High Energy Beam Test of the PHENIX Lead–Scintillator EM Calorimeter

T.C. Awes [e] A. Bazilevsky [g] S. Bathe [d] D. Bucher [d] H. Buesching [d] Y. Goto [g] K. Imai [c] M.S. Ippolitov [b] E. Kistenev [a] V. Mexner [d] T. Peitzmann [d] N. Saito [f,g] H. Torii [c,f] S.N. White [a]

[a] *Brookhaven National Laboratory, Upton, NY 11973-5000, USA*

[b] *Russian Research Center "Kurchatov Institute", Moscow, Russia*

[c] *Kyoto University, Kyoto 606-8502, Japan*

[d] *Institut fuer Kernphysik, University of Muenster, D-48149 Muenster, Germany*

[e] *Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA*

[f] *RIKEN, Wako, Saitama 351-0198, Japan*

[g] *RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, NY 11973-5000, USA*

Abstract

In the PHENIX experiment at RHIC, the electro-magnetic calorimeter plays an important role in both the heavy-ion and spin physics programs for which it was designed. In order to measure its performance in the energy range up to 80GeV, a beam test was performed at the CERN-SPS H6 beam line. We describe the beam test and present results on calorimeter performance with pion and electron beams.

Key words:
Calorimeters, Relativistic heavy-ion collisions, Spin physics
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1 Introduction

The PHENIX experiment at RHIC started data taking in 2000, with relativistic heavy-ion collisions. Subsequent runs will also use polarized proton beams to carry out a program of spin physics. In PHENIX, the electro-magnetic (EM) calorimeter is the primary tool for measuring photons and electrons/positrons. In order to cover topics in both physics programs, e.g. a thermal photon measurement in relativistic heavy-ion collisions, and prompt photon, π^0 and weak boson measurements in spin physics, the EM calorimeter needs to cover a wide energy range extending from a few hundred MeV to 80GeV. A goal of the spin physics program is to measure differential cross sections of prompt photon and π^0's to an accuracy of 10%. A 2% accuracy in the calorimeter energy scale is required to achieve this for $p_T > 10\text{GeV}/c$ of interest, because the cross sections fall steeply as their energy increases. The EM calorimeter was originally designed for relativistic heavy-ion physics. There are two kinds of calorimeter in the PHENIX detector. One is a Shashlik [1–3] type lead–scintillator sampling calorimeter (PbSc) and another is a lead glass calorimeter (PbGl). Table 1 shows their basic parameters. A "super-module" is composed of 12×12 channels for the PbSc calorimeter and 4×6 channels for the PbGl calorimeter. The total EM calorimeter system in the PHENIX detector consists of the PbSc super-modules and the PbGl super-modules.

		PbSc	PbGl
radiation length (X_0)	[mm]	21	29
Moliere radius	[mm]	~30	37
channel			
cross section	[mm^2]	52.5×52.5	40×40
depth	[mm]	375	400
	[X_0]	18	14
η coverage		0.011	0.008
ϕ coverage		0.011	0.008
super-module			
number of channels		144 (12×12)	24 (4×6)
sector			
number of super-modules		18 (3×6)	192 (12×16)
total system			
number of sectors		6	2
number of channels		15552	9216
η coverage		0.7	0.7
ϕ coverage		90°+45°	45°

Table 1
Basic parameters of two kinds of PHENIX EM calorimeter.

The calorimeter's energy resolution, linearity and hadron rejection had already been measured at BNL-AGS in the energy range up to 7GeV [4]. In order to extend these measurements to the energy range up to 80GeV, a beam test was performed at the CERN-SPS H6 beam line in 1998.

In this article, we describe the beam test and present results of the PbSc data analysis.

2 Setup

Figure 1 shows a setup of the beam test. One PbSc super-module and four PbGl super-modules were located at the H6 beam line, and both were tested with electron beams in the momentum range of 10GeV/c to 80GeV/c and π^+ beams of 40GeV/c. Both kinds of calorimeter were placed on a movable platform to change positions and angles of the incident beam on the calorimeter. Delay-line Wire Chambers (DWC) [5] were located just in front of the calorimeter for measurements of the vertical and horizontal beam incident position. Incident-position dependence of the energy deposit were measured and corrected using the DWC. Two scintillators (S1 and S2) were used as trigger counters, and two other scintillators (muon counters) were set behind iron blocks to identify muons in the beam. There was a Čerenkov Differential counter with Achromatic Ring focus (CEDAR) further upstream of the S1 for electron identification.

We used the 10GeV/c muon beams for channel-by-channel gain adjustment of the PbSc super-module channels in addition to the electron beams. For time-dependent gain drift correction of the PbSc calorimeter, we used a laser monitoring system [6].

The DWC has good position resolution (0.2mm) and high single-particle detection capability (2×10^5 particles/sec). It consists of one anode-wire plane and two cathode wire planes which surround the anode plane. The cathode planes have 2mm wire spacing. Their wires are connected with a delay-line through which signals are read out by a TDC module. Timing information corresponds linearly to position information. The active area is 100×100 mm^2, and the area with linear response is 80×80 mm^2

A beam trigger was composed of a S1 signal ("$S1$"), a S2 signal ("$S2$") and a coincident signal of two muon counters ("μ"). An electron trigger was made by $S1 \otimes S2 \otimes \bar{\mu}$ and a muon trigger was made by $S1 \otimes S2 \otimes \mu$. Triggers for pedestal measurement and for the laser monitoring system were used to take those data between beam spills.

We used two different HV settings;

- a "normal" HV setting (1.23–1.29kV) for energy measurements up to 80GeV

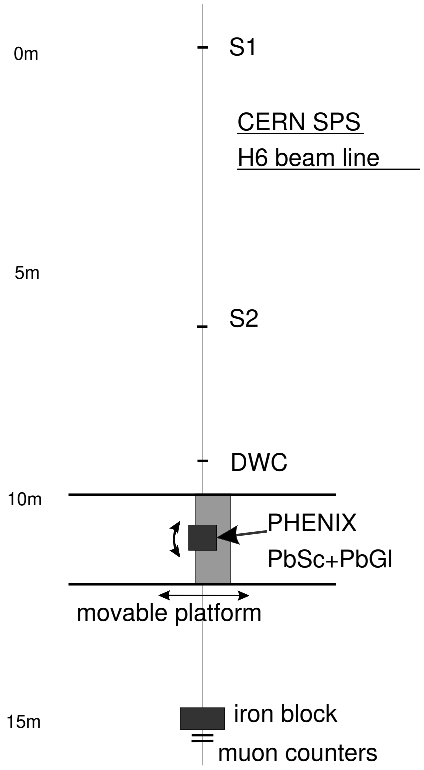

Fig. 1. Setup of the high energy beam test at CERN.

- a "low" HV setting (1.13–1.19kV) for energy measurements up to 160GeV.

To readout PMT signals from the calorimeter, we used front-end electronics (FEE) from the CERN experiment WA98[7].

3 Analysis

The deposited energy in each channel was calculated by multiplying the ADC count by a calibration factor, $C(t)$ (GeV/count). The calibration factor has time dependence. We parameterize the time dependence by an initial gain factor, G (GeV/count), and a gain drift, $D(t)$.

$$C(t) = G \times D(t).$$

The time dependent factor, $D(t)$, is defined to be 1 at the time of the muon calibration run.

The ADC count is derived from low and high gain ADCs which are both implemented to cover a wider dynamic range. We found a 1% difference between the ratio of high-to-low gain in electron trigger events and in laser trigger events. To determine the channel dependent high-to-low gain ratio, we use the measured ratio in electron beam trigger events for the 40 channels which have hits in the electron beam data. For the other channels, we measure the ratio with the laser trigger events. These channels have only a small contribution to the electron beam energy measurement hence a small effect on the systematic error. The average value of the high-to-low ratio is 7.8. The ADC value is derived from the low gain ADC when the low gain ADC count is larger than 90 counts. We also found there is no time dependence of the high-to-low ratio during whole run. The systematic error caused by the high-to-low ratio is less than 1% for those channels which have the electron beam data. There is a negligible contribution of the other channels to the systematic error.

The gain factor is adjusted channel-by-channel by using muon trigger events. In order to identify muons, the following selections are applied.

(1) The channel which has the largest energy deposit in all channels must have more than 80% of the energy sum of all channels.
(2) The number of channels which have energy deposit more than 130MeV must be zero or one.

When a muon beam penetrates one channel longitudinally, the most probable energy deposit is about 300MeV. Selection 1 requires that there are some hits which make a peak on that channel. Selection 2 requires it is a minimum-ionizing single particle and rejects background from other kinds of particles, and multi-hit of particles. By requiring both selections, muons which penetrate one channel are selected.

After the muon selection, we have more than 100 muons in each of the 40 channels. We adjust gains of these 40 channels so that the MIP peak position is at the same energy. The peak position is determined to a precision of 2–3%. In order to improve precision of the gain adjustment and to obtain the gain factor for the other channels, we use electron beam trigger events. The remaining errors of channel-by-channel adjustment of the gain factor is 3% in total. These errors are statistical ones. The systematic errors are smaller than these.

An absolute value of the gain factor to provide correct energy scale is fixed at the electron beam energy of 20GeV. The result shows the average value of the gain factor is 110 (count/GeV).

The time dependence of the gain was obtained using laser trigger events. The time variation of the laser amplitude was less than 3% reflecting the stability of the laser output. To monitor the fluctuation of the laser output, we use a truncated mean of the laser amplitude.

The gain drift factor obtained with this method works reliably over periods of order a few hours. Between some sets of runs the gain drift is normalized by using the beam energy of 20GeV in the period. The accuracy of the beam energy is 1% at 15GeV[8].

In this analysis, the total deposited energy is defined as a sum of energies in the 5×5 channels centered on the channel with the maximum energy deposit. The total energy is corrected by a position dependent factor.

The upper-left figure of Fig.2 shows the hit position dependence of the energy sum in 5×5 channels for the 20GeV electron beam. In this figure, the coordinate (X, Y) shows a hit position in one channel obtained by the DWC. The hit position $(0, 0)$ presents the center of the channel and $(1, 1)$ presents the edge of the channel. The position dependence is fitted as shown in the upper-right figure of Fig.2 by the following formula.

$$1 + a \times (X^2 + Y^2) + b \times (X^4 + Y^4) + c \times X^2 \cdot Y^2 \qquad (1)$$

We obtained a best fit with the following parameters;

$$\begin{aligned} a &= -0.3079 \\ b &= 0.3643 \\ c &= -0.02894 \end{aligned}$$

We use these parameters to correct for the position dependence of the energy measurement. The lower-left figure shows the deviation of the energy sum from the fitted hit position dependence and the lower-right figure shows a projection of the deviation. The deviation is 0.5% of the energy sum. The systematic error remaining after the position dependence correction is evaluated to be 0.5%.

4 Results

Figure 3 shows the efficiency for the 40GeV positron beam when we require a measured energy deposit greater than E_{cut}, and the pion rejection power for the 40GeV π^+ beam obtained with the same cut.

The energy resolution at each energy point was obtained by fitting a Gaussian distribution within $\pm 2\sigma$ around the electron peak. The electron trigger events contained a 10% pion contamination. The contamination in the electron peak region is less than 0.1% because only 1% of the pions deposit more than 90% energy in the calorimeter. The χ^2 of the fitting is reasonably small.

Figure 4 shows energy resolution obtained by both beam tests at CERN and BNL. They can be fit with linear or quadratic expressions. Only statistical

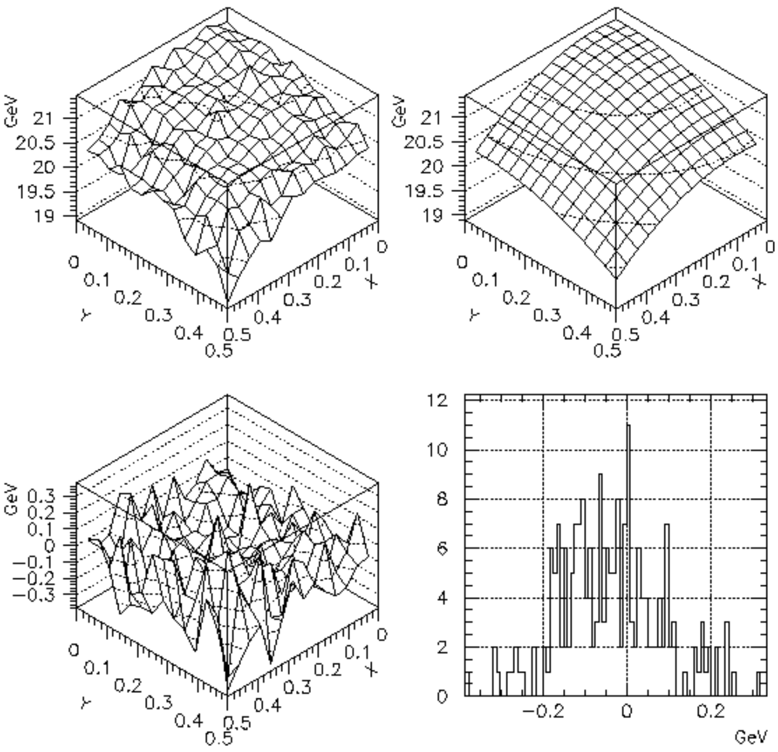

Fig. 2. Upper-left: Hit position dependence of the 5×5 energy sum for the 20GeV electron beam, where (X, Y) shows a hit position obtained by the DWC. Upper-right: Fitted hit position dependence. Lower-left: Deviation of the energy sum from the fitted position dependence Lower-right: Projection of the deviation.

errors are taken into account in the fits. We estimate an additional 1% systematic error based on the reproducibility of the measurements at each energy point. The results of the fits are

$$\sigma_E/E = 1.2\% + \frac{6.2\%}{\sqrt{E(GeV)}}$$

$$\sigma_E/E = 2.1\% \oplus \frac{8.1\%}{\sqrt{E(GeV)}}$$

where $\oplus$ denotes a square of the quadratic sum, $\alpha \oplus \beta = \sqrt{\alpha^2 + \beta^2}$. They are valid in the energy region of 0.5GeV to 80GeV with 1% systematic uncertainty.

Figure 5 shows the residual (measured energy with the calorimeter less the beam energy, divided by the beam energy) of the energy sum in 5×5 channels versus the beam energy. We see that the calorimeter response is linear within 2% systematic uncertainties in the energy region from 20GeV to 80GeV. There is some indication of a 2% deviation from linearity at 10GeV, however this is within our systematic errors. Such a deviation cannot be due to one of the

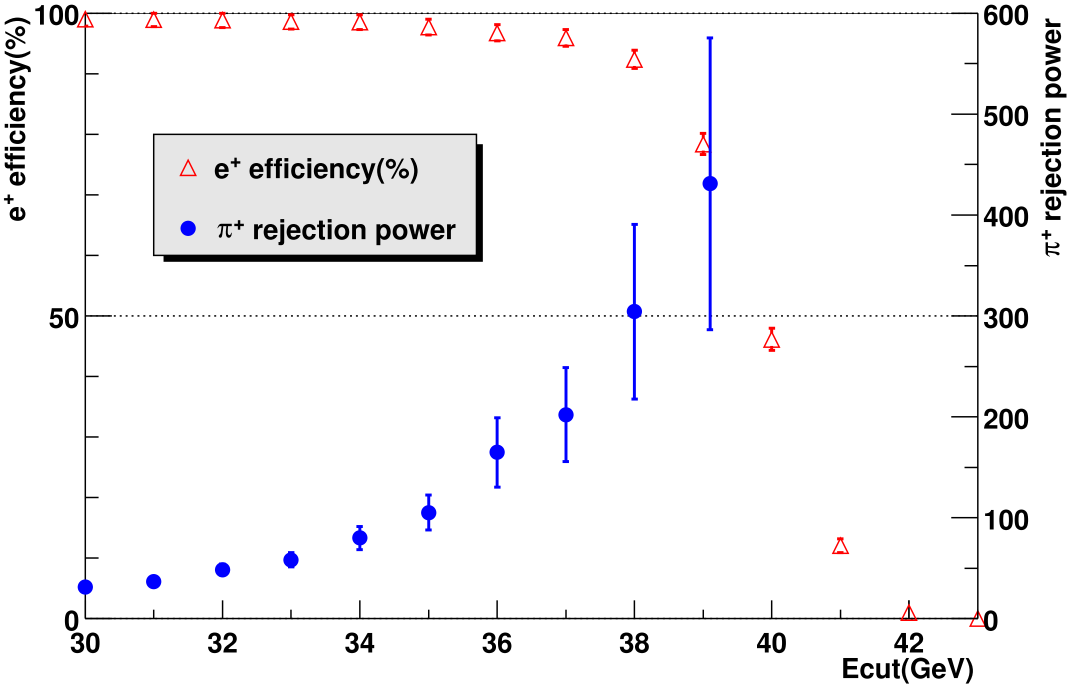

Fig. 3. The efficiency for the 40GeV positron beam when we require a measured energy deposit greater than E_{cut}, and the pion rejection power for the 40GeV π^+ beam obtained with the same cut.

following corrections; the gain drift correction, pedestal subtraction, high-to-low ratio correction, or the energy sum of 5×5 channels. We considered the following possible sources;

- run-time problems in the monitoring system
- linearity of the WA98 FEE
- linearity of the PMT
- an inherent non-linearity in the calorimeter due for example to the interplay between light attenuation in the wave-length-shifter (WLS) readout fibers and longitudinal shower leakage beyond the calorimeter.

Linearity of the WA98 electronics which was used to digitize signals from the calorimeter was investigated. We found that it has linear response within 1%. Linearity of the PMT had also been investigated and confirmed to have linear response within 2% [9]. The light leakage in the WLS fiber is evaluated by the simulation program. The energy leakage is evaluated to be 1% at 10GeV and 4% at 80GeV [10,11]. These effects tend to cancel one another, so we do not expect the intrinsic non-linearity to be as large as 2%. In summary, the only place where the measured residual approaches the limit of 2% is at 10 GeV. Nevertheless, the residual is consistent within our systematic error of being linear at this energy. We've examined a number of possible causes for a

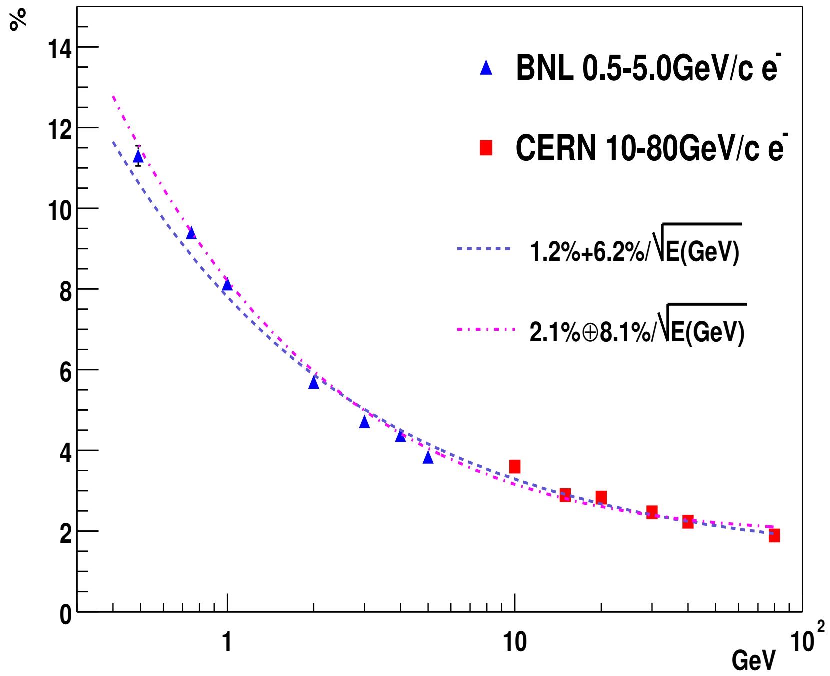

Fig. 4. Energy resolution obtained by both beam tests at BNL and CERN. A dashed line shows the result of fitting by a linear formula, $\sigma_E/E = 1.2\% + 6.2\%/\sqrt{E(GeV)}$. A dashed dotted line shows the result of fitting by a quadratic formula, $\sigma_E/E = 2.1\% \oplus 8.1\%/\sqrt{E(GeV)}$.

deviation from linearity but none has been found.

Position resolution of the beam hit position is evaluated with the logarithmic method [12]. In the logarithmic method, the position is determined by the following formula.

$$X = \frac{\sum_{i=1...N} C_i \times x_i}{\sum_{i=1...N} C_i}$$

where x_i denotes a center of each channel in the horizontal direction. Similarly, Y is defined in the vertical direction. The weights C_i are;

$$R_i = Max[0, E_i/E_{total}]$$
$$C_i = Max[0, log(R_i) + C_0]$$

where E_{total} is the total energy, $E_{total} = \sum_{i=1...N} E_i$ and C_0 is a constant. A larger value of α and β is expressed by $Max[\alpha, \beta]$.

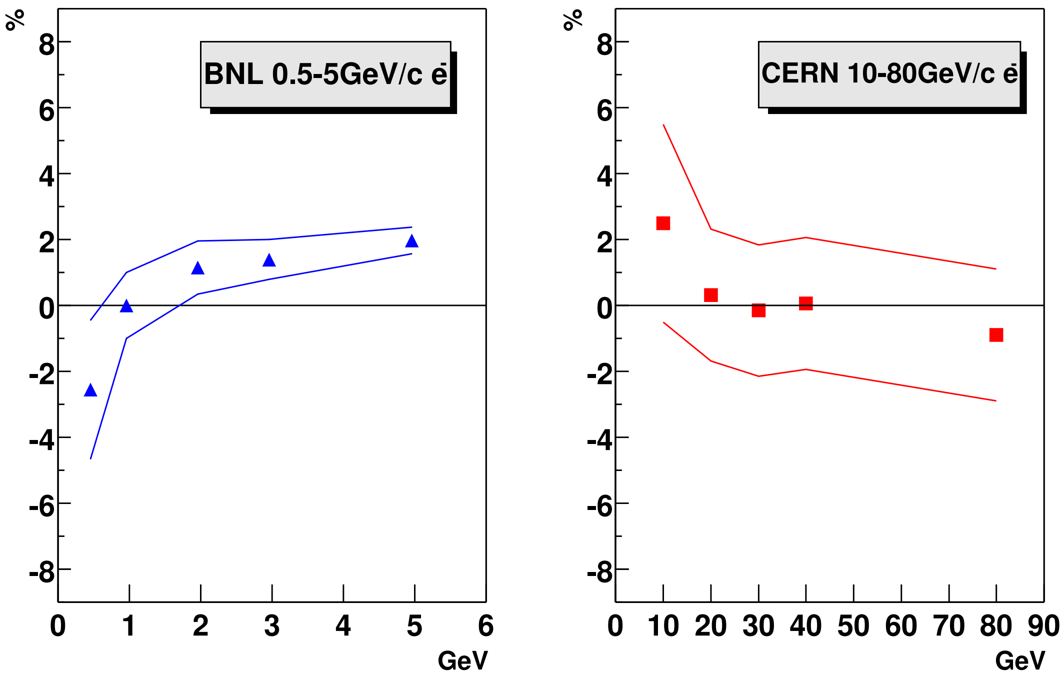

Fig. 5. Linearity of the 5×5 energy sum for both beam tests at BNL (left) and CERN (right). Solid lines show total systematic uncertainties in the analysis. Absolute level of two beam test is not normalized.

The deviation in a short period shows that systematic uncertainty in the logarithmic method is 2mm.

Figure 6 shows the position resolution obtained by both beam tests at CERN and BNL. The points can be fitted by a formula;

$$\sigma_x(\mathrm{mm}) = 1.4(\mathrm{mm}) + \frac{5.9(\mathrm{mm})}{\sqrt{E(\mathrm{GeV})}}.$$

5 Conclusion

We measured the energy resolution, linearity and position resolution of the PHENIX EM calorimeter in a test beam at CERN. For the PbSc calorimeter, we obtained energy resolution of;

$$\sigma_E/E = 1.2\% + \frac{6.2\%}{\sqrt{E(GeV)}}$$

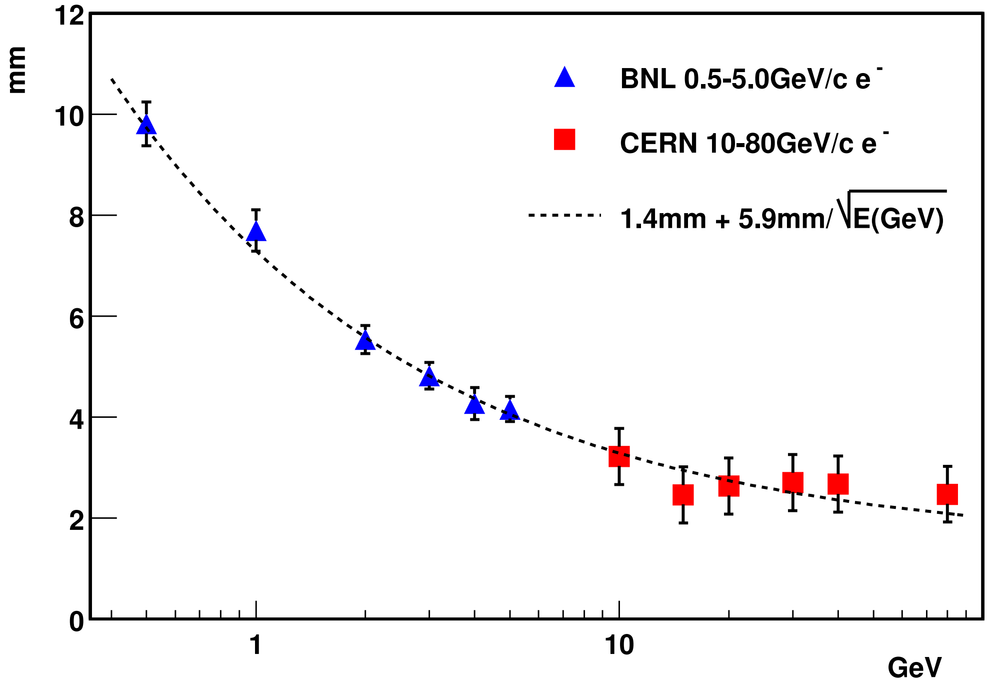

Fig. 6. Position resolution obtained by both beam tests at BNL and CERN. A dashed line shows the result of fitting, 1.4 mm + 5.9 mm / $\sqrt{E(GeV)}$.

$$\sigma_E/E = 2.1\% \oplus \frac{8.1\%}{\sqrt{E(GeV)}}$$

and position resolution;

$$\sigma_x(\mathrm{mm}) = 1.4(\mathrm{mm}) + \frac{5.9(\mathrm{mm})}{\sqrt{E(\mathrm{GeV})}}.$$

A major purpose of the test was to investigate the performance of the calorimeter in the energy range up to 80GeV and, in particular, the linearity of response versus beam energy. Since our goal in PHENIX is to measure prompt photon and π^0 production cross sections with the calorimeter within 10% errors it is important to understand the linearity of the calorimeter at the level of 2%. In the analysis of the PbSc calorimeter, the response is found to be linear to approximately this level.

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References

[1] S. N. White, Proc. of the Fourth Int. Conf. on Calorimetry in High Energy Physics (1994).

[2] J. Badier *et al.*, Nucl. Instr. and Meth. A 348 (1994) 74.

[3] E. Tarkovsky, Nucl. Instr. and Meth. A 379 (1996) 515.

[4] G. David *et al.*, IEEE Trans. Nucl. Sci. **45** (1998) 692.

[5] J. Spanggaard, *Delay Wire Chambers A Users Guide*, CERN SL-Note-98-023 (1998).

[6] G. David *et al.*, IEEE Trans. Nucl. Sci. **45** (1998) 705.

[7] A. L. Wintenberg *et al.*, Proc. of the Fourth Int. Conf. on Electronics for Future Colliders, LeCroy Corp. (1994).

[8] G. Ambrosini *et al.*, Eur. Phys. J. C **10** (1999) 605.

[9] G. David *et al.*, IEEE Trans. Nucl. Sci. **42** (1995) 306.

[10] D. Muller, Phys. Rev. **5** (1972) 2677.

[11] G. Bathow *et al.*, Nucl. Phys. B **20** (1970) 592.

[12] T. C. Awes *et al.*, Nucl. Instr. and Meth. A 311 (1992) 130.