HARP: a Hadron Production Experiment for the Neutrino Factory and for the Atmospheric Neutrino Flux

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The HARP experiment will carry out, at the CERN PS, a large programme of measurements of secondary hadron production, over the full solid angle, produced on thin and thick nuclear targets by beams of protons and pions with momenta in the range 2 to 15 GeV/c. The first aim of the experiment is to acquire adequate knowledge of pion yields for an optimal design of the recently proposed neutrino factory. The second aim is to reduce substantially the existing $\sim 30\%$ uncertainty in the calculation of absolute atmospheric neutrino fluxes and the $\sim 7\%$ uncertainty in the ratio of neutrino flavours.

1. INTRODUCTION AND PHYSICS MOTIVATIONS

The HARP experiment, approved by CERN on 17 February 2000, and included in the European R&D towards the neutrino factory will take data the next year.
The main motivation is twofold: to acquire adequate knowledge of pion yields for an optimal design of the recently proposed neutrino factory [1–3] and to improve substantially the calculation of the atmospheric neutrino flux which is needed for a refined interpretation of the evidence for neutrino oscillation from the study of atmospheric neutrinos in present and forthcoming experiments [4,5].

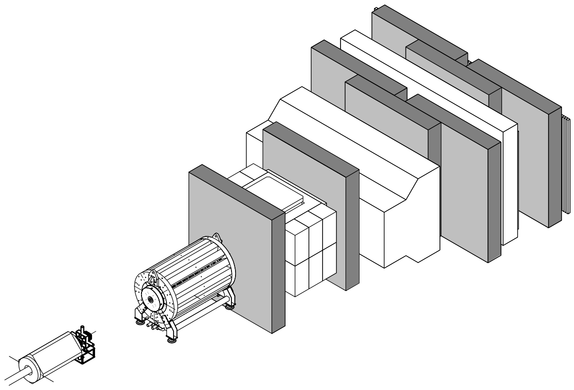

Figure 1. fig1: Layout of the HARP experiment.

1.1. Pion production in a neutrino factory

A neutrino factory is a complex machine to produce neutrinos from circulating muons decaying in a storage ring [1]. The generic layout of a neutrino factory consists of a proton accelerator, a target and a muon storage ring [3]. A high power (4 MW) proton beam impinges on a target producing pions which are collected with a high magnetic field. In a drift space, they decay into a muon and a muon neutrino. After this, the muon phase space is reduced with ionization cooling, the muons are accelerated to energies of up to 50 GeV and fed into a decay ring where they decay into an electron/positron and two neutrinos ($\mu^+ \to e^+ + \nu_{\rm e} + \overline{\nu}_\mu$). In this context, accurate knowledge of pion production yields are very important to achieve the desired neutrino fluxes and to design a cost-effective machine [6]. The design goal is to maximize the number of accelerated muons in the decay ring of each sign. Current simulations of the pion yield with FLUKA and MARS show a 30%–100% discrepancy in the pion production [7]. The reason for this uncertainty is the lack of experimental data. A high-precision pion production experiment is thus a requirement for the final design of a neutrino factory. The variables affecting the pion production are proton energy, target material and target geometry (diameter and length). A pion production experiment should give the set of data necessary to optimize both proton energy and target material in order to achieve the highest number of potentially collected pions *of both charge signs* per unit of energy.

1.2. Atmospheric neutrino flux

The SuperKamiokande collaboration has presented evidence for neutrino oscillation based on a high-statistics sample of atmospheric neutrino interactions [4,5]. The detailed interpretation of these data requires reliable calculations of fluxes of atmospheric neutrinos. Several of those calculations have been published [8–11] and the large differences found can be traced in large part to differences in the representation of pion production by protons interacting with nuclei in the atmosphere. Recalling that what is important for the calculation of the neutrino flux is the total yield of pions integrated over all phase space, there is a pressing need for a single experiment that covers pion production at several beam energies around 10 GeV/c. Targets should be as close as possible to the constituents of the atmosphere, especially nitrogen. Also the use of a beam of helium will be interesting. In fact 15% of nucleons are bound in alpha particle.

2. SETUP DESCRIPTION AND EXPECTED PERFORMANCES

The goal of the HARP esperiment will be the measurement of secondary hadrons with a 4π angular acceptance using various beams energies and targets. Both for the neutrino factory and for the atmospheric neutrino flux, an overall precision of 2% for the inclusive cross-section of secondary particles is the primary aim. This is motivated by the wish to obtain 5% precision both on the production of accepted muons in the neutrino factory's front stage, and on the atmospheric neutrino flux. A 2% overall accuracy requires some 10^6 events for each measured point to minimize the statistical error. The largest challenge will come from understanding efficiencies with an error of the order of 1%. This calls for as much redundancy as can be afforded, with a view to cross-calibrating efficiencies and to keep under control the systematics. Furthermore, at different energies the purity of the pion sample is affected by different backgrounds that requires good particle identification detectors.

The HARP experiment (see Fig. 1) comprises a large-acceptance charged-particle magnetic spectrometer of conventional design, located in the East Hall of the CERN PS and using the T9 tagged charged-particle beam. The crucial detector for low-energy secondaries is a cylindrical

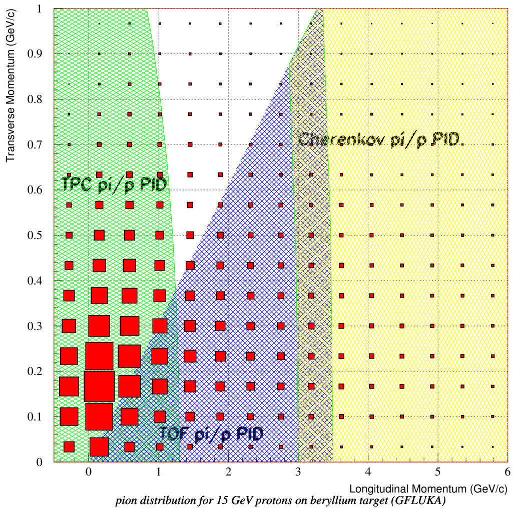

Figure 2. fig 2: Production spectrum (by GEANT+FLUKA) $d^2N/dp_T\ dp_L$ of (left) secondary pions produced in collisions of protons of 15 GeV/c with a thin beryllium target. Superimposed are the areas of phase space expected to be covered by the π/p particle identification of the TPC and the TOF.

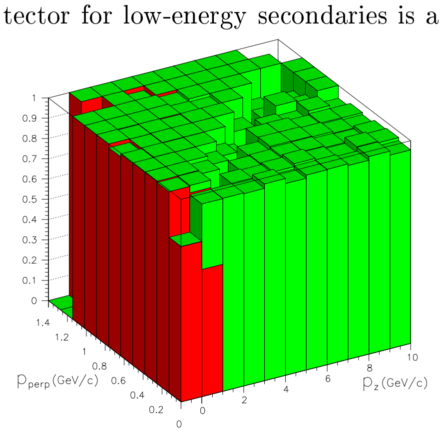

Figure 3. fig 3: Combined acceptance for pions produced by a proton beam of 15 GeV/c incident momentum on Be measured either by the TPC or the magnetic spectrometer

TPC inside a solenoid magnet which surrounds the target. Downstream, the TPC is complemented by a forward spectrometer with a large dipole magnet. This setup ensures nearly full 4π coverage for the momentum measurement of charged secondary particles. Their identification is achieved by $\mathrm{d}E/\mathrm{d}x$ in the TPC, by time of flight (TOF), by a threshold Cherenkov detector, and by an electromagnetic calorimeter. The experiment will re-use existing equipment whenever possible, notably calorimeter modules from CHORUS [13] and drift chambers from NOMAD [12]. A Monte Carlo simulation of HARP has been carried out using the GEANT [14] package, with the FLUKA [15] interface for the hadronic interactions. As an example of the expected performance, data with 15 GeV/c protons impinging on a beryllium target with 2% λ_{I} thickness have been simulated. In Fig. 2 we can see the distribution of events in the transverse–longitudinal momentum plane ($\mathrm{d}^2N/\mathrm{d}p_{\mathrm{T}}\ \mathrm{d}p_{\mathrm{L}}$) for the secondary pions produced in the interactions. Overlayed on this plot one can see the approximate regions of parameter space covered by the π/p identification capabilities of the TPC and the TOF. The π/p separation can be achieved unambiguously for most of the phase space. In the Fig. 3 we can see the three-dimensional plot of the p_{L}–p_{T}-plane in which the third coordinate is the acceptance of the TPC for pions produced by 15 GeV/c incident protons (dark grey) or the corresponding acceptance of the magnetic spectrometer (light grey). This plot shows that the acceptance of pions over the full phase space is almost 100% and confirms the 4π capabilities of the HARP detector.

3. SCHEDULE and CONCLUSIONS

The construction of HARP is on schedule, and will permit data taking with a complete detector in 2001. In addition, a second round of measurements with a special configuration is planned for the first half of 2002: the primary proton target of the PS beam line would be removed and deuterium and helium nuclei would be sent directly to the target of the experiment. A technical run took succesfully place from 25 September to 25 October 2000. The TPC, the Cherenkov detector and the TOF wall were still not available. However, a number of well-defined and valuable tests of the trigger, of the NOMAD drift chambers, of the DAQ and of the reconstruction software were performed. The schedule is tight; however, at present there is nothing known which calls our plan into question and we are confident to be able to reach the result.

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