Talk presented at the workshop (CBPF, Rio de Janeiro, July, 1982) on "High Energy Interactions Results on Multiple Production of Particles mainly with Emulsion Chamber Detectors and Comparison with Accelerator Results".

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COMPARISON OF C-JET EVENTS WITH ACCELERATOR RESULTS

by

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ABSTRACT

A comparison is made of cosmic-ray induced C-jet events with accelerator results, mainly from the CERN ISR and the CERN SPS $p\bar{p}$ Collider. The distributions of energy, emission angle and transverse momentum of γ-rays are discussed. Importance of the study on such events with high multiplicity, large p_T, jet structure and association of new particles is emphasized.

INTRODUCTION

The Brasil-Japan Collaboration has been studying the multi-particle production phenomena in the energy region 10**13 - 10**17 eV by means of emulsion chambers. Since 1969, a series of two-storey chambers of large-size have been exposed on Mt. Chacaltaya, Bolivia, 5220 m above sea-level, and aimed at detecting high-energy atmospheric interactions in upper chambers (A-jets) and relatively lower energy local interactions in lower chambers (C-jets).

It was 1971 when an extremely exotic event, "Centauro", was recorded in the 15th chamber, and both the upper and the lower chambers were fully utilized to analyze the event.[1] The same chamber also detected several C-jet events of higher quality with high multiplicity and large p_T which had been observed only in A-jet events. Then it was realized that two-storied chambers were really powerful for studying the multi-particle production phenomena in the concerned energy region.

Until now, a few hundred C-jet events have been accumulated and four kinds of exotic phenomena (Centauro family) have been observed in our experiment. Topics on the latter have been reported elsewhere.[1] We report here some results of C-jet events in comparison with accelerator results.

At almost the same period of the 15th chamber, a new accelerator ISR started its operation at CERN, and it has been used to study various aspects of the phenomena up to $\sqrt{s}$ = 63 GeV. Recently much bigger accelerator SPS has started its operation as $p\bar{p}$ collider at $\sqrt{s}$ = 540 GeV. This energy is nearly equivalent to that of C-jet events with visible energy greater than 20 TeV. It is important to compare the C-jet events with accelerator results, mainly from the CERN ISR and the CERN SPS $p\bar{p}$ Collider, at the present moment.

EMULSION CHAMBERS AND C-JET EVENTS

The cosmic-ray events we are comparing with accelerator results were detected in two-storied emulsion chambers exposed on Mt. Chacaltaya by the Brasil-Japan Collaboration. Fig. 1 shows the outline of the 17th chamber, as an example. It consists of an upper chamber, a lower chamber, a target layer and a spacing gap. Both chambers consist of alternate sandwiches of lead plates and photo-sensitive materials (industrial X-ray films and a nuclear emulsion plate).

The upper chamber works as a detector of atmospheric electrons and γ-rays and also as their absorber for the lower chamber. The lower chamber works as a detector of nuclear interactions occurring in the target layer of petroleum-pitch, which are called carbon-jets or C-jets. γ-rays produced in a C-jet are converted into electron showers via electro-magnetic cascade processes and recorded as dark spots on X-ray films and electron tracks in the corresponding nuclear emulsion plates. As the gap between the target layer and the lower chamber is large enough, γ-rays emitted are separated sufficiently from each other. The energy of each γ-ray is determined with an accuracy of $\lesssim 10$ % by track counting.

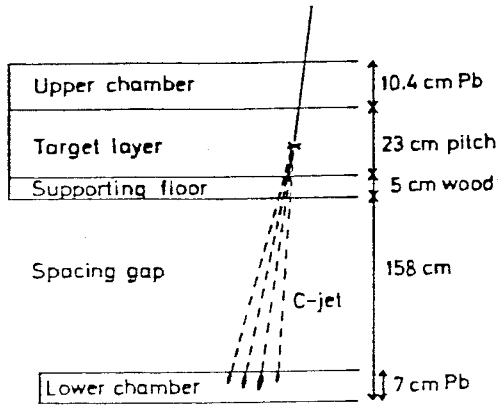

Fig.1 The outline of the 17th emulsion chamber.

The detection thresholds in scanning γ-rays in C-jet events are 0.1 - 0.2 TeV in energy and ~10**(-3) rad. in emission angle. The energy region we study here is $\sum E_\gamma \geq 20$ TeV (corresponding to ~500 GeV in $\sqrt{s}$ as shown later), where $\sum E_\gamma$ is the sum of energies of observed γ-rays in each event. The 80 events used here were chosen from the most energetic group seen in C-jet events, in which the γ-rays observed are almost all in the forward half of the forward hemisphere.

The emulsion chamber experiments are described in greater detail in ref.1.

ISR EVENTS AND MONTE CARLO SIMULATION

We use the minimum-bias events in pp collisions at $\sqrt{s}$ = 53 GeV measured with the Split Field Magnet Facility at CERN ISR by the British-French-Scandinavian Collaboration[2] to make a comparison with the C-jet events and to find their acceptance efficiency together with a Monte Carlo simulation.

As the experimental conditions are different between the C-jet and the ISR events, we arrange the latter in the following procedures. 1) we choose charged tracks with good momentum resolution, 2) supply artificial tracks for ones missed in the experiment so as to reproduce the multiplicity distribution and several inclusive spectra measured at ISR, 3) transform the corrected ISR events to the C-jet energy region by boosting them along the rapidity axis, event by event, according to the known spectrum of cosmic-ray particles, $\propto E_0$**(-1.8), 4) take all the negative particles to represent π^0's and allow them to decay into two γ-rays in a random way, 5) take into account the effects of successive interactions in the chamber, and 6) set the selection criteria on each γ-ray as $E_\gamma \geq 100$ GeV, $\theta_\gamma \leq$ 10**(-2.6) rad. and E_γ GeV/10**5.7 $\geq \tan\theta_\gamma$, and the additional criteria on each event as $N_\gamma \geq 4$ and $\sum E_\gamma$ = 20 - 200 TeV, where E_γ

and θ_γ , respectively, stand for energy and emission angle of a γ-ray and N_γ and ΣE_γ , respectively, the number of γ-rays satisfying the criteria and the sum of E_γ's.

As a cross-check of the ISR events which are used as the standard for comparison with the C-jet events, we also produce simulation events at $\sqrt{s}$ = 500 GeV and apply the same procedure as to the ISR events.

The ISR events, the simulation events and our procedure are described in more detail in ref.3.

THE COMPARISON

Here we compare the C-jet events with the ISR minimum-bias events under the same experimental conditions. And on the basis of the ISR and the simulation events, the C-jet data are corrected for bias effects and acceptance to be compared in a suitable way with the other accelerator results, mainly from the SPS $p\bar{p}$ collider.

The average γ-ray inelasticity k_γ ($= \Sigma E_\gamma / E_0$) is obtained to be 0.32 and we can estimate the average energy of the C-jet events as ~130 TeV in E_0 and ~500 GeV in $\sqrt{s}$.

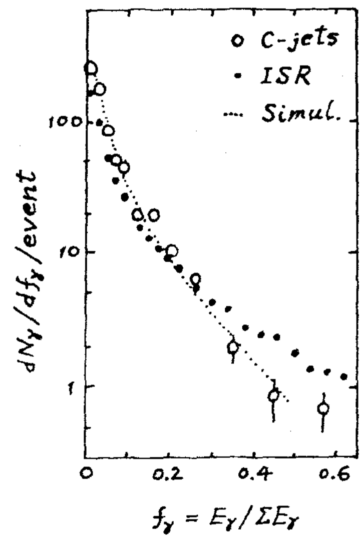

Fig.2 The distributions of fractional energy of γ-rays.

Energy distribution Fig.2 shows the energy distributions of γ-rays in the C-jet events, the ISR events and the simulation events in a fractional form.[3] $f_\gamma (= E_\gamma/\Sigma E_\gamma)$ is approximately equivalent to x/k_γ in the forward region, where $x = 2p_{\parallel}/\sqrt{s}$. From the figure we notice that ΣE_γ is divided more minutely into a larger number of γ-rays in the C-jet events.

Angular distribution The scaling violation seen in fig.2 appears in a simpler way in the angular distributions shown in fig.3, where those of log tan θ of γ-rays are presented for the C-jet, the ISR [3] and the FNAL [4] events at 205 GeV/c. It is clear that the particle density in the rapidity space in the C-jet events is remarkably higher than those of ISR and FNAL.

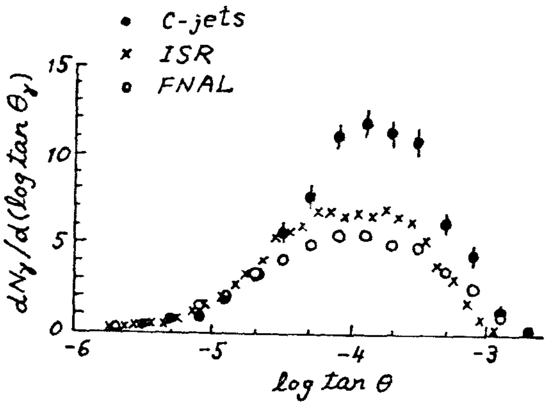

Fig.3 The distributions of log tan θ_γ of γ-rays

Ellsworth et al.[5] pointed out in their simulation study that the boosting procedure of lower energy data lowers the average rapidity density , but we found that this effect is negligibly small for the C-jet events we study here.[3]

In fig.4, we show the (pseudo-) rapidity distribution of γ-rays in the C-jet events [3] in cms together with those of accelerator results [5-7] including the $p\bar{p}$ result.[8] That[9] of the charged particles at $\sqrt{s}$ = 540 GeV is also shown in the figure. Here the correction to

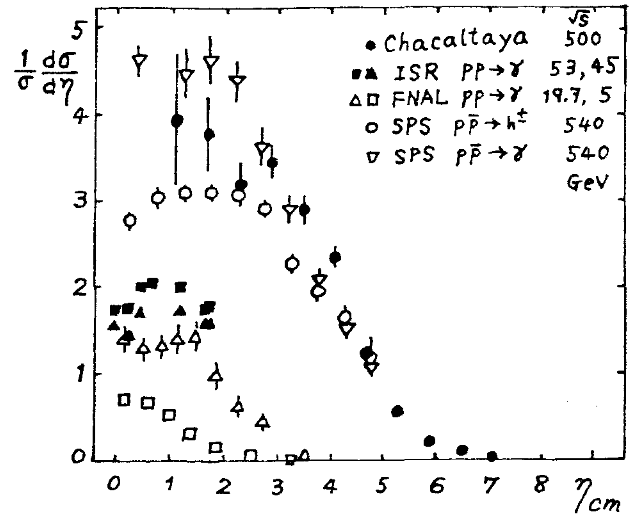

Fig.4 The distributions of rapidity of γ-rays in cms. That of charged particles in $p\bar{p}$ collisions is also shown.

the C-jet events was made with help of the ISR and the simulation events. The average value of the two cases are shown in the figure only with statistical errors, the error due to uncertainties on the corrections being estimated to be ~10 % on the average.

We see in the figure that the particle density increases as the energy goes higher. The γ-ray density in the C-jet events is about two times higher than that in the ISR energies, which is quite consistent with the results of $p\bar{p}$ collider.

Integrating over the above distribution, we can obtain the average γ-ray multiplicity $\langle n_\gamma \rangle$ in the C-jet events as 32.2 ± 3.8 including the systematic error, assuming a forward-backward symmetry. This can be compared with the $p\bar{p}$ results [8,9] at $\sqrt{s}$ = 540 GeV: $\langle n_{ch} \rangle$ = 27.4 ± 2.0 (for non-diffraction) and $\langle n_\gamma \rangle$= 34 ± 2 ($|\eta| < 5$).

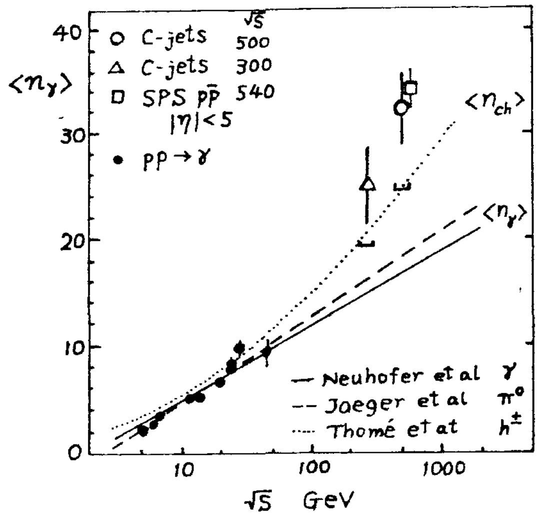

Fig.5 The average γ-ray multiplicity vs energy of cm.

The $\langle n_\gamma \rangle$ of the C-jet events[3] at $\sqrt{s}$=500 GeV is plotted in fig.5 where the value corrected for nuclear target effect (32.2/1.3 =24.8) is also shown assuming again a forward-backward symmetry. The preliminary result[10] of C-jet events with ΣE_γ= 10-20 TeV (corresponding to ~300 GeV in $\sqrt{s}$) is also shown (25 ± 4) together with the $p\bar{p}$ result [9] and the low energy accelerator results compiled in ref.3. The two fits[5,11] to $\langle n_\gamma \rangle$ in the low energy region and one fit[12] to $\langle n_{ch} \rangle$ are also shown.

As for the average γ-ray multiplicity, the deviation from the log s dependence has not been observed up to $\sqrt{s}$ = 45 GeV, but the results of C-jet events clearly show more rapid growth which is consistent with the $p\bar{p}$ collider results.

TRANSVERSE MOMENTUM DISTRIBUTION

Fig.6 shows the transverse momentum distributions [3] of γ-rays in the C-jet and the ISR events. In the low p_T region, the two sets of data behave similarly except for the absolute value, but a larger tail is observed in the region $p_T \gtrsim$ 500 MeV/c in the C-jet events. Even for the γ-rays observed in the region covered by the C-jet events, the average p_T increases about 20 % between $\sqrt{s}$ = 53 GeV and ~500 GeV.

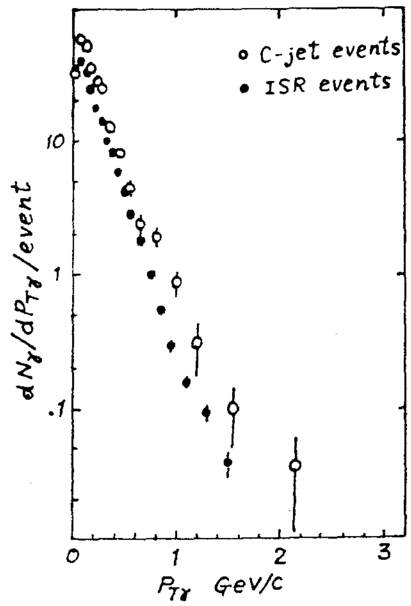

Fig.6 The transverse momentum distributions of γ-rays.

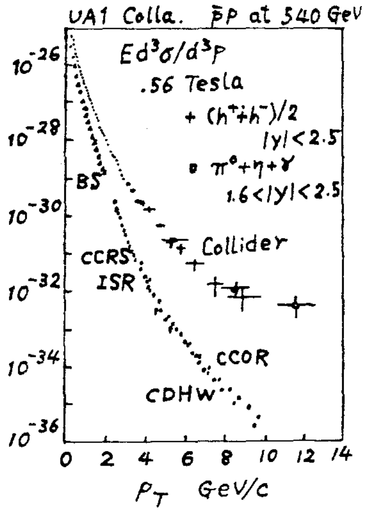

Fig.7 The transverse momentum distributions in Collider and ISR.

Fig.7 shows the p_T distributions [13] of charged particles in the central region in $\sqrt{s}$ = 540 GeV and the ISR energies. Here also we see a remarkable tail in the $p\bar{p}$ collider data.

Fig.8 shows the p_T flow [3] of γ-rays per unit rapidity in the mirror (or projectile) system. Systematic error 10 % is included. Also shown in the figure are the results on γ-rays at the CERN ISR [7] and that of $p\bar{p}$ collider.[14] For the former, p_T-flow was calculated from the reported values of $\langle p_{T\gamma} \rangle$ and γ-ray density, and, for the latter, the total transverse energy reported in cms was simply divided by 3 and shifted to the projectile system. The p_T-flow of γ-rays in the C-jet events behaves similarly to the ISR results in the very forward region, but it deviates from them and approaches ~1 GeV/c, the level of $p\bar{p}$ collisions.

If we take 4 as the γ-ray density (fig.4) and 1 GeV/c as the p_T-flow at y=0, we obtain 250 MeV/c as the average p_T of γ-rays which gives the average p_T of π^0's as ~500 MeV/c. Together with the multiplicity increase, the increase of p_T-flow and $\langle p_T \rangle$ means that the phenomena at $\sqrt{s}$ ~500 GeV are quite different from those at ~50 GeV in general features.

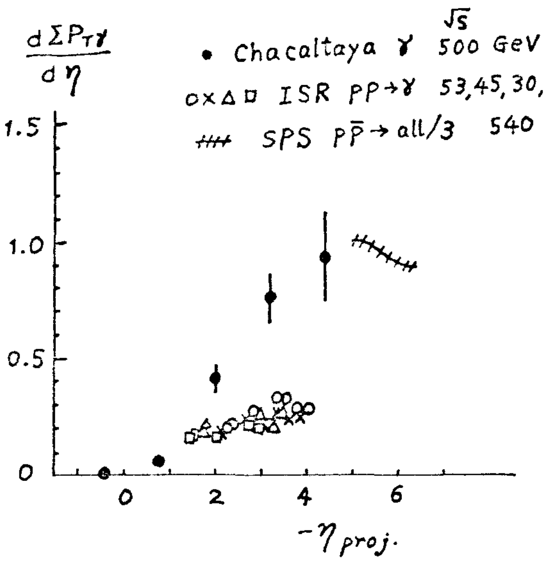

Fig.8 The p_T-flow distributions in the mirror system.

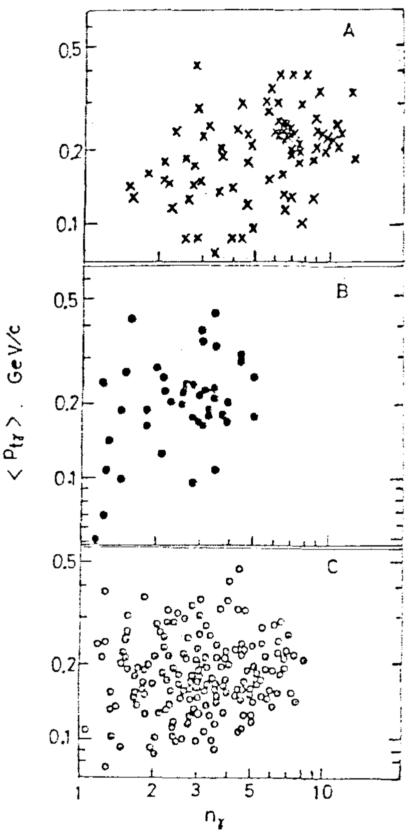

Fig.9-A,B,C The γ-ray density vs $\langle p_{T\gamma}\rangle$.
A: C-jet events
B: FNAL events [4]
C: ISR events [3]

LARGE MULTIPLICITY AND HIGH P_T

As shown above, the particle spectra observed in the C-jet events are quite consistent with those of $\bar{p}p$ collisions recently reported at the CERN SPS.

One of the most importent points that the Brasil-Japan Collaboration have insisted in the C-jet study is that the average p_T grows as the multiplicity increases.[1,3] This positive correlation has not been reported up to the ISR energy. For example, Kafka et al [15] observed the negative correlation at 205 GeV/c,i.e. a decrease of $\langle p_T\rangle_n$ as the multiplicity increases ; Oh et al [16] reported the same behavior at 300 GeV/c.

Fig. 9 shows the correlation diagrams between the γ-ray density and the average $p_{T\gamma}$. The former is defined by $n_\gamma = (N_\gamma - 1)/(\eta_2 - \eta_m)$ where η_2 and η_m denote the rapidity of γ-rays emitted in the 2nd most forward direction and at the largest angle in each event, respectively. The γ-ray emitted in the most forward angular region is omitted in order to eliminate its large fluctuation effect. In fig.9A, the results from the C-jet events are plotted. We easily see the positive correlation between $\langle n_\gamma\rangle$ and $\langle p_{T\gamma}\rangle$ and we notice that ~50 % of C-jet events are distributed around n_γ= 2 ~ 4 and that the remaining around n_γ= 6 ~ 8 behave quite differently. The former is called as Mirim-type and the latter as Açu-type by the Brasil-Japan Collaboration.[1] In the plots of the FNAL[4] and the ISR events[3] shown in figs.9B and 9C, they are roughly distributed in the region similar to that of the Mirim-type C-jet events.

Fig.10 shows the multiplicity dependence of mean transverse energy per particle observed in the $p\bar{p}$ collider[17], where the positive correlation is seen in the high multiplicity region.

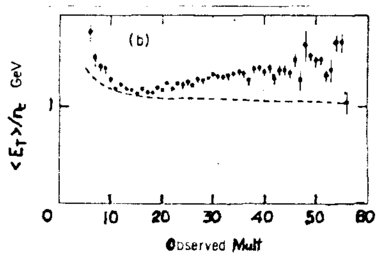

Fig.10 The mean E_T per particle vs observed multiplicity in $p\bar{p}$ collider.

If we assume a production and decay of fire-balls in a collision, Açu-type C-jet events with large multiplicity and high p_T requires heavier fire-balls. In fig.11, we show the distributions of fire-ball mass liberated into γ-rays for the C-jet, the ISR and the simulation events.[3] The algorithm for estimating the fire-ball mass is based on the relation between two quantities: the invariant mass and the sum of p_T of γ-rays which is described in detail in ref.1. It is seen that again ~50 % of the C-jet events of Mirim-type are similar to the ISR events and that the remaining half behave quite differently. The fire-ball problem will be studied in more detail in ref.21.

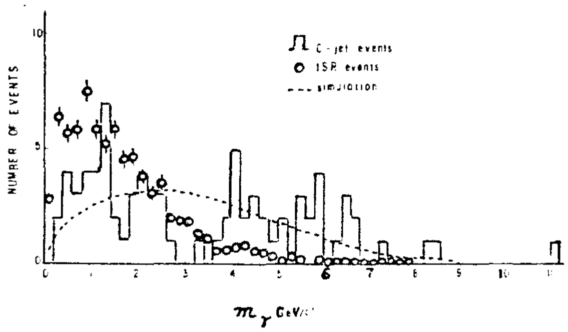

Fig.11 The distributions of fire-ball mass liberated into -rays

Figs.9 and 11 indicate that the big difference between the ISR and the C-jet events comes from the existence of Açu-type C-jet events which are characterized by large γ-ray density in rapidity space and higher average p_T.

Fig.12 shows an example of C-jet event, CH17-153I,[18] with large multiplicity and high p_T in the momentum distribution on the p_T-plane. 40 γ-rays are observed with $\Sigma E_\gamma = 42$ TeV and $\langle p_{T\gamma} \rangle = 500$ MeV/c, and the event is classified as a Guaçu-type. Multi-jet structure is clearly seen, one of which with a special mark in the figure is interpreted as a decay product from a long-lived unstable heavy particle.

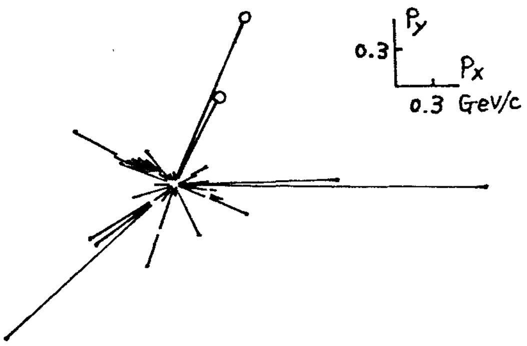

Fig.12 Momentum vectors of γ-rays in a C-jet event, CH17-153I, on p_T-plane.

Sawayanagi[19] searched for unstable heavy particles in C-jet events and found such particles only in Açu- and Guaçu-type events. In the fire-ball picture, it can be understood that the higher temperature of heavier fire-balls defrostate new degrees of freedom.[1, 18]

It was reported [20] that, in $p\bar{p}$ collisions at $\sqrt{s}$ = 540 GeV, K mesons are produced more frequently than in the ISR energies with a remarkably high p_T (~0.7 GeV/c on the average), and they seems to have crossed some threshold for strange particle production. How this behavior of kaons is connected with the X-particles in cosmic-ray interactions may be an interesting problem in the near future.

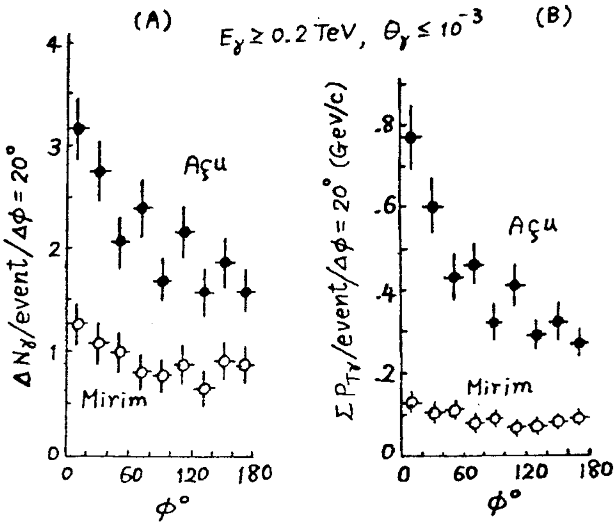

Fig.13 The azimuthal distributions of γ-rays (A) for number flow and (B) for p_T-flow. The trigger sits at 0° , and is omitted in the figure.[22]

As for the azimuthal structure, we can pick up a special azimuthal asymmetry also in Açu-type C-jet events[22] if we take the direction of the highest energy π^0 as z-axis and that of the highest p_T γ-ray as y-axis, where p_T-plane is defined on the x-y plane. Fig.13 shows the γ-ray flow and the p_T flow in several bins of azimuth angle for C-jet events, in which a special structure is observed only in Açu-type C-jet events. The choice of the above reference axis is nearly similar to that of trigger particle often used in the high p_T study in the accelerator experiments.

CONCLUSION

We have compared the cosmic-ray induced C-jet events of Chacaltaya emulsion chamber experiment with the accelerator results, mainly from the CERN ISR and the CERN SPS $p\bar{p}$ Collider.

The general features of multiple meson production phenomena change remarkably between $\sqrt{s}$ ~50 GeV and ~500 GeV. In the C-jet energy region, the rapidity density of γ-rays is about two times higher and the p_T distribution shows a stronger tail in the large p_T region than in the ISR energies; the mean γ-ray multiplicity grows more rapidly than log s dependence; when multiplicity increases, the average p_T also increases. All these features in the C-jet events are quite consistent with the recently reported results of $p\bar{p}$ collider experiments.

The big difference between the C-jet and the ISR events comes from the existence of Açu- and Guaçu-type events which are characterized by large multiplicity, high p_T, jet structure and association of new particles. We would like to expect that these characteristics in C-jet events be well investigated in hadronic interactions in accelerator experiments.

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