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First Results from MIPP

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Abstract. Measurements of neutrino cross-section and oscillations depend heavily on neutrino flux predictions. Such predictions rely on hadron-nucleus interaction cross-section data, and yet the data are scarce. The E907 Main Injector Particle Production (MIPP) experiment at Fermilab is a full acceptance spectrometer with excellent particle identification capabilities. MIPP has collected $\sim 15 \times 10^6$ events of p's, π's and K's at various momenta (from 5 to 120 GeV) on several targets including beryllium and carbon. In particular, MIPP has collected hadron production data on a spare NuMI target using 120 GeV/c protons from the Main Injector. We review the experiment, performance of the spectrometer and show preliminary results of particle production ratios of π^-/π^+, K^+/π^+, K^-/π^-, and K^-/K^+ in bins of longitudinal and transverse momentum for thin and thick carbon targets.

Keywords: NuMI, Main Injector, particle production, neutrino, long baseline
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INTRODUCTION

Purpose of the Experiment

At the Neutrinos at the Main Injector (NuMI) facility at FNAL, 120 GeV/c protons from the Main Injector strike a 90 cm-long graphite target. Two magnetic "horns" focus the secondary charged mesons into a 675 m long decay pipe, at the end of which are hadron and muon absorbers. The neutrino beam is produced from secondary meson decay (eg, $\pi^+ \to \mu^+ + \nu_\mu$).

The predicted flux of the NuMI beam is typically derived from Fluka[1] Monte Carlo simulations. Hadron production simulations of the proton-target interactions are only reliable for the momenta and nuclei where cross-section data are available, however such data are severely lacking. The lack of data to tune the simulation results in very large uncertainties of the NuMI beam flux. Indeed a comparison of several different, yet correlated, Monte Carlo simulations shows differences of up to 30% in the predicted NuMI flux.

The Main Injector Particle Production (MIPP) experiment is a fixed-target experiment located in the Meson Line at Fermilab. The experiment features a a beam of secondary π, K and p in a range of momenta from 5 to 85 GeV/c, as well as primary 120 GeV/c protons from the Main Injector, and a full-acceptance spectrometer with excellent particle identification capabilities. The spectrometer, shown in Fig. 1, consists of the two dipole magnets, each giving a ~ 1 T·m kick in opposite directions, a time-projection chamber (TPC) that sits just downstream of the fixed target and inside the first dipole magnet, four drift chambers (three of which are located between the two dipole magnets), two multiwire proportional chambers downstream of the second dipole magnet, a time-of-flight (ToF) detector, a Čerenkov (Ckov) detector and a Ring Imaging Čerenkov (RICH) detector. Secondary particle track and vertex reconstruction are accomplished using reconstructed hits in the TPC and downstream drift and wire chambers. Particle identification (PID) in the range of 0.2-1 GeV/c is accomplished using dE/dx data from the TPC. In the range of 0.5-2 GeV/c, PID is obtained from velocity measurements using ToF data. The Čerenkov detector is used to determine PID in the momentum range between 2.5-17 GeV/c, and the RICH detector is used to determine PID in the momentum range between 17 and 80 GeV/c. Not shown in Fig. 1 are three beam wire chambers and two differential Čerenkov detectors located upstream of the target for beam particle identification and tracking.

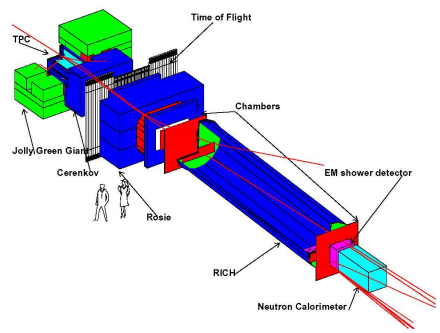

FIGURE 1. View of the MIPP spectrometer.

Data Collected

The primary goal of the MIPP experiment was to collect a comprehensive hadron production cross-section

data set. This includes a measurement of hadron production off of the NuMI target using 120 GeV/c protons from the Main Injector. During the 2005 data run, MIPP collected over 1.6×10^6 events of 120 GeV/c protons on the NuMI target, and over 20×10^6 events of π, K and p at beam momenta 5, 20, 35, 60 and 120 GeV/c on thin (1-2% interaction length) LH_2, C, Be, Bi, and U targets.

TRACK AND VERTEX RECONSTRUCTION

In the MIPP offline reconstruction, beam tracks are reconstructed using wire hits in the three upstream beam wire chambers. We then reconstruct charged secondary tracks by combining helical track segments in the TPC, straight line track segments in the first set of three drift chambers, and if possible, straight line track segments in the second set of three wire chambers. The combined track segments are then refit using a three-dimensional map of the measured magnetic fields. We next find vertices by determining the point of closest approach for all intersecting tracks, after which we perform a vertex-constrained fit to simultaneously determine for the vertex position and track parameters at the vertex.

One major complication in the track reconstruction comes from very large distortions in the path of the drift electrons in the TPC. The TPC used in the MIPP experiment was designed to sit inside a dipole magnet such that the the $\vec{E}$ and $\vec{B}$ fields in the TPC drift volume are parallel (both point along the positive y, or vertical, direction). In such a configuration, the drift electrons in the TPC follow exactly along the $\vec{E}$ field lines straight down to the bottom of the TPC chamber where an array of 120 $\times$ 128 "pads" digitize the electron signal into ADC and TDC signals.

However, the magnet used by MIPP is small compared to the size of the TPC, and as such there are large non-uniformities of the dipole magnetic field in the TPC drift volume. The large (B_x, B_z) components of the magnetic field cause the electrons to drift along a distorted helical path instead of a straight line, effectively shifting the observed position of the track in all three dimensions. If these electron drift distortions are not properly accounted for the effect is very large, accounting for more than a 3 cm shift in the hit positions near the edges of the TPC where the non-uniformities of the magnetic field are largest.

Using the Magboltz[2] microscopic simulation of the electron drift and diffusion in the TPC gas volume with the measured magnetic field map, we have derived a non-linear correction to the TPC drift distortions. An order of magnitude reduction in the width of track fit residuals is observed with this method, and the remaining shift in the TPC hit positions is less than 2 mm. This shift is treated as a systematic uncertainty in the momentum resolution of reconstructed tracks.

PARTICLE IDENTIFICATION

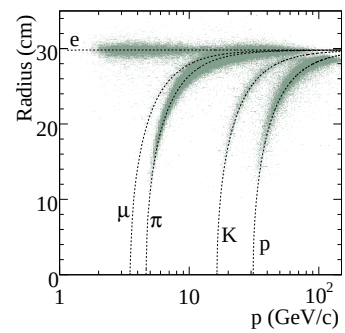

FIGURE 2. Reconstructed RICH ring radii vs. track momentum for positive tracks produced off of the NuMI target.

MIPP uses a variety of detectors to provide particle identification for nearly the entire range of secondary track momenta. At the time of this workshop, only the TPC and the RICH detector had been calibrated. The TPC provides PID below $\sim$1 GeV/c, whereas the RICH provides PID above $\sim$20 GeV/c. The RICH detector consists of a 10 m long gas vessel filled with CO_2. Sixteen spherical mirrors on the downstream end of the gas vessel reflect Čerenkov light from traversing charged particles onto an array of 1994 1/2-inch photomultiplier tubes at the upstream end of the gas vessel. The image formed on the PMT array is that of a ring of light, the radius of which is proportional to the velocity of the particle. Fig. 2 shows a scatter plot of reconstructed RICH ring radii versus reconstructed track momenta for positive particles produced off of the NuMI target. Lines are drawn for the predicted RICH ring radii for each particle type, and we see excellent agreenment between the predicted and measured PID bands.

PARTICLE PRODUCTION RATIOS

Two analyses were done to measure the four particle production ratios π^-/π^+, K^+/π^+, K^-/π^-, and K^-/K^+ as a function of (p_z, p_T) for $p_z > 20$ GeV/c off of the thin carbon target [3] and the thick NuMI target [4] using Main Injector 120 GeV/c protons. Although both analyses make use of the RICH for PID, the two analyses differ in the actual PID algorithm used and the method to determine backgrounds (the largest systematic uncertainty).

The thin carbon target analysis used a PID variable based on the reconstructed RICH ring radius, whereas the NuMI target analysis used a slightly more sophisticated log-likelihood based on the predicted and measured number of hits in the RICH PMT array. In the former case, rings are fit to the hit PMTs in the array and the

ring radius is then converted to a mass-squared of the particle. The RICH ring reconstruction algorithm takes into account the RMS width of the ring, temperature and pressure changes, and shared hits between multiple charged tracks.

The log-likelihood-based RICH PID used for the thick NuMI target analysis predicted the number of PMT hits for each particle type based on the expected wavelength-dependent reflectivity and transmission probabilities of CO_2 and wavelength-dependent response of the PMT tubes. The algorithm also took into account temperature and pressure effects and corrected for shared hits. Log-likelihoods were then calculated using the predicted and measured PMT hit distribution, and the PID determined from the largest likelihood. The advantage of this approach over the RICH-ring method used in the thin-target analysis is that dispersion is taken into account, increasing PID capabilities at high momenta where the π, K and p ring radii are differences are smaller than the thickness of the RICH ring.

Both analyses make use of a GEANT3[5]-based Monte Carlo simulation to correct for geometric acceptances, interactions in the spectrometer, Kaon decay in flight, and large angle multiple scattering and to estimate the background contamination of the PID variable from other particles. The uncertainties on the corrections are typically 50%, however their contribution to the overall systematic uncertainty in the ratio measurements are small ($<$ 10%). On the other hand, the effect of backgrounds can result in systematic uncertainties as large as 50%.

The method of background estimation differs between the two analyses in that the thin carbon target analysis estimated the backgrounds using the Fluka generated secondary spectra out-of-the-box, and the NuMI target analysis used an iterative, data-driven approach to renormalize the Fluka-generated spectra to account for backgrounds. The latter approach reduced the estimated systematics due to backgrounds from 50% to 10%.

CONCLUSION

Some results of the two analyses are shown in Fig. 3, where double ratios of Data/MC production ratios are plotted as a function of p_z in slices of p_T (eg, $R(\pi^-/\pi^+) = (\pi^-/\pi^+)_{\mathrm{Data}}/(\pi^-/\pi^+)_{\mathrm{MC}}$). For readability, the double ratios for each slice of p_T are offset by the amount shown in the key in Fig. 3. The ratios for thin and thick target differ in the expected stronger dependence of each ratio to p_T for the thick target than for the thin target. However, the data show a disagreement with the Fluka prediction by as much as 30-40% in the π^-/π^+ and K^-/K^+ ratios, whereas reasonable agreement with the prediction for the K/π ratios.

A comparison has also been made to the particle

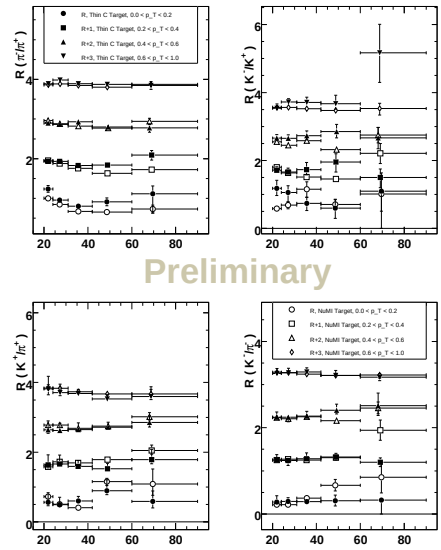

FIGURE 3. Comparison of particle production double ratios in bins of (p_z, p_T) between a Fluka2005 simulation of hadron production off of the NuMI target (open shapes) and thin carbon (solid shapes) and thick NuMI target data collected by MIPP[4]. The double ratios for each slice of p_T are offset by the amount shown in the key.

production ratios as determined from the MINOS reweighted neutrino energy spectra in the near detector[6], and there is excellent agreement between the MIPP results up to approximately 50 GeV/c. Above 50 GeV/c there are some obvious outliers in the MIPP results that need to be further investigated. Further improvements in the background estimation for the final PID algorithm are also expected. Finally, the MIPP collaboration will soon produce hadron production cross-sections for the NuMI target data set with PID below 20 GeV/c using the Čerenkov, ToF and TPC detectors.

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