Results and Status from the HARP and MIPP Hadron Production Experiments

M Sorel

IFIC, CSIC and Universidad de Valencia, Spain

E-mail: `sorel@ific.uv.es`

Abstract. Recent results and status from the HARP and MIPP hadron production experiments are reviewed. After a brief description of the experimental setups and the large amounts of data collected with those, we emphasize the relevance of precision hadron production measurements for neutrino physics. Three types of neutrino sources are discussed: conventional accelerator-based neutrino beams, advanced neutrino sources, and atmospheric neutrinos. We conclude by discussing prospects from additional hadron production measurements to be expected in the near future.

1. The experiments

HARP and MIPP are recent experiments aiming to correct the lack of precision hadron production data. The physics of strongly interacting matter probed in these experiments is not only interesting *per se*, but is also a crucial input to neutrino physics experiments. Compared to past hadron production experiments, HARP and MIPP combine large phase space coverage and excellent track reconstruction and particle identification capabilities (discussed in this Section), together with high-statistics samples collected for a variety of beam particle types, beam momenta, nuclear target materials, and target interaction lengths (see Sec. 2).

The HARP experiment [1], shown in Fig. 1, took data in the T9 beamline of the CERN PS in 2001-2002. Beam particles are tracked and identified with multi-wire proportional chambers, beam time-of-flight and two threshold Cherenkov detectors upstream of the target, and by a beam muon identifier downstream. Secondary particles produced in the beam-target interactions along the forward direction ($\theta < 250$ mrad) are measured via a forward spectrometer. Track reconstruction in the forward spectrometer is performed with large area drift chambers located upstream and downstream of a dipole magnet; secondary particle identification is obtained via a third threshold Cherenkov detector (for track momenta $p > 2.6$ GeV/c), a time-of-flight wall ($0.5< p <5$ GeV/c), complemented by an electromagnetic calorimeter [2]. In the large angle region ($\theta > 350$ mrad), track reconstruction and particle identification ($p < 0.8$ GeV/c) is mainly performed by a Time Projection Chamber (TPC) surrounding the nuclear target and immersed in a solenoid magnet [3], complemented by Resistive Plate Chambers surrounding the TPC [4].

The Main Injector Particle Production (MIPP) experiment [5] (Fig. 1) operated in the FNAL Meson Line in 2004-2006. MIPP targets were exposed to 120 GeV/c beam protons from the Main Injector, and to lower-energy secondary beams of mixed composition. The MIPP detector configuration is fairly similar to the HARP one, with some differences due to the higher momenta probed. Drift chambers are used to track beam particles, and a beam threshold Cherenkov

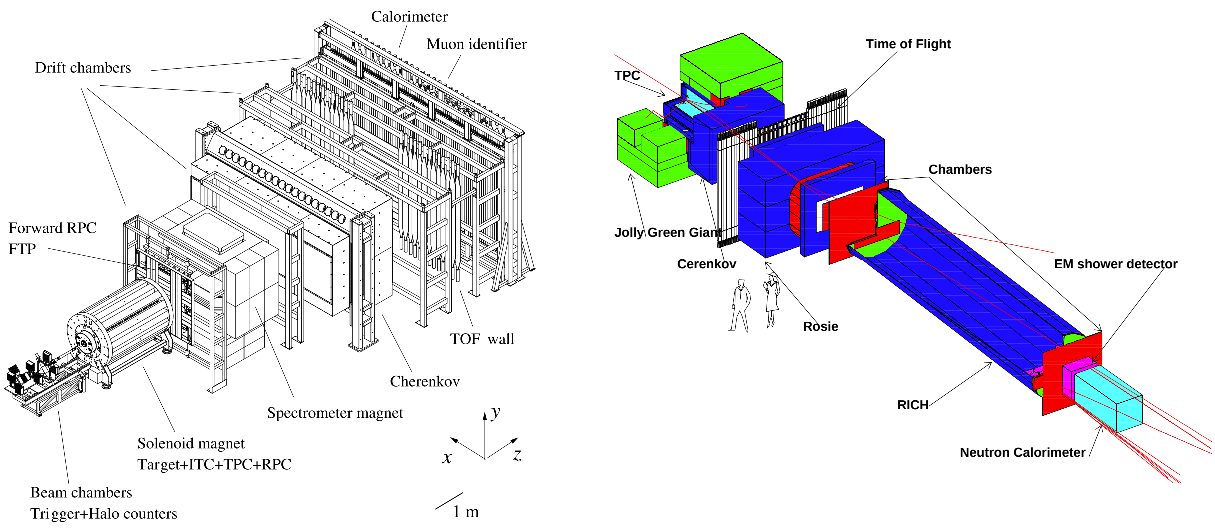

Figure 1. Schematic drawings of the HARP (left) and MIPP (right) detectors.

detector is used to tag the beam particle type. Tracks are reconstructed making use of two dipole magnets deflecting secondary particles in opposite directions, plus a TPC, drift chambers and proportional wire chambers. As for HARP, the TPC, a time-of-flight wall (ToF), and a threshold Cherenkov detector are used for particle identification. In addition, MIPP uses also a Ring Imaging Cherenkov detector (RICH) for high-momentum particles. The momentum range for particle identification covered by the MIPP sub-detectors is approximately: $p > 17$ GeV/c (RICH), $2.5 < p < 17$ GeV/c (Cherenkov), $0.5 < p < 2.5$ GeV/c (ToF), $0.1 < p < 1$ GeV (TPC).

2. The data

As shown in the left panel of Fig. 2, HARP data samples span 2-15 GeV/c beam momenta. Both positively and negatively-charged beams have been used, allowing to tag pure samples of proton, π^+, and π^- beam interactions on nuclear targets. Target materials cover the full periodic table of elements, from hydrogen to lead (see Fig. 2, left panel). To allow a systematic study of reinteractions in the target of the produced secondaries, and to mimic the conditions of specific neutrino beamlines, targets of several geometries have been used, roughly from 2% to 200% of a nuclear interaction length (λ_I). In this paper, only thin target results are discussed.

HARP reported particle production cross section measurements for π^+, π^-, and proton secondaries. Denoting with p and ϑ the momentum and polar angle with respect to the beam direction of the produced secondaries, results have been provided for the following phase space: ($0.75 < p < 8$ GeV/c, $30 < \vartheta < 240$ mrad) via the forward spectrometer, ($0.1 < p < 0.8$ GeV/c, $350 < \vartheta < 2150$ mrad) via the large-angle spectrometer. The phase space covered by the HARP forward and large-angle spectrometers is shown in the middle panel of Fig. 2, together with the typical binning used to report differential cross-section results.

MIPP collected high-statistics data samples at higher beam energies compared to HARP: from 20 to 120 GeV/c (see Fig. 2, left panel). As for HARP, targets have been exposed to both positively and negatively-charged beams. In addition to proton and pion beams, MIPP is also able to select high-purity interaction samples due to Kaons in the beam. MIPP also covered a wide range of nuclear materials, from hydrogen to uranium, although in a somewhat sparser way compared to HARP. Thin (2% λ_I) and thick (λ_I=165%) targets have been used in MIPP, the latter being a replica of the Fermilab NuMI target currently serving the MINOS experiment.

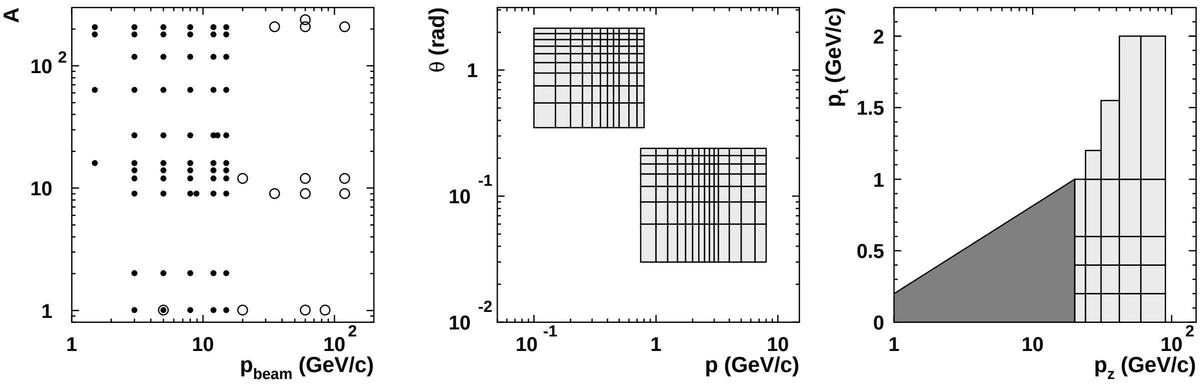

Figure 2. Left: target atomic weight A versus beam momentum p_{beam} for the HARP (filled circles) and MIPP (empty circles) run configurations. Middle: angle ϑ with respect to the beam direction versus momentum p for the secondary particles measured with the HARP forward (high momenta, forward direction) and large-angle (low momenta, large angles) spectrometers. Right: secondary particle transverse momentum p_t versus total momentum p measured with the MIPP detector (RICH-only); the dark grey area is the phase space that will be covered by the TPC, ToF and Cherenkov detectors. In the middle and right panels, lines within the phase space covered indicate the typical binning used to quote results.

Preliminary MIPP results include π^+, π^-, K^+, and K^- production in the ($20< p <90$ GeV/c, $0< p_t <2$ GeV/c) range in (total, transverse) secondary momentum space, that is the region covered by the RICH detector (see right panel of Fig. 2). Full use of the Cherenkov, ToF, and TPC particle identification capabilities will allow to extend the measurements to lower secondary particle momenta.

In the following, we discuss the relevance of selected HARP and MIPP hadron production results for neutrino experiments making use of conventional accelerator-based neutrino beams (Sec. 3), advanced neutrino sources (Sec. 4), and atmospheric neutrinos (Sec. 5).

3. Conventional accelerator-based neutrino beams

In conventional accelerator-based neutrino beams [6], protons from a man-made particle accelerator impinge on a thick nuclear target. Secondary mesons produced in the interactions are focused along the beam direction via a magnetic horn system. Decay in flight of a significant fraction of those mesons occurs in the decay region downstream of the target. A beam dump follows the decay region to absorb all beam components except neutrinos produced in meson or muon decays. While conventional accelerator-based beams allow for very high luminosities and tunable neutrino beam energies, they suffer from limited knowledge of the properties of the neutrino flux illuminating the neutrino detectors. Rate measurements performed in the neutrino detectors do not allow to break the degeneracy between neutrino flux and neutrino cross-sections, often complicating data analyses. Neutrino oscillation experiments alleviate the impact of neutrino flux uncertainties with two-detector setups and neutrino detector tagging individual neutrino flavors. Still, hadron production affects the flux extrapolation between detector sites, and the relationship between, *e.g.*, muon and electron neutrinos in the beam.

HARP inaugurated a new era of hadron production results in 2005 with the measurement of forward ($30< \vartheta <210$ mrad) π^+ production in the interactions of 12.9 GeV/c protons on a thin (λ_I=5%) aluminum target [7]. This measurement is particularly relevant for the K2K long-baseline oscillation experiment, which operated with the same beam momentum and target material. The HARP measurement of the double-differential cross-section $d^2\sigma/(dpd\Omega)$ has been used in the final K2K oscillation results, as input to the K2K beam simulation. This allowed to reduce the contribution of the near-to-far neutrino flux extrapolation to the uncertainty in the number of unoscillated muon neutrinos expected at Super-Kamiokande from 5.1% to 2.9% [8]. In addition, the HARP low-momentum reach allowed to directly measure the pions responsible for the $\simeq$0.6 GeV neutrinos that are most affected by neutrino oscillations in K2K.

After [7], HARP published π^+ production results allowing to better understand the Fermilab Booster Neutrino Beamline (BNB) serving the MiniBooNE and SciBooNE (until August 2008) experiments [9]. Pions from the interactions of 8.9 GeV/c protons on a λ_I=5% beryllium target have been measured. A 5% (statistical plus systematic error) π^+ production cross-section measurement over the ($0.75< p <6.5$ GeV/c, $30< \vartheta < 210$ mrad) pion phase space measured was obtained, together with detailed spectral information. HARP results compare well with beam momentum-rescaled BNL E910 results obtained at 6.4 and 12.3 GeV/c beam momentum [10]. As a consequence, both HARP and BNL E910 results are used to tune the FNAL BNB beam Monte Carlo simulation. HARP π^+ production results together with MiniBooNE ν_μ interaction measurements put tight constraints on the knowledge of the beam ν_e contamination from the $\pi^+ \to \mu^+ \to \nu_e$ decay chain, allowing not to spoil the MiniBooNE $\nu_\mu \to \nu_e$ sensitivity [11]. Concerning SciBooNE/MiniBooNE neutrino cross-section measurements, the muon neutrino flux normalization uncertainty has first been reduced to 16% using HARP π^+ production data (early, conservative estimate [11]), with the final goal of understanding the BNB flux normalization uncertainty to 10% or better. In addition to π^+ production, preliminary results on secondary proton and π^- production are also available [12], allowing to better understand the BNB beam in the ongoing antineutrino run, and reinteraction effects in the BNB thick target.

As for the BNB beamline, also the understanding of the Fermilab NuMI beamline (120 GeV/c protons) depends upon hadron production knowledge. Two approaches have been followed by MINOS to constrain hadron production. First, by performing a spectrum fit of MINOS near detector data. The fit includes several beam configurations and fit parameters, including pion (p_z, p_t) yields and Kaon yield normalization [13]. Second, by measuring hadron production in dedicated experiments. Two hadron production experiments are particularly useful to NuMI: NA49 at CERN, and MIPP at FNAL. The MIPP experiment has provided so far preliminary results of direct relevance only to the high neutrino energy tail of the spectrum, by measuring several fully corrected yield ratios of particles produced in the interactions of 120 GeV/c protons on both thin carbon [14] and NuMI replica [15] targets: π^-/π^+, K^+/π^+, K^-/K^+, and K^-/π^-. The NA49 experiment, on the other hand, has the advantage of providing an excellent phase space coverage, and to have already produced $\pi^\pm$ absolute cross-sections; however, results exist only for 158 GeV/c proton beam momenta, and only for thin carbon targets [16]. MIPP results, including a preliminary systematic error evaluation, measure similar particle production ratios between thin carbon and NuMI carbon targets. In addition, a reasonable agreement of MIPP data with NA49 and MINOS spectrum fit results is found up to $p \sim 40$ GeV/c secondary momenta, while discrepancies under investigation are found at higher momenta.

4. Advanced neutrino sources

The neutrino factory concept is among the most promising ideas for advanced neutrino sources under consideration. By storing 4-50 GeV muons in a ring with long straight sections, one could produce a factory of neutrinos as the result of muon decay [17]. Given that in such a setup the stored beam properties and muon decay kinematics are well known, small neutrino flux uncertainties are expected. Therefore, the challenge is not, in this case, the reduction of flux uncertainties, but flux optimization, as one needs to optimize the collection efficiency of π^+ and π^- produced in the collisions of protons with the high-Z targets typically considered in neutrino factory designs. The question of which beam momentum is best for the neutrino factory proton driver, and which momentum range is acceptable, needs to be addressed.

To this end, HARP recently measured $\pi^{\pm}$ production in the collisions of 3-12 GeV/c protons with high-Z thin targets such as lead [18] and tantalum [19]. Results were reported over (0.1<p<0.8 GeV/c, 350< ϑ <2150 mrad) pion momentum and angle, providing a good match with a typical neutrino factory pion phase space acceptance (about 70%, design-dependent). The measured pion yield normalized to the beam proton kinetic energy has been studied for several pion kinematic ranges, the most restrictive one (0.25<p<0.5 GeV/c, 350< ϑ <950 mrad) being the most representative of typical neutrino factory designs. The conclusion of this study is that the optimum pion yield in this kinematic coverage occurs for 5-8 GeV/c beam protons, both for π^+ and π^-, and both for lead and tantalum targets. While the optimization procedure just described is clearly simplistic, a more quantitative optimization of the proton driver for a neutrino factory is possible, given the detailed pion spectral information now available.

5. Atmospheric neutrinos

Atmospheric neutrinos are decay products of hadronic shower particles produced in the Earth's atmosphere as a consequence of the interactions of primary cosmic rays with nuclei (nitrogen, oxygen). In addition to an accurate understanding of the primary cosmic ray spectrum, a precise knowledge of hadronic interactions determining the shower development is needed for accurate atmospheric neutrino flux predictions. As for accelerator-based beams, flux flavor and flux directional ratios are better known than absolute fluxes (at the few % level, while absolute flux uncertainties are of order 15-20%), but are not error-free and are dominated by hadron production uncertainties [20]. Since a cosmic ray primary of a given energy produces atmospheric neutrinos of about one order of masgnitude lower energy, HARP (MIPP) data can help to better understand sub-GeV (multi-GeV) atmospheric neutrinos.

HARP published results for $\pi^{\pm}$ production in the interactions of 12 GeV/c protons on a cryogenic nitrogen target [21]. This is the first time that pion production is measured for a nitrogen target in this low-energy range. A 6% total uncertainty for $\pi^{\pm}$ production over the full phase space measured (0.5<p<8.0 GeV/c, 50< ϑ <250 mrad) was obtained. In addition, results for both oxygen [21] and carbon [22] targets for the same beam momentum setting have also been obtained, allowing to verify that carbon target data show a similar behavior, in terms of pion production cross-sections, compared to nitrogen and oxygen targets, as has been commonly assumed in the past. Pion production results in pion-nucleus interactions, also of relevance to atmospheric air showers development, have also been reported in the same energy range [22],

The MIPP particle production ratios discussed in Sec. 3 in the interactions of 120 GeV/c protons on a 2% λ_I carbon target are also important for multi-GeV atmospheric neutrinos. The differential ratios agree within ~30% with past meson production results off carbon targets, and with a parametrization based on beryllium target data [23]. Overall, the HARP and MIPP data sets represent an extremely useful resource to benchmark and tune hadronic interaction models used in air shower simulations.

6. Future prospects

MIPP expects to produce soon, possibly by the end of 2008, first $\pi^{\pm}/K^{\pm}$ absolute differential cross-sections. Highest priority is given to meson production in the collisions of 120 GeV/c protons with the NuMI target replica, to be followed by thin carbon, beryllium and bismuth target data sets. First cross-section results will include a measurement for secondary momenta below 20 GeV/c as well. Other short-term physics goals being pursued include: π/K production for lower beam momenta (20, 60 GeV/c) and $p/K/\pi$ projectiles; measurement of the neutron-to-proton production ratio for all beam momenta and thin target settings; K^0 production cross-sections. In addition, a proposal to upgrade the MIPP experiment has been submitted [5], and is now under consideration. The main reason for this proposed upgrade is that the experiment was limited by TPC readout time ($\sim$ 30 Hz). This resulted in only about 20% of the desired statistics for the NuMI target replica run. In addition, the Jolly Green Giant (JGG) magnet failed at the end of the run. An upgrade of the TPC electronics can increase the TPC readout speed by two orders of magnitude, allowing for the measurement of hadron production for any target in a matter of just a few days. Other improvements that would be obtained by a MIPP upgrade would result in a more stable TPC performance, greatly reduced $E \times B$ effects in the TPC, and an improved beamline for low momentum (down to $p_{beam} \simeq 1$ GeV/c) running. Fermilab has purchased ALTRO chips for the TPC upgrade, and JGG repair has begun.

HARP future prospects are more limited, as most physics goals have already been achieved. Work remains to be done to complete the analysis of π/p cross-sections in both the forward direction and at large angles, for all beam and thin target settings. This systematic campaign of particle production has already started [24]. Other objectives include $K^{\pm}$ production measurements for the highest beam momentum runs, and particle yields from thick targets.

In addition, the NA61-SHINE hadron production experiment at CERN [25] is also expected to produce results of relevance to neutrino physics. A pilot run was performed in 2007 [26], with a physics run expected in late 2008. This experiment reuses the NA49 detector, with an extended forward acceptance provided by a new time-of-flight wall. Neutrino physics goals that are part of the NA61 program include the measurements of hadron production that are needed to characterize the T2K neutrino beam, and the measurement of hadron production in proton-carbon interactions for a better understanding of cosmic-ray air showers.

Acknowledgments

The author would like to thank M. G. Catanesi, J. J. Gomez-Cadenas, H. Meyer, J. Paley, J. Panman, R. Raja, and D. Schmitz for the many suggestions and material provided for this talk, and the Neutrino 2008 organizers for a very successful and pleasant conference.

References

[1] Catanesi M G *et al.* (HARP) 2007 *Nucl. Instrum. Meth.* **A571** 527–561
[2] Catanesi M G *et al.* 2007 *Nucl. Instrum. Meth.* **A572** 899–921
[3] Catanesi M G *et al.* 2008 *JINST* **3** P04007
[4] Bogomilov M *et al.* (HARP) 2007 *IEEE Trans. Nucl. Sci.* **54** 342–353
[5] Isenhower D *et al.* (MIPP) 2006 (*Preprint* `hep-ex/0609057`)
[6] Danby G *et al.* 1962 *Phys. Rev. Lett.* **9** 36–44
[7] Catanesi M G *et al.* (HARP) 2006 *Nucl. Phys.* **B732** 1–45 (*Preprint* `hep-ex/0510039`)
[8] Ahn M H *et al.* (K2K) 2006 *Phys. Rev.* **D74** 072003 (*Preprint* `hep-ex/0606032`)
[9] Catanesi M G *et al.* 2007 *Eur. Phys. J.* **C52** 29–53 (*Preprint* `hep-ex/0702024`)
[10] Chemakin I *et al.* (E910) 2008 *Phys. Rev.* **C77** 015209 (*Preprint* `0707.2375`)
[11] Aguilar-Arevalo A A *et al.* (MiniBooNE) 2008 (*Preprint* `0806.1449`)
[12] Schmitz D W FERMILAB-THESIS-2008-26
[13] Adamson P *et al.* (MINOS) 2008 *Phys. Rev.* **D77** 072002 (*Preprint* `0711.0769`)
[14] Lebedev A V 2007 *Ratio of Pion Kaon Production in Proton Carbon Interactions* Ph.D. thesis Harvard University Cambridge, MA
[15] Seun S M FERMILAB-THESIS-2007-61
[16] Alt C *et al.* (NA49) 2007 *Eur. Phys. J.* **C49** 897–917 (*Preprint* `hep-ex/0606028`)
[17] Geer S 1998 *Phys. Rev.* **D57** 6989–6997 (*Preprint* `hep-ph/9712290`)
[18] Catanesi M G *et al.* (HARP) 2008 *Eur. Phys. J.* **C54** 37–60 (*Preprint* `0709.3458`)
[19] Catanesi M G *et al.* (HARP) 2007 *Eur. Phys. J.* **C51** 787–824 (*Preprint* `0706.1600`)
[20] Barr G D, Gaisser T K, Robbins S and Stanev T 2006 *Phys. Rev.* **D74** 094009 (*Preprint* `astro-ph/0611266`)
[21] Catanesi M G *et al.* (HARP) *Astropart. Phys.* Article in press
[22] Catanesi M G *et al.* (HARP) 2008 *Astropart. Phys.* **29** 257–281
[23] Bonesini M, Marchionni A, Pietropaolo F and Tabarelli de Fatis T 2001 *Eur. Phys. J.* **C20** 13–27 (*Preprint* `hep-ph/0101163`)
[24] Catanesi M G *et al.* 2008 *Phys. Rev.* **C77** 055207
[25] Gazdzicki M *et al.* CERN-SPSC-2006-034
[26] Abgrall N *et al.* (NA61) CERN-SPSC-2008-018