by -2.75.

III. SIMULATION OF THE EXPERIMENT

The specific features of the Mt. Chacaltaya emulsion-chamber experiments which were included in the simulation are the following:

(1) For the energy spectrum of the incident hadrons we assumed a power law, $dn/dE \propto E^{-2.7}$.

(2) We took account of multiple interactions as well as conversions of γ rays in the target, which we assumed to have a thickness of 34 g/cm^2. The first interaction point was randomly distributed over the depth of the target.[14] The Monte Carlo program followed each created hadron and generated new interactions until either (a) the hadron left the target, or (b) the energy of the hadron was below a nominal threshold. This threshold was taken to be 200 GeV, the stated energy detection threshold in the emulsion chamber.[3] All produced π^0's were allowed to decay into γ's and the γ's were "trajected" into the emulsion chamber, with allowance for conversion in the remainder of the target.

(3) Finite energy and angular resolution were included. The main sources of experimental error are the energy resolution of the chamber for individual γ's, the lack of knowledge of the lateral position of the incident hadron, and the depth of the interaction in the target. The procedure used by the experimenters is to find the energy-weighted center of the set of γ's associated with an event. This was then taken to be an estimate of the intersection point of the incident hadron trajectory with the detector. The interaction was assumed to have occurred mid-deep in the target. This permitted the reconstruction of the emission angle of each γ. The effect of these uncertainties is shown schematically, for a vertically incident hadron in Fig. 2. We have assumed that the zenith angle of the incident hadron was determined with negligible error by the emulsion chamber, so only vertically incident hadrons were simulated. The program puts in these experimental conditions through the following steps: (a) The energy of each γ is randomly shifted by an energy error drawn from a Gaussian with 25% width. (b) The position of the intersection of the γ with the top of the detector is assumed to be determined with negligible error. The energy-weighted center of the γ cluster is computed as $X=(\sum E_j)^{-1}(\sum E_j X_j)$. The reconstructed interaction point is then directly above the energy-weighted center, in the middle of the target. This yields the reconstructed emission angle θ_j, which is used in the computation of the invariant mass (see Sec. V).

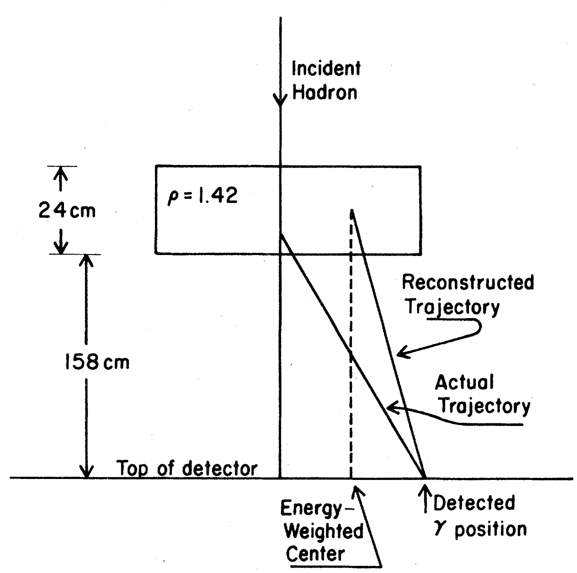

FIG. 2. Schematic diagram of actual and reconstructed trajectories.

(4) Events were selected as follows. To be considered for further analysis, an event must have at least four γ rays with energies greater than 200 GeV each. We counted hadrons that interacted in the first 1.3 cm of the lower chamber as photons.

IV. ENERGIES AND PSEUDORAPIDITIES

The most direct test of scaling would be a comparison of x distributions at cosmic-ray energies with those at lower energies. This is impossible, however, since only photons are detected. Instead, the scaling variable that can be measured is $f \equiv E_\gamma/\sum E_\gamma$, where $\sum E_\gamma$ is the total visible energy. Figure 3 shows a comparison between data and simulation for three different input models: (1) The dashed line is the result for the standard model; (2) the solid line is for a model with $A \to 1.5A$ in Eq. (1); and (3) the lowest (dash-dot) line results from cutting off all secondary mesons with $x > 0.1$ in all interactions with $E_0 > 50$ TeV. Thus the data are consistent with scaling to ~100 TeV but the test is not a very sensitive one. This insensitivity is a consequence of the fact that E_0 is not measured and that there are correlations between E_γ and $\sum E_\gamma$ for each event. Moreover, fluctuations in $\sum E_\gamma/E_0$ are large so that the correlation between $\sum E_\gamma$ and E_0 is weak. (The ratio $\sum E_\gamma/E_0$ has a mean of 0.37 and standard deviation of 0.17 for proton induced events. See Ref. 4 for further discussion of this point.) It is worth noting that, despite the insensitivity of the f distribution to the underlying x distribution, the data limit use of some extreme models commonly used in cosmic-ray calculation in which there are essentially no very energetic secondaries at high energies.[15]

The distribution of pseudorapidities is shown, in Fig. 4, for the Chacaltaya emulsion-chamber data, the Monte Carlo simulation, and accelerator measurements at 200 GeV.[16]

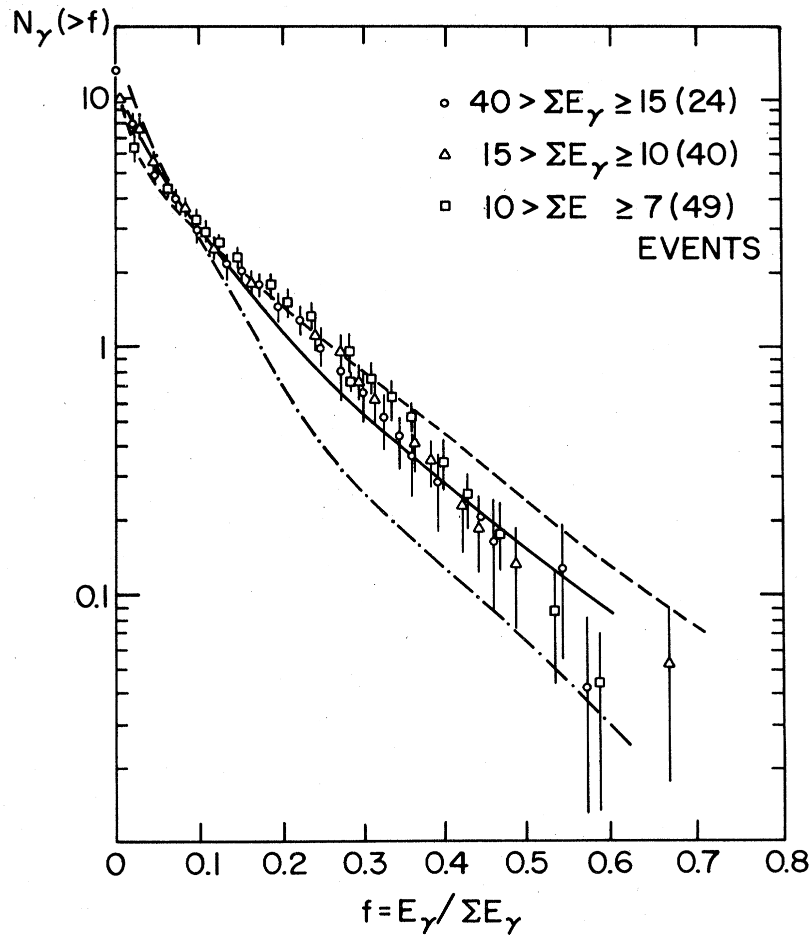

FIG. 3. Simulation and experimental results for the integral distribution of $f = E_\gamma/\sum E$.

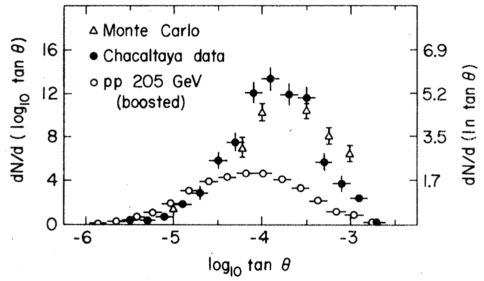

FIG. 4. Distribution of pseudorapidity density per event for the Chacaltaya data, the Monte Carlo simulation using the high-P_T tail, and 200-GeV accelerator data (Ref. 16).

The multiplicity of photons appears to be rather high, but it is difficult to evaluate the implications of this fact because of the extreme sensitivity of the results to details of the threshold for detecting individual photons (most photons being near the threshold). It appears that much of the apparently high multiplicity arises from selection effects. In addition, the pseudorapidity density of photons in the input model is 3 at $E_0 = 100$ TeV, showing some increase over the value of 2 at CERN ISR energies due to our use of radial scaling.[17]

V. EFFECTS OF HIGH P_T

A feature of the Chacaltaya data that is often emphasized is the M_γ distribution. This is a histogram of events classified by the invariant mass of γ rays within a certain angle of the energy-weighted center of the event. The cone is defined (event by event) so that if the γ rays come from isotropic decay of a cluster of particles and if selection effects can be ignored, then M_γ is the cluster mass times the fraction of π^0's in the cluster. Specifically, M_γ is obtained by the following algorithm: Define the invariant mass of γ's inside a cone θ as $M_\gamma(\theta)$. Then

$$M_\gamma(\theta)=\left[\left(\sum_\theta p^\gamma\right)^2\right]^{1/2}\simeq\left|\sum_\theta E_\gamma\sum_\theta E_\gamma\theta^2\right|^{1/2}.$$

Also define the total transverse momentum inside θ,

$$P_T(\theta)=\int^\theta P_T\,d\theta\cong\sum E_\gamma\theta_\gamma .$$

For small θ, $M_\gamma(\theta)<(4/\pi)P_T(\theta)$, and for large θ, $M_\gamma(\theta)>(4/\pi)P_T(\theta)$. Define $M_\gamma\equiv M_\gamma(\theta_0)$, where θ_0 is the solution of $M_\gamma(\theta_0)=(4/\pi)P_T(\theta_0)$. In practice this involves an interpolation.

Nearly half the events among the 68 reported have $M_\gamma>3$ GeV, a much larger fraction than found in the simulation of Ref. 4. Events with large M_γ are also seen among the lower-energy data, but with a lower frequency. Moreover, the events with large M_γ also have high multiplicity. On the basis of these features of the data, the Japan-Brazil group argue that there is a threshold (around 50 TeV) for production of events with large clusters or fireballs.

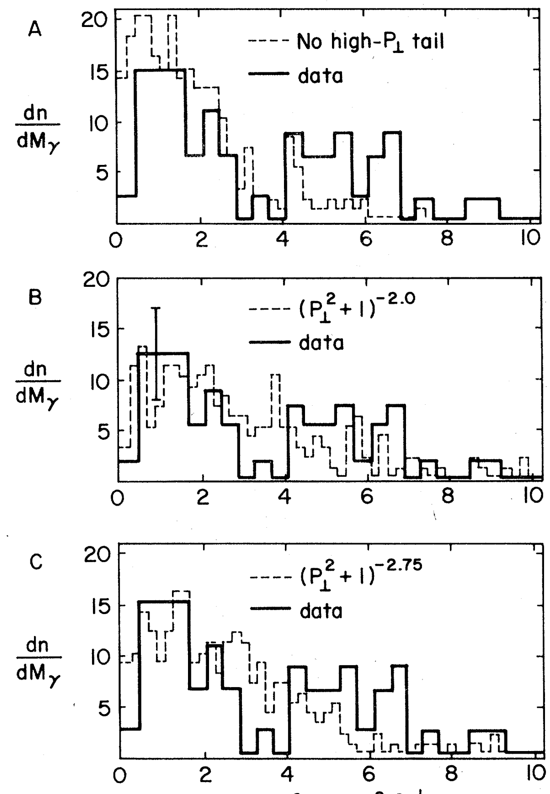

FIG. 5. Actual and simulated M_γ distributions for (A) no high-P_T tail; (B) a tail of the form $(P_\perp^2+1)^{-2.0}$ (in GeV units); (C) $(P_\perp^2+1)^{-2.75}$.

It is clear from the definition of M_γ that there is a correlation between transverse momentum and M_γ. Halzen[12] suggested some time ago that the events with large M_γ might be due to hard scattering. Although this is probably not true on an event-by-event basis, our simulation shows that a large fraction of events with large M_γ can arise as a consequence of the hard-scattering component. Figures 5(a) and 5(b) show the Brazil-Japan M_γ distribution,[18] normalized to the simulation results for the case of no high-P_T tail [$C=0$ in Eq. (2)]. Better agreement is obtained when the hard-scattering component is included, as shown in Figs. 5(b) and 5(c). However, the softened P_T distribution, as for the parton-model calculation of Ref. 13, does not produce as good agreement as the original $(P_\perp^2+1)^{-2.0}$ distribution.

VI. CONCLUSIONS

We summarize here the conclusions we have drawn from this study.

(A) There is no evidence for violation of radial scaling in the fragmentation region for incident energies up to several hundred TeV. But the sensitivity of experiment is low; large-scale changes in the x distribution would be necessary to cause an observable effect.

(B) The falling energy spectrum and fixed threshold favor selection of high-multiplicity events. The mean primary energy is 2.7 times $\sum E_\gamma$.

(C) Simulations are capable of producing an M_γ distribution that is consistent with the data, provided a sufficiently large component of hard scattering is assumed. We must emphasize that the experiment is sensitive only to the small-P_T part of hard scattering, a region in which calculations do not have a firm theoretical foundation. A test of the basic idea that events with large M_γ are correlated with hard scattering would be to look for asymmetries corresponding to jet production, as suggested by Gaisser and Sidhu.[19] Arata[20] has made a study of azimuthal structure in terms of the fireball model. He finds that azimuthal structure is present in C jets with $M_\gamma > 3$ GeV but not in those with $M_\gamma < 3$ GeV. He also shows that a model similar to that used here but without the hard scattering does not reproduce the azimuthal structure. It remains to be investigated whether the hard-scattering model will reproduce the azimuthal structure in the data.

ACKNOWLEDGMENTS

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[1] See T. K. Gaisser and G. B. Yodh, Annu. Rev. Nucl. Part. Sci. (to be published); Y. Fujimoto, in *International Cosmic Ray Conference, Kyoto, 1979, Conference Papers* (Institute of Cosmic Ray Research, University of Tokyo, Tokyo, 1979), Vol. 14, p. 308 for reviews and for the references on emulsion-chamber terminology, techniques, and results.

[2] See R. W. Ellsworth *et al.*, paper presented at the XXth International Conference on High Energy Physics, Madison, 1980 (unpublished), for a preliminary report of simulations of these atmospheric events.

[3] Y. Fujimoto *et al.*, Brazil-Japan Emulsion-Chamber Collaboration, in *Cosmic Rays and Particle Physics—1978,* proceedings of the Bartol Conference, edited by T. K. Gaisser (AIP, New York, 1979), p. 94.

[4] R. W. Ellsworth, G. B. Yodh, and T. K. Gaisser, see Ref. 3, p. 111.

[5] An error was discovered in the simulation of Ref. 4 which had the effect of incorrectly giving extra transverse momentum to secondaries in those events with multiple interactions in the thick target. When this error was corrected, the simulation without high P_T gave only a small number of events with $M_\gamma > 3$ GeV. This error had no effect on results involving only longitudinal quantities, such as distributions of $E_\gamma/\sum E_\gamma$. This was the situation reported by R. W. Ellsworth, G. B. Yodh, and T. K. Gaisser, at the 1979 Cosmic Ray Conference at Kyoto, Report No. HE 3-37 (unpublished).

[6] E. Yen, Phys. Rev. D 10, 839 (1974); K. Kinoshita and H. Noda, Prog. Theor. Phys. 49, 896 (1973); F. E. Taylor *et al.*, Phys. Rev. D 14, 1217 (1976) for further data on radial scaling.

[7] W. Busza *et al.*, Phys. Rev. Lett. 34, 383 (1975).

[8] M. Bardadin *et al.*, in *Proceedings of the Siena International Conference on Elementary Particle Physics, Siena, Italy, 1963* edited by G. Bernardini and G. Puppi (Societa Italiana di Physica, Bologna, 1963), Vol. I, p. 628.

[9] See Fig. 5 of T. K. Gaisser, R. J. Protheroe, K. E. Turver, and T. J. L. McComb, Rev. Mod. Phys. 50, 859 (1978) for a comparison of this assumption with data from p-p collisions.

[10] J. R. Johnson *et al.*, Phys. Rev. D 17, 1292 (1978).

[11] D. Cutts *et al.*, Phys. Rev. Lett. 40, 141 (1978).

[12] F. Halzen and J. Luthe, Phys. Lett. 48B, 440 (1978); F. Halzen, Nucl. Phys. B92, 404 (1975).

[13] T. Shibata, in *Sixteenth International Cosmic Ray Conference, Kyoto, 1979, Conference Papers* (Ref. 1), Vol. 7, p. 3462.

[14] We used energy-dependent interaction lengths as described by Gaisser and Yodh (Ref. 1).

[15] We have in mind here the use of high-multiplicity models above thresholds as low as 50 TeV. In particular, the CKP model [G. Cocconi, Nucl. Phys. B28, 341 (1971) and references therein] at 100 TeV has essentially no secondaries above $x=0.1$—see Fig. 5 of T. K. Gaisser, J. Franklin Inst. 298, 271 (1974).

[16] The accelerator data is from T. Kafka *et al.*, Phys. Rev. D 16, 1261 (1977). A recent review article by the Brazil-Japan group [G. M. G. Lattes, Y. Fujimoto, and S. Hasegawa, Phys. Rep. 65, 3 (1980)] describes a procedure in which individual secondaries from 200-GeV interactions are given a rapidity boost corresponding to a primary energy drawn at random from a cosmic-ray spectrum. The resulting rapidity distribution does not display the increase in density seen in our simulation. This is not surprising, since the boosting procedure does not take into account the large increase in the width of the rapidity plateau between 200 GeV and

100 TeV. Simply boosting the 200-GeV distribution produces, at fixed incident energy, a distribution with no population over several units of rapidity where it should be filled. Averaging over incident energy then lowers the average rapidity density.

[17]R. W. Ellsworth, in *Sixteenth International Cosmic Ray Conference, Kyoto, 1979, Conference Papers* (Ref. 1), Vol. 7, p. 333 discusses the relation between radial scaling and the increase in height of the plateau in rapidity.

[18]Presented in a rapporteur talk by Y. Fujimoto, in *Sixteenth International Cosmic Ray Conference, Kyoto, 1979, Conference Papers* (Ref. 1). A subset of events, those for which the γ's are exhausted before determining an M_γ, have been removed from both the data and the simulation.

[19]T. K. Gaisser and D. P. Sidhu, in *Proceedings of the Fifteenth International Conference on Cosmic Rays, Plovdiv, 1977,* edited by B. Betev (Bulgarian Academy of Science, Sofia, 1977), Vol. 7, p. 18.

[20]N. Arata, in *Sixteenth International Cosmic Ray Conference, Kyoto, 1979, Conference Papers* (Ref. 1), Vol. 6, p. 283.