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MULTI-CORE EVENTS IN COSMIC-RAY INDUCED INTERACTIONS WITH LEAD AT AROUND 10 TEV

by

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ABSTRACT

The analysis is made on the cosmic-ray induced interactions with lead at around 10 TeV on the basis of emulsion chamber data at Chacaltaya. A special attention is paid to the events detected as multi-cores under the spatial resolution of a few tens of microns. The observation of six double-core events and two triple-core events with the average invariant mass of 1.8 GeV/c^2 leads to the estimation on production frequency of such multi-cores as about 5 % at 10 TeV at the atmospheric depth 540 gr/cm^2.

Key-words: Cosmic ray; Emulsion chamber; Multi-cores.

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In this Letter, we report the results on cosmic-ray induced interactions with lead (Pb-jets) at around 10 TeV which are detected as multi-cores in the emulsion chamber.

When a cosmic-ray hadron (nuclear-active particle) interacts with lead in the emulsion chamber, it creates a cascade shower through the multiple pion production followed by the decay of $\pi^0 \rightarrow 2\gamma$ and the electro-magnetic cascade. Pb-jets are usually observed as cascade showers of single core on nuclear emulsion plates as well as on X-ray films because the space between the interaction point and the observation level (a few centi-meters) is not large enough to separate the secondary particles.

But in the course of careful analysis on atmospheric nuclear interactions which contain, as their members, some local nuclear interactions with lead, special characteristics have come to be observed in Pb-jets. They appear as multi-cores of a few tens of microns separation, and the mutual distance between the cores increases when the observation layer becomes deeper. This already indicates special phenomena of large transverse momentum. Up to now, 9 multi-core Pb-jets have been reported in the energy region above 5 TeV; among these seven are 2-core events [1,2], one is 3-core event [3,4] and one 4-core event [4,5].

Our results are based on the systematic study on the Pb-jets recorded in the lower part of the 21st emulsion chamber which was exposed at Mt. Chacaltaya (Bolivia, 5220 m above sea-level or 540 gr/cm^2 in atmospheric depth) for 653 days by the Brasil-Japan Collaboration. Fig.1 shows a schematic view of our detector. The chamber has a two storey structure: the upper part, consisting of an upper chamber (7 cm of lead) followed by a target layer

(23 cm of petroleum pitch), and the lower part of a lower chamber (11 cm of lead). They are separated from each other by an empty space (216 cm of air). Both the upper chamber (41.6 m^2) and the lower chamber (32.4 m^2) are multi-layered sandwiches of lead plates and photo-sensitive materials (X-ray films and nuclear emulsion plates).

Basically the upper chamber works as a detector (and an absorber) of atmospheric electro-magnetic components: the photo-sensitive materials are set at the depths of 3, 4, 5, 6 and 7 cm from the top of the chamber. The lower chamber works as a detector of local nuclear interactions which occur in the target layer or in the lower chamber itself: the X-ray films are set at every 1 cm from 2 to 11 cm for the whole area and additionally at 1.5 and 2.5 cm for some area from the top of the lower chamber, and the nuclear emulsion plates at 2, 3, 4 and 5 cm depth for all the blocks and additionally at 1.5 and 2.5 cm depth for some blocks. Details of the experimental aims of two storey structure can be found in Ref.[6].

In Fig. 2, the schematic illustration is shown for the shower development of single-core Pb-jet and double-core Pb-jet in the emulsion chamber. Only a partial energy of incident hadrons is measured in the experiment, which is liberated in the form of electro-magnetic cascade showers. The energy of cascade showers is determined by measuring the light opacity on N-type X-ray films and/or by counting the number of electron tracks on nuclear emulsion. In the theoretical transition curves adopted here, the so-called LPM effect and spacing effect are correctly taken into account [7].

We have analyzed 6.4 m^2 (32 blocks of unit area 40 cm × 50 cm) of the lower chamber of Rio part for all the shower spots recorded on N-type X-ray films. The detection threshold on X-ray films lies at 1 - 2 TeV. The total statistics is 873, among which 548 events are identified as local nuclear interactions occurring in the lower chamber (Pb-jets). The fine structure of cascade showers can be studied in details for 239 Pb-jets in nuclear emulsion plates. The majority of the events appear as cascade showers of single core as usually expected: the space between the adjacent photo-sensitive layers (1 cm) is normally regarded as not enough to separate the secondary particles produced in the interaction.

The Pb-jet events, at which we are now focussing, appear as cascade showers of multi-cores with the mutual distance of a few tens of microns. In Fig. 3, we show, as an example of double-core event, the 2-dimensional lateral distribution of electron tracks at the cross-section of shower development (3 cm depth). Since an electron is recorded as a track with a sequence of fine grains in nuclear emulsion and we usually use the dip control of microscope in scanning, the double-core structure seen in the figure is impressed in an enhanced way to our observation.

We have found 8 events of multi-core structure among 239 Pb-jets: 6 events with two cores and 2 events with three cores. For these 8 events, Figs. 4 (a - h) show the variation of relative distances between two cores in function of the slant depth, i.e., the distance from the top of the lower chamber that the event traverses with some incident zenithal angle. The straight lines are drawn in the figures as best fits to experimental points.

We notice from the figures that the relative distances between two cores increase as the observation depth becomes deeper due to rather large emission angles of these cores. We also notice that, for 6 events among 8, the production point of multi-cores is located in the lower chamber as expected; for the rest, it is a little above the top of the lower chamber.

Based on the measurement on energy and variation of the relative distance, we can calculate the emission angle and the transverse momentum of each core and the invariant mass of all the cores observed in each event. The characteristics of the 8 multi-core Pb-jet events, which we have analyzed, are summarized in Table 1; the results of multi-core Pb-jets which have been reported up to now [1 - 5] are summarized in Table 2. The emission angles and the transverse momenta are measured with respect to the moving direction of energy-weighted center of the event so that the vector sum of transverse momenta equals to zero. The average energy of 8 events in Table 1 is 4 TeV which roughly corresponds to 10 - 20 TeV of the hadron inicial energy assuming a normal γ-ray inelasticity. The average invariant mass of multi-cores is 1.8 GeV/c^2 in the 8 events (Table 1) which is about one third as small as the average in the 9 events (Table 2).

Simple estimation on the relative frequency of such multi-core Pb-jets can be made as 8/239 = 3 %. In Fig. 5, we show the energy spectrum of the 8 events in a scale of absolute vertical flux together with the total hadron flux at Chacaltaya. The latter was constructed with the events of local nuclear interactions in the 21st chamber (Rio part) and is expressed as

$$F(>E) = (3.50 \pm 0.25)\times 10^{-10}\ (E/5\,\mathrm{TeV})^{-(1.9\pm 0.1)}\ [\mathrm{cm}^2\ \mathrm{s}\ \mathrm{sr}]^{-1}.$$

Using the same value of power index to the former, we can estimate the above frequency as 5 %.

In summary, we have analyzed systematically the cosmic-ray induced nuclear interactions with lead by means of emulsion chamber exposed at Chacaltaya by the Brasil-Japan Collaboration. We have found six double-core events and two triple-core events among 239 Pb-jet events, the average of invariant masses being 1.8 GeV/c^2. The production frequency of such events is estimated to be about 5 % at 10 TeV at the atmospheric depth 540 $\mathrm{gr/cm}^2$.

We would like to thank all the members of the Brasil-Japan Collaboration on Chacaltaya emulsion chamber experiments for their kind and continuous supports. This work has been done under the financial supports to the Collaboration in part from CNPq, FINEP and FAPESP, in Brasil, and ICRR (Univ. Tokyo) and Grant-in-Aid from the Ministry of Education, in Japan.

Figure Captions

Fig. 1 Schematic view of the 21st emulsion chamber at Chacaltaya which has a two storey structure.

Fig.2 Schematic illustration of shower development of (a) single-core Pb-jet and (b) double-core Pb-jet recorded in the emulsion chamber. Em, X and Pb mean, respectively, emulsion plate, X-ray film and lead plate.

Fig. 3 Lego plot of the lateral distribution of electrons observed as cascade showers in the double-core event 21-I27-502 at the depth of 3.6 cm. Unit block (with the base of $4.3 \times 4.3\ \mu m^2$) represents one electron.

Figs. 4 (a-h) Relative distance R_{ij} between two cores versus slant depth t from the top of the lower chamber. Event name is indicated in each figure.

Fig. 5 Integral energy spectrum of the 8 multi-core Pb-jets (closed circles) normalized to the total hadron flux (open circles) at Chacaltaya ($540\ gr/cm^2$). The part of hadron energy liberated as an electro-magnetic cascade is measured.

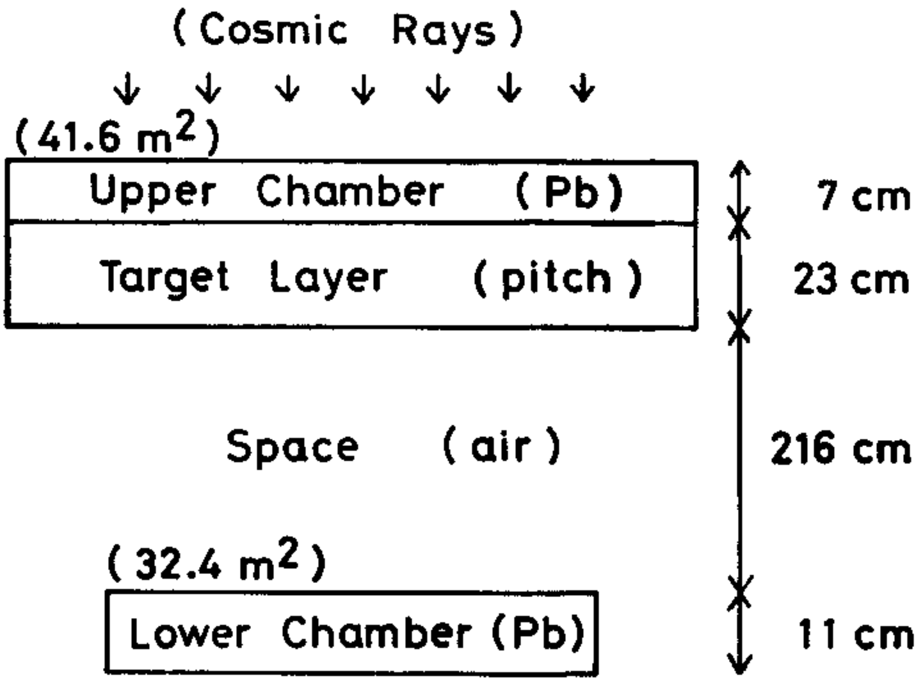

(Cosmic Rays)
(41.6 m2)
Upper Chamber (Pb)
Target Layer (pitch)
Space (air)
(32.4 m2)
Lower Chamber (Pb)
7 cm
23 cm
216 cm
11 cm

Fig. 1

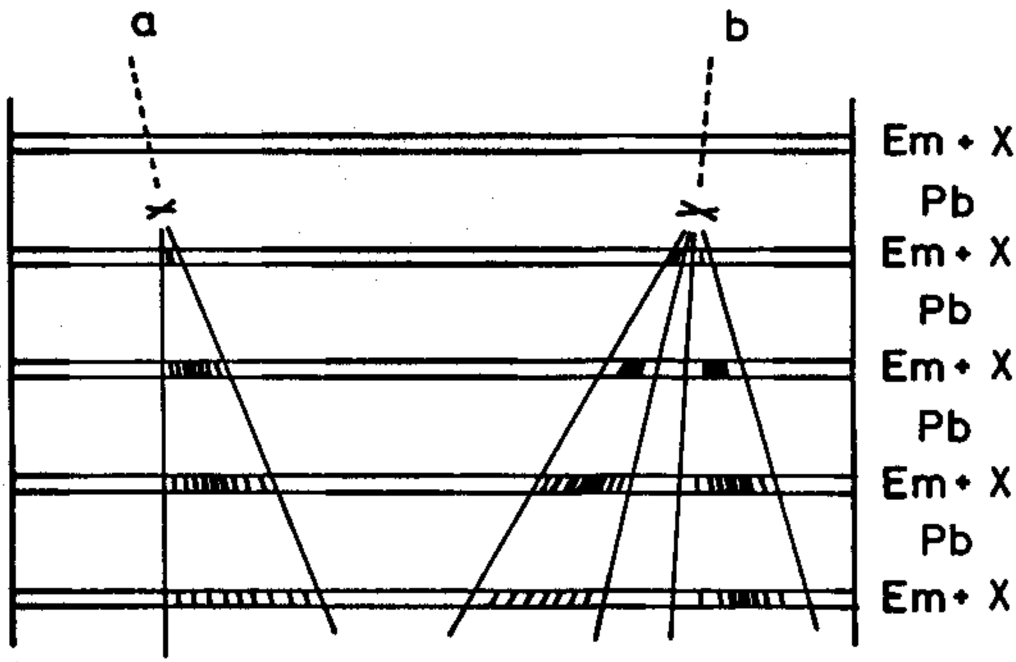


Fig. 2

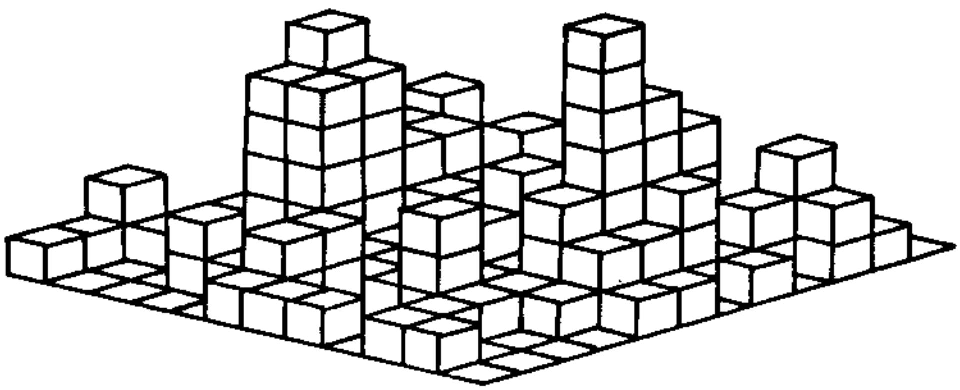
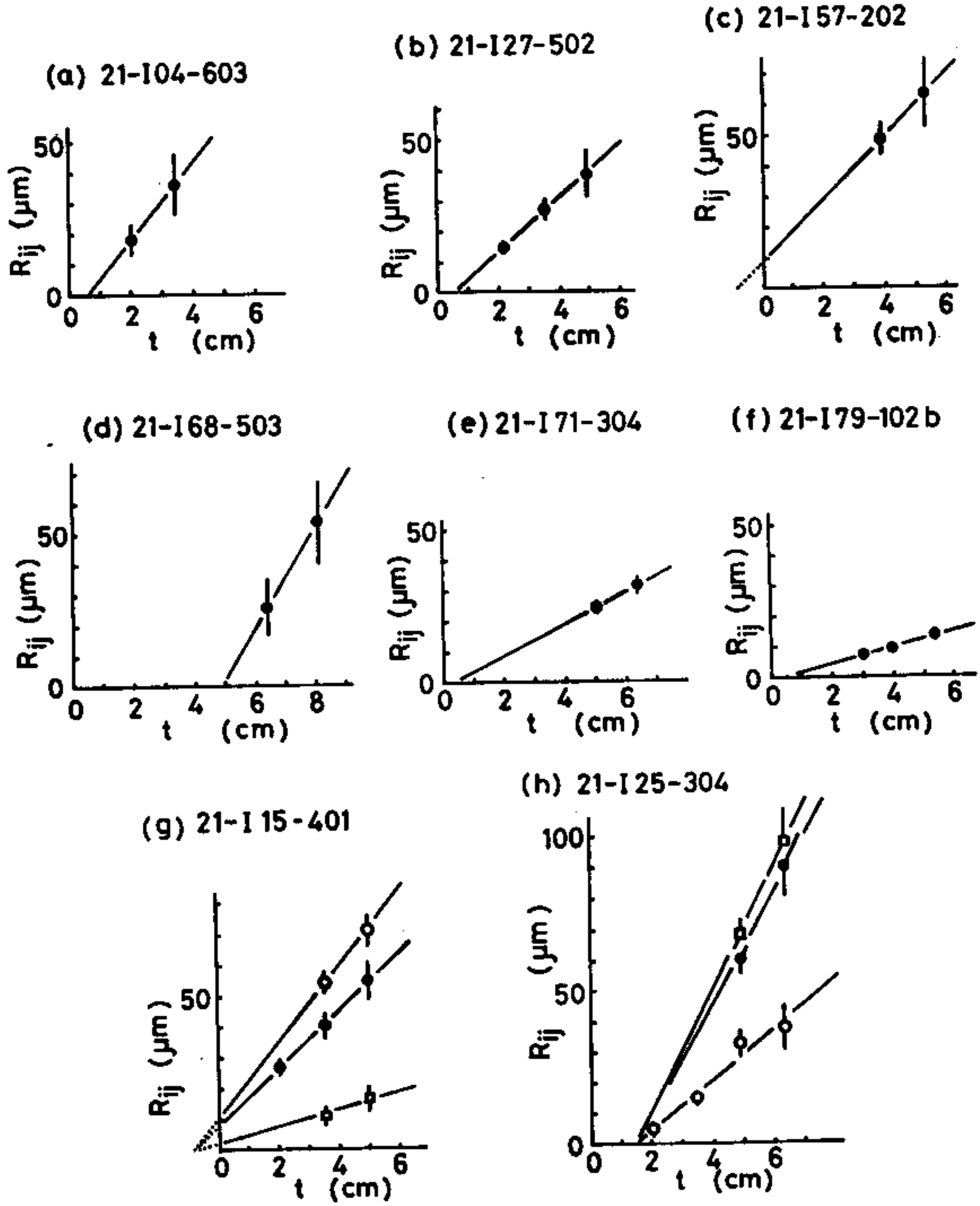


Fig. 3


(a) 21-I04-603
(b) 21-I27-502
(c) 21-I57-202
(d) 21-I68-503
(e) 21-I71-304
(f) 21-I79-102 b
(g) 21-I 15-401
(h) 21-I 25-304
Rij (μm)
t (cm)

Figs. 4 (a-h)

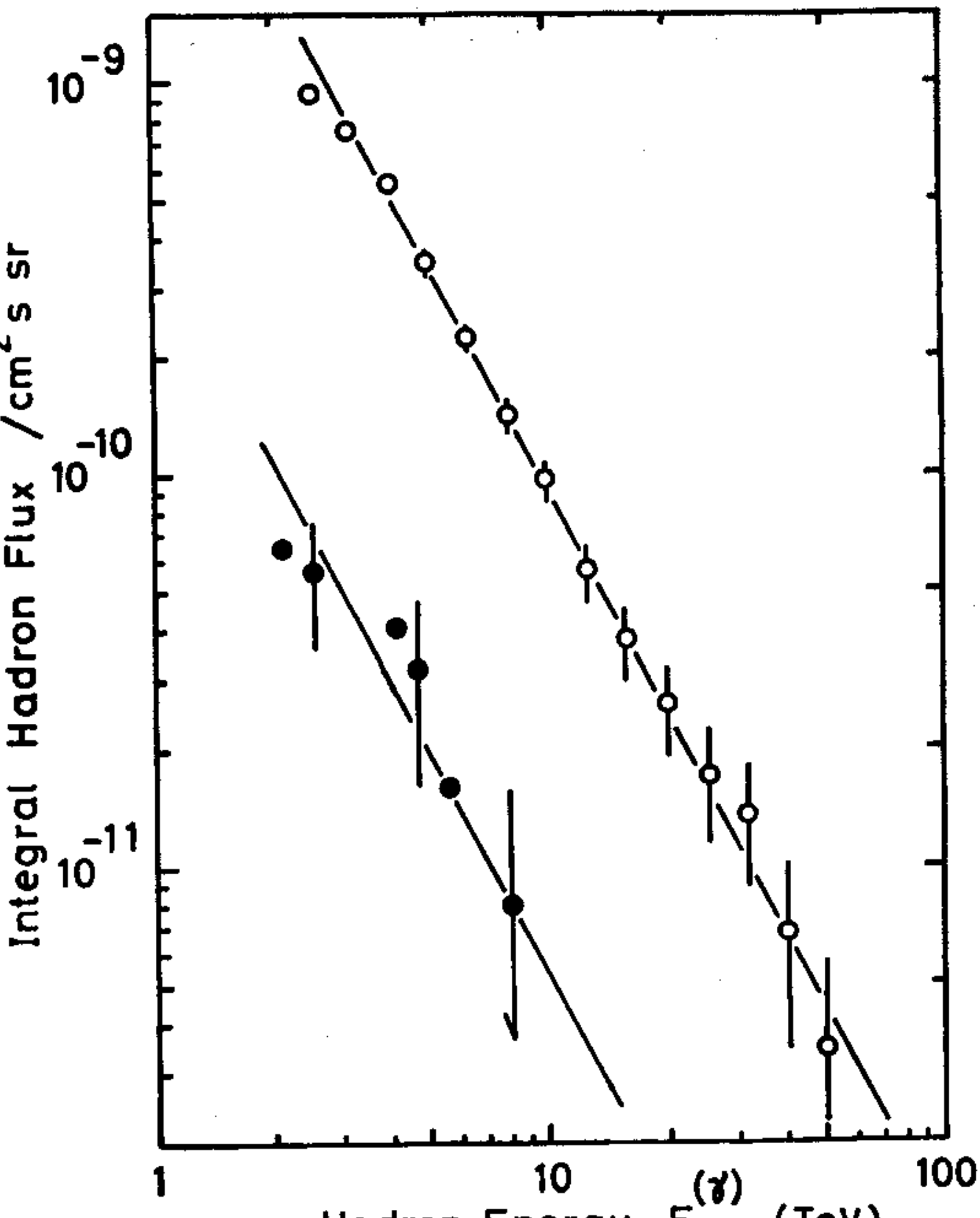

10^{-9}
10^{-10}
10^{-11}
Integral Hadron Flux /cm^2 s sr
1
10
100
Hadron Energy $E_h^{(\gamma)}$ (TeV)

Fig. 5

Table Captions

Table 1 Characteristics of 8 multi-core Pb-jets detected in this experiment.

Table 2 Characteristics of 9 multi-core Pb-jets which have been reported up to now [1-5].

Table 1

Event Name	Number of cores	Energy (TeV)	Angle (10^{-4} rad.)	P_t (GeV/c)	Mass (GeV/c^2)
21-I04-603	2	1.4	4.20	0.59	1.25
		0.7	8.40	0.59	
21-I27-502	2	2.8	3.51	0.98	2.02
		1.8	5.47	0.98	
21-I57-202	2	2.0	2.08	0.42	1.04
		0.5	8.32	0.42	
21-I68-503	2	1.4	7.22	1.01	2.04
		1.1	9.18	1.01	
21-I71-304	2	4.5	2.15	0.97	1.95
		3.3	2.92	0.97	
21-I79-102b	2	3.0	1.19	0.36	0.72
		2.5	1.43	0.36	
21-I15-401	3	2.0	5.63	1.13	2.30
		2.0	3.68	0.74	
		0.6	6.50	0.39	
21-I25-304	3	2.1	4.04	0.85	3.34
		1.2	7.49	0.90	
		0.8	15.16	1.21	

Table 2

Event Name	Number of cores	Energy (TeV)	Angle (10^{-4} rad.)	P_t (GeV/c)	Mass (GeV/c^2)	Ref.
17-93-A	2	16.0	1.21	1.9	4.9	[1]
		4.0	4.86	1.9		
18-154S-133I-c4b'	4	15.0	1.05	1.6	16.3	[4,5]
		15.0	1.05	1.6		
		3.5	6.90	2.4		
		2.4	15.0	3.6		
19-47S-17I-507	3	4.2	4.2	1.8	5.1	[3,4]
		4.0	4.0	1.6		
		3.3	5.2	1.7		
19-96-2	2	3.5	4.32	1.5	3.3	[1]
		1.5	10.08	1.5		
19-109S-69I-A3	2	17.0	1.14	1.9	5.4	[2]
		3.0	6.46	1.9		
19-83-46	2	7.0	1.40	0.98	2.8	[1]
		1.2	8.15	0.98		
21-85-3	2	5.0	3.73	1.86	4.0	[1]
		2.4	7.77	1.86		
21-87-44	2	4.8	4.09	1.96	3.9	[1]
		4.0	4.91	1.96		
21-128-C	2	4.0	4.67	1.87	3.8	[1]
		2.9	6.44	1.87		

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