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HIGH ENERGY PHOTOPRODUCTION OF μμ AND μE EVENTS

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A high energy broad band neutral beam was designed and constructed at the Fermi National Accelerator Laboratory combined with a detecting system that would allow us to identify and measure the energy of leptons, photons, and hadrons. The earlier experiments used 300 GeV/c and 380 GeV/c protons to produce neutrons and photons; results from these previous experiments have been published.[1/]

This paper is a progress report on the analysis of μμ and μe events produced in the most recent experiment using high energy photons produced by 400 GeV/c protons. During photoproduction experiments, approximately 34 meters of liquid deuterium are used to attenuate and effectively remove the neutrons from the beam. The resulting photon spectrum is shown in Fig. 1. A schematic drawing of the detection apparatus is shown in Fig. 2. The main components are: five multiwire proportional chambers combined with a magnet which allows us to measure

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the angles and momentum of the tracks of charged particles, five scintillation counter hodoscopes which are used in a variety of triggers, electromagnetic shower detectors to measure the energies of electrons and photons, a hadron calorimeter which gives a measure of the energy of hadronic particles, a quantmeter for monitoring and measuring the total number of photons in the beam, and a muon identifier which consists of approximately 2 meters of steel with both vertical and horizontal scintillation counter hodoscopes. More details on the beam and on the detection apparatus are given in the published articles.[1]

μμ Events

In a run using moderate intensity and a 2.45 cm beryllium target in the photon beam, we obtained the mass distribution of μμ events shown in Fig. 3. The smooth curve superimposed on the data represents the predicted number of accepted events due to the Bethe-Heitler pair production process. The calculation of the coherent and quasi-elastic contributions to muon pair production has been done following the prescription given by Y. S. Tsai.[2] The relative normalization of 45 events/nanobarns accepted was determined from the low mass (0.4-0.6 GeV) muon pairs. The data is in good agreement with the Bethe-Heitler predictions for masses less than 2.6 GeV. In this data we also see the production of the $\psi(3.1)$[3,4] and $\psi'(3.7)$[5] resonances.

Very interestingly we also see the production of four events clustered in the mass region of 4.7 GeV/c^2. During this run our experimental mass resolution was approximately 300 MeV/c^2 FWHM. The extrapolation of the coherent and quasi-elastic Bethe-Heitler process leads to a prediction of a total of 0.8 events for masses greater than 4.2 GeV/c^2.

The question we tried to study further was whether the four μμ events clustered at 4.7 GeV/c^2 are due to a new resonance or are due to a statistical fluctuation in the Bethe-Heitler production process. In order to try to clarify the above, a higher intensity run using targets with different Z was undertaken, specifically two 7.62 cm beryllium targets and a 2.54 cm copper target were used,

each separated by 25 cm. In order to run at higher intensities and to reduce the flux of charged particles passing through our spectrometer a 25 cm lead absorber (of electrons, positrons, and photons) was placed in the beam 52 cm downstream of the Cu target. With the lead, we are limited to looking only at muons, and the multiple scattering in the lead broadens the mass resolution curve. With such an absorber it is becoming standard to calculate the invariant mass of the two particles by projecting the vectors of the particles to approximately the center of the absorber and then calculating the opening angle between the two particles from the projected points in the absorber to the center of the target. The details of this procedure of calculating the mass are given elsewhere.[6/]

The dimuon mass distribution for the combined high intensity and moderate intensity running is shown in Fig. 4. The smooth curve is again the predicted number of accepted events due to the Bethe-Heitler coherent and quasi-elastic processes. The normalization of the curve for the high intensity running was determined by demanding that the cross section of $\psi(3.1)$ production as measured from the first beryllium target be identical to that obtained from the moderate intensity running. Once again, deviations from the Bethe-Heitler predictions are seen in the $\psi(3.1)$ and $\psi'(3.7)$ regions; the total number of $\psi \rightarrow \mu\mu$ events is approximately 1400. In the mass interval 4.5 to 4.8 GeV/c^2, 8 $\mu\mu$ events are observed where 2.6 events are expected from the two Bethe-Heitler processes.

In our recent neutron production experiments using effectively the same apparatus and the same analysis programs, we found only one $\mu\mu$ event with mass greater than 4.2 GeV in a sample that contained over 600 $\psi(3.1) \rightarrow \mu^+\mu^-$ events. We therefore conclude that the events we are seeing in the photoproduction experiments are a real physical process and not due to the apparatus or our analysis programs. For all the observed high mass $\mu\mu$ events, we have also

checked obvious things such as goodness of fit, distance of closest approach, point of closest approach, positions at the exit plane in the magnet, etc.

For trying to determine whether these events above 4.2 GeV/c^2 are typical of the Bethe-Heitler process, we have the additional information of the ratio of production in the beryllium and copper targets, the ratio of the energy asymmetry of the pair $\eta = \frac{|E_+ - E_-|}{E_+ + E_-}$, and the average value of $p_\perp^2$. We can compare these quantities for the events above 4.2 GeV/c^2 with the events in the region 1.8-2.6 GeV/c^2 where we believe the Bethe-Heitler process is dominant. For the events in the mass region above 4.2 GeV/c^2, we find the values obtained in each of these separate tests has a probability of less than 7% of arising from the Bethe-Heitler process. The quantities we have been able to evaluate indicate that the events above 4.2 GeV/c^2 are quite consistent with being from a new resonance and have a low probability of arising from the Bethe-Heitler coherent and quasi-elastic processes.

Are there other processes which may be giving rise to the high mass $\mu\mu$? We are aware of one other process which is the photoproduction of μ-pairs accompanied by hadrons; unfortunately very little information exists on this process. The cogent experimental fact is that none of the μ-pair events with mass greater than 4.2 GeV/c^2 are accompanied by any additional tracks.

μe Events

During the photoproduction experiments a variety of electronic triggers were used simultaneously, including one for $\mu^\pm e^\mp$ events. Such events would arise from the production of pairs of particles, each of which weakly decays leptonically or semi-leptonically, - one via the μ channel and the other via the e channel. In that neutrinos are also present, such events should be non-coplanar. Perl et al[7] have reported the observation of such μe events produced by the colliding beams at SPEAR.

The value of the cross section x (Branching Ratio)^2 which one can obtain in the presence of a hadron photoproduction total cross section of the order of 100 microbarns, depends on our ability to reject two or more hadrons which simulate μe events. In our experimental setup the path length was such that a 15 GeV pion had a probability of about 1.5% of decaying into a muon; this probability decreases linearly with increases in the energy of the pion. The extent to which a pion can simulate an electron was determined experimentally in our apparatus. The electrons were obtained by using Bethe-Heitler pairs produced in a very thin lead foil upstream of a small sweeping magnet which bends the electron events into various regions of the detector; such runs were routinely made to check the photon spectrum. The sample of pions was obtained from the prolific production of rho mesons.

Electrons bremsstrahl a certain fraction of the time, depending on the thickness of the target, and the additional bremsstrahlung energy shows up in the electromagnetic shower detector which is along the trajectory of the original electron. The process involved is illustrated in Fig. 5 for an electron pair event. Obviously, for very thin targets, the ratio measured in the spectrometer E/p (total energy in the electron shower detector/momentum of the charged particle track) should be very close to unity. The distributions of E/p for electrons and for pions are shown in Fig. 6 for the 2.45 cm Be target used in this study of μe events.

Our electromagnetic shower detectors, as well as being divided into left and right hodoscopes are also divided into front and back hodoscopes. The front counters contain six radiation lengths of lead and the back counters contain sixteen radiation lengths of lead. The probability for a $\pi^{\pm}$ to produce a π^{o} and to give a large pulse in the front counters is much less than the probability that it will give a large pulse in the back counter. However an electron will lose an appreciable fraction of its energy in the front counter.

To make this quantitative we define the ratio

$$f' \equiv \frac{1}{N}\left(\frac{E_F}{E_F + E_B}\right) \ln \left(\frac{p}{.022\ \text{GeV}}\right)$$

where E_F is the energy in the front shower detector, E_B is the energy in the back shower detector, and the logarithmic factor corrects for the dependence of the electron shower development on the momentum of the incoming particle. Some of the time we used two additional radiation lengths of lead in front of a counter hodoscope which was upstream of the shower detectors; when the lead was in, the value of N was 5.19; when the lead was out, the value of N was 3.5. The distributions of f' for electrons and for pions is shown in Fig. 7. When we had the additional lead sheets in front of the shower detectors, we also measured the pulse height in the scintillation counter hodoscope behind the lead.

We determined the pulse height from pions and electrons in the hadron calorimeter. Using a criteria that the amount of energy deposited in the hadron calorimeter was less than 4% of the momentum of the charge particles measured in the spectrometer resulted in a further π/e rejection, without a further decrease in electron efficiency.

At the present time, μe events have been looked for in only 2/3 of the data sample obtained with the moderate intensity running. Criteria included that there be one μ and one e in the event, that there be only two tracks, that there be no additional hits in the upstream scintillation counters that defined the aperture of the multiwire proportional counter P1 (See Fig. 2). We also demanded that there be less than 1 GeV of extra photon energy in shower detector- that were not being hit by the electron or its bremsstrahlung. Table I gives

the various requirements on E/p and f' for different levels of π/e rejection. At the present time, the cuts we are using give us a 90% efficiency for observing electrons and a total π/e rejection ratio of 1.5×10^{-3} when we use level III. If we use level I, namely $E/p > 0.3$, then we find about 10 μe-like events with $M_{\mu e} > 1.1$ GeV. If we use level III, $E/p > 0.8$, then there are 2 events with $M_{\mu e} > 1.1$ GeV/c^2.

Fig. 8 shows the total distribution of μe-like events in the mass region above .6 GeV/c^2. We attribute the events at mass below 1.1 GeV/c^2 to a residue of vector mesons that have simulated μe with an overall rejection ratio of the order of 3×10^{-5}, namely 1.5×10^{-3} for electrons and approximately 1.5×10^{-2} for muons.

Some of the parameters of the two higher mass events are given in Table II. These two higher mass events, if they are real, correspond to

$$\sigma(BR)^2 \times \text{Acceptance} = 4 \times 10^{-35}\ \text{cm}^2$$

Basically this is a progress report; our initial analysis effort was limited to events that contain only two tracks. We have started analyzing the μe-like events where other tracks are present.

Further high intensity photoproduction experiments are approved which we hope will clarify the origin of the cluster of $\mu\mu$ events seen at 4.7 GeV/c^2 and the nature of the μe events.

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Table I

π/e Rejection Ratio Dependence on Requirements

Level	Requirements	π/e Rejection
I	$E/p > 0.3$, $.5 < f' < 1.5$, (H.C.)* $< .04\ E$	.015
II	$E/p > 0.8$, $.5 < f' < 1.5$, (H.C.)* $< .04\ E$	3×10^{-3}
III	Same as Level II, plus large pulse height in hodoscope behind additional lead.	1.5×10^{-3}

* (H.C.) is the energy measured in the hadron calorimeter

Table II

Characteristics of Two μe Events

Mass GeV/c^2	E/p	f'	$p_e + p_\mu$ GeV/c	$\Sigma' \vec{p}_\perp$ GeV/c	$p_\perp^e$	$p_\perp^\mu$	Coplanarity* mr
1.24	.87	.55	125	.67	.42	.33	- 1.72
1.52	1.09	.85	45	.52	.52	.86	8.92

* Coplanarity $\equiv \dfrac{\vec{k}_\gamma \cdot \vec{k}_e \times \vec{k}_\mu}{|k_\gamma|\,|\vec{k}_e \times \vec{k}_\mu|}$

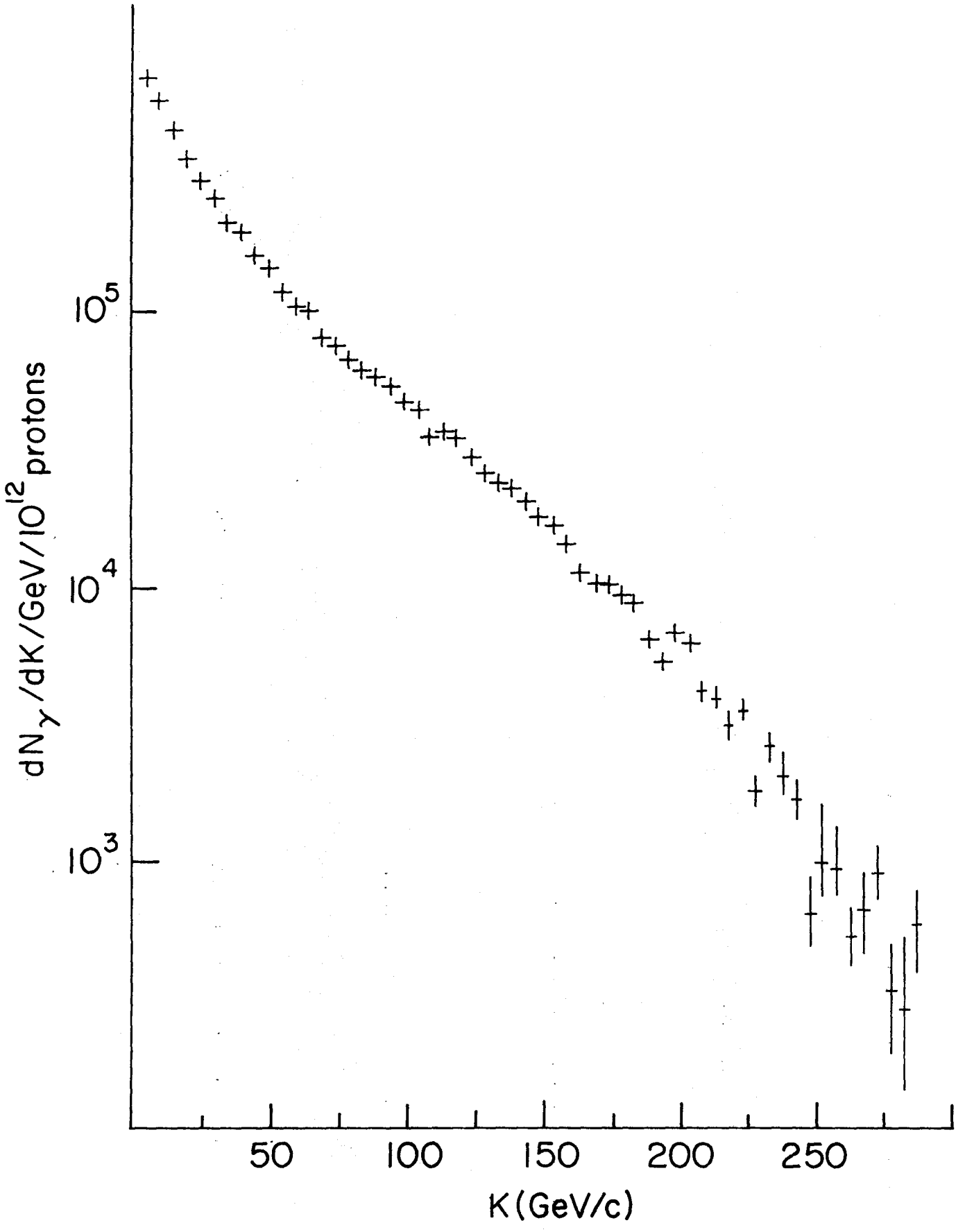

Fig. 1. Photon Spectrum from 400 GeV/c protons with 34 m. of D_2

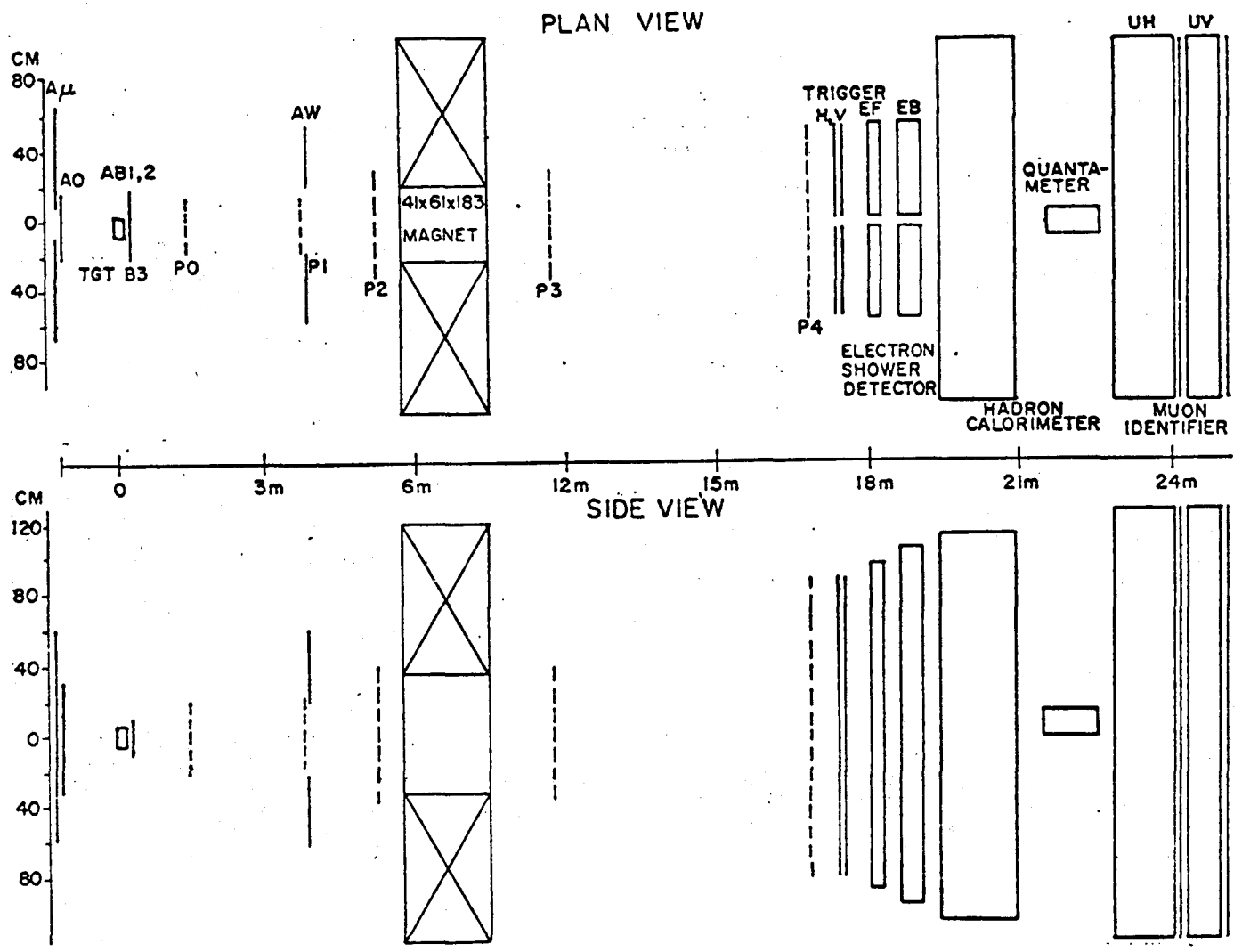

Fig. 2. Typical arrangement of apparatus for photoproduction experiments

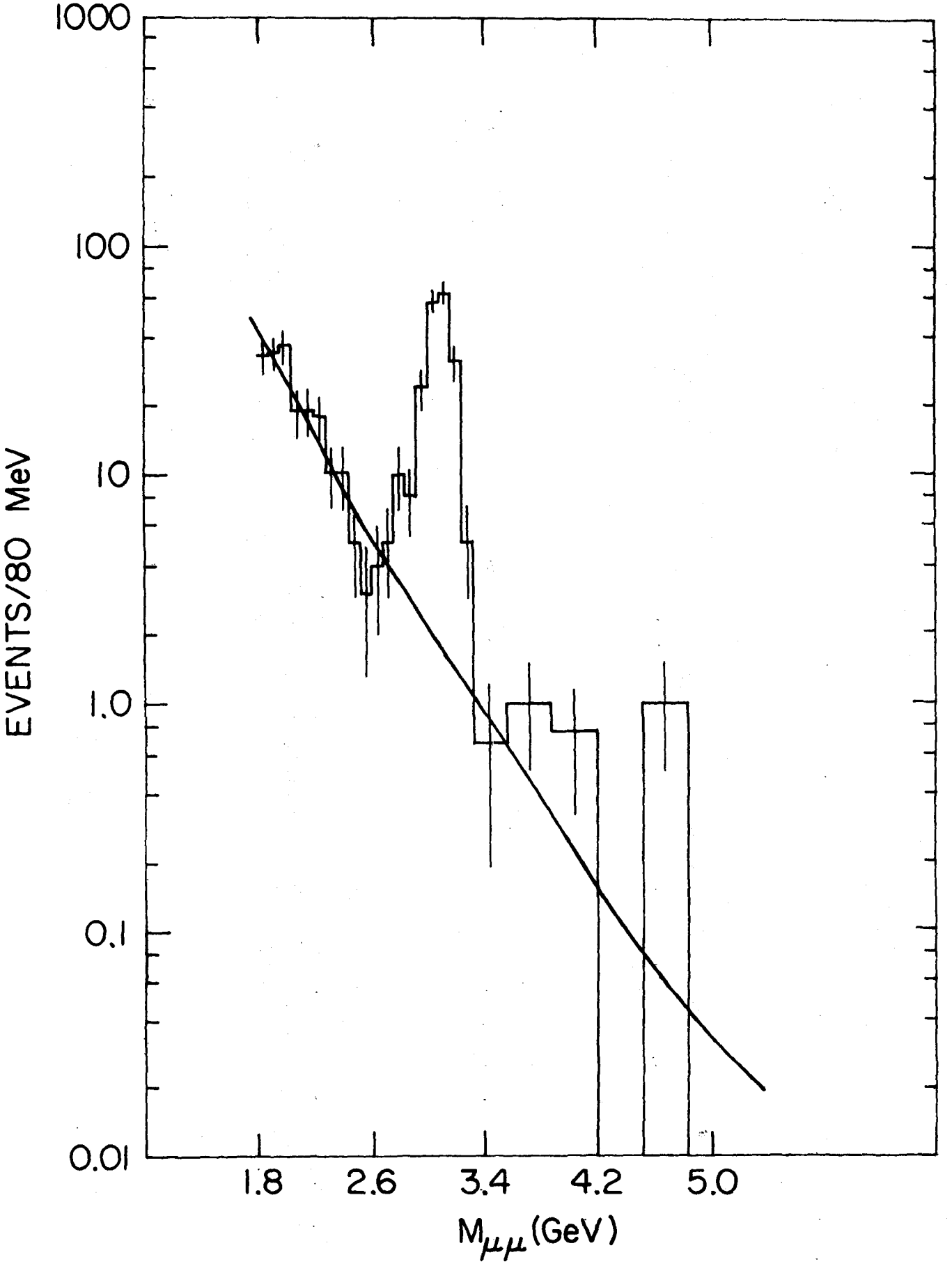

Fig. 3. The mass distribution of μμ events from 2.45 Be target with moderate intensity. The solid curve is the experimentally normalized predicted Bethe-Heitler distribution.

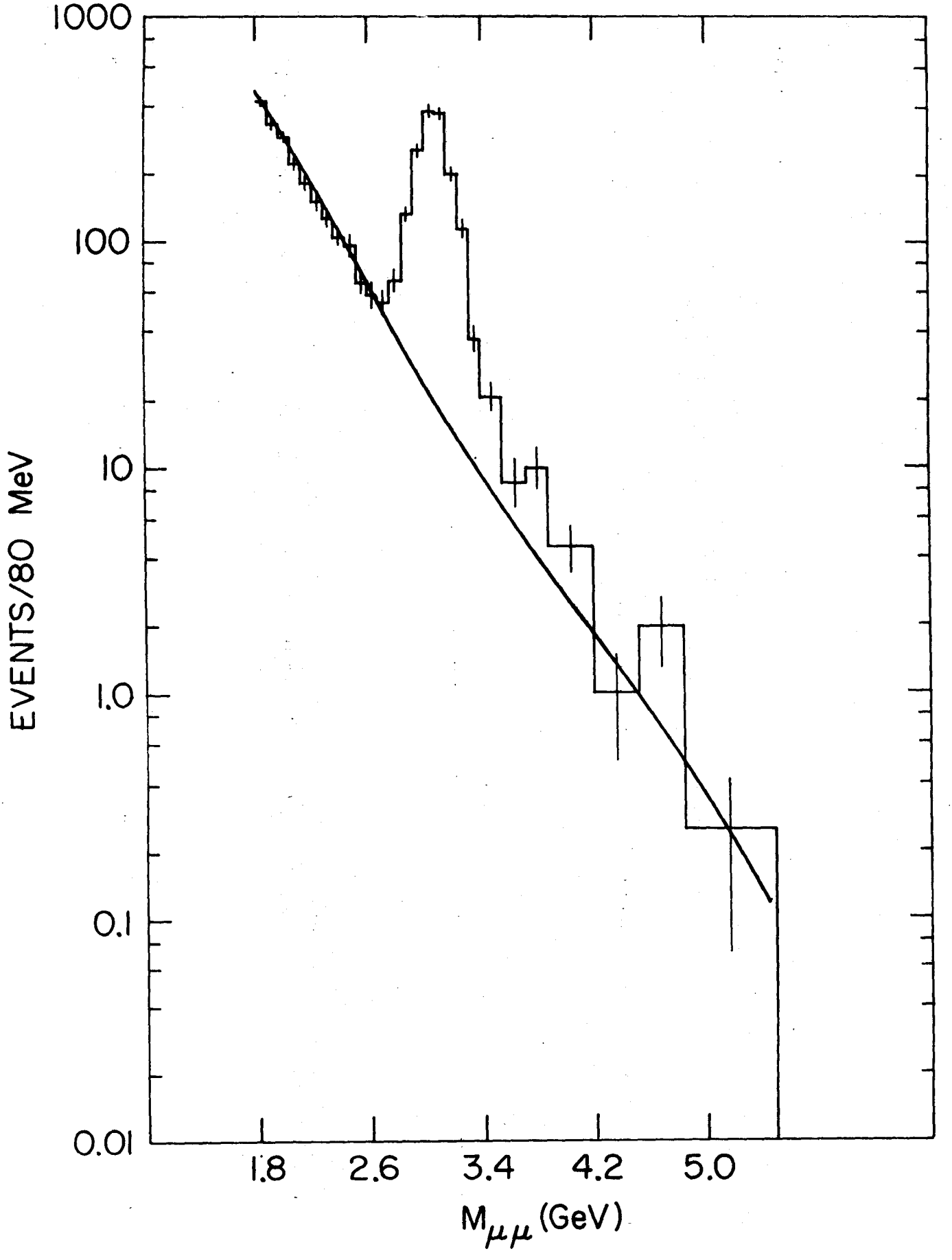

Fig. 4. The mass distribution of μμ events from all runs. The solid curve is the Bethe-Heitler distribution

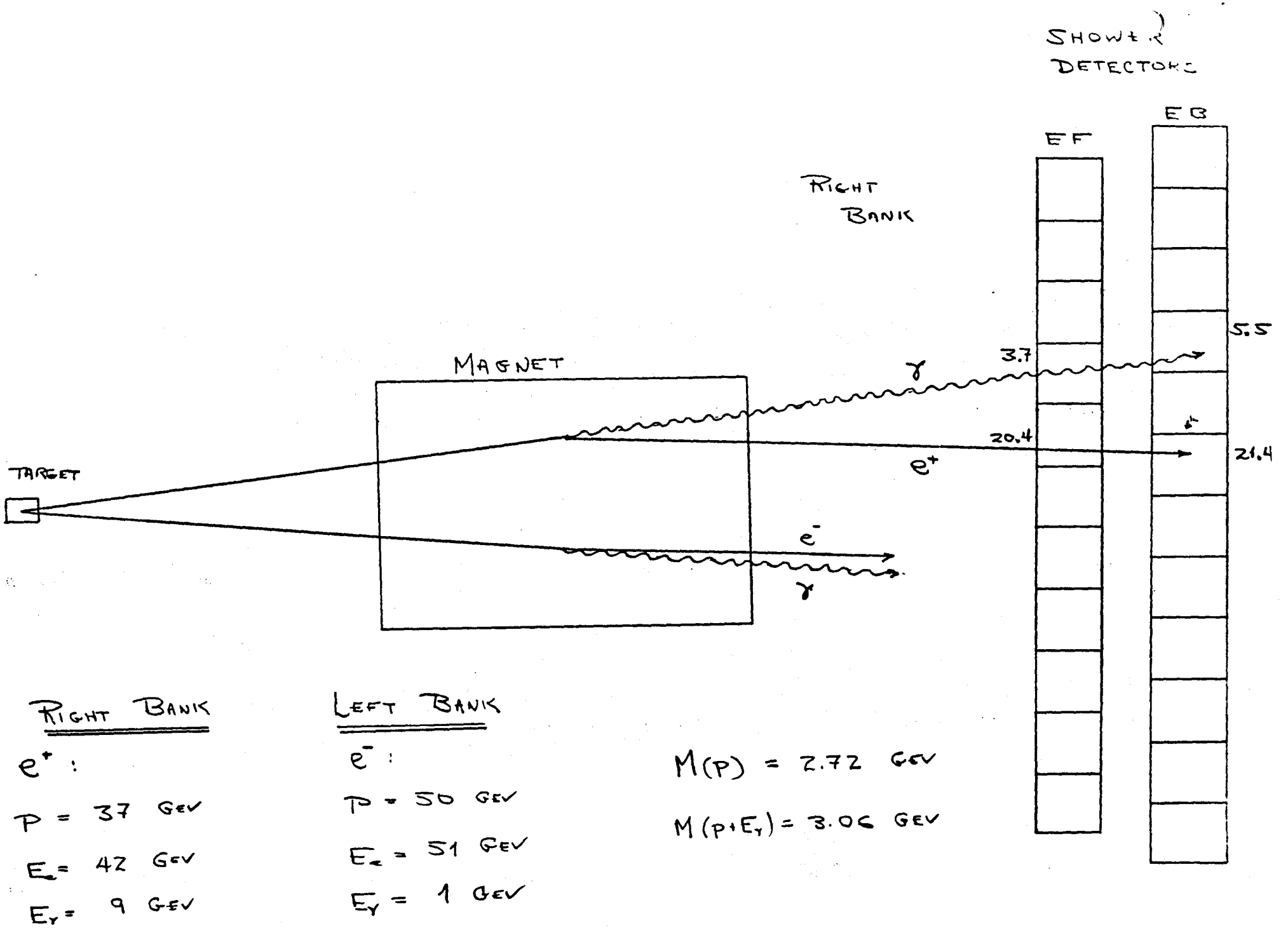

Fig. 5. An e^+e^- pair event with the accompanying bremsstrahlung.

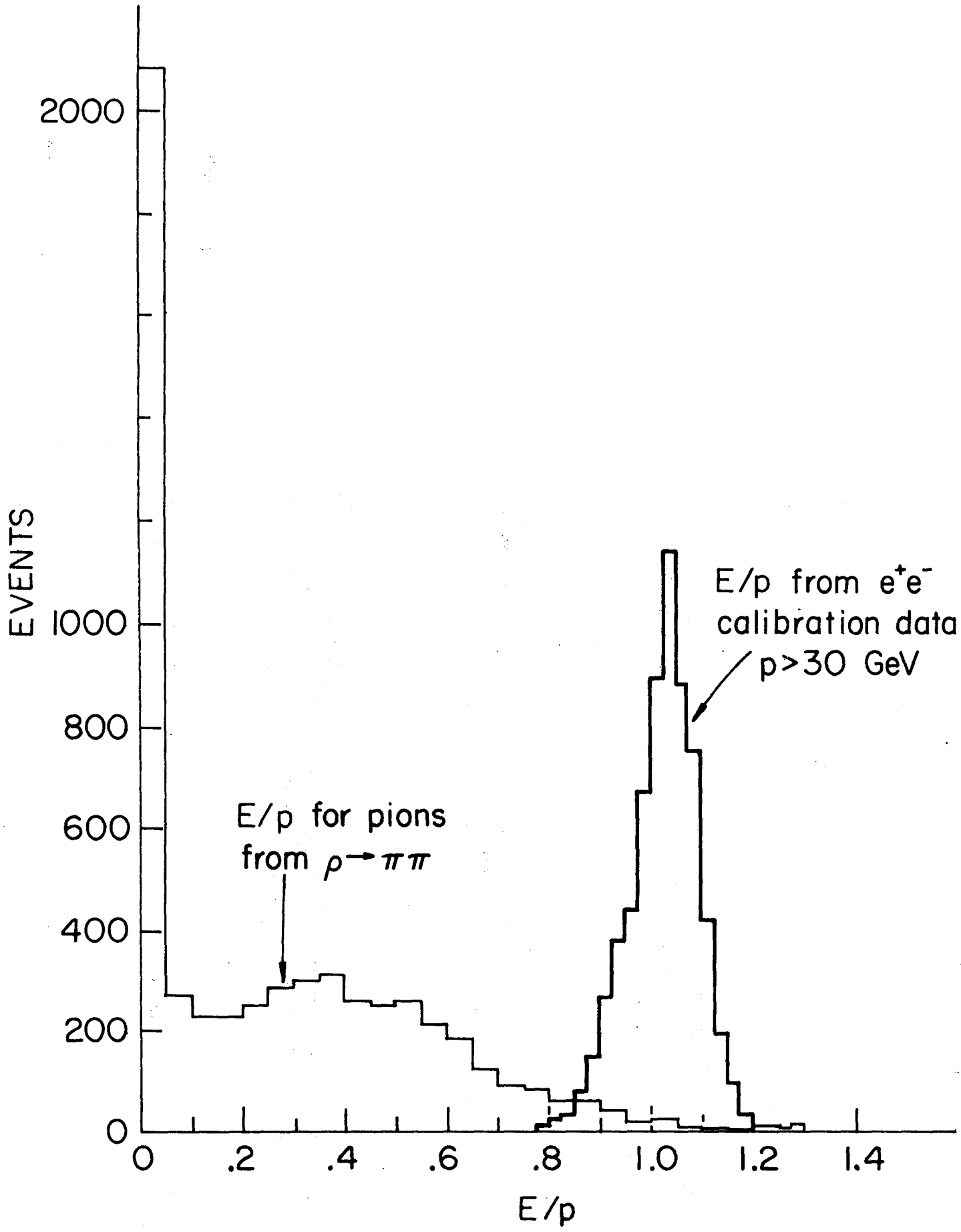

Fig. 6. $\frac{E}{p} \equiv \frac{\text{Energy measured in shower detector.}}{\text{Momentum of charged particle measured in spectrometer}}$ for pions and electrons.

Electrons are darker lines.

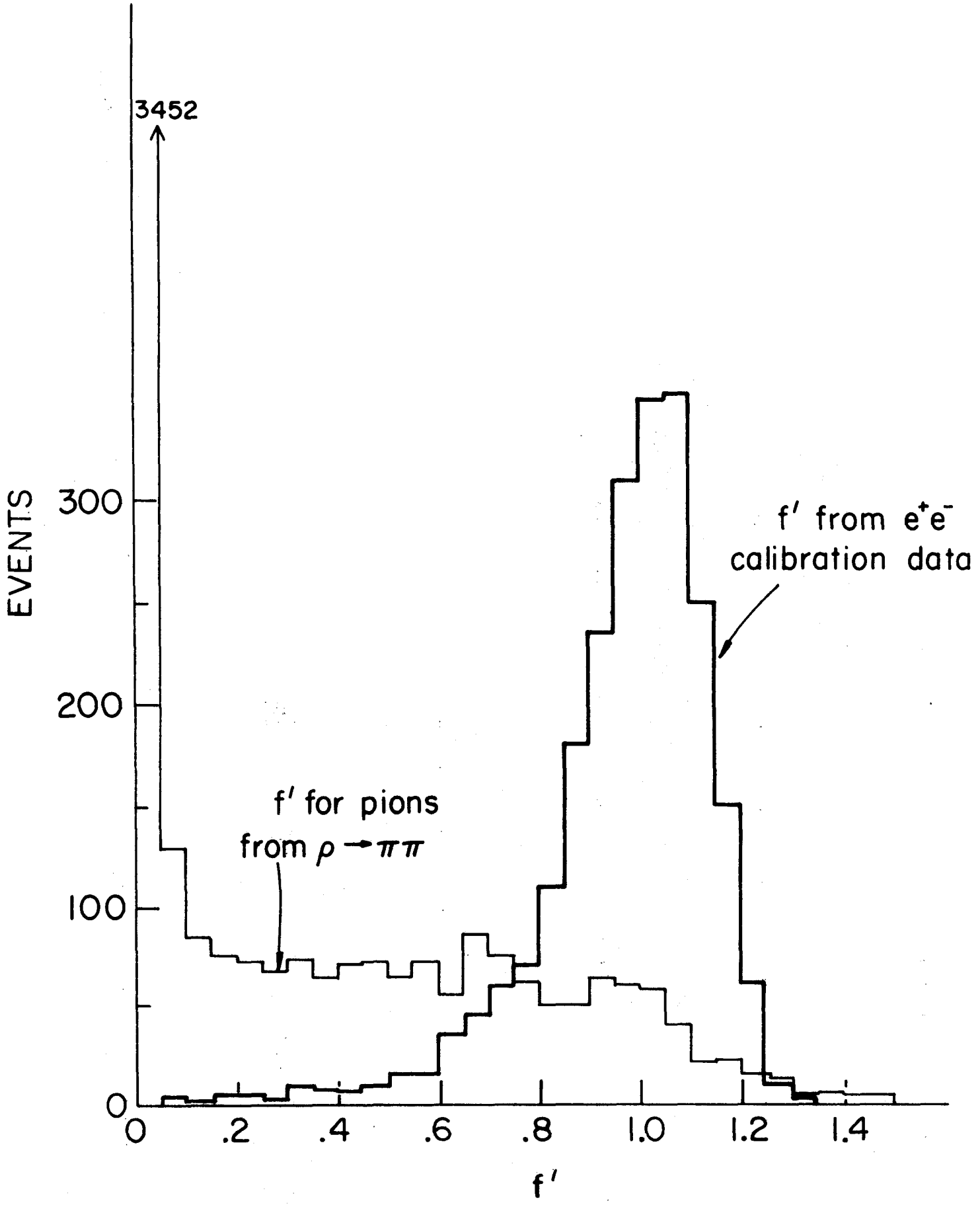

Fig. 7. $f' \equiv$ (Normalization) $\frac{\text{Pulse height in front shower detector}}{\text{Total pulse height in shower detectors}}$ for pions and electrons. Electrons are darker lines.

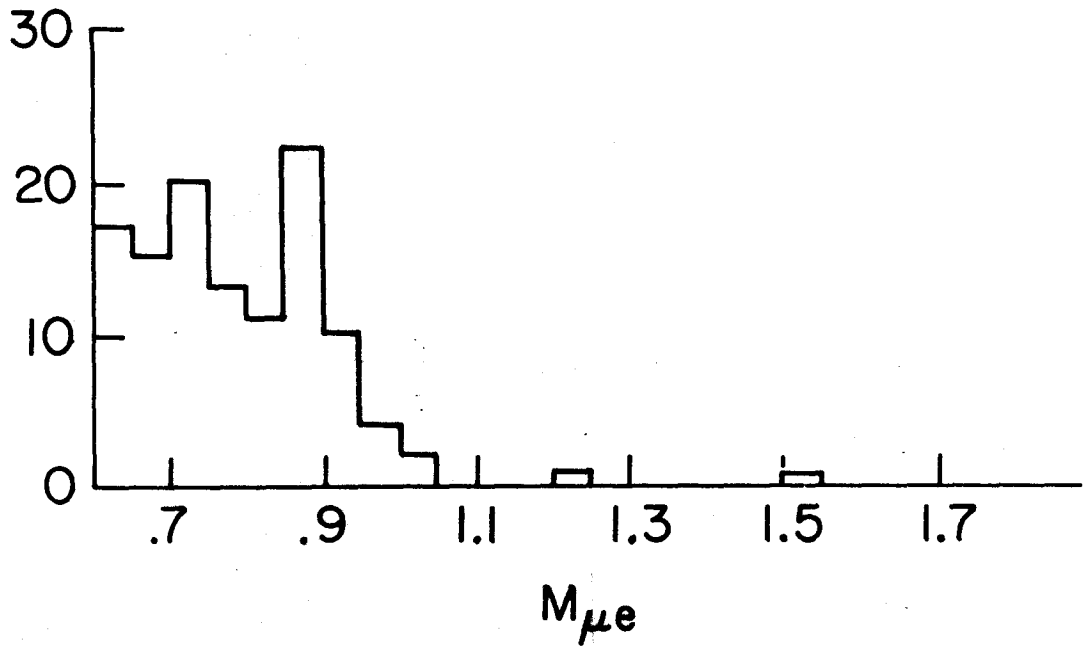

Fig. 8. Mass distribution for μe events above $M_{\mu e} > 0.6$ for Level III π/e rejection (see Table I)