

Final Scientific Report

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Proton Radiography: Cross Section Measurements and Detector Development

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Executive Summary

Proton radiography offers significant advantages over conventional X-ray radiography, including the capability of looking into thick, dense materials, better contrast for a wide range of materials, sensitivity to different materials of similar density, and better resolution because of the ability to focus beams. In order to achieve this capability it is crucial to understand the background due to neutrons and photons and to develop techniques to reduce it to tolerable levels.

The physics goal of this project is to measure forward production of neutrons and photons produced by high-energy proton beams striking a variety of targets. This work is being carried out in conjunction with the Fermilab Experiment 907 (MIPP) collaboration including physicists from Lawrence Livermore Laboratory. Our group is responsible for the E907 forward neutron/photon calorimeters. These are the only detectors in the experiment that provide information on neutrons and photons. We are taking a leading role in obtaining and analyzing the forward production data and in developing an optimal detector for proton radiography. With the support of our Stewardship Science Academic Alliances grant, we were able to design, build, and commission the calorimeters on budget and ahead of schedule. E-907 officially started physics running at Fermilab in January 2005, and data taking continued through February 2006. Data were taken on a range of targets, from liquid hydrogen to uranium, at beam energies from 5 GeV/c to 120 GeV/c. The analysis of the data is challenging because data from many different detector systems must be understood and merged and over 31 million events were accumulated.

Our recent efforts have been devoted to the calibration of the neutron and photon detectors, to track and shower reconstruction, identification of forward-going neutrons, and simulation of the calorimeters in a Monte Carlo. Reconstruction of the data with improved tracking is underway.

Introduction

The MIPP spectrometer is shown in Figure 1. A 120 GeV/c proton beam from the Fermilab Main Injector hits a target upstream producing a secondary beam whose momentum can be varied between 5 and 120 GeV/c. When positive beams are selected the secondary beam contains a mixture of protons, π^+ , and K^+ . When negative beams are selected, it consists of π^- , K^- , and antiprotons. Beam particles are identified by upstream Cerenkov counters. Targets are mounted on a target wheel just upstream of the Time Projection Chamber (TPC). The TPC is mounted inside a large-aperture magnet, the "Jolly Green Giant". The TPC can identify low momentum charged tracks through their ionization, and their momentum can be measured with fair accuracy. The TPC is followed by a series of large wire chambers to accurately measure track trajectories, a Cerenkov counter, an array of small scintillators to measure time of flight, and a Ring Imaging Cerenkov counter (RICH).

The electromagnetic calorimeter (EMCAL) consists of 10 layers of 5.08 mm thick lead interspersed with planes of gas proportional chambers. The proportional chambers are made of aluminum extrusions. There are 64 anode wires with 25.4 mm spacing in each plane. The chambers used a gas mix of P10 (90% Argon and 10% Methane) and CF_4 . The EMCAL active area was 1.6 m wide, 1.5 m high and 0.3 m long along the beam direction. The total thickness was ~ 10 radiation lengths. The EMCAL readout consisted of 640 channels that measured the charge deposited on each wire. Photons and electrons produce electromagnetic showers in the lead plates and deposit most of their energy in the EMCAL. Hadrons, such as neutrons, usually pass through the EMCAL into the hadron calorimeter (HCAL).

The hadron calorimeter (HCAL) was composed of 64 layers of 24.1 mm thick Fe and 5 mm thick scintillator. It was originally built for the HyperCP (E871) experiment. The total thickness of the HCAL was 9.6 interaction lengths (88.5 radiation lengths). Its active area was 0.99 m wide, 0.98 m high and 2.4 m along the beam direction. For readout purposes it was subdivided into four longitudinal and two lateral sections for a total of 8 cells that were read out with 8 photomultiplier tubes.

A side view of the EMCAL and HCAL is shown in Figure 2.

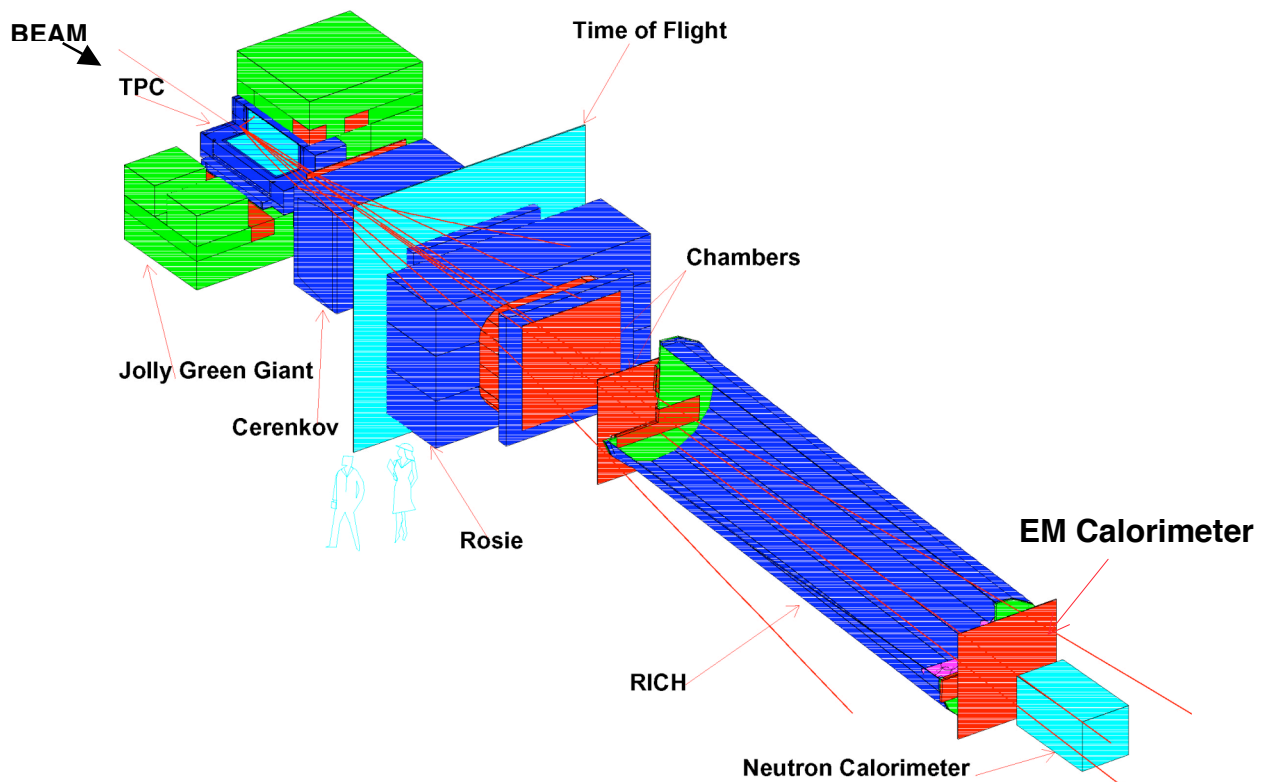


Figure 1 – Perspective view of the MIPP detector. The beam enters from the upper left.

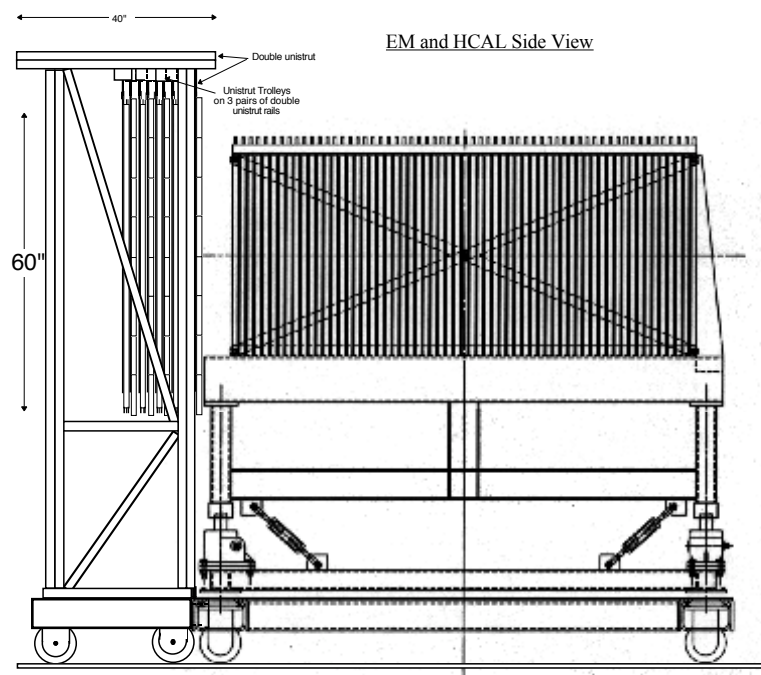


Figure 2 – Side view of the EMCAL and HCAL

Personnel

Michael J. Longo – Principal Investigator (2 months summer salary from this grant)
Dick Gustafson – Senior Research Scientist (1 month salary from this grant)
Durga Rajaram – Assistant Research Scientist (full-time)
Turgun Nigmanov – Postdoc (full-time, started 2006)
HyangKyu Park – (Postdoc, left 2006)
Helmut Schick, George Flanagan, Dave Northacker – Temporary technicians who helped with installation
Prashant Subbarao – Student (Full-time starting February, 2007)

Milestones & Status

- 5 vertical and 5 horizontal wire proportional chamber planes were built and EMCAL installed in beam line (Spring 2003)
- EMCAL readout (designed by Dick Gustafson) installed and debugged (Summer 2003, Spring 2004)
- With University of Virginia group, HCAL refurbished and installed in beam line (Spring 2004)
- Took data during MIPP's Engineering Run for calibration, and other studies (Summer 2004). The EMCAL and HCAL were the first detectors to be fully operational.
- EMCAL & HCAL operational and started taking data Jan. 2005. MIPP Run I ended Feb. 27, 2006.
- MIPP started physics running in Jan. 2005 and completed in Feb. 2006.
- Have taken data on several targets at various energies (~ 31 Million events)
- Data quality was good and spectrometer performed stably.
- EMCAL and HCAL operated reliably throughout the run.
- Reconstruction and analyses now in progress.
- MIPP has proposed and is preparing for an upgraded run in 2008. The electronics for the EMCAL and HCAL will be completely replaced.

Data Summary

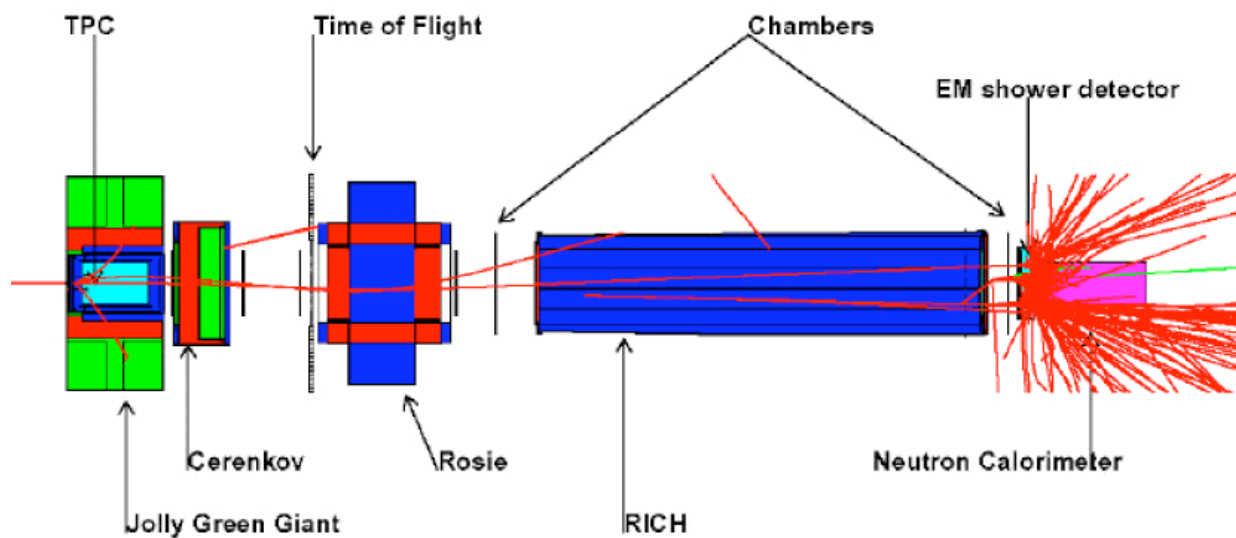
| Data Summary 27 February 2006 | | | Acquired Data by Target and Beam Energy Number of events, x 10 ⁶ | | | | | | | | | | |
|----------------------------------|-----------------------|-------------|--|------|------|------|------|-------|------|------|------|-------|------|
| Target | | | E GeV/c | | | | | | | | | Total | |
| Z | Element | Trigger Mix | 5 | 20 | 35 | 40 | 55 | 60 | 65 | 85 | 120 | | |
| 0 | Empty ¹ | Normal | | 0.10 | 0.14 | | | 0.52 | | | 0.25 | 1.01 | |
| | K Mass ² | No Int. | | | | 5.48 | 0.50 | 7.39 | 0.96 | | | 14.33 | |
| | Empty LH ¹ | Normal | | 0.30 | | | | 0.61 | | | 0.31 | 7.08 | |
| 1 | LH | Normal | 0.21 | 1.94 | | | | 1.98 | | | 1.73 | | |
| 4 | Be | p only | | | | | | | | | 1.08 | 1.75 | |
| | | Normal | 0.10 | | | 0.56 | | | | | | | |
| 6 | C | Mixed | | | | | | | 0.21 | | | 1.33 | |
| | C 2% | Mixed | 0.39 | | | | | | 0.26 | 0.47 | | | |
| | NuMI | p only | | | | | | | | | 1.78 | 1.78 | |
| 13 | Al | Normal | 0.10 | | | | | | | | | 0.10 | |
| 83 | Bi | p only | | | | | | | | | 1.05 | 2.83 | |
| | | Normal | 0.52 | | | 1.26 | | | | | | | |
| 92 | U | Normal | | | | | | | 1.18 | | | | 1.18 |
| Total | | | 0.21 | 2.73 | 0.86 | 5.48 | 0.50 | 13.97 | 0.96 | 2.04 | 4.63 | 31.38 | |

Status of Analysis

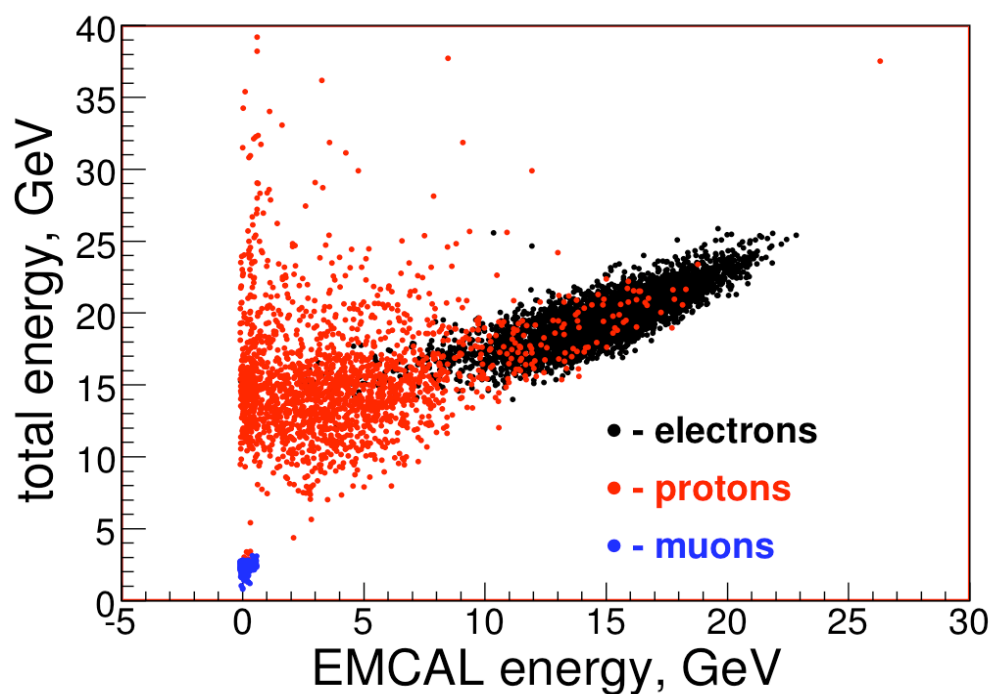
- The calorimeters have been aligned using data.
- The EMCAL and HCAL have been calibrated with protons and electrons. (*T.S. Nigmanov et al., Proc. XII International Conference on Calorimetry in High Energy Physics, 2006*)
- Algorithm for reconstructing showers has been developed
- Software for Monte Carlo simulation and digitization of calorimeters complete; MC production has started.
- Tracking and vertexing software vastly improved. Data processing is underway.

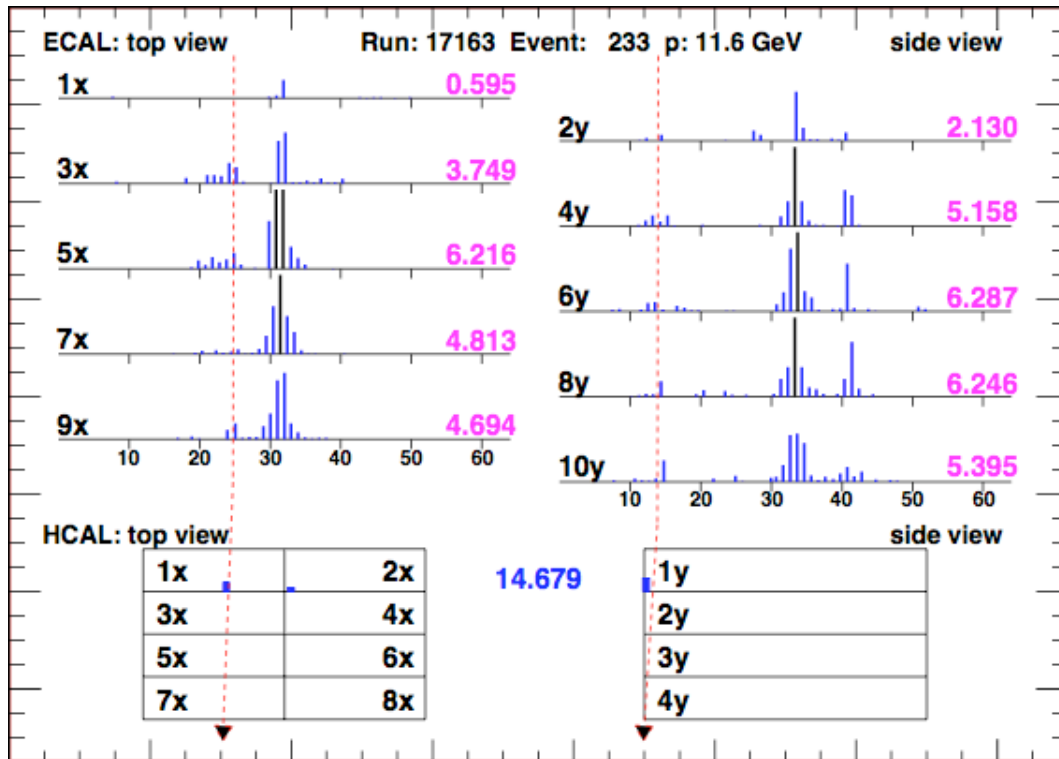
Examples of some of these are shown in the following figures.

Monte Carlo of showers in the EMCAL and HCAL

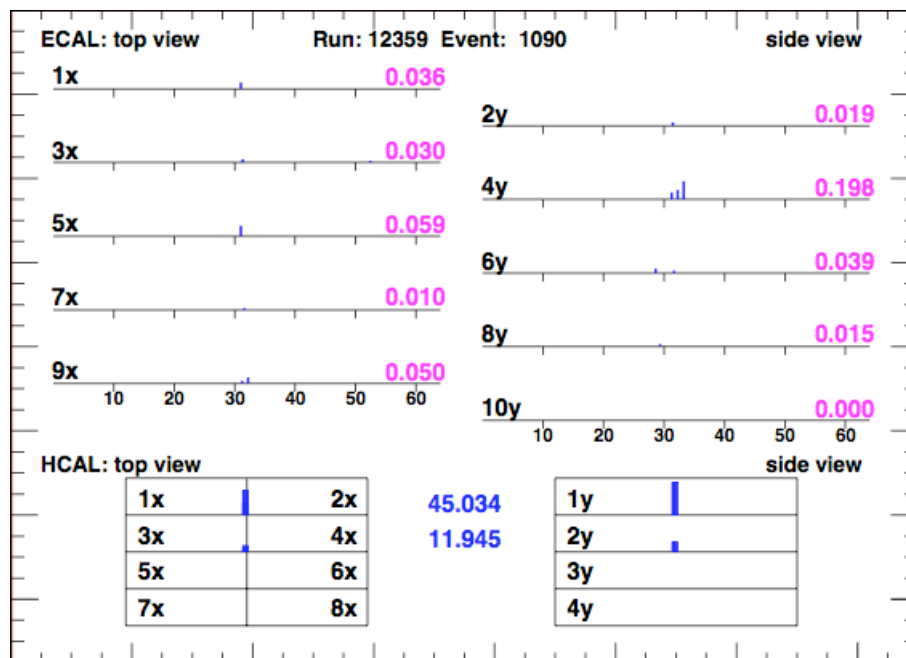


Performance of EM and Hadron Calorimeters





Electromagnetic shower in the calorimeters. The vertical bars show the pulse height from each PWC wire. The numbers show the energy deposited in each EMCAL plane in GeV. The energy deposited in the HCAL is shown at the bottom. An 11.6 GeV/c charged track from upstream is shown as the red dashed line.



$p \rightarrow n$ charge exchange candidate depositing almost all of its energy in the HCAL.

The analysis of the huge data set to measure forward-going neutron/ γ energies and angles accurately will be a challenging task. We are working on reconstruction software and data processing with other detector groups. Identifying and reconstructing neutron/ γ induced showers requires charged-particle tracking and vertexing. After the cross section analysis is complete, the data will have to be incorporated into Monte Carlo code that can be used for radiography and other simulations. We hope to work on this with collaborators from LLNL.

Summary

- We have successfully built, installed, and commissioned electromagnetic and hadron calorimeters to measure forward neutron/photon production for proton radiography.
- The Michigan group has contributed to all aspects of MIPP from the initial design, through installation, setup, debugging, and shift-taking. Rajaram, Nigmanov, and Subbarao are now working full-time on data analysis.
- MIPP has accumulated a large body of data on a wide range of targets over a broad energy spectrum.
- The calorimeters have been calibrated and shower reconstruction and Monte Carlo digitization software for the calorimeters have been developed.
- Data processing is underway. Several analysis efforts are in progress. We are focusing on measuring forward production of neutrons and photons and are getting ready to analyze the reconstructed data. This work will continue with support from our grant renewal.
- MIPP has proposed to upgrade its data acquisition system (DAQ) to increase data acquisition by a factor of 100 and run again in 1998. This upgrade is already underway. If the second run is approved, we will contribute to the upgraded DAQ, data taking, and analysis.

Conference Papers

XII International Conference on Calorimetry in High Energy Physics, T.S. Nigmanov, CALOR '06, Chicago, Illinois, 2006

Towards a better understanding of MINOS neutrino flux with MIPP hadronic production data, A. Lebedev, APS Meeting, Jacksonville, Florida. April 2007

MIPP Status Talk, A. Lebedev, XLII Recontres de Moriond, La Thuile, Italy. March 2007

The Main Injector Particle Production Experiment at Fermilab, H. Meyer, Second Meeting of the APS Topical Group on Hadronic Physics, Nashville. October 2006

MIPP at Neutrino Factory, A. Godley, Muon '07, Los Angeles, California. January 2007

Hadron Production Uncertainties and Neutrino Beams, R. Raja, Nufact '06, Irvine, California. August 2006

The MIPP Experiment and its application to neutrino beam simulations, A. Godley, APS Meeting, Dallas, Texas. April 2006

Status of E907, J. Paley, 2006 Neutrino Beams Instrumentation Workshop, CERN. September, 2006

Hadronic Cross Sections for Neutrino Production in MIPP, J. Paley, Miami '05

Hadronic Cross Sections for Neutrino Production in MIPP, J. Paley, PANIC '05, Santa Fe, New Mexico. Oct 2005