Performance of Preshower and Shower-maximum Detectors with a Lead/Plastic-scintillator Calorimeter

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Abstract

The electron/hadron separation in the calorimetry can be improved if we measure an early stage of the electromagnetic shower development. The incident positions of electrons and photons can be precisely measured with a position sensitive detector placed near the electromagnetic shower maximum. We constructed a set of prototype preshower and shower-maximum detectors to be attached in front of a main calorimeter. Performance of the detectors was studied in combination with a lead/plastic-scintillator calorimeter module using high energy beams up to 100 GeV at a test beam facility at Fermi National Accelerator Laboratory.

Key words: calorimeter, preshower, shower-maximum, electron identification, position resolution
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1 Introduction

A high performance calorimetry is required for future linear collider experiments to fully achieve the physics research [1]. First of all, the calorimetry is required to have excellent energy resolutions both for electromagnetic and hadronic showers. The target energy resolutions are determined so that Z and W jets are well discriminated by reconstructed hadron jet masses. We are going to realize the target energy resolutions with a hardware-compensating calorimeter with tile/fiber readout technique as the primary candidate. The hadron (electromagnetic) calorimeter will have a sandwich structure with 8 (4) mm-thick lead plates and 2 (1) mm-thick scintillator plates. For a series of R&D studies, we constructed a hadron calorimeter module. Performance of the module was evaluated with test beam facilities at High Energy Accelerator Research Organization (KEK) and at Fermi National Accelerator Laboratory (FNAL) [2,3].

In addition to the excellent energy resolutions, the calorimetry is desired to have

- good electron identification capability,
- good photon identification capability against π^0, and
- good position resolution for photons and electrons,

for precise tests of the standard model as well as for new particle searches. Our early work on the electron identification and the position resolution can be found in [4,5], where performances of a preshower detector, a Si-pad detector, and a lead-scintillation fiber calorimeter were evaluated using a test beam facility at KEK. Some of previous studies by other groups can be found in [6–11].

In order to improve the performance, we newly constructed a preshower detector (PSD) and a shower-maximum detector (SMD) using the same tile/fiber technique as the hadron calorimeter module. The PSD measures an early stage

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of the shower development and discriminates electromagnetic showers from hadron showers. The SMD is a position sensitive detector placed near the electromagnetic shower maximum, and measures the shower position and the lateral shower spread. The SMD can also be used for electron identification. The two detectors were tested in combination with the hadron calorimeter module at a test beam facility at FNAL. The nominal beam momentum was set to be 50, 75, and 100 GeV where good electron and pion samples were obtained. We present the results in this paper.

2 Detector Description

Before describing the PSD and the SMD, we briefly describe the hadron calorimeter module which was tested in combination with them. A more detailed description of the hadron calorimeter module and its performance can be found in an accompanied paper [3]. The module consists of lead absorber and scintillator plates of a "hanging file" configuration, where the plates are hung over a pair of parallel beams. The module has a cross-section of 1000×1000 mm^2 and has a total of 130 layers, where a layer consists of an 8 mm-thick lead plate and a 2 mm-thick scintillator plate. Kuraray SCSN38 polystyrene-based scintillator plates are used.

The first 80 layers, called FCAL, make a 5×5 tower structure and are divided into four longitudinal sections (20 layers for each). The thickness of a section is 28.8 X_0 in radiation length and 1.04 λ_I in nuclear interaction length. On the other hand, remaining 50 layers, called RCAL, have no such tower structure and each five successive layers make a superlayer. The most downstream RCAL superlayer has no lead absorbers, and is used as a leak-veto counter. The total thickness of the RCAL is 64.5 X_0 and 2.22 λ_I.

A tile/fiber technique [12,13] is employed for the optical readout system. Scintillator plates are grooved to place wavelength shifter (WLS) fibers being spliced to a clear fiber at the end. In the FCAL, 2 mm-thick fiber routing plates made of acrylic plastic are used. Each 20 successive clear fibers of a FCAL tower are bundled. Clear fibers from a superlayer of the RCAL are bundled at each of left and right ends. The clear fiber bundles are connected to photo-multiplier tubes (PMTs). Fine-mesh PMTs (Hamamatsu H6614-01) are used for sections 1 and 2 of the central tower to avoid saturation, while conventional PMTs (Hamamatsu H1949) are used for others. The FCAL and the RCAL have 100 and 20 signals in total, respectively.

The PSD and the SMD are designed to have an effective cross-section of 200×200 mm^2, to cover the front surface of the central FCAL tower. The tile/fiber technique is also employed in the readout system. Polystyrene-based scintillator (Bicron BC408), WLS fibers (Kuraray Y11 multi-clad) and clear fibers (Kuraray clear-PSMS) are used both for the PSD and the SMD.

The PSD consists of six layers of a lead absorber plate and a plastic scintillator plate in a sandwich structure. A schematic view of the PSD is shown in Figure 1. The thicknesses of the lead plate and the scintillator plate are chosen to be 4 mm and 1 mm, respectively, to keep the same volume ratio (4:1) as the FCAL and the RCAL. The total thickness of the PSD is 4.3 X_0 and 0.14 λ_I. The four sides of the scintillator plates are painted with white emulsion paint (Nippon Paint 'Odecoat'), and the plates are covered in Ti-O_2-added white PET films. Each scintillator plate has six straight grooves with a key hole shape in which WLS fibers are embedded. The diameters of the WLS fiber and the hole are 0.75 mmϕ and 0.80 mmϕ, respectively. The WLS fiber is connected to a 1.0 mmϕ clear fiber at each end. Clear fibers from three successive layers are bundled to make a superlayer. Each clear fiber bundle is connected to a PMT (Hamamatsu H7195). The PSD has four signals in total (left and right signals of two superlayers).

The SMD, to be positioned between the PSD and the FCAL, has two scintillator layers as shown in Figure 2. Each of the layers consists of twenty scintillator strips with a dimension of 200 mm (length) $\times$ 10 mm (width) $\times$ 5 mm (thickness). The two layers are aligned to be orthogonal to each other to measure the shower position in two dimensions. A 0.83 mmϕ WLS fiber is embedded in a 0.90 mmϕ straight key hole groove. The WLS fiber is connected to a clear fiber at one end to a clear fiber, while the other end of the fiber is mirrored by sputtering to increase the light collection efficiency. Each scintillator strip is wrapped by the white PET film. The outer surface of the PET film is painted black to avoid light cross-talks among the strips at this level. The scintillation light from each of the strips is individually fed into a pixel of multi-anode photo-multiplier tubes (MAPMTs, Hamamatsu R5900U).

The light yields of the PSD scintillator plates and the SMD scintillator strips were measured at a test bench using penetrating β-rays from a ^{90}Sr source, where a conventional PMT (Hamamatsu H5783P) was used for the readout. The average light yield of a PSD scintillator plate is 1.6 photoelectrons for a PMT at each side. The average light yield of a SMD scintillator strip is measured to be 7.0 at the test bench. However, as the quantum efficiency of the MAPMT is about one half of that of the conventional PMT, the light yield of the SMD at the test beam is estimated to be about 3.5 photoelectrons.

3 Experimental Setup

The test beam experiment (FNAL T912) was carried out at the MT6 test beam facility at FNAL in September 1999. The experimental setup of the beamline is schematically shown in Figure 3. The FCAL, RCAL, PSD, and SMD were mounted on a stage which was able to move horizontally and vertically.

Measurements were performed with negative charged particles. The beam was unseparated and contained mainly pions, electrons, and muons. The beam parameters including the target material and the magnet currents were tuned so that we had either electron-rich or pion-rich beams at each momentum. The available particle momentum ranged from 10 to 200 GeV. For this study we set the nominal momentum to be 50, 75, and 100 GeV, where good electron and pion samples were obtained. The electron-rich and pion-rich beams were individually tuned aiming at the nominal momentum. However, the momentum measured by the magnet current and the track curvature showed some discrepancy from the nominal momentum. The measured momentum values are listed in Table 1.

There were four single-wire drift chambers (SWDCs) in the beamline, two upstream of the bending magnet and the other two downstream of the magnet. A SWDC had four measurement planes, two for the horizontal (x) coordinate and the other two for the vertical (y) coordinate. The SWDCs determined the particle trajectory and momentum event by event. There was a counter to detect synchrotron radiation from electrons passing through the magnetic field in the bending magnet. This counter was called a synchrotron radiation detector (SRD) and was used to identify high energy electrons.

The trigger signal was made by a coincidence of two trigger scintillation counters (T4 and T5). The coincidence area of the trigger counters was 40 mm$\times$40 mm. Another scintillation counter (100 mm$\times$200 mm), called TPSD, was placed in front of the PSD. When an iron block filter (50 mm-thick, $2.8X_0$) was placed just in front of the TPSD, the signal was used to efficiently remove the electron component in the beam. A run with the iron block filter in front of the TPSD and with the pion-rich beam is called a "pion run", while a run without the iron block filter and with the electron-rich beam is called an "electron run". A larger scintillation counter (the muon counter, 250 mm$\times$250 mm) was placed behind the calorimeter to detect penetrating particles such as muons.

During our test beam experiment, other test experiment detectors were located between the last SWDC and our trigger counters across the beamline. The material thickness amounted to about 0.5 X_0 in total. Part of beam particles, especially electrons, interacted with the material, resulting in multi-track events. Such multi-track events are reduced by offline analysis.

The signals of the calorimeter and beam counters were fed into LeCroy 2280 ADCs, while the SWDC timing signals were fed into LeCroy 3377 multi-hit TDCs. The triggered events were read out by a PC-based CAMAC system.

4 Analysis and Results

4.1 Calibration

For each FCAL tower, calibration runs were performed with the pion-rich beam of 50 GeV nominal momentum. The incident position of the beam at the FCAL front surface was set so that minimum ionizing particles (MIPs) in the beam penetrated the whole longitudinal sections of the tower. Events with a hit in the muon counter and no hits in other FCAL towers are used for the calibration. The calibration runs for the central tower are used for the RCAL and the PSD too. Additional data were taken for the SMD calibration where the incident position at the SMD was changed by a 20 mm step in horizontal (x) and vertical (y) directions. The MIP peak in the ADC distribution of each counter is fitted to the Landau function, and the inverse of the peak value is assigned to the gain factor.

We suffered from saturation and cross-talk effects of the MAPMTs which were used for the SMD signal readout. The saturation effect of the MAPMT gain for a large light input is corrected using the gain curve obtained at a test bench. The effect of the cross-talk is typically a few percent among neighboring anodes in a MAPMT. This effect is partly compensated by subtracting a common value proportional to the total signal in a MAPMT from each anode signal. However, as these corrections are imperfect, the two effects degrade the SMD performance.

The energy deposit in each component of the calorimeter is normalized to that of a MIP passing through a FCAL section. Firstly an ADC count is multiplied by the gain factor. The left and right values of the PSD and the RCAL superlayers are averaged. The value is multiplied by a material thickness factor (0.075, 1.0, and 0.25 for a PSD superlayer, for a FCAL section, and for a RCAL superlayer, respectively) to obtain the normalized energy deposit. The SMD signals are not used for the energy calculation.

4.2 Event Selection

The data contain a large amount of multi-track events which were caused by interactions of particles with materials somewhere upstream of the beamline. The TPSD and the SWDC information are used to select single-track events. Most of muon component in the data is removed at the same stage using the last superlayer of the RCAL. The following three cuts are common to select both electron and pion samples.

Cut 1 : There is one and only one hit in each wire of the two SWDCs downstream of the bending magnet. The timing relation of the hits must be consistent with a passage of a single particle. The particle trajectory reconstructed by the two SWDCs must point to the 40 mm×40 mm area defined by the trigger counters.

Cut 2 : The energy deposit in the TPSD counter is consistent with that of a MIP. This cut not only reduces multi-track events but also removes most of electron component in the pion run as an electron starts its electromagnetic shower development in the iron block filter placed in front of the TPSD counter.

Cut 3 : The last superlayer of the RCAL does not have a hit. This cut is to remove muons.

The energy deposit in each detector is calculated as follows.

$$E_{PS} = \sum_{i=1,2} E_{PS}(i)$$

$$E_{FC} = \sum_{i=1,4} \sum_{j=1,25} E_{FC}(i,j)$$

$$E_{RC} = \sum_{i=1,9} E_{RC}(i)$$

where E_{PS}, E_{FC}, and E_{RC} are the energy deposit in the PSD, FCAL, RCAL, respectively, while $E_{PS}(i)$, $E_{FC}(i,j)$, and $E_{RC}(i)$ are the normalized energy deposit in each individual component of the detectors with i and j being indices of longitudinal divisions and towers, respectively. Figure 4 shows the relation of E_{PS} and $(E_{FC}+E_{RC})$ for the single-track events at 75 GeV nominal momentum.

The single-track events in electron runs still contain pions. To make pure electron samples, an event in electron runs is required to satisfy the following cut.

Cut 4 : there is a good energy deposit in the SRD. This cut is applied only to select electron events.

The distribution of the total energy deposit in the calorimeter, $E_{tot} = E_{PS} + E_{FC} + E_{RC}$, is shown in Figure 5 for the data of 75 GeV nominal momentum. The energy resolution is obtained by fitting the distribution with the Gaussian function. The fit results are shown in Figure 6 and summarized in Table 2. The energy resolutions are expressed as

- $\sigma_E/E = (24.4 \pm 0.5)\%/\sqrt{E} \oplus (0.0 \pm 1.9)\%$ for electrons, and
- $\sigma_E/E = (44.8 \pm 0.2)\%/\sqrt{E} \oplus (0.0 \pm 0.4)\%$ for pions.

Only statistical errors are considered here. One can refer to the accompanied paper [3] for systematic errors. The resolutions are consistent with those obtained by the hadron calorimeter module without the PSD and the SMD in front [3].

The energy distributions have very small components of non-Gaussian tails in both sides. The lower tail is due to events where some interaction occurred in the upstream beamline and only part of the resulting particles reached the calorimeter. The higher tail is caused by events where a particle made a trigger and opened an ADC gate, within which additional particles entered into the calorimeter. To remove these events for further analysis, we apply an additional cut.

Cut 5 : The total energy E_{tot} should be in the region $\mu_E - 3\sigma_E < E_{tot} < \mu_E + 3\sigma_E$, where μ_E (mean) and σ_E (standard deviation) are the results of the Gaussian fit.

The numbers of events in the final electron and pions samples are listed in Table 1.

The contamination in the electron samples is estimated to be less than 0.02 %, where it is estimated from the SRD signal distribution for the pion samples. The electron contamination in the pion samples is estimated to be less than 0.01% according to a Monte Carlo simulation based on GEANT3 [14].

4.3 Electron Identification

Once a selection for electron identification is defined, the electron efficiency (ϵ_e) and the pion rejection factor (r_π, inverse of the pion efficiency ϵ_π) are calculated as follows.

$$\epsilon_e = N_e^{sel}/N_e^{tot}$$
$$r_\pi = 1/\epsilon_\pi = N_\pi^{tot}/N_\pi^{sel}$$

where $N^{tot}_{e(\pi)}$ and $N^{sel}_{e(\pi)}$ are numbers of total and selected events in the electron (pion) sample. In the following we define various simple cut variables and evaluate the pion rejection factors at given electron efficiencies.

4.3.1 The PSD Energy Deposit

First of all, we use ratios of the energy deposit in the PSD to the total energy deposit E_{tot}. We define three ratios, R_{PS}, R_{PS1}, and R_{PS2} as follows.

$$\begin{aligned} R_{PS} &= E_{PS}/E_{tot} \\ R_{PS1} &= E_{PS}(1)/E_{tot} \\ R_{PS2} &= E_{PS}(2)/E_{tot} \end{aligned}$$

Figure 7 shows the distributions of the ratios for 75 GeV data. The best pion rejection factor is obtained by using the ratio R_{PS2}, as the second PSD superlayer is closer to the electromagnetic shower maximum. The electron and pion efficiencies are shown in Figures 8(a)-(c) as functions of the threshold value. Figure 8(d) shows the pion rejection factors as functions of the electron efficiency. Numerical values of the pion rejection factors are listed in Table 3.

4.3.2 Hit Multiplicity in the SMD

The hit multiplicity of the SMD scintillator strips is a good measure for the lateral spread of the electromagnetic shower. In this analysis the threshold value for a strip hit is set at a rather high level (5 times the MIP peak) to minimize the effect of the cross-talk among the MAPMT anodes. The distributions of the hit multiplicities in the x- and y-planes, and the sum (N_x, N_y, and N_{hit}, respectively) are shown in Figure 9. The pion rejection factors using N_{hit} are listed in Table 4.

4.3.3 Lateral Spread and Longitudinal Depth of the Shower

We parameterize the lateral and longitudinal shower development in the following way.

The S value is the lateral shower spread calculated only from the FCAL towers as

$$S = \sqrt{\frac{\sum_i d_i^2 E_{FC}(i)}{E_{FC}}}$$

where $E_{FC}(i)$ is the energy deposit in the i-th tower of the FCAL, and d_i is the lateral distance of the tower from the central tower to which particles are incident.

The D value stands for the longitudinal depth of the shower, which is calculated by using the energy deposits in the two PSD superlayers, the four FCAL sections, and the nine RCAL superlayers, as

$$D = \frac{\sum_j z_j E_j}{E_{tot}}$$

where z_j denotes the longitudinal depth of the j-th detector component measured from the front surface of the PSD and E_j is the energy deposit in it.

The distributions of the S and D values are shown for the 75 GeV data in Figure 10. The electron and pion efficiencies of 75 GeV data are shown in Figures 11(a) and (b) as functions of the threshold values. The pion rejection factors are shown as functions of the electron efficiency in Figures 11(c) and (d). Numerical values of the pion rejection factors are listed in Table 5.

To see the dependence of the pion rejection factor on the material thickness, we define other D values by using only a part of the detector.

- $D_1 = D$ value with the PSD and the 1st section of the FCAL,
- $D_2 = D$ value with the PSD and the 1st and 2nd sections of the FCAL,
- $D_3 = D$ value with the PSD and the 1st, 2nd, and 3rd sections of the FCAL, and
- $D_4 = D$ value with the PSD and the FCAL (without RCAL).

The distributions are shown for 75 GeV data in Figure 12. The efficiencies and pion rejection factors are shown in Figure 13. Numerical values of the pion rejection factors are listed in Table 6.

4.3.4 Combination of the Cuts

Although the cut variables used for the electron identification are not fully independent of one another, a combination of two or more variables improves the pion rejection factor in general. As the PSD energy deposit and the SMD hit multiplicity are strongly correlated, we here consider combinations of two variables out of R_{PS2}, S, and D values. Correlation plots of these variables are shown in Figure 14 for 75 GeV data, where each selection cut is defined in a two-dimensional plane. To calculate the electron efficiency and the pion rejection factor, we fix one of the two cut thresholds. Namely, we fix the cut $R_{PS2} > 0.03$ in the combination of (R_{PS2},S) and (R_{PS2},D), while the threshold for the S value is fixed to 8.0 in the combination (S,D). The cut areas of 95% electron efficiency are indicated in the same figures. The resulting pion rejection factors are summarized in Table 7. Among the three, the combination of the D-value and R_{PS2} provides the best pion rejection factor in most cases.

4.4 Position Resolution of Electrons

The incident position of an electron can be determined by the energy deposits in the SMD with various methods such as energy-weighting and analytical methods. Among the methods we have used, the best performance is obtained by a 3-strip analytic method using the Lorentzian line-shape function. The algorithm is the following.

- Find the strip with the largest energy deposit. The energy deposits of the strip and the two neighboring strips are used for the position measurement.
- Assuming the Lorentzian line-shape function, the position x_{SMD} is given by a simple formula from the center position of the strip with the maximum energy deposit (x_{max}), and the three energy deposits, E_1, E_{max}, and E_2, as

  $$x_{SMD} = x_{max} + \frac{E_{max}(E_2 - E_1)\Delta}{2[E_{max}(E_2 + E_1) - 2E_1E_2]}$$

  where Δ is the strip width (=10 mm).

The position calculated by the SMD is compared with that determined by the SWDCs (x_{SWDC}). The correlation plot and the distribution of the difference are shown in Figure 15. The resolution is typically 2∼3 mm as summarized in Table 8. The resolution of the position determined by the SWDCs is estimated to be less than 0.2 mm at the PSD surface. Therefore the influence to the SMD position resolution is negligible. The resolution is well described by the formula

$$\frac{(37.7 \pm 2.5)}{\sqrt{E}} - (1.75 \pm 0.28)\,\mathrm{mm}$$

in the energy region 50 GeV $< E <$ 100 GeV, as shown in Figure 16. We consider the intrinsic resolution of the scintillator strips should be a little better, as we suffered from the saturation and cross-talk effects of the MAPMTs.

5 Summary

We constructed a set of prototype preshower and shower-maximum detectors using a tile/fiber technique. The two detectors were tested in combination with the hadron calorimeter module at a test beam facility at FNAL. The data at nominal energies of 50, 75, and 100 GeV were taken and analyzed.

The energy resolutions of the hadron calorimeter module with the PSD and the SMD are obtained.

- $\sigma_E/E = (24.4 \pm 0.5)\%/\sqrt{E} \oplus (0.0 \pm 1.9)\%$ for electrons, and

- $\sigma_E/E = (44.8 \pm 0.2)\%/\sqrt{E} \oplus (0.0 \pm 0.4)\%$ for pions.

The resolutions are consistent with those of the hadron calorimeter module without the PSD and the SMD.

The electron identification capability is examined by various simple methods. By using the ratio of the PSD signal to the total energy deposit of the calorimeter, a pion rejection factor of more than 10 is obtained at 95% electron efficiency. The pion rejection factor is improved by the longitudinal segmentation of the PSD. The hit multiplicity in the SMD strips provides a comparable pion rejection factor. The lateral shower spread measured by the hadron calorimeter module with a tower structure shows a good pion rejection factor, roughly 20 at 95% electron efficiency. As a single cut value, the best performance is obtained by the D value, which represents the longitudinal depth of the shower. The pion rejection factor of several hundred is easily obtained at 95% electron efficiency. The longitudinal segmentation of the calorimeter is essential to obtain a good pion rejection factor.

The pion rejection factor is further improved by combining the cut variables. Among the combinations of two cut variables, the combination of the PSD ratio and the longitudinal shower depth is the best, where the pion rejection factor can exceed 1000 at 95% electron efficiency.

The incident position of an electron can be measured by the SMD. The position resolution is typically 2$\sim$3 mm in the energy range of 50 GeV$< E <$ 100 GeV. We consider the intrinsic resolution of the scintillator strips should be a little better, as we suffered from saturation and cross-talk effects of the readout MAPMTs.

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	electron-run			pion-run		
nominal momentum (GeV)	measured momentum (GeV)	trigger events	electron sample	measured momentum (GeV)	trigger events	pion sample
50	55.3	50,523	1,157	49.2	81,000	16,557
75	83.0	61,000	1,776	73.5	101,630	15,100
100	101.1	58,035	637	96.7	120,000	9,842

Table 1
Nominal and measured momentum, numbers of trigger events, numbers of electron/pion samples used in this study.

electrons			pions		
real energy (GeV)	mean (MIPs)	σ/E (%)	real energy (GeV)	mean (MIPs)	σ/E (%)
55.3	168.2	3.2	49.2	153.6	6.5
83.0	252.0	2.8	73.5	229.3	5.2
101.1	307.0	2.3	96.7	285.6	4.4

Table 2
Fit results of the E_{tot} distributions.

Method	R_{PS1}			R_{PS2}			R_{PS}		
ϵ_e (%)	90	95	98	90	95	98	90	95	98
r_π at 50 GeV	12.4	10.8	9.4	21.9	15.6	12.2	16.5	13.2	11.0
r_π at 75 GeV	12.1	10.8	9.7	19.6	16.0	12.1	16.1	14.0	11.5
r_π at 100 GeV	10.8	9.5	8.4	18.9	12.3	10.3	14.7	11.2	10.0

Table 3
Pion rejection factors with the ratio of the PSD energy deposit to the total energy deposit.

Energy	50 GeV		75 GeV		100 GeV	
N_{hit}	ϵ_e (%)	r_π	ϵ_e (%)	r_π	ϵ_e (%)	r_π
≥ 10	98.9	9.4	99.6	8.1	99.7	7.0
≥ 11	97.6	10.5	99.2	8.9	99.4	7.6
≥ 12	94.6	12.2	97.8	10.0	98.3	8.3
≥ 13	91.0	14.2	95.8	11.3	97.0	9.2
≥ 14	84.4	17.2	91.2	13.0	95.3	10.3
≥ 15	74.4	21.6	86.5	15.2	90.4	11.8
≥ 16	63.6	27.5	78.2	18.3	83.4	13.7

Table 4
Pion rejection factors with the SMD hit multiplicity.

Method	S value			D value		
ϵ_e (%)	90	95	98	90	95	98
r_π at 50 GeV	33.2	21.3	13.3	828	571	502
r_π at 75 GeV	43.8	30.2	20.5	1001	719	629
r_π at 100 GeV	43.6	31.3	19.8	984	820	703

Table 5
Pion rejection factors with the S and D values.

Method	D_1			D_2		
ϵ_e (%)	90	95	98	90	95	98
r_π at 50 GeV	4.8	4.1	3.6	210	158	128
r_π at 75 GeV	5.0	4.5	4.0	296	248	207
r_π at 100 GeV	4.9	4.3	4.0	317	246	229

Method	D_3			D_4		
ϵ_e (%)	90	95	98	90	95	98
r_π at 50 GeV	591	436	318	752	551	460
r_π at 75 GeV	629	503	458	839	604	559
r_π at 100 GeV	656	547	469	894	703	615

Table 6
Pion rejection factors with the D_1, D_2, D_3 and D_4 values.

Method	S value and R_{PS2}			D value and R_{PS2}			D and S values		
ϵ_e (%)	90	95	98	90	95	98	90	95	98
r_π at 50 GeV	473	312	180	1274	1104	720	1183	828	753
r_π at 75 GeV	657	487	343	1258	1162	944	1510	1162	888
r_π at 100 GeV	984	656	281	1640	1406	1406	984	820	656

Table 7
Pion rejection factors with the combinations of R_{PS2}, S and D values.

measured energy	$\sigma_{\Delta x}$ (mm)	$\sigma_{\Delta y}$ (mm)
55.3 GeV	3.31 ± 0.09	3.20 ± 0.12
83.0 GeV	2.49 ± 0.05	2.42 ± 0.07
101.1 GeV	1.97 ± 0.09	1.84 ± 0.08

Table 8
The position resolution determined by a Gaussian fit to the difference of the positions measured by the SWDC and the SMD.

Fig. 1. A schematic view of the preshower detector.

Fig. 2. A schematic view of the shower-maximum detector.

Fig. 3. A schematic view of the T912 beam line setup (not to scale).

Fig. 4. Scatter plots of E_{PS} and $E_{FC} + E_{RC}$ for single-track events in (a) electron and (b) pion runs at 75 GeV.

Fig. 5. The distribution of E_{tot} for single track events in (a) electron and (b) pion runs at 75 GeV.

Fig. 6. The energy resolution for electrons (circles) and pions (triangles). The error bars are too small to be visible. The fit results are also shown.

Fig. 7. Distributions of the ratio of the energy deposit in the PSD to the total energy deposit for electron and pion samples at 75 GeV. (a) R_{PS}, (b) R_{PS1}, and (c) R_{PS2}. Entries of pions are normalized to those of electrons.

Fig. 8. Electrons and pion efficiencies with respect to threshold values (a) R_{PS}, (b) R_{PS1}, and (c) R_{PS2}. Figure (d) shows the pion rejection factors as functions of the electron efficiency. The figures are made for 75 GeV data.

Fig. 9. Distributions of the SMD hit multiplicities. (a) number of hits in the x-plane, (b) number of hits in the y-plane, and (c) the sum. Entries of pions are normalized to those of electrons.

Fig. 10. Distributions of the (a) S and (b) D values. The figures are made for 75 GeV data. Entries of pions are normalized to those of electrons.

Fig. 11. Electron and pion efficiencies with respect to the (a) S and (b) D threshold values. The pion efficiency in (b) is multiplied by 100 to be visible. Pion rejection factors are shown as functions of the electron efficiency in (c) and (d), for S and D, respectively. The figures are made for 75 GeV data.

Fig. 12. Distributions of the shower depths (a) D_1, (b) D_2, (c) D_3, and (d) D_4 for 75 GeV data. Entries of pions are normalized to those of electrons.

Fig. 13. Electron and pion efficiencies using (a) D_2, (b) D_3, and (c) D_4, as functions of threshold values. The figures are made for 75 GeV data. The pion efficiencies are multiplied by 100 to be visible in the figures. The pion rejection factors are shown in (d) as functions of the electron efficiency.

Fig. 14. Scatter plots of cut variables : (a) S value and R_{PS2}, (b) D value and R_{PS2}, and (c) D and S values. Filled circles are electrons and dots are pions. Examples of 95% electron efficiency zones are shown in the plots.

Fig. 15. (a) A scatter plot of the positions measured by the SWDC and the SMD. (b) The difference of the positions measured by the SWDC and the SMD.

Fig. 16. The SMD position resolution of electrons as a function of the incident energy. The circles and triangles are for x- and y-coordinates, respectively. The fit result is also shown.