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Studies of Compensation of Iron/TMP and Lead/TMP Sampling Calorimeters

WALIC Collaboration

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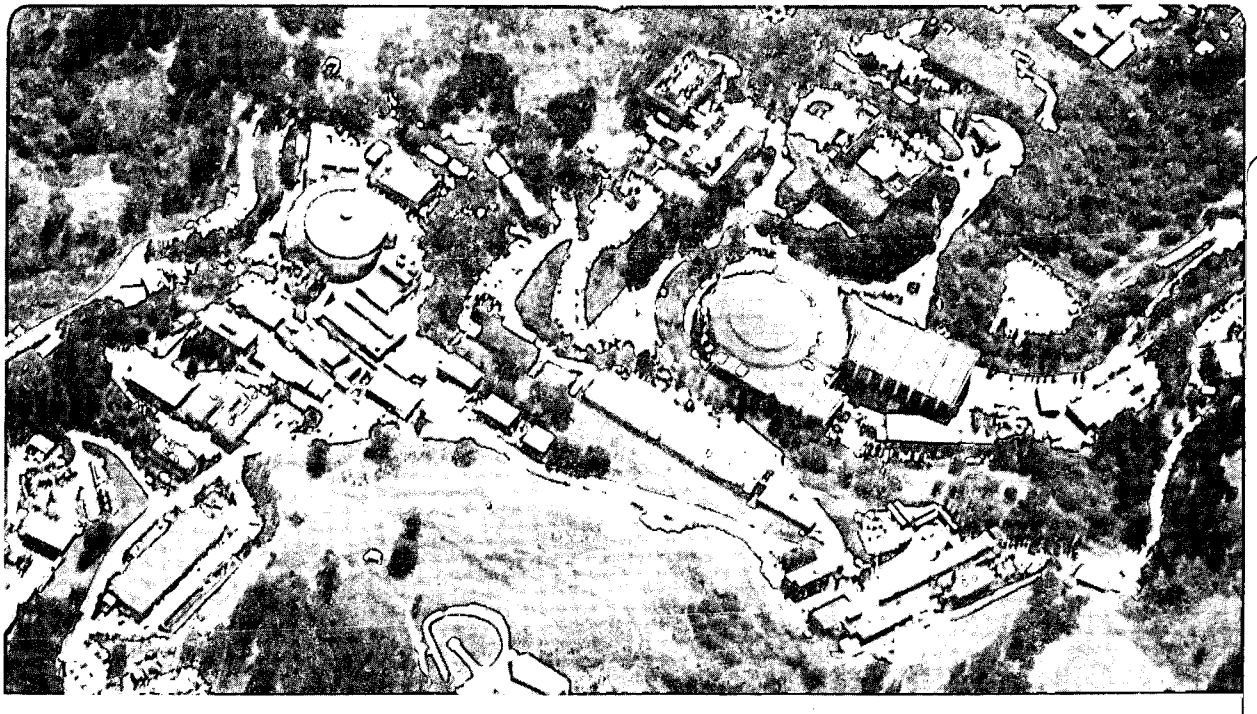

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Studies of compensation of Iron/TMP and Lead/TMP sampling calorimeters*

WALIC Collaboration

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ABSTRACT

We present results of an extensive study of the response of a modular TMP hadron calorimeter to electron and pion beams from 5 to 150 GeV/c. The signal response ratio, e/π, was measured as a function of both the absorber material type and the ratio of absorber-to-TMP thicknesses. The absorbers were iron, lead and aluminum-clad lead. A detailed comparison of all the results to a Monte-Carlo simulation is presented. The results with the lead absorber are consistent with those from a more limited study reported previously.

(Submitted to Nuclear Instruments and Methods A)

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1. Introduction

Optimum performance in a hadronic calorimeter can be achieved only if it is compensated, i.e. the responses to electromagnetic and hadronic particles of equal energies are equal, defined by: $e/h = 1$ [1,2]. As is well known, the fluctuations in the division of incident energy between these two types of particles is largely responsible for poor energy resolution in uncompensated calorimeters. Lack of compensation comes primarily from insensitivity to several sources of undetected hadronic energy loss, including nuclear binding energy and escaping neutrinos and neutrons. These losses can be partly offset by exothermic processes such as fission that occur more favorably in elements of high Z. A different but very important effect of high-Z absorbers on electromagnetic particles is the reduction of the electron signal response because of the relatively greater electromagnetic energy loss in the absorber than in the lower Z readout material. Thus, uranium has been emphasized as an absorber of choice, providing for both a reduced electron signal and an enhanced hadronic signal [1]. However, recent theoretical study [2] indicates that the signal equalization of e and h depends also very much on the properties of the readout material, including the free proton content: the presence of hydrogen allows the detecting medium to respond to fast neutrons, thereby considerably enhancing the hadronic signal. Therefore, it was expected that compensation could be achieved with a combination of hydrogenous active readout media and other passive absorber materials which are cheaper and more convenient to use than uranium.

The WArm LIquid Calorimetry (WALIC) collaboration has performed an experiment (E795) at Fermilab to make a systematic study of compensation by measuring e/π as a function of both the absorber material type and the thickness ratio of passive absorber-to-active detection medium. Since the quantities actually measured are the signal responses to electron and pion beams, we present the results for e/π instead of the inferred energy-independent ratio e/h, where h is the non-electromagnetic part of the hadron-induced shower. Lead, iron and aluminum-clad lead composite were the absorber materials used, in conjunction with the hydrogenous warm-liquid, 2,2,4,4 Tetramethylpentane (TMP), as the active medium. The calorimeter was highly-modularized [3], with TMP isolated from

the absorber plates to facilitate changes of configuration. Each gap of TMP had its own independent readout. This allowed for finely sampled measurements of the longitudinal shower development, with intervals as small as 0.1 interaction lengths for hadron showers and 0.8 radiation lengths for electromagnetic showers. The total calorimeter depth was 7 to 9 interaction lengths, depending on the configuration. The combined study, in one experiment with common systematics, of e/π and shower shape as a function of absorber type and thickness, provides a rigorous set of constraints for hadron calorimetery models.

Our first results obtained with the lead/TMP configurations have already been reported [3]. They indicate that e/π is not sensitive to the thickness ratio of lead/TMP. On the other hand, for large ionization density e/π is quite sensitive to ion recombination effects causing signal saturation, which in turn depends strongly on the applied electric field in the ionization gap [4,5]. Thus, e/π can be tuned by adjusting the electric field. Our saturation measurements [5] together with our measured e/π ratios [3], indicate that compensation can be achieved with a lead/TMP calorimeter for electric fields of about 20 kV/cm, a value which can be easily attained. Much higher fields would lead to overcompensation, that is, $e/\pi < 1$.

We report here our results from beam tests using absorbers of iron and composite aluminum-clad lead. These tests were done with approximately twice the number (70) of TMP detecting planes used in the initial study (34) with purely lead absorbers [3]. As a consistency check, one of the previous lead/TMP configurations was repeated with the new setup. This allowed for a more sensitive and direct comparison, presented below, of the results with lead and iron absorbers.

The study of the composite aluminum-clad lead absorber was for the purpose of determining the effect on the e/π ratio of atomic number, Z, of the material at the surface boundary between the absorber and the active medium. This "transition region effect" [6] is expected to affect primarily the electromagnetic shower component. The effect is attributed, in part, to the fact that the critical energy in the absorber is substantially less than in the active medium. Thus, electrons deposit much more energy in the higher Z absorbers. The low energy tail of this deposition extends into the active medium, in the

so-called "transition" region. In principle, therefore, by "cladding" the high-Z absorber plates with low-Z material to absorb this energy, the response of the active medium to electrons would decrease. A comparison was made of the responses obtained with aluminum-clad lead versus those with bare lead plates placed adjacent to the detecting planes. A large effect would be expected from the results of Mockett and Boulware [7], but subsequent simulation by Donahue and Groom [8] indicated it should be smaller. Recent measurements by Engler et al. [9], comparing lead and iron absorber boundaries, also showed a small effect, which was consistent with a GEANT simulation [10].

2. Experimental Setup

A complete description of the apparatus and the set-up in the beam is given in reference 3, with a brief summary of the main features provided below.

In order to permit the many configuration changes investigated, the calorimeter was designed to be highly modular. The TMP detector planes were isolated from the absorber plates. The liquid was contained in sealed, thin-walled (150μm), boxes of stainless steel, similar to those developed by the UA1 group at CERN [11]. Each box has dimensions approximately $30 \times 60 \times 0.3$ cm^3 with a four-electrode collecting plane centered in a 2.5 mm-thick gap of TMP. This provides two 1.25-mm active liquid gaps per electrode. Each electrode has lateral dimensions 13×26 cm^2, is 0.05cm thick, and was read out independently. As added structural protection, each box was enveloped by a 1-mm thick aluminum folder. For our measurements of e/π, two boxes were mounted one above the other in a hanger frame, forming a 60×60 cm^2 detecting plane of eight electrodes. This resulted in a small dead space, 0.6 cm high by 60 cm wide, between the TMP detecting volumes caused by the box boundaries. The operating electric field was 6.7 kV/cm.

A salient feature of the calorimeter was that each component (absorber plates, TMP box planes, etc.) was independently suspended by a frame hanging from a support structure. After each change of configuration, the entire stack was compressed to remove any excess space. In order to ensure a perfect flattening of the TMP boxes, "bladders" of thin-walled (150μm) stainless steel were inserted in every fourth gap between absorber

plates and were inflated with nitrogen gas. After each compression, the TMP gap width was found to be reproducible to within $\pm 5\%$, determined by measuring the capacitance to ground of each electrode. This was confirmed by comparing the signals from muon beams. The entire calorimeter was enclosed in a perforated aluminum Faraday cage which reduced the external rf noise by a factor of about 50,000 [3].

Figure 1 displays schematically the various configurations of the present study. The configuration with the maximum hydrogen content consists of a TMP plane, or its equivalent, after each absorber plate. With absorber plates 6.0 or 6.35 mm thick and TMP planes 2.5 mm thick, the absorber/TMP thickness ratio was approximately 2.5/1, the smallest ratio used in our tests. In this configuration, the TMP detector planes were actually placed after every second absorber plate and the alternate gaps were filled with an equivalent thickness of "dummy TMP planes" which had CH_2 as a substitute for TMP (C_9H_{20}), (fig. 1). This procedure of augmentation, used because there were insufficient TMP detectors to fill all the gaps, is similar to the procedure used in reference 3. The dummy boxes, of the same thickness (gm/cm^2) and effectively the same nuclear composition, represent TMP planes without signals. Thus, the combination of 70 TMP and 70 CH_2 planes was equivalent to 140 planes of TMP, with signals read from every second plane. This gives the same e/π ratio, but with a resolution degraded by the reduced sampling frequency. This was verified by the good agreement (see section 3.2 below) between the results from reference 3 for the lead "had.1" configuration, which had dummy boxes in three out of every four gaps, and those from the present lead configuration which had dummy boxes in only half the gaps. It is only this 2.5/1 configuration for lead and iron which required the use of dummy boxes (fig. 1). With iron absorbers, three configurations were investigated, corresponding to Fe/TMP nominal thickness ratios of 2.5/1, 15/1 and 30/1. For lead absorber only the 2.5/1 configuration was studied again. In reference 3 four hadronic configurations with lead absorber were studied, of which two, "had.1" and "had.3," had the same material as in the present investigation, corresponding to Pb/TMP thickness ratios of 2.5/1 and approximately 15/1.

To study the transition effect at a surface boundary, two configurations were required in order to change the boundary surface material in front and back of the TMP planes

while keeping the total composite absorber the same. In the so-called "aluminum-clad lead" configuration, with aluminum nearest the TMP (Al-Pb-Pb-Al in fig. 1), a sheet of 2 mm thick aluminum is followed by two plates of 6.35 mm thick lead, which in turn is followed by another 2mm thick aluminum sheet and then a TMP plane. This cell structure is repeated 70 times. The change from aluminum to a lead boundary near the TMP plane merely involved changing the order of the absorber plates, with a lead plate followed by the two aluminum sheets, and then by another lead plate preceding the TMP plane (Pb-Al-Al-Pb in fig. 1). In both cases, the total absorber has the same thickness and front and back symmetry about the TMP planes. Thus, the hadron showers should be relatively unchanged between the two configurations, whereas the electromagnetic showers are expected to be affected by the differences at the boundaries [8,10].

The data were collected from dedicated runs with electron and pion beams between 5 and 150 GeV/c. The beams were mostly, but not purely, of one kind of particle. The pion fraction in the "pion" runs varied between 70 and 95% at beam energies above 10 GeV and was about 30% at the lower energies. In the "electron" runs, taken only above 25 GeV/c, the electron fraction varied between 70 and 85%. The electrons were tagged by a Cherenkov counter at beam energies below 50 GeV/c and by a synchrotron radiation detector at higher energies. At 50 GeV/c both types of electron identification counters were used. After tagging, the small residual uncertainty in particle identification was accounted for from the measured longitudinal shower profiles in the calorimeter, which provide a distinctive signature for electrons and pions. The presence of electrons in pion runs (and vice versa) provided an important cross-check of the efficiency of the particle identification. To reduce the systematic uncertainty, the ratios of the signal responses, e/π, were taken from the same beam run, rather than from different electron and pion beam runs. The resulting systematic uncertainty in this ratio was 1-2%. Muons were identified by a muon counter located downstream of approximately 10 interaction lengths of calorimeter absorber.

Absolute calibration of the detector was provided by dedicated muon runs. The electronics response was continually monitored with special pedestal and gain runs immediately before and after each data-taking run. In addition, the presence of muons in

all data runs allowed for further monitoring of second-order corrections to these electronics constants. For the full complement of 70 TMP detecting planes, the rms pedestal variation was 1/5 of the most probable signal measured for 25 GeV/c muons.

3. Results

The results are presented here along with a discussion of the general features of the data. Comparison with Monte-Carlo simulation is provided below in section 4.

3.1 Spectra and Shower Profiles

Many of the properties of the calorimeter are directly evident in the plots of the signal response spectra. Figure 2 shows the pulse height spectra for beam particles (muons, pions and electrons) at 25 GeV/c for the iron (fig. 2a) and lead (fig. 2b) absorber configurations with the same absorber/TMP ratio of 2.5/1. In both cases, three peaks are clearly visible, with the separation between electron and pion peaks greater for the Fe/TMP configuration ($e/\pi = 1.43$) than that for Pb/TMP ($e/\pi = 1.23$). This indicates that iron is less effective than lead absorber for purposes of compensation. Another noticeable feature is that the electron signal resolution (width-to-peak ratio) is narrower in the iron than in the lead configuration. This is because the fewer radiation lengths per plane in the iron configuration give a greater sampling frequency.

The longitudinal profiles for electron and pion showers at 25 GeV/c are shown in fig. 3 for the Fe/TMP = 2.5/1 configuration. Here, each plane number corresponds to 0.10 interaction lengths and 0.84 radiation lengths. The pion shower is measured to a depth of 7 interactions length. The electron shower signal drops to zero near 25 radiation lengths. Figure 4 shows the results of a horizontal scan across the calorimeter for the Fe/TMP = 30/1 configuration at the same energy.

3.2 e/π

(a) Iron Absorber

In Table I, we list the e/π results as a function of the geometrical thickness ratio, Fe/TMP, for the three configurations, Fe/TMP = 2.5/1, 15/1 and 30/1. They are also plotted in fig. 5(a). The ratios are of the deposited energies in the liquid gaps and are not corrected for hadron shower leakage. The results are quite striking: For a very large change in the absorber/TMP ratio, from 2.5/1 to 30/1, the values of e/π change hardly at all! This is consistent with our previous observations with lead absorbers [3] over a smaller range of absorber thicknesses.

(b) Lead Absorber

The corresponding results for the one lead configuration repeated in this run, Pb/TMP = 2.5/1, are also listed in Table I and plotted in fig. 5(b). A comparison with our previous results for the analogous configuration, "had.1" in reference 3, shows good agreement at all the four energies (Table II). The agreement is a confirmation that the dummy boxes of CH_2 are a good facsimile of the TMP boxes for measuring e/π. Moreover, in comparing the lead- and iron- absorber results, we see that at each energy the value of e/π is definitely smaller for lead, as was indicated in the deposited energy spectra of fig. 2 for 25 GeV/c electrons and pions.

(c) Composite Aluminum-Lead Absorber

To study transition effects at the surface boundary between absorber and active medium, we took data with the composite absorbers described earlier, (Al-Pb-Pb-Al and Pb-Al-Al-Pb in fig. 1). The only difference between the two cases is the boundary material of the absorber. In the one case, there is a 2-mm thick sheet of aluminum at the boundary with the TMP box, and none at this boundary in the second case. However, because the TMP boxes themselves have a protective folder cover of 1-mm thick aluminum, the true difference in the configurations is 3 mm versus 1 mm of aluminum.

The results are listed in Table I and shown in fig. 6. The e/π values for the Pb-Al-Al-Pb configuration are about 2% greater than for the "aluminum-clad" lead configuration (Al-Pb-Pb-Al).

4. Comparison of Results with Monte-Carlo Simulation

As in our previous study [3], we simulated the response of the detector for each configuration by using the GEANT 3.14 code [10] associated with the Gheisha 8 code [12] for the generation of hadron showers. This package simulates electron or hadron showers, following particle energies down approximately to the critical energy. In addition, an important requirement of this simulation for e/π studies is to parameterize accurately the yield of ionization electrons in the TMP liquid as a function of the energy loss density per unit length, dE/dx. In particular, it is essential to include properly the saturation of the signal at large ionization densities due to recombination, an important effect in TMP [5]. This was done using Birks' law [13], where the saturation (Birks') constant, K_b, has been parameterized ad hoc as a function of electric field strength and the angle between the particle and electric field directions, in accordance with our measurements [5] of this functional dependence. More details are provided in reference 3. As stated previously [3], the experimental error in K_b gives an overall uncertainty of approximately 10% in the simulation values of e/π. However, for a given beam energy, this uncertainty is fully correlated among configurations, so that comparisons of configurations should be more precise.

The simulated longitudinal distributions of electron and pion showers agree quite well with the measured data, as shown in fig. 3 for the finest hadronic sampling configuration, Fe/TMP = 2.5/1. Likewise, the lateral profile from the horizontal beam scan of configuration Fe/TMP = 30/1, shown in fig. 4, is also well reproduced. This agreement suggests that the Monte-Carlo can be used to estimate reliably the leakage of hadronic showers out of the calorimeter. We did so by simulating infinite size calorimeters of each configuration for comparison and thereby determined the total (i.e. lateral plus longitudinal) leakage of the measurable hadronic signal. Most of the leakage is lateral. We find

the total measurable signal leakage to be 7±2%, the same, within the errors, for all the configurations and energies. This value is the reduction correction to be applied to our measured e/π values to obtain the values expected for an infinitely large calorimeter.

As for the more complex predictions of compensation, that is, e/π, the Monte-Carlo simulates well the general features for the Fe/TMP configurations, within the normalization uncertainties, as can be seen in fig. 5(a). The principal conclusions are: (i) there is very little dependence of e/π on the ratio of Fe-to-TMP thickness; (ii) the energy dependence is in reasonable agreement, and (iii) the e/π values are larger (worse) for iron than for lead absorbers. A striking feature is the prediction that e/π would still be far from unity even if the calorimeter were operated at higher electric fields (e.g., $E \simeq 40$ kV/cm), where the saturation effects of the ionization signal are considerably reduced. This indicates that, in contradiction with a prediction by Wigmans [2], an iron/TMP calorimeter can never be fully compensating, regardless of electric field and the ratio of iron-to-TMP thickness.

Figure 5(b) shows the corresponding predictions for the Pb/TMP configuration, which also agree reasonably well with the data. An interesting feature is the prediction that $e/\pi \lesssim 1$ at a larger electric field of 40 kV/cm. For a much larger calorimeter with smaller leakage corrections, this means $e/\pi < 1$, that is, slight overcompensation. The simulation predicts $e/\pi = 1$ for electric fields of about 20 kV/cm for an infinitely large calorimeter. Thus, unlike the case for iron absorber, one can obtain compensation with a lead-TMP calorimeter at an electric field which is easily achievable in a TMP calorimeter of a more traditional design, such as the "swimming-pool" configuration with the absorber immersed in the liquid. We have already built and successfully operated such a calorimeter prototype at fields as high as 35 kV/cm; results are being prepared for publication.

For the transition effect at the absorber-TMP boundary, the simulation predicts a small difference, approximately 2%, in e/π between the Pb-Al-Al-Pb and Al-Pb-Pb-Al composite absorbers. This value agrees rather well with our data in both sign and magnitude of the effect, as seen in fig. 6. Furthermore, according to the Monte-Carlo

simulation, the maximum value of this effect for any thickness would be less than 5%, compared with the case for no aluminum whatsoever at the boundary of lead and TMP. Thus aluminum cladding of absorber can have but a small effect on e/π.

5. Conclusions

- e/π is larger in iron/TMP than in lead/TMP calorimeters.
- Compensation ($e/\pi = 1$) cannot be achieved with an iron/TMP calorimeter, but is achievable with a lead/TMP calorimeter for electric fields of about 20 kV/cm.
- e/π is very sensitive to signal saturation for large ionization density and therefore, to electric field strength. Thus, e/π can be tuned by adjusting the electric field strength. At the relatively small electric field (6.7 kV/cm) used in these tests, saturation effects in TMP are quite important.
- e/π is insensitive to the thickness ratio of absorber/TMP, for both Pb and Fe absorbers.
- Comparison of e/π for different materials at absorber-TMP boundaries confirm transition effects, which are well simulated by GEANT-Gheisha Monte-Carlo. Aluminum cladding of lead has a definite but small effect, decreasing e/π by up to 5%.
- The Monte-Carlo GEANT 3.14 and Gheisha 8, reproduces the general behavior of e/π versus energy reasonably well for the wide variety of configurations considered here, and to within about 5% in normalization. It also simulates very well the transverse and longitudinal shower distributions.

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Figures

1. Schematic of calorimeter configurations; the beam direction is from left to right.

2. Calorimeter response for muons, pions and electrons at 25 GeV/c for: (a) iron absorber configuration Fe/TMP = 2.5/1 and (b) lead absorber configuration Pb/TMP = 2.5/1. Deposited energy in TMP(MeV).

3. Electron and pion longitudinal shower distributions at 25 GeV/c for configuration Fe/TMP = 2.5/1. Each plane corresponds to 0.10 interaction lengths and 0.84 radiation lengths in depth. The curves are from the Monte-Carlo simulations discussed in the text.

4. Horizontal beam scan profiles across the calorimeter for electron and pion beams at 25 GeV/c, for configuration Fe/TMP = 30/1. The curves are from the Monte-Carlo simulations discussed in the text. The segmented lines near the bottom indicate the tower positions laterally.

5. e/π as a function of energy for: (a) iron absorber configurations, Fe/TMP = 2.5/1, 5/1, and 30/1; (b) lead absorber configuration, Pb/TMP = 2.5/1. The curves labelled MC are the Monte-Carlo simulation for these configurations. The dashed curves labelled MC (2.5/1, E=40kV/cm, K_b = 0.086cm/MeV) are the predictions from the Monte-Carlo, with the TMP ionization signal saturation parameter, Birks' constant K_b, corresponding to that measured for an electric field of 40 kV/cm (ref. 5).

6. e/π as a function of energy for composite Al-Pb-Pb-Al and Pb-Al-Al-Pb absorbers. The curves labelled MC are the corresponding Monte-Carlo predictions with the overall normalization reduced by 6%.

Table I. Measurements of e/π for the various configurations, from deposited energy in the calorimeter liquid. (Errors represent the sum of systematic and statistical errors in quadrature. The systematic errors are dominant.)

Configuration	Beam Momentum (GeV/c)	e/π
Fe/TMP=2.5/1	10	1.47 ± 0.06
	25	1.43 ± 0.03
	50	1.40 ± 0.03
	100	1.42 ± 0.03
	150	1.38 ± 0.03
Fe/TMP=15/1	8.5	1.41 ± 0.05
	25	1.34 ± 0.03
	50	1.32 ± 0.03
	100	1.30 ± 0.03
	150	1.28 ± 0.02
Fe/TMP=30/1	8.5	1.46 ± 0.06
	25	1.32 ± 0.03
	50	1.34 ± 0.03
	100	1.26 ± 0.03
	150	1.24 ± 0.02
Pb/TMP=2.5/1	5	1.54 ± 0.11
	10	1.29 ± 0.03
	25	1.23 ± 0.02
	50	1.22 ± 0.02
	100	1.20 ± 0.02
	150	1.16 ± 0.03
Pb-Al-Al-Pb	8.5	1.19 ± 0.03
	25	1.17 ± 0.02
	50	1.17 ± 0.02
	100	1.16 ± 0.02
	150	1.16 ± 0.02
Al-Pb-Pb-Al	8.5	1.19 ± 0.03
	25	1.14 ± 0.02
	50	1.13 ± 0.02
	100	1.12 ± 0.02

Table II. Comparison of e/π from different sampling fractions: TMP detectors in every fourth gap versus every second gap, and dummy CH_2 boxes in all the other gaps. In both cases, Pb/hydrogen ratio is the same.

Beam Momentum (GeV/c)	e/π from configuration "had.1" of ref. 3 (TMP in every 4th gap)	e/π from present Pb/TMP=2.5/1 configuration (TMP in every 2nd gap)
5	1.40± 0.08	1.54 ± 0.11
10	1.31± 0.02	1.29 ± 0.03
25	1.27± 0.01	1.23 ± 0.02
50	1.22± 0.02	1.22 ± 0.02

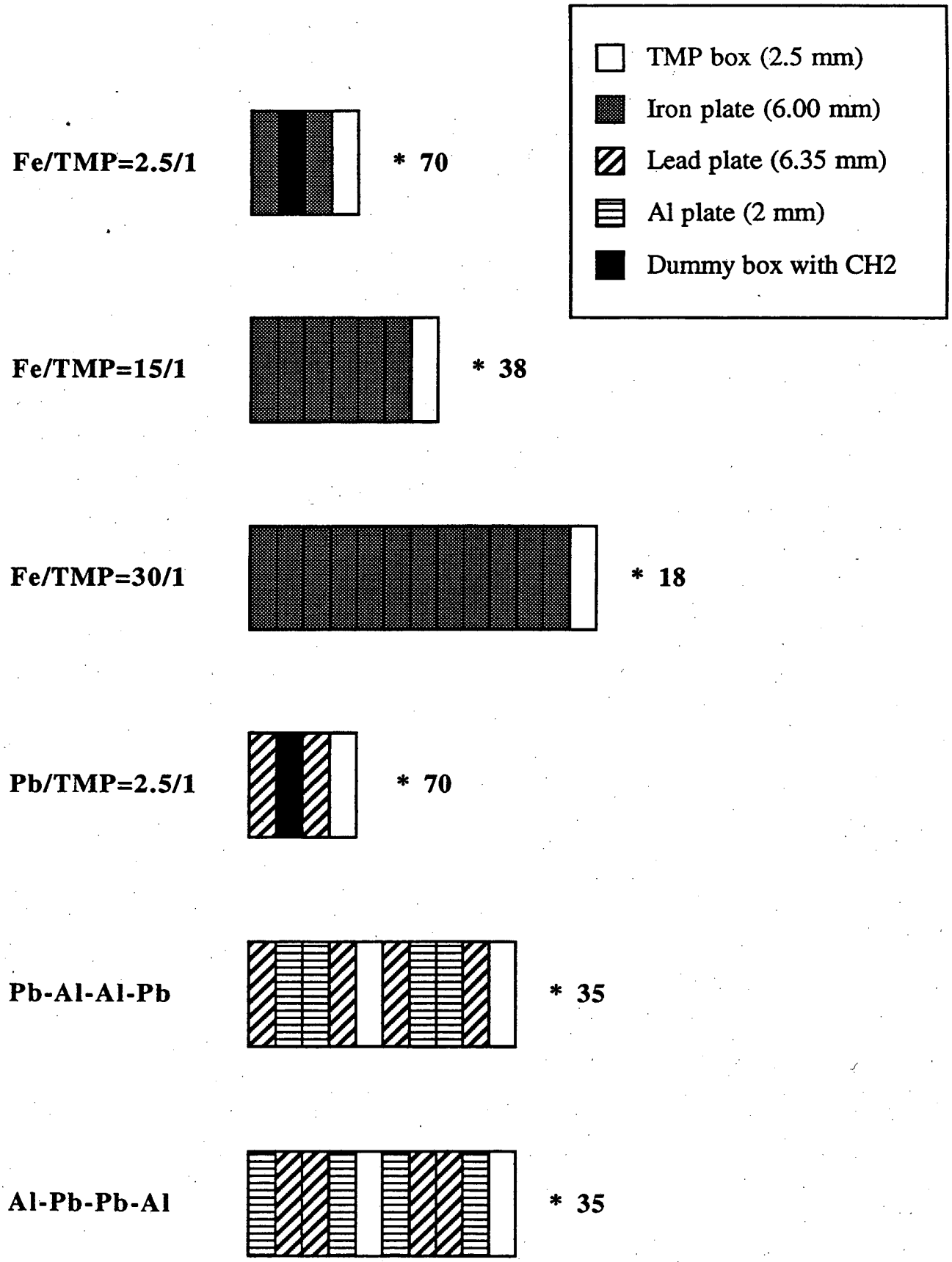
TMP box (2.5 mm)
Iron plate (6.00 mm)
Lead plate (6.35 mm)
Al plate (2 mm)
Dummy box with CH2
Fe/TMP=2.5/1
* 70
Fe/TMP=15/1
* 38
Fe/TMP=30/1
* 18
Pb/TMP=2.5/1
* 70
Pb-Al-Al-Pb
* 35
Al-Pb-Pb-Al
* 35

Figure 1

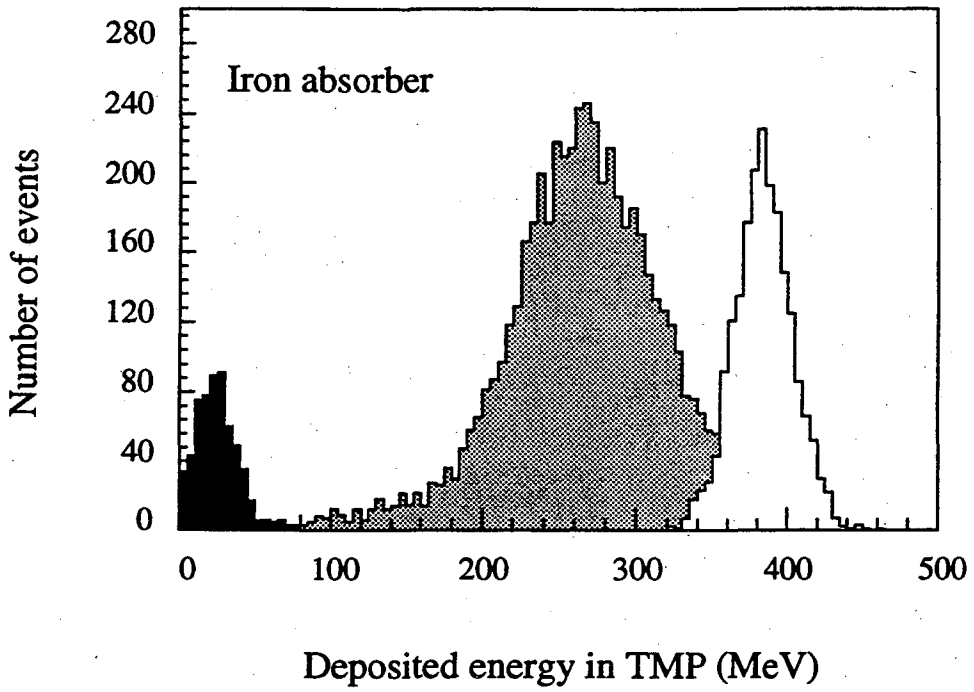

Figure 2.a

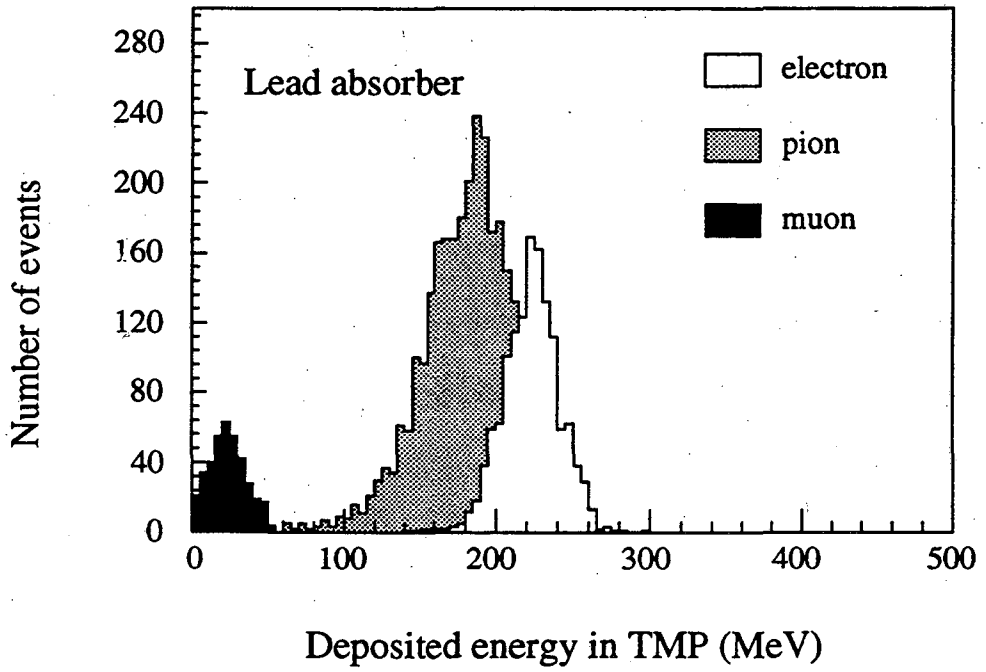

Figure 2.b

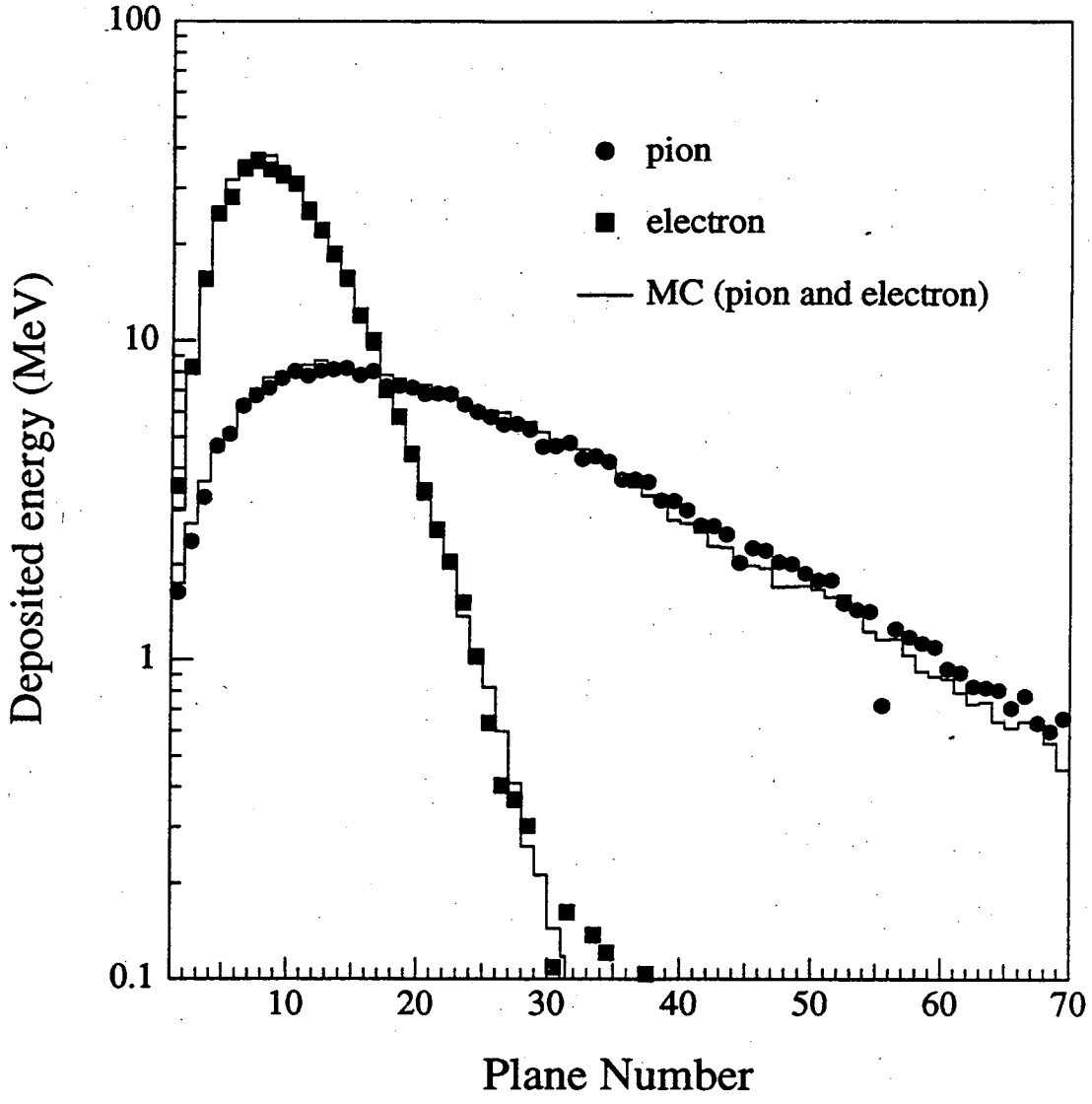
100
10
1
0.1
Deposited energy (MeV)
pion
electron
MC (pion and electron)
10
20
30
40
50
60
70
Plane Number

Figure 3

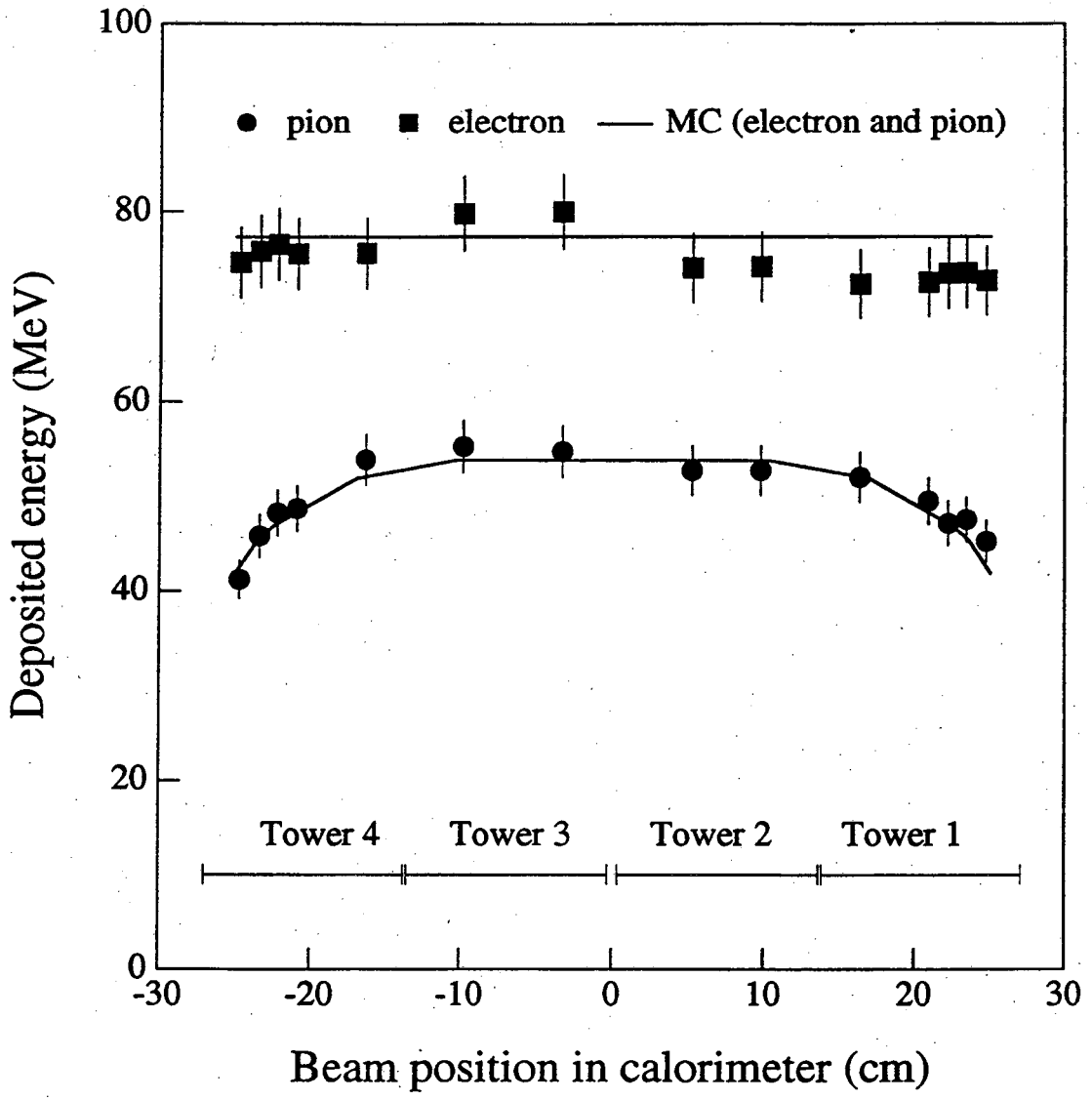
100
80
60
40
20
0
-30
-20
-10
0
10
20
30
pion
electron
MC (electron and pion)
Tower 4
Tower 3
Tower 2
Tower 1
Deposited energy (MeV)
Beam position in calorimeter (cm)

Figure 4

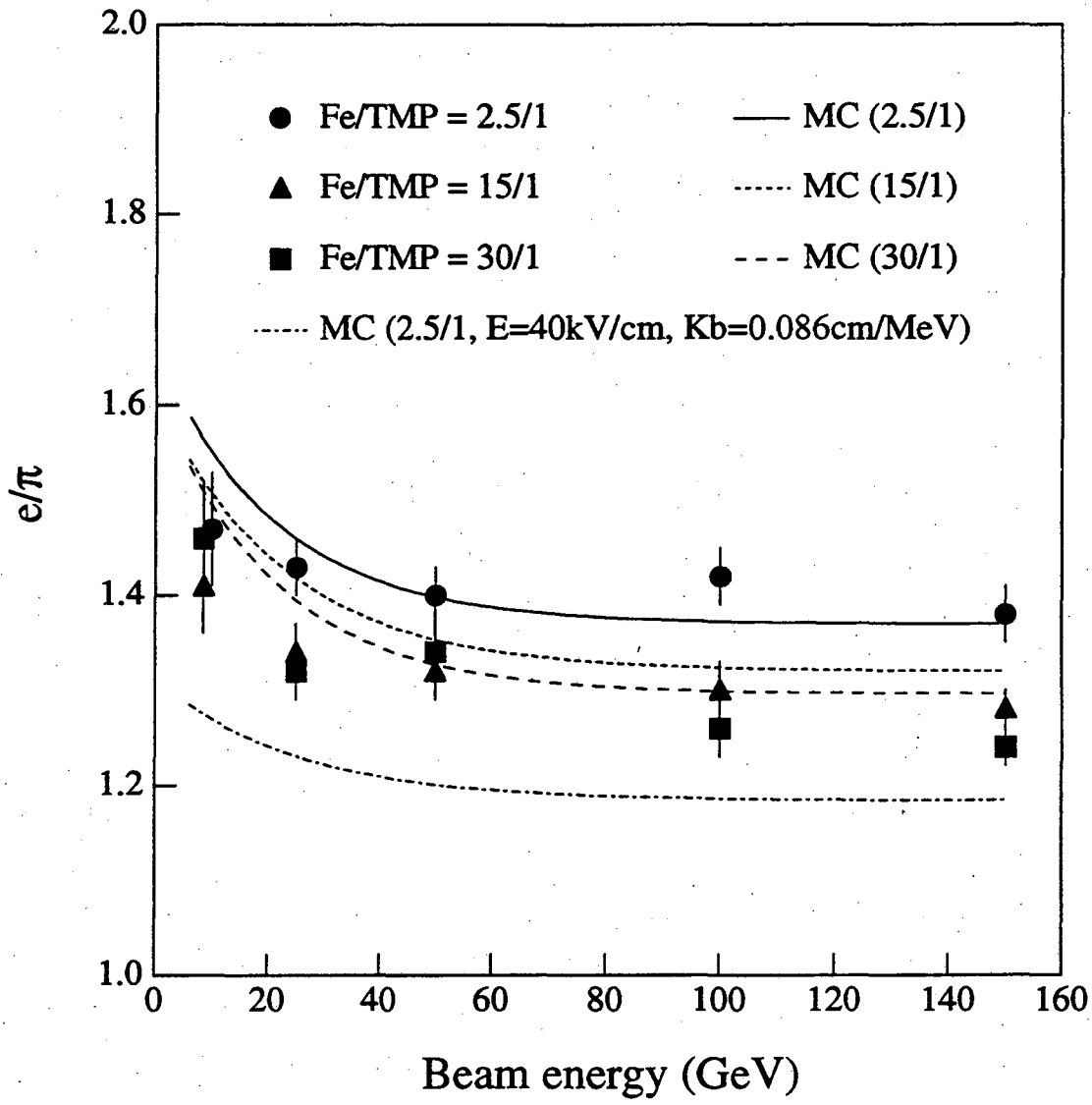
2.0
1.8
1.6
1.4
1.2
1.0
e/π
Fe/TMP = 2.5/1
Fe/TMP = 15/1
Fe/TMP = 30/1
MC (2.5/1)
MC (15/1)
MC (30/1)
MC (2.5/1, E=40kV/cm, Kb=0.086cm/MeV)
0
20
40
60
80
100
120
140
160
Beam energy (GeV)

Figure 5.a

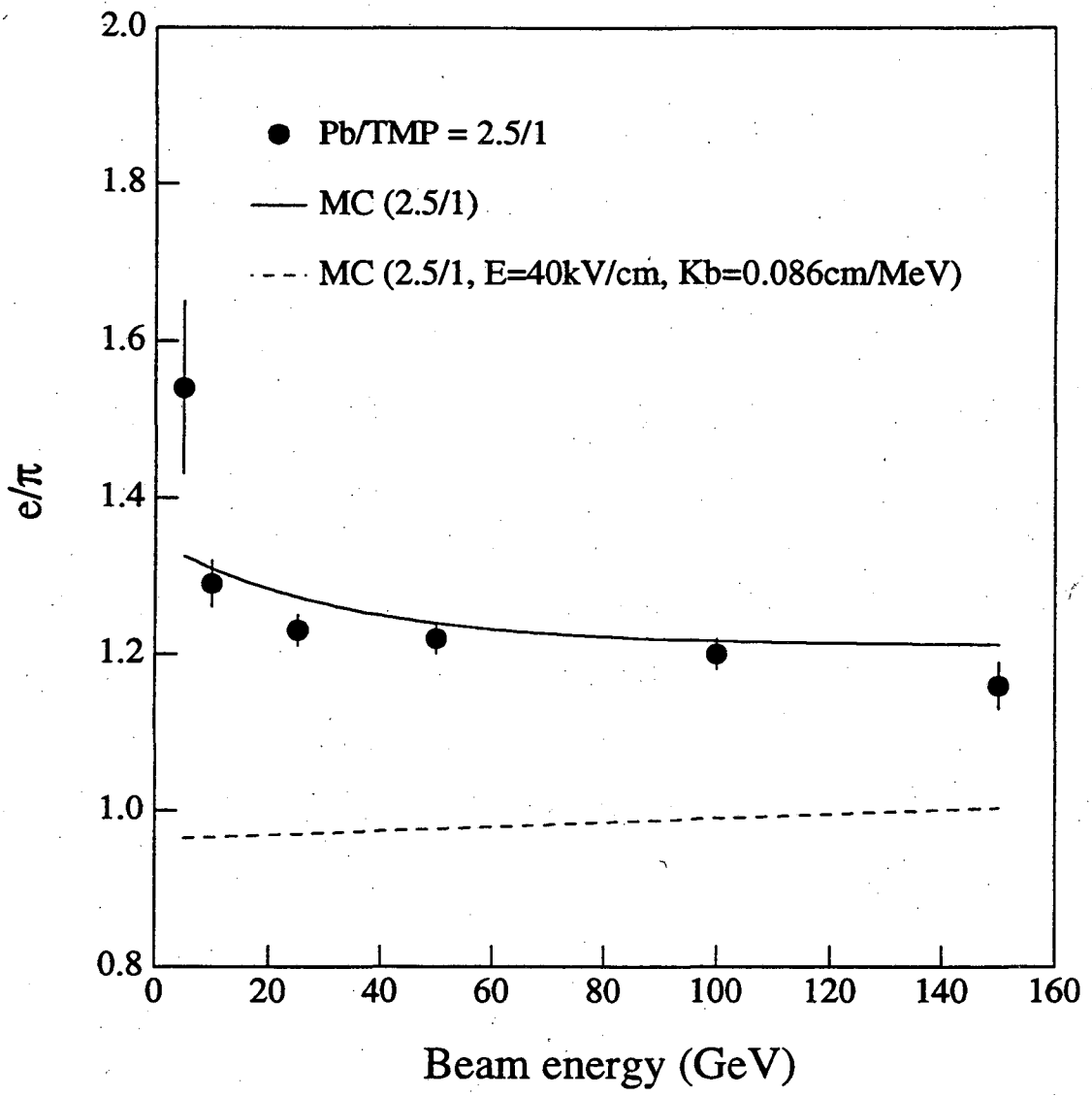
Pb/TMP = 2.5/1
MC (2.5/1)
MC (2.5/1, E=40kV/cm, Kb=0.086cm/MeV)
e/π
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0
20
40
60
80
100
120
140
160
Beam energy (GeV)

Figure 5.b

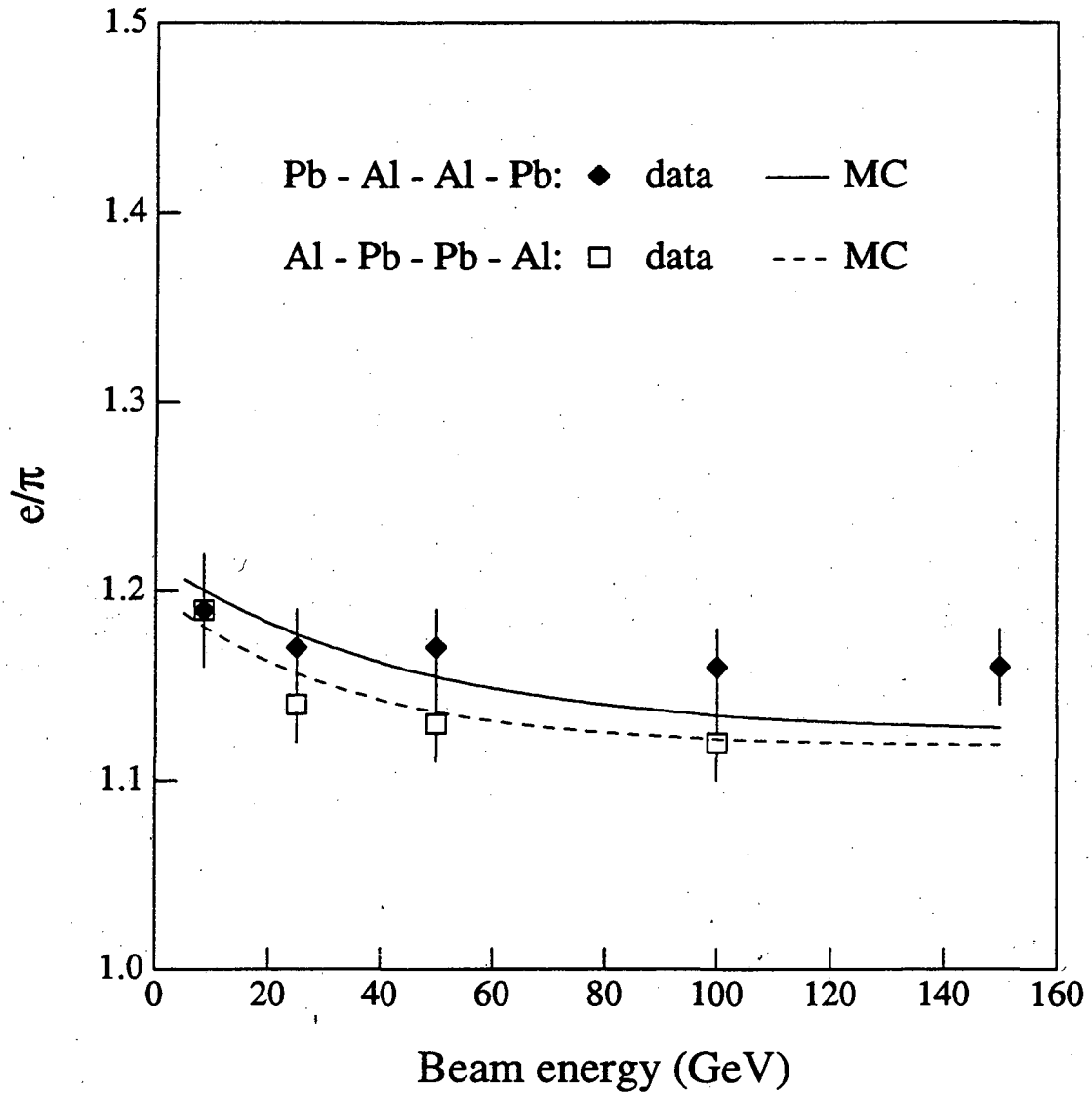
Pb - Al - Al - Pb: ◆ data —— MC
Al - Pb - Pb - Al: □ data - - - MC
e/π
1.5
1.4
1.3
1.2
1.1
1.0
0
20
40
60
80
100
120
140
160
Beam energy (GeV)

Figure 6

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