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SEARCH FOR CENTAURO LIKE EVENTS AT THE CERN PROTON ANTIPROTN COLLIDER

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Abstract

A search for events having the characteristics of cosmic ray Centauros has been made in 540 GeV centre of mass proton-antiproton collisions, using information on charged particle multiplicities and transverse momenta from our central detector image chamber, together with energy deposition in our calorimeters. No such events were found in 48,000 low bias events.

The CERN proton-antiproton collider with a centre of mass energy of 540 GeV corresponds to 155 TeV incident energy on a stationary nucleon. Cosmic ray experiments using the emulsion chamber technique have previously studied details of several hundred events having energies above 100 TeV[1)], and a number of features suggested by these experiments have now been seen in the analysis of the data taken in 1981 by ourselves and other experiments at the collider[2)].

In particular, cosmic ray experiments observed an increase with energy of the mean charged particle multiplicity $<n_c>$ consistent with :

$$<n_c> = a + b \ln s + c(\ln s)^2$$

implying a rise of the central plateau with energy. The values of $<n_c>$ and $<dn_c/dy>_{y=0}$ found in collider experiments[3,4,5)] are in agreement with these indications and, in addition, the broad "KNO" shape of the multiplicity spectrum[4,5,6)] verifies that high multiplicities should indeed be common in cosmic ray events. Similarly the increase with energy of the mean transverse momentum $<p_t>$ of charged particles has been confirmed[7)] at the collider and the same phenomenon has been shown to be true for neutral secondaries[8,9)] ; it was also found that $<p_t>$ is correlated with n_c, so that values of $<p_t>$ greater than 1 GeV/c would not be unusual in very high energy cosmic ray events. Finally jets have been seen at the collider[10,11)] as they have in cosmic rays. These facts have prompted us to look for one of the most spectacular features found in cosmic ray interactions : the Centauro events.

The Centauros reported in cosmic rays[1,12)] are 6 very high energy events characterised by a high multiplicity of hadrons and a multiplicity of electromagnetically showering particles which is consistent with zero. For the 2 Centauros where it has been possible to measure the emission angles of particles, and for a number of related events, the transverse momenta have been found to be high. The emulsion chamber shows separate signatures for electromagnetically showering particles and for other hadrons, but is only sensitive to the latter via secondary electromagnetic cascades produced by them. Hence both the total energy and transverse momenta in Centauro events depends on a knowledge of the fraction K_γ of the total hadronic energy which is converted into electromagnetic cascades. K_γ is found to be around 0.2 for nucleons, but might be higher for charged pions[13,14]. In addition there are uncertainties associated with the mean transverse momentum, $<p_t>$, since this depends on the accuracy of measuring the height of the Centauro vertex above the emulsion chamber. However it is likely that $<p_t>$ is greater than 1 GeV/c.

An analysis of the 5 Centauros found in the Mt. Chacaltya experiment by the Brasil-Japan collaboration[1] shows that all of them have energies between $330/K_\gamma$ TeV and $370/K_\gamma$ TeV at the vertex. This clustering around 1700 TeV (assuming $K_\gamma \sim 0.2$), coupled with the steeply falling flux of cosmic rays, might indicate a threshold for Centauro production above that available at the CERN $p\bar{p}$ collider. However the collider has ten times the centre of mass energy previously available from a machine, and vastly greater interaction rates than found in high energy cosmic rays, so a search for Centauros appears worthwhile.

In this preliminary study, we search for Centauro-like events produced in low bias data[4,7] at the CERN $p\bar{p}$ collider at a centre of mass energy of 540 GeV. We do this by studying the distribution of energy for each event into a hadronic and electromagnetic component, taking account also of minimum requirements of average transverse momentum and multiplicity of the charged tracks in the relevant parts of our apparatus.

The central detector image chamber[15] of the UA1 apparatus shows trajectories of charged tracks, whose momenta can be obtained from curvature in the uniform magnetic field, which had a value of 0.56 T for this study.

The central detector is surrounded by an inner layer of finely divided sheets of lead and plastic scintillator, the so-called electromagnetic calorimeter, followed by a coarsely divided structure of iron and plastic scintillator, the hadron calorimeter. Different calorimeters are used in the end-cap regions $5^0 < \theta < 30^0$ and $150^0 < \theta < 175^0$ and in the region $30^0 < \theta < 150^0$. The calorimeters were designed to allow the experiment to be triggered by various patterns of flow of energy or of transverse energy, and to provide good energy resolution for individual high energy particles. Details of the calorimeters, including sheet thickness, have been given elsewhere[16]. The electromagnetic calorimeters are sampled in 4 depths and the hadron calorimeter in 2 depths. The response of the calorimeters to electrons, photons and charged hadrons has been studied extensively using test beams of high energy electrons and hadrons, and data from 540 GeV collisions in which well-isolated low energy tracks with momentum measured in the image chamber are extrapolated into the calorimeters. These experimental calibrations have been complemented by Monte Carlo studies for low energy hadronic showers and electromagnetic showers. We are thus able to understand not only the response of the calorimeters to photons and hadrons of definite energies, but also the sharing of energy depositions in the various depth-samplings.

All hadrons deposit some of their energy in the electromagnetic calorimeter. For the purpose of this study which involves high multiplicities and relatively low momenta per particle, a useful division is to take the first sampling ($\sim$ 4 radiation lengths) in the lead scintillator calorimeters as a measure of electromagnetic showers, and the third and fourth samplings plus the signal from the iron scintillator calorimeters as a measure of hadronic energy. The average responses in these 2 divisions for both hadrons and photons are shown in fig. 1. Since both hadrons and photons deposit significant energy in the second sampling ($\sim$ 8 radiation lengths), the signal from this has been excluded in the present analysis. We note that there is some overlap of response between hadrons and photons below about 0.3 GeV/c, but above 0.4 GeV/c where the majority of particles are found, the separation is reasonably clean.

An analysis was carried out on 48,000 low bias events. The trigger for these required at least one charged outgoing particle between 12 mrad and 56 mrad on each end of the collision. Fig. 2 shows scatter plots of electromagnetic versus hadronic energy for all events, using the criteria described earlier. Fig. 2c) shows energies registered in the calorimeters in the complete region $5^\circ < \theta < 175^\circ$. Figs. 2a) and 2b) show for all events the energies in the end-cap and barrel regions, and Fig 2d) shows results from a Monte Carlo program whose ingredients are given in Table 1.

We note that no clustering of events with abnormally low electromagnetic and high hadronic energy content is seen, and that the Monte Carlo reproduces the data fairly well.

In Fig. 3 we show scatter plots of $<p_t>$ versus charged particle multiplicity, globally and into the two selected regions. The plots saturate heavily, but it can be seen that relatively few events have $<p_t>$ values greater than 1 GeV/c.

The signature of Centauro-like events in our apparatus depends on the transformation of the cosmic ray events into the centre of mass. This in turn depends on the total hadronic energy,obtained by dividing the visible shower energy by the K_γ factor, and on the method assumed for their production. The K_γ value normally used by the Brasil-Japan collaboration is 0.2 but this is based on the assumption that the outgoing particles are nucleons or antinucleons. If the outgoing particles are charged pions, K_γ will have a higher value because of leading particle effects. Experiments with the Tien Shan calorimeter[13,14]) have suggested that for mixed hadrons found near the core of cosmic ray showers, the value of K_γ might be ~ 0.24 and an extrapolation to hadrons consisting purely of $\pi^\pm$ indicates, within considerable errors, a value of $K_\gamma^\pi \sim 0.33$. In our analyses we use two values of K_γ : 0.2 corresponding to nucleon-antinucleon pairs, and 0.3 corresponding to a mixture of hadrons which is normal apart from lacking the electromagnetically showering components.

For Centauro I, the first discovered and best determined event in the family, the initial vertex was found by triangulation to be located ~ 50 m above the emulsion chamber. Energies and angles of the individual hadrons from this event were made available to us by Prof. S. Hasegawa and were used to transform the event into the centre of mass in order to investigate various hypotheses, using the procedure of Kinnunen and Rubbia[17]).

Hypothesis 1a assumes that the vertex is the collision of an incident high energy particle with an air nucleon, and that the outgoing particles are mixed hadrons as described earlier, so that $K_\gamma = 0.3$. Hypothesis 1b assumes a collision but with outgoing nucleons and antinucleons only so that $K_\gamma = 0.2$.

These hypotheses result in different total hadronic energies and hence different Lorentz factors when converting to the centre of mass. As a result of these transformations we would expect about half the outgoing hadrons to have centre of mass angles $5^\circ < \theta < 30^\circ$ and therefore to be directed towards an end-cap calorimeter. Most of the remainder have lower angles, and would not have registered in the central calorimeters.

Hypothesis 2a assumes that the observed event is primarily the decay of a new massive object with unusual properties, and that some mechanism has separated out the decaying Centauro from the parent interaction that caused it. The decay products are mixed hadrons so that $K_\gamma = 0.3$. Hypothesis 2b assumes that such decay products are nucleons and antinucleons so that $K_\gamma = 0.2$. The Lorentz factors are found by transforming to a system where the algebraic sum of the longitudinal momenta is zero. Since there is now no target particle, the Lorentz factors are larger, by an order of magnitude. The slightly different values for the two decay hypotheses are caused by the different rest masses of the decay particles. The transformations result in angular distributions which are consistent with being isotropic, and hence 87% of the hadrons would be directed towards our barrel calorimeter which covers the angular range $30^0 < \theta < 150^0$.

The present analysis is restricted to tracks in our apparatus which are associated with a single vertex and also assumes that the Centauro is produced with only a low Lorentz factor in our experiment. The testing of the decay hypothesis is more ambiguous than that of the collision hypothesis, since the production and decay vertices of Centauros must coincide in this analysis, and the special features of Centauros may be diluted by the additionally produced particles.

Table 2 lists some observed features of Centauro I and the parameters which are relevant for the transformation into our apparatus for the various hypotheses. The number of hadrons actually observed via their electromagnetic showers was 49, and the energy resulting from this showering was 222 TeV. Correcting for unobserved hadrons caused by punch through in the emulsion chamber, and for atmospheric jets above the chamber, the corrected number becomes 74 and the energy 330 TeV. These numbers are shown in the first 2 rows. The third row shows the assumed fraction K_γ of hadron energy which was converted to electromagnetic showers. The fourth row shows the Lorentz factors required to transform the Centauro into the centre of mass. The table then lists the relevant angular regions in our apparatus and the expected number of hadrons. For the collision hypotheses we insert a factor 0.85 to allow possible scaling down of multiplicity from cosmic ray to collider energy. We then list an acceptance factor for good tracks, using the normal criteria associated with our track-finding. Next we list the expected ratio of charged to total particles, since our image chamber gives charged particle multiplicity whereas the emulsion chamber gives total mutiplicity. This results in the expected track multiplicities for Centauros in the relevant parts of our apparatus. The energies expected in the selected regions of our apparatus are listed next. These are obtained as follows. For collisions we take the 270 GeV going into one hemisphere and multiply by the energy ratio into the end- cap calorimeter coming from our transformations. For decays we take 74 hadrons, extrapolate these to 100 as described in the Centauro literature$^{1)}$ to allow for hadrons below emulsion chamber threshold, multiply by the solid angle factor of our barrel calorimeter and by the mean energy found in our transformation. We then calculate the expected visible energies in the electromagnetic and hadronic portions of our calorimeters. Finally we list the expected mean values of transverse momenta.

In Fig. 4 we again show scatter plots of energies into the two selected regions, but now after the application of cuts which demand that $\langle p_t \rangle > 1.0$ GeV/c and charged multiplicity > 10 into one region. Only 9 events remain in the first case and only 25 in the second. Also shown on these plots are the expected location of Centauro events under the various hypotheses. There is no concentration of events near these regions.

We conclude that although a number of features found in cosmic ray interactions have been confirmed at the collider, we have found no events having Centauro-like characteristics in 48,000 low bias events at the $p\bar{p}$ collider, using the criteria of large hadronic and low electromagnetic energy content, taking account also of multiplicity and mean transverse momentum.

We note that, using a different method, no high multiplicity events having Centauro features were found by the UA5 Collaboration in a sample of 3600 events$^{18)}$.

Assuming the validity of the assumptions stated in this paper, we can place an upper limit for the production cross-section of around a microbarn for Centauro-like events at the collider (155 TeV equivalent energy). We stress again the problems associated with testing the decay hypotheses, namely that Centauros with decay paths more than a few mm would have been excluded by our track-association routines, and that a rapidly decaying Centauro might be contaminated by the particles produced with it. A more complete analysis is continuing.

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References

1) C.M.G. Lattes et al., Physics Report Vol.65 No.3 (1980).

2) For recent comparisons of cosmic ray and collider results see :
N. Yamdagni "Physics Results from the CERN SPS $\bar{p}p$ Collider and their Comparison with the Cosmic Ray Results", Proceedings of the International Workshop on Very High Energy Interactions in Cosmic Ray, University of Pennsylvania (April 1982)
N. Yamdagni "Event Structure in Collider and Cosmic Ray Experiments", Physics in Collision, Stockholm (June 1982).

3) K. Alpgard et al., Phys. Lett. 107B, 310 (1981).

4) G. Arnison et al., Phys. Lett. 107B, 321 (1981).

5) G. Arnison et al., CERN EP/82-134 (1982).

6) K. Alpgard et al., Phys. Lett. 107B, 315 (1981).

7) G. Arnison et al., CERN/EP/82-125 (1982).

8) M. Banner et al., Phys. Lett. 115B, 59 (1982).

9) G. Arnison et al., CERN/EP/82-120 (1982).

10) M. Banner et al., "Observation of very large Transverse Momentum Jets at the $p\bar{p}$ Collider", submitted to Phys. Lett.B.

11) A. Astbury, Invited contribution to XXI International Conference on High Energy Physics, Paris (July 1982).

12) M. Ballester et al., Proc. 17th International Cosmic Ray Conference (Paris 1981) (CEA, Saclay, 1981) Vol. 11 p. 159

13) S.I. Nikolosky et al., Proc. 15th International Cosmic Ray Conference (Plovdiv, 1977) (Bulgarian Acad. Sci. 1977).

14) V.I. Yakovlev et al., Proc. 15th International Cosmic Ray Conference (Plovdiv, 1977) (Bulgarian Acad. Sci. 1977) Vol. 7 p. 115.

15) M. Calvetti "The UA1 Central Detector" International Conference. on Instrumentation for Colliding Beam Physics, SLAC, Stanford, 17-23 Feb. 1982.

16) G. Arnison et al., to be published, CERN/EP 82-122.

17) R. Kinnunen and C. Rubbia, Proc. 17th International Cosmic Ray Conference (Paris 1981) (CEA, Saclay, 1981) Vol. 11, p 112

18) K. Alpgard et al., CERN-EP Preprint 82/60 and Submitted to Physics Letters.

TABLE 1

Ingredients of Monte Carlo program to generate normal events

1. Particles are uniformly distributed in rapidity and with a density $dn_c/dy=3.9$ for charged particles.[4)]

2. The average number $<n>$ of secondary particles is taken to be 1.7 times the average number $<n_c>$ of charged secondaries. The distribution of n has the same "KNO" shape as the one we found[4)] for n_c in low bias events.

3. For each value of n the numbers n_c and n_0 of the charged and neutral secondaries ($n_c+n_0=n$) are chosen randomly such that $<n_c/n>=1/1.7$.

3. The distribution of charged particle multiplicities is the one found in our experiment for low bias events.

4. The p_t distribution is the one found in our experiment for low bias events[7)].

5. Fluctuations in energy deposited in each sampling of our calorimeters is reproduced track by track, assuming the neutrals are π^0 and that charged tracks are like those seen in our data whose momenta have been measured.

TABLE 2

MODE	COLLISION		DECAY	
HYPOTHESIS	1a	2b	2a	2b
Outgoing particles	Hadron Mixture	Nucleon Antinucleon	Hadron Mixture	Nucleon Antinucleon
Number of hadrons at vertex	74	74	74	74
Extrapolated E-M Energy (TeV)	330	330	330	330
Assumed fraction converted to E-M, K_γ	0.3	0.2	0.3	0.2
Lorentz factor γ	740	900	9000	8000
Selected angular region in CMS	$5^\circ < \theta < 30^\circ$		$30^\circ < \theta < 150^\circ$	
No. of particles transformed into this region	37	37	87	87
Scale factor to collider energy	0.85	0.85	1	1
Charged/Total particles	0.9	0.5	0.9	0.5
Acceptance for good tracks	1	1	0.6	0.6
Expected charged tracks in selected region	30	16	46	26
Energy into selected region GeV	110	140	140	200
Expected visible energy in first 4 rad.length	3	3	8.7	8.7
Beyond 12 rad lengths	44	56	56	80
$\langle p_t \rangle$, GeV	1.4	1.7	1.4	1.7

Figure Captions

Fig. 1. Approximate response of our central calorimeters to photons and to hadrons measured as visible energy divided by momentum as a function of momentum. The calorimeter segments have been grouped, as described in the text so as to give good measures of "electromagnetic" and of "hadronic" energies. The curves for γ's were derived from the EGS Monte Carlo program. Those for hadrons come from isolated tracks in our real data (see text).

Fig. 2. Scatter plots of "electromagnetic" versus "hadronic" energies for 48,000 low bias events. For each event the energies into two angular regions and into the total central region are shown.

Fig. 3. Scatter plots of mean transverse momentum versus multiplicity for charged particles for those 48,000 events.

Fig. 4. The scatter plots of Fig. 2 but with cuts in charged particles multiplicity and $<p_t>$ as shown. The approximate positions of Centauro I under the various hypotheses are shown.

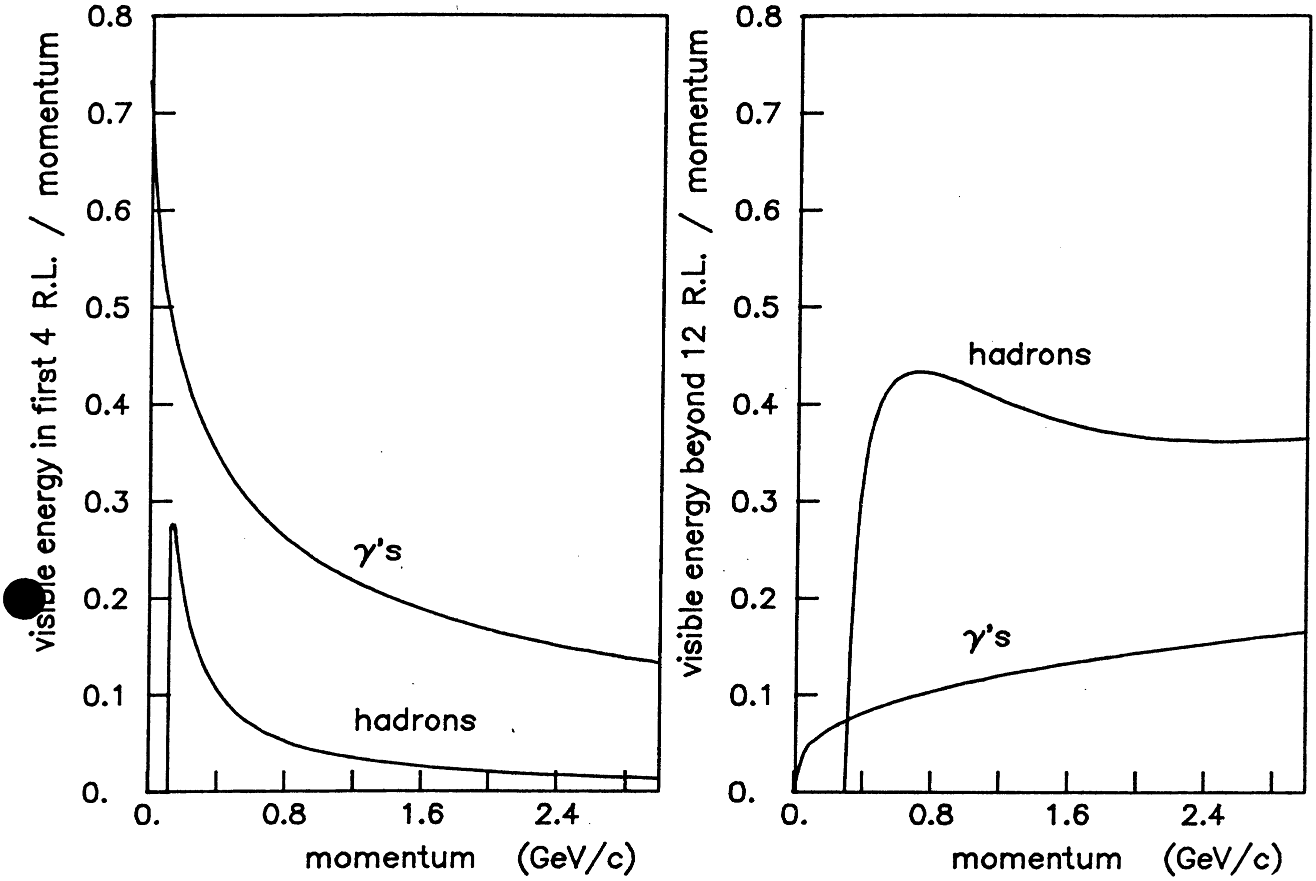
visible energy in first 4 R.L. / momentum
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.
γ's
hadrons
0.
0.8
1.6
2.4
momentum (GeV/c)
visible energy beyond 12 R.L. / momentum
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.
hadrons
γ's
0.
0.8
1.6
2.4
momentum (GeV/c)

Fig. 1

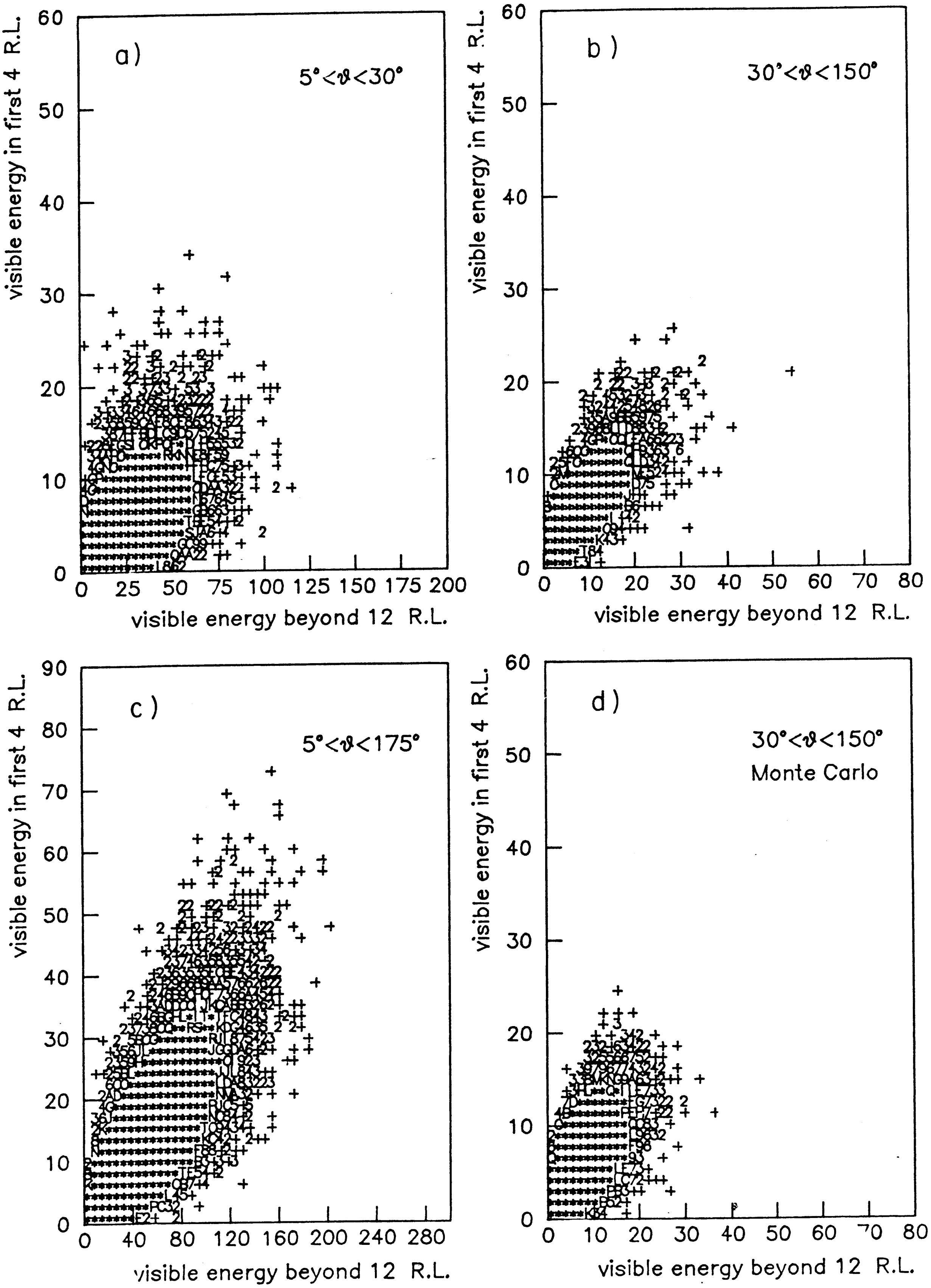
a)
5°<ϑ<30°
visible energy in first 4 R.L.
0
10
20
30
40
50
60
0 25 50 75 100 125 150 175 200
visible energy beyond 12 R.L.
b)
30°<ϑ<150°
visible energy in first 4 R.L.
0
10
20
30
40
50
60
0 10 20 30 40 50 60 70 80
visible energy beyond 12 R.L.
c)
5°<ϑ<175°
visible energy in first 4 R.L.
0
10
20
30
40
50
60
70
80
90
0 40 80 120 160 200 240 280
visible energy beyond 12 R.L.
d)
30°<ϑ<150°
Monte Carlo
visible energy in first 4 R.L.
0
10
20
30
40
50
60
0 10 20 30 40 50 60 70 80
visible energy beyond 12 R.L.

Fig. 2

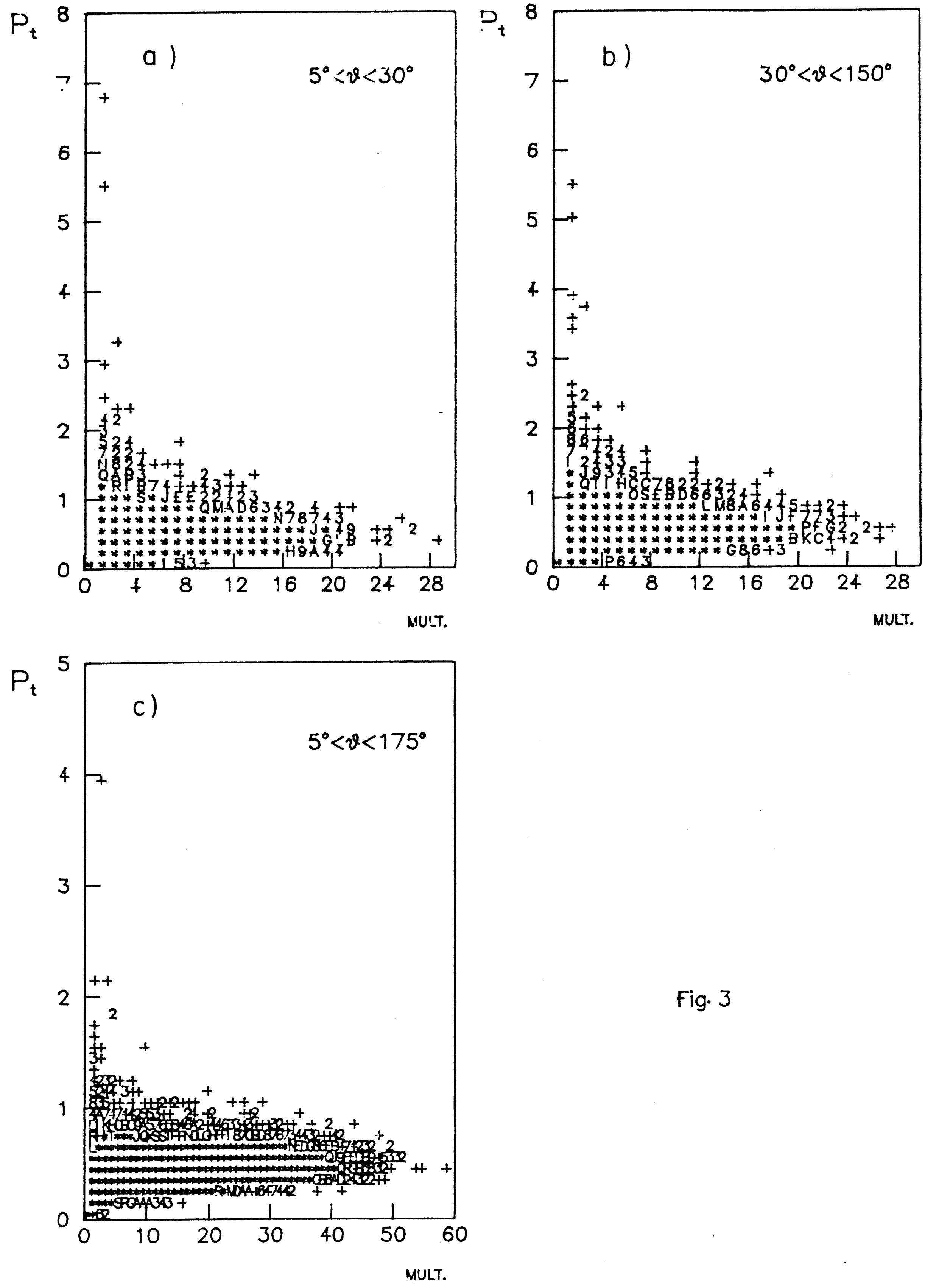
P
t
a)
5°<ϑ<30°
8
7
6
5
4
3
2
1
0
0
4
8
12
16
20
24
28
MULT.
b)
30°<ϑ<150°
0
4
8
12
16
20
24
28
MULT.
c)
5°<ϑ<175°
5
4
3
2
1
0
0
10
20
30
40
50
60
MULT.

Fig. 3

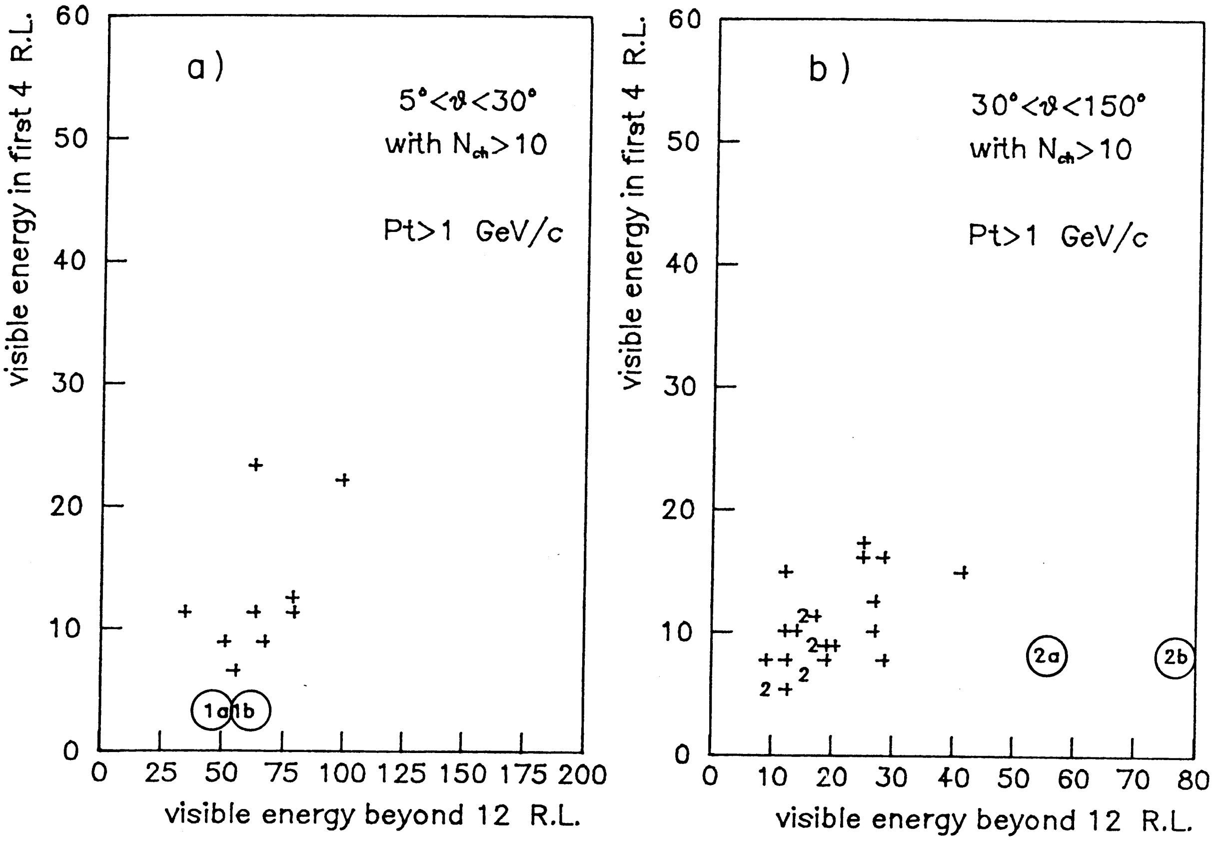
a)
$5° < \vartheta < 30°$
with $N_{ch} > 10$
Pt>1 GeV/c
visible energy in first 4 R.L.
60
50
40
30
20
10
0
0
25
50
75
100
125
150
175
200
visible energy beyond 12 R.L.
1a
1b
b)
$30° < \vartheta < 150°$
with $N_{ch} > 10$
Pt>1 GeV/c
visible energy in first 4 R.L.
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
visible energy beyond 12 R.L.
2
2
2
2
2a
2b

Fig. 4