Determination of background from β-n coincidences

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Introduction

The idea of using β - neutron coincidences to determine the exact neutron background in the SNO detector has been around for a long time and has been studied in some detail by both the author and by Mike Lowry. Nothing was ever put in print though. In the following I will present a consistent analysis of both signal and potential backgrounds using all available information. Throughout this document 'White Book' contamination levels have been assumed (see table 1).

The present thinking is to identify β - neutron coincidences using a 'look-back' scheme. Data from the front-end electronics is buffered for a certain time (3 to 4 neutron capture times) before being discarded except when a 'neutron' event occurs. In that case everything in this time period is saved. Since we have no way of distinguishing a neutron from say a CC event we would be triggering on all signals exceeding a certain threshold. This threshold would be a compromise between noise and efficiency but given our assumed background it is easy to establish to a good approximation where it would be. Figure one shows the total energy spectrum for events reconstructed inside the D_2O (one detector year with NaCl added). Figure 2 shows just the events due to neutron capture. A threshold of 35 to 40 hits is reasonable in that about 90% of the NC events would result in a trigger and the total number of events above this threshold is in the vicinity of 100 per day. Of course this depends somewhat on what rate we assume for the CC process. Figure 1 is done for 1/3 SSM ν_e and 1 SSM ν_x.

With NaCl added to the D_2O, the average capture time is around 4 ms for a 12 m diameter vessel so that a 16 ms look-back and 100 triggers per day leads to a total detector live-time of some 600 seconds per year. Any other event happening in this time interval is a potential background.

Simulation of coincidences

The standard EGS4 code was modified to include photodisintegration in the Compton scattering section and one years worth of 2.614 MeV and 2.445 MeV γ-rays were started uniformly throughout the D_2O and Acrylic. The contribution from the H_2O and the PMTs was ignored even though they produce a small number of neutrons. All photodisintegration events were written to disk on an event by event basis. The standard neutron code was then used to track the neutrons and the Queen's Monte Carlo code simulated the Cl captures. Finally, the β-γ Monte Carlo code followed the rest of the ^{208}Tl or ^{214}Bi decay with subsequent recoding of the events. The end result was two event by event files, one for the neutron captures on Chlorine and one for the β's. Table 2 contains a summary of the total event numbers involved.

Of the 816 captures from ^{208}Tl γ's in the D_2O a total of 736 reconstruct with 35 or more hits inside $r = 600$ cm and of the 1008 β's where the corresponding γ led to a photodisintegration a total of 168 reconstruct with 5 or more hits inside the active volume (defined as $r \leq 867$ cm). At or above 8 hits the equivalent number is 50. However, only some of these are associated with Chlorine captures. If we demand $N_{hit} \geq 35$ and $r \leq 600$ for the Cl captures and $N_{hit} \geq 5$ and $r \leq 867$ for the β's then there are 155 events left. Figure 3 shows the distribution of the distance between the two reconstructed vertices. A total of 77 events are within 200 cm. Raising the β - threshold to 8 hits leaves 48 coincidences with 42 having a distance less than 200 cm (figure 4).

For ^{208}Tl events originating from the Acrylic there are 611 Cl capture events ($N_{hit} \geq 35$, $r \leq 600$) and 62 β's above $N_{hit} \geq 5$. The distance distribution is histogrammed in figure 5. It is somewhat more spread out than the one for the D_2O and only 35 β's reconstruct within 200 cm of the corresponding Cl vertex. If we demand eight or more hits for the β this number drops to 8 . Table 3 summarizes the results.

In a real experiment we will of course just measure the total number of of coincidences from the D_2O and Acrylic. By gating on the reconstructed radius of the neutron capture event we can separate them. Figures 6 and 7 show the D_2O and the Acrylic events respectively. Half the Acrylic events are outside $r = 560$ cm and 90% are outside 500. Of the 70 coincidences originating from the D_2O with β - $N_{hit} \geq 8$ a total of 43 are inside $r = 500$ cm.

Simulation of backgrounds

The background in this method of determining the number of neutrons comes from random events in the 16 ms 'look-back' window. Any other event whether real or not which gives a reconstructed vertex near a 'trigger event' within the 16 ms window is a potential candidate for a β - neutron event. Using the rate mentioned above of about 100 events per day we arrive at approximately 600 seconds of detector livetime per year. In this short time we do not have to worry about solar neutrino events or any high energy γ-rays from the PSUP and/or the cavity. This leaves the isotopes ^{208}Tl, ^{214}Bi, ^{228}Ac, ^{212}Bi,^{234}Pa and ^{40}K in the 'interior' parts of the detector. For the H_2O, Acrylic and D_2O the numbers are so low that in order to get reasonable statistics a factor of a hundred more data was simulated for the Th/U chains and the final results were scaled appropriately. The ^{40}K was done for the full time. For the PMTs the full 600 seconds was simulated for all isotopes. The Th/U chains account for some 1.2×10^7 events and the 0.5 g Potassium in each tube contributes another 8.8×10^7 events. On top of that there is the 1 kHz electronic noise per tube. At very low N_{hit} there is a finite chance that say 5 tubes firing within a 100 ns interval will produce a vertex somewhere in the detector. In the 600 seconds there will be some 4 ×

10^8 occurrences with 4 or more tubes in the 100 ns trigger interval. A total of 10^7 events were simulated and the results were scaled up.

Each of the background data files were scanned and events within 200 cm of a pre-determined (random) set of 10,000 vertices in the D_2O were histogrammed. The average number of coincidences in the 600 seconds interval is listed in table 4 as function of N_{hit}. Since the backgrounds are extracted with the same cuts as the real β - neutron events and for the same time they can be compared directly. Note that the background is averaged over many trigger vertices in the D_2O. This is to remove any systematic effects due to the coupling between reconstructed radius and N_{hit} and volume effects. The real problem is the rapid rise in the electronic component at small N_{hit}. At 5 hits we would see an average of just over 3 'events' per neutron trigger in the 16 ms.

Conclusion

From table 5 it would appear that it is possible to measure the *total* number of neutrons from all internal detector components using the coincidence method provided we can record and reconstruct the β's above about 8 hits. We would see 105 coincidences per year and a total background of 1,193. This background can be determined by measuring 'out of time' and the 1 σ uncertainty would be 35. The components in table 4 can be grouped according to whether they vary with time or not. The PMT radioactivity will be constant but the electronic noise will likely decrease with time. The D_2O radioactivity will no doubt change and furthermore the ^{40}K will vary independent of the Th/U. At 'White Book' levels the Th/U in the D_2O is not a problem and there is a possibility that improved fitting techniques will get rid of at least part of the events from the PMTs. This could leave the ^{40}K from the D_2O as the major source of background. These events cannot be removed by clever fitters since they are real. The only way to remove them is by reducing the Potassium to 1 ppm or lower in the salt .

The present analysis was done with a 'neutron' trigger threshold of 35 hits. Since the signal to noise is poor it is worthwhile to investigate what the effect of raising the threshold to say 50 hits would be. The backgrounds are easy to deal with since they simply scale with the number of triggers which

	Mass(tonnes)	Th(g/g)	U(g/g)	K(g/g)
D_2O	1000	11×10^{-15}	11×10^{-15}	2.5×10^{-8}
Acrylic	30.0	1.9×10^{-12}	3.6×10^{-12} -	
H_2O	1667.7	22×10^{-15}	15×10^{-15} -	
PMT	7.5	0.1×10^{-6}	0.1×10^{-6}	6.67×10^{-4}

Table 1: Masses and levels of ^{232}Th, ^{238}U and nat. K in various detector components. (Note that the Potassium level is equivalent to 10 ppm in the NaCl)

Source	Region	Decays/year	$\gamma + D \rightarrow n + p$	Cl captures
^{208}Tl	D_2O	508,848	1008	816
^{214}Bi	D_2O	4,255,199	100	83
^{208}Tl	Acrylic	2,636,758	1876	794
^{214}Bi	Acrylic	41,778,328	320	141

Table 2: Backgrounds per year

drop from about 100 per day to 36 per day. Thus the background at 8 hits go down to 423 per year instead of 1193.

The signal goes from a total of 105 to 68 so there is virtually no change in the 1 σ to signal ratio.

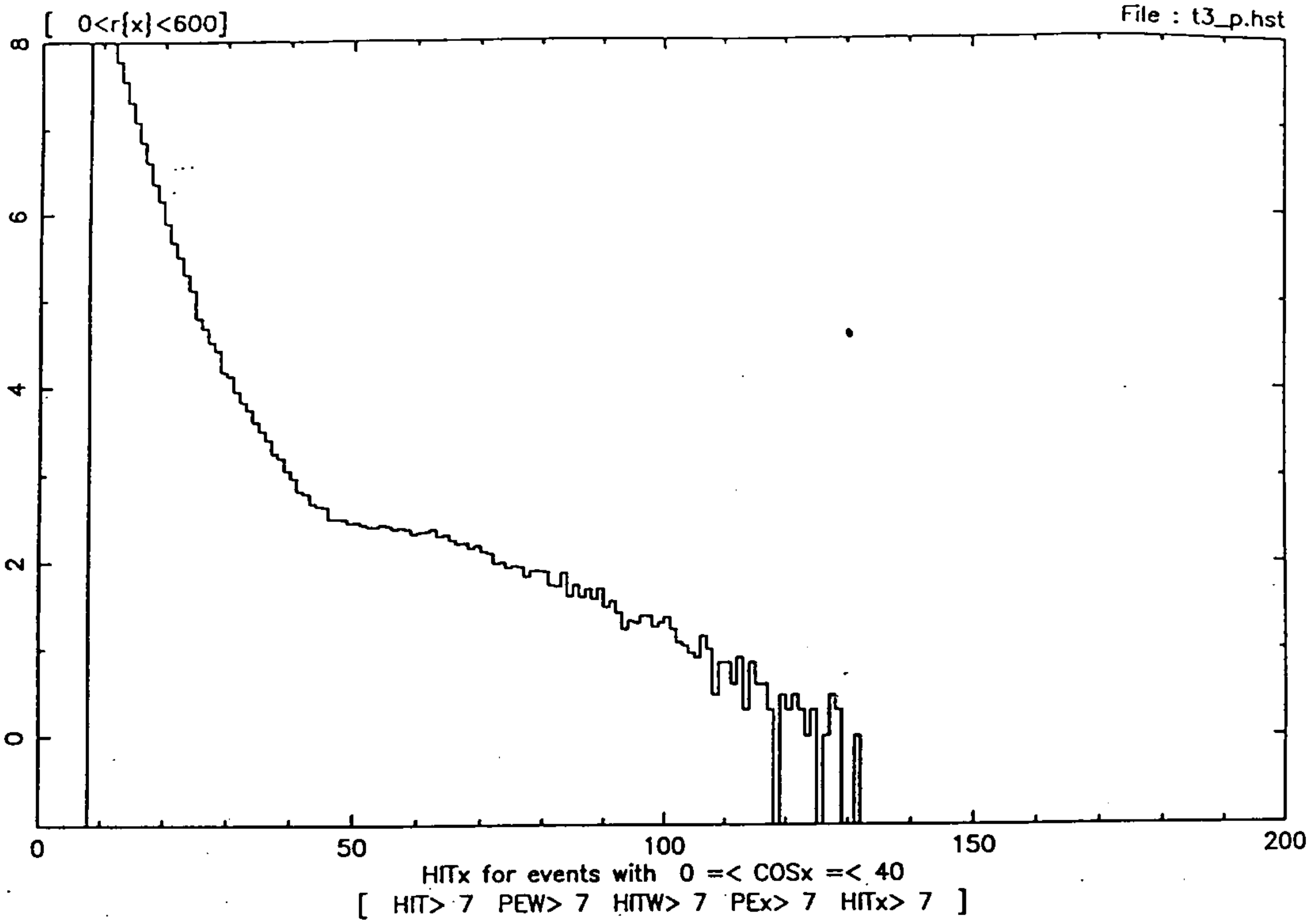
Source	Region	Cl captures	β-n coincidences	
			$N_\beta \geq 5$	$N_\beta \geq 8$
^{208}Tl	D_2O	816	77	42
^{214}Bi	D_2O	83	39	28
^{208}Tl	Acrylic	794	35	8
^{214}Bi	Acrylic	141	33	27
Total		1834	184	105

Table 3: Coincidences per year

Source	$N_{hit} \geq 5$	$N_{hit} \geq 6$	$N_{hit} \geq 7$	$N_{hit} \geq 8$
D_2O,Acr & H_2O[Th/U]	15.5	13.6	11.7	10.0
D_2O[^{40}K]	1,214	855	561	351
PMT[Th/U]	3,501	2,200	1,347	813
PMT[^{40}K]	241	94	37.7	13.6
Electronic	114,941	7,167	267	5.3
Total	119,913	10,330	2,224	1,193

Table 4: Randoms per year

Fig1.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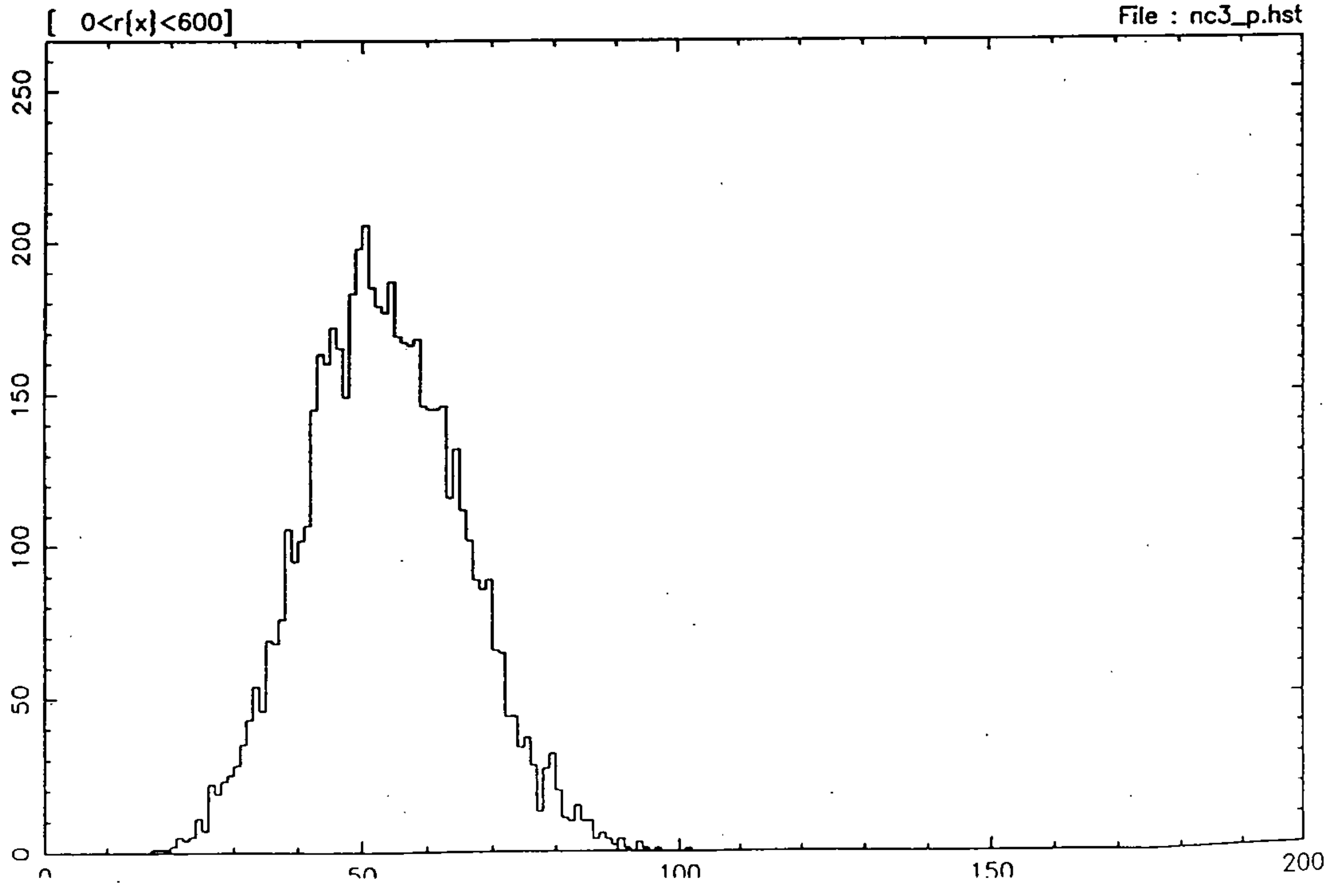
8
6
4
2
0
0
50
100
150
200
HITx for events with 0 =< COSx =< 40
[HIT> 7 PEW> 7 HITW> 7 PEx> 7 HITx> 7]

Fig 2.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150
100
50
0
0
50
100
150
200

Fig. 3

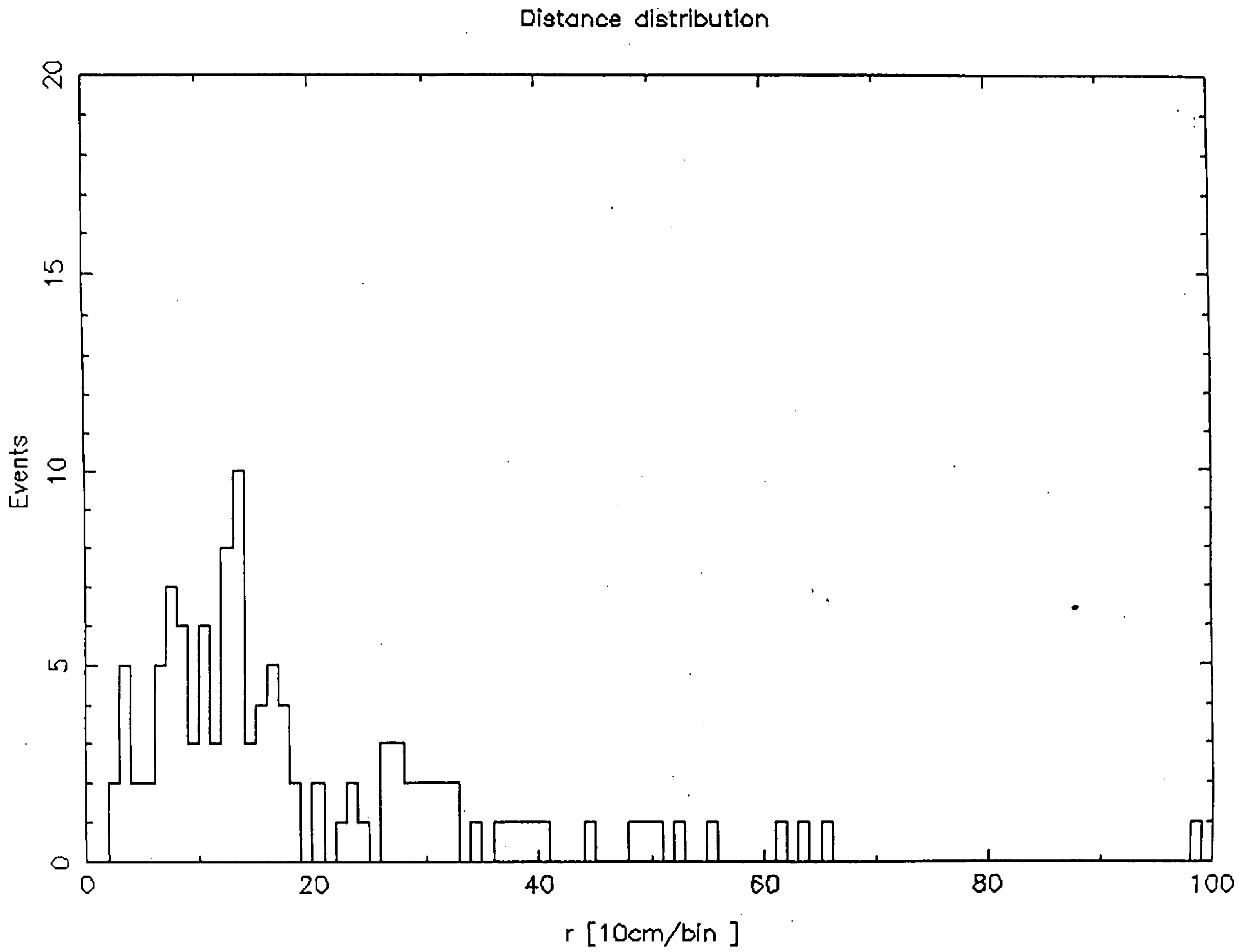

Distance distribution
Events
0
5
10
15
20
0
20
40
60
80
100
r [10cm/bin]

Fig. 4.

Fig 4

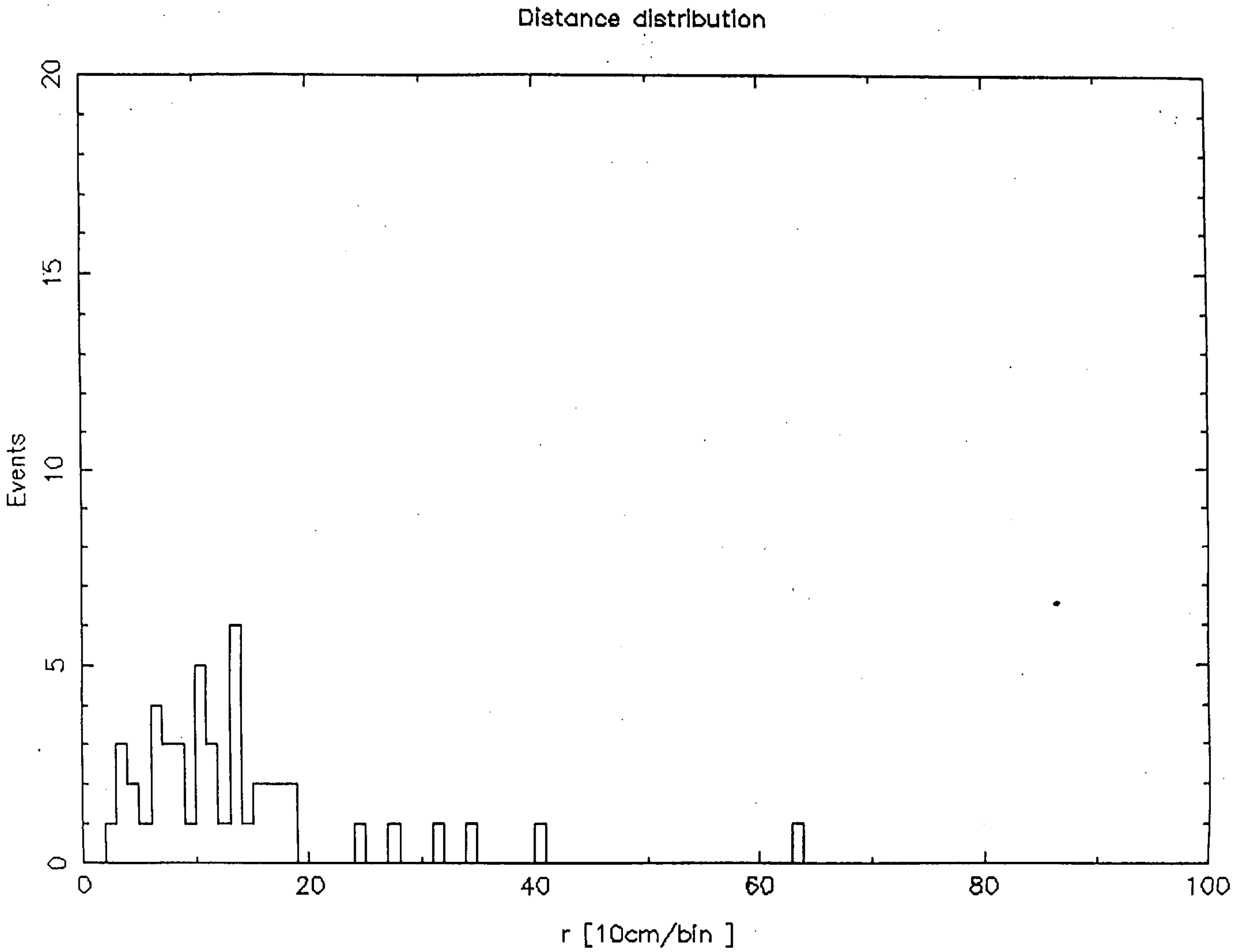

Distance distribution
Events
0
5
10
15
20
0
20
40
60
80
100
r [10cm/bin]

Fig 5

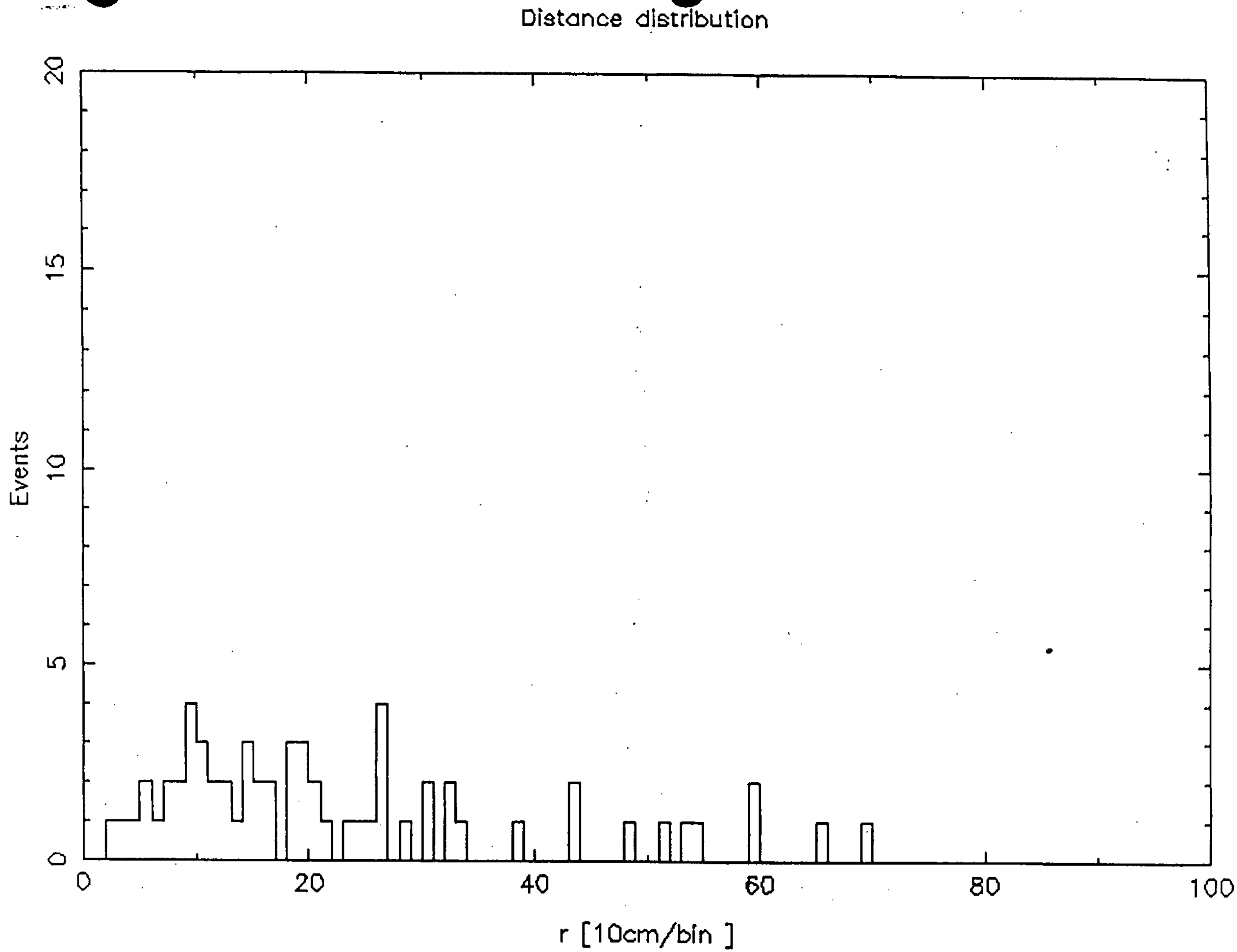
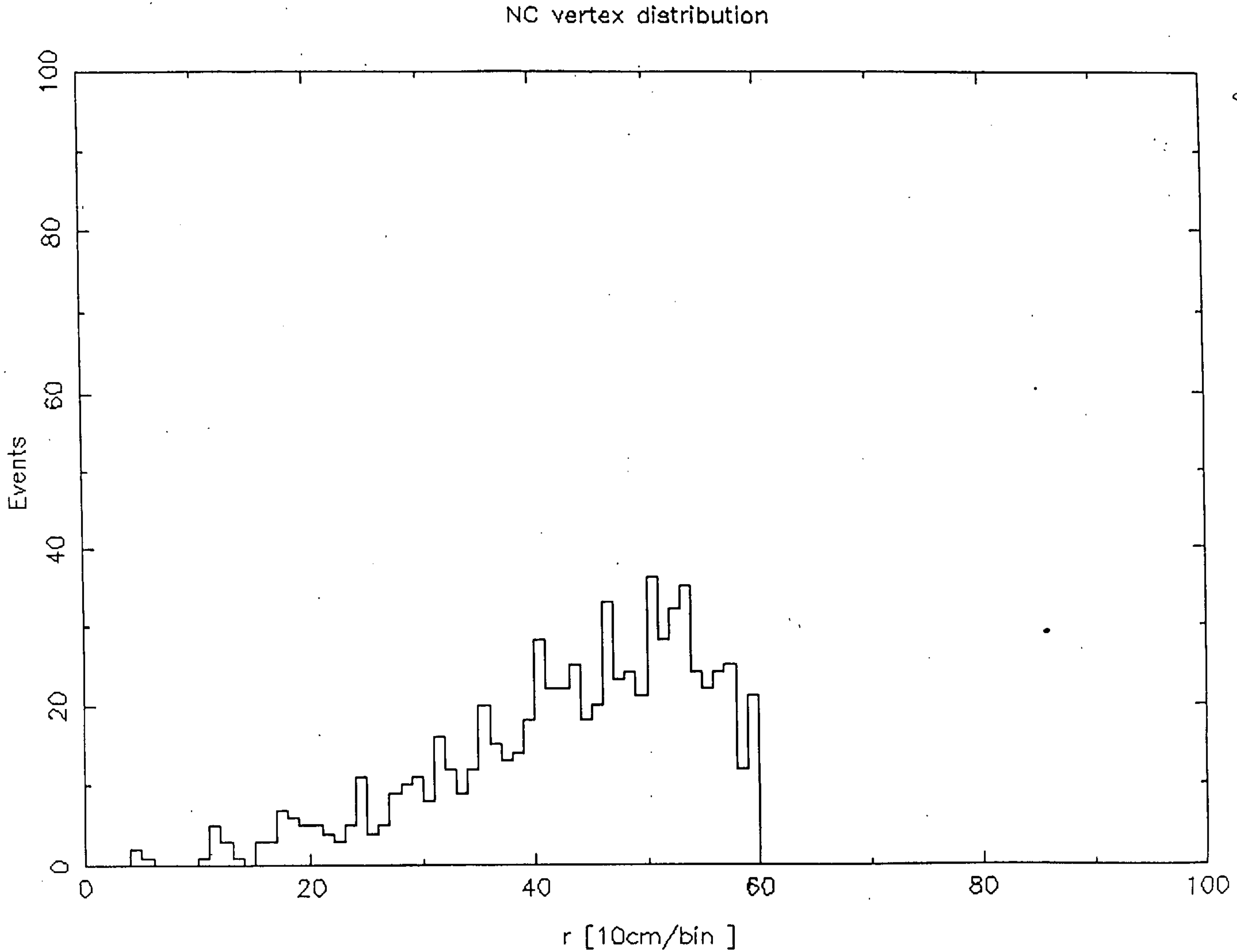

Distance distribution
Events
0
5
10
15
20
0
20
40
60
80
100
r [10cm/bin]

Fig6.

Fig 6



NC vertex distribution

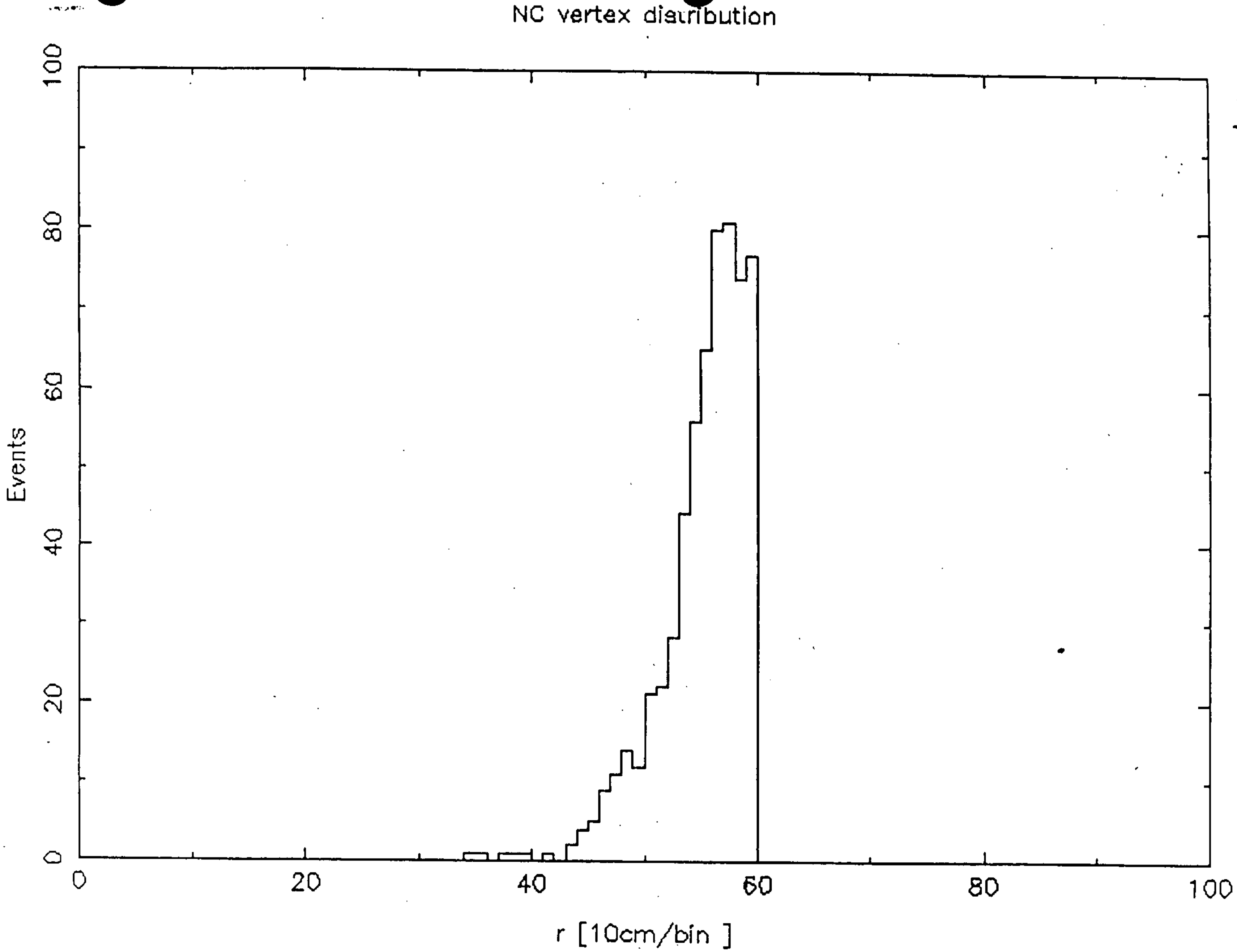

NC vertex distribution
Events
0
20
40
60
80
100
0
20
40
60
80
100
r [10cm/bin]

Fig. 7