Hadron Production Measurements

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Abstract

A major component of the difficultly in providing accurate predictions of the unoscillated neutrino fluxes in underground detectors is the lack of hadron production data over a large enough region of phase space to be able to tune the models with confidence. This paper describes the current situation and several new experiments which either have recently completed analyses, are currently analyzing or are currently collecting data.

1. Introduction

Neutrino oscillations were first identified by an observation of a deficit [1] of muon neutrinos produced in the atmosphere by cosmic ray collisions on the other side of the earth [2]. An approximate, but correct computation of the ratio of fluxes of muon type neutrinos to electron type neutrinos is possible by simply counting neutrino types associated with both production and decay of muons to give $\Phi(\nu_\mu)/\Phi(\nu_e) \sim 2$. This works because there is a relatively small energy available in the centre-of-mass of a decaying pion and so all three neutrinos associated with a muon have on average about the same energy.

In order to perform precision measurements with the current data sets of atmospheric neutrinos, in particular the extensive statistics available at the Super Kamiokande detector [2], a more sophisticated calculation is necessary. Such calculations have been done by several groups (see [3] for a recent survey of calculations) using the Monte-Carlo technique. The Monte-Carlo technique allows inclusion of the details of the primary cosmic ray spectrum, secondary production probabilities in hadron collisions with air molecules, the Earth's magnetic field, the curvature of the Earth, the profile of the atmospheric pressure with altitude and the energy loss of secondary particles (in particular muons). Most of the above effects are well understood, and in particular the primary cosmic ray fluxes are now known considerably better due to recent measurements by both balloon and satellite borne experiments. Hadron production has always been a major

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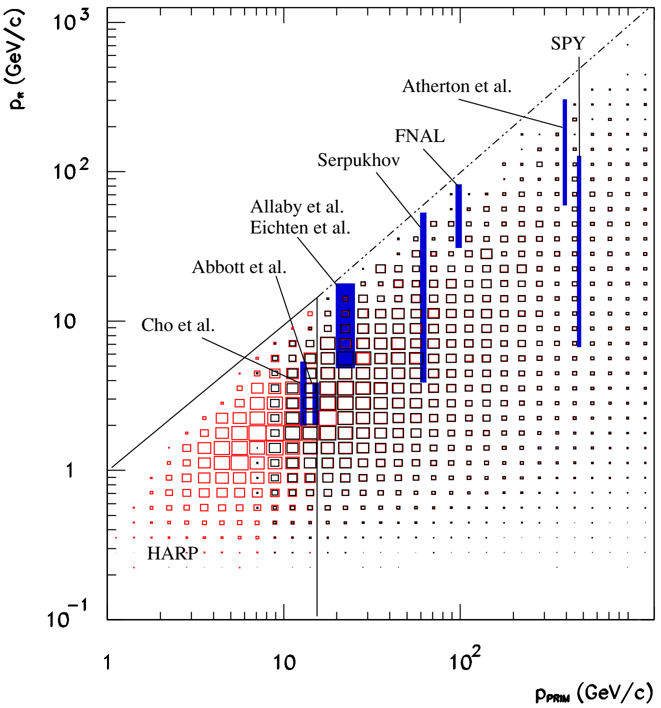

Fig 1. Important regions of hadron production phase space for contained atmospheric neutrino events (boxes). The coverage of various measurements are shown.

uncertainty in these calculations and is now the dominant source of uncertainty.

This paper specializes in the hadron production uncertainty, the other effects are reviewed elsewhere in these proceedings [4, 5]. We review the measurements available from experiments which are used as input to the current generation of Monte-Carlo hadron collision generators and discuss recent measurements for which results are either just available or are soon to be available which will help to improve the situation. The prediction of atmospheric neutrinos will not be the only field to benefit in an improved knowledge of hadron production, high energy physics applications will benefit generally. Neutrino beam experiments require a similar level of precision to understand their beams and indeed many of the experiments mentioned here are/were run specifically with the understanding of the spectra of particular beams of neutrinos in mind. Another example is the simulation of extensive air showers induced by ultra high energy cosmic rays which rely on the knowledge of the lower energy interactions which occur late in the development of the shower in order to relate the primary energy and composition of the cosmic rays to the observations which can be made on the ground.

2. Existing measurements

Figure 1 shows a diagram of the phase space which is applicable for the production of contained events in underground detectors (indicated by the boxes). Two of the three variables are shown, the primary energy and the daughter energy. The third phase space variable, the transverse momentum (p_T) of the daughter particle is not shown on the figure. The important measurements of hadron production are:

1. Measurements over a wide range of primary and daughter particle energies - contained events underground are generated from primaries in the range from 2 GeV up to over 100 GeV.

2. The cross sections must be integrated over the full range of p_T — the actual p_T distributions are less important because only one neutrino at most from a given cosmic ray cascade is ever likely to be detected.

3. The most important hadrons to use as projectiles are protons. Neutrons are also important, but experimental considerations are more difficult. Since meson interactions in the atmosphere are only important above a few hundred GeV for pions (and higher for charged kaons due to their shorter lifetime), it is less urgent to measure their interactions.

4. Kaons become very important producers of neutrinos at high energy, however for neutrinos up to 10 GeV in energy (the ones most considered in this workshop), pions are the dominant source of neutrino production and therefore the most important secondary meson type to be measured.

Figure 1 also indicates some of the early measurements of hadron production, the ones which have been used to shape the currently available hadron production generators in use in Monte-Carlos today. Measurements have been made using emulsions (where important information on multiplicity can be obtained), bubble chambers and by using the secondary beam line at an accelerator facility as a spectrometer. This last technique was used in several cases e.g. [6, 7, 8] and allows specialized (and high quality) particle identification techniques to be used which can be tuned to the specific momentum the beam line is set to transport. Unfortunately, each element of secondary phase space (momentum and angle) needs an individual measurement for each primary energy and target type and so an insufficient number of points are available for constructing or tuning a comprehensive Monte-Carlo generator.

The modern experiments to be described in the remainder of this article all use large volume time projection chamber (TPC) detectors and can measure

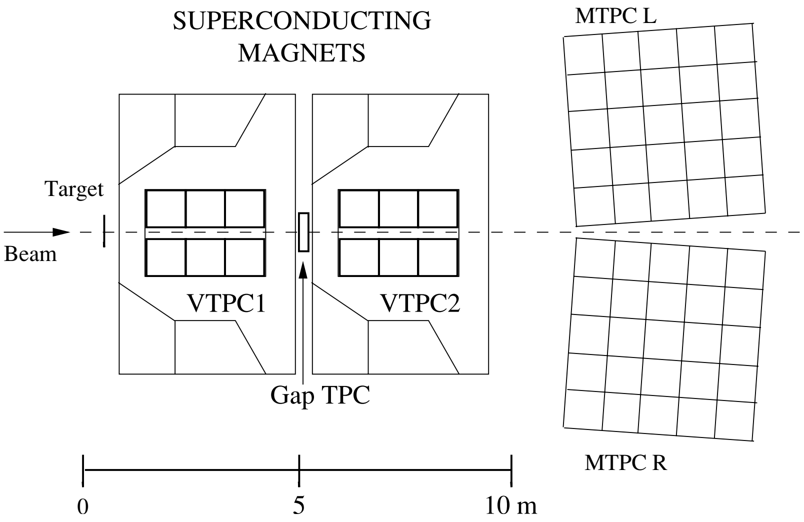

Fig 2. Layout of the NA49 experiment.

a large fraction of the phase space in one go. Most use several methods of particle identification to cover the whole range of secondary particle momenta. The following sections describe four new measurements: a short measurement with the NA49 apparatus at the CERN SPS at 158 and 100 GeV; a dedicated hadron production experiment, HARP at the CERN PS at energies up to 15 GeV; a measurement with the Brookhaven experiment E910 at 6, 12 and 18 GeV and the MIPP experiment, currently taking data at Fermilab at energies up to 120 GeV. As the author has involvement and therefore more familiarity in the first two of these experiments, they will be described in more detail here.

3. NA49

The NA49 experiment [9] at CERN was built to study lead-lead collisions when the SPS accelerator was used to accelerate fully ionized heavy ions. It uses four large time projection chambers to measure tracks as shown in figure 2 and is capable of handling the very high multiplicities found in Pb-Pb collisions. The experiment is ideally suited to the measurement of hadron collisions and to augment the NA49 collaboration's own measurement programme of proton projectiles on nuclear targets, a dedicated series of measurements was taken by an extended group including neutrino physicists over a one week period. The measurement used a 1% interaction length carbon target mounted in front of the TPC system and used a minimum bias trigger. The run was immediately preceded by a longer NA49 run with a liquid hydrogen target and the same trigger and

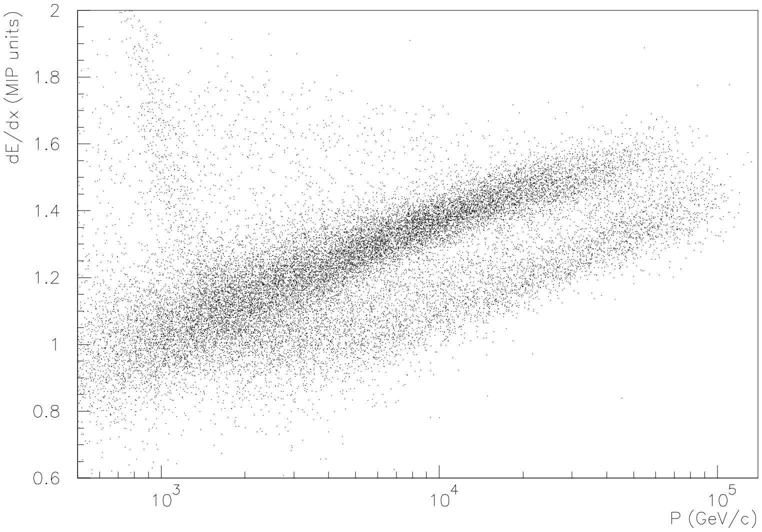

Fig 3. Ionisation loss measurements as a function of particle momentum.

many calibration and systematic issues are common to the two runs. 500,000 triggers were taken at a beam energy of 158 GeV and a further 160,000 triggers with a beam energy of 100 GeV.

The beam was produced by striking the main T2 North Area target with the primary proton beam from the CERN SPS running at 400 GeV. The particles produced in this interaction were momentum selected and transported to the experiment where they hit the carbon sample which contained the target nuclei under study. Beam position monitors upstream of the sample allowed the position of the impact of the parent to be determined. The signals from a series of threshold Cerenkov detectors in the beam were used to select only proton projectiles in the trigger of the experiment. In addition, the trigger comprised positive signals from three trigger counters in the beam upstream of the target and an absence of a signal in a small counter (S4) downstream of the target along the line of flight the uninteracted parent beam would take. This trigger produces an almost unbiased selection of events where an interaction takes place. It does introduce biases either when the leading particle is not deviated sufficiently to miss the S4 counter or where a secondary particle with a given p_T accidentally curves in the magnetic field by the right amount to hit the S4 counter. Small corrections are applied to the data for each of these effects.

The TPCs are arranged with two 'vertex TPCs' immersed in 1.7 T mag-

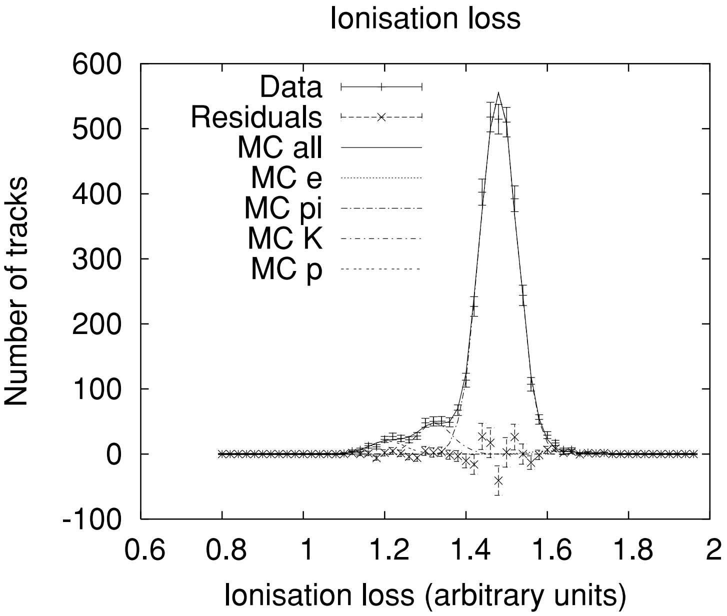

Fig 4. Ionisation loss in one hadron production bin showing the expected positions of the pion, kaon and proton peaks.

netic fields and two 'main' TPCs downstream with no magnetic fields. A vertical gap down the centre of the detector allows the uninteracted beam to pass through the detector without generating space charge in the active TPC volume. This is crucial for the lead ion beam with charge $92e$. For both the proton-carbon run and the preceding proton-proton run described here, a thin 'gap' TPC was added to the experiment to allow particle detection in the gap. The magnetic fields and the electron drifts are vertical with the pads and readout situated on the top of the detector. The number of samplings per track ranges from 30 to over 100 and these are used to make an ionisation loss measurement for particle identification purposes. Detailed care in the design and data analysis procedure of this detector have been made to allow particle type differentiation in the relativistic rise region of the Bethe-Bloch ionisation loss curves as shown in figure 3, i.e. for secondaries above 4 GeV. The data are separated into bins in both Feynman-x and p_T and the ionisation loss is analyzed in each bin separately. The predicted position of the ionisation peaks from the Bethe-Bloch function is used as a guide for where to find the peaks for each particle species, but small (1%) shifts are permitted to account for residual miscalibrations and deviations from the Bethe-Bloch function. An example of the ionisation curves is shown in figure 4.

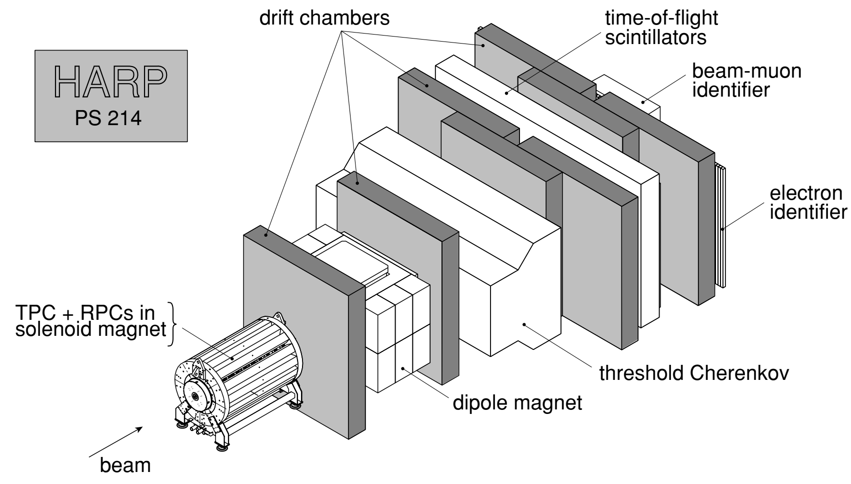

Fig 5. Layout of the HARP experiment.

4. HARP

HARP at the CERN proton synchrotron is purpose-built to measure hadron production for parent energies up to 15 GeV. The detector is shown in figure 5. The target is surrounded by a large time projection chamber (TPC) detector contained in a solenoidal magnetic field which allows all secondaries including those which are emitted backwards in the lab frame to be measured. The TPC is surrounded by a plane of resistive plate detectors for time of flight particle identification. Downstream of the TPC, a series of detectors are used to measure particles going forward in the laboratory frame. A spectrometer composed of drift chambers recuperated from the Nomad neutrino experiment measure the tracks in up to four longitudinal positions and momentum is measured by bending in a vertical magnetic field. Particle identification is provided by a number of detectors sensitive to different secondary particle energy ranges. A time of flight plane provides a resolution of 160 ps giving 3σ separation between π and protons up to 4.5 GeV/c and between π and kaons up to 2.4 GeV/c. A threshold Cerenkov counter with a 30m^3 volume of C_4F_{10} gas at atmospheric pressure is used for particle ID at higher momenta. An electromagnetic calorimeter is used for electron identification.

The beam used by HARP is a secondary beam generated from the CERN PS 24 GeV proton beam. Due to limitations in the secondary beam line, the maximum parent energy is 15 GeV. The beam is instrumented with time of flight and Cerenkov detectors for parent particle identification. Beam position measurement drift chambers are used to extrapolate to the beam impact point on the target. A

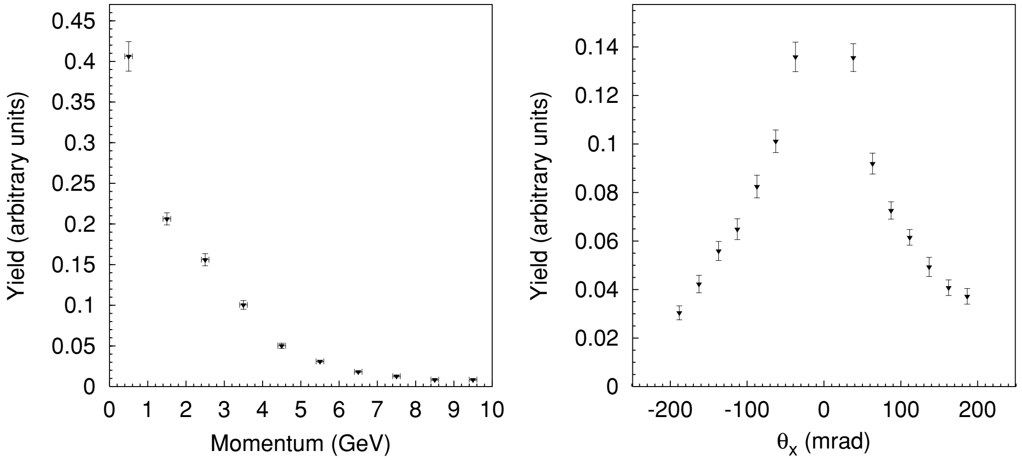

Fig 6. Recent HARP hadron production data on a thin aluminium target (K2K target replica) as a function of momentum and of angle in the horizontal plane (from [10]).

comprehensive set of data were taken at a range of parent energies (both positives and negatives) with a range of targets of different nuclear size. The most relevant for atmospheric neutrino production are the carbon and aluminium targets (the practical nuclei with A closest to the nuclei found in air) and liquid nitrogen and oxygen targets. The first data to be analyzed is a thin Aluminium target taken from a replica of the neutrino target used in the K2K long baseline experiment. Preliminary distributions are available [10] and are shown in figure 6 as measured by the forward components of the detector.

5. Brookhaven E910

The E910 experiment at Brookhaven was designed to study proton-nucleus and heavy ion collisions. It was run with a minimum bias trigger in a tagged proton beam operated at momenta of 17.5, 12.3 and 6.4 GeV/c on gold, copper lead and beryllium targets. The beryllium data are particularly important for input to beam simulation for the neutrino beam for the MiniBoone experiment at Fermilab. The detector consists of a spectrometer using a large TPC and drift chambers. Particle identification is performed with ionisation loss measurements in the TPC, threshold Cerenkov and time of flight.

Preliminary results of π^+ production have been presented recently [11]. The results span a large region of phase space at all three primary energies and up to 78 bins in secondary particle phase space (momentum, opening angle). This is the first experiment to measure particle production at such low secondary momentum, a very important region for atmospheric neutrino fluxes.

6. MIPP

The MIPP experiment [12] is purpose-built to measure hadron production off a wide range of targets of different A with both primary 120 GeV protons from the Fermilab Main Injector and parent particles produced in a secondary beam to obtain hadron production data at lower energies. A TPC (indeed the same TPC used previously in the E910 experiment) situated directly downstream of the target measures tracks with a wide acceptance. Particle identification allows K/p and π/K separation to better than 3σ over practically the entire secondary particle phase space using a combination of ionisation loss measurement, time of flight, threshold Cerenkov and ring-imaging Cerenkov (RICH) technologies. The experiment was approved in 2001 and is now (winter 2005) in production data taking mode.

MIPP will be able to provide the first high statistics sample of hadron production data at high secondary particle momenta with excellent kaon identification. This is particularly important for predicting the fluxes of the high energy neutrinos responsible for upward muons which traverse the underground detectors because at high energies, kaons are the dominant source of neutrino production and due to the steeply falling primary cosmic ray spectrum, high energy secondaries are the most important.

7. Conclusions

Overall, the level of hadron production data which can be used to tune Monte-Carlo calculations is the single most limiting factor in the prediction of unoscillated atmospheric neutrino fluxes. This is because the number of variables over which the hadron production can vary is large and the available data is of high quality, but sparse. A variety of new experiments involving the use of large area detectors covering most of the secondary particles have recently been performed and some of the results are just becoming available now. In particular the Brookhaven E910 experiment have presented production data at primary energies of 6, 12 and 18 GeV with secondary coverage extending down to low momenta. HARP has an analysis of an aluminium target which is nearly complete with other targets to follow and have already presented preliminary results. The analysis of the NA49 data is also nearly complete. The MIPP experiment is currently in data taking.

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