CHARMONIUM $\bar{p}p$ EXPERIMENTS

Ezio A. Menichetti

INFN - Torino, Italy

Abstract: we discuss some aspects of a new experimental technique for the study of charmonium states. After a general introduction to the main physics motivations for such experiments, different experimental options are compared, showing that internal beam crossing a dense jet of hydrogen is able to provide the required intensity and energy resolution. Results from the pioneering R704 experiment at the CERN ISR, and prospects for the recently approved E760 effort at the Fermilab Accumulator are presented.

1. Introduction: $p\bar{p}$ vs. e^+e^-

The bulk of experimental information on the charmonium states (fig. 1 and 2) comes from e^+e^- colliders. The fact that only states allowed through one-photon intermediate state (fig. 3), i.e. states with $J^{PC} = 1^{--}$, have reasonable production rates, is clearly reflected in the accuracy of the available data from such machines. While the mass determination of J/ψ was performed with $\pm$100 KeV uncertainty[1], the same measurement for the χ_2 resulted in an error of $\pm$400 KeV (statistical), with a systematics of $\pm$4 MeV, coming mainly from the detector energy resolution and absolute scale, and background subtraction[2]. In $p\bar{p}$ annihilation into 2 or 3 gluons (fig. 4), all J^{PC} combinations allowed for a fermion-antifermion system are available to form a resonant state: this is therefore an appealing approach for the study of charmonium states with $J^{PC} \neq 1$. Such an experiment features excellent resolution for both mass and total width determination, since accelerator techniques can be exploited to measure the beam momentum, and to get very small momentum bite. On the other hand, large, non-resonant hadronic background has to be expected, indicating that electromagnetic decays of the resonances under study have to be selected to obtain a clean sample of the signal.

2. The initial state: machines

The resonant cross-section for a given charmonium state can be easily calculated from elementary scattering theory:

$$\sigma(E_{CM}) = \frac{\pi \lambda^2 \Gamma_i \Gamma_f (2J+1)}{2(2S_1+1)(2S_2+1)} \frac{1}{(E_{CM}-M_R)^2 + \Gamma_t^2/4}$$

where $s_{1,2}$ are the spin of the beam and target particles, J is the resonance spin, Γ_i and Γ_f are the decay partial widths of the resonance to the initial and final states, and Γ_t is the total width of the state. For charmonium, apart from 1^{--} levels, existing data and theory indicate:

$$\sigma_{peak} \sim 10pb \div 1nb$$

$$M_R \sim 3 \div 4 \quad GeV$$

$$\Gamma_t \sim 1 \div 10 \; MeV$$

The required momentum range is then 4÷ 7 GeV/c for a fixed target experiment, while is 1.5÷ 2 GeV/c for a collider. To obtain a reasonable event rate, a high luminosity annihilation source has to be designed, with $L_o \sim 10^{31}$ $cm^{-2}s^{-1}$. Very good beam momentum resolution (10^{-4}) is required to measure with good accuracy the total width of narrow states. It should be pointed out that the measured event rate as a function of the c.m. energy is not a direct measurement of the resonance line width for narrow levels, unless the beam momentum bite is exceedingly small. In a realistic case, the rate always results from the overlap between the resonant cross-section and the beam momentum profile (fig.5). One has then to reconstruct the resonant line shape using standard statistical methods, as likelihood maximization. The last (but not least) main requirement from the machine is a very good reproduc ibility of any given momentum setting, to ensure accurate absolute energy calibration of the experiment. It is worthwhile to briefly discuss three different experimental environments where a charmonium experiment could be performed:

1) Collider

The main advantage of this solution lies on the fact that a large acceptance detector, as required to get acceptable event rates and background rejection, can be made less complicated and expensive than for a fixed target experiment. The most serious drawback, apart from the fact that a dedicated machine has to be built, comes from the need of very high $\bar{p}$ beam current (and cooling power) to obtain the required luminosity.

2) Extracted beam

At first this looks like the most natural solution. It is certainly conceivable to construct and succesfully operate a $\bar{p}$ facility of the required momentum range; a 25 cm long liquid hydrogen target would provide 10^{31} luminosity with 10^7 pps incident beam intensity, not too much more than the actual LEAR intensity. The most serious problem stems from the need of measuring beam momentum and vertex cohordinate to ensure good energy resolution: for the given $\bar{p}$ flux, this does not seems to be an easy task.

3) Internal beam + jet-target

This idea, first suggested in 1979[3], takes advantage of standard accelerator techniques to get a very precise measurement of the beam momentum in a storage ring: 1 MeV/c accuracy was routinely achieved at the ISR, and is now being obtained at the Fermilab $\bar{p}$ Accumulator. It has been proven feasible to construct a hydrogen gas jet-target of the required density, with no effect on the machine vacuum[4]: the stored beam lifetime can be kept very long by full exploitation of the novel stochastic cooling techniques[5]. The obtainable luminosity can be expressed as:

$$L_o = N_p \, n_{jet} \, t_{jet} \, f_{rev}$$

Take for example the ISR case:

$n_{jet} \sim 10^{14}$ cm^{-3}

$t_{jet} \sim 1$ cm

$f_{rev} \sim 10^{6}$ Hz

$N_{\bar{p}} \sim 10^{11}$

The momentum resolution of an internal $\bar{p}$ beam can be pushed very far with appropriate cooling, so the main requirements of the experiment are fulfilled. Small source size ($\sim 1*1*1$ cm^3), total absence of secondary interactions in the target, and full utilization of the stored $\bar{p}$ beam (as compared to a traditional, extracted beam experiment) are among the extra bonuses obtained with this solution.

3. The final state: detectors

The efficient detection of electromagnetic final states from charmonium decay provides a powerful tool for the accurate measurements of the fundamental parameters of the $c\bar{c}$ system, as well as a sensitive probe for finding the missing states. On the other hand, the small value of the effective cross section requires a large acceptance detector. The high level of hadronic background demands that the detector possess accurate tracking for both charged particles and γ rays, good energy resolution for electrons and γ, and finally very good e/h discrimination. It should be mentioned that π^0/γ separation, a crucial requirement for many of the physics topics to be investigated, can only be achieved by designing a detector which has excellent spatial resolution and two-shower identification, and good detection efficiency for γ's with energy as low as 50 MeV. A further requirement is the ability to handle an interaction rate as large as 1 MHz, since the luminosity will be limited by this feature of the detector rather than by beam current or jet density. The need of a large acceptance makes it difficult to design a magnetic spectrometer, given the presence of the jet-target system and of the additional high vacuum equipement needed to counteract any gas diffusion in the beam pipe. On the other hand, by concentrating on e/γ final states one is naturally lead into choosing a non-magnetic, high granularity calorimeter for the detector. It should be stressed that the quasi-pointlike interaction volume inherent to the jet-target/$\bar{p}$ beam complex greatly facilitates the design of a compact apparatus.Electron tagging can be obtained by the use of threshold, atmospheric pressure gas Cerenkov counters[6]; standard tracking devices will serve as elements of a charged particles telescope. To get a rather precise measurement of the instantaneous luminosity of the experiment, one can measure the elastic rate at very small t, in the Coulomb-nuclear interference region, through the use of a telescope of silicon detectors operating directly in the machine vacuum.

4.The first generation: R704 at the CERN ISR

The experiment, performed in 1983-84, was pioneering this new technique with a limited acceptance detector: significant physics results were obtained in a relatively short data-taking period of about 8 weeks.In fig. 6 we have sketched a simplified view of the detector, also showing part of the jet-target system; a detailed description of the apparatus and of the machine operation can be found elsewhere[7,8]. Since most of the e^+e^- physics results have been published[9,10,11], I would like to concentrate on some preliminary data on γ-γ final state at the η_c c.m. energy, aiming to show that the extraction of a γ-γ signal from the large background of a hadronic experiment was indeed possible, if not easy. At the same time it will be stressed that to obtain a clean measurement of the most important η_c parameters (total width and branching ratio to γ-γ) some improvements have to be implemented.

a) $\gamma\gamma$ trigger and event selection

The first level neutral trigger required no charged track in the two detector arms or in the guard counter array, and a positive shower signal from both the calorimeter scintillator hodoscopes: a loose requirement on multiplicity was also required. A second level trigger was then asking for at least 70% of the total energy to be measured in the calorimeter, rejecting in this way most of the low energy and neutral hadronic background. Subsequent, off-line shower reconstruction was implemented by requiring a tight correspondence between the response of the three longitudinal sections of the calorimeter to detect a good, γ-induced shower. Since a major source of triggering events was suspected to come from $\pi^0\pi^0$ (or $\pi^0\pi^0$ equivalent, from the detector point of view) final states, we made a careful event selection, keeping track of all events with 1 or 2 showers per arm to get some measuremet of this background. In fig.7, the $\gamma\gamma$ mass distribution is plotted for these events: a nice π^0 peak is found.

b) Analysis

After having reconstructed the showers in the calorimeter, one is left with a sample of events containing 0,1 or 2 π^0's.The c.m. angular distributions for these events are plotted in fig.8: the three distributions are indeed similar, confirming that the dominating background to the "true" $\gamma\gamma$ signal comes from the same source producing the other two distributions, namely $\pi^0\pi^0$. The "γ-γ" event sample contains "true" $\gamma\gamma$ events together with some fraction of $\pi^0\pi^0$ events where two of the four γ's were missed. There are two reasons for failing to identify the π^0:

b1) symmetric π^0 decays, where the two showers are not separated. We do not expect a large background from this source, just because the granularity of the calorimeter was estimated to be sufficient to separate out two nearby showers from a γ within our acceptance.

This is shown in fig. 9, where we have plotted the measured opening angle distribution for $\pi^0\pi^0$ events, together with a Monte-Carlo prediction; starting from the $\pi^0\pi^0$ angular distribution, we simulated π^0 isotropic decay: taking into account the fact that the program was not simulating the finite detector angular resolution, one would conclude that no obvious loss at small opening is apparent.

b2) strongly asymmetric decays, where the lower energy γ is missed. This background can be reduced by improving either the detection of the low energy γ, or the measurement of the deviation of the energetic γ from the expected direction. In general, one may say that for a low energy π^0 the angular resolution is more efficient, while for higher π^0 energy the detection of the soft γ is more effective. While it is relatively easy to build up a χ^2 cut on the two directions, to test the hypothesis of "true" $\gamma\gamma$, it is not straightforward to set a cut on what could be called the "extra activity" in the apparatus. As done before to check our two-shower separation capability, we made a Monte-Carlo calculation to get a feeling of our detection efficiency for soft γ's, just taking reconstructed $\pi^0\pi^0$ events and letting the π^0's to decay isotropically. Results are shown in fig. 10, indicating serious losses below 80 MeV. This is partly due to the fact that some threshold has to be fixed in the shower reconstruction algorithm;one is led to try a different approach to the problem of discriminating against π^0 background. One possible way of doing that is to append a sort of additive "background index" to each event, according to whether the χ^2 was high, or there was some activity in the calorimeter or in the guard counters array, and so on. It is then possible to cut progressively on this index, always keeping track of efficiency reduction by comparison with reconstructed $J/\psi \rightarrow e^+e^-$ events. In fig. 11 we have shown angular distributions for " $\gamma\gamma$ " events with different cuts on the background index: comparing with known efficiency reduction, one can estimate the effectiveness of the cut. Inspection of fig. 11 also suggests to restrict the analysis to the region $\cos\theta^* < 0.3$, where the background is lower. We report here the main result of this work, by collecting the number left at three different c.m. energies (below, on and above resonance):

$\sqrt{s}$ (MeV)	$\int L\,dt$ (nb^{-1})	no. of evts
2965	100	1
2980	448	15
3020	98	2

By assuming a branching ratio to $p\bar{p}$ of 1.1 10^{-3} and a total width of 11 MeV, the following upper limit is found:

$$\Gamma_{\gamma\gamma} < 7 \text{ KeV} \qquad (84\ \%\ \text{C.L.})$$

5. The second generation: E760 at the Fermilab Accumulator

E760 will be a second generation experiment, intended to cover the same physics topics pioneered by R704. Among the main goals of the experiment I will quote:

- find final evidence for the singlet P-wave level;
- find final evidence for the decay $\eta_c \to \gamma\gamma$, and measure B.R.;
- find η_c'
- look for D-wave states

In an attempt to extend the succesful experience of R704 at the ISR, it was soon realized that the $\bar{p}$ Accumulator Ring at FNAL was ideally suited to perform this task, providing an intense, cooled $\bar{p}$ beam in the appropriate momentum range, and giving a possibility of running in parallel to fixed target Tevatron operation: details on the proposed beam handling procedures can be found elsewhere[12,13]. The detector, sketched in simplified form in fig. 12, will consist of a barrel assembly and a forward end-cap. 'Hermetic' e.m. calorimetry between 14° and 70° will be provided by a large, fine-grained lead-glass barrel detector (see fig. 13), consisting of about 2000 tapered blocks pointing to the small interaction volume. From preliminary test results, we are confident that this calorimeter will be detecting low energy γ-rays down to about 30 MeV. A multi-cell gas Cerenkov counter will be used to tag electrons over the full acceptance of the barrel detector. Tracking will be provided by a set of devices: a double ring of straw tubes just outside the beam pipe, a cylindrical, radial-drift projection chamber (also useful as a dE/dx detector, a very important feature to reject early converted γ-rays firing the Cerenkov counter), and an external cylinder of limited streamer tubes with strip read-out. The forward end-cap will contain a planar MWPC and a calorimeter made from radiation resistant (Cerium doped) lead-glass blocks. We plan to have one additional (annular) MWPC to cover the angular range 14°- 22° to improve tracking.

While featuring an acceptance increased by a factor 4÷5 with respect to R704, this detector will also improve the π^0 rejection, reducing the background to $\gamma\gamma$ final states by a factor ~3. A sphisticated trigger, including calorimeter information at an early stage, is now being finalized.

With a luminosity increased by a factor ~ 3, we expect signal rates at least tenfold the rates of R704, with reduced background: while enabling us to obtain a final answer on several specific questions ($\eta_c \to \gamma\gamma$, $\eta'_c \to \gamma\gamma$, 1P1, χ-states angular distributions), this experiment could be opening a way to explore new physics (D-wave levels,?).

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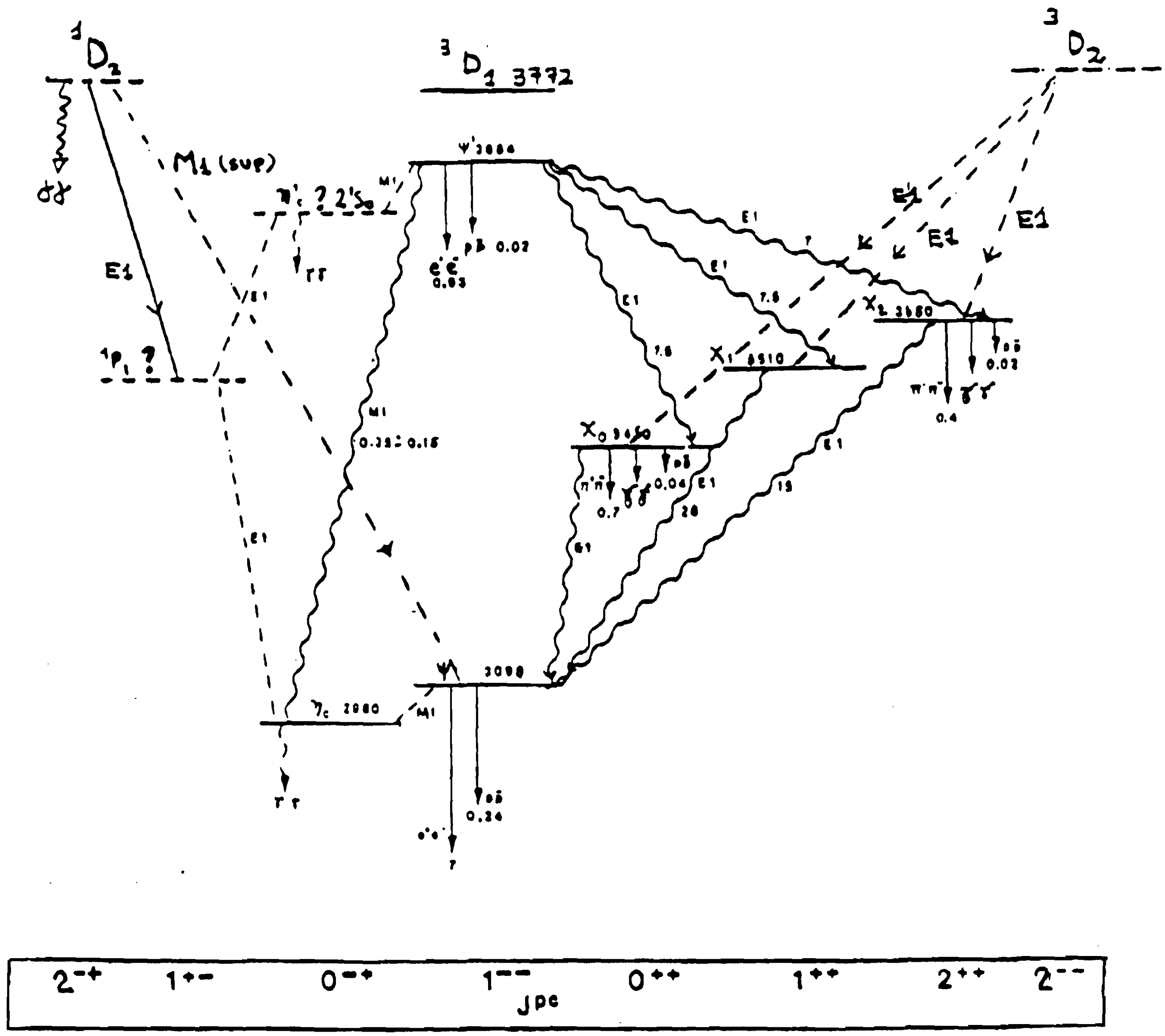


Mass spectrum of charmonium states

Fig. 1

L \ S	0	1
0	^1S_o (0^{-+})	$^3S_1$ (1^{--})
1	$^1P_1$ (1^{+-})	$^3P_{0,1,2}$ $(0^{++},1^{++},2^{++})$
2	$^1D_2$ (2^{-+})	$^3D_{1,2,3}$ $(1^{--},2^{--},3^{--})$

Charmonium quantum numbers

Fig. 2

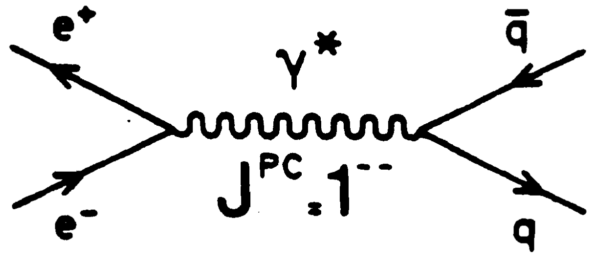


Fig. 3

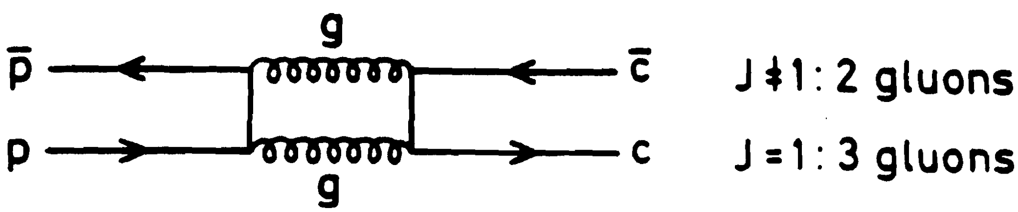
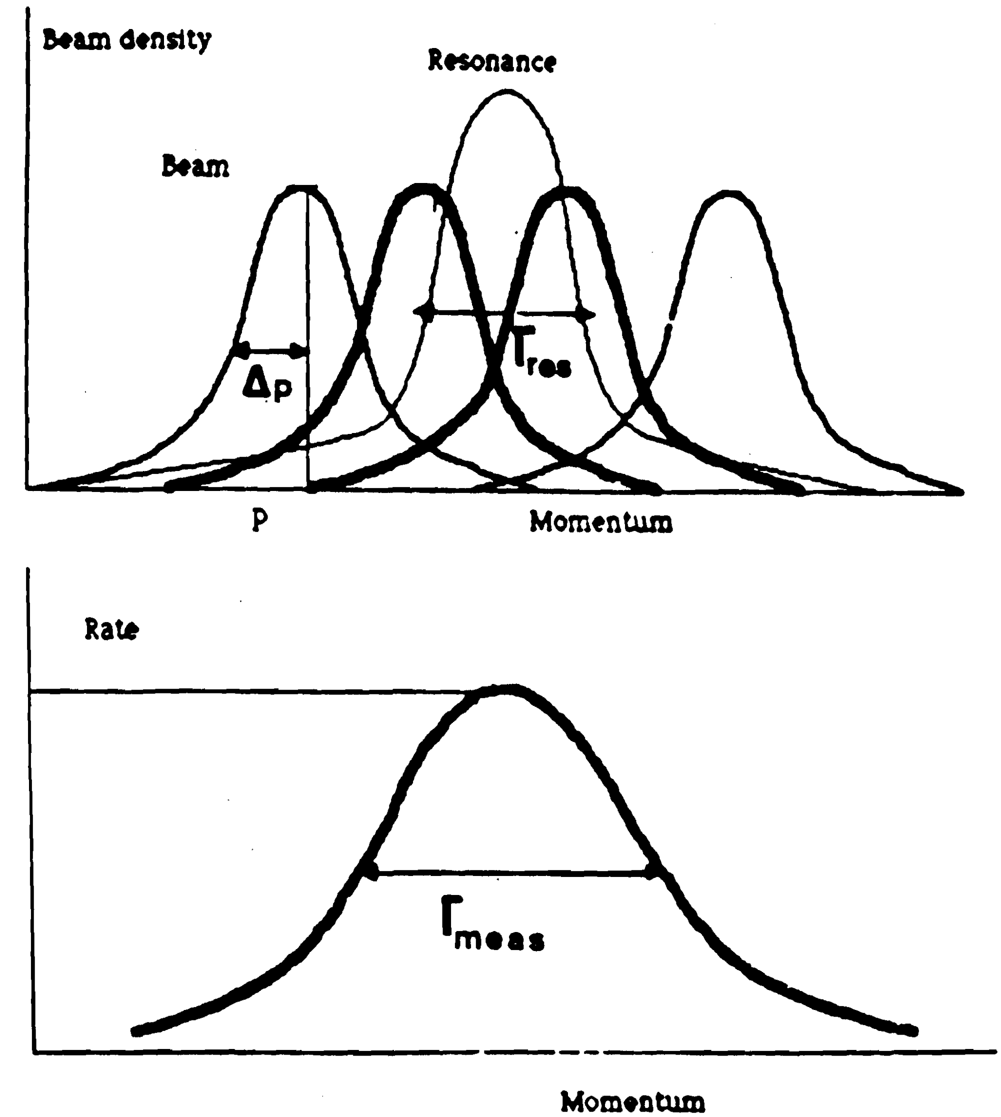
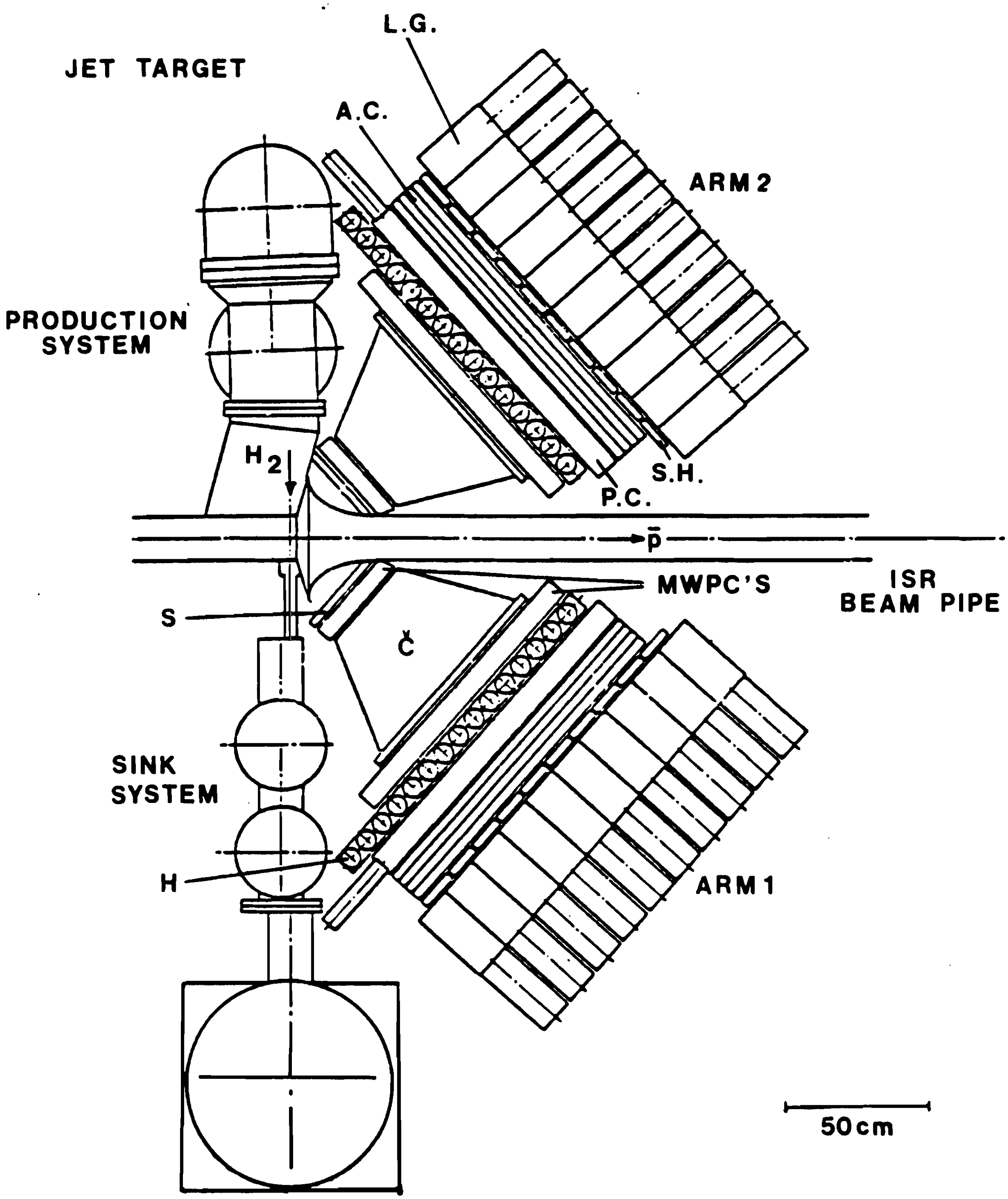


Fig. 4



Line shape reconstruction from rate vs. momentum measurement

Fig. 5



R704 experimental set-up

S Scintillator
MWPC Digital chambers
C Cherenkov
H Hodoscope
PC Precalorimeter
AC Analog chambers
SH Shower hodoscope
LG Lead glass

Fig. 6

γ-γ mass spectrum

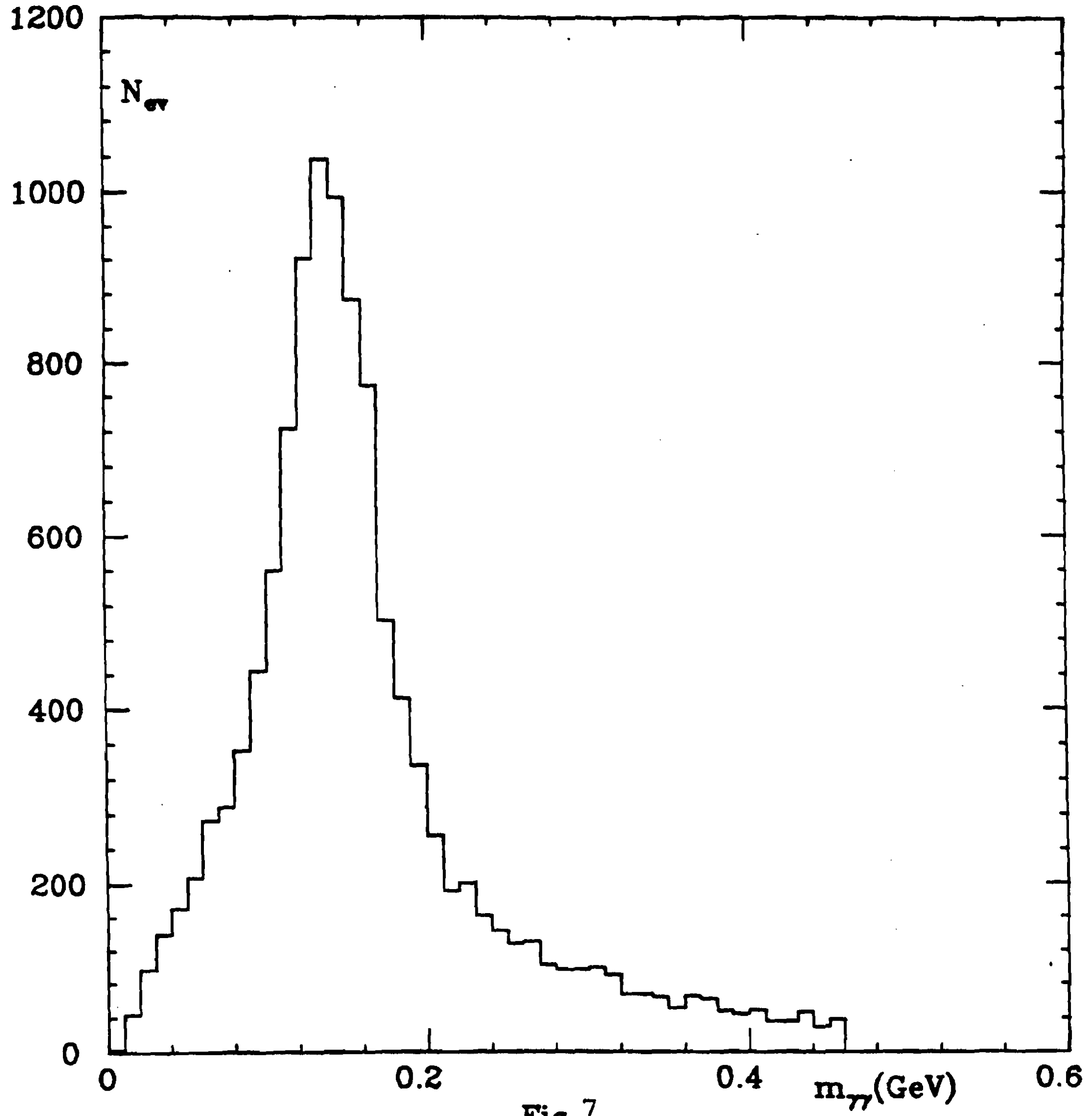


Fig. 7

C.M. angular distributions for neutral events

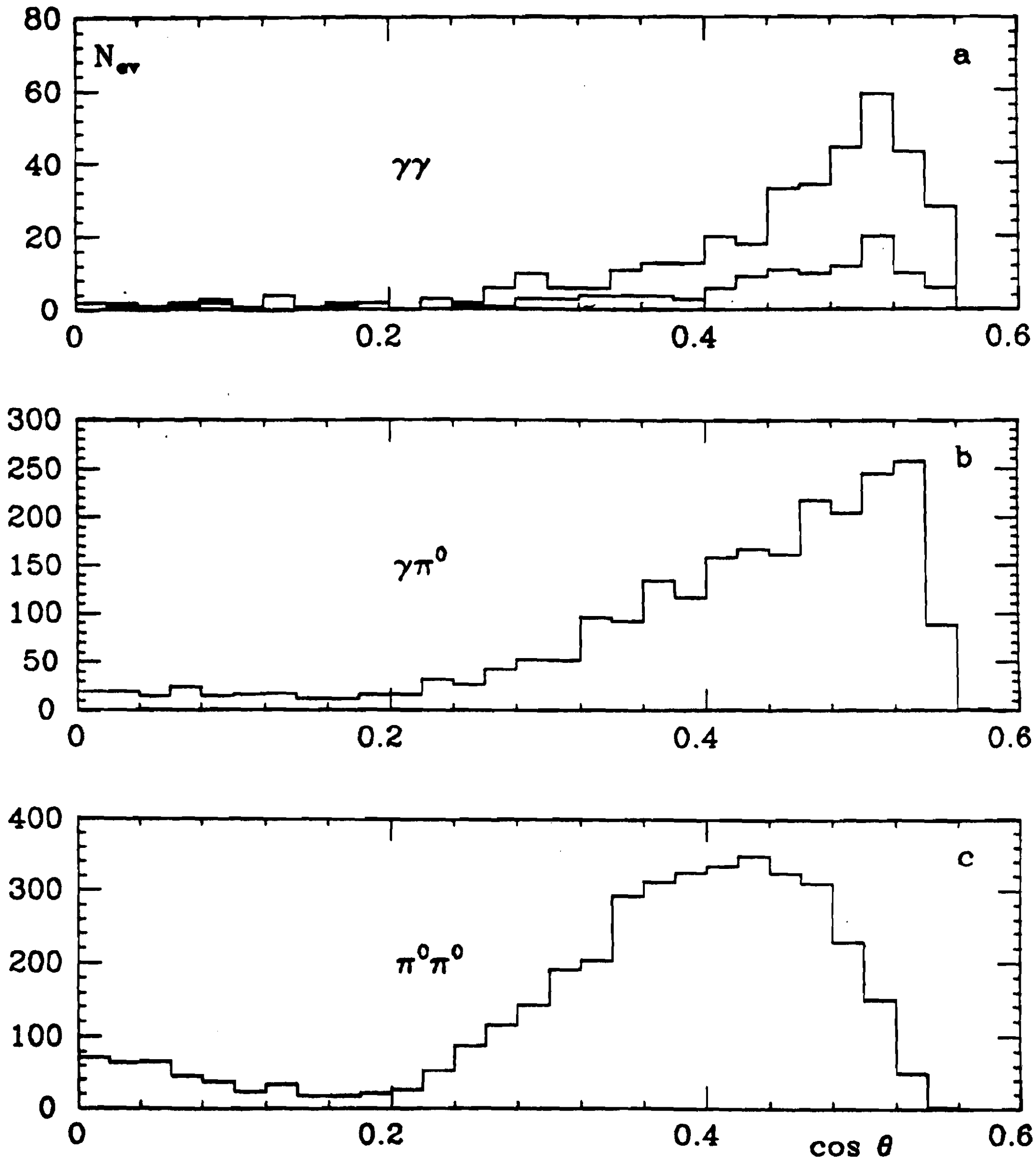


Fig. 8

Opening angle distribution for $\pi^0\pi^0$ events

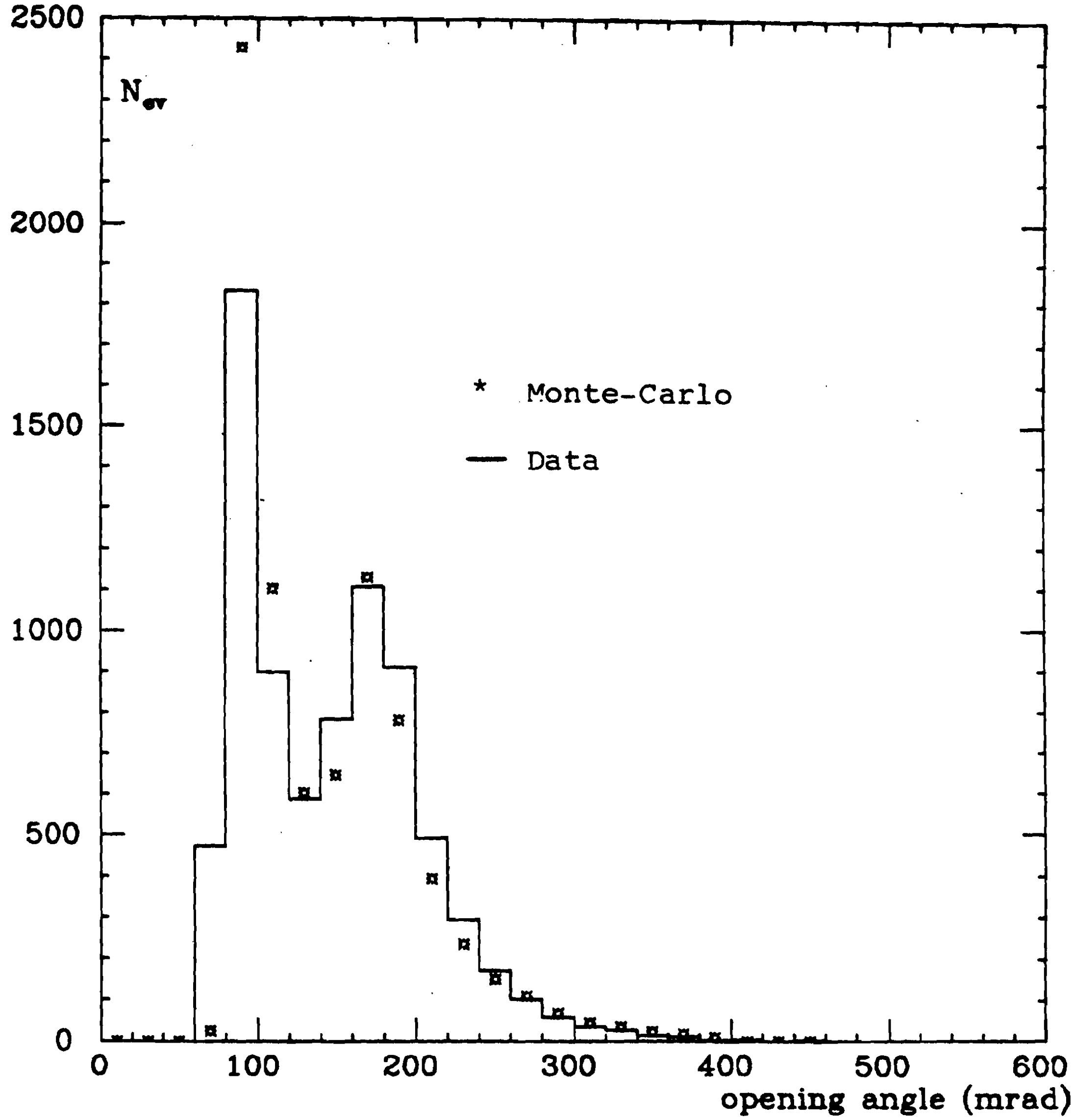


Fig. 9

Lower end of Υ-ray energy spectrum vs. Monte-Carlo

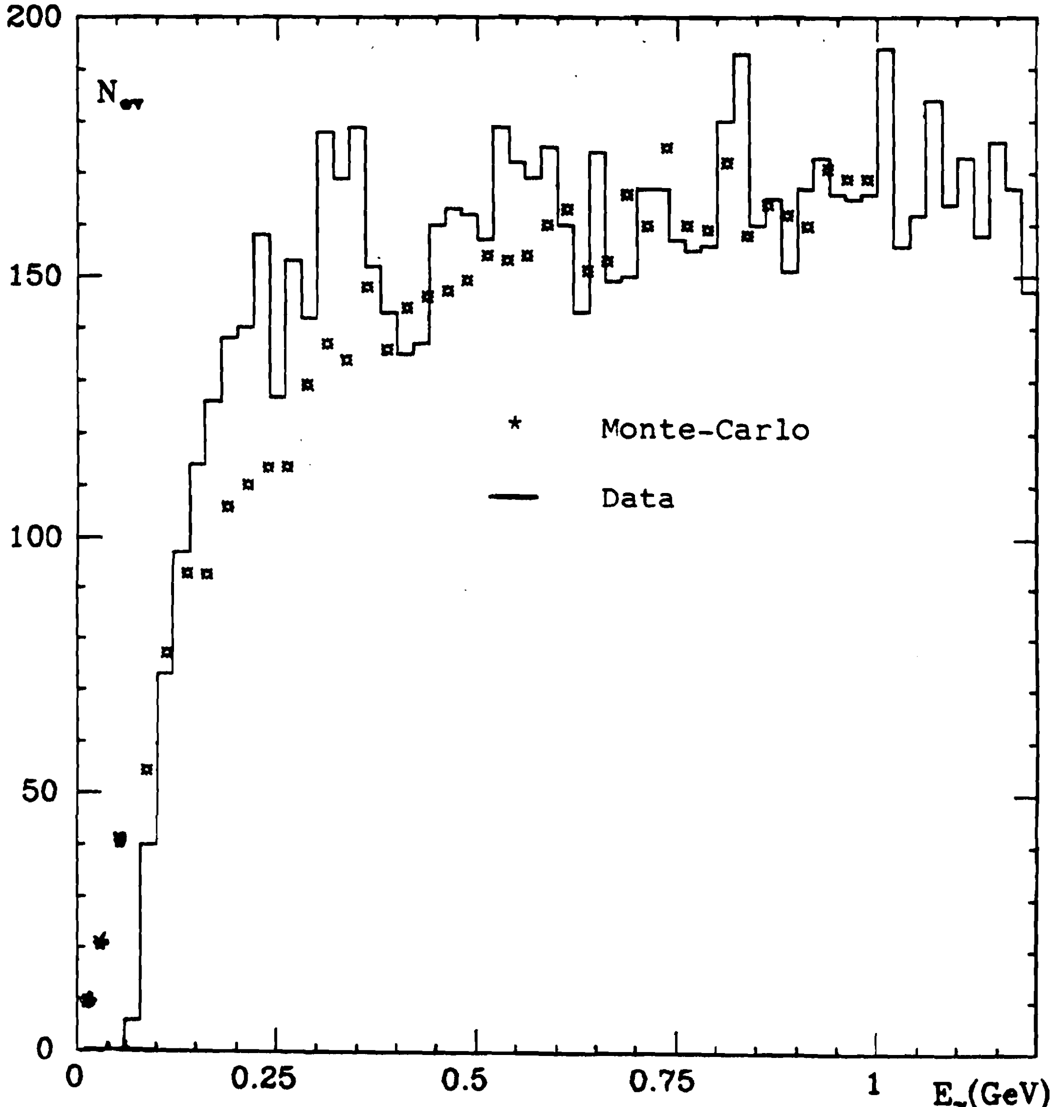


Fig. 10

C.M.angular distributions for "ϒ-ϒ" events

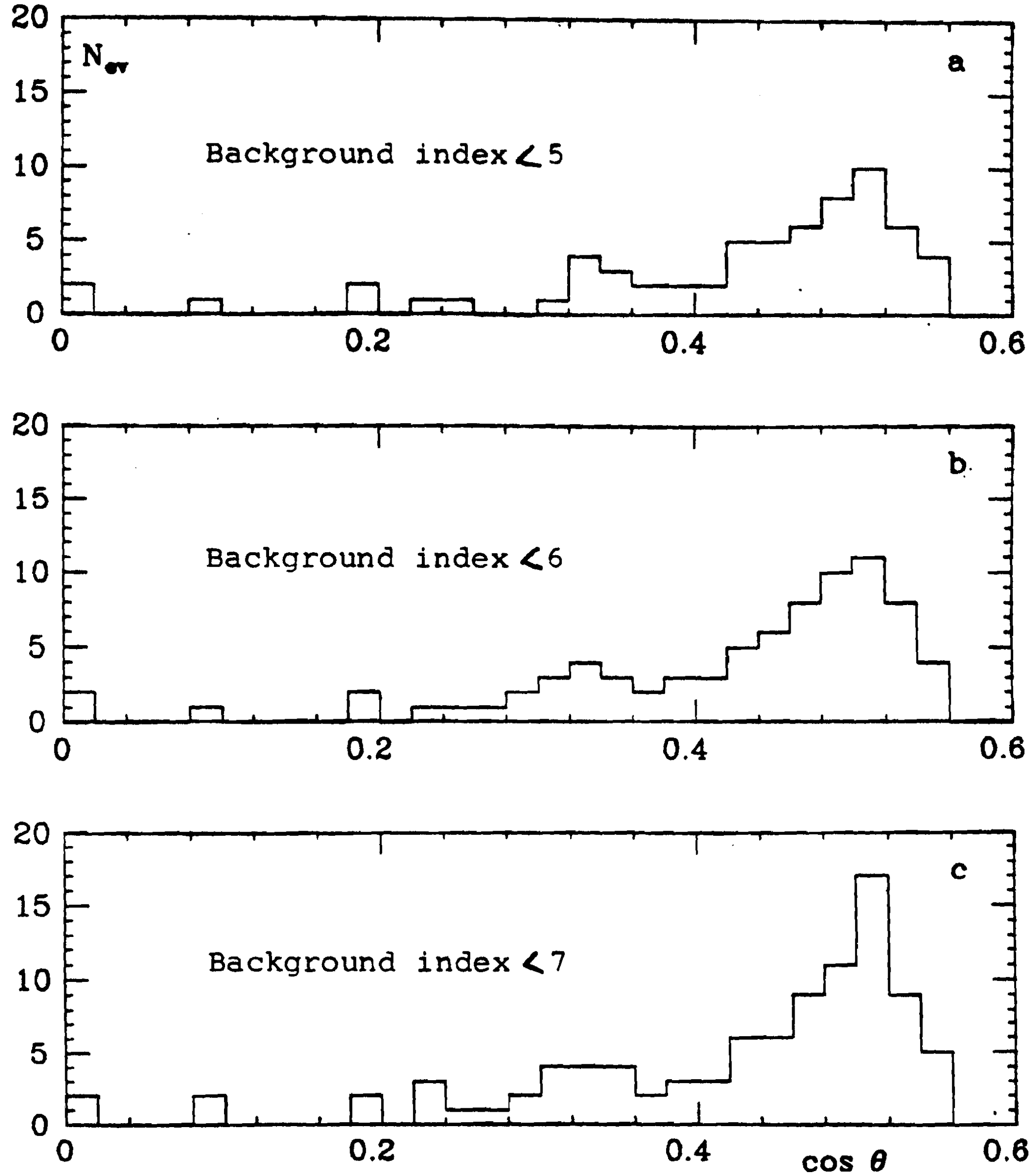


Fig. 11.

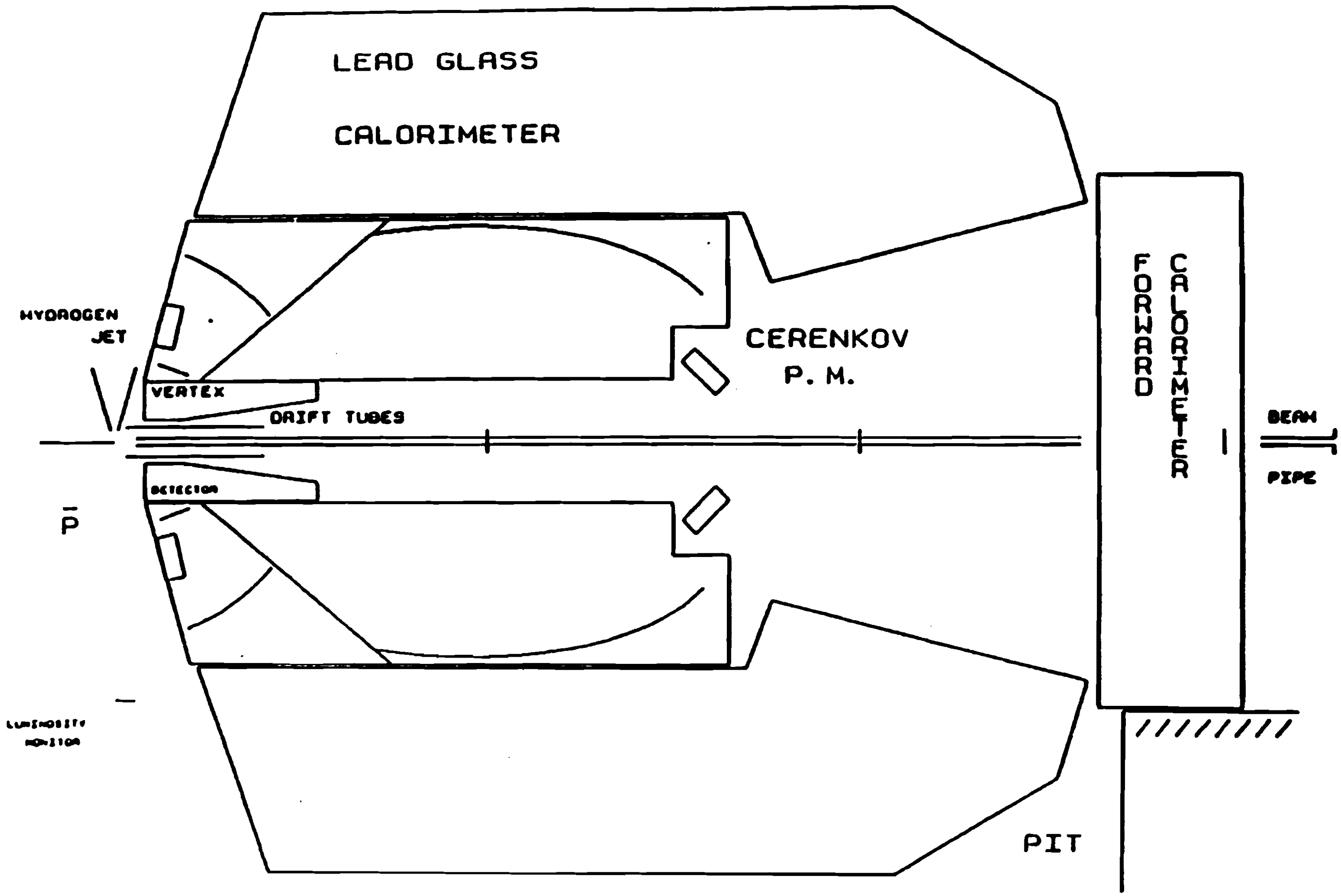


Figure 12 - E760 Detector

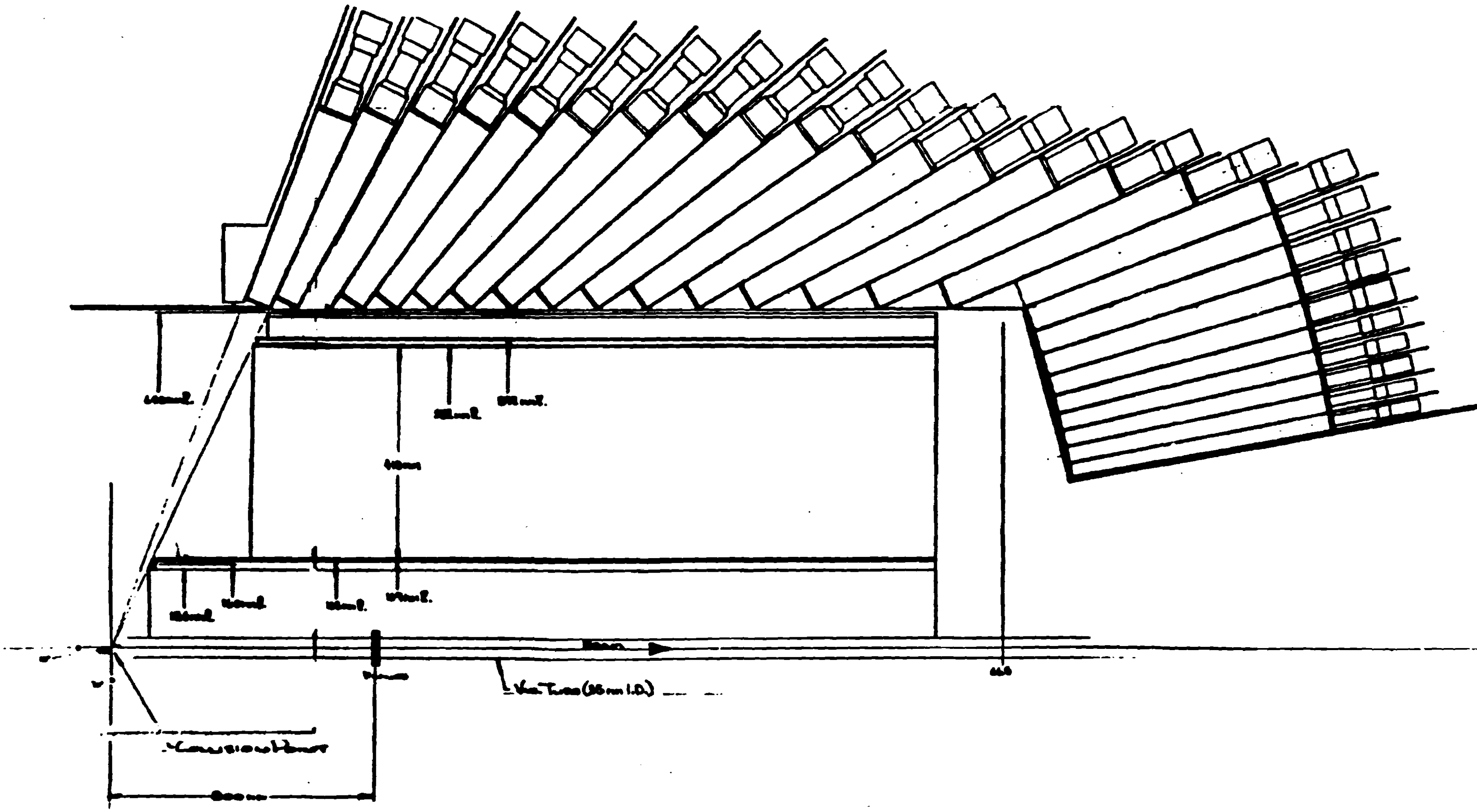


Fig. 13 E760 barrel lead-glass calorimeter