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KEK Preprint 94-169
December 1994
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*Submitted to Nucl. Instrum. Meth.*

**National Laboratory for High Energy Physics, 1994**

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# Performance of VENUS lead glass counters in pion and electron beams and in an upgraded VENUS detector

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## Abstract

The response of an array of VENUS lead glass counters was studied by using pion and electron beams as well as real events in an $e^+e^-$ colliding beam experiment. The measured pion rejection factors were about 45~65 for various incident energies of 1, 2, 3, 4 GeV with an electron efficiency of 89%. In the real colliding beam experimental data, electrons and pions were separated by using both the E/p method and the difference between a track and a cluster position. We obtained a pion rejection factor of about 45 in the isolated region of hadron jets with an electron efficiency of 89%, which was almost the same result as that obtained in the present beam test. In the core region of hadron jets we obtained a pion rejection factor of about 13~20 with an electron efficiency of 86%. An energy resolution of $\sigma/E = 6.3\%/\sqrt{E} + 2.7\%$(E in GeV) was obtained in the real $e^+e^-$ colliding beam experiment.

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## 1. Introduction

Electron identification is one of the important subjects in $e^+e^-$ colliding beam experiments, since it provides a tool for flavor tagging. It also plays an important role in searching for new particles, such as a heavy quark or a heavy lepton. In the VENUS detector,[1] a lead glass array having a semi-tower geometry is used as an electromagnetic calorimeter in the barrel region[2] as shown in Fig. 1. To identify electrons in a jet by the E/p method, knowledge concerning the energy spectrum of pions is indispensable. Moreover, the lateral spreads of electron and pion showers are necessary in order to determine the cluster size for electrons and pions. Motivated by these facts, we tested a 3×3 array of VENUS lead glass counters at the π2 beam line of the KEK 12-GeV proton synchrotron. In this paper we report on the results of a beam test and the performance using real data of $e^+e^-$ reactions at TRISTAN.

## 2. Experimental Procedure

Electrons and pions produced at the π2 internal target of the KEK 12-GeV proton synchrotron were incident in a 3×3 array of VENUS lead glass counters. The electrons and pions were identified by two freon-filled gas Cherenkov counters. The beams were defined by two $1 \times 1$ cm$^2$ trigger counters. Two anti-counters placed in the horizontal direction were used to reject multi-hit events. In the vertical direction, four drift chambers were used to define the beam position as well as to reject any multi-hit events. The typical beam intensity was 5 kHz and 40 Hz for the pions and electrons, respectively. The lead glass counters had a size of $11.6 \times 12$ cm$^2$ in cross section, and 18 radiation lengths (30 cm) in depth. A 3" phototube (R1911 of Hamamatsu Photonics[3]) was attached through a 6 cm long plastic light guide. Lead glass counters were mounted in a 3×3 configuration with a 1.5 mm spacing on a movable table, where 1.5 mm was the average gap between the lead glass counters mounted in the real VENUS detector. They were covered with 5 cm thick styrofoam in order to keep the ambient temperature of the phototubes constant. The variation in the temperature was less than 2 degrees during the experiment, which corresponded to the variations of the pulse heights of the lead glass counters less than ±0.4%. Signals from the lead glass counters were digitized by a LeCroy ADC, 2249W,[4] and read by a Micro Vax at a rate of 100 events/burst. The relative gains of the nine modules were adjusted by exposing each module on the 2-GeV electron beam.

## 3. Results of a Beam Test

### 3-1 Pion Response

The pion energy spectra at 1, 2, 3, and 4 GeV/c are shown in Figs. 2(a), (b), (c), and (d), respectively, where the incident positions of the pion beam are at the center. In Fig. 3 the pion spectrum for an incident position at 1 cm from the edge is shown. Two features are noted.

Firstly, the spectrum of the pion response far exceeds the incident energy. This can be understood in terms of the additional Cherenkov light emitted by particles at a light guide placed between the lead glass and a phototube. The particles produced by a hadronic cascade shower, which starts at a longitudinally deep position in a lead glass counter, enter the light guide and emit additional Cherenkov light. Since a light guide is attached directly to a phototube, the light emitted in the light guide may be enhanced by several times compared to the light emitted in the lead glass counter. Hence, a long tail is produced in the spectrum of the pion response.

Secondly, the peaks caused by the minimum ionizing particles for Figs. 2(a)~(d) are positioned at an energy as high as 600 MeV. This is also due to the additional Cherenkov light at the light guide, that is, a pion penetrating a light guide emits additional light. When the incident point moves from the center and incident particles don't enter into the light guide, the peak shifts to around 200 MeV, as can be seen in Fig. 3.

In Table 1, the pion contamination rates are given against the acceptance byte of $|E/p-1|$ for various energies. In the same table the electron efficiencies are also given. The typical contamination rate is 1.5~2.2% (corresponding to a rejection factor of 45~65) for $0.85 < E/p < 1.15$ at 2 GeV/c, where the electron efficiency is 89%. The pion contamination rate becomes large at 1 GeV due to a high peak of 600 MeV. The pion contamination rate decreases in accordance with the incident point, moving towards the edge of the lead glass block. This can also be explained by the light guide effect.

### 3-2 Lateral Shower Spread

The lateral shower spread of the pion response is shown in Fig. 4 (closed circles) for 2 GeV/c pions, where the electron spectrum is also shown as a histogram. R is defined by the following equation:

$$R = E_{cent}/E_{tot},$$

where $E_{cent}$ is the energy deposited in the central module and $E_{tot}$ is the sum of the energies of 9 modules. The peak at R = 1 for pions in Fig. 4 corresponds to the minimum ionizing particles, whose signals are confined only to a central module. The signals of pions have longer tails on the lower energy side, while electron signals have a narrow peak and no lower energy tail. Moreover, we found that the pion response is irregular, that is, the energies deposited in the modules are asymmetric with respect to the central module. This fact means that the incident position calculated by the weighted mean of the energy deposited greatly differs from the real incident point. Using this fact we can effectively separate pions from electrons. We discuss this point in the next section.

The energy deposited beyond the 3×3 modules was studied by observing the energy deposited in the lowest 3 modules with incident particles entering at the center of the uppermost modules. The mean energy deposit is around 10 MeV for 2 GeV/c pions. By multiplying by 4, we can estimate that the total energy deposited beyond the 3×3 modules is 40 MeV, which corresponds to about 7% of the total energy deposited in the 3×3 modules. This fact means that the pion cluster size sometimes becomes greater than the 3×3 array, while electrons are well confined within 3×3 array, or sometimes a 2×2 array. In fact, in the real data obtained in a colliding beam experiment we can see that pion clusters are often larger than the 3×3 array.

## 4. Electron Response in a Hadron Jet

In this section we discuss the energy resolution, energy loss and identification of electrons in hadronic events of a VENUS $e^+e^-$ colliding beam experiment at TRISTAN. The details concerning the VENUS detector are described elsewhere.[1] Here, we recall two detectors relevant to electron identification: a lead glass calorimeter (LG)[2] and a central drift chamber (CDC).[5]

The tracks of charged particles are measured by a CDC. The CDC is a cylinder with an inner radius of 25 cm, an outer radius of 126 cm and a length of 300 cm. It has 20 axial layers and 9 stereo layers, with a stereo angle of ±3.3°. The magnetic field inside the CDC is 0.75T. The momentum resolution and angular resolutions are $\Delta p_t/p_t = \sqrt{(0.008p_t)^2 + (0.013)^2}$ ($p_t$ in GeV/c) and $\Delta\theta = 0.8 \times 10^{-2} \sin^2\theta$ within an angular range of $|\cos\theta| \leq 0.75$, respectively.

The LG comprises 5160 lead glass counters (120 segments in the $\phi$-direction and 43 segments in the z-direction). It covers a polar angle of between 37° and 143°. One counter has a typical cross section of 11.6×12 $cm^2$ and a length of 30 cm, corresponding to 18 radiation lengths ($18X_0$). The energy resolution before upgrading the VENUS detector, that is, before installing a transition radiation detector (TRD)[6] and a vertex chamber[7] is expressed as $\sigma/E = 5.4\%/\sqrt{E} + 2.8\%$(E in GeV).

Two kinds of data sample are used here, which were collected after the TRD was installed. The data samples correspond to 75 $pb^{-1}$ with $\sqrt{s}$ =58 GeV:

i) Electron sample: radiative Bhabha events and single-electron events from the $e^+e^- \rightarrow e^+e^-\gamma$ reaction.

ii) Hadron sample: $e^+e^- \rightarrow q\bar{q}$ events, where more than 90% of the charged tracks are hadrons. We rejected the remaining electrons in the sample by requiring the energy deposit on the TRD[6] to be less than 10 keV. After the cut, the electron contamination in the sample is less than 0.5%.

### 4-1 Energy Resolution and Energy Loss

The energy resolution of a LG for the upgraded VENUS detector is shown in Fig. 5. As can be seen in the figure, the energy resolution is well expressed as $\sigma/E = 6.3\%/\sqrt{E} + 2.7\%$(E in GeV). The data were by about 1% worse than that obtained by the LG before the upgraded VENUS detector. This can be explained by an increase in the material ($0.2X_0$), resulting in a total material of $0.9X_0$ in front of the LG due to installation of the TRD[6].

In Fig. 6, the E/p is plotted against the electron energy. With $0.9X_0$ material in front of the LG, we can observe that the energy loss becomes substantial at around 3 GeV and it reaches at about 10% at 0.75 GeV. This result is consistent with the result obtained by the previous beam test.[8]

### 4-2 Electron Identification

Here, we describe electron identification by the LG in the $e^+e^-$ colliding beam experiment and compare the results with that obtained by the present beam test. The electron identification using both the TRD and the LG is discussed in ref. [9].

The first step of electron identification is to use the E/p method. As mentioned in the previous section, it is effective to use this method in order to reject pions. According to the beam test, about a 1.5~2.2% pion contamination rate is obtained with an 89% electron efficiency. However, using real data, the material in front of the lead glass counter deteriorates the electron response in two ways: i) a decrease of the shower energy as observed in the preceding section, and ii) a larger shower spread. Therefore, the electron response becomes more like that of pions. Moreover, electrons often overlap with nearby tracks in a hadron jet, so that pion contamination rate may become worse than that obtained by the beam test. Since the momentum resolution worsen proportionally to the momentum itself, we used, instead of S(=E/p), the variable $\mu$ defined as

$$\mu = \frac{S-<S>}{\sigma_S},$$

where <S> is the mean value of S and $\sigma_S$ is a deviation of S. The distribution of $\mu$ is shown in Figs. 7(a) and (b) for electrons and pions, respectively. The electrons show a Gaussian shape with a unit variance around 0.0 and pions distribute far below 0, peaking $\mu$ at around −9. We choose a cut value $\mu > -2.5$ to select electrons. The resulting pion efficiencies are about 15~16% (corresponding to a rejection factor of 6~7) in the core region of hadron jets with a $p_t$ less than 1.0 GeV/c, where $p_t$ is the transverse momentum with respect to the jet axis. The electron efficiency is about 98%. This result is by about eight times worse than the results of the beam test. When a $p_t$ is between 1.0 and 2.0 GeV/c, the pion efficiencies decrease by about factor three and become to be 4.4~6.0% (corresponding to a rejection factor of 16~22) with an electron efficiency of 98%. This result is also by about twice worse than the results of the beam test. In the isolated region of hadron jets where a $p_t$ is greater than 2.0 GeV/c, the pion efficiencies become to be 3.2-4.3% (corresponding to a rejection factor of 23~30) with an electron efficiency of 98%. This result is slightly worse than the result obtained in the present beam test.

In the second step, we use the matching of a track and a cluster position where the tracks are extrapolated to the LG through the TRD and a magnet coil. As we observed in the beam test, the pion response is rather broad and asymmetric, so that matching of the pion cluster position and the pion track is worse than that of the electron cluster and the track. Here, the cluster position ($\bar{x}$) is obtained by the energy-weighted mean, expressed by

$$\bar{x}=\Sigma E_i x_i/\Sigma E_i,$$

where $E_i$ is the energy of the i-th module in the cluster and $x_i$ is the center position of the i-th module. In Figs. 8(a) and (b), the distributions of the position difference for the electrons (solid line) and pions (dashed line) are shown for z and $\phi$ directions, respectively. We multiply radius (r) to $\phi$ in order to convert an angle $\phi$ to a length. As expected, the pions have a longer tail than electrons. We choose a position cut value $\Delta z$, $r\Delta\phi < 6.5$ cm to select electrons Pions are rejected by about 52~63%, while the electron efficiency is about 90%.

By combining the E/p method and position cuts we could improve the pion rejection factor as summarized in tables 2 and 3. We obtained pion rejection factor of about 13~20 with an electron efficiency of about 86% in the core region of hadron jets with a $p_t$ less than 1.0 GeV/c for a momentum range between 1 to around 10 GeV/c. When a $p_t$ is between 1.0 and 2.0 GeV/c, the pion rejection factor is around 29~42 with an electron efficiency of 86%, which is slightly worse than the result of the present beam test. In the isolated region of hadron jets where a $p_t$ is greater than 2.0 GeV/c, the pion rejection factor is about 45 with electron efficiecy of 89% for a momentum range between 1 and 6 GeV/c, which is almost the same result as that obtained in the present beam test.

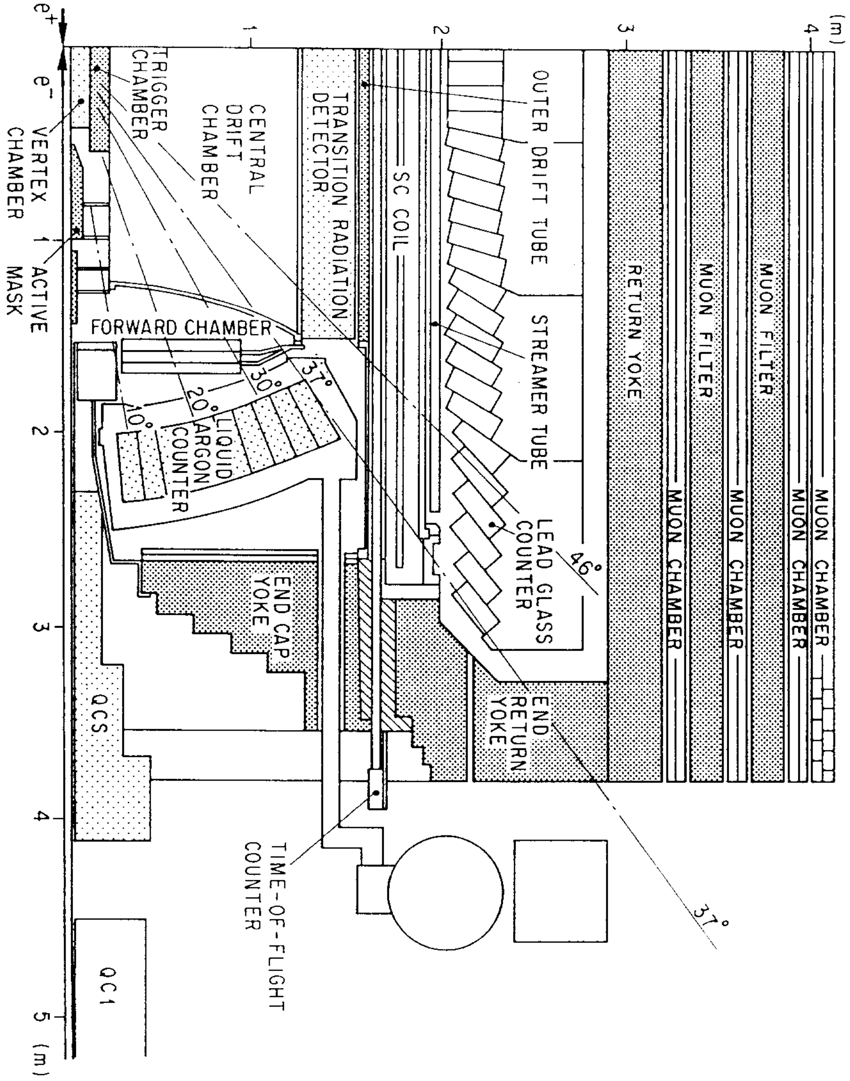
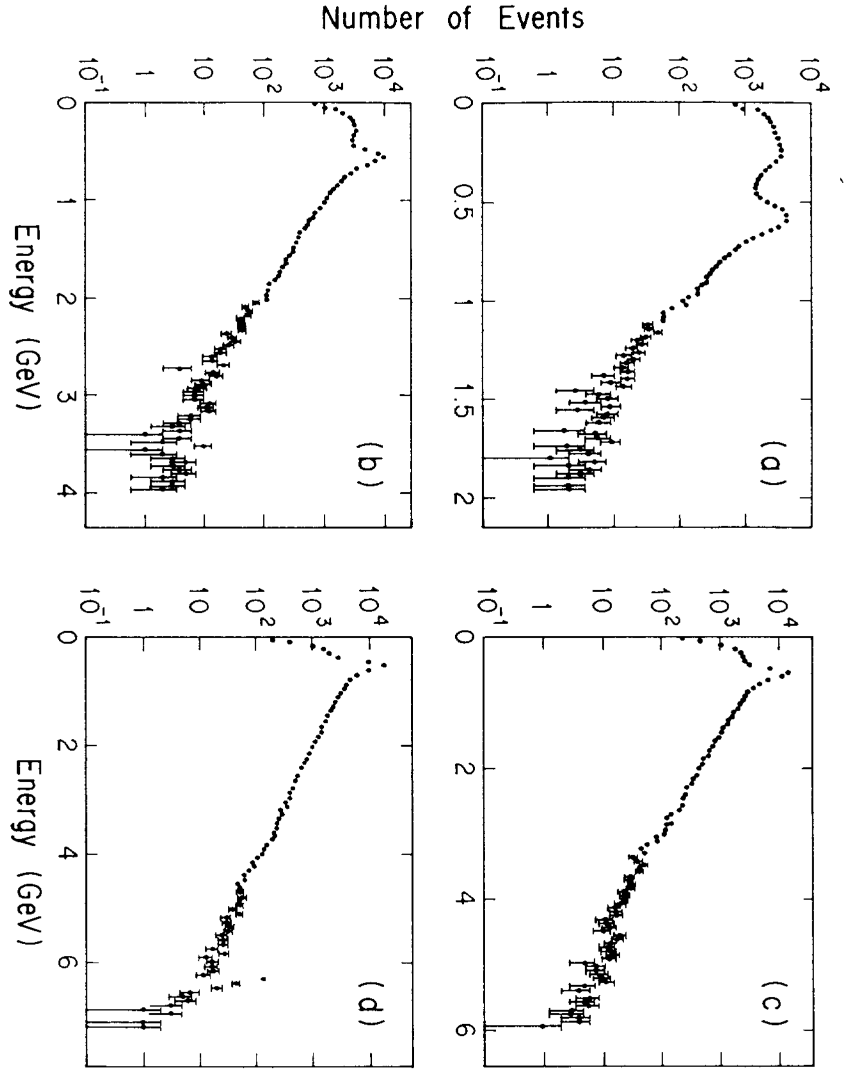

(m)
1
2
3
4
5
e+
e−
VERTEX CHAMBER
ACTIVE MASK
TRIGGER CHAMBER
CENTRAL DRIFT CHAMBER
TRANSITION RADIATION DETECTOR
SC COIL
OUTER DRIFT TUBE
STREAMER TUBE
LEAD GLASS COUNTER
RETURN YOKE
MUON FILTER
MUON CHAMBER
FORWARD CHAMBER
LIQUID ARGON COUNTER
10°
20°
30°
37°
46°
END CAP YOKE
END RETURN YOKE
QCS
QC1
TIME-OF-FLIGHT COUNTER

Fig.1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$10^2$
$10^3$
$10^4$
(a)
(b)
(c)
(d)
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0.5
1
1.5
2
3
4
6
Energy (GeV)

Fig.2

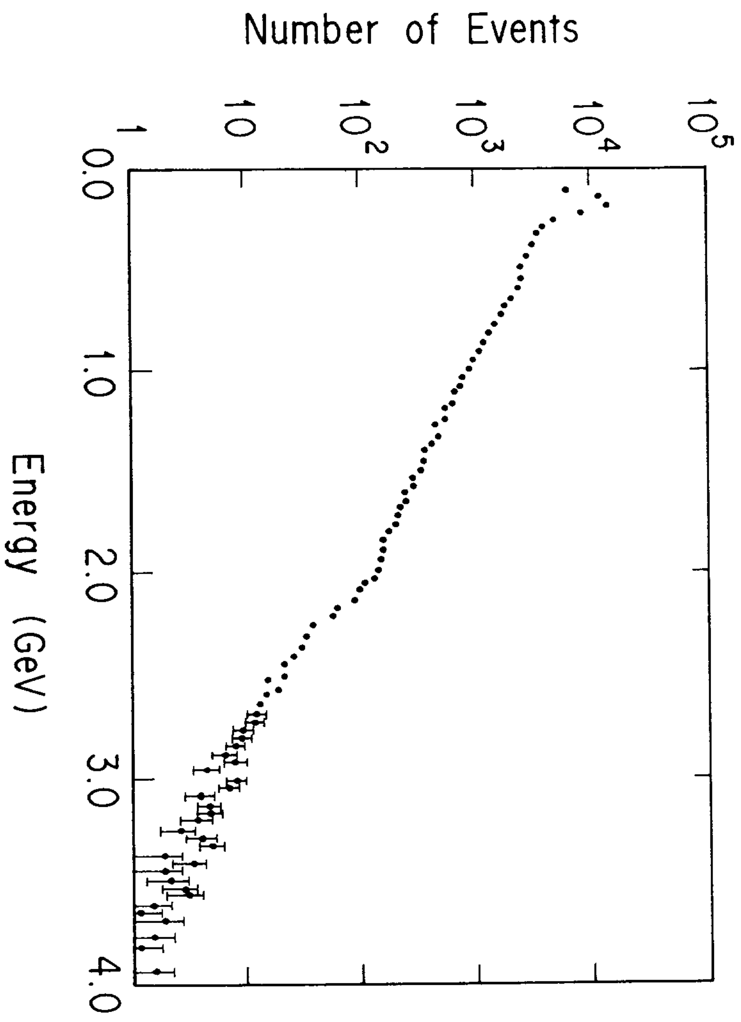
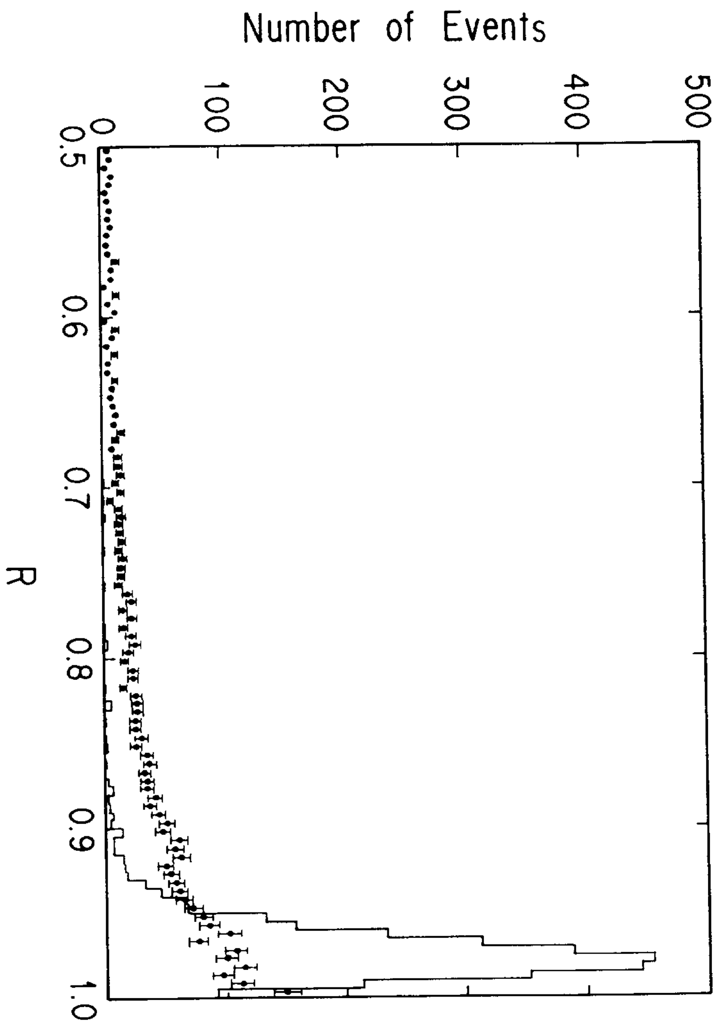

Number of Events
1
10
$10^2$
$10^3$
$10^4$
$10^5$
0.0
1.0
2.0
3.0
4.0
Energy (GeV)

Fig.3


Number of Events
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400
500
0.5
0.6
0.7
0.8
0.9
1.0
R

Fig.4

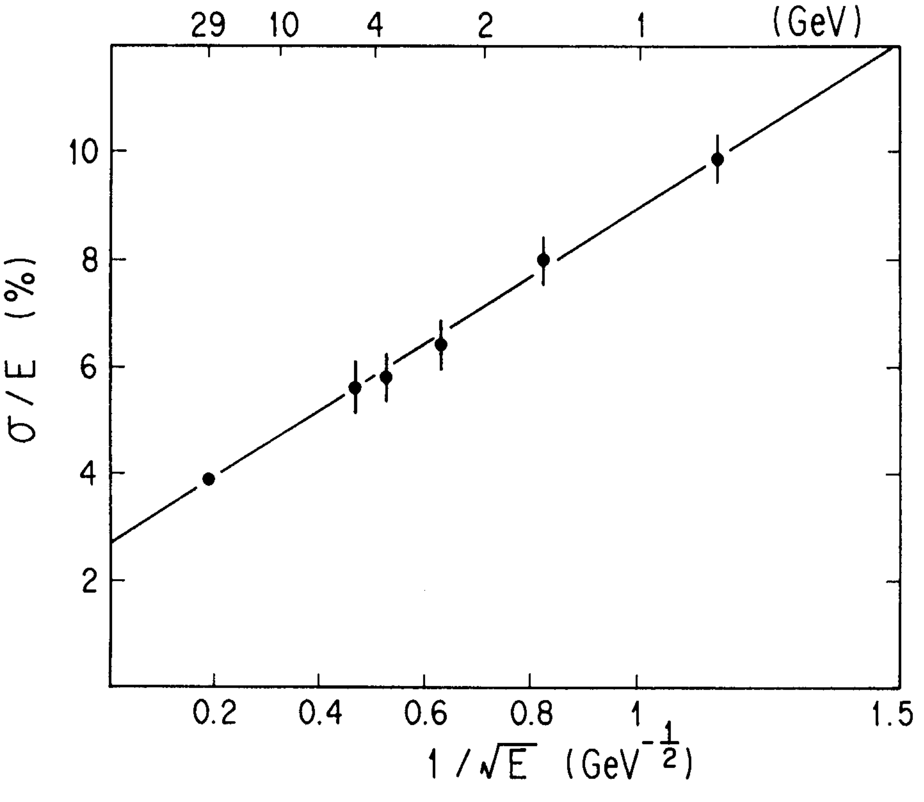

29
10
4
2
1
(GeV)
10
8
6
4
2
σ / E (%)
0.2
0.4
0.6
0.8
1
1.5
1 / √E (GeV^-1/2)

Fig.5

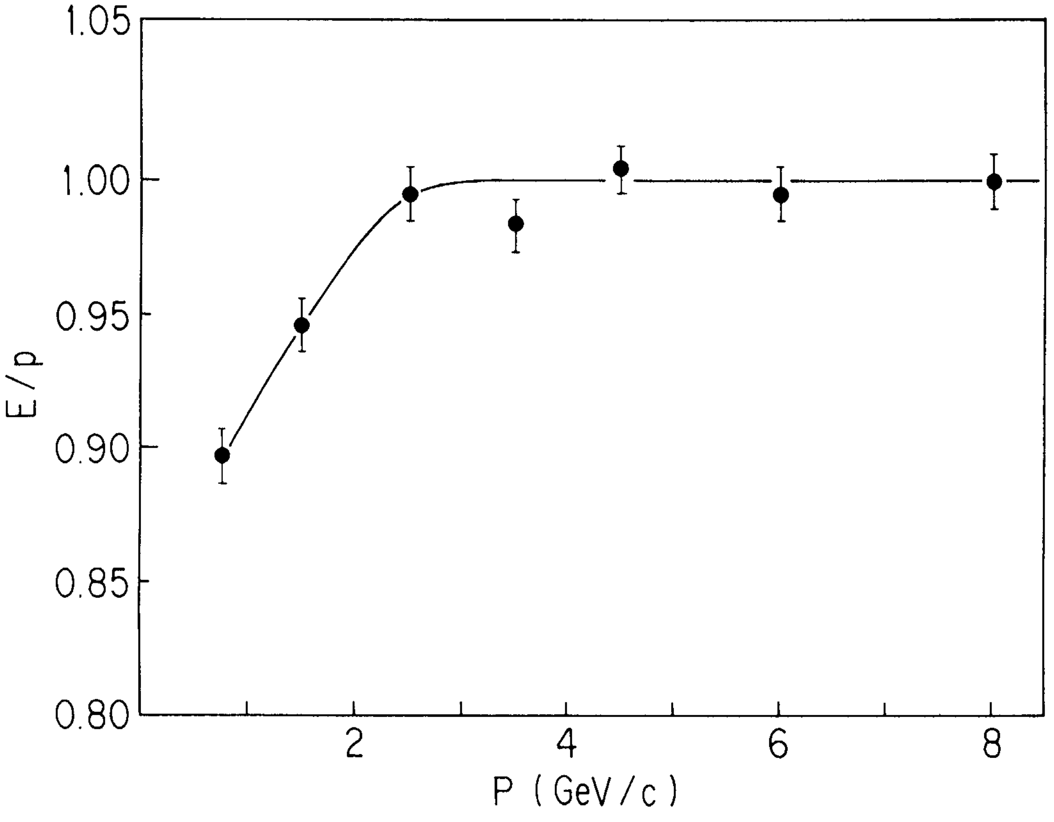
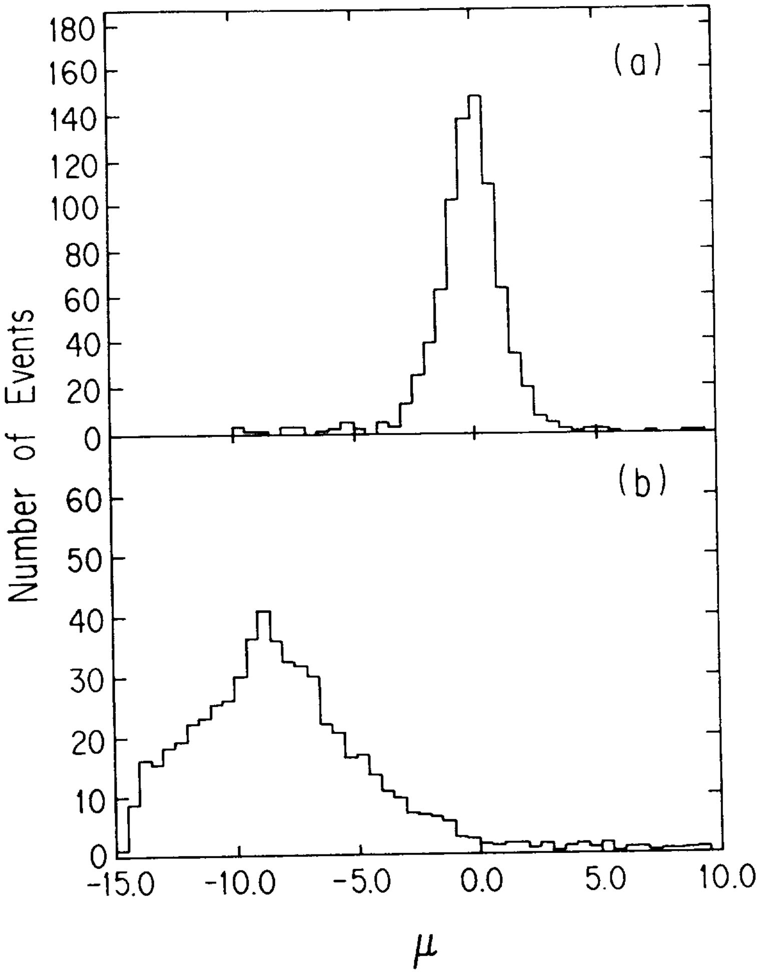

1.05
1.00
0.95
0.90
0.85
0.80
E / p
2
4
6
8
P ( GeV / c )

Fig.6


Number of Events
(a)
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20
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60
80
100
120
140
160
180
(b)
0
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20
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50
60
-15.0
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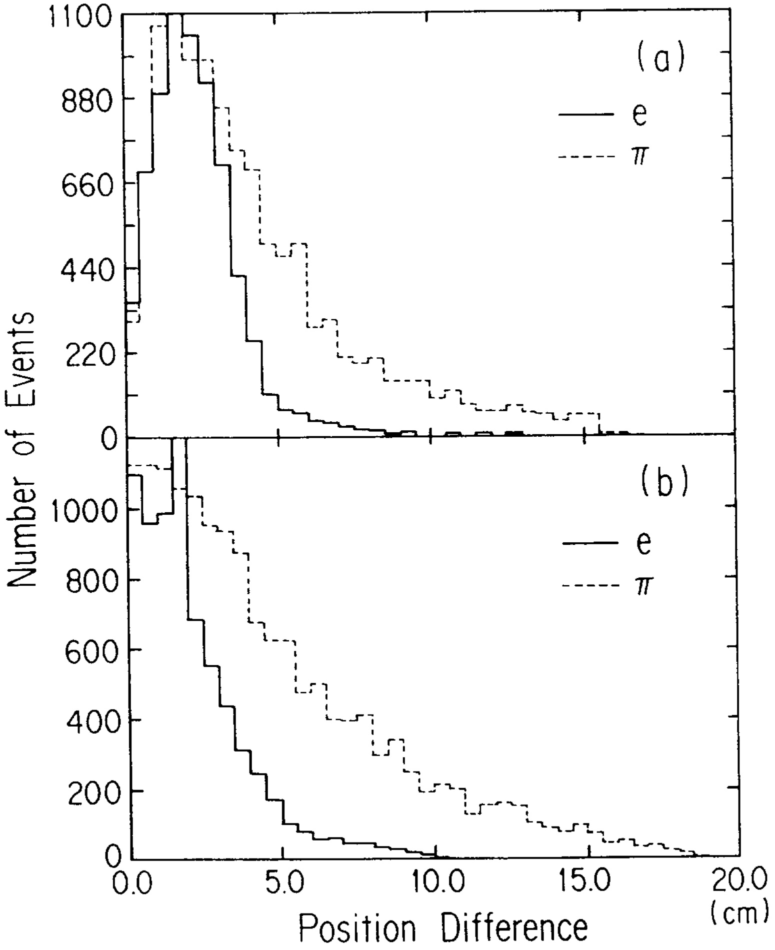
-5.0
0.0
5.0
10.0
$\mu$

**Fig.7**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$\pi$
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220
440
660
880
1100
(b)
e
$\pi$
0
200
400
600
800
1000
0.0
5.0
10.0
15.0
20.0
(cm)
Position Difference

**Fig.8**