EXPERIMENTAL INFORMATION ABOUT MULTIPLE MESON PRODUCTION AT SUPER-HIGH ENERGIES

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Some advantages of the use of log tan θ variable in the analysis of the experimental data on the multiple particle production at very high energies are given. A selection of a few well established observations concerning this phenomenon in collisions at TeV energies are presented.

We shall understand the region of 1000 GeV which is typical, for cosmic ray research of jets in nuclear emulsion, the super-high energy region.

Let us start with the description of a very simplified picture of the phenomenon of multiple meson production in collisions of nucleons at super-high energies. This picture arose from many years work done mainly in nuclear emulsions irradiated by primary cosmic rays [1]. After the collision of two nucleons in their CM system they emerge with about one half of their primary energy. The produced particles, mainly pions, have rather low momenta. This process is called "pionization". The surviving or leading nucleons can emerge in excited states and in such a case their deexcitation is a source of particles with large momenta. This process is called traditionally the "isobar process". The pionization has its internal structure. The pions often form two groups with well separated longitudinal momenta. They look like the explosion in flight of two slowly moving drops of some kind of hot mesonic matter. Such groups are called "fireballs". This model of pionization is called the two-centre model or the fireball model, and was introduced by experimentalists as a convenient way of describing the observations. It served also as a fruitful working hypothesis.

Unfortunately the nice new term "fireball", though having a precise experimental meaning, has been used far and wide and has been attributed to everything, even to the "isobar process". This introduced much confusion to the understanding of the experimental situation, which is complicated enough from the nature of things.

The sources of these complications are manifold:

1°. The photographic emulsion is a complicated target. As you see in Table I there is a 64% chance for a nucleon producing a collision in emulsion to collide two or more

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times inside the target nucleus. Even in the remaining 36% of collisions which occur with a single nucleon, the produced particles in 32% of cases move inside the nucleus, having a chance to be scattered or to produce again a secondary collision. Bearing this in mind we see that the information from emulsion involves mainly collisions with nuclei and not elementary ones.

2°. The majority of produced particles are relativistic in the laboratory frame of reference. Therefore the ionization loss is close to its minimum value and gives very little

TABLE I

Relative probabilities (in %) of various kinds of interactions of a nucleon impinging photographic emulsion

Collision with	H	CNO	Ag Br	Emulsion
1 nucleon	4	11	21	36
2 nucleons		6	21	27
3 nucleons		3	16	19
4 nucleons		1	10	11
more than 4 nuc.			7	7
	4	21	75	100

information. Also the Coulomb scattering is measurable for a small part of the slowest particles only. The magnetic field is of not much use either. The only well-measurable quantity is the angle of emission of produced particles.

3°. In the majority of observed collisions the energy of the primary particle can be estimated only to within very large errors.

4°. The majority of collected samples of interactions are not natural in the composition or, in other words, are strongly biased by the methods of finding the events.

You can easily come to the conclusion that in these lamentable conditions there is nothing to be done. We shall try, however, to show you that this is not the case. However, the complications presented make it necessary to use some methods of presentation of the data which are not very familiar in high energy physics. Therefore we shall spend some time in describing these methods.

Variables used in cosmic ray jet research

For the presentation of the best measurable quantity, the angular distribution of secondary particles, we use the variable log tan θ_L, where θ_L is the angle between the direction of flight of the initiating (primary) and the produced (secondary) particle in the laboratory frame of reference. The use of this variable is not a question of taste. It has some unique, very convenient features connected with the Lorentz transformation. Let us assume a particle π moving with the velocity β_π at an angle of θ_C in the reference frame C. Let the reference

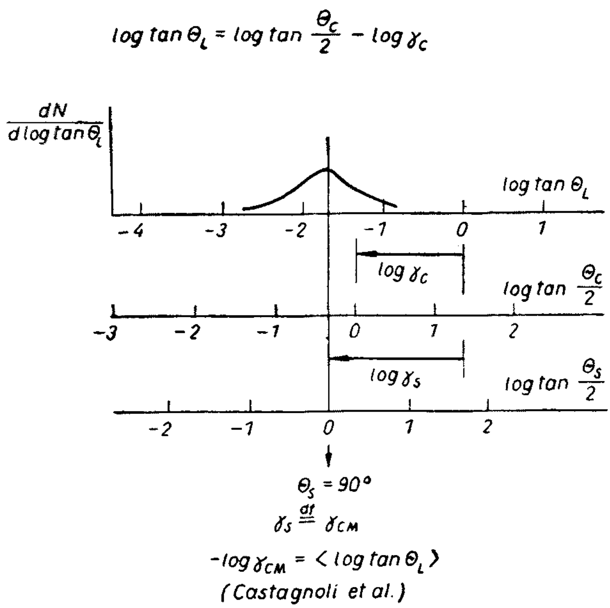

Fig. 1. Sumary of the features of the log tan θ-plot

frame C move in the reference frame L with the velocity β_C at the angle 0°. The angle θ_L at which the particle π moves in the L system is expressed by

$$\tan \theta_L = \frac{\sin \theta_C}{\left(\cos \theta_C + \frac{\beta_c}{\beta_\pi}\right) \gamma_c}$$

where γ_c is the Lorentz factor of the C system in the L system. If we assume that $\frac{\beta_C}{\beta_\pi} = 1$ we obtain

$$\gamma_C \tan \theta_L \approx \tan \frac{\theta_C}{2}$$

We must always have in mind the condition $\frac{\beta_C}{\beta_\pi} \approx 1$ under which this approximation is valid. It is fulfilled for instance for the extreme relativistic case $\beta_C = \beta_\pi = 1$. This condition seems to be fulfilled for the majority of particles produced in a collision at super high energy and for the transformation from the laboratory system (L) to the CM system of colliding nucleons (C).

Now the advantages of presenting the measured angular distribution in log tan θ_L — variable can be easily seen, since

$$\log \tan \theta_L^{\blacksquare} \approx \log \tan \frac{\theta_C^{\blacksquare}}{2} - \log \gamma_C^{\blacksquare}.$$

Let us see how the distribution looks like in the reference frame which moves with the Lorentz factor γ_C with respect to the laboratory frame (Fig. 1). We have only to shift the scale by a distance equal to $\log \gamma_C$ and read it as $\log \tan \frac{\theta_C}{2}$. There is no change in the shape of the distribution. In this sense the shape of $\log \tan (\theta/2)$ is Lorentz invariant (within the limits of validity of $(\beta_C/\beta_\pi) = 1$). We can move the scale further (say, by a distance which we call $\log \gamma_S$) till the distribution becomes symmetric with respect to 0 (corresponding to 90°). It is quite reasonable to believe that such a Lorentz factor γ_S is a good estimate of the Lorentz factor γ_{CM} of the CM system of colliding nucleons. This is the basis of the so-called Castagnoli method [2] of estimating the energy of the primary particle from the angular distribution of produced particles:

$$-\log \gamma_{CM} = \langle \log \tan \theta_L \rangle .$$

The convenience of the variable $\log \tan \theta_L$ is that you see directly how does the distribution, which is known in the laboratory system, look like in any system which moves in the laboratory fast enough.

In Fig. 2, we see the comparison of the $\log \tan (\theta/2)$ scale with other often used variables. The $\cos \theta_{CM}$ variable is very useful if we know precisely the CM system and if we have to do

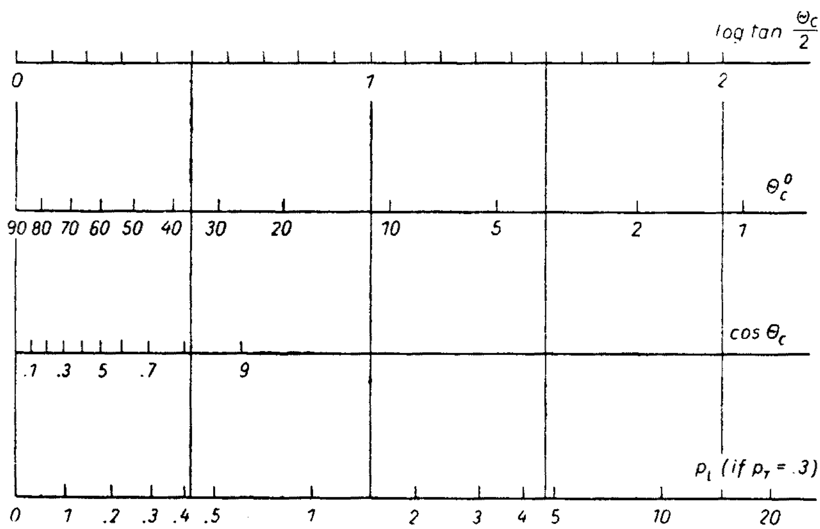

Fig. 2. Comparison of $\log \tan (\theta/2)$-scale with corresponding values of θ, $\cos \theta$ and longitudinal momentum calculated for a constant value of $p_T = 0.3$ GeV/c

with distributions close to the isotropic one. On the contrary, at very high energies, the produced particles are often strongly forward and backward collimated. The $\log \tan (\theta/2)$ scale has a much better resolution in these regions of angles.

Another advantage of this scale is its strong correlation with the scale of longitudinal momenta. It is a well established and fundamental experimental fact that the transverse momenta of produced particles are independent of the energy of the primary particle and are limited to small values ($\langle p_T \rangle \approx 0.4$ GeV/c). In such a situation, since $\left| \log \tan \frac{\theta}{2} \right| \approx \left| \log \frac{p_L}{p_T/2} \right|$, the average longitudinal momenta of particles in the C system can be easily read on the log tan $(\theta/2)$ scale (last scale in Fig. 2). Fig. 3 shows the limits of the approximate identity of $\left|\log \frac{p_L}{p_T/2}\right|$ and $\left|\log \tan \frac{\theta}{2}\right|$ scales.

The isotropic distribution is represented in the log tan $(\theta/2)$ variable as a nearly Gaussian distribution and has the dispersion $\sigma = 0.39$. The approximate Lorentz invariance of the shape of the distribution in log tan $(\theta/2)$ variable helps to recognize immediately whether for a given distribution which is measured in the laboratory system there exists a reference

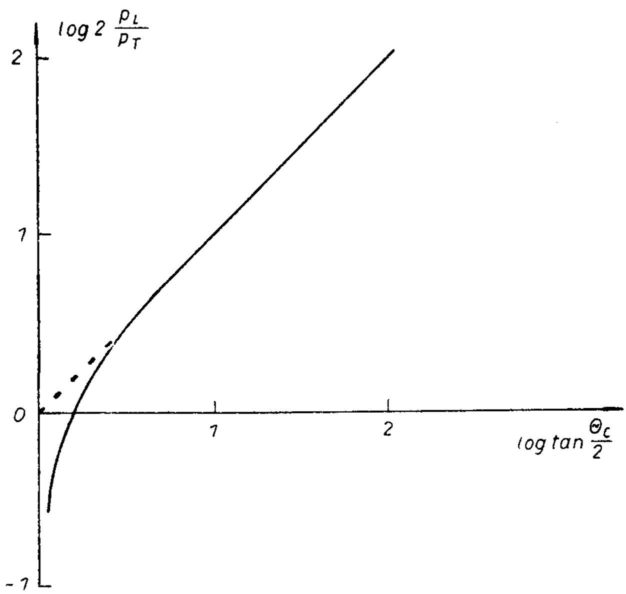

Fig. 3. Relation between $\left|\log \tan \frac{\theta}{2}\right|$ and $\left|\log 2 \frac{p_L}{p_T}\right|$ showing that for values above 0.5 the average value of p_L can be directly read on the log tan $(\theta/2)$ scale

frame in which this distribution becomes isotropic. The question is identical with that whether the shape in log tan θ_L is Gaussian and has the dispersion 0.39, or not. The forward backward collimation of the angular distribution in CM system is reflected in a dispersion larger than 0.39. Therefore the dispersion of log tan θ_L distribution is often called the anisotropy parameter.

A further question concerns the parameter which could reflect the shape of the angular distribution. Since the latter is Gaussian for isotropic distribution, it is reasonable to ask whether it remains Gaussian for forward-backward peaked distributions, or not. For this purpose let us divide a given angular distribution into two parts: the central one with log tan $\frac{\theta}{2}$ values within the limits of $\pm 0.67\sigma$ and the outer parts. Let us call the number of particles emitted at angles in the central part by n_i and the remaining number by n_e. The expectation value for the parameter $D = n \frac{n_e - n_i}{n_e + n_i}$ is zero for the Gaussian distribution. For the distribution which is stronger populated at the wings, it is positive.

The three parameters defined here: the mean value of the log tan θ_L distribution, the dispersion σ of this ditribution and the parameter of shape D are useful tools for the analysis of the properties of angular distributions.

Observations in a worldwide sample of cosmic ray jets

Bearing all this in mind we can ask how do the experimental data look like. In a typical eventof collision of a super-high energy proton in emulsion we can recognize immediately two processes: the production of particles and the evaporation of the target nucleus. The particles produced are strongly collimated and they give tracks of minimum ionization losses. Their number is usually denoted by n_s (shower particles). The evaporation particles are nearly isotropically distributed and since they are slow, they are characterized by strong ionization and produce black or grey tracks. Their number is denoted by N_h (heavily ionizing particles). An event often called a cosmic ray jet is described by $(N_h+n_s)\,p$. p denotes that the primary particle has charge equal to 1 (not necessarily a proton). If the primary has no charge we write n instead of p. The number N_h can serve as rough indication of the nature of the target nucleus. If N_h is larger then 8 we are sure that the target was Ag or Br nucleus since Z of the heaviest of the light nuclei in the emulsion (oxygen) is 8. On the contrary, N_h smaller than 8 does not indicate that the target was a light nucleus. However, we always try to analyse the data with N_h larger than 8 separately from the remaining. The strong positive correlation between N_h and $\langle n_s \rangle$ (especially for N_h larger than 8) suggests that the intranuclear cascade is responsible for a part of the high multiplicity events. Therefore when analysing cosmic ray jets we often do also a division into groups according to the multiplicity n_s. We except that the high multiplicity group is more contaminated by complicated intranuclear processes then the low multiplicity group.

Let us now have a look at a large sample of over 1000 cosmic ray collisions [5]. The ways of collecting these events were different and therefore the sample is subject to many experimental biases. However, it has the advantage of being large and may be treated as a world-wide sample. We shall try to look at it with much care in order not to draw any tentative conclusions to which we would not be entitled. The only question which we ask is whether there are any correlations between the three parameters of the angular distributions expressed in log tan θ_L variable: the mean value $\langle x \rangle = \langle \log \tan \theta_L \rangle$, the dispersion

$$\sigma = \sqrt{\sum_i \frac{(\log \tan \theta_i - \langle \log \tan \theta \rangle)^2}{n_s - 1}}$$

and the parameter of shape

$$D = \frac{n_e - n_i}{n_s}$$

According to what was said before, we shall look for the correlations in four separate groups of events characterized by N_h smaller or greater than 8 and multiplicity n_s smaller or greater than 15. In the analysis the statistical errors of each parameter have been used to attribute a proper weight to each event. Fig. 4 shows that in all groups there is a positive correlation between the mean value $\langle x \rangle$ and the dispersion σ. This quite formal result of the correlation between the first and the second statistical moment of the distribution is interpreted as the increase of the forward-backward collimation of produced particles with the increase of the primary energy. This is a well-known feature of the phenomenon of multiple meson production which was observed in many particular investigations of cosmic ray jets [6]. In the first group of jets characterized by small multiplicity and small evaporation an additional grouping of events around the value of dispersion 0.3–0.4 is seen, especially at highest values of log γ_C. The events responsible for this grouping correspond to the

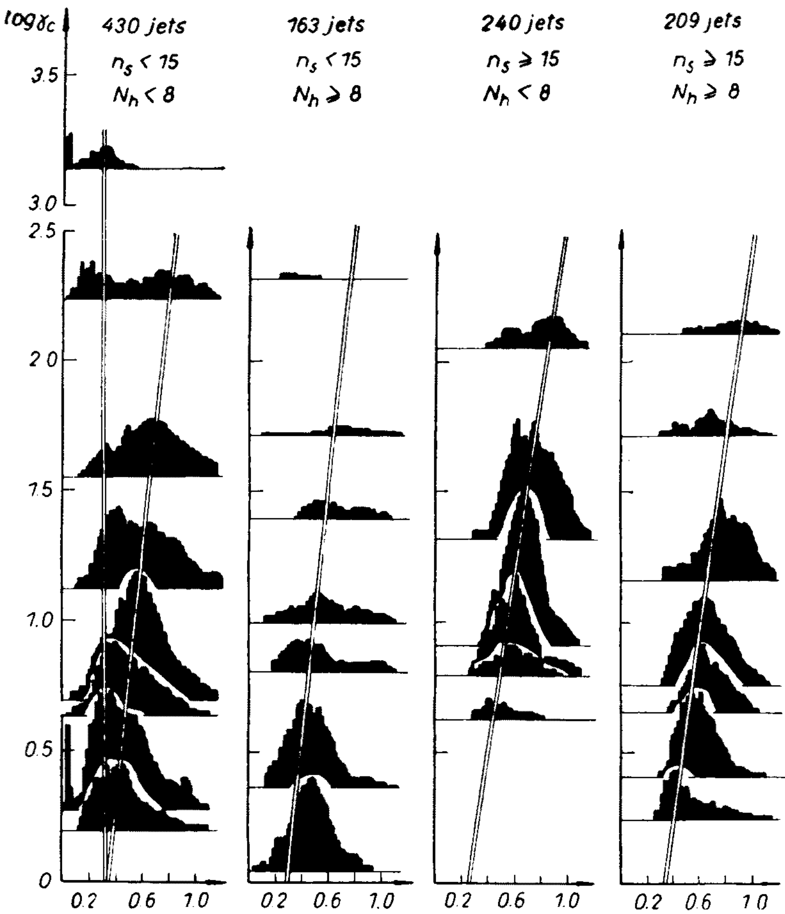

Fig. 4. Constant area histograms of σ for cosmic ray jets grouped in narrow intervals of $\langle x \rangle = \log \gamma_c$. The peak of each histogram corresponds to the most probable value of σ. Its position along the log γ_c axis corresponds to the weighted mean value of log γ_c. The histograms are compatible with purely statistical fluctuations around the most probable value, except of the histograms corresponding to $n_s < 15$ and $N_h < 8$. These are rather compatible with fluctuations around two values of σ: one equal to 0.3–0.4 and the other which increases with the increase of log γ_c. The lines are freehand fits to the peaks

known phenomena of coherent production by high energy pions on heavy nuclei [7] and to the so-called asymmetric jets [8]. Both phenomena were found in particular investigations some time ago. They appear here as a separated group from the whole variety of events mixed in this big sample as a result of our formal analysis of angular distributions.

Another positive correlation appears between the dispersion σ and the shape of the angular distribution expressed by the parameter D. Fig. 5 shows the σ-D plane on which the individual events are presented as overlapping boxes of equal volume. The bottom of each box is a rectangle with the sides equal to the statistical errors in σ and D respectively. As a result of overlapping of the boxes we obtain a hill which is presented in the figure as a contour map. The black shoulder of the "σ-D-mountain" indicates a systematic increase of D with the increase of σ. The curve presented in the figure corresponds to the relation between σ and D in a distribution obtained from two, partially overlapping Gaussian distri-

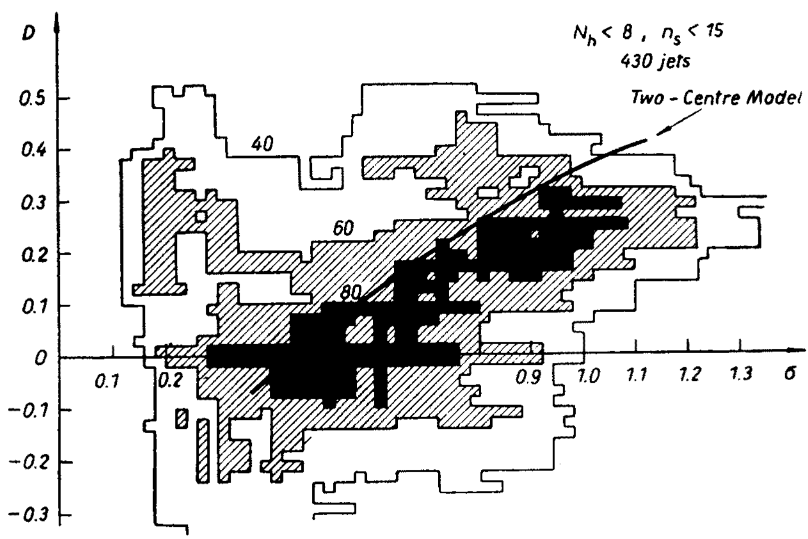

Fig. 5. Constant volume histogram of D *vs* σ presented as a contour map. The numbers at the contour lines denote the hight in arbitrary units. The curve corresponds to the two-center model relation between σ and D

butions with the dispersion 0.39 each. This relation is connected with the change in the distance between the centres of two partial distributions. We see that the correlation of experimental data is just close to this curve. This indicates that with increasing forward-backward peaking the distribution starts to be bimodal in shape. Such bimodality was observed in many particular investigations of cosmic ray jets.

We want to stress that the experimental material used in this analysis, which, we believe, we can call the world material of cosmic ray jets, is certainly a sample subject to many biases and does not reflect the proportions in a natural sample of super-high energy interactions. However, it seems to us that the correlations present in it cannot be influenced by the biases. We showed this result to convince you that some regularities reported on the basis of analyses done on smaller statistics are present in the largest material of cosmic ray jets analysed in a very formal way without any tendency in mind.

Observations in an unbiased sample of nucleon interactions

Now let us have a look at a sample of cosmic ray jet interactions of highest quality. Under high quality we understand two things: 1°. The primary energy or the Lorentz factor of the centre-of-mass of colliding nucleons for these events is known *a priori* as in the accelerator beam. It is not estimated from any parameters of the event itself. 2°. The sample of events is unbiased since they are found in the systematic following along the tracks of high energy particles. In addition to this, the beam of primary nucleons producing these events is nearly monoenergetic (about 1000 GeV). We can really speak here about a beam, because as the source of high energy nucleons we used the fragmentations of heavy nuclei of the primary cosmic radiation (Fig. 6). If a fast heavy nucleus collides in the emulsion, it

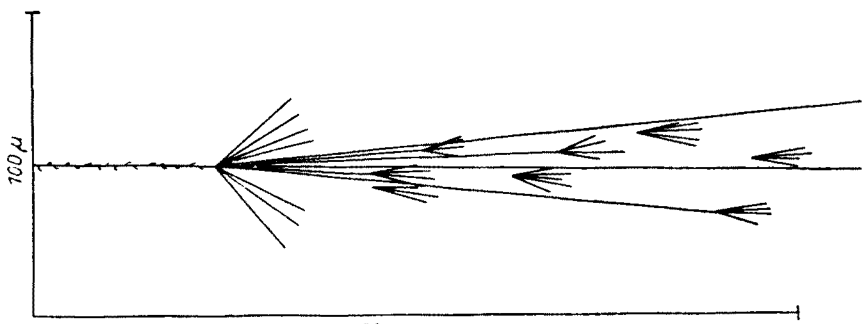

Fig. 6. Shematic drawing of the fragmentation of a heavy primary nucleus of cosmic origin with the pernucleon energy about 1 TeV

evaporates in its own rest frame. The momentum distribution of the evaporation fragments is well known. Therefore we can estimate the average per nucleon energy in the beam from the angles-of-fragmentation in the laboratory frame of reference. Such beams at the energy of about 1 TeV are strongly collimated and it is rather easy to trace systematically all the tracks and to find interactions produced not only by protons but by the neutrons too.

We collected such a sample of 55 interactions from 6 fragmentations of heavy nuclei with the per nucleon energies very close to one another [9]. Since the primary energy is known *a priori*, we can calculate from it the corresponding value of log γ_{CM} for a nucleon-nucleon collision. Knowing this we can see which and how many events have forward-backward symmetry of the angular distribution in this frame of reference. Fig. 7 shows the evaluated positions of the centre of log tan θ_L distribution for each event with its statistical error. The vertical band in the figure represents the absolute limits of the logarithm of the Lorentz factor estimated from the angles of fragmentation. It is clearly seen that 42 events are, in limits of statistical fluctuations, compatible with the symmetry of the angular distri-

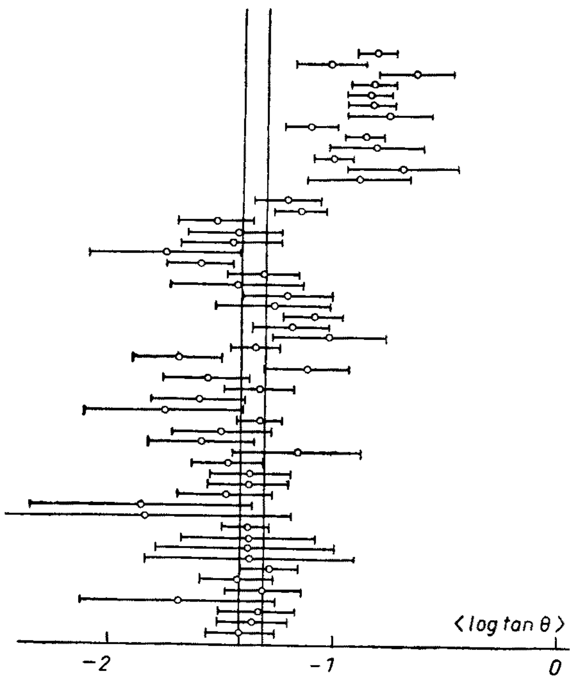

Fig. 7. The positions of the mean value of log tan θ_L (equal by definition to log γ_c) for 55 jets constituing an unbiased sample of interactions of nucleons with emulsion nuclei. The vertical band corresponds to the absolute limits of log γ_{CM} evaluated *a priori* from fragmentation angles

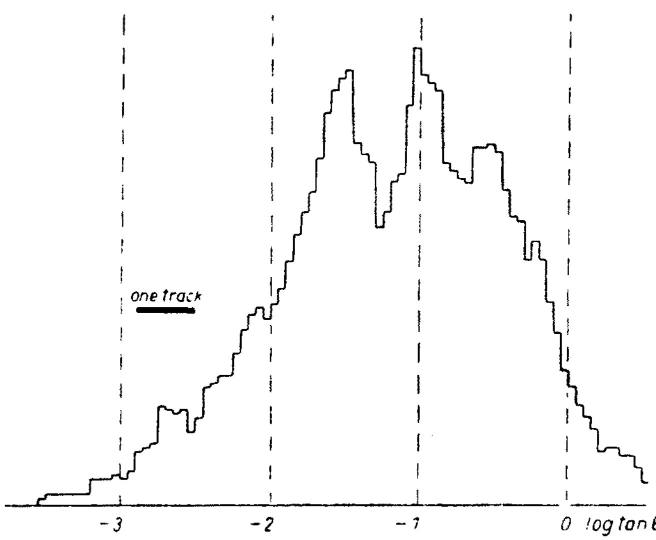

Fig. 8. The composite angular distribution in the laboratory system for a whole unbiased sample of 55 nucleonic interactions

bution in the nucleon-nucleon centre-of-mass system. The 13 remaining events are very strongly backward asymmetric. The 42 events correspond to about 75% of all interactions. It is significantly more than 36% expected for the number of collisions with a single nucleon within the nuclei of the emulsion (see Table I). Therefore we must conclude that the symmetry in the nucleon-nucleon CM system must be attributed not only to the collisions with one nucleon within a nucleus.

Looking for possible characteristic features of the shape of the angular distribution we can profit by the fact that the primary energy of all our events is nearly the same. We can construct the composite angular distribution for all events (in the laboratory system in which they have been measured) without any individual transformations. Fig. 8 shows this distribution. Two features can be seen at once. There is a dip in the neighbourhood of 90° in the CM system and a bump at large angles. Let us separate this distribution into two: one corresponding to symmetric events and the other corresponding to asymmetric ones. Fig. 9 shows these distributions. They look completely different. The spectra of

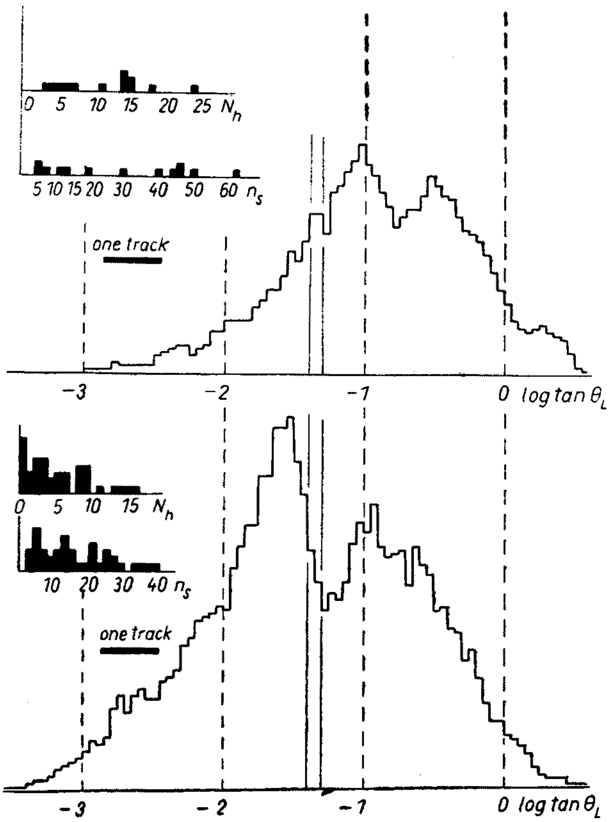

Fig. 9. The composite angular distributions in laboratory system for 13 backward asymmetric events (upper histogram) and for 42 symmetric events (lower histogram). The same vertical bands as in Fig. 7 shows the limits for the angle corresponding to 90° in the nucleon-nucleon centre-of-mass system. The inserts show the respective distributions of evaporation and multiplicity

multiplicities and evaporations also differ, indicating a difference in the process. For symmetric events which are correlated with small multiplicity and evaporation there are two maxima divided by a dip in the region of 90° in nucleon-nucleon CM system. This indicates the existence of two groups of particles separated in angles. From the well-established fact of the smallness of transverse momenta and the values of emission angles we see that the longitudinal momenta of particles in these groups are rather small. This is just what is called "pionization". It seems to be well separated into two groups in momentum space, at least for a fraction of events, as we shall see later.

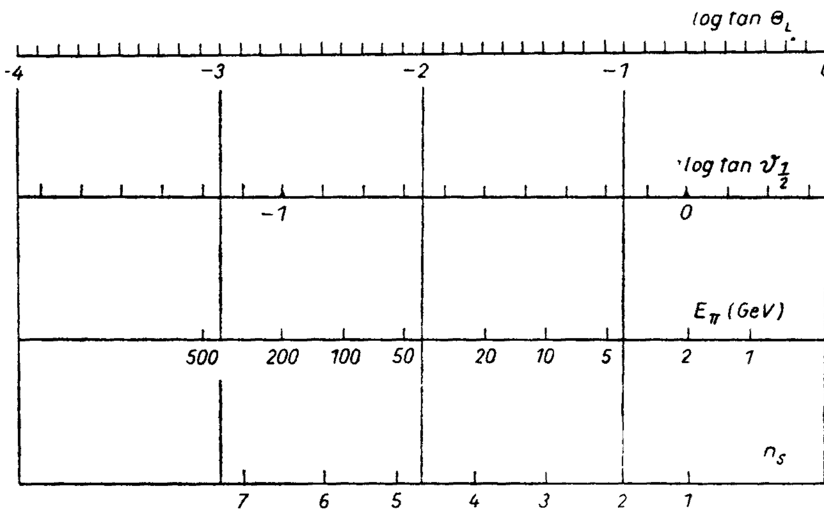

Fig. 10. The relations between the angle of emission of a secondary pion (first scale), the median angle $\vartheta_{1/2}$ of a jet produced by such a pion (inside a nucleus — second scale), the energy of such a pion (third scale) and the average multiplicity of charged particles produced by such a pion (fourth scale). The relations help to forsee roughly the result of an intranuclear cascade

Asymmetric events are correlated with large multiplicity and evaporation indicating heavy nuclei as targets. There is no indication for a forward maximum while the backward maximum is clearly seen. In addition a bump at quite large laboratory angles suggests the presence of wide angle particles, produced probably by secondary interactions of pions in a heavy nucleus. As can be seen from Fig. 10, the particles responsible for production of such a bump could correspond to the angular region in which the forward maximum is observed in symmetric events. We can tentatively say that maybe the primary process in all events looks like in the symmetric case. In some cases, mainly in heavy nuclei, the particles from the forward maximum produce an intranuclear cascade and they are removed from the small angle region.

There is an unanswered question why do these two kinds of processes seem to be well separated showing a non continuous transition from one to the other. However, owing to small statistics no definite statement can be made.

Now the question arises whether the features observed in the shape of the composite distribution are present in individual events or were they maybe, artificially produced by the

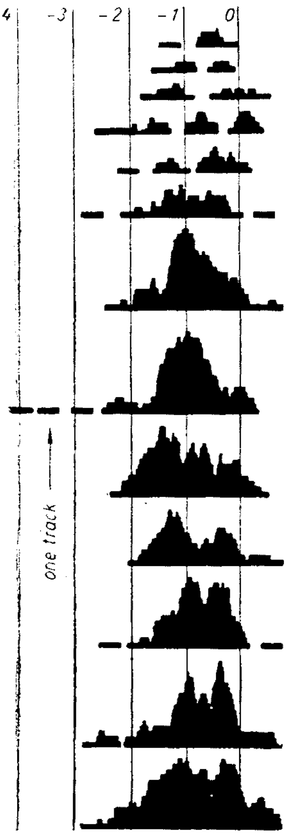

Fig. 11

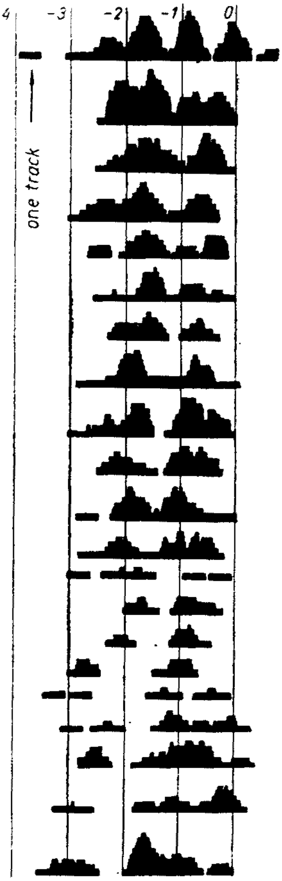

Fig. 12

Fig. 13

Fig. 11. Individual angular distributions of 13 backward asymmetric events, presented as ideograms. The hight of the plot at a particular point of log tan θ_L — scale corresponds to the average density of particles in an interval of 0.4 of log tan θ (dN/d log tan $\theta = 0.4$)

Fig. 12. Individual angular distribution for symmetric events showing a dip in the central part

Fig. 13. Individual angular distributions for remaining symmetric events (with no clear dip)

summation. Therefore let us have a look at individual events. The asymmetric events (Fig. 11) show clearly much similarity to the composite picture. In this sense the composite shape is more or less representative. On the contrary, symmetric events indicate a wider variety of shapes (Fig. 12 and 13). However, the characteristic dip which is seen in the composite distribution (Fig. 9) seems to be produced not in an artificial way, but is characteristic for about one half of events. We chose them by rough inspection and collected them separately (Fig. 12). The remaining events (Fig. 13) show again a variety of shapes indicating nothing very characteristic in common. The corresponding composite distributions (Fig. 14) for the two subgroups have in this situation the following meaning: The first one, having the bimodal shape is a representative distribution for a large part of events. The details of the shape in individual events fluctuate but not the dip around 90°. This is the only detail which remains in the composite picture. On the contrary, the shape of the second composite distribution is not a representative shape for the individual events of which the distribution consists. It is rather artificially produced.

One could say that the procedure of the selection done is a very subjective one. We agree. However, at present nothing better can be done. The sample is unbiased (natural in composition) and therefore the selection made may not be regarded as a tendency to

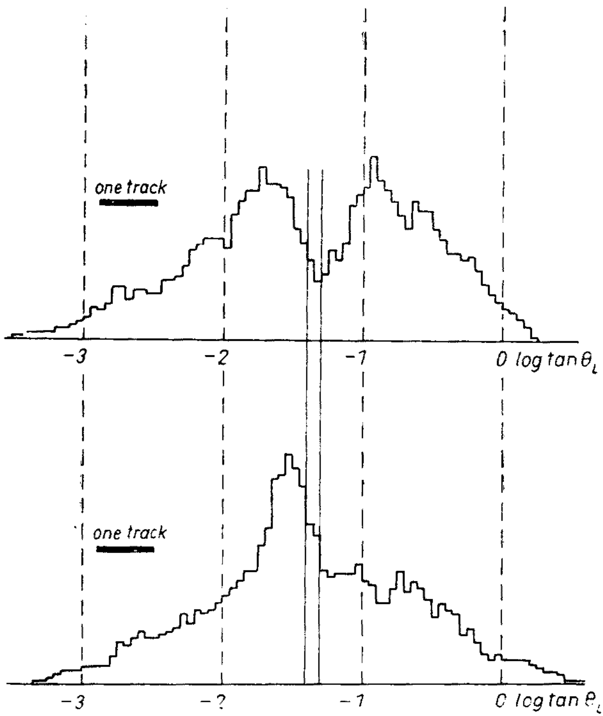

Fig. 14. Composite angular distributions in laboratory system for symmetric events. Upper part of the figure corresponds to jets from Fig. 12, lower corresponds to jets from Fig. 13. Vertical band indicates 90° in nucleon-nucleon CM system

amplify a fluctuation but rather as an effort to see whether there exists something which is common to many events. It seems to us that such a way of reasoning is a very general basis of an early stage of recognition of new regularities.

Now the temptation arises to answer the often asked question as to what is the absolute frequency of these bimodal events. Really the present material offers the strongest basis to answer this question. As you have seen, the formal number is 30% to 40% of the total number of interactions in emulsion. However, much reserve should be attributed to this number because of the subjective way of selection and small statistics.

We have finished the presentation of well established experimental facts for nucleonic collisions. Now we want to inform you briefly about some additional observations which in our opinion seem to be interesting. First of all, we see in cosmic ray jets, events in which the seperation into two groups is large (larger than that in Fig. 14). In such cases both groups look like Gaussian distributions with the dispersion close to about 0.39. As we know, this means that for each group a reference frame exists in which the distribution becomes isotropic [10]. This seems to be a tendency indicated schematically in Fig. 15. However, the two groups are still rather close to 0 at the log tan ($\theta/2$) scale which means that they correspond to the "pionization" component rather than to the "isobar" component.

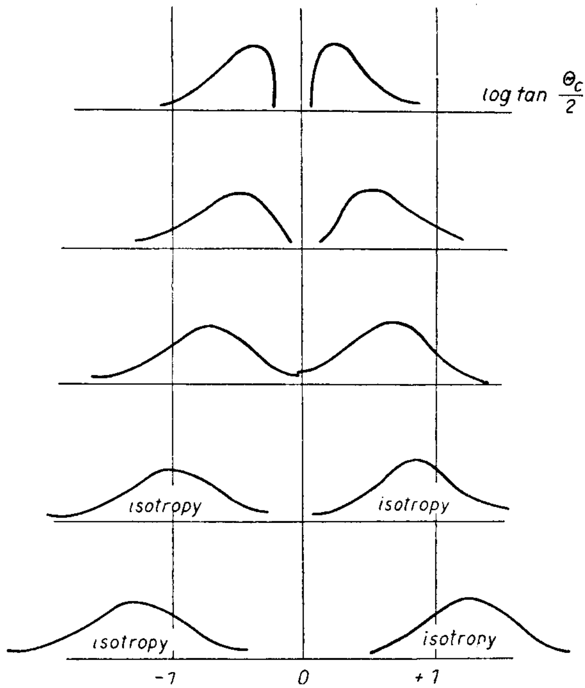

Fig. 15. Tendency of the change of the shape of the angular distribution with the increase of the dispersion. At large dispersions the frames of reference exist in which particular groups approach isotropy

As concerns the last component, we cannot say much about it, at least quantitatively, at the TeV energies. There is some evidence of its existence. Nothing sure is known about their frequency.

The next comment concerns the tendencies at higher energies. The pure extrapolation of the 1 TeV picture would be (say, for a part of events) the increase in separation of the two groups. There are some very weak indications that maybe more than two groups appear. The technique of the so-called emulsion chambers [11] is suitable to attack a much higher region of energies, say 100 TeV. Observations show at these energies that groups composed of many very forward collimated particles exist. However, the technique is not suitable as yet to detect simultaneously eventual particles at wider angles. Therefore it is not clear whether the very forward group is separated in angles (and momenta) from the remaining part of the angular distribution which is unobservable by means of this method. It may be that these observations concern only the "isobar process" and not the "pionization" part. Unfortunately the term "fireball" is widely used here, losing its original experimental meaning.

This article was not a systematic survey. On the contrary it was a selection of some methods and experimental facts done by experimentalists who want to inform theoreticians what they observe and what they do not. The authors have tried to select the observations which are certain and seem to be important, though not very widely known.

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