Pion Production for Neutrino Factory - challenges

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Abstract. One of the key issues in the design of a Neutrino Factory target station is the determination of the optimum kinetic energy of the proton beam due to the large uncertainties in simulations of protons impinging on nuclear targets. In this paper we have developed a procedure to correct GEANT4 simulations for the HARP data, and we have determined the yield of muons expected at the front-end of a Neutrino Factory as a function of target material (Be, C, Al, Ta and Pb) and energy (3-12 GeV).The maximum muon yield is found between 5 and 8 GeV for high Z targets and 3 GeV for low Z targets.

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1. INTRODUCTION

The International Scoping Study (ISS) defined the parameters needed for future neutrino accelerator facilities, including a Neutrino Factory [1]. The optimum energy of the proton beam impinging on the Neutrino Factory target remains a key issue. A study using the MARS V14 simulation code [2, 3], compared muon yields through the Study 2a Neutrino Factory front-end [4] for liquid mercury and carbon targets. The maximum proton energy for a mercury target was between 5 and 10 GeV, while for the carbon target it was at 5 GeV. The MERIT experiment [5] successfully demonstrated the feasibility of a liquid mercury target with 4 MW proton power in a 20 T magnetic field. There is additional R&D to study the feasibility of solid targets at 4 MW proton power but the lifetime of these targets is yet to be determined reliably. For these reasons, a liquid mercury target with a proton energy between 5 and 15 GeV has been adopted by the International Design Study to be the baseline target system at a Neutrino Factory.

However, there was very little hadronic production data to test particle production simulation models. The HARP experiment [6] was designed to measure hadron production yields from protons impinging on a variety of nuclear targets for proton energies between 3 and 15 GeV. HARP data [7] will be used to fine tune hadronic production models and to calculate neutrino fluxes for a number of current and future neutrino experiments. Comparison between production models (mainly MARS and GEANT4 [8]) and data were performed, but no firm predictions have been made for a Neutrino Factory. The aim of this paper is to compare HARP pion production data in a variety of targets at different proton energies to GEANT4 production models and to reweight the GEANT4 data, taking into account Neutrino Factory acceptance functions, to predict muon yields and to determine the optimum proton energy at a Neutrino Factory.

2. HARP DATA

HARP investigated the pion and kaon cross-sections from protons impinging on nuclear targets (hydrogen to lead) between 3-15 GeV/c. The experiment was proposed in 1999, was installed between 2000 and 2001 in the East Area of the CERN Proton Synchrotron (PS) and took data between 2001 and 2002.

The experiment consists of beam detectors (Cherenkov, Time of Flight TOF, multi-wire proportional chambers and trigger scintillators) to identify the incident particles, a target inserted inside a gaseous Time Projection Chamber (TPC) with Resistive Plate Chambers (RPC) inside a solenoid magnet (0.7 T) for large angles, and a forward spectrometer consisting of drift chambers from NOMAD, a dipole magnet (with field 0.66 T m), a large area downstream TOF, a Cherenkov detector and an electromagnetic calorimeter for particle identification [9]. HARP recorded a total of 420 million events with more than 300 different configurations. The data used for this analysis consists of the large angle HARP data for the following targets and proton energy: Beryllium (3, 5, 8, 8.9, 12 GeV), Carbon (3, 5, 8, 12 GeV), Aluminium (3, 5, 8, 12, 12.9 GeV), Tantalum (3, 5, 8, 12 GeV) and Lead (3, 5, 8, 12 GeV), published in [10, 11, 12, 13, 14, 15, 16]. Data were shown in terms of a differential cross-section for particle α in bins of momentum and angle:

$$\frac{d^2\sigma_\alpha}{dpd\theta}(p_i,\theta_j) = \frac{A}{N_A\rho t}\frac{1}{\Delta p\Delta\theta}\frac{1}{N_{pot}}M^{-1}_{ij\alpha i'j'\alpha'}N^{\alpha'}_{i'j'}(p_{i'},\theta_{j'}), \tag{1}$$

where $N^{\alpha'}_{i'j'}$ is the number of particles of observed type α' as a function of reconstructed momentum and angle $(p_{i'},\theta_{j'})$ and the inverse of the response matrix $M^{-1}_{ij\alpha i'j'\alpha'}$ unfolds the true variables $ij\alpha$ from the reconstructed variables $i'j'\alpha'$, taking into account re-interactions, detector efficiency and resolution. N_{pot} is the number of incident protons, A, ρ and t are the atomic number, density and thickness of the target, N_A is Avogadro's number, and Δp and $\Delta\theta$ are the momentum and angular bin widths. Angular bins are between 0.35-1.55 rad, and outgoing momentum bins between 0-800 MeV/c. The data used were for targets of 5% interaction length Λ_I.

3. SIMULATED DATA

We ran GEANT4 simulations for comparison to HARP data. The GEANT4 hadronic models and recommended validity ranges are described in the GEANT4 Physics Reference Manual [17]. Simulations were performed within the G4beamline package on 5% Λ_I and 1% Λ_I targets with 5 million and 25 million incident protons respectively, for the LHEP, QGSP, QGSC, QGSP-BIC and QGSP-BERT physics models, for beryllium, carbon, aluminium, tantalum and lead targets, with incident proton momenta of 3, 5, 8 and 12 GeV/c (plus 8.9 GeV/c for Be and 12.9 GeV/c for Al). There were about 2.5×10^5 pions for each simulation. Differential cross-sections were calculated with the same angle-momentum bins as in the HARP data, by applying equation 1, with $M^{-1}_{ij\alpha i'j'\alpha'}$ the unitary matrix. This was repeated for the 5%Λ_I and 1%Λ_I simulations, and extrapolated for each bin to 0%, to obtain a true cross-section in which re-absorption and secondary particles are neglected. Holes in the distributions were found for QGSP-BIC and QGSP-BERT at $\sim$ 300 MeV/c and low angle (0.35-0.55 rad), probably due to an internal matching problem in the two physical models. QGSC and LHEP showed smooth distributions but the agreement between HARP and these models was not very good in some monentum bins (see Figure 1).

4. REWEIGHTING HARP DATA

We performed the HARP to GEANT4 ratio for each target and proton energy E_k, as a function of (p_i,θ_j):

$$R_{ijk} = \frac{HARP(p_i,\theta_j,E_k)}{GEANT4(p_i,\theta_j,E_k)}. \qquad (2)$$

We performed an empirical 5th order polynomial fit in (p,θ) to the reweighting coefficients R_{ijk} for each energy E_k to extend the reweighting function beyond the measured HARP phase space:

$$w(p,\theta,E_k) = \sum_{m=0}^{5}\sum_{n=0}^{5} C_{mn}p^m\theta^n. \qquad (3)$$

For each pion of (p,θ) at proton energy E_k, we ran the 5% Λ_I simulation again, multiplied by the polynomial $w(p,\theta,E_k)$ and compared with the original HARP data. We determined the error of the method by calculating the average residuals of the reweighting functions at each of the HARP bins and adding in quadrature with the HARP error for each bin. For example, the results of reweighting the QGSC distributions for 12 GeV protons on aluminium (Figure 1) improved agreement with HARP from 26.4% to 8.3%. This same procedure was repeated for all the targets and incident proton energies.

5. MUON YIELDS

To determine the muon yields per proton per GeV, we take the muon acceptance probability $Prob_{\pi\rightarrow\mu}(p_T,p_L)$ that a pion produced in the target produces a muon at the end of the front-end of a 25 GeV Neutrino Factory, as a function of pion transverse and longitudinal momentum (p_T, p_L) [18]. Then we sum over the whole muon acceptance to obtain the total muon yield:

$$Y_\mu(E_k) = \frac{f}{E_k N_{prot}} \sum_{\pi_i} Prob_{\pi\rightarrow\mu}(p_{T_i},p_{L_i})w(p_i,\theta_i,E_k), \qquad (4)$$

where $\tan\theta_i = p_{T_i}/p_{L_i}$ and $p_i = \sqrt{p_{T_i}^2 + p_{L_i}^2}$. The yields are calculated for a 100%Λ_I target (the factor $f = 20$ converts from 5%Λ_I to 100%Λ_I).

The final muon yields at a Neutrino Factory can be seen in Figure 2, as a function of target material per incident proton momentum (the results are the average of both μ^+ and μ^- yields). Results for reweighting the LHEP and the QGSC pion distributions yield nearly identical results, as a validation of the method. For high Z targets (Ta, Pb), the maximum yield of 0.017 muons/(proton GeV) is found between 5 and 8 GeV. For low Z targets (Be, C, Al), the maximum yield is 0.022 muons/(proton GeV) at a lower proton energy of 3 GeV. No correction for reinteractions in the target was made. Another HARP paper [19] compared thin (5%Λ_I) and thick (100%Λ_I) targets, and the factor is between 0.8 and 1.0 for Be, C and Al, while for Ta and Pb the factor is $\sim$ 0.65. A comparison with another MARS target simulation, using the same front-end acceptance probability function [18], shows similar results, with maximum yields of 0.015 muons/(proton GeV) for proton energies between 8 and 10 GeV for high Z Hg and Ta targets. A maximum yield of 0.020 muon/(proton GeV) was achieved at a proton energy around 5 GeV for a carbon target. In reference [20], HARP cross-sections were reweighted by Neutrino Factory acceptance calculations using MARS, finding also a maximum yield at 7 GeV.

6. CONCLUSIONS

We have developed a procedure to correct GEANT4 simulations for the HARP data. We use reweighting func-

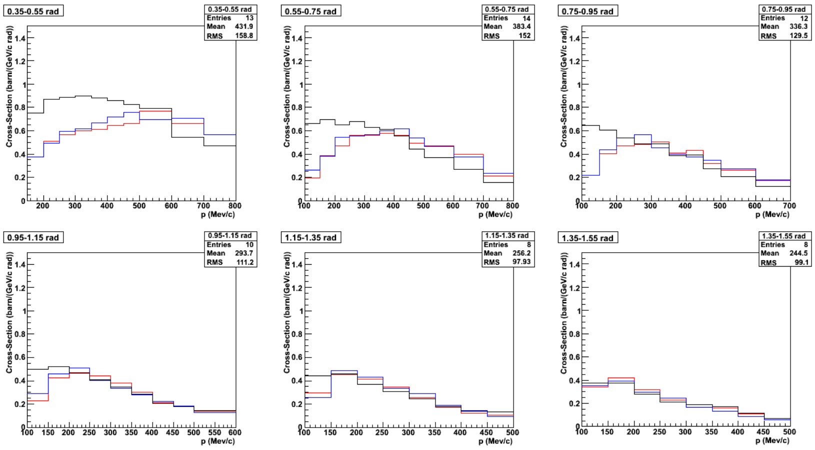

FIGURE 1. Comparison of GEANT4 QGSC model (black line) with HARP data (blue line) from 12 Gev protons on an aluminium target (26.4% agreement). The red line is the reweighted distribution (8.3% agreement with HARP).

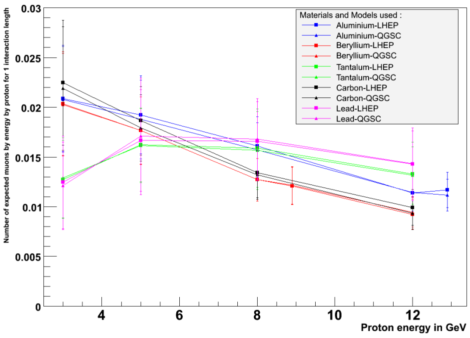

FIGURE 2. Muon yields as a functions of proton beam energy and target material.

tions for HARP data that can be multiplied as a weight for each pion in GEANT4 based simulations. Using the latest Neutrino Factory good muon acceptance matrix, we can calculate the muon yields. The correction method works well regardless of hadronic model used in the simulation, thereby creating a HARP data simulator. For high Z targets (tantaluma and lead), a maximum yield of 0.017 muons/(proton GeV) is found at a proton energy between 5 and 8 GeV and for low Z targets (beryllium, carbon and aluminium), a maximum yield of 0.022 muons/(proton GeV) is found at the lowest proton energy of 3 GeV. However, we have not taken into account reabsorption and re-interactions in thick targets, so these corrections still need to be performed.

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