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THE AGS BROAD BAND NEUTRINO BEAM

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THE AGS BROAD BAND NEUTRINO BEAM

Introduction

We describe the broad band neutrino beam in the north area of the AGS and discuss the calculation of the neutrino flux. The horns were initially designed by Robert Palmer and this beam has been used for almost all neutrino running at the AGS. All of the wide band running for E734 has been done in the beam we discuss below. E734 is an experiment designed to measure elastic scattering of neutrinos and antineutrinos on electrons and protons. The detector is sufficiently large (≈ 170 tons) that enough events can be detected to make precision measurements of cross sections. In particular, the reaction

$$\nu_{\mu} + e \rightarrow \nu_{\mu} + e$$

has been detected with more than 100 events¹, requiring a detailed understanding of the beam characteristics for normalization. The normalization method uses the quasi elastic reactions

$$\nu_{\mu} + n \rightarrow \mu^{-} + p$$

$$\bar{\nu}_{\mu} + p \rightarrow \mu^{+} + n$$

These cross sections are relatively well known, below 1 GeV they rise approximately linearly with neutrino energy and then become rather independent of neutrino energy above 1 GeV. The approach to constant behavior is quite different between ν and $\bar{\nu}$ so that accurate relative normalization requires a detailed

knowledge of the ν_μ spectrum of both polarities. The study of neutrino oscillations between $\nu_\mu + \nu_e$ ² requires a systematic understanding of the inherent ν_e flux in the ν_μ beam and this problem we address also in this report.

The calculation of absolute ν flux and the comparison with measured data is even more difficult than the relative comparisons we allude to above. The method that is used rests on our understanding of the charged current quasi elastic reactions.³ The charged current cross section is related to the electron scattering data through CVC and the major uncertainty is in the value of the axial vector mass m_A . Knowledge of this mass which is obtained from angular distribution measurements, allows an absolute calculation of the cross section. The magnitude of the cross section together with the event distribution permits an absolute determination of the ν flux. Although the physics of the situation is clear, technical difficulties have limited the agreement between calculation and measurement to the 20% level. As we expect to show, the understanding of this neutrino beam has progressed enough that relative normalizations appreciably better than this are possible.

Beam Hardware

A schematic of the target area is shown in Fig. 1. The proton beam is extracted in a single turn from the AGS and transported down to the target of Fig. 1. The incident proton beam energy has been 28.3 GeV/c and the spot size at the target has been typically 2 mm full width. The time structure of the beam from the accelerator RF

3.

is preserved, and so 12 bunches 224 ns apart appear at the target. The width of each bunch is about 30 ns. This time structure is invaluable in separating events induced by neutrinos and events which originate from less direct sources. The overall spill is just a little longer than 2.5 μ sec.

The secondary particles that originate in the target are focussed in the B field of the two horns as we describe in the next section. The B field is generated by a current of ≈ 200 -300 KA which flows in the horn conductor. A simple schematic of the power supply is shown in Fig. 2. The energy storage capacitors, C, are charged in the 1.4 sec between pulses to ≈ 12 KV at constant current. The capacitors are arranged in modules 42 μ F each and each module is switched on to the load through an ignitron - the resistor R_L ($5 \times 10^{-3} \Omega$) is in series with 14 transmission lines in parallel driving the horns H1 and H2 in series through a characteristic impedance of about 1 Ω . Immediately after the horn current is switched on, the system acts as a series RLC circuit with a time constant of ≈ 20 μ sec. The ignitrons are triggered by a pulse derived from the AGS radio frequency, which implies that the horn current pulse is stable with respect to beam time to about 20 ns. The current pulse is shown in Fig. 3. When the current falls to zero the ignitrons I2 crowbar the system preventing reverse voltage from being developed across I1. The current is monitored precisely in one module and approximately in the other eleven. The charging time represents a monitor of the functioning of all twelve modules, in that it is linearly dependent on the number of modules that are recharged.

In the shield at the end of the decay region, ion chambers are installed which monitor the muon flux in the shield. These chambers are primarily used to monitor the beam alignment although the radial distribution of the muons agrees with the results of the NUBEAM calculation.

Horn Optics

A schematic diagram of the wide band horns is shown in Fig. 4. The target is embedded in the front of horn 1 and the charged particles that are produced in the target are reduced in angular spread between the two horns. The second horn then produces a nearly parallel beam so that the length of the particle trajectory in the decay region is maximized. In the simplest terms, the horn functions as a simple lens and for this to be true the length of the horn as a function of radius is important. The B field at a distance from a current carrying conductor varies as $1/r$; for focussing to occur, the angular change of the charged particle must vary as r so that $\int B dl$ must also vary as r . The horn length must vary approximately as r^2 therefore. This geometry can only produce a parallel output beam at one energy, and since we are usually concerned with maximizing the charged particle flux over an energy band, the variation of aperture with charged particle momentum is important.

The production cross section $d\sigma/d\Omega = \exp - \frac{a^2}{\sin^2 \theta}$, a function which falls rapidly with angle. The number of particles which are produced in an annulus $d\theta$ at θ is $d\sigma/d\Omega \sin \theta d\theta$ which is 0 at $\theta = 0$

and rises to a maximum at $\theta_{\max}$ for a given momentum. The horn system we are describing is designed so that particles at this production angle $\theta_{\max}$ are focussed as we have described to a parallel beam after horn 2. The chromatic properties of this lens system are optimized by this means to produce a wide band of transmitted momenta after horn 2 with the angular acceptance peaking near the optimal production angle. The horns are produced as a stepwise linear approximation to the necessary shape.

Using the NUBEAM program⁴ which we discuss below we have calculated the enhancement in the neutrino flux produced by this horn system over the bare target spectrum without focussing. The central momentum of this horn system at 250 KA current is expected to be at 3 GeV/c. For $\pi \rightarrow \mu + \nu_{\mu}$, the neutrino momentum is $\approx .42 p_{\pi}$ in the forward direction so that we would expect the maximal enhancement from the horns to be at 1.3 GeV/c. In Fig. 5 we show the calculated enhancement with a broad peak centered at 1.3 GeV/c and extending to high momenta. At low momenta, the particles are over focussed and are deflected so as to strike the walls of the enclosure and be absorbed before they can decay. Also in Fig. 5 is the effect of the horn for the "wrong sign" particles. Near the optimal point we notice that the effect of the horns is actually to reduce the number of charged particles that are transmitted as we would expect. At high momenta there is also a moderate enhancement which will ultimately decrease to one at the highest momenta, when the bending effect of the horns becomes negligible.

The enhancement drops rapidly at low momenta partly from momentum dependent effects and also because the optimal production angle moves outside the aperture of the system. This production angle is given by $p_{\perp} \approx 0.25 \text{ GeV/c}$ so that below 1.5 GeV/c pion momenta the fraction of particles that are transmitted rapidly decreases, this combined with the chromatic effects produces a very rapid fall off at low momenta. Moreover the rapidity of the fall off causes this region of the spectrum to be very dependent on the details of the calculation.

Particle Sources

Both charged π and K mesons produce neutrinos through their decay. The ratio of the production rate of π and K differs by about a factor of 20 but as we shall see below the neutrinos from K decay appear at higher momentum and are observable at the high end of the spectrum. The predominant branching mode of the π meson is $\pi \rightarrow \mu + \nu_{\mu}$ and at the relevant energies any reasonable detector only detects neutrinos close to the forward direction. The kinematics is such that

$$E_{\nu} \approx \frac{\frac{m_{\pi}^2 - m_{\mu}^2}{2}}{m_{\pi} + p_{\pi} \cos \theta_{\nu}} \cdot p_{\pi}$$

so that when $\theta_{\nu} = 0$ $E_{\nu} = 0.42 p_{\pi}$ and at the maximum angle for neutrinos in the E734 detector (33mr) the neutrino momentum drops to about $.28 p_{\pi}$, about two thirds of the maximum. The neutrino spectrum from $\pi \rightarrow \mu$ decay is a slightly broadened version of the

pion spectrum that is transmitted by the horn system modified by the decay probability. The central momentum of the pions is 3 GeV/c and so that $\gamma c\tau$ is about 160 m, much longer than the decay region of the horn, and so a small fraction of the pions decay before reaching the shield. The ν_μ spectrum from pion decay is shown in Fig. 6. The lifetime of the muon is 2200 ns and on the average the muons traverse only one half of the decay distance. The ratio of the fraction of muons that decay to the pion decays is $\approx 2 \times 10^{-3}$. This gives rise to a contamination of electron neutrinos which is shown in Fig. 7. The ν_e spectrum is similar to the ν_μ spectrum but lower in energy by about a factor of two.

The K mesons contribute to the ν_μ spectrum primarily through the $K_{\mu 2}$ decay mode. The kinematics are similar to the two body pion decay except that the forward neutrinos are very close to the charged kaon momentum throughout the angular range of the E734 detector. The ν_μ spectrum for K^+ decay is shown in Fig. 6 together with the total of π and K. The spectrum from $K_{\mu 2}$ is significantly harder as one would expect from the kinematics. The low energy enhancement in the K^+ induced spectrum is due to the secondary decay of π mesons from the decay mode $K^+ \rightarrow \pi^+ + \pi^0$.

The branching mode $K^+ \rightarrow \pi^0 + e^+ + \nu_e$ gives ν_e directly with a branching ratio of .05. The energies of ν_e from this mode are spread over the entire spectrum up to the end point with a typical neutrino energy of about one third of the K^+ energy. The production rate of K^+ is about .05 of π^+ , the branching ratio is .05 but the

ratio of $\gamma\tau$ for kaon and pion is 7.5. These combine to give an expected ν_e/ν_μ ratio of 6×10^{-3} for the entire beam spectrum. We show in Fig. 7 the ν_e spectrum from K^+ decay with the characteristics we describe.

The contribution of other particles to the ν_μ spectrum is rather small and is customarily neglected. However in the case of ν_e since the major sources are already small we need to consider other possibilities in arriving at a careful estimate of the ν_e component. The principal contribution other than those we have described comes from K_L^0 decay. Although K_L^0 do not have the enhancement of the charged particle focussing, $\gamma\tau$ is comparable with the pion value and the branching ratio to $K \rightarrow \pi e \nu$ is 0.40. We show the yield of ν_e from K_L^0 in Fig. 7, an identical contribution of $\bar{\nu}_e$ is also present. The total ν_e spectrum is also in Fig. 7.

NUBEAM

The yields in Figs. 6,7 were calculated using a program NUBEAM from CERN.⁴ We discuss the program here in general terms with an emphasis on the possible uncertainties. The beam elements, target, horns, shield, etc. are specified by piecewise linear models to any degree of detail that one has the patience to introduce. The currents are specified in the horns and the B field is calculated at initialization. Particles are produced in the target according to a production spectrum which is specified as a table in secondary particle momentum and angle. The particle is traced through the

beam elements and a probability calculated for decay. A decay stack is set up specifying the possible modes of decay of all the particles. The weighted probabilities are stored for subsequent plotting. The muons are traced through the shield and multiple scattering is included in the ray tracing.

Hadrons are produced with a distribution specified by the included spectra⁶ and then subsequently absorbed according to cross sections appropriate to the material being traversed. The absorption cross section as usually defined⁵ includes protons which scatter through angles small enough to remain in the target and which may then interact. Since the majority of protons that interact will have the potential of reinteracting either in the target or the inner conductor of the horn, the cross sections of Ref. 5 are appropriate.

The protons which remain after interaction do so with reduced energy. The loss of proton energy has a significant effect on the momenta of the secondary pions. To calculate this process exactly would entail creating a model of the hadron cascade which is prohibitive for the beam calculation. An alternative procedure which we have followed is to make an estimate of the production of secondary pions from reinteracting protons and add it to the production spectrum of the pions from the original beam. The composite spectrum is also reproduced in Table I for both π^+ and π^- production. This yield is compatible with that from charged particle beams at the AGS.⁷

These considerations are not important for the secondary particles that traverse material in the horns and beam line because that material is a small fraction ($\approx 10\%$) of an interaction length and the effect is negligible.

Comparison with Measured Data

The neutrino beam spectrum has been measured with three techniques described in detail in Ref. ⁸. We show in Fig. 8 a composite neutrino spectrum together with the results of the calculation. The agreement is seen to be good although the freedom that was used in estimating the effective secondary flux should be noted. The effect of the protons that are degraded in energy producing secondary particles is important in achieving the agreement of calculation and measurement that is shown here.

Acknowledgments

This work was part of experiment E734 at the AGS. My colleagues are listed in reference 1 and a more comprehensive account of the analysis of the spectra is being prepared as reference 8. It is a pleasure to acknowledge the collaboration with Roger Carlini in understanding NUBEAM.

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Figure Captions

- Fig. 1. A schematic of the neutrino beam area. The slots for muon detectors are shown in the shield. In the neutrino detector enclosure, the main detector, the gamma catcher and muon spectrometer are shown.
- Fig. 2. The capacitors C are $42\mu\text{F}$, the inductance of the two horns in series is $1.25\mu\text{H}$ and the load resistor R_L is $5 \times 10^{-3} \Omega$.
- Fig. 3. The current pulse on the horn system at $20 \mu\text{sec/cm}$.
- Fig. 4. A schematic of the conductor geometry of the horn system. The target is embedded in the throat of horn 1. Note that the axial and radial scales differ.
- Fig. 5. The enhancement factor produced by the horn system at 250kA as a function of neutrino momentum at the detector.
- Fig. 6. The ν_μ spectrum at the detector as a function of the neutrino energy. The spectrum is integrated over a radius of 1.5m and the particle production spectrum is that of Table I.
- Fig. 7. The ν_e spectrum as a function of neutrino energy integrated over a radius of 1.5m .
- Fig. 8. The ν_μ spectrum as a function of neutrino energy both calculated and measured.
- Fig. 9. The ν_e spectrum as a function of neutrino energies, both calculated and measured.

TABLE - 1

Positive Pion Spectra

Angles start at 0.5 degrees, increment by 1 degree 18 steps
Momenta start at 0.5 Gev increment by 1 Gev, -8 steps

0.171E+01	0.160E+01	0.150E+01	0.141E+01	0.132E+01	0.124E+01
0.117E+01	0.110E+01	0.103E+01	0.968E+00	0.909E+00	0.853E+00
0.800E+00	0.752E+00	0.704E+00	0.354E+01	0.350E+01	0.346E+01
0.384E+01	0.374E+01	0.365E+01	0.355E+01	0.350E+01	0.291E+01
0.258E+01	0.247E+01	0.203E+01	0.178E+01	0.155E+01	0.137E+01
0.122E+01	0.108E+01	0.968E+00	0.374E+01	0.366E+01	0.358E+01
0.367E+01	0.367E+01	0.367E+01	0.354E+01	0.309E+01	0.253E+01
0.206E+01	0.166E+01	0.132E+01	0.104E+01	0.801E+00	0.626E+00
0.488E+00	0.399E+00	0.311E+00	0.244E+00	0.194E+00	0.147E+00
0.369E+01	0.369E+01	0.369E+01	0.329E+01	0.255E+01	0.192E+01
0.146E+01	0.105E+01	0.741E+00	0.532E+00	0.393E+00	0.287E+00
0.207E+00	0.143E+00	0.104E+00	0.89E-01	0.689E-01	0.480E-01
0.222E+01	0.222E+01	0.212E+01	0.171E+01	0.121E+01	0.855E+00
0.573E+00	0.371E+00	0.238E+00	0.164E+00	0.122E+00	0.871E-01
0.583E-01	0.403E-01	0.260E-01	0.151E-01	0.971E-02	0.427E-02
0.171E+01	0.171E+01	0.149E+01	0.107E+01	0.722E+00	0.501E+00
0.320E+00	0.171E+00	0.177E+00	0.686E-01	0.471E-01	0.304E-01
0.192E-01	0.106E-01	0.477E-02	0.164E-02	0.830E-04	0.100E-06
0.139E+01	0.139E+01	0.102E+01	0.634E+00	0.425E+00	0.281E+00
0.179E+00	0.863E-01	0.532E-01	0.310E-01	0.167E-01	0.783E-02
0.142E-02	0.116E-02	0.830E-04	0.830E-04	0.830E-04	0.830E-04
0.340E+01	0.131E+01	0.880E+00	0.463E+00	0.286E+00	0.153E+00
0.440E+01	0.326E+01	0.276E-01	0.120E-01	0.436E-02	0.114E-02
0.88E-01	0.52E-01	0.74E+00	0.830E-04	0.830E-04	0.830E-04
0.830E-04	0.830E-04	0.830E-04	0.830E-04	0.830E-04	0.830E-04
0.139E+01	0.119E+01	0.754E+00	0.391E+00	0.194E+00	0.102E+00
0.579E-01	0.302E-01	0.124E-01	0.238E-02	0.830E-04	0.830E-04
0.830E-04	0.830E-04	0.830E-04	0.830E-04	0.830E-04	0.830E-04
0.125E+01	0.946E+00	0.525E+00	0.266E+00	0.125E+00	0.659E-01
0.326E-01	0.138E-01	0.317E-02	0.830E-04	0.830E-04	0.830E-04
0.830E-04	0.830E-04	0.830E-04	0.830E-04	0.830E-04	0.830E-04
0.144E+01	0.392E+00	0.489E+00	0.224E+00	0.102E+00	0.492E-01
0.191E-01	0.497E-02	0.750E-04	0.750E-04	0.750E-04	0.750E-04
0.750E-04	0.750E-04	0.750E-04	0.750E-04	0.750E-04	0.750E-04
0.117E+01	0.766E+00	0.377E+00	0.161E+00	0.703E-01	0.317E-01
0.106E-01	0.136E-02	0.529E-04	0.529E-04	0.529E-04	0.529E-04
0.529E-04	0.529E-04	0.529E-04	0.529E-04	0.529E-04	0.529E-04
0.967E+00	0.60E+00	0.290E+00	0.194E+00	0.129E+00	0.185E-01
0.400E-02	0.529E-04	0.529E-04	0.529E-04	0.529E-04	0.529E-04
0.529E-04	0.529E-04	0.529E-04	0.529E-04	0.529E-04	0.529E-04
0.777E+00	0.459E+00	0.208E+00	0.157E+00	0.113E+00	0.798E-02
0.529E-04	0.529E-04	0.529E-04	0.529E-04	0.529E-04	0.529E-04
0.529E-04	0.529E-04	0.529E-04	0.529E-04	0.529E-04	0.529E-04
0.629E+00	0.362E+00	0.152E+00	0.529E-01	0.172E-01	0.268E-02
0.529E-04	0.529E-04	0.529E-04	0.529E-04	0.529E-04	0.529E-04
0.529E-04	0.529E-04	0.529E-04	0.529E-04	0.529E-04	0.529E-04
0.493E+00	0.283E+00	0.106E+00	0.357E-01	0.930E-02	0.529E-04
0.529E-04	0.529E-04	0.529E-04	0.529E-04	0.529E-04	0.529E-04
0.529E-04	0.529E-04	0.529E-04	0.529E-04	0.529E-04	0.529E-04
0.379E+00	0.210E+00	0.713E-01	0.238E-01	0.534E-02	0.529E-04
0.529E-04	0.529E-04	0.529E-04	0.529E-04	0.529E-04	0.529E-04
0.529E-04	0.529E-04	0.529E-04	0.529E-04	0.529E-04	0.529E-04
0.265E+00	0.137E+00	0.370E-01	0.119E-01	0.135E-02	0.529E-04
0.529E-04	0.529E-04	0.529E-04	0.529E-04	0.529E-04	0.529E-04
0.529E-04	0.529E-04	0.529E-04	0.529E-04	0.529E-04	0.529E-04

```
Angles start at 0.5 degree increment by 1 degree 18 steps
Momenta start at 0.5 Gev, increment by 1 Gev 18 steps
```

0.376E+00	0.365E+00	0.341E+00	0.314E+00	0.288E+00	0.254E+00
0.243E+00	0.228E+00	0.218E+00	0.199E+00	0.178E+00	0.166E+00
0.155E+00	0.142E+00	0.131E+00	0.122E+00	0.113E+00	0.103E+00
0.150E+01	0.147E+01	0.138E+01	0.127E+01	0.114E+01	0.100E+01
0.875E+00	0.784E+00	0.684E+00	0.588E+00	0.499E+00	0.438E+00
0.384E+00	0.332E+00	0.294E+00	0.265E+00	0.240E+00	0.215E+00
0.285E+01	0.277E+01	0.259E+01	0.231E+01	0.198E+01	0.163E+01
0.132E+01	0.103E+01	0.798E+00	0.627E+00	0.468E+00	0.357E+00
0.277E+00	0.207E+00	0.156E+00	0.123E+00	0.102E+00	0.798E-01
0.227E+01	0.217E+01	0.205E+01	0.167E+01	0.177E+01	0.135E+01
0.100E+01	0.698E+00	0.479E+00	0.341E+00	0.223E+00	0.152E+00
0.110E+00	0.743E-01	0.523E-01	0.357E-01	0.220E-01	0.931E-02
0.168E+01	0.113E+01	0.996E+00	0.108E+01	0.110E+01	0.779E+00
0.525E+00	0.342E+00	0.207E+00	0.127E+00	0.768E-01	0.456E-01
0.291E-01	0.166E-01	0.105E-01	0.627E-02	0.213E-02	0.830E-04
0.205E+01	0.148E+01	0.116E+01	0.117E+01	0.798E+00	0.509E+00
0.299E+00	0.170E+00	0.930E-01	0.519E-01	0.249E-01	0.105E-01
0.627E-02	0.213E-02	0.830E-04	0.830E-04	0.830E-04	0.830E-04
0.188E+01	0.173E+01	0.134E+01	0.888E+00	0.554E+00	0.305E+00
0.156E+00	0.768E-01	0.373E-01	0.166E-01	0.421E-02	0.830E-04
0.830E-04	0.830E-04	0.830E-04	0.830E-04	0.830E-04	0.830E-04
0.173E+01	0.151E+01	0.110E+01	0.681E+00	0.384E+00	0.189E+00
0.871E-01	0.294E-01	0.187E-01	0.627E-02	0.830E-04	0.830E-04
0.830E-04	0.830E-04	0.830E-04	0.830E-04	0.830E-04	0.830E-04
0.152E+01	0.126E+01	0.838E+00	0.477E+00	0.234E+00	0.104E+00
0.436E-01	0.187E-01	0.830E-02	0.213E-02	0.830E-04	0.830E-04
0.830E-04	0.830E-04	0.830E-04	0.830E-04	0.830E-04	0.830E-04
0.132E+01	0.105E+01	0.647E+00	0.334E+00	0.143E+00	0.581E-01
0.228E-01	0.830E-02	0.213E-02	0.830E-04	0.830E-04	0.830E-04
0.830E-04	0.830E-04	0.830E-04	0.830E-04	0.830E-04	0.830E-04
0.104E+01	0.780E+00	0.448E+00	0.214E+00	0.825E-01	0.319E-01
0.112E-01	0.193E-02	0.750E-04	0.750E-04	0.750E-04	0.750E-04
0.750E-04	0.750E-04	0.750E-04	0.750E-04	0.750E-04	0.750E-04
0.603E+00	0.426E+00	0.225E+00	0.952E-01	0.325E-01	0.117E-01
0.993E-02	0.520E-04	0.520E-04	0.520E-04	0.520E-04	0.520E-04
0.520E-04	0.520E-04	0.520E-04	0.520E-04	0.520E-04	0.520E-04
0.484E+00	0.327E+00	0.160E+00	0.582E-01	0.182E-01	0.520E-02
0.134E-02	0.520E-04	0.520E-04	0.520E-04	0.520E-04	0.520E-04
0.520E-04	0.520E-04	0.520E-04	0.520E-04	0.520E-04	0.520E-04
0.387E+00	0.247E+00	0.112E+00	0.351E-01	0.910E-02	0.134E-02
0.520E-04	0.520E-04	0.520E-04	0.520E-04	0.520E-04	0.520E-04
0.520E-04	0.520E-04	0.520E-04	0.520E-04	0.520E-04	0.520E-04
0.302E+00	0.185E+00	0.770E-01	0.208E-01	0.393E-02	0.520E-04
0.520E-04	0.520E-04	0.520E-04	0.520E-04	0.520E-04	0.520E-04
0.520E-04	0.520E-04	0.520E-04	0.520E-04	0.520E-04	0.520E-04
0.234E+00	0.139E+00	0.507E-01	0.117E-01	0.134E-02	0.520E-04
0.520E-04	0.520E-04	0.520E-04

ν_μ FLUX / m² / GeV / 10¹³ PROTONS ON TARGET

ν_e FLUX / m² / GeV / 10¹³ PROTONS ON TARGET

ν_μ FLUX / $\text{m}^2/\text{GeV}/10^{13}$ PROTONS ON TARGET