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P_T-FLOW IN 10 - 1000 TeV*

and

MICROSCOPIC ANALYSIS ON SHOWERS RECORDED AS SINGLE CORE ON X-RAY FILMS**

by

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p_T-FLOW IN 10 - 1000 TEV

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Abstract

We study here how the flow of transverse momenta (Σp_T or ΣER) behaves in multi-particle production phenomena in the region of visible energy 10 - 1000 TeV, using the emulsion chamber data of Brasil-Japan Collaboration.

1. Introduction

Multiplicity, n, and transverse momentum, p_T, are useful quantities to study the multi-particle production phenomena. We have studied/1,2/ the cosmic-ray induced so-called C-jet events at $E_0 \sim 100$ TeV and found a clear scaling violation both in n and p_T. When we use the data of atmospheric interactions (A-jet events) to study the phenomena at $E_0 \sim 1000$ TeV, the sum of energy-weighted distances, ΣER, may be a useful quantity. This quantity is related with the sum of p_T's as $\Sigma ER = H.\Sigma p_T$, where H stands for the interaction height.

By summing up the values of ER, we can diminish the effect of cascade processes which may increase n and decrease p_T. By assuming a plausible average H, we can combine the A-jet events with the C-jet events which are interactions occurring in a fixed target.

We study the behavior of p_T-flow in the region $\Sigma E_\gamma = 10 - 1000$ TeV using the C-jet and the A-jet events of Brasil-Japan Collaboration, where ΣE_γ is the sum of energies of electro-magnetic components (here-after abbreviated as γ-rays).

2. Experiment and Data

The Brasil-Japan Collaboration has been exposing a series of two-storied emulsion chambers at Mt.Chacaltaya, Bolivia, 5220 m above sea-level. The chambers consist of an upper chamber, a target layer of petroleum pitch, a spacing air gap of ~1.5 m and a lower chamber. Both the upper and the lower chambers are of multi-layered sandwiches of lead plates and photo-sensitive materials (X-ray films sometimes with nuclear emulsion plates). The upper chamber works as a detector of atmospheric interactions (A-jets) and also as an absorber for the lower chamber. The lower chamber works as a detector of local nuclear interactions (C-jets) occurring in the target layer.

In this paper, we study 206 C-jet events of ΣE_γ = 10 - 100 TeV and 100 A-jet events of ΣE_γ = 100 - 1000 TeV. The threshold energy in the scanning of γ-rays is 0.1 - 0.2 TeV in C-jet events and 1 - 2 TeV in A-jet events.

The emulsion chamber experiments were described in more detail/1/.

3. Simulation

As a reference, we performed a simple Monte Carlo simulation based on a scaling model. Artificial particles are produced in the following procedures: 1) the collision energies follow the power spectrum ($\gamma \sim 1.7$), 2) the energy of surviving proton (and meson on successive interactions) is sampled from a flat distribution of x ($= 2p_{\parallel}/\sqrt{s}$), a p_T distribution of the form $\exp(-4\,p_T)$ and a flat azimuth distribution, 3) the pions are produced with equal probability for each charge state, 4) the values of rapidity y, p_T and azimuth angle for pions are sampled in a way that each vector is directed into the octant opposite to the vector sum of momenta of all previously produced particles, and 5) the last pion is included (or excluded) with 50% probability and the energy conservation is required within 5%.

For the item 4), we use the rapidity distribution $1/[1 + \exp\{(y-y_0)/\Delta\}]$ where $\Delta = 0.54$ and $y_0 = 3 + \ln(\sqrt{s}/53)$. The p_T distribution is assumed to be exponential with the average value expressed as $(2/6)\cdot[1 - \exp\{-0.21\,(y_{lb} + 1.9)^2\}]$ GeV/c, where $y_{lb} = y_p - y_{cm}$/2/. This choice of y and p_T approximately results in $\exp(-8x)$ for $x \gtrsim 0.1$ independently on energy and a flat rapidity plateau with height ~1.1 for each charge state. Thus we can regard our simulation as a scaling model which roughly extends the phenomena at FNAL, SPS and ISR energies up to the cosmic-ray regions.

For the simulation of atmospheric interactions, we followed the method of ref. 3. We used 80 and 120 gr/cm^2 for λ_p and λ_π, respectively, and neglected lateral spread due to electro-magnetic cascade processes.

We used the following criteria: 1) energies of γ-rays $\geq$ 2 TeV in A-jet events and $\geq$ 0.2 TeV in C-jet events ($\geq$ 2 TeV also being tried), and 2) the number of γ-rays $N_\gamma \geq 4$. We did not apply any criteria to the lateral spread.

4. Results

Fig. 1 shows the scatter plots of $\Sigma p_{T\gamma}$ vs. ΣE_γ for the C-jet events where $\Sigma p_{T\gamma}$ and $\Sigma_{E\gamma}$ are, respectively, the sum of transverse momenta and the sum of energies of γ-rays. Here the minimum energy E_m for γ-rays is set to be 0.2 TeV. Note that, in the C-jet events, we can directly measure the p_T because of the fixed height of interactions. Fig. 2 shows the scatter plots of Σ ER vs. ΣE_γ for the A-jet events, where Σ ER is the sum of products of E and R of γ-rays. Here E_m = 2 TeV, and the distance R is measured from the energy-weighted event center. In both figures, we notice that the p_T-flow increases when the energy rises.

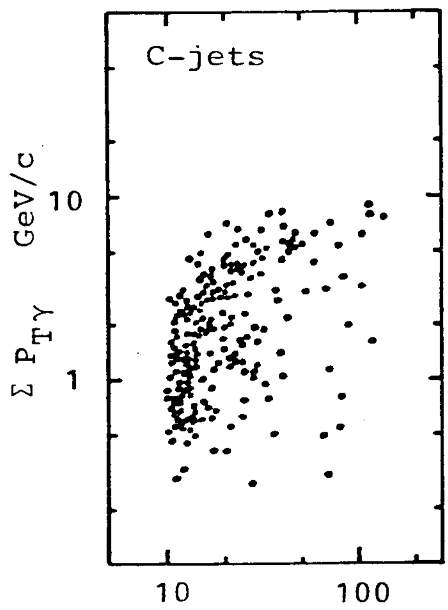

Fig.1

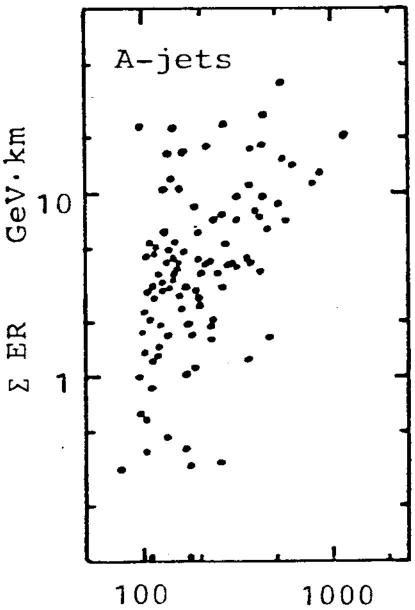

Fig.2.

Fig. 1

$\Sigma P_{T\gamma}$ vs. ΣE_γ.
C-jet events.
E_m = 0.2 TeV.

Fig. 2

Σ ER vs. ΣE_γ.
A-jet events.
E_m = 2 TeV.

Fig. 3 shows the energy dependence of average p_T-flow in 10 - 1000 TeV, combining the C-jet and the A-jet events at $\Sigma p_{T\gamma} = \Sigma ER/ 1$ km. The left hand scale is for the C-jet and the right hand one for the A-jet events. Note that $\lambda \sim 1.2$ km at Chacaltaya and that the choice of average height (1 km) is consistent with that of previous works/4,5/. In the figure, the A-jet events are indicated by the open circles where E_m = 2 TeV; the C-jet events by the squares (E_m = 0,2 TeV) and the closed circles (E_m = 2 TeV). If we use the expression as $<p_T\text{-flow}> \propto (\Sigma E_\gamma)^\alpha$, then we find $\alpha \sim 0.72$ (0.46) in case of E_m = 0.2 (2) TeV for the C-jet events and $\alpha \sim 0.72$ for the A-jet events.

In fig. 3, also shown are the results of simulation calculations based on scaling models: the solid and the broken lines are for the C-jet events in cases of E_m = 0.2 and 2 TeV, respectively, and the dotted ones for the A-jet events. The dotted lines indicate the region covered by various simulations for atmospheric interactions performed by the four groups/6/, all being based on proton primary and scaling models. We calculate Σ ER using the reported values of $<n>$ and $<\overline{ER}>$; in fig. 4, the closed circles stand for our results, the open circles for those of Wrotniak et al., the squares for those of Gaisser et al. and the triangles for those of M.Shibata. (As for the details of these simulations and differences in inputs and procedures, see ref. 6 and refs. therein.)

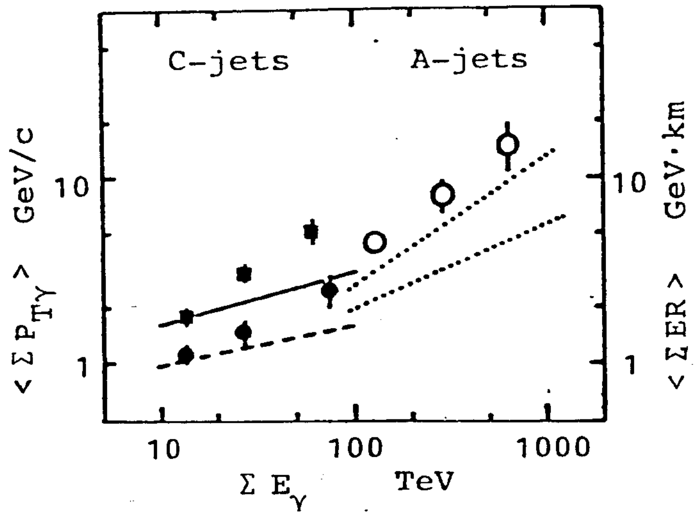

Fig.3 The average p_T-flow vs. ΣE_γ. (■) and (●) stand for $<\Sigma p_{T\gamma}>$ of C-jet events with $E_m = 0.2$ and 2 TeV, respectively, and (o) for $<\Sigma ER>$ of A-jet events. The solid and the broken lines stand for the simulations with $E_m = 0.2$ and 2 TeV, and the dotted lines for the region of simulations for A-jet events (the same as shown in fig.4).

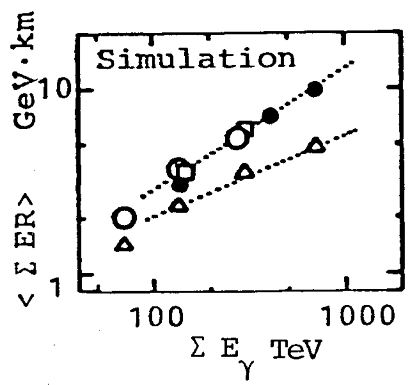

Fig.4 The average ΣER vs ΣE_γ. The simulation results for A-jet events based on proton primary and scaling models; (●) Ours, (o) Wrotniak et al., (□) Gaisser et al. and (Δ) M. Shibata /ref.6 and references therein/. The dotted lines are the same as in fig.3.

5. Discussions and Conclusions

In the energy region of C-jet events, ΣE_γ = 10 - 100 TeV, the p_T-flow (Σp_T) of γ-rays is clearly higher and its growth is more rapid than expected by the scaling model. Although the deviation seems to start at ~10 TeV, it does only mean that the scaling nearly holds in the main observed angular region. In practice, we made corrections on bias and acceptance to the C-jet events with ΣE_γ = 10 - 20 TeV as in ref. 2, and obtained the average γ-ray multiplicity 25 ± 4 at $\sqrt{s}$ = 300 GeV assuming a forward-backward symmetry /7/, which already deviated from a simple extrapolation from lower energies. Thus we can say, from the results of refs. 2 and 7 and the present study in the C-jet region, that the scaling violation which already starts at ΣE_γ ~ 10 TeV continues to grow up to ΣE_γ ~ 100 TeV.

In the energy region of A-jet events, ΣE_γ = 100 - 1000 TeV, the growth of p_T-flow (ΣER) is more rapid than 10 - 100 TeV if we apply E_m = 2 TeV also to the C-jet events. But, if we use E_m = 0.2 TeV in 10 - 100 TeV and E_m = 2 TeV in 100 - 1000 TeV so that the ratio is the same, the p_T-flow grows now similarly. The results of simulation calculations seem to depend on what kind of inputs and procedures they take; however, we see that the passage in atmosphere tends to make the p_T-flow grow more rapidly, as the energy increases, than in a single interaction. Thus, it might be the case that the scaling violation seen in 10 - 100 TeV continues to grow up to ~ 1000 TeV almost in a similar way.

More statistics are needed especially in $\Sigma E_\gamma \gtrsim 500$ TeV. How the exotic phenomena (Centauro family) /1,8/ play a role in this line of study is one of the important problems.

Acknowledgements

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MICROSCOPIC ANALYSIS ON SHOWERS RECORDED AS SINGLE-CORE ON X-RAY FILMS

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Abstract

We study cosmic-ray particles recorded as single dark spots on X-ray films with use of the emulsion chamber data of Brasil-Japan Collaboration. Some results of microscopic analysis of such single-core-like showers on nuclear emulsion plates are reported here.

1. Introduction

The Brasil-Japan Collaboration has been exposing a series of emulsion chambers on Mt.Chacaltaya, Bolivia, 5220 m above sea-level, to study the extremely high energy cosmic ray interactions.

As the chambers are of multi-layered sandwiches of lead plates and photo-sensitive materials, cosmic-ray particles are recorded in the form of electro-magnetic cascade showers as dark spots on X-ray films and as electron-positron tracks on nuclear emulsion plates.

We pay a special attention to single spots on X-ray films with energy $\gtrsim$ 10 TeV because they may be one of the best carriers of direct information from the nuclear interactions. As the first step of this line of approach, we study here the microscopic information of such single dark spots on the nuclear emulsion plates.

Microscopic observation on emulsion plates brings some information on fine-structure of such showers, and sometimes we observe multi-core structure in them due to cascade processes and/or nuclear interactions.

2. Experiment and Data

The emulsion chamber experiments are described in detail in refs. 1 and 2.

In the 19th and the 20th chambers on Mt.Chacaltaya, nuclear emulsion plates were used together with X-ray films in the whole area of both the upper and the lower chambers.

Until now, we have analyzed $28 \times 0.4 \times 0.5$ m^2 of the upper part of the 19th chamber in Rio de Janeiro, under the principal line that the family event should be analyzed irrespective of its size if it contains one or more dark spots on X-ray films with energy $\gtrsim$ 10 TeV. In five family events analyzed in the 20th chamber, we found some dark spots satisfying our criteria. In addition, we use the single spots in the family events with energy $\gtrsim$ 100 TeV which have been detected in the blocks with emulsion plates in the 14th - 18th chambers.

The selection criteria are as follows: the total energy of dark spot $\gtrsim$ 10 TeV, and the energy of constituent cores in the spot $\gtrsim$ 1 TeV. We do not distinguish here between the electro-magnetic and the nuclear-active components.

Sometimes we observe so complicated configuration of shower spots, mainly in the region of family energy $\gtrsim$ 100 TeV, that we can not separate clearly two or more dark spots. Thus, we here simply define "single spot" as the area within ~1 mm. Practically, a circle with diameter ~1 mm is set so as to contain the highest energy core and as many accompanying subcores as possible inside the circle; the same core can not be included in different spots. As the spatial resolution is $\lesssim$ 100 microns even in the N-type X-ray films, our definition is not definitive; ~1 mm roughly corresponds to the resolution of naked eyes in the first scanning.

Fig. 1 shows the lateral distribution of constituent cores in the spots with $N_c \gtrsim 2$, where N_c is the number of cores and the distance R_c is measured from the energy-weighted center of the spot.

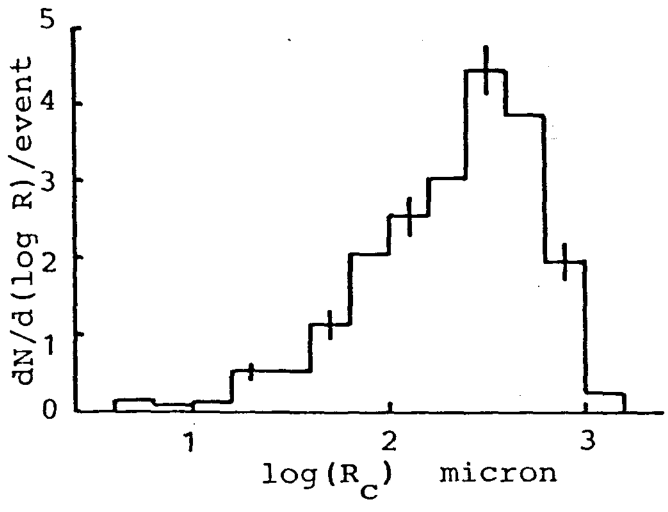

Fig. 1

Distance distribution of constituent cores in the single spots with $N_c \gtrsim 2$, N_c being the number of cores. The distance is measured from the energy-weighted center of the spot.

3. Results

Fig. 2 shows the energy spectrum of 263 single spots in the integral form. The energy ranges from 10 TeV to 260 TeV. The distribution is not exponential nor power-like, but somewhere in-between.

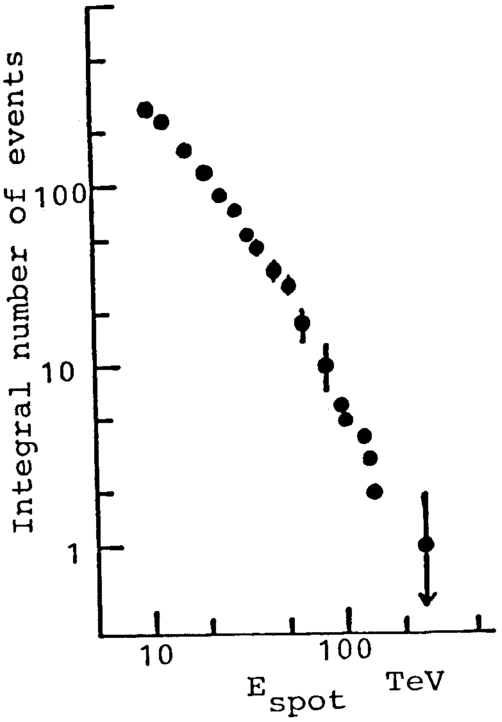

Fig. 2
Integral energy spectrum of single spots. $N_C \gtrsim 1$, $R_C \lesssim 1$ mm and $E_C \gtrsim 1$ TeV.

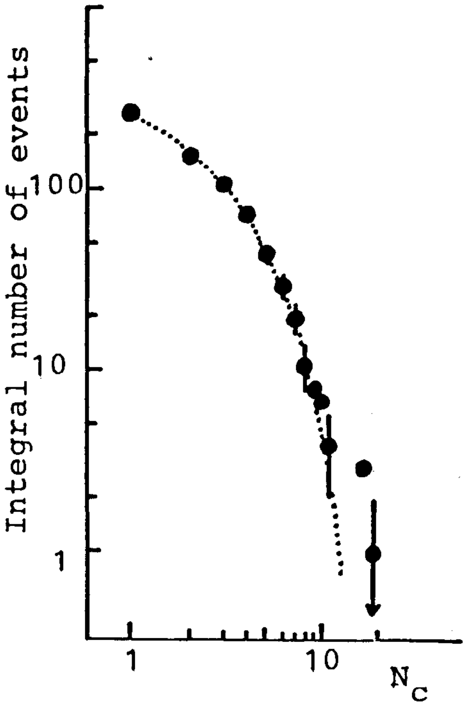

Fig. 3
Integral spectrum of multiplicity of constituent cores in the single spots. Dotted line: 400exp(-0.44N).

Fig. 3 shows the integral distribution of multiplicity of constituent cores in each spot, where the minimum energy for each core is set to be 1 TeV. The distribution can be well approximated by the exponential form

$$\propto \exp(-B\, N_C) \quad \text{with} \quad B \sim 0.44$$

as shown in the figure.

Fig. 4 shows the correlation diagram between the energy of each spot and the number of cores in the spot. We notice a positive correlation there: when the energy increases, the number of cores also increases. The average values of N_C are also plotted in the figure for the energy intervals 10-20, 20 - 30, 30 - 50 and 50 - 100 TeV.

If we use

$$\langle N_C \rangle = A\, (E_{spot}/E_{min})^{\alpha}$$

as an approximation, we obtain

$$A \sim 0.28 \quad \text{and} \quad \alpha \sim 0.73$$

with the minimum energy E_{min} = 1 TeV in the region E_{spot} = 10 - 100 TeV.

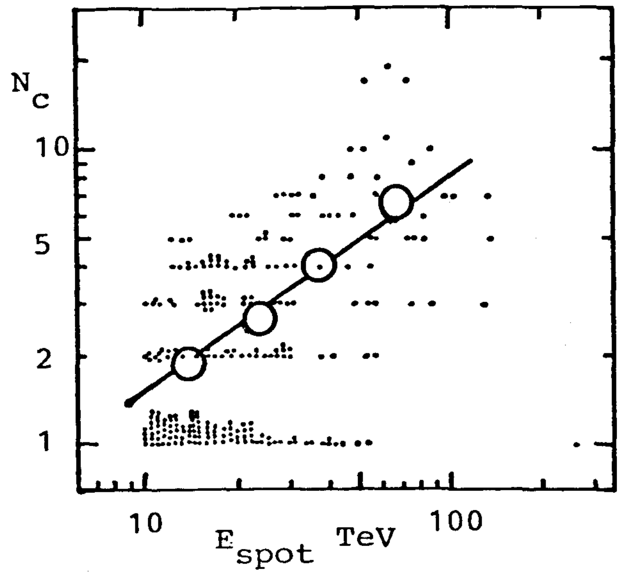

Fig. 4

Correlation diagram between the energy of spot and the number of constituent cores. Open circles stand for the average values, and the line for the case $A = 0.28$ and $\alpha = 0.73$ with $E_{min} = 1$ TeV.

4. Discussions and Conclusions

We have studied emulsion chamber data of the Brasil-Japan Collaboration which were analyzed both on the X-ray films and on the nuclear emulsion plates, paying a special attention to the "single-core-like" showers recorded as dark spots on X-ray films.

We have observed a rather strong positive correlation between the energy of spot and the number of constituent cores in the spot. Under the criteria $E_c \gtrsim 1$ TeV and $R_c \lesssim 1$ mm, a single dark spot on the X-ray films contains, on the average, ~ 1.5 cores at 10 TeV and ~ 8 cores at 100 TeV.

The information from nuclear emulsion is very important to study the family phenomena. Such information may also be valuable in analyzing the data detected only by X-ray films. The more precise analyses on both the longitudinal and the lateral behaviors of single-core-like showers, especially in correlation with the family size, are now going on.

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