ALEPH 89-84
PHYSIC 89-36
J. Miguel et al.
11.05.89

Selection of muon pair events for the determination of $\sin^2\theta_W$ in ALEPH

R. Miquel, J.A. Perlas, E. Tubau
Universitat Autònoma de Barcelona

May 9, 1989

Abstract

The electroweak parameter $\sin^2\theta_W$ will be determined using $\mu^+\mu^-$ events in the ALEPH detector. To perform this, some criteria to select the events are discussed. Also a classification for the final sample and for those events that don't survive our considered cuts is given. The most important backgrounds are considered. Finally, $\sin^2\theta_W$ is determined using a sample of multiweighted events.

1 Introduction

One of the first measurements that we will try to perform at LEP will be that of the value of $\sin^2\theta_W$. It can be done using several kind of events, but, since muon pair events are amongst the cleanest ones in e^+e^- detectors, the method of extracting $\sin^2\theta_W$ from the angular distribution of μ pair events will be one of the best.

In this note, we study how this can be done with the ALEPH detector. As of yet, we have not dealt with the problem of triggering. First we show how μ pair events can be identified with ALEPH. To do this we have generated a sample of 3000 events (a realistic number for the first runs) using KORL02, GALEPH 22.0 (without TPCSIM) and JULIA 2.22 and explored the response of the detector using ALPHA 101 and DALI. Our results will refer to this sample although we have also obtained some results with earlier versions. This selection is done in section 2.

In section 3, we study the more important backgrounds and propose some kinematical cuts to remove them while keeping most of the μ events. Section 4 deals with the method to fit $\sin^2\theta_W$ from the angular distribution of $\cos\theta_{\mu^+}$ together with the results obtained. The conclusions are given in section 5.

2 Detection of muon pairs

2.1 Classification of the events

We have used for this section a sample of 2479 events generated as follows: BREM02, GALEPH 20.2 without TPCSIM and JULIA 2.19. The input parameters were: $E_{beam} = 46.1\ GeV$, $M_Z = 92\ GeV$, $M_{top} = 60\ GeV$ and $M_{Higgs} = 100\ GeV$ and the angular region: $10^0 < \theta < 170^0$; $0 < \phi < 2\pi$.

In order to eliminate those clearly unwanted events we have made a *first cut* in our sample. This cut consists in the following requirements:

- two charged tracks
- one main vertex
- no V^0 vertices
- both tracks related to the main vertex

In this way the sample was reduced to 2205 events, which represents a $(88.9 \pm 0.6)\%$ of events that pass this cut. In the following we will give a classification for those events that pass that *first cut* and also for those which don't, explaining the reason of being in each subgroup.

2.1.1 Events that don't pass the first cut

We can give several reasons for an event to belong to this group:

- Events that have less than two reconstructed tracks
  - Only one reconstructed track
    1 event
  - Events that have no reconstructed tracks
    78 events, $(3.2 \pm 0.4)\%$ (referred to total sample)
    REASON: they have low θ angle; in fact we find
    75 events with $\theta < 15^0$
    3 events with $15^0 < \theta < 25^0$
- Events that have more than two reconstructed tracks
  - Conversion events (V^0's)
    26 events, $(1 \pm 0.2)\%$
    To identify a V^0 we use the information given in bank 'PYER'
  - Other than V^0's
    - Events that have more than two TPC reconstructed tracks
      35 events, $(1.4 \pm 0.3)\%$
      REASON: they go through a TPC crack; see fig. 1.
    - Events that have two or less TPC reconstructed tracks
      85 events, $(3.4 \pm 0.4)\%$
      REASON: there is a mismatch between TPC and ITC due to software problems in JULIA; see fig. 2.
- Events that have two reconstructed tracks without associated vertex
  49 events, $(2 \pm 0.3)\%$
  REASON: they go at low θ angle; difficulty in vertex finding due to the fact that a small error in θ causes a big one in the z coordinate

At this point it is interesting to note that although we have found 26 V^0's in fact GALEPH produces 70. The difference goes mainly into the subgroup of events that have more than two TPC reconstructed tracks.

2.1.2 Events that have passed the first cut

In this study we have only used the first Muon Chambers layer as this will probably be the ALEPH installation status in the first run(s). We have found the different types of events quoted below:

- Events that have two tracks with associations in the Muon Chambers (MC) and in the Hadronic Calorimeter (HC)
  1927 events, $(87.4 \pm 0.7)\%$ (referred to events that have passed the *first cut*)

- Events that have one track with associations in the MC and the other in the HC with identification flag given by bank 'HMAD' ($\equiv$ IF) equals one (i.e. is identified as a muon)
  160 events, $(7.3 \pm 0.6)\%$

- Events that have one track with associations in the MC and the other in the HC with $IF = 0$ (i.e. not classified)
  - Events that have few hits in the HC
    20 events, $(0.9 \pm 0.2)\%$
  - Events that have no hits in the HC
    81 events, $(3.7 \pm 0.4)\%$
    REASON: software problem with 'HMAD' bank in JULIA

  Let us remark that for the two last subgroups the track that doesn't hit the MC goes through a HC crack. We are studying the possibility to keep those events using the wire information in the ECAL.

- Events that have one track with associations in the MC and the other in the HC with $IF = -1$ (i.e. identified as a hadron)
  - No difference (as seen by DALI) with a muon track
    8 events
  - There is some spread simulating a hadron
    3 events

- Events that don't fit in the above classification
  Few events

2.2 Muon pair identification criteria and efficiency

With the above classification in mind we can now give the requirements to identify a $\mu^+\mu^-$ pair:

- Make a first cut (two charged tracks associated to main vertex)

- Further requirements:

- Both tracks with Muon Chambers associations or
- One track with Muon Chambers associations and the other with Hadron Calorimeter associations and identified as a muon (using 'HMAD' bank information)

Using this criteria we can find our efficiencies in the detection:

TOTAL SAMPLE	2479 events
TOTAL SAMPLE INSIDE ACCEPTANCE	2403 events
AFTER FIRST CUT	2205 events
FINAL SAMPLE AFTER ALL CUTS	2087 events

So we end up with 2087 events which represents (86.8 ± 0.7)% (global efficiency inside acceptance) or (94.7 ± 0.5)% (referred to events that pass the *first cut*).

2.3 Comparison with other versions

We have also generated a sample of events using KORL02 in the angular range $0^0 < \theta < 180^0$; $0 < \phi < 2\pi$. This is a more precise event generator including also multiphoton events. We have used GALEPH 22.0 without TPCSIM and JULIA 2.22.

The results are as follows:

TOTAL SAMPLE	2993 events
TOTAL SAMPLE INSIDE ACCEPTANCE	2896 events
AFTER FIRST CUT	2653 events
FINAL SAMPLE AFTER ALL CUTS	2432 events

The final number of events represents 91.7 % referred to the events that pass the first cut, 84.0 % as global efficiency inside acceptance and 81.3 % as global efficiency including also geometrical efficiency.

A comparison with the *old* sample (% referred to events that pass the first cut) gives:

	OLD SAMPLE	NEW SAMPLE
2 MC assoc. tracks	87.4%	85.6%
1 MC assoc. track 1 HC with $IF = 1$	7.3%	6.1%
1 MC assoc. track 1 HC with $IF = 0$	4.6%	4.2%
1 MC assoc. track 1 HC with $IF = -1$	0.5%	3.8%

There is a difference of 3 % for the sum of the first two groups (which represents the final sample that we will keep to make the later analysis). This difference, as can be seen comparing the two above tables, doesn't come from the first cut. There is also a remarkable difference in the last group coming from the changes made in the HCAL reconstruction software in JULIA.

Finally let us stress that there are still remaining software problems in JULIA 2.22, i.e. mismatch between ITC and TPC and the problem with 'HMAD' bank.

3 Backgrounds

In the last section we have chosen a set of cuts to select muon pairs. Now we must find some additional kinematical cuts in order to eliminate contamination from another processes. We study the most important processes which may simulate $e^+e^- \to \mu^+\mu^-$. These ones are

- $e^+e^- \to \tau^+\tau^-$, mainly with one of the τ's decaying into a μ and the other one decaying into one charged prong $(e, \mu, \pi, etc.)$.
- Two photons process, $e^+e^- \to e^+e^-\mu^+\mu^-$, being the electron and positron scattered into the beam pipe.
- Cosmic rays.

3.1 Taus background

To study this background, we have used a sample of about 3000 tau events generated as follows: KORL02, GALEPH 22.0 without TPCSIM and JULIA 2.22. Let us remember that our sample of muon pairs consisted of 2993 events that were obtained using the same programs.

Since, within the Standard Model, the cross-sections of $e^+e^- \to \tau^+\tau^-$ and $e^+e^- \to \mu^+\mu^-$ are almost the same, and the branching ratio for τ decaying into a μ ($\tau^- \to \nu_\tau \overline{\nu}_\mu \mu^-$) is about 17%, we expect the background to be about 3%. That's too large, so we'll try to reduce it.

We compare distributions of significant kinematical variables in order to determine the optimal cuts to remove most of the unwanted events while keeping most of the signal. These distributions are the total charged energy, the acollinearity, the minimum charged track energy, the maximum charged track energy and the acoplanarity.

In figures 3 to 7 are shown the histograms for the five variables mentioned above. We compare the histograms obtained from taus sample with the ones corresponding to muons. To obtain all these histograms we rejected the events that don't verify, for all charged tracks, $15^0 < \theta < 165^0$, so we end up with 2896 muon pairs instead of 2993. After comparing both sets of histograms, we decide to apply the following cuts:

- Acollinearity $< 15^0$
- Total charged energy > 60 GeV
- We require that the most energetic track has at least 35 GeV

The muon sample, after the selection cuts explained in the previous section and the above kinematical cuts, is reduced to 2395 events. From the tau sample, there are 9 events that are recognized as muon pairs by our analysis program.

Finally, the efficiency for the last set of cuts is very high, $(98.5 \pm 0.3)\%$, and the global efficiency is $(80.0 \pm 0.7)\%$. The expected contamination has been reduced by an order of magnitude, $(0.3 \pm 0.1)\%$, small enough for our purposes.

3.2 Two photons background

We have generated a sample of 10^5 pure Monte-Carlo events with GGFF02. This Monte-Carlo only includes the contribution from multiperipheral diagrams, which are the dominant ones for low Q^2 (the invariant mass of the two photons) configurations; and this contribution is computed with the equivalent photon approximation. The cross–section obtained if no cut is made in the range of Q^2 ($2m_\mu < M_{\gamma\gamma} < \sqrt{s}$) is, for $\Theta_{\mu^\pm} \in [15^0, 165^0]$, $\sigma = (42.6 \pm 0.1)$ nb. We confirmed this with DIGQ01, which includes all the tree level QED diagrams, obtaining good agreement : $\sigma = (43.3 \pm 0.8)$ nb.

In figure 8 are shown the histograms corresponding to the total charged energy, maximum charged track energy and acollinearity for the two muons using DIGQ01. If we apply the cuts chosen for the τ background to this sample, no events survive. However, since the cross-section is so large, this doesn't mean that there is no background at all. We have to look at the range of Q^2 which can produce muons with enough energy to pass our cuts.

Now we compute the cross-section for high Q^2, with $25\ GeV < M_{\gamma\gamma} < \sqrt{s}$, $\Theta_{\mu^\pm} \in [15^0, 165^0]$. We obtain $\sigma = (0.13 \pm 0.01)$ pb using GGFF02 and $\sigma = (1.51 \pm 0.01)$ pb with DIGQ01. There is a large difference in the results. Since DIGQ01 is supposed to be more accurate, we conclude that GGFF02 is not reliable enough for this high Q^2 calculation. We have redone the calculation using DIGZ01, which includes all the electroweak tree level diagrams leading to an $e^+e^-\mu^+\mu^-$ final state and have found that the inclusion of the Z^0 diagrams doesn't change very much the results.

We show in fig. 9 the distributions for this configuration obtained with DIGQ01. We see a small peak in the high energy zone. This peak is explained by the diagrams called 'annihilation' diagrams. In those diagrams the incoming electron and positron annihilate to a photon giving another e^+e^- pair but one of them radiates a virtual photon in the initial state which converts into a muon pair. If these muons have a large energy, the Q^2 of the annihilation photon can be very small and then its propagator ($1/Q^2$) can be very large giving a huge cross–section. This effect doesn't show up in the distributions obtained with GGFF02, since this kind of diagrams are not included in this calculation.

Using the same cuts as before with the DIGQ01 sample, we find 339 events passing the cuts from a total sample of 9372. This means that we expect a background of around 0.05 pb.

If we compare this numbers with the signal cross–section at the peak ($\simeq 1$ nb), we can conclude that the contamination will be less than 5 parts in 10^5, therefore completely negligible. In moving away from the Z^0 pole, say three Z^0 width away, the signal cross-section drops by a factor of 30 whilst the $\gamma\gamma$ cross–section varies slowly, so that the contamination would be around 2 per mil. Probably this is too small a background to need a subtraction.

3.3 Cosmic ray background

From H. Wachsmuth (ref.[1]) we find that the total cosmic ray flux from the upper hemisphere per horizontal cm^2 on top of ALEPH is roughly 4.3 $cm^{-2}day^{-1}$.

Considering a vertex area upper bound of about 10 cm^2 and a beam crossing gate of 100 ns, we find a cosmics rate of about 0.2 events/day, considering that the bunches cross every 22.2 μs. That is, 20 events/year if we take a *running year* of 100 days.

Requiring also a minimum energy per track (same cut as defined in a previous section) we get ~10 events/year. This represents the following contaminations depending on the beam energy and the LEP luminosity achieved (we will consider a running time of one year): at the Z^0 peak with a luminosity of $3 \cdot 10^{30}\ cm^{-2}s^{-1}$ one expects 10^6 Z^0's or, equivalently, $3 \cdot 10^4$ muon pairs, that is, a contamination of $\approx 0.03\%$; at the Z^0 peak with a luminosity of $3 \cdot 10^{29}\ cm^{-2}s^{-1}$ one expects 10^5 Z^0's, or $3 \cdot 10^3$ muon pairs, i.e., a contamination of $\approx 0.3\%$; and finally three Z^0 widths away from the peak with a luminosity of $3 \cdot 10^{30}\ cm^{-2}s^{-1}$ one expects $3 \cdot 10^4$ Z^0's, equivalent to 10^3 muon pairs, which represents a contamination of $\approx 1\%$.

In fact, it is planned to measure this background taking cosmics ray data in intervals of time out of the beam crossing gate. This will give us an exact measurement of this type of events for a later subtraction in the real data.

In figures 10 and 11 are plotted two different cosmic ray events reconstructed by JULIA, one of which can simulate a muon pair event while the other cannot.

4 Determining $\sin^2\theta_W$

Once we have selected our μ pair events, we want to extract the value of $\sin^2\theta_W$ from the angular distribution. It is clear that, since there are no analytical formulae for the distribution including radiative corrections and one has to take into account the detector effects, one cannot compare directly theory with experimental results.

One of the standard approaches is the one called 'correcting data'. It consists on computing the effects due to the detector (and sometimes also the ones due to radiative corrections) using Monte Carlo, and then correct the data and compare the corrected data with theory with radiative corrections (or without them if this effect has been applied to the data). These detector effects are computed as factors multiplying the contents of a bin in a given distribution and are then applied in the same way : the same factor multiplies all the events in a bin.

This method presents in our understanding two drawbacks. If the correction factor depends in the particular choice of the input parameters of the generator which has been used in the Monte Carlo study, a bias will likely be introduced in the measure. Furthermore, it is not each event which is corrected for the detector effects but the bin as a whole with a single factor. Furthermore, the bin cannot be too small in order to avoid low statistics (for instance, in the first runs).

The alternative method would consist in having a number of samples simulated through GALEPH and JULIA, each one corresponding to a different value of $\sin^2\theta_W$ and compare them directly (since they are comparable) to the real data. Of course, this would pose a big problem in the consumption of CPU time and in disk space needs.

Since we don't need to have a lot of samples but just a lot of distributions of $\cos\theta_{\mu^+}$ each one obtained with a different value of $\sin^2\theta_W$, we can use the method described in ref.[2]

In short, it consists in having just one Monte Carlo sample of *multiweighted* events, each weight being computed in such a way that the weighted distribution obtained with those events reproduce the theoretical distribution for one given value of $\sin^2\theta_W$. Then, we pass the events through GALEPH and JULIA and we end up with a single sample of events from which one can extract a set of distributions of $\cos\theta_{\mu^+}$ and find the one which fits better the distribution of the real data.

We have generated a sample of 3000 unweighted events to simulate the real data. We have used KORL02 with input parameters $M_Z = 92\,GeV$, $M_{top} = 100\,GeV$ and $M_{Higgs} = 100\,GeV$ which give $\sin^2\theta_W = 0.225$ and GALEPH 22.0 (no TPCSIM) and JULIA 2.22. The Monte Carlo sample needed for the analysis consists on 3000 events generated with KORL02 with $M_Z = 92\ GeV$, $M_{top} = 150\ GeV$ and $M_{Higgs} = 100\ GeV$ ($\sin^2\theta_W = 0.220$) and the same versions of GALEPH and JULIA. Of course, there is no need for the sample being exactly as large as the 'data' one. Actually, it should be as large as possible. The choice of 3000 events for this Monte-Carlo sample is just due to our limitations in CPU time and disk space. We plan to increase this number in the near future in order to reduce the error on the predicted numbers.

We apply to those events the cuts explain in section 2 : we select the events with only two charged tracks and with one muon identified in the muon chambers and the other one either in the muon chambers or in the HCAL. Furthermore we require the event to fulfill the following conditions :

- μ^+ and μ^- angles between 15^o and 165^o.
- Total charge of the event = 0.
- Acollinearity $< 15^o$.
- Sum of the energy of the muons $> 0.5\sqrt{s}$.

The first one defines our acceptance while with the second one we avoid events with misidentified charges. We have seen that double misidentification of charge is completely negligible. The last two would reduce the τ and $\gamma\gamma$ background. The total efficiency (including geometrical acceptance) is $(79.3 \pm 0.7)\%$.

Each event in this sample has 20 weights, corresponding to values of $\sin^2\theta_W$ ranging from 0.200 to 0.238. Since $\sin^2\theta_W$ is determined internally by the Monte Carlo, the only way of varying its value was by changing the values of M_{top} and M_{Higgs}.

Once we have these two samples, we can compare the distributions of $\cos\theta_{\mu^+}$ for the 20 weights with that of the 'real data' sample and find the best fit using, for instance, a χ^2 test. We have done it with purely Monte Carlo events (no detector simulation) and found

$$\sin^2\theta_W = 0.232 \pm 0.011 \quad (\textit{True value} = 0.225) \tag{1}$$

with $\chi^2/d.o.f. = 19.1/50$. With the fully simulated events, we can redo the fitting, and we find (fig. 12)

$$\sin^2\theta_W = 0.236 \pm 0.013 \quad (\textit{True value} = 0.225) \tag{2}$$

with $\chi^2/d.o.f. = 19.6/50$.

We have repeated the fit using Maximum Likelihood and Kolmogorov tests and the results are essentially the same. As can be seen, the mean value lies close to an edge of our range in $\sin^2\theta_W$, thus making it impossible for us to know the plus error. We have just assumed symmetrical errors. The central value lies in the one standard deviation range.

5 Conclusions

A classification of muon pair candidate events is given using the ALEPH detector simulation and reconstruction programs. We study the reasons why an event can pass or not our defined cuts. Using the obtained $\mu^+\mu^-$ sample a method for fitting the $\sin^2\theta_W$ parameter is also given. Our result turns out to be 0.236 ± 0.013 for a given *true value* of 0.225 using different statistical tests.

Acknowledgements

We thank S. Orteu for many useful suggestions and for the technical help with the ALEPH software and also for providing us with the taus sample; also to H. Wachsmuth and A. Putzer for their help on the understanding of the cosmic ray background, P. Colas for useful comments on the $\gamma\gamma$ background and J. Morfin for careful reading of the manuscript.

Figure captions

1. Event with more than two TPC reconstructed tracks. In 1.a the hits are shown, in 1.b are plotted the tracks reconstructed by JULIA.
2. Event with more than two ITC or TPC reconstructed tracks. In 1.a we only see the hits, in 1.b are plotted the tracks reconstructed by JULIA.
3. Total charged energy (GeV)
    3.a for the μ's sample.
    3.b for the τ's sample.
4. Acollinearity (deg)
    4.a for the μ's sample.
    4.b for the τ's sample.
5. Maximum charged track energy (GeV), solid line for the μ's sample, and dashed line for the τ's sample.
6. Minimum charged track energy (GeV), solid line for the μ's sample, and dashed line for the τ's sample.
7. Acoplanarity (deg)
    7.a for the μ's sample.
    7.b for the τ's sample.
8. Distributions for the two muons using DIGQ01 without any Q^2 cut.
    8.a Total charged energy (GeV).
    8.b Maximum charged track energy (GeV).
    8.c Acollinearity (deg).
9. Distributions for the two muons using DIGQ01 for high Q^2.
    9.a Total charged energy (GeV).
    9.b Maximum charged track energy (GeV).
    9.c Acollinearity (deg).
10. Reconstructed cosmic ray event which would not pass our cut.
11. Reconstructed cosmic ray event which would pass our cut.
12. Distribution of $\cos\theta_{\mu^+}$. Solid line for the 'real data sample', and dashed line for the best fit.

References

1. H. Wachsmuth; Aleph 87-64, Note 87-12 (1987)
2. R. Miquel, S. Orteu; Aleph 89-63, Physic 89-27 (1989)

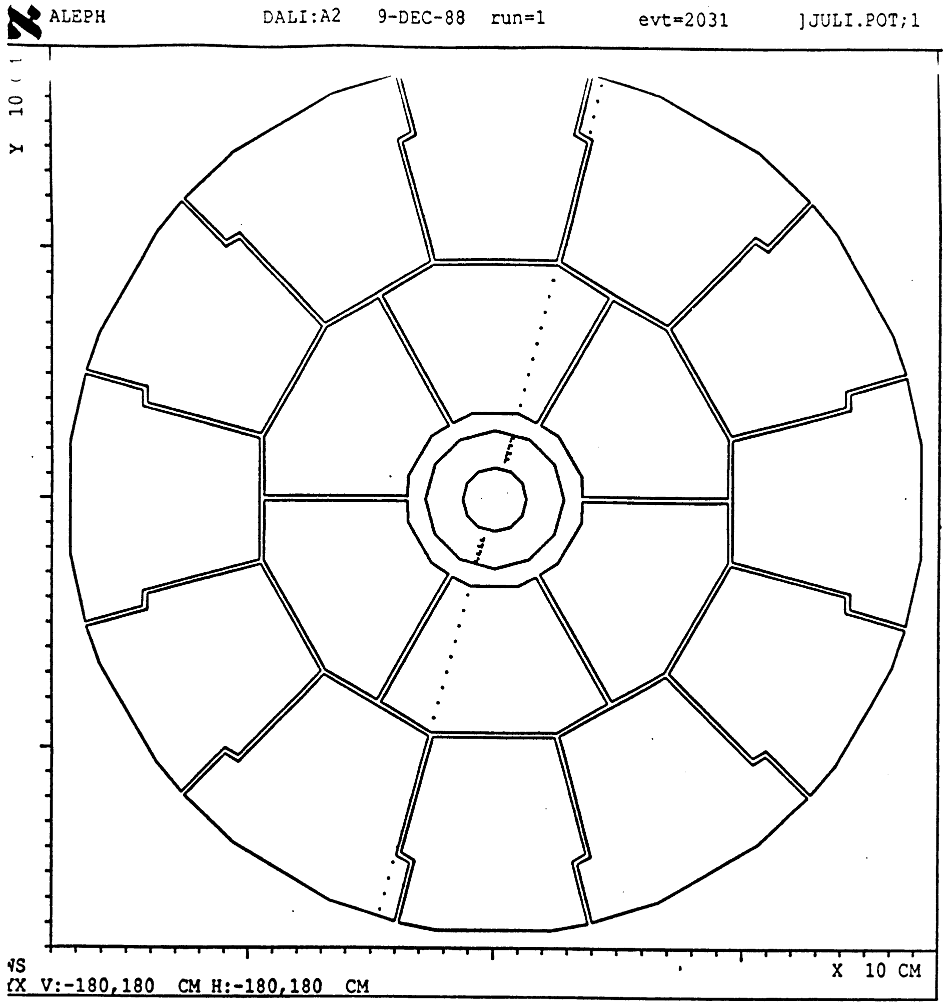
ALEPH
DALI:A2 9-DEC-88 run=1
evt=2031
]JULI.POT;1
Y 10
X 10 CM
V:-180,180 CM H:-180,180 CM

Fig. 1.a

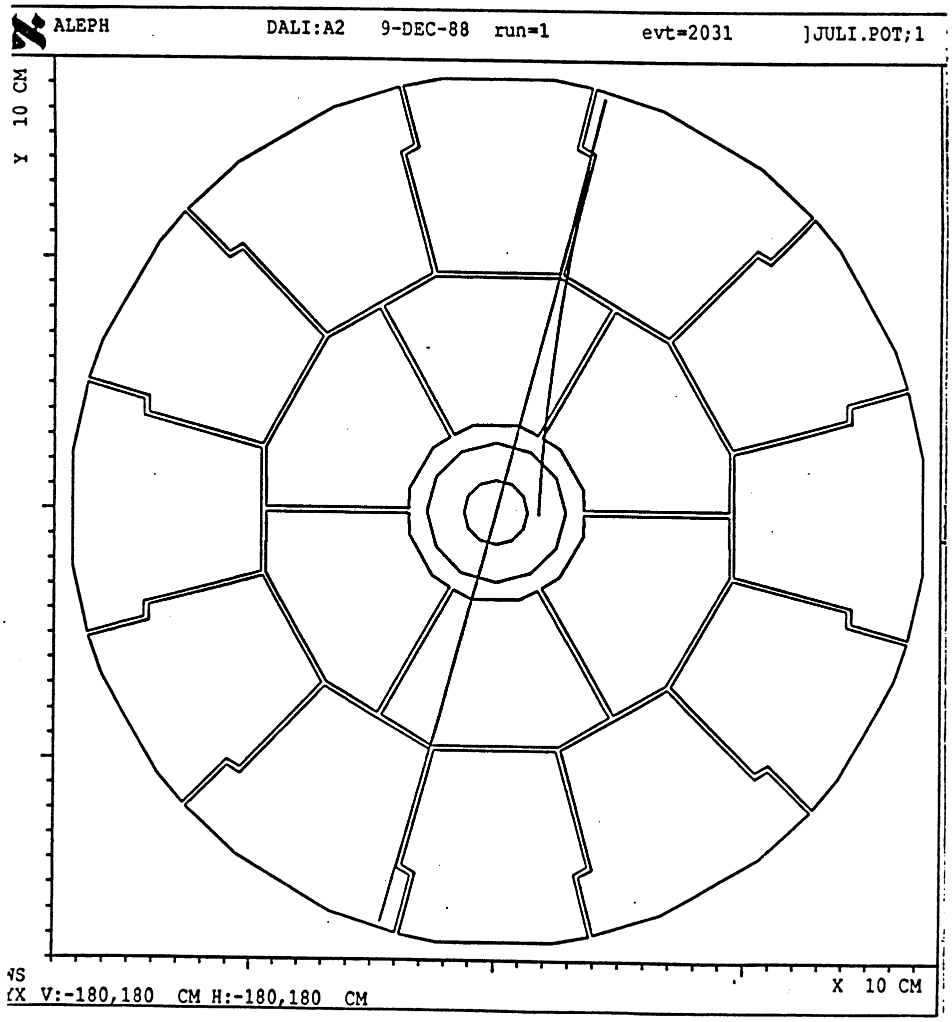
ALEPH
DALI:A2 9-DEC-88 run=1
evt=2031
]JULI.POT;1
Y 10 CM
X 10 CM
V:-180,180 CM H:-180,180 CM

Fig. 1.b

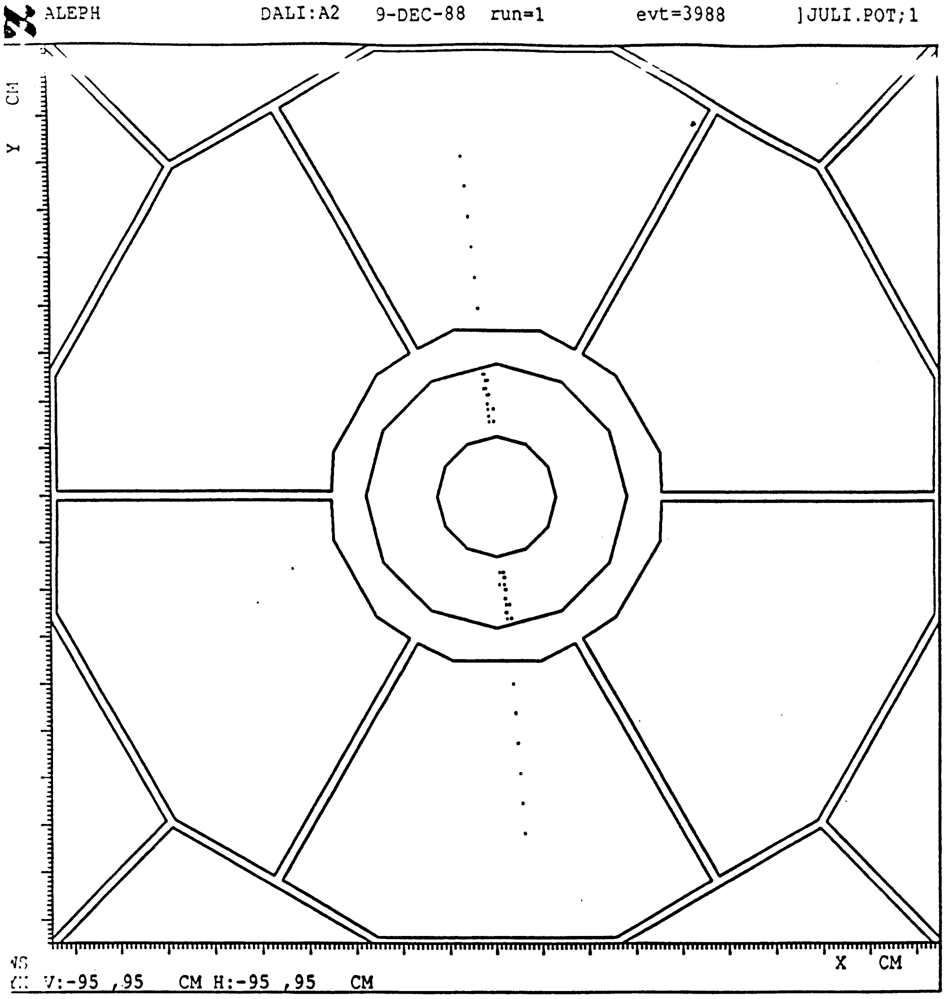
ALEPH
DALI:A2
9-DEC-88
run=1
evt=3988
]JULI.POT;1
Y CM
X CM
V:-95 ,95 CM H:-95 ,95 CM

Fig. 2.a

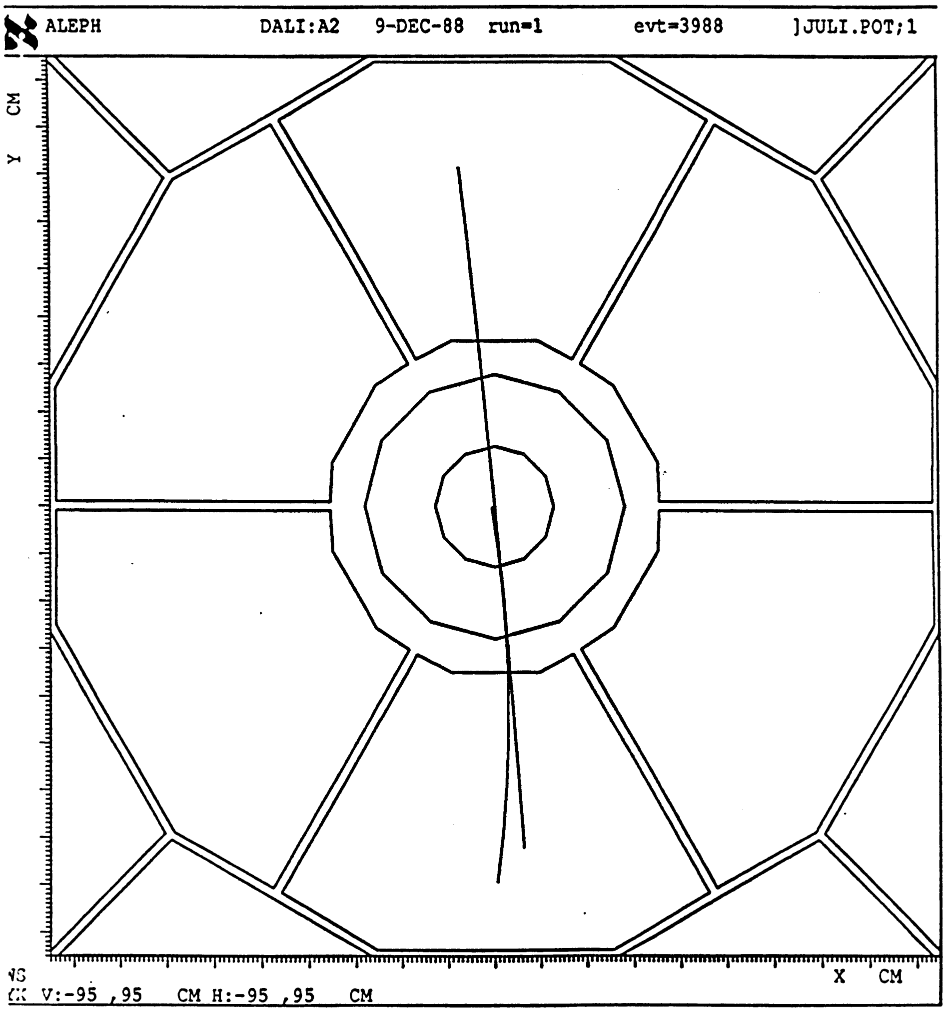
ALEPH
DALI:A2
9-DEC-88
run=1
evt=3988
]JULI.POT;1
Y CM
X CM
V:-95 ,95 CM H:-95 ,95 CM

Fig. 2.b

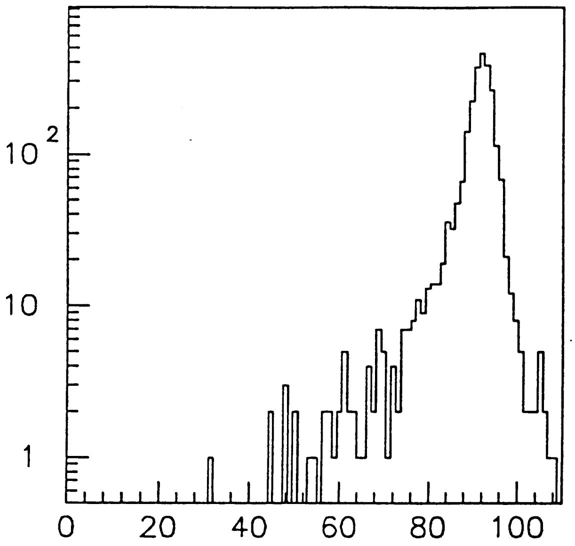

Fig. 3.a

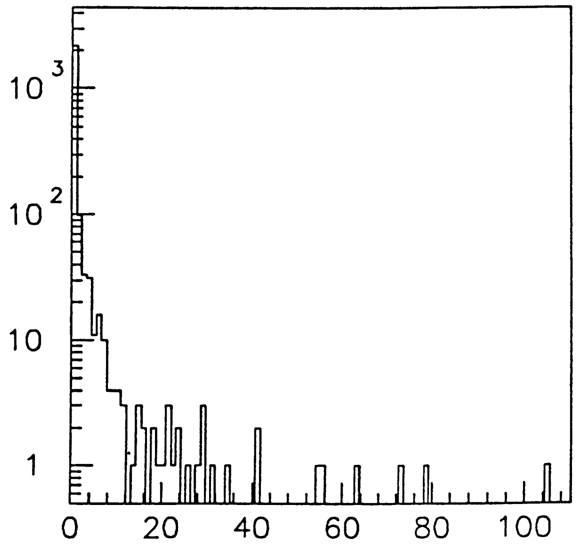

Fig. 4.a

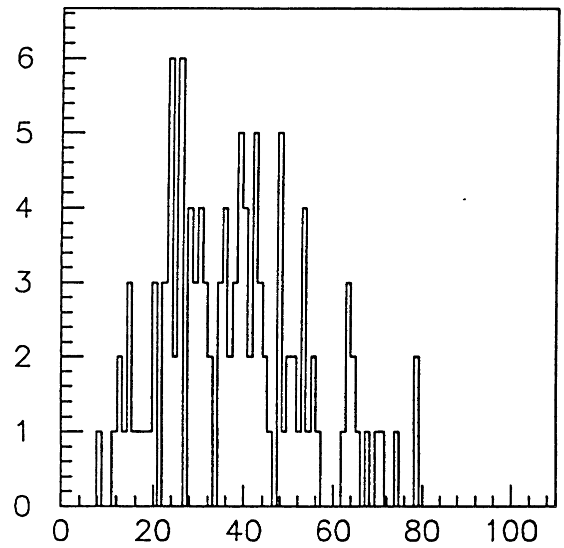

Fig. 3.b

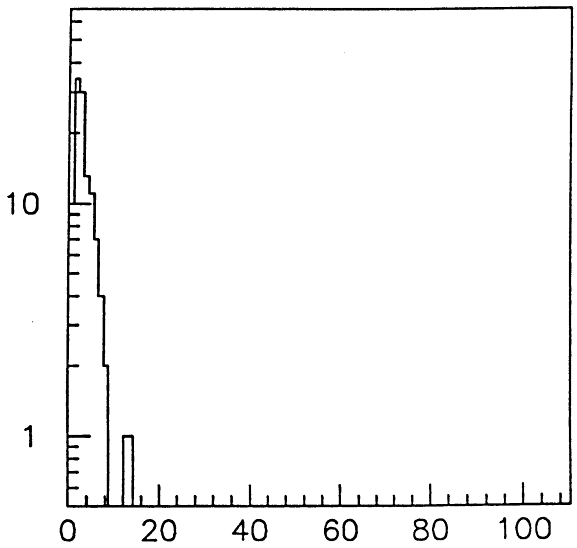

Fig. 4.b

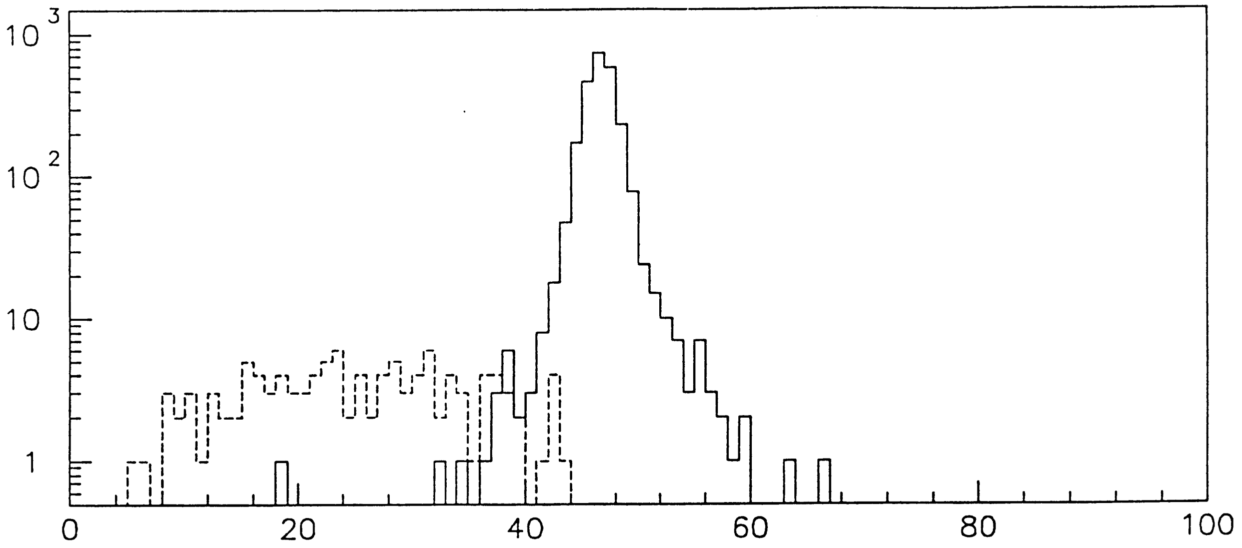

Fig. 5

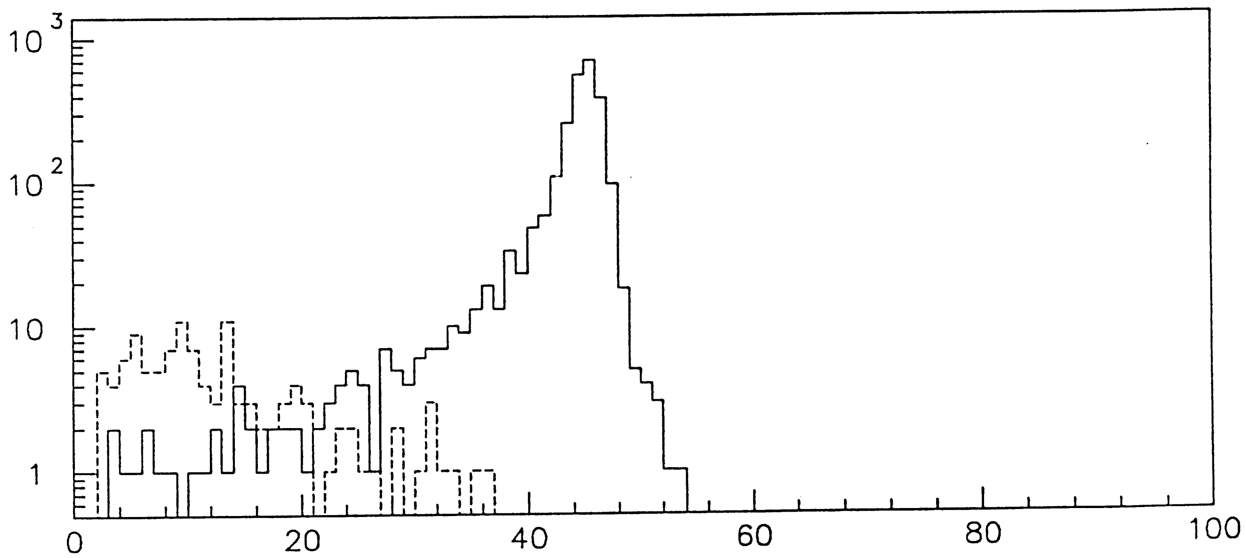

Fig. 6

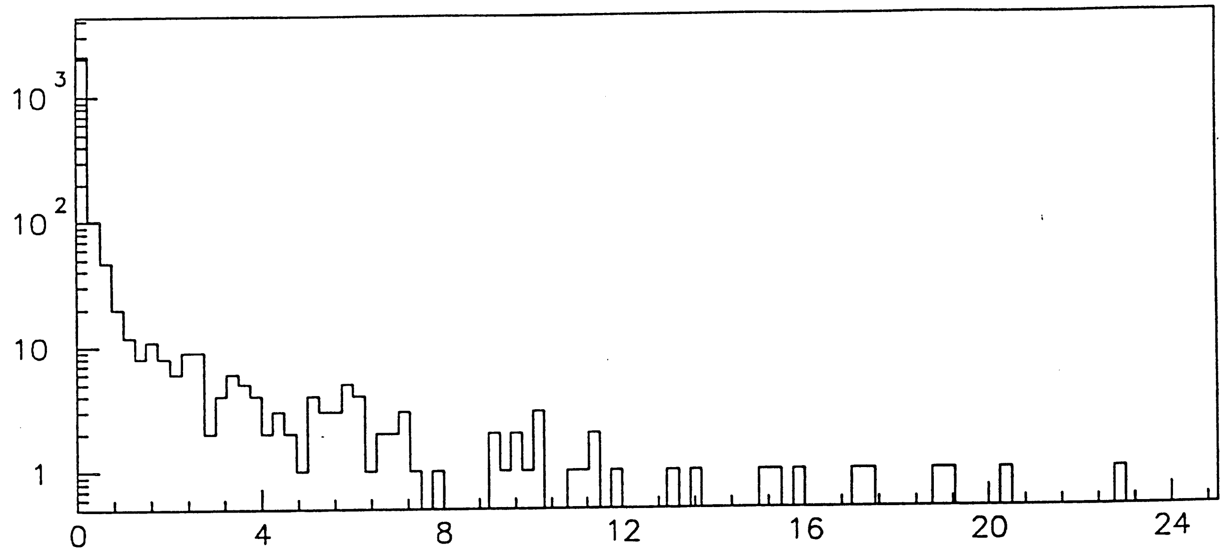

Fig. 7.a

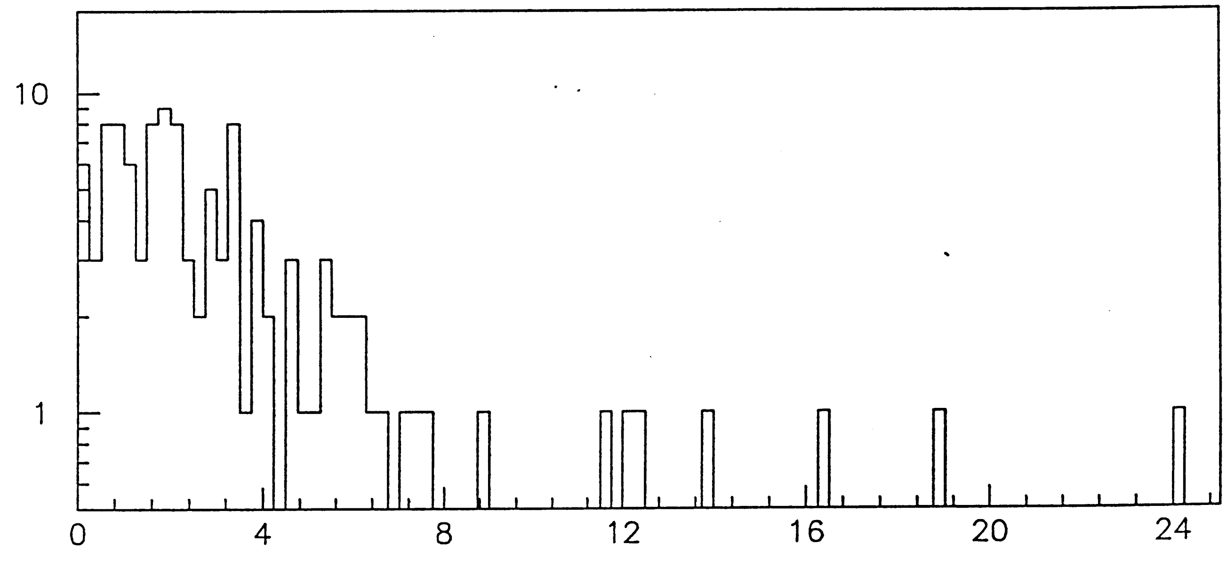

Fig. 7.b

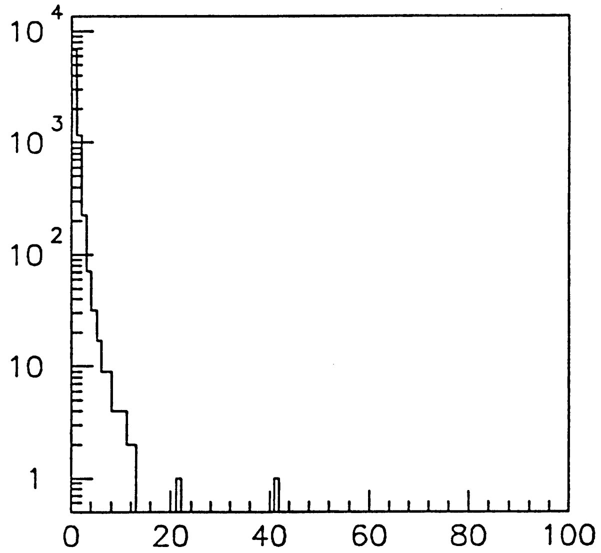

Fig. 8.a

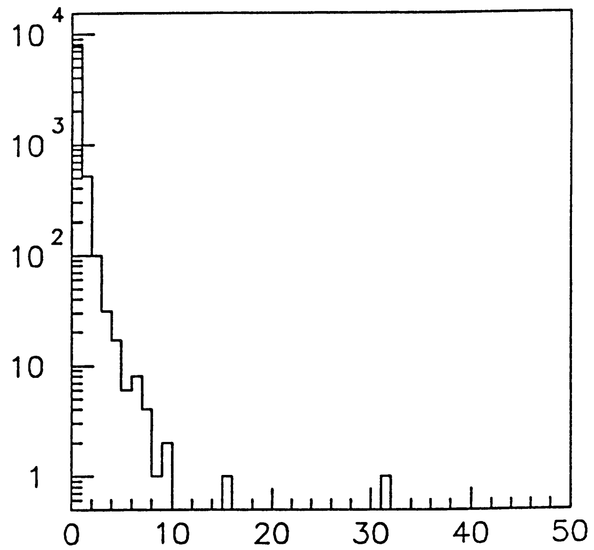

Fig. 8.c

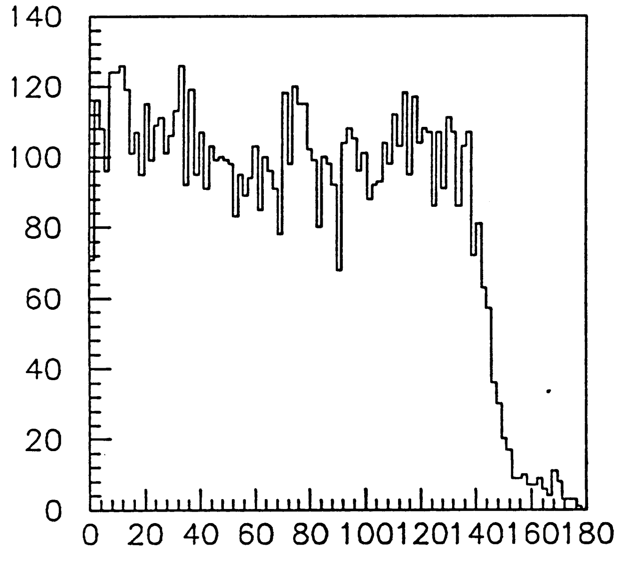

Fig. 8.b

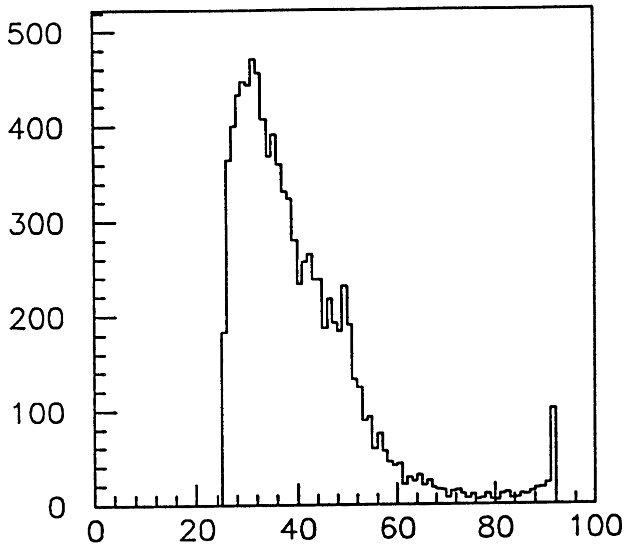

Fig. 9.a

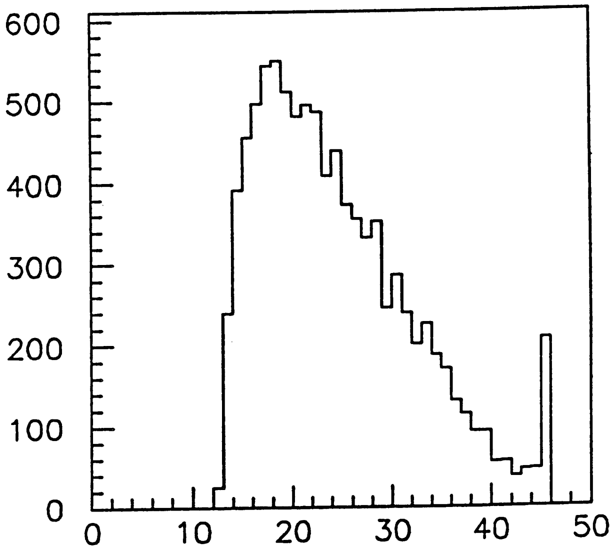

Fig. 9.c

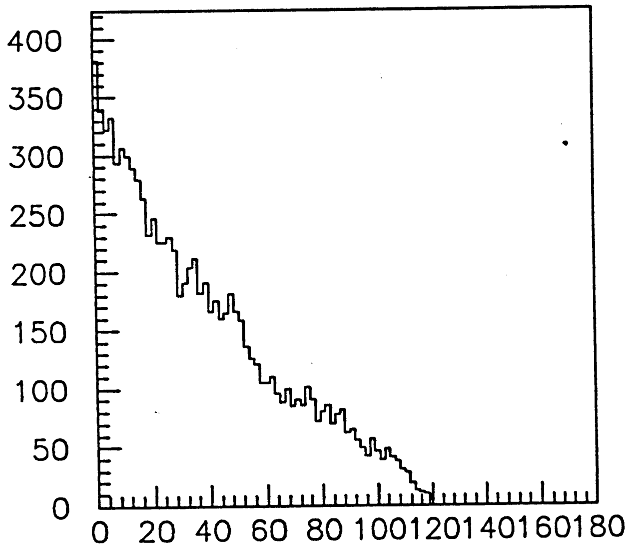

Fig. 9.b

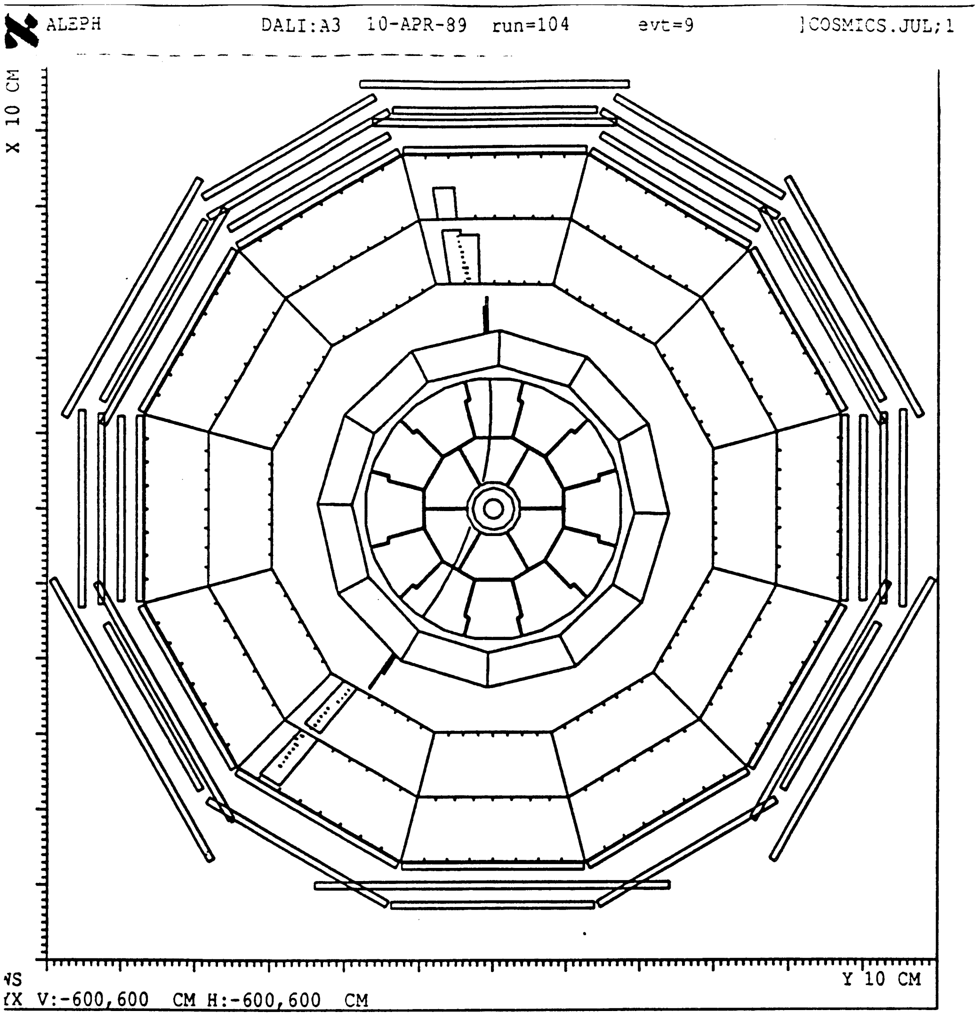
ALEPH
DALI:A3 10-APR-89 run=104 evt=9
]COSMICS.JUL;1
X 10 CM
Y 10 CM
V:-600,600 CM H:-600,600 CM

Fig. 10

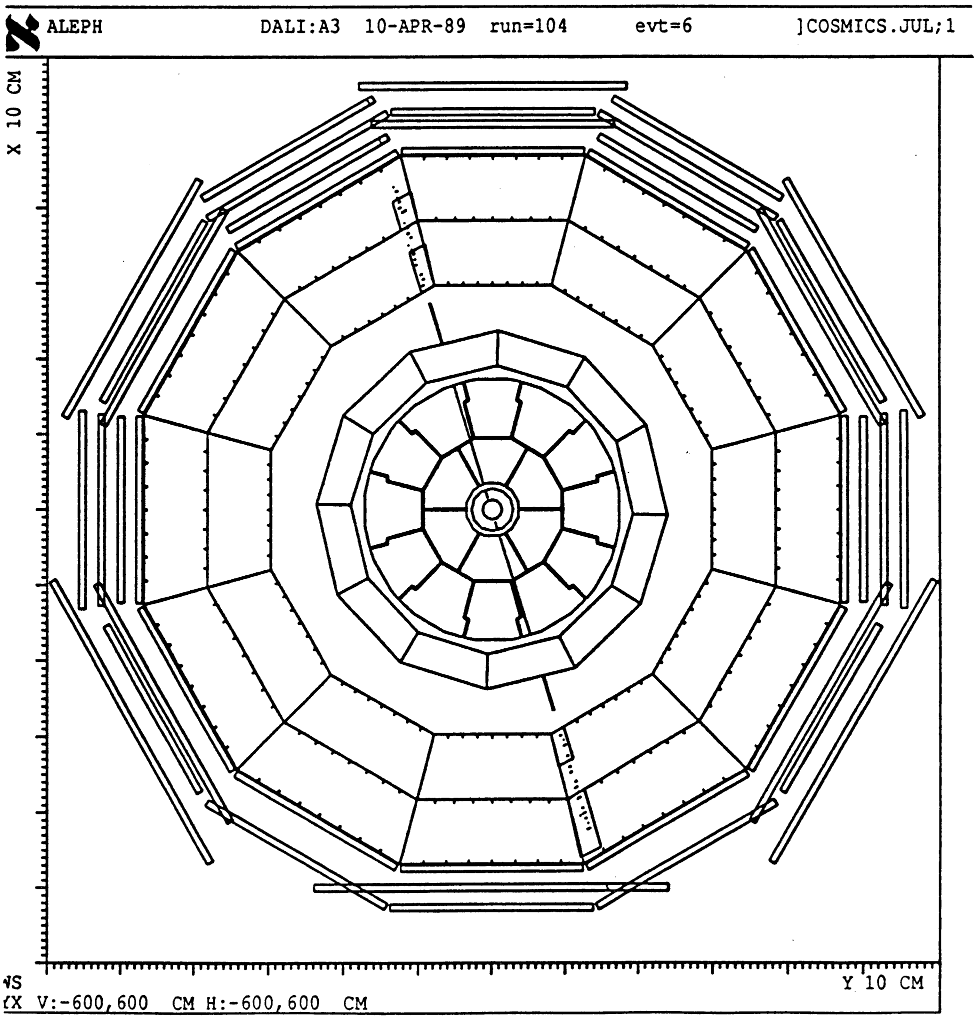
ALEPH
DALI:A3 10-APR-89 run=104 evt=6
]COSMICS.JUL;1
X 10 CM
Y 10 CM
V:-600,600 CM H:-600,600 CM

Fig. 11

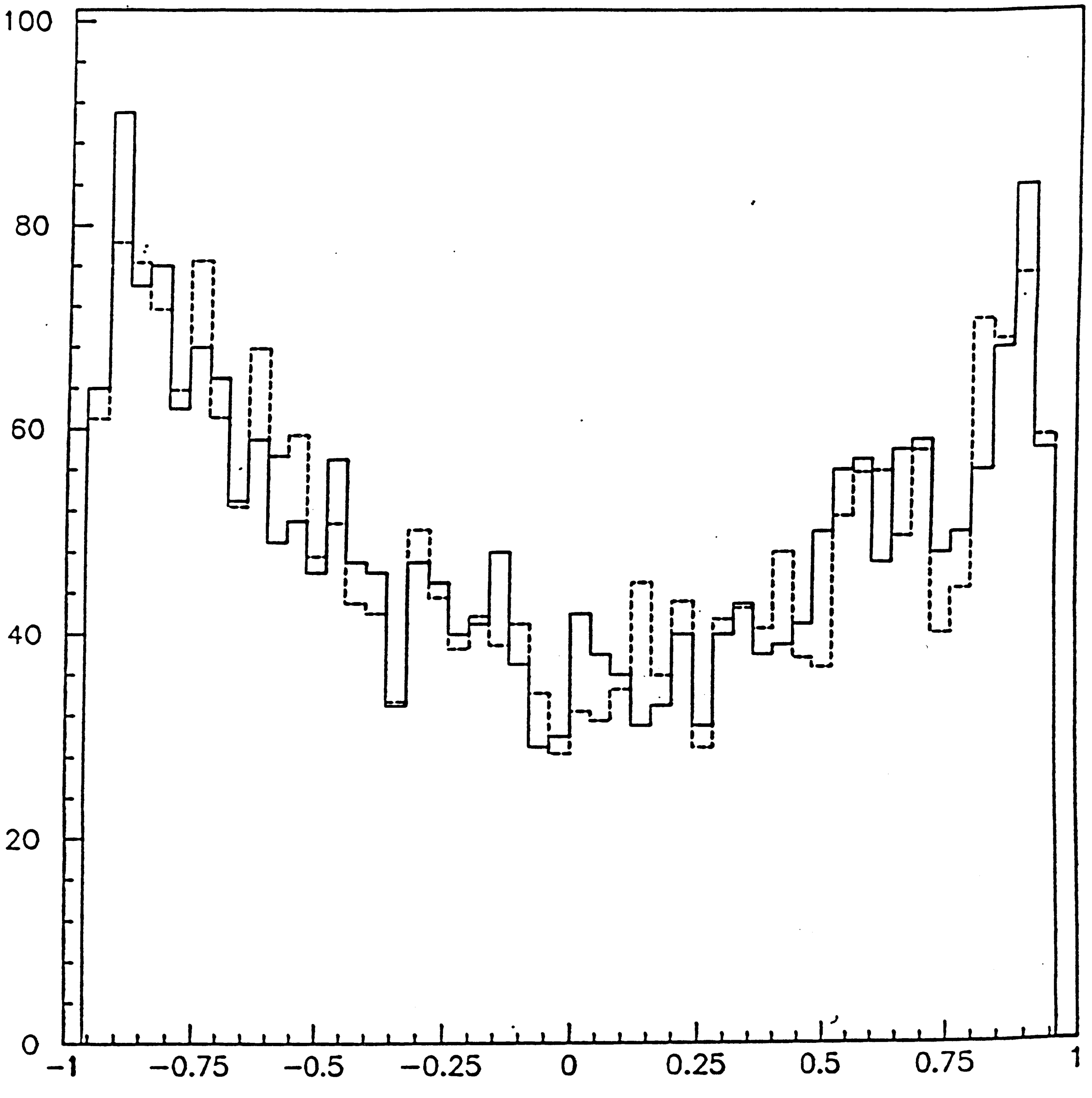

Fig. 12