Fermi National Accelerator Laboratory

FERMILAB-Conf-92/273

The e/π and π^0/π Ratios Measured, and Monochromatic γ and π^0 Beams Explored in the DØ Test Calorimeter

Michael A. Tartaglia
for the DØ Collaboration

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

October 1992

Presented at the *3rd International Conference on Advanced Technology and Particle Physics,* Como, Italy, June 22-26, 1992

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CHO3000 with the United States Department of Energy

Disclaimer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

The e/π and π^0/π Ratios Measured, and Monochromatic γ and π^0 Beams Explored in the DØ Test Calorimeter

Michael A. Tartaglia, for the DØ Collaboration**

Fermi National Accelerator Laboratory, Batavia, IL 60510 USA
Work supported by the U.S. Department of Energy under contract No. DE-AC02-76CH03000.

The e/π response ratio of the DØ end calorimeter has been measured by comparing data from 10 to 150 GeV/c electron and pion beams. The "intrinsic" e/π of the fine-hadronic module has also been studied with the pions alone, by selecting π^0-like showers contained within individual layers of the calorimeter. The measurements are compared to GEANT Monte Carlo simulations.

A technique to generate monochromatic test beams of photons and neutral pions was successfully investigated. Preliminary results from central calorimeter modules exposed to these beams are discussed, and are compared to calculated expectations.

1 INTRODUCTION

This paper discusses two independent topics regarding beam tests of the DØ calorimeter modules[1, 2], performed in 1990 and 1991. First, the e/π ratio[2] measurements are presented. The analysis of response to electron and pion beams is described, and results are compared to GEANT Monte Carlo simulations performed with two hadron shower generators; one of these reproduces the energy dependent ratio well, and the other does not. An alternative approach has also been taken to study the inherent e/π ratio by focusing on the response to pions alone in the *homogeneous* fine-hadronic module. In this case, the "e" response is extracted by isolating short, mostly-electromagnetic (π^0) showers, by virtue of the fine longitudinal segmentation of the calorimeter. This method has different systematic conditions, and illuminates some basic characteristics of the calorimeter.

Second, a simple modification of the beam line made it possible to generate photon and neutral pion beams. With a small target station plus an efficient charged parti-

**THE DØ COLLABORATION– Universidad de los Andes, Bogota, Colombia; University of Arizona; Brookhaven National Laboratory; Brown University; University of California, Riverside; Centro Brasiliero de Pesquisas Fisicas, Rio de Janeiro, Brasil; CINVESTAV, Mexico City, Mexico; Columbia University; Delhi University, Delhi, India; Fermi National Accelerator Laboratory; Florida State University; University of Hawaii; University of Illinois, Chicago; Indiana University; Iowa State University; Lawrence Berkeley Laboratory; University of Maryland; University of Michigan; Michigan State University; Moscow State University, Russia; New York University; Northeastern University; Northern Illinois University; Northwestern University; University of Notre Dame; Panjab University, Chandigarh, India; Institute for High Energy Physics, Protvino, Russia; Purdue University; Rice University; University of Rochester; CEN Saclay, France; State University of New York, Stony Brook; Superconducting Supercollider Laboratory, Dallas; Tata Institute of Fundamental Research, Bombay, India; University of Texas, Arlington; Texas A&M University.

Proceedings of the 3rd International Conference on Advanced Technology and Particle Physics, Como, Italy, 22-26 June 1992

cle veto placed in the beam line just upstream of the calorimeter, electron bremsstrahlung and pion charge exchange were found to produce significant rates above background for events at the beam energy. Preliminary calorimeter results and simple model calculations are used to begin exploring the beam properties and the calorimeter's response.

1.1 DØ TEST CALORIMETER

The DØ (test) calorimeter modules[1] are stacks of uranium plates with gaps filled by liquid argon and readout pads on signal boards. Pads are ganged longitudinally in layers to form a pseudo-projective tower geometry. The readout has granularity of 0.1 unit in both pseudo-rapidity (η) and azimuthal angle (ϕ), except the third layer electromagnetic (EM) section which is more finely segmented, $\Delta\eta = \Delta\phi = 0.05$. Layer thicknesses vary, and are described below. Materials were inserted in the test cryostat (and Monte Carlo) at the correct locations to simulate the DØ cryostat walls and vertex chamber wall (Load 1).

The cryostat containing the load of modules and preamplifier electronics is supported on a massive transporter. The device is able to position modules precisely in the test beam, to $\sim$ 1 mm, to simulate a desired η, ϕ particle trajectory at the collider. An (X,Y) PWC is located on the cryostat to measure incident charged particle positions.

1.1.1 Load 1

The Load 1 (1990) tests exposed the end calorimeter (EC) electromagnetic and inner-hadronic (EC EM & IH) modules, which were subsequently installed at DØ . The modules were arranged as in DØ with the beam incident on the EM, followed by the IH. Of particular importance to this study is the fact that the EC IH is segmented longitudinally into 1.3 interaction length (L_{int}), 30 radiation length (L_{rad}) layers; thus a pion shower longitudinally contained in a single layer is dominantly electromagnetic.

Electron (e) and pion (π^-) energy scans, from 10 to 150 GeV, were recorded at η values of 1.95, 2.30, 2.55. At the lowest η, small lateral leakage of pion showers occurs out the side of the cylindrical IH module. Due to the limited number of electronics channels used in the test, a wedge-shaped sector in ϕ was instrumented. Preamplifier gains were monitored regularly with special (beam off) pulser runs, and pedestal data were recorded during (and between) beam spills to monitor baseline levels throughout the exposures. Frequent runs at benchmark positions ($\eta = 1.95$ for 100 GeV e, and $\eta = 2.30$ and 2.55 for 100 GeV π^-) were recorded to monitor the apparatus stability (better than 2%).

1.1.2 Load 2

For the Load 2 (1991) test, the cryostat contained 4 central calorimeter (CC) electromagnetic (CC EM), 2 fine- and 2 coarse-hadronic (CC FH, CH) modules, configured identically to an octant of the DØ ring of CC modules. Calibration procedures were similar to those in Load 1. The neutral beam tests occurred during the Load 2 run and details are discussed in Section 3.

1.2 DØ TEST BEAM LINE

The beams of electrons or negative pions were made in a 3-bend spectrometer. For each event the beam momentum was measured to 0.25% (the beam RMS was 1.5%). There were two helium Čerenkov counters to identify electrons; these provided tagged data with less than 10^{-4} e contamination in the π^- beam. The trigger required three beam-defining scintillators in coincidence and no halo scintillator signal. A scintillation counter was located after the cryostat to tag punch-through particles, followed by an iron shield and scintillation counter to identify muons (μ).

1.3 DETECTOR SIMULATION

The DØ test apparatus was modeled using the GEANT version 3.14 Monte Carlo (MC) program[3]. The calorimeter was simulated with a uranium plate/argon gap geometry, with EM and hadronic particles tracked down to low energies of 10 keV and 100 keV, respectively. Pion showers were simulated with two hadron generators: NUCRIN and GHEISHA. Uranium noise that exists in the data was not incorporated in this version of the DØ MC. However, this introduces only a slight resolution smearing and no bias in the average response.

2 THE e/π RATIO

The e/π response ratio of a calorimeter is important because it can influence linearity and the ability to measure hadron jet energies. The MC is relied upon heavily to model response to hadronic jets, so it is crucial that it accurately reproduce single particle data. We present two independent determinations of e/π using Load 1 data and MC.

2.1 THE e/π MEASUREMENT

There are systematic differences in the response to pions and electrons in extracting the e/π ratio. First, the cryostat material affects e and π^- showers differently. Second, the EM and IH module sampling fractions are different, which allows some freedom to adjust the relative EM/IH weight and alter the e/π ratio. Adjusting the weights affects linearity and resolution. We choose those weights which optimize linearity and resolution, rather than altering the e/π ratio.

2.1.1 Event Selection

Events used in this analysis were required to have the appropriate Čerenkov tag, and no muon tag. At 10 GeV, additional μ removal was necessary because multiple scattering causes some muons to miss the tag scintillator, and because the μ and π^- calorimeter energies overlap. These muons were identified by their very narrow transverse energy distribution in the calorimeter. Tracking cuts were applied to ensure a reliable momentum measurement. For pions, less than 1 GeV energy in the first layer was required to remove interactions upstream of the calorimeter.

2.1.2 Analysis

The raw pulse height for each electronic channel was corrected by subtracting the average pedestal (taken during the spill), and applying a correction for channel-to-channel gain variations (within a few percent of unity). Sampling weights for each layer were then applied: these weights were determined by fits to energy scan data where linearity and resolution were optimized over the 10-150 GeV range. The fit values agree with the dE/dx sampling fractions, except for the first EM layer where upstream material must be taken into account.

The detector response was calculated the same way for both π^- and e. The corrected pulse height was summed for all cells in a $\eta \times \phi = 1.5 \times 1.5$ region centered on the beam position. Total pulse height divided by measured particle momentum gave the response for each event. For each beam setting the response distribution was well fit by a Gaussian function, whose mean value we refer to as the <response>. The measured raw

e/π ratio is then:

$< e$ response$> / < \pi^-$ response$>$.

The raw e/π results agree, within errors, for the η positions (2.30, 2.55) at which full longitudinal containment is expected. Although the average pion shower is contained, fluctuations cause energy to be lost from the summed region, leading to a reduction in the $< \pi^-$ response$>$. To estimate this leakage we rely upon the Monte Carlo as described below.

2.1.3 Monte Carlo Comparison

To test that the Monte Carlo reproduces the general characteristics of the data, we compared pulse height spectra in individual layers; the agreement is good. The η-dependent pion response, which checks longitudinal and lateral leakage, also agrees well with data. The transverse shape was compared by plotting the average cell pulse height versus η at constant ϕ. The agreement is good when the beam position spread is included in the MC.

Table 1:
Uncorrected e/π ratios.

Energy	Data	GHEISHA	NUCRIN
$10 GeV$	1.16	1.20	1.31
25	1.11	1.10	1.19
50	1.09	1.07	1.16
100	1.07	1.08	—
150	1.06	1.05	—

Statistical errors are < 1 %.

The uncorrected e/π ratios (averaging $\eta = 2.30, 2.55$ results) are displayed in Table 1. The GHEISHA generator reproduces the data quite well, while NUCRIN significantly overestimates the measured e/π. To estimate the energy lost from windowed and

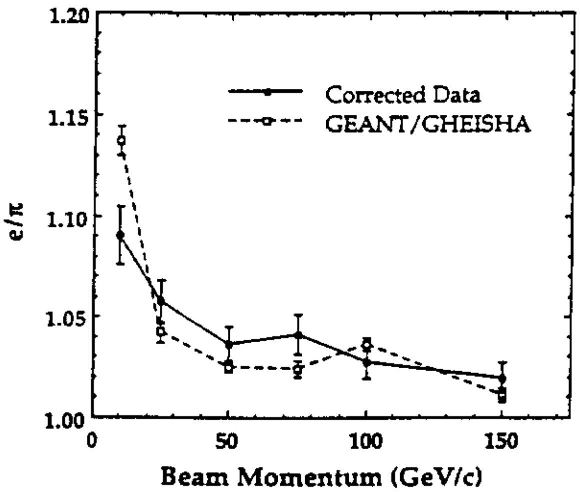

Figure 1: Corrected data and MC e/π versus energy.

instrumented regions, we applied the same η, ϕ cuts to MC as data, and studied the change in $< \pi^-$ response$>$ versus the window size. The GHEISHA results and leakage-corrected data are plotted against energy in Figure 1.

2.2 THE π^0/π MEASUREMENT

By using only pions to study the e/π ratio, we can bypass the issues of upstream material and relative EM and IH sampling weights, and explore the inherent value for the hadron calorimeter. The large sample (several $\times$ 10^5) of 100 GeV pion showers makes it possible to study the relatively rare occurrence (approx. 10^{-3} per π^-) in which most of the pion energy is deposited in a single layer of the EC IH calorimeter. Such events are caused by charge exchange interactions that result in π^0 production and electromagnetic shower development.

We select pions with less than 5 GeV deposited in the EC EM layers, and plot the $<$ response $>$ versus the fraction of the total energy that is contained within one layer of the EC IH; e.g., layer 1 (IH1). Fig. 2 shows that the response goes up as the IH1 fraction approaches unity, and clearly demonstrates that e/π is greater than 1.

The <response> for pions with more than 90% of the energy in any one hadronic layer (IH1-4), we call the $< \pi^0$ response> (Extrapolation to 100% containment in a layer gives the same result, within errors). Comparing this to all pions showering *within the IH*, we obtain the π^0/π ratio in Table 2. The same quantity was evaluated with the Monte Carlo by starting π^0 showers at the front of an IH layer. The Monte Carlo ratio, also shown in Table 2, is slightly above the data but agrees within errors.

Table 2:
100 GeV Data and Monte Carlo π^0/π ratios.

	Data	GHEISHA
$\pi^0/\pi =$	1.061 ± 0.008	1.081 ± 0.010

One may expect some dilution (*mostly*, but not *all* π^0) in the data, since electron showers are somewhat shorter than the layer thickness of 30 L_{rad}. Some studies of the $< \pi^0$ response> have been made by selecting π^- showers that are also *transversely* electron-like (narrow), and with Load 2 data in which the second hadronic layer is also 30 L_{rad}, but the third layer is 25 L_{rad}. The preliminary determination is that the π^0/π ratio in data is underestimated by 2 ± 2%.

The MC agrees with both the e/π and π^0/π results. These two numbers differ because the electrons lose a few percent of their energy in the vertex chamber and cryostat walls, which most pions do not. Therefore the π^0/π ratio reflects the underlying response of the *IH module*, while the e/π ratio gives a better representation of the *global calorimeter* response to electrons and pions. Note, however, that a small fraction of pions will deposit a significant amount (> 1 GeV) of energy in the first EM layer (they were removed from this analysis). Further studies of this effect on the e/π ratio for data and MC are in progress.

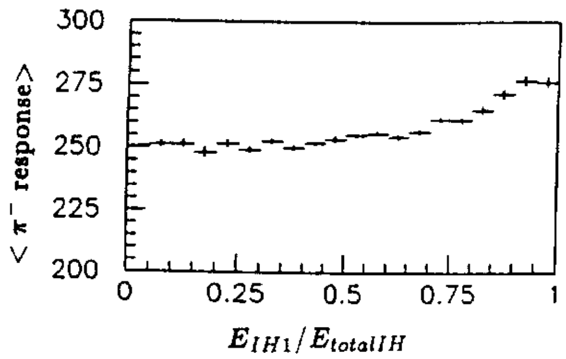

Figure 2: $< \pi^-$ response> versus fraction of energy contained in the first EC IH layer.

3 NEUTRAL BEAMS

The DØ calorimeter was designed to study hard scattering processes in $\bar{p}p$ collisions through electron, photon, and jet identification and measurement. The identification of electron and photon (γ) signals is difficult in a hadron environment, and backgrounds from π^0 production are a formidable challenge for many topics of study. The MC shower simulation plays a crucial role in understanding what details best contrast the signal to background, and how well algorithms can recognize the subtle differences between them. It is thus important to confront the MC with data wherever possible.

Charge-exchange production[4] of π^0's (CEX) that occurs early in the calorimeter limits the ability to distinguish a single π^- from an electron. To study this process, we recorded samples of such events by triggering on neutral states produced by the π^- beam in targets placed 2 meters upstream of the cryostat. Details of the π^0 data and preliminary results are discussed in section 3.2.

We found a similar technique can select γ events, in which an electron has radiated most of its energy while passing through a thin radiator. We were thus able to collect large samples of highly monochromatic photons at the electron beam energy. The γ data sets and results are described in section 3.3. Features common to both γ and π^0 beams are discussed below.

3.1 General Features

The trigger for the neutral beams required the usual beam coincidence and was vetoed by any charged particle emerging forward from the target by a pair of 1/4"-thick scintillators. The beam transverse size was 2" $\times$ 4", and the veto covered an 8" $\times$ 16" area. The inefficiency of this veto was about 10^{-6} for charged particles. The 5" $\times$ 5" cryostat-mounted PWC gave an additional 99%-efficient charged particle identification offline. In both neutral beams this PWC showed very few charged track (presumably conversion) events.

Trigger rates and scintillator efficiencies were monitored throughout the studies, and were stable. The rates for both beams are dominated by upstream interactions that accidentally satisfy the trigger. Typical raw CC EM calorimeter pulse height spectra are shown in Figures 3 and 4, for 25 GeV neutral pion and photon events with no PWC hits. Signals are clearly visible above background at the beam energy. Arrows are drawn in Figures 3 and 4 to show the energy above which preliminary signal rates are measured. (The cutoff value for rate measurements at other settings was scaled with the beam energy).

3.2 Pions

The π^0 data were recorded at 25 GeV for $\eta = 0.05$ only. This energy setting was chosen for physics interest, as well to compromise between the energy-dependent (rising) pion intensity and (falling) CEX cross-section. Comparison e and π^- runs were taken for energy scale normalization.

The CEX cross-section experiments[4] found that events with multiple π^0's occur at about the same rate as single π^0's. To explore the systematics of signal and background, we used both low-Z (15 cm polyethylene) and high-Z (5 cm and 10 cm iron) targets. In addition to no-target background runs, data were taken with a 2 L_{rad} lead converter, and with a prototype DØ Upgrade scintillator pre-shower detector. These data are under study to determine the multiple π^0 content by counting converted photons.

The total raw trigger rate for the neutral pion beam was $.0050 \pm .0005$ per incident π^-. Near the beam energy, the showers are electromagnetic and transversely narrow and electron-like. The π^0 peak near the beam energy in Fig. 3 is similar at the high end to the electron spectrum, but has much more tail on the low side. This may be due to neutrons which emerge from the CEX reaction with small but finite energy transferred, that is not deposited in a narrow calorimeter road. This effect will be studied in the future with the GEANT Monte Carlo.

The neutral pion rates are about a factor of two above those calculated from the 20 microbarn CEX cross-section at 25 GeV, consistent with the expectation that the multiple-π^0 production rate is equivalent to CEX. Further work is in progress to understand the rates and beam composition in more detail. These events are under study to enhance the understanding of π^0 identification in the DØ EM calorimeter.

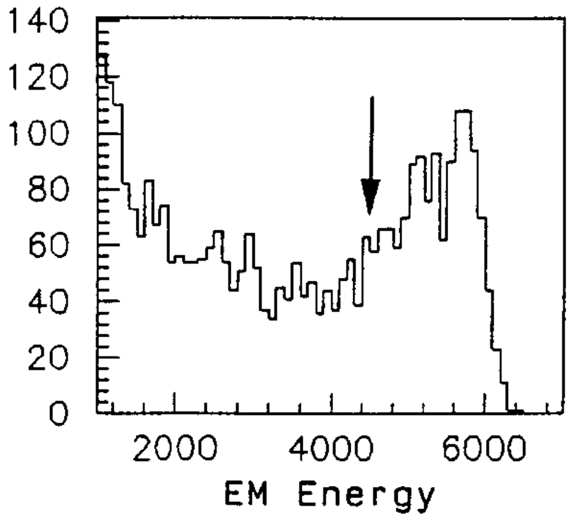

Figure 3: Raw total pulse height spectrum for 25 GeV π^0 beam (Polyethylene sample). The arrow shows the cutoff value for rate measurement.

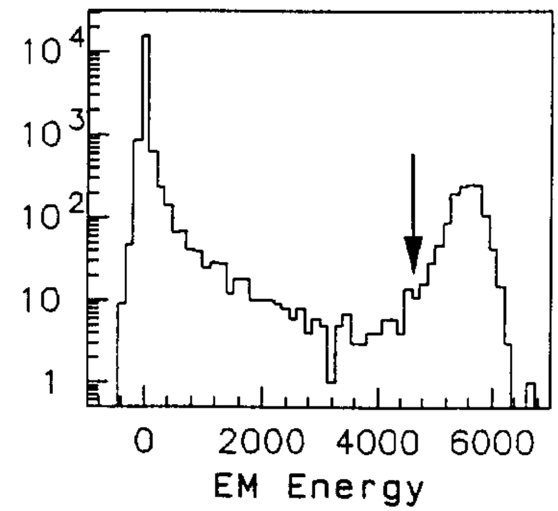

Figure 4: Raw total pulse height spectrum for 25 GeV γ beam (BL sample). The arrow shows the cutoff value for rate measurement.

3.3 Photons

The photon data were recorded at 10 and 25 GeV, for $\eta = 0.05$ and 0.45. Comparison electron runs were taken at each setting to normalize the calorimeter energy scale. Two thin targets were utilized: a) the beam line-only (BL) case, with about 15% L_{rad} material downstream of the final bend magnet, and b) a 2 mm Pb foil (PB), adding an additional 35% L_{rad}, was placed before the veto.

The raw neutral trigger rate was $.013 \pm .001$ per incident electron, independent of energy. The photon signal rates (above cutoff) scaled inversely with the incident electron energy, as one would expect for bremsstrahlung.

A simple model for the photon beam is an incident electron radiates all but a small fraction of its energy while moving through the thin radiator. The remaining energy is below some cutoff value E_f that is insufficient to escape the radiator and penetrate the veto. To calculate rates and beam properties under this scenario we obtained a 1-dimensional EM shower Monte Carlo program[5] which propagates particles through material in 1% L_{rad} steps.

The measured γ rates are in reasonable agreement with the model for $E_f \sim 100$ MeV (there is some dependence on the radiator thickness). The calorimeter energy spectra for γ and e are indistinguishable, except that the mean γ energy is *approximately* 100-200 MeV lower than the e. A careful analysis of the γ and e calorimeter energies is underway to constrain E_f and improve the model.

With the simple MC model, one can predict the number of radiated photons and their energies. Typically more than one γ is radiated; however this simple model indicates (Fig. 5) that most of the time a single γ carries all of the energy. Occasionally (25% for BL, about 50% for PB) a second γ carries more than 5% of the energy. The γ energy spectrum is found to be insensitive to E_f.

The longitudinal shower profiles, plotted in Fig. 6, offer clear evidence that these particles are photons. Photons in both data and MC start showering, on the average, about 1 L_{rad} deeper than electrons. This is be-

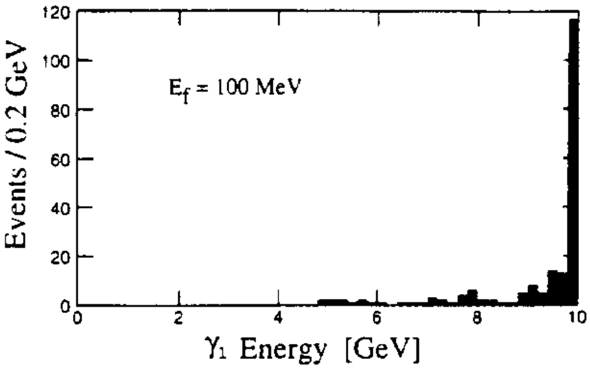

Figure 5: Prediction of most energetic photon spectrum for 15% L_{rad} radiator.

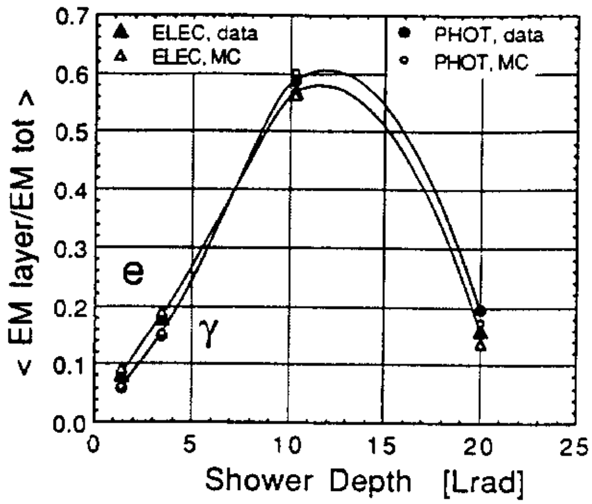

Figure 6: Average e and γ shower profiles, MC and Data (smooth curve, not fit).

cause energy deposition does not occur until the γ converts. The individual layer profiles hold more information than the average shower shape, and comparison with MC is in progress.

4 CONCLUSIONS

We find good agreement between DØ test calorimeter measurements and GEANT Monte Carlo calculations of the e/π and π^0/π ratios, using the GHEISHA hadron shower simulation.

The γ and π^0 beams show significant, largely monochromatic signals above falling backgrounds at the beam energy. The preliminary rates are in good accord with predictions, and we anticipate further studies of test data and Monte Carlo to better understand the composition of the beams, and particle identification in the DØ calorimeter.

References

[1] More detailed descriptions and results from DØ calorimeter tests can be found in: S.Aronson, *et al.*, Nucl. Instr. & Meth. A269(1988)492; M. Abolins, *et al.*, Nucl. Instr. & Meth. A 280(1989)36; H. Aihara, *et al.*, "The Design, Construction, and Performance of the DØ End Calorimeter Electromagnetic Module", Lawrence Berkeley Laboratory Report LBL-31378 (to be published in Nucl. Instr. & Meth.); S. Abachi, *et al.*, "Beam Tests of the DØ Uranium Liquid Argon End Calorimeters," Fermilab-PUB-92/162, (to be published in Nucl. Instr. & Meth.).

[2] First International Conference on Calorimetry in High Energy Physics, Fermi National Accelerator Laboratory, Batavia, IL, editors D.F.Anderson, M.Derrick, H.E.Fisk, A.Para, C.M.Sazama; World Scientific, 1991.

[3] R. Brun, *et al.*, CERN/DD/EE/84-1, GEANT Users Guide, September 1987.

[4] A.V.Stirling, *et al.*, Phys. Rev. Lett. 14(1965)763; *Ibid.*, Phys. Rev. Lett. 18(1965)200; V.N.Bolotov, *et al.*,Nucl. Phys. B73(1974)365; A.V.Barnes, *et al.*, Phys. Rev. Lett. 37(1976)76.

[5] P.Kasper, Priv. Comm., Fermilab Wide Band Photon Beam MC; based upon Y.S.Tsai, Rev.Mod.Phys. 46(1974)815.