

## Simulation of multi-muon detection in the DUMAND II array

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### Abstract

Detection of multi-muons with the DUMAND II array has been studied by a Monte Carlo simulation. Here mainly profiles of multi-muon events viewed through the DUMAND detector are shown, and a preliminary approach to the question whether we can separate the multi-muon events from very high energy single muon events is described. My tentative answer to the question is 'Yes, hopefully'. The PMT pulse width seems a good parameter to select multi-muon events, particularly those with high multiplicity.

### Introduction

The study of multi-muon detection is related to the design of circuit in our optical module. In the collaboration meetings both at Bern and at Sendai, the circuit design was discussed<sup>1)</sup>, but the Monte Carlo study to back up the design work was not adequate.

Except for the leading edge of the PMT output pulse which is the most important information, three candidates of quantities have been being discussed as information we should obtain through the circuit. Those are pulse widths (time-over-threshold), total charge (integrated pulse height) and notches which indicate rising points in overlapping multiple pulses. At Sendai, I placed a stress on the fact that not only a multi-muon but also a high energy single muon gives rise to multi-pulses in PMTs, which is ascribed to accompanying cascade showers produced through electromagnetic interactions. In this report, I will re-examine the problem.

T. Hayashino has argued about the lateral configuration of each multi-muon event<sup>2)</sup>. It seems very difficult to determine each configuration experimentally from data even using all the above quantities. Can we get at least any evidence that an event has a finite lateral spread? This is our great concern.

### Method of simulation

Multi-muon events at the DUMAND depth, simulated by T. Hayashino<sup>2)</sup>, were supplied to my Monte Carlo program<sup>3)</sup> of the DUMAND array. A program to get the pulse width and the notches at each OM (Optical Module) was added to my old program. In Fig. 1, a rough flow chart of the present calculation is shown. The old part of the program was not changed except for the overall detection efficiency of PMT, which was reduced from 20 to 15 % taking into account the recent M. Ito's measurement of the quantum efficiency<sup>4)</sup>.

The PMT pulse form corresponding to just one p.e. (photo-electrons) is assumed to be given by :

$$f(t) = 0.752(t-5.25) \exp(-t/7) + 3.948 \exp(-t/3)$$

where the unit of  $t$  is nanosecond. The function peaks at  $t=10.63$  and then has  $f(10.63) = 1.0$ . This function form is merely a tentative one. We will precisely measure the form for coming new PMT soon.

Actually, the PMT output pulse charge is widely distributed when only one p.e. comes in the first dynode. We assume a kind of Gamma function after J. Learned<sup>5)</sup> as the distribution of the charge  $Q$  :

$$g(Q)_{1 \text{ p.e.}} = 4Q \exp(-2Q).$$

Then, for  $n$  p.e. :

$$g(Q)_{n \text{ p.e.}} = 4^n Q^{2n-1} \exp(-2Q) / (2n-1)!$$

So,  $Q$  is sampled randomly out of  $g(Q)$  and the PMT pulse is given :

$$\text{Pulse} = Q(n)f(t)$$

An example is shown in Fig. 2(a).

More generally, photons do not reach the PMT simultaneously. Delayed pulses are produced from multi-muons and also from cascade showers associated with a muon, because in general such photons take longer paths before reaching the PMT. Then :

$$\text{Pulse} = \sum Q(n_i)f(t-t_i)$$

Such multi-pulses have a variety of forms as shown in Fig. 2. The pulse width

is defined as the time-over-threshold of a discriminator output with a fixed threshold of 0.33.

Dotted curves in Fig.2 are simulated pulses after the clipping with a 3 ns delay line (i.e. 3 ns both ways). The pulses are assumed to suffer a small integration with a time constant of 2 ns. Notches are produced by another discriminator with a fixed threshold of 0.1 for now.

Since there is no ideal differential circuit, we have to have some uncomfortable problems. For instance, as seen in Fig.2(d) and (f), it is difficult to get a notch for a relatively small pulse behind a big pulse.

M.Jaworski, J.Learned and D.O'Connor once discussed the possibility of using double differential pulse<sup>6</sup>) instead of single differential one (i.e. clipping) to produce notches. In their case, the above difficulty is diminished, but I am afraid that sometimes over-shoot pulses could go up over the threshold and give rise to additional useless output pulses.

#### Notches or widths ?

Examples of events are shown in Fig.3, multi-muon events in Fig.3(a), (b), (c) and a single muon event in (d). Area of each circle indicates the PMT pulse charge at the correspondent OM. The mark '+' means the OM has notches. The two PMTs having notches in Fig.3(a) correspond to pulse forms shown in Fig.2(b) and (c), respectively. Fig.2(d) and (e) are also picked up from the same event shown in Fig.3(a). The events in Fig.3(a) and (c) suggests that multi-muon does not always produce notches.

Contrary to that event, another event shown in Fig.3(b) has produced many notched pulses. It happens that there is a large spatial gap between two muons, and many OMs occupy good positions to observe the gap. This is a lucky case. An energetic single muon also produces a lot of notches as shown in Fig.3(d).

The ratio of the number of OMs with notches to that of all the hit OMs in an event has a wide distribution. Fig.4(a) is for multi-muon events, and Fig.4(b) and (c) are for single muons of energy 20 TeV and 10 TeV respectively. It looks impossible to select multi-muon events by the number of notches.

For a PMT single pulse, the pulse width is roughly linear to  $\log(Q)$ . But, for an overlapping multi-pulse, the width deviates from the linear

relation. In Fig. 5, values  $R_q = w/\ln(Q/0.08)$  of all the hit PMTs in many events are plotted against  $Q$ , where  $w$  is the width (ns) of the first pulse over the threshold 0.33 and  $Q$  is the total charge including the first, second, third pulses and so on if they exist. The dark curve in the figure corresponds to the single pulses. (The form of the curve depends on the assumed pulse form mentioned above.) Fig. 5(a), (b) and (c) are for multi-muons, single muons of 20 TeV and single muons of 10 TeV, respectively. The number of points is equal to each other. In case of the multi-muons, there are many deviated points above the dark curve compared to the cases of the single muons.

In Fig. 6, the distribution of the rate of OM's having the value  $R_q$  greater than 10.5 in each event is shown. Fig. 6(a), (b) and (c) correspond again to multi-muons, single 20 TeV muons and 10 TeV ones. Apparent difference of the distribution between them can be seen. The difference is much more distinct for events with high multiplicity as seen in Fig. 7, where the same rate as in Fig. 6 vs. number of muons in each multi-muon event is plotted. But to get a definite answer, we need to take into account the single muon energy spectrum and relative flux of multi-muon events including their detection efficiencies. I think I have to collaborate for the problem with T. Hayashino who supplied multi-muon events.

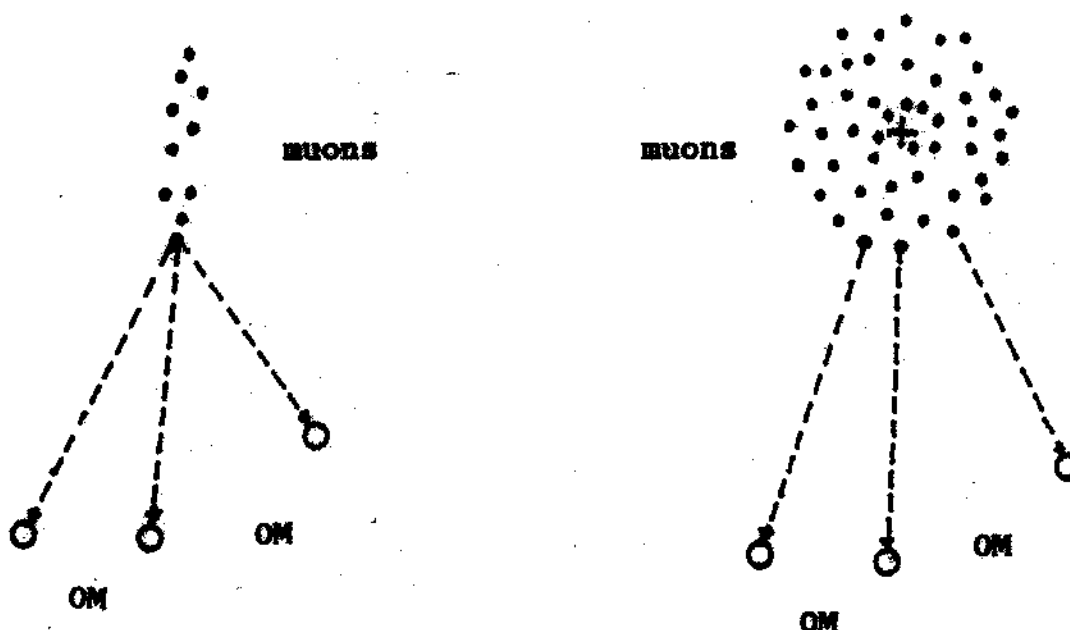
#### Reconstruction of multi-muon events (?)

It is easy to get the averaged muon track (i.e. 'core axis') of a multi-muon event by passing data through my fitting program for single muon. Here, the leading edge of the first pulse is used as the time data of each OM. The resultant distribution of the angle error is shown in Fig. 8(a) and that of the location error in Fig. 8(b). We can divide space around the obtained core axis into two, three or four regions, and perform individual fittings in each region using only the OM's belonging there. If the shape of muon distribution on the perpendicular plane to the muons is long and very narrow like the left case below (which is most simply realized by a two-muon event), the fitted track location differs from region to region and we may be able to estimate the rough shape of distribution. Then the procedure turns out to verify that the event has a finite spread and is not a single muon.

But this scenario does not hold when the shape of distribution is round

like the right case below. In principle, we get a similar answer to each other in all the regions, that is, the core axis (denoted by '+'). This happens because we do not know the absolute time when the muons come in and then we think the Cherenkov light has come from the position '+'. From this analysis, we can not say anything about how wide the distribution is.

If a few OM's are among muons by chance, we may be able to get more information. But, so far I have no particular good idea to analyze such events.



### Concluding Remarks

The pulse width seems to be a good parameter to select multi-muon events, particularly effective for those with high multiplicity. On the other hand, it is expected that the notch and the timing data (used in the track fitting) are effective rather for low multiplicity events, i.e. two or three muons with considerable mutual distances. My job to prove it quantitatively is not finished yet. The track fitting using a part of the detector array as mentioned above is not so easy, because the fitting error is much larger than that using all hit OM's in the whole array. (This large fitting error is partially due to the PMT performance of being rather insensitive to vertical muons.)

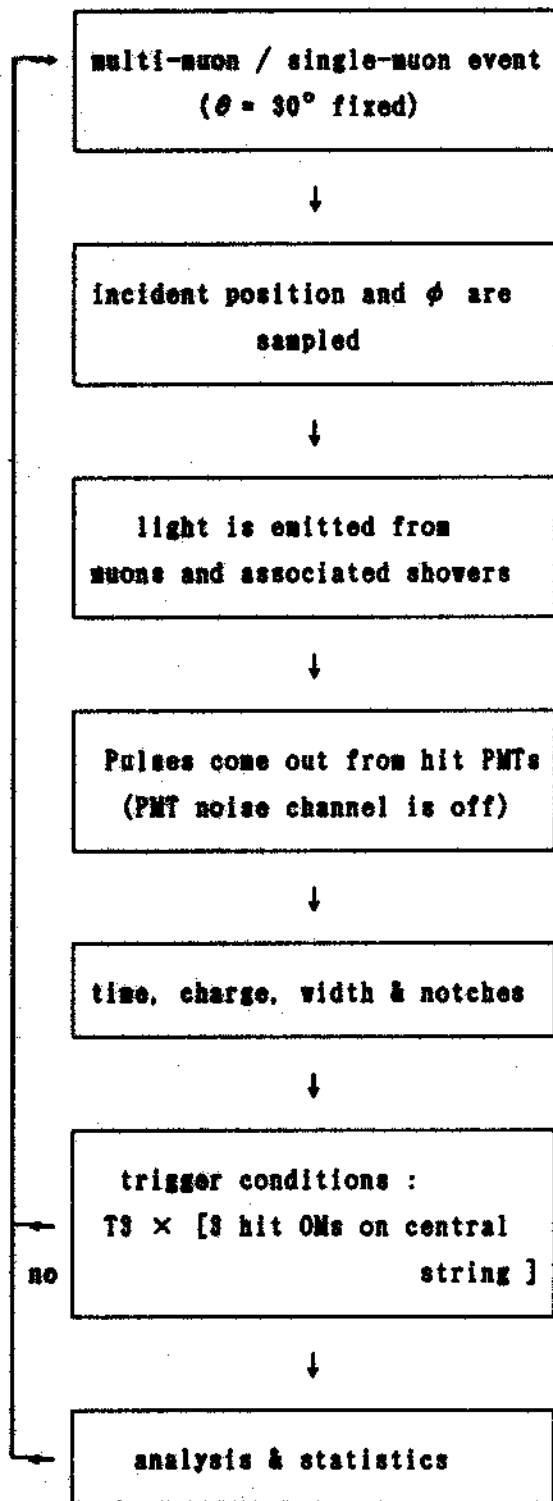
Which type of multi-muon will bring us more interesting physics, low multiplicity or high multiplicity? Both? Or neither?

## References

- 1) see H. Kawamoto, elsewhere in this proceedings
- 2) T. Hayashino, elsewhere in this proceedings
- 3) A. Okada, ICRR-Report-209-90-2
- 4) M. Ito, elsewhere in this proceedings
- 5) J. Learned, A. Okada and S. Uehara, elsewhere in this proceedings
- 6) private communication

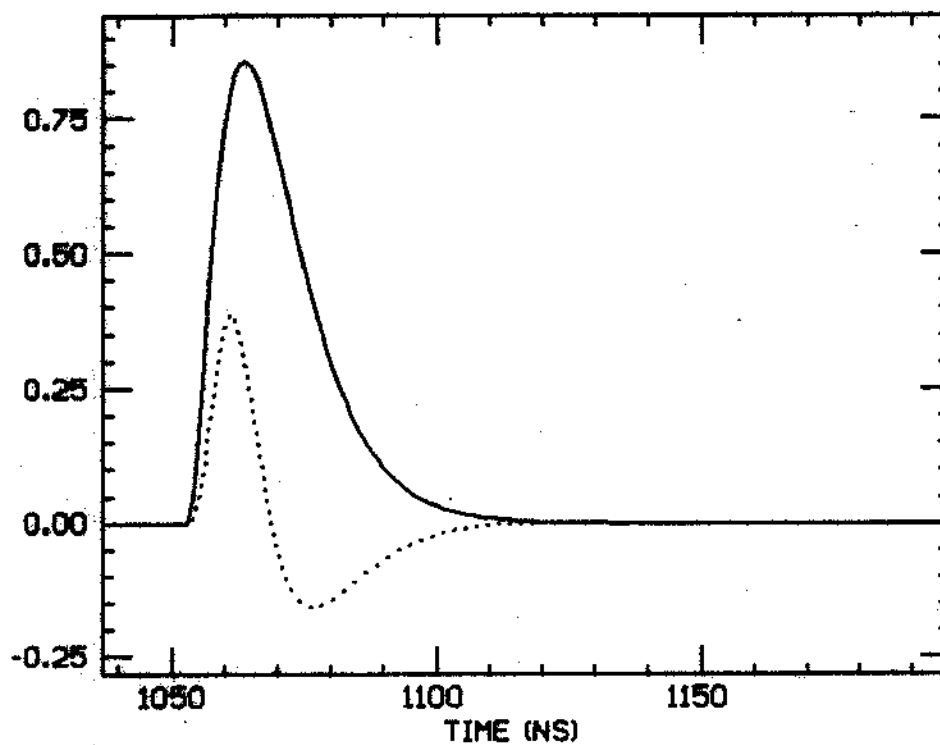
## Figure Captions

- Fig. 1 : Flow Chart of the present Monte Carlo calculation.
- Fig. 2 : Examples of PMT output pulses. Dotted curves are those after clipping with a delay line of 3 ns. Fig. 2(a) shows a single pulse and the others are overlapping pulses.
- Fig. 3 : Examples of event in DUMAND array (see Ref. 3).
- Fig. 4 : Distribution of the ratio of the number of OMs with notches to that of all the hit OMs in each event.
- Fig. 4(a): for multi-muons.
- Fig. 4(b): for single 20 TeV muons
- Fig. 4(c): for single 10 TeV muons
- Fig. 5 :  $R_w = w/\ln(Q/0.06)$  against  $Q$ , where  $Q$  is total pulses charge and  $w$  is width of the leading pulse.
- Fig. 5(a): for multi-muons (2500 points).
- Fig. 5(b): for single 20 TeV muons (2500 points).
- Fig. 5(c): for single 10 TeV muons (2500 points).
- Fig. 6 : Distribution of the percentage of OMs having the value  $R_w$  (see Fig. 5) greater than 10.5 among all the hit OMs in each event.
- Fig. 6(a): for multi-muons.
- Fig. 6(b): for single 20 TeV muons.
- Fig. 6(c): for single 10 TeV muons.
- Fig. 7 : The percentage defined in Fig. 6 vs. muon multiplicity.
- For the mark 'x', the primary cosmic ray is iron.
- For the mark '•', the primary cosmic ray is proton.
- Fig. 8 : The error distribution of reconstructed angles (Fig. 8(a)) and reconstructed locations (Fig. 8(b)) of multi-muon core axes.



**Fig.1** flow chart

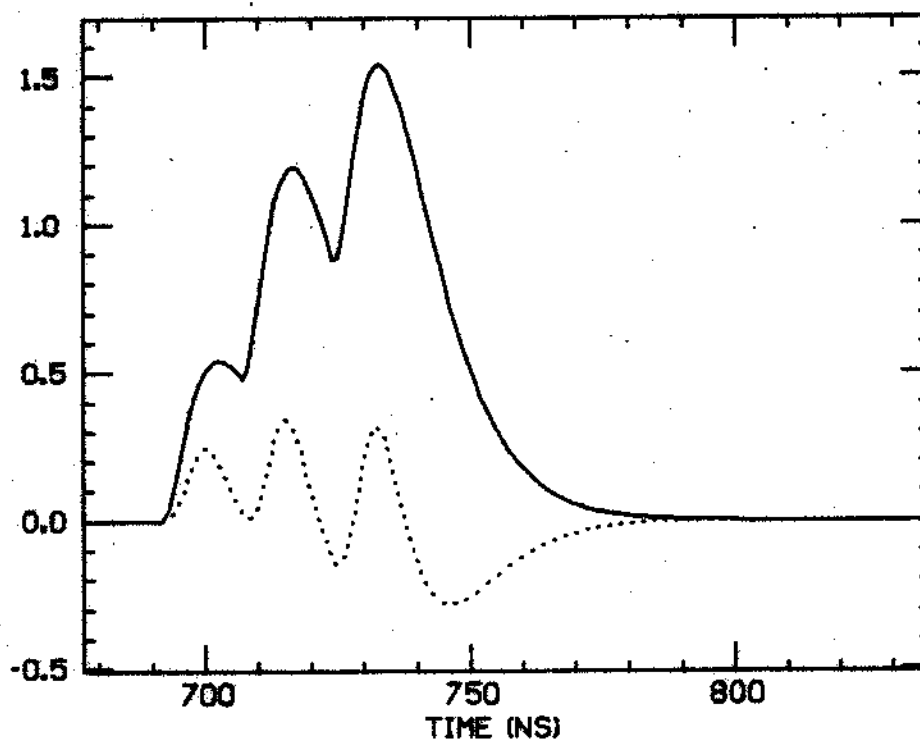
# 98 ( 5, 1)



A- 56 M- 6 E0/N- 4.49E+02

Fig. 2(a)

# 1294 ( 1, 9)

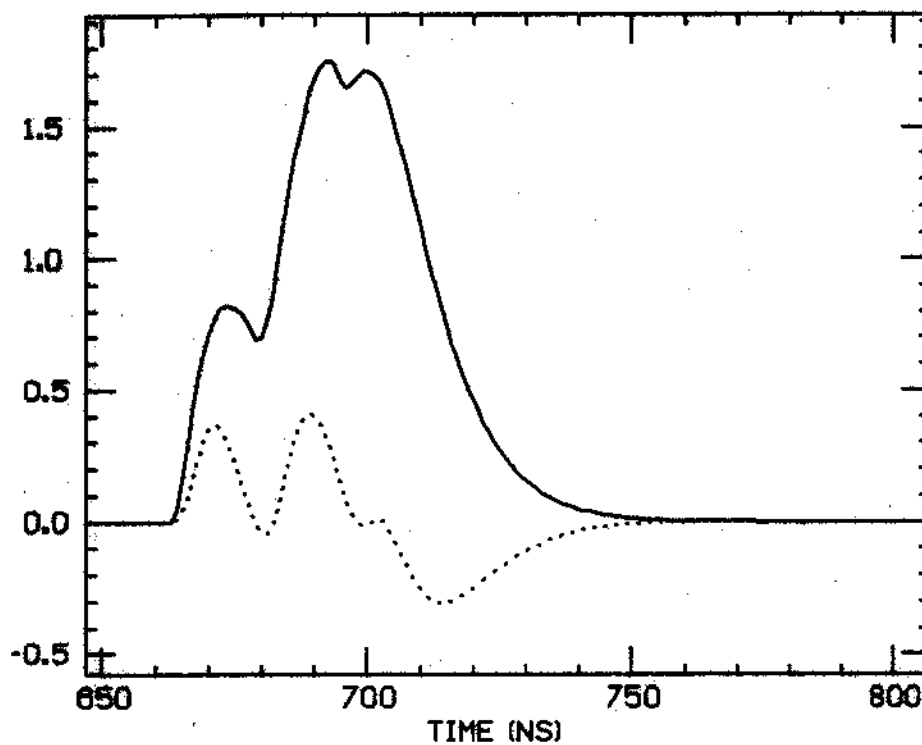


A- 56 M- 7 E0/N- 2.01E+02

Fig. 2(b)



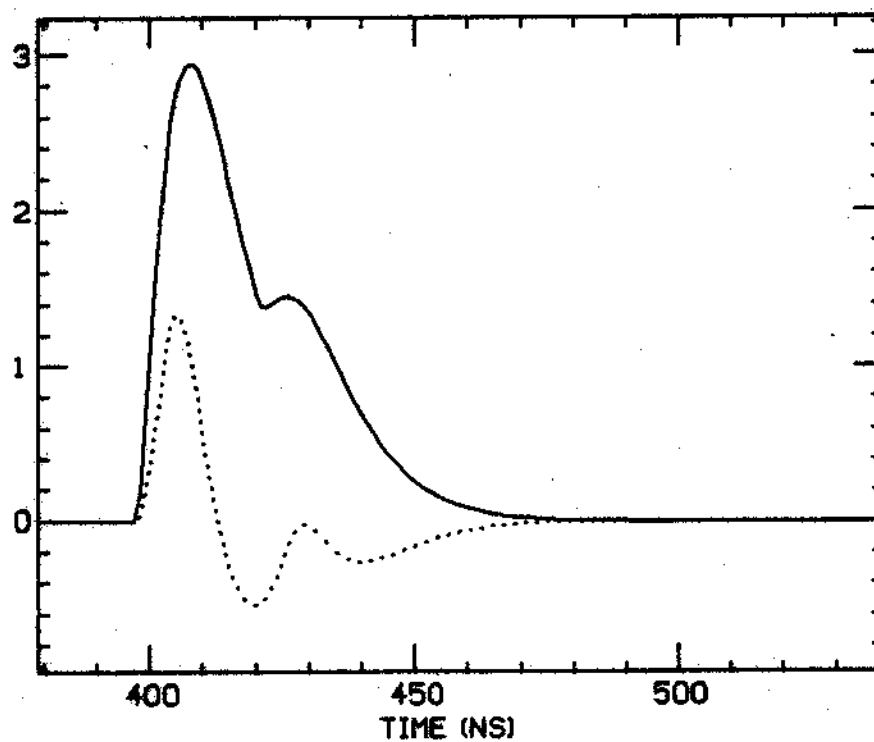
# 1294 ( 1,10)



A= 56 M= 7 EO/N= 2.01E-02

Fig. 2(c)

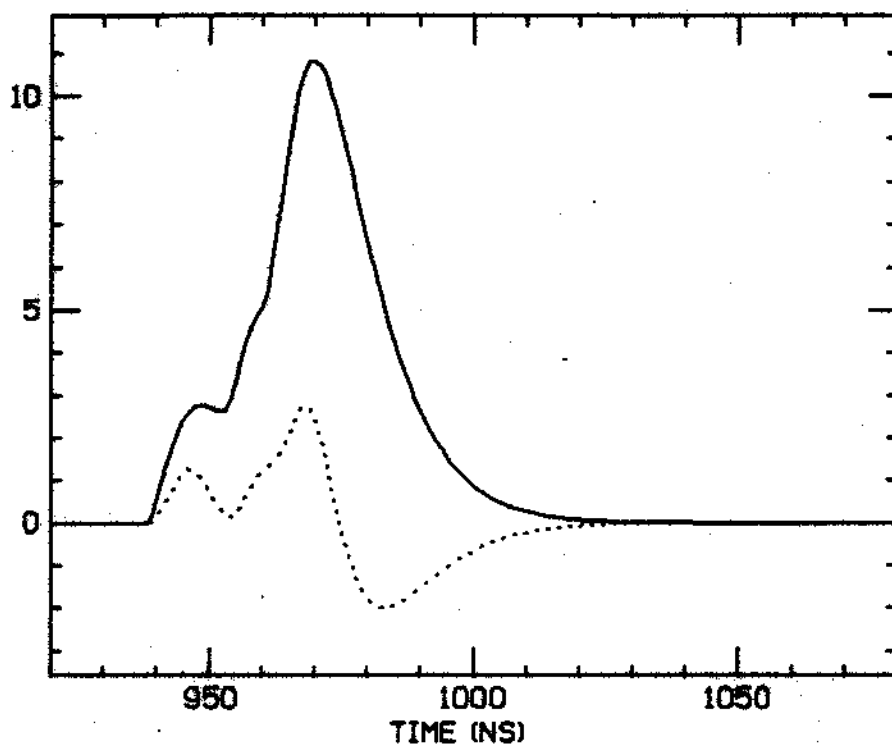
# 1294 ( 3,16)



A= 56 M= 7 EO/N= 2.01E-02

Fig. 2(d)

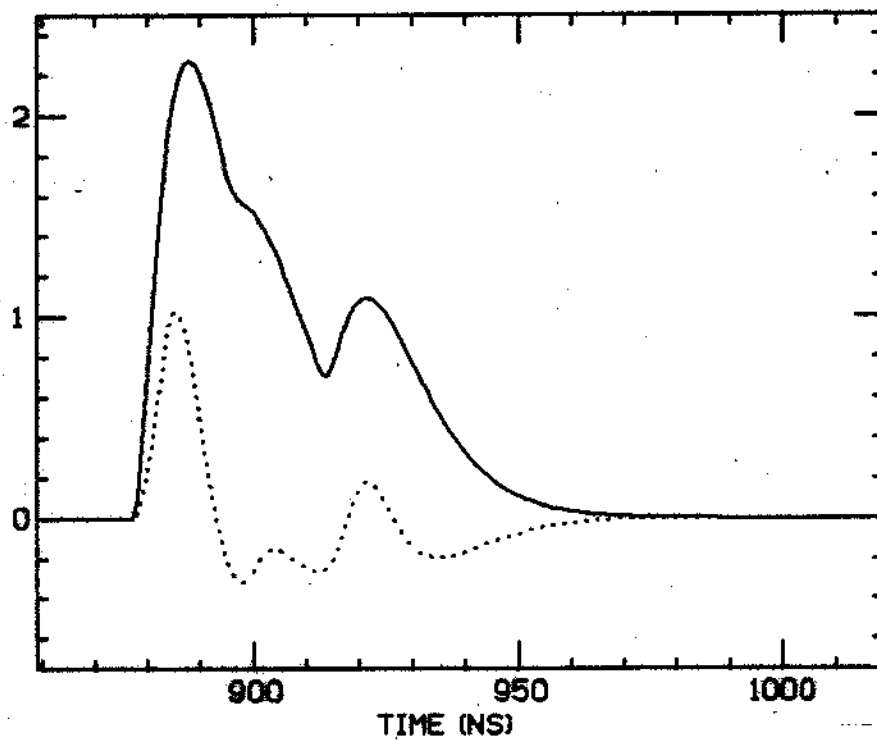
# 1294 ( 8, 3)



A- 56 M- 7 E0/N- 2.01E-02

Fig. 2(e)

# 1139 ( 7, 4)



A- 1 M- 6 E0/N- 3.77E-02

Fig. 2(f)

# 1294 PE DISTR. A:56 EO/N= 2.01E+02 TEV

EMU- 0.24E+04 7 MUONS 204.6 P.E.S 47 OMS 2 NOTCH

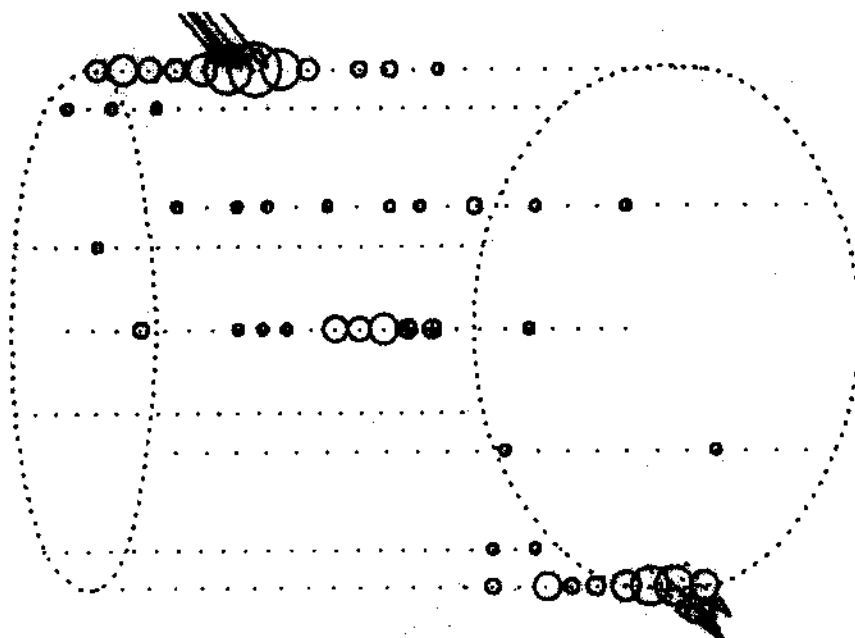


Fig. 3(a)

#28790 PE DISTR. A: 1 EO/N= 1.01E+03 TEV

EMU- 0.30E+04 6 MUONS 177.9 P.E.S 37 OMS 16 NOTCH

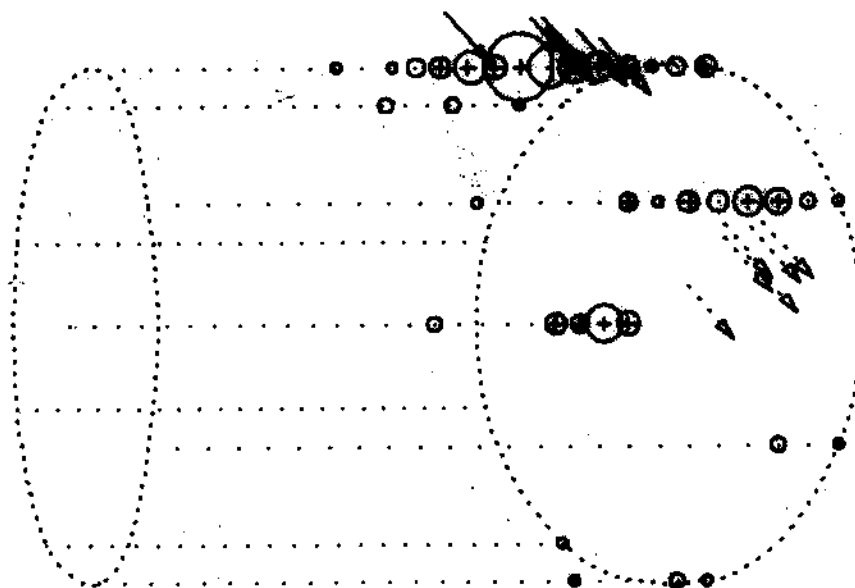


Fig. 3(b)

#15458 PE DISTR. A: 1 E0/N= 1.30E+05 TEV

EMU- 0.14E+05 16 MUONS 222.1 P.E.S 40 OMS 1 NOTCH

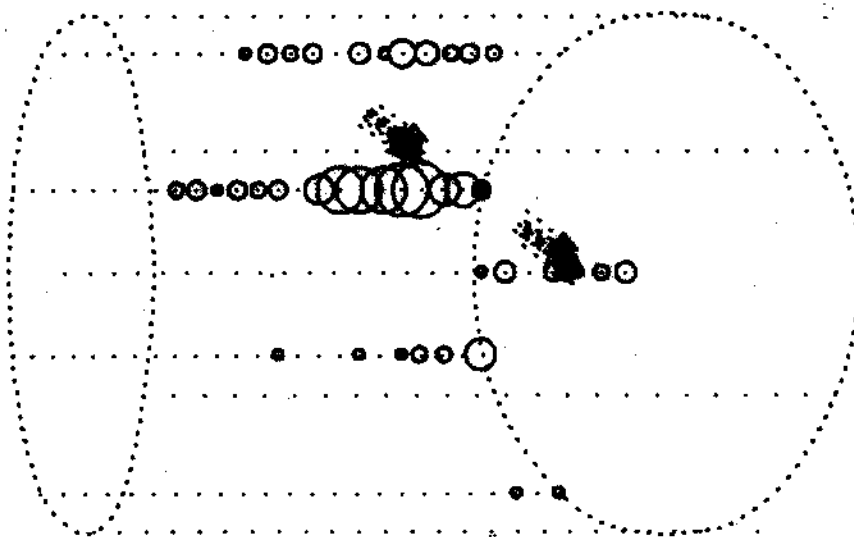


FIG.3(c)

# 20 PE DISTR. A: 0 E0/N= 2.00E+01 TEV

EMU- 0.20E+05 1 MUONS 328.9 P.E.S 58 OMS 23 NOTCH

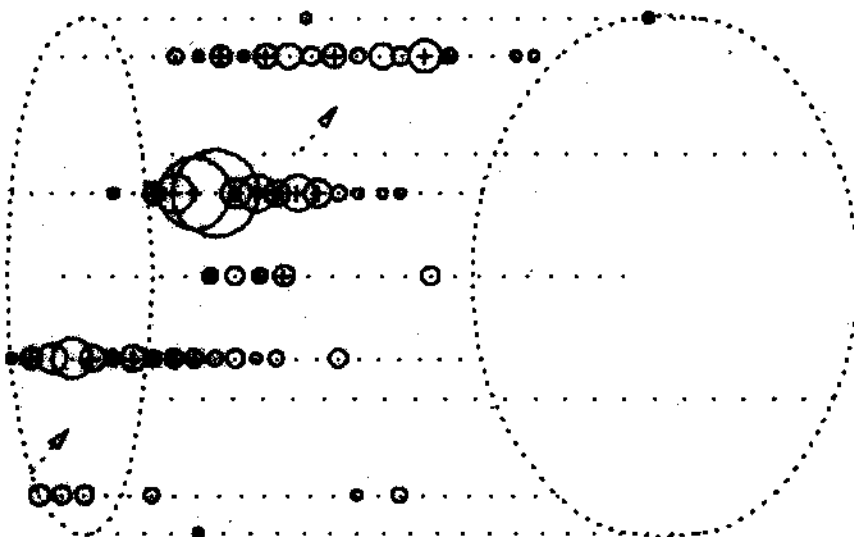
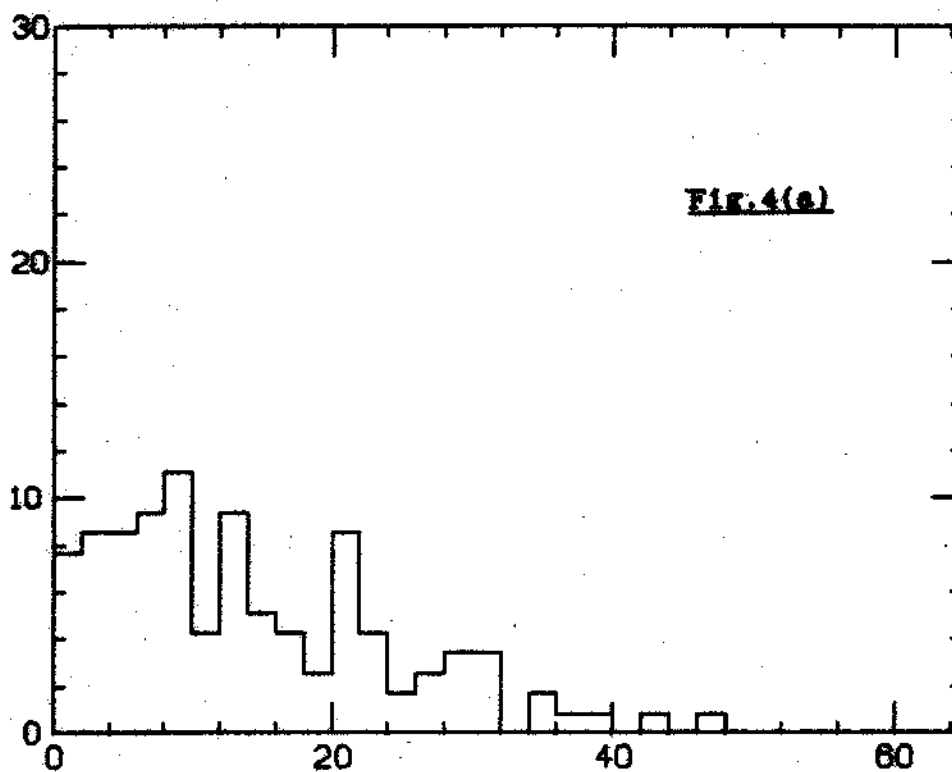
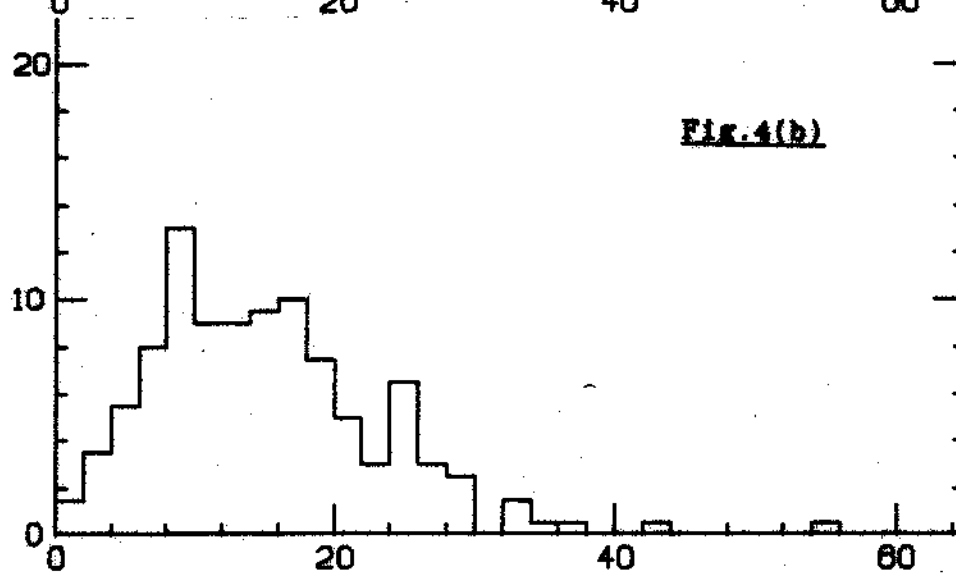


FIG.3(d)

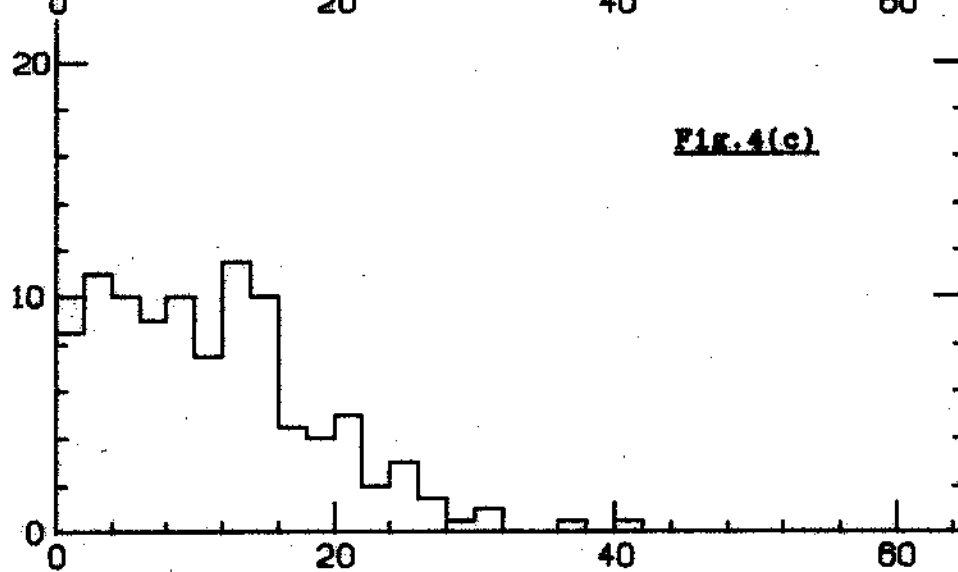
EVENTS (%)



EVENTS (%)



EVENTS (%)

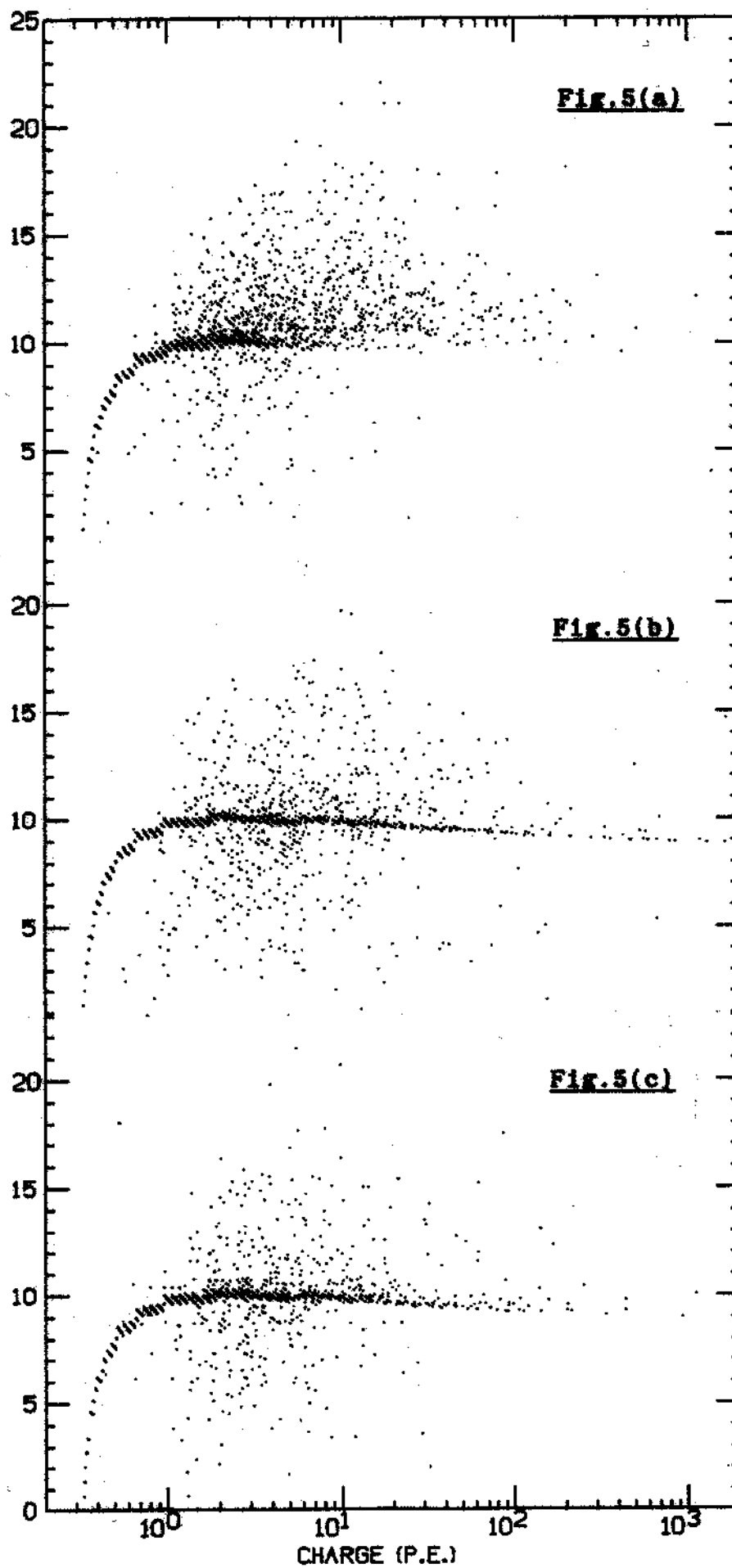


RATIO OF NOTCHED OMS (%)

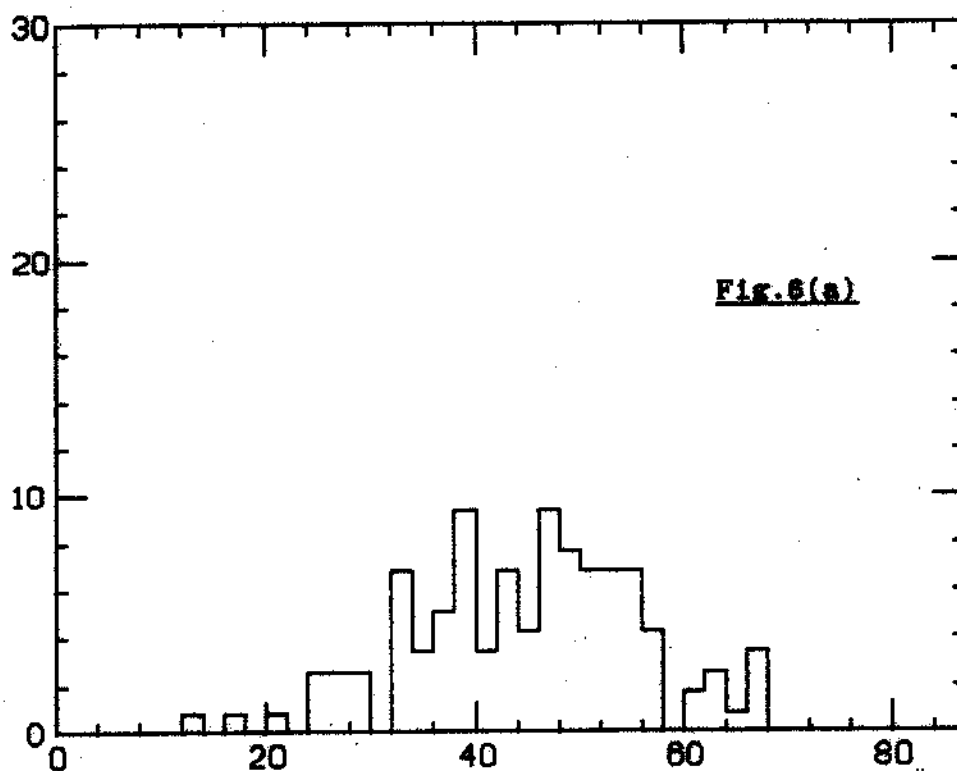
WIDTH(NS) / LOG(CHARGE(P.E.)/.08)

WIDTH(NS) / LOG(CHARGE(P.E.)/.08)

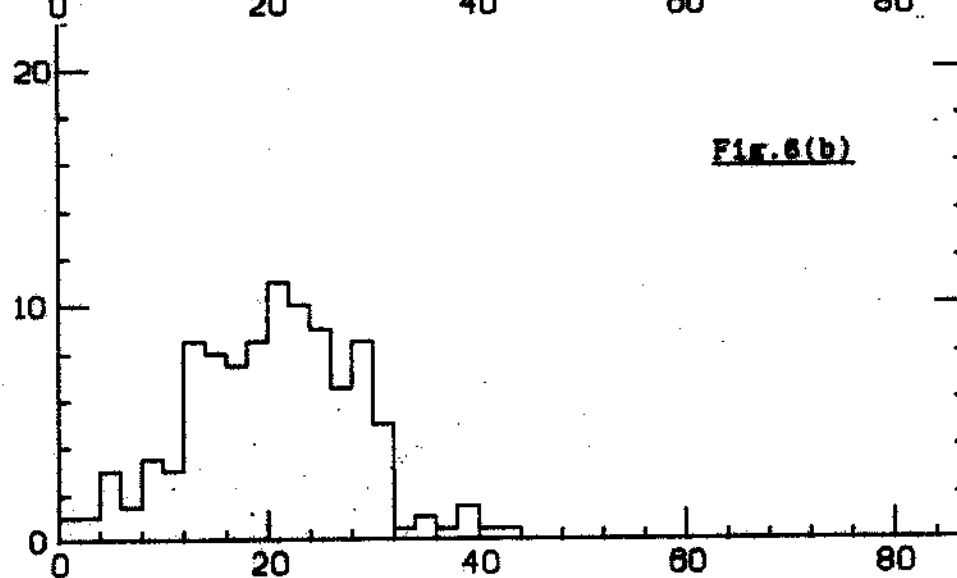
WIDTH(NS) / LOG(CHARGE(P.E.)/.08)



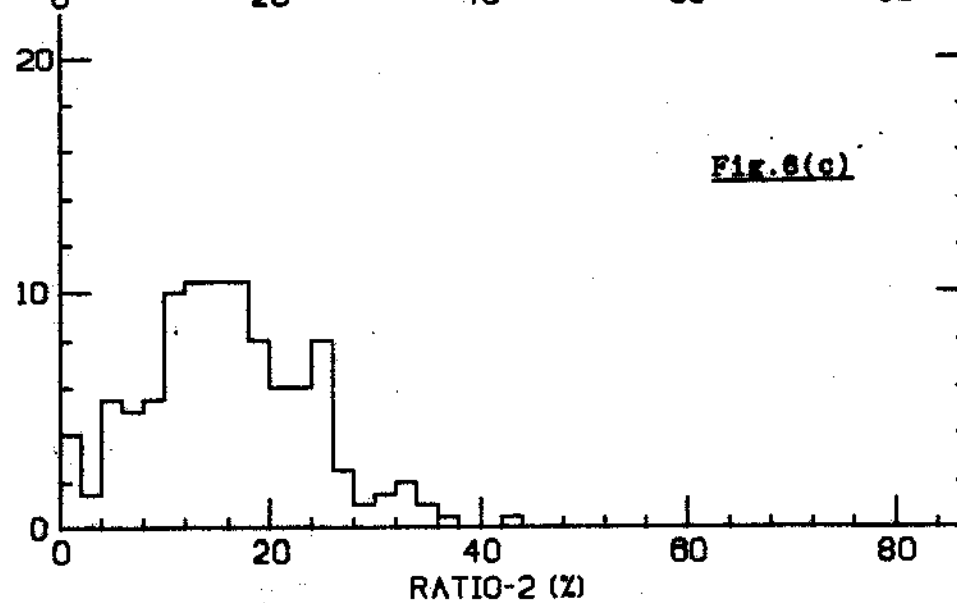
EVENTS (%)



EVENTS (%)



EVENTS (%)



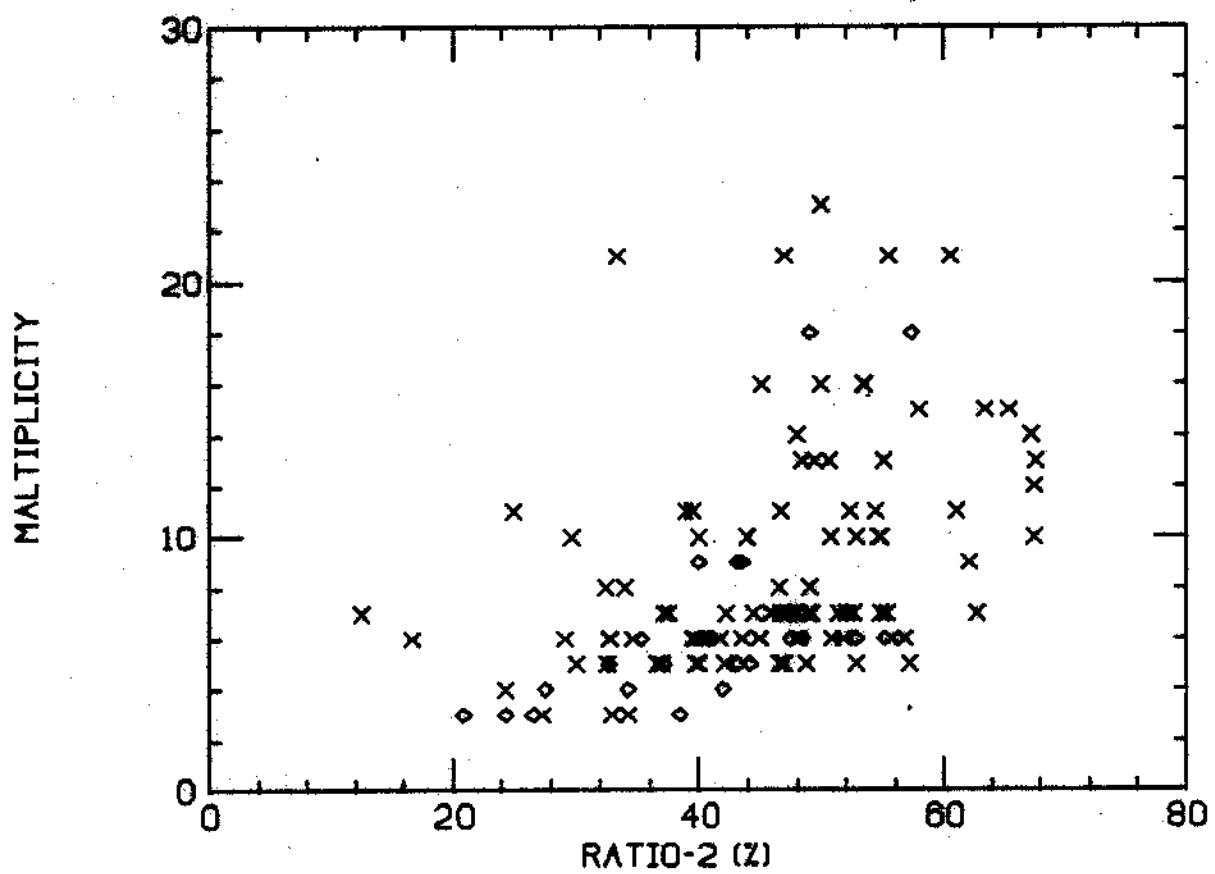


Fig. 7



## ANGULAR RESOLUTION FOR MULTI-MUONS

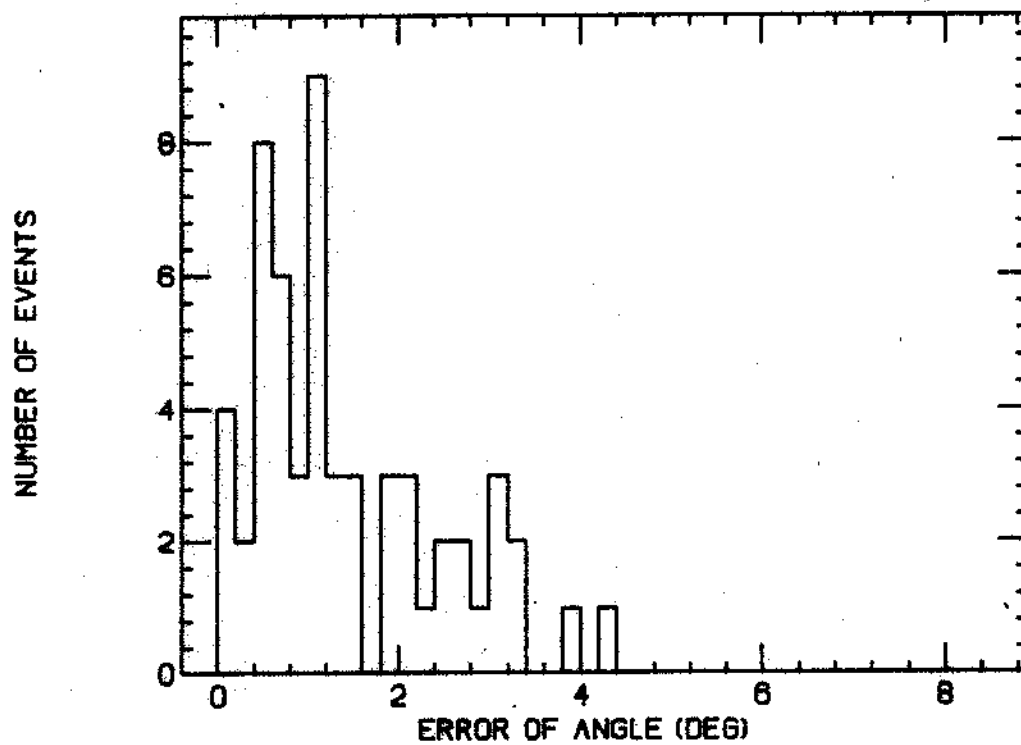


Fig. 8(a)

## SPACE RESOLUTION FOR MULTI-MUONS

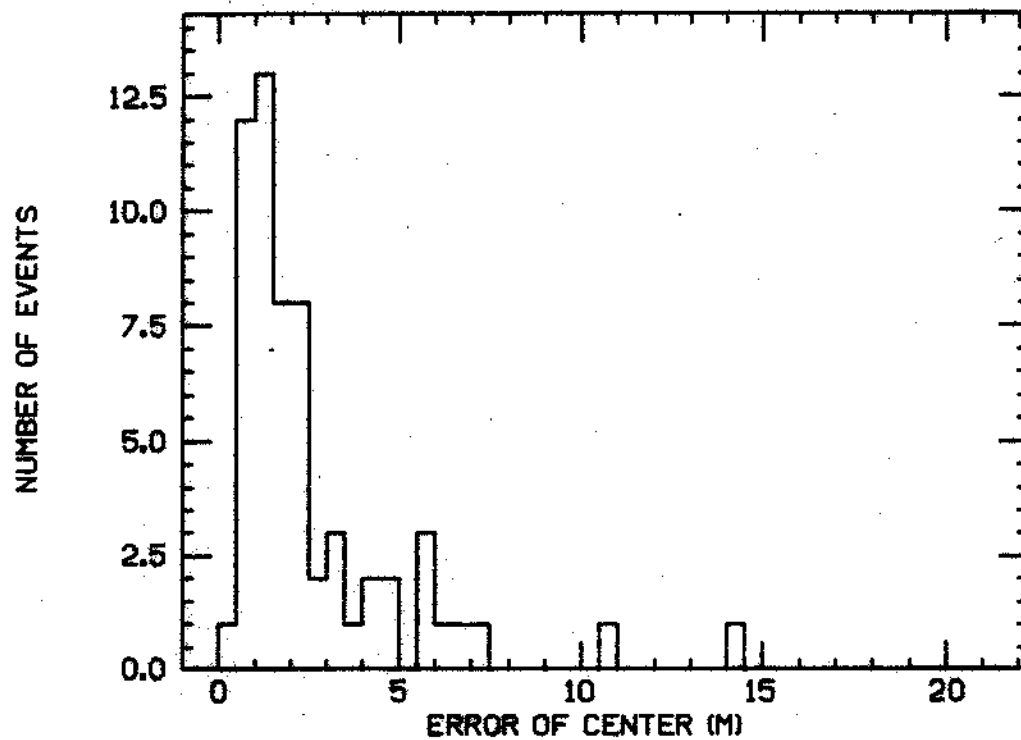


Fig. 8(b)