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# Neutrino fluxes from a conventional neutrino beam using CERN SPL

A. Blondel<sup>a</sup>, M. Donegà<sup>b1</sup>, S. Gilardoni <sup>a2</sup>

<sup>a</sup> Département de Physique, Université de Genève, Switzerland

<sup>b</sup> Dipartimento di fisica, Università degli studi di Milano

## Abstract

This note describes a possible low energy neutrino beam from a horn-focused pion beam generated by 2.2 GeV protons.

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<sup>1</sup>Erasmus student at the Université de Genève and CERN

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# 1 Introduction

It has been suggested that a conventional low energy neutrino beam from pion decay could be used to study neutrino oscillations [1], [2]. Based on the horn study for pion collection for the neutrino factory [3],[4], the fluxes of neutrinos are calculated here for a decay tunnel of 1 meter radius and 5 to 30 meter length. The SPL proton energy of 2.2 GeV (kinetic energy) was assumed.

The advantage of the low energy proton beam is that strange particle production is negligible.

# 2 System configuration

Pions are produced from a proton beam of 2.2 GeV (kinetic energy) impinging on a Hg target and focused with a magnetic horn (see Figure 1).

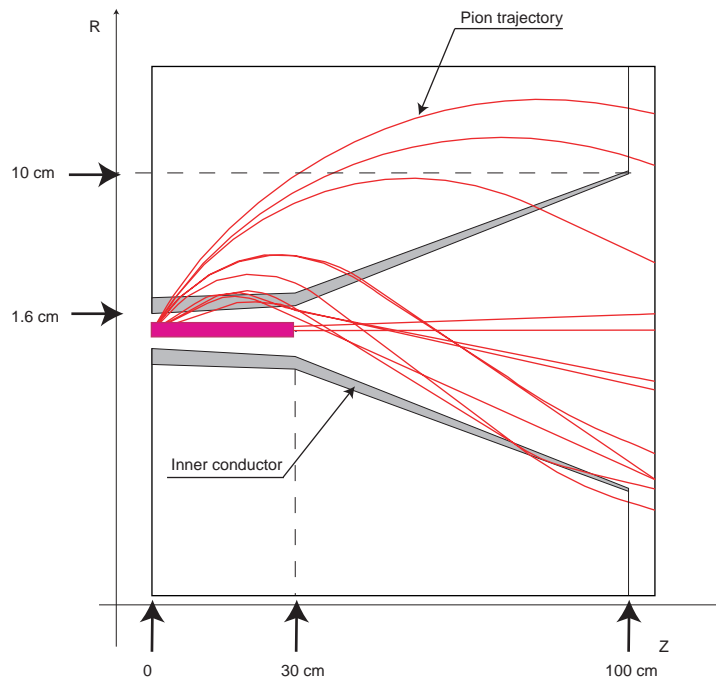


Figure 1: Focusing system

The magnetic horn focuses only  $\pi^+$ , while  $\pi^-$  are defocused (and vice-versa reversing the current in the horn). Pions and muons decay in a cylindrical decay tunnel of 1 meter radius and 5 to 30 meters length. The fluxes are calculated considering a detector of area  $A=10 \text{ m} \times 10 \text{ m} = 100 \text{ m}^2$  at a distance  $L= 50 \text{ km}$ . This solid angle is so small that the flux for different (long) distances can be assumed to scale as  $A/L^2$ .

Pions are generated and tracked by MARS [5].

Instead of a Monte Carlo simulation, an analytical expression of the decay probabilities has been calculated for both pion and subsequent muon decay and for the probability of neutrinos to reach the detector. Muon polarisation has been neglected for this first evaluation.

### 3 Neutrinos from Pions

Each pion is first propagated through the horn (pion decays in the focusing system are not accounted for). The probability to decay in the decay tunnel is then calculated. Finally the probability that the neutrino coming from that pion reaches the detector is evaluated.

As soon as the particle reaches the walls of the decay tunnel, it is assumed to be absorbed, and no further decay is considered. Since pion decay is a two body process only one set of centre of mass decay angle produces a neutrino that reaches the far detector. The analytical formula for the probability that a pion with a certain angle and energy produces a neutrino that reaches the detector is given below. It is assumed that the proton beam and the decay tunnel are in line with the detector and the target. The tunnel radius and length are considered small with respect to the target-detector distance.

$$P(\alpha, \beta) = \frac{1}{4\pi} \left( \frac{A}{L^2} \right) \frac{1-\beta^2}{(\beta \cos \alpha - 1)^2}$$

$\alpha$  = angle between pion trajectory and decay tunnel-detector axis

$\beta$  = speed of the pion (in speed of light units)

A = detector area

L = distance between decay tunnel and detector

## 4 Neutrinos from Muons

Muon decay is a three body process and there is a family of neutrinos of different energies that can reach the detector. The muons produced in pion decay produce neutrinos from the process  $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ . The calculation of the flux requires integration over the following variables:

- pion decay angles  $\theta$  and  $\varphi$
- pion decay length
- neutrino energy in the muon rest frame.

This integration is performed by uniform sampling. Once these are determined, there is only one set of neutrino angles in the muon rest frame for which the neutrino reaches the detector, and the probability that the muons decay before reaching the walls of the decay tunnel can be readily calculated. The analytical formula for the probability density that a muon with a certain angle and energy produces a  $\nu_e$  or a  $\bar{\nu}_\mu$  that reaches the detector is as follows. It is still assumed that the proton beam and the decay tunnel are in line with the detector and the target. The tunnel radius and length are considered small with respect to the target-detector distance.

For  $\mu^+ \rightarrow \nu_e (\bar{\nu}_\mu e^+)$

$$\frac{dP}{dE_\nu L^2 d\cos\theta^* d\varphi} = \frac{6}{2\pi} \frac{A}{L^2} x^2 (1-x) \left( \frac{2}{E_\mu} \frac{1}{1+\beta_\mu \cos\theta_\nu^*} \right) \left( \frac{1-\beta_\mu^2}{(\beta_\mu \cos\delta - 1)^2} \right)$$

For  $\mu^+ \rightarrow \bar{\nu}_\mu (\nu_e e^+)$

$$\frac{dP}{dE_\nu L^2 d\cos\theta^* d\varphi} = \frac{1}{2\pi} \frac{A}{L^2} x^2 (3-2x) \left( \frac{2}{E_\mu} \frac{1}{1+\beta_\mu \cos\theta_\nu^*} \right) \left( \frac{1-\beta_\mu^2}{(\beta_\mu \cos\delta - 1)^2} \right)$$

with

$$x = \frac{2E_\nu}{E_\mu} \frac{1}{1+\beta_\mu \cos\theta_\nu^*}$$

$\delta$  = angle between muon trajectory and decay tunnel-detector axis

$\beta_\mu$  = speed of the muon (in speed of light units)

A = detector area

L = distance between decay tunnel and detector

$\theta_\nu^*$  = angle of the emitted neutrino in the centre of mass of the muon decay

$E_\mu, E_\nu$  = muon and neutrino energies in the laboratory frame

## 5 Results

### 5.1 Fluxes for a 30 meter long decay tunnel

Figures 2,3,4,5,6,7, are the fluxes of neutrinos reaching a 100 m<sup>2</sup> detector situated at 50 km from the target for a decay tunnel of 30 m length, and a proton beam of 2.2 GeV kinetic energy impinging on a Hg target. The fluxes of neutrinos per 20 MeV bin are given for 10<sup>23</sup> protons (i.e. the number of protons given by the SPL for one year).

### 5.2 Fluxes for a 5 meter long decay tunnel

Figure 8,9,10,11,12,13, are the fluxes of neutrinos reaching a 100 m<sup>2</sup> detector situated at 50 km from the target for a decay tunnel of 5m length, and a proton beam of 2.2 GeV kinetic energy impinging on a Hg target. The fluxes of neutrinos per 20 MeV bin are given for 10<sup>23</sup> protons (i.e. the number of protons given by the SPL for one year).

### 5.3 Event number

In order to illustrate the sensitivity of such a beam for a search of  $\nu_\mu \rightarrow \nu_e$  oscillations we give in Table 5.3 the number of events making the (unphysical) assumptions that:

- all  $\nu_\mu$  oscillates to  $\nu_e$
- $\nu_e$  do not oscillate

The cross section used is  $0.710^{-38} \text{ (cm}^2 \text{ /GeV) } E_\nu \text{ (GeV)}$  which is a reasonable approximation of the  $\nu_e n \rightarrow e^- p$  cross section in the relevant energy range. Events number are calculated for neutrinos reaching a 1 kT detector situated at 50 km from the target, considering 10<sup>23</sup> protons.

length of decay tunnel	30 m	20 m	10 m	5 m
$\nu_\mu \rightarrow \nu_e$ from $\pi^+$ decay	259	219	145	84
$\nu_e$ from $\mu^+$ decay	1.2	0.7	0.3	0.08
Ratio	$4.5 \cdot 10^{-3}$	$3.3 \cdot 10^{-3}$	$1.8 \cdot 10^{-3}$	$0.9 \cdot 10^{-3}$

Table 1: Number of events for different decay tunnel lengths.

It can be seen that the contamination of the  $\nu_e$  from the beam can be controlled and reduced below  $10^{-3}$  by reducing the length of the decay tunnel.

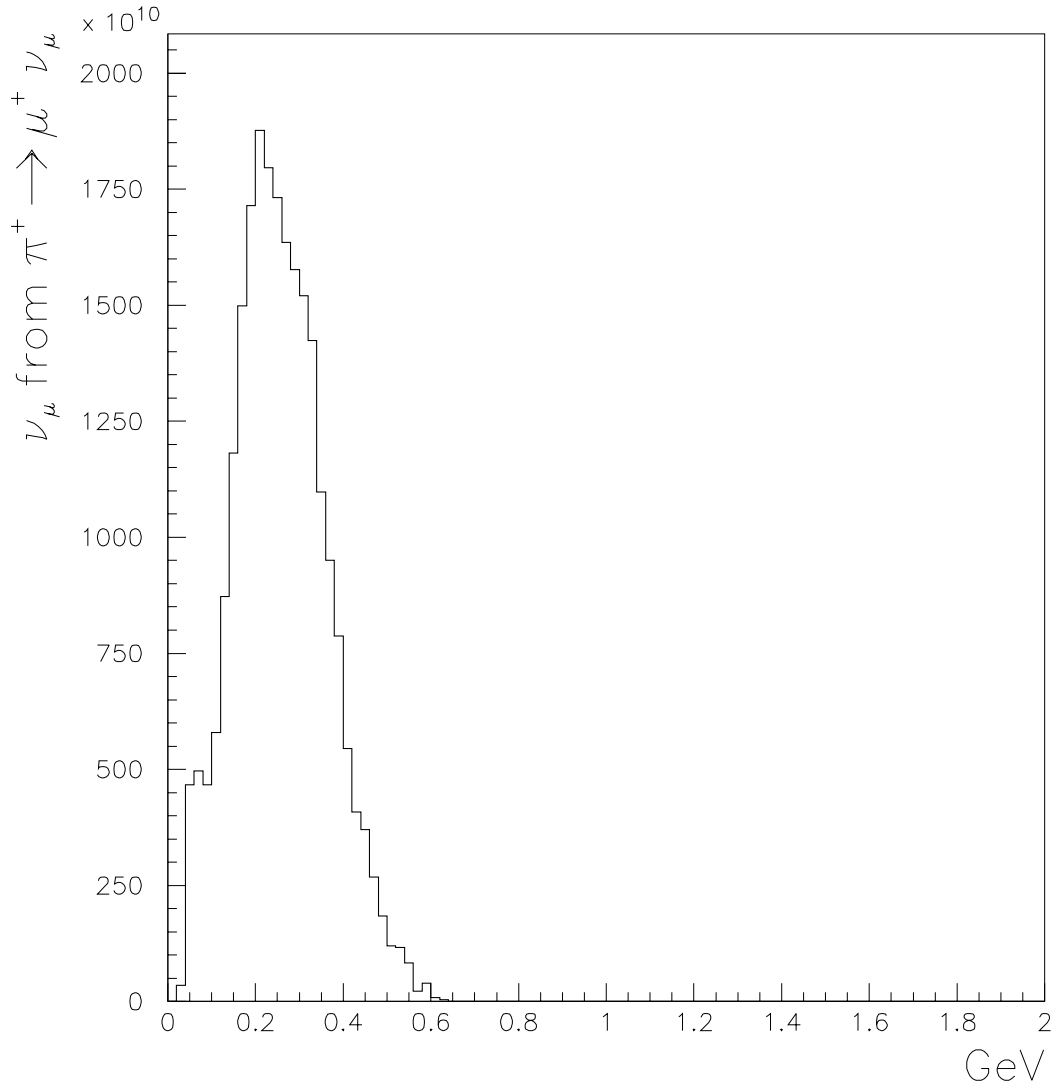


Figure 2:  $\nu_\mu$  from pion decay ( $\pi^+ \rightarrow \mu^+ \nu_\mu$ ). Flux of neutrinos reaching a 100 m<sup>2</sup> detector situated at 50 km from the target for a decay tunnel of 30 m length, and a proton beam of 2.2 GeV kinetic energy impinging on a Hg target. The flux of neutrinos per 20 MeV bin is given for  $10^{23}$  protons.

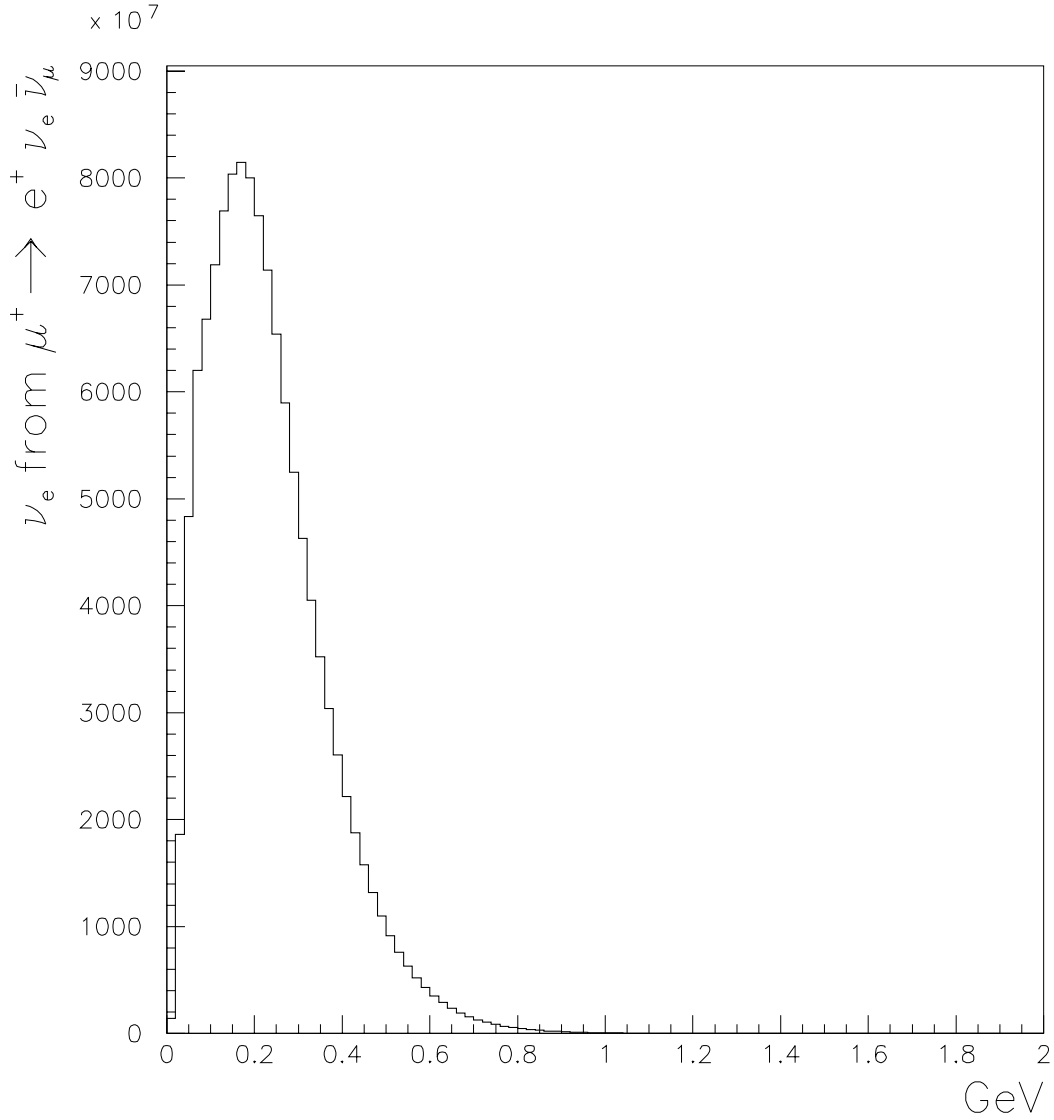


Figure 3:  $\nu_e$  from muon decay ( $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ ). Flux of neutrinos reaching a  $100 \text{ m}^2$  detector situated at 50 km from the target for a decay tunnel of 30 m length, and a proton beam of 2.2 GeV kinetic energy impinging on a Hg target. The flux of neutrinos per 20 MeV bin is given for  $10^{23}$  protons.

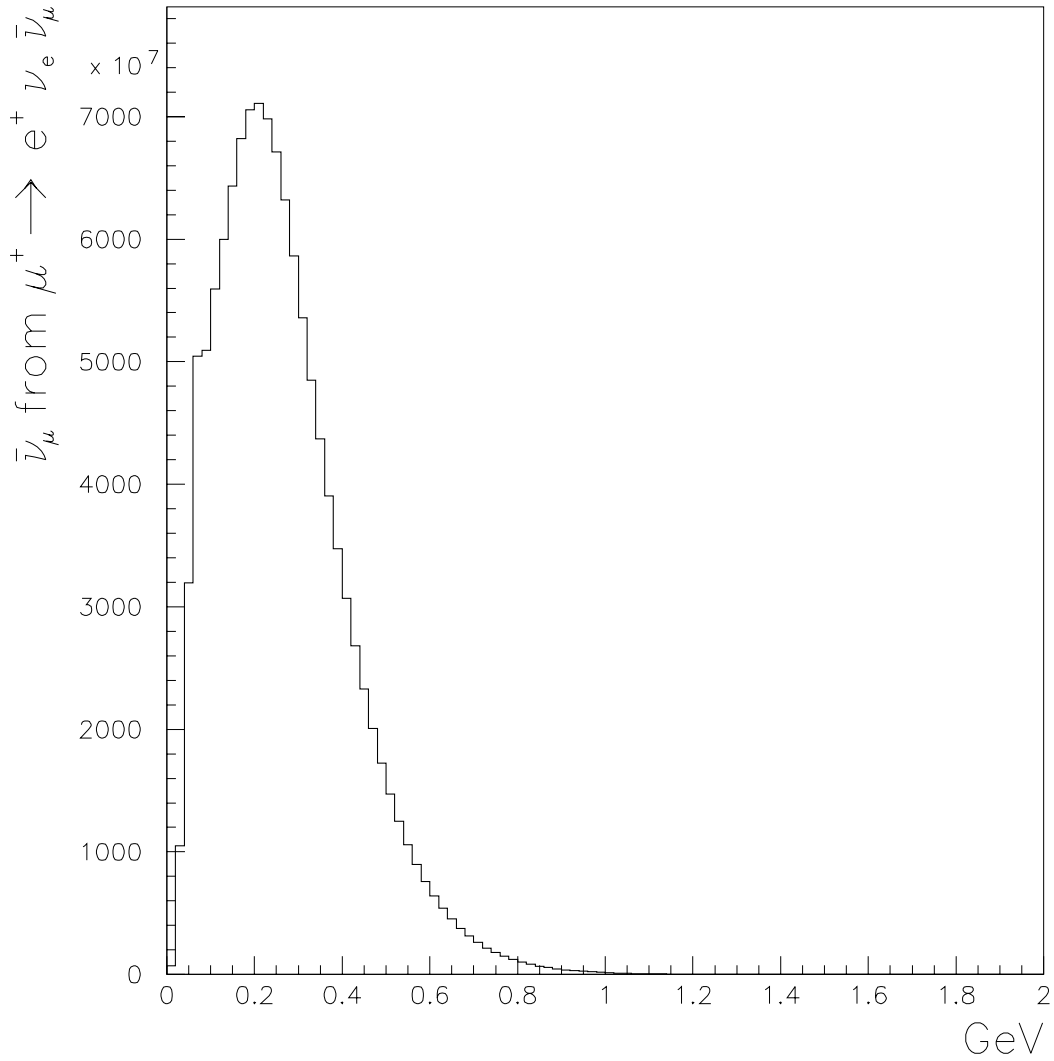


Figure 4:  $\bar{\nu}_\mu$  from muon decay ( $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ ). Flux of neutrinos reaching a 100 m<sup>2</sup> detector situated at 50 km from the target for a decay tunnel of 30 m length, and a proton beam of 2.2 GeV kinetic energy impinging on a Hg target. The flux of neutrinos per 20 MeV bin is given for  $10^{23}$  protons.



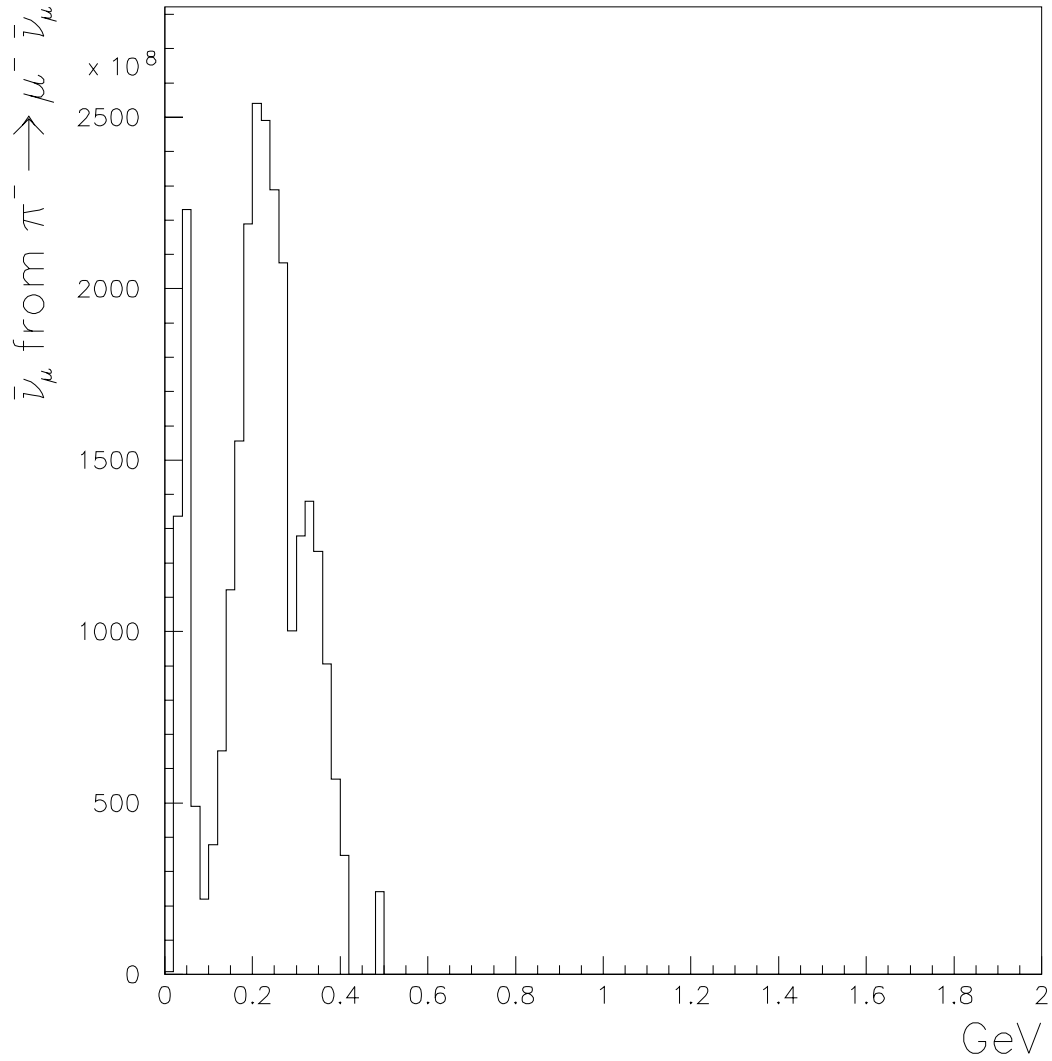


Figure 5:  $\bar{\nu}_\mu$  from pion decay ( $\pi^- \rightarrow \mu^- \bar{\nu}_\mu$ ). Flux of neutrinos reaching a 100 m<sup>2</sup> detector situated at 50 km from the target for a decay tunnel of 30 m length, and a proton beam of 2.2 GeV kinetic energy impinging on a Hg target. The flux of neutrinos per 20 MeV bin is given for  $10^{23}$  protons.

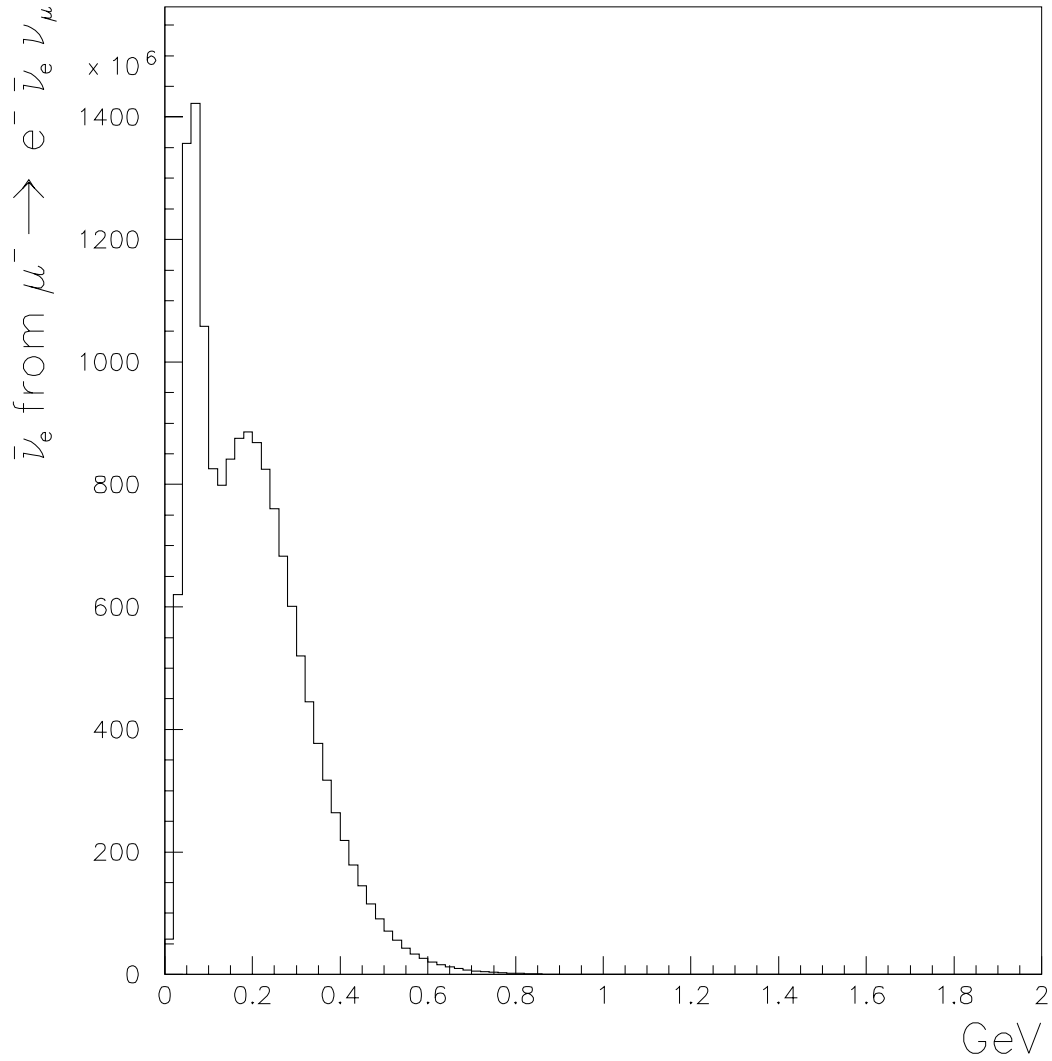


Figure 6:  $\bar{\nu}_e$  from muon decay ( $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$ ). Flux of neutrinos reaching a 100 m<sup>2</sup> detector situated at 50 km from the target for a decay tunnel of 30 m length, and a proton beam of 2.2 GeV kinetic energy impinging on a Hg target. The flux of neutrinos per 20 MeV bin is given for  $10^{23}$  protons.

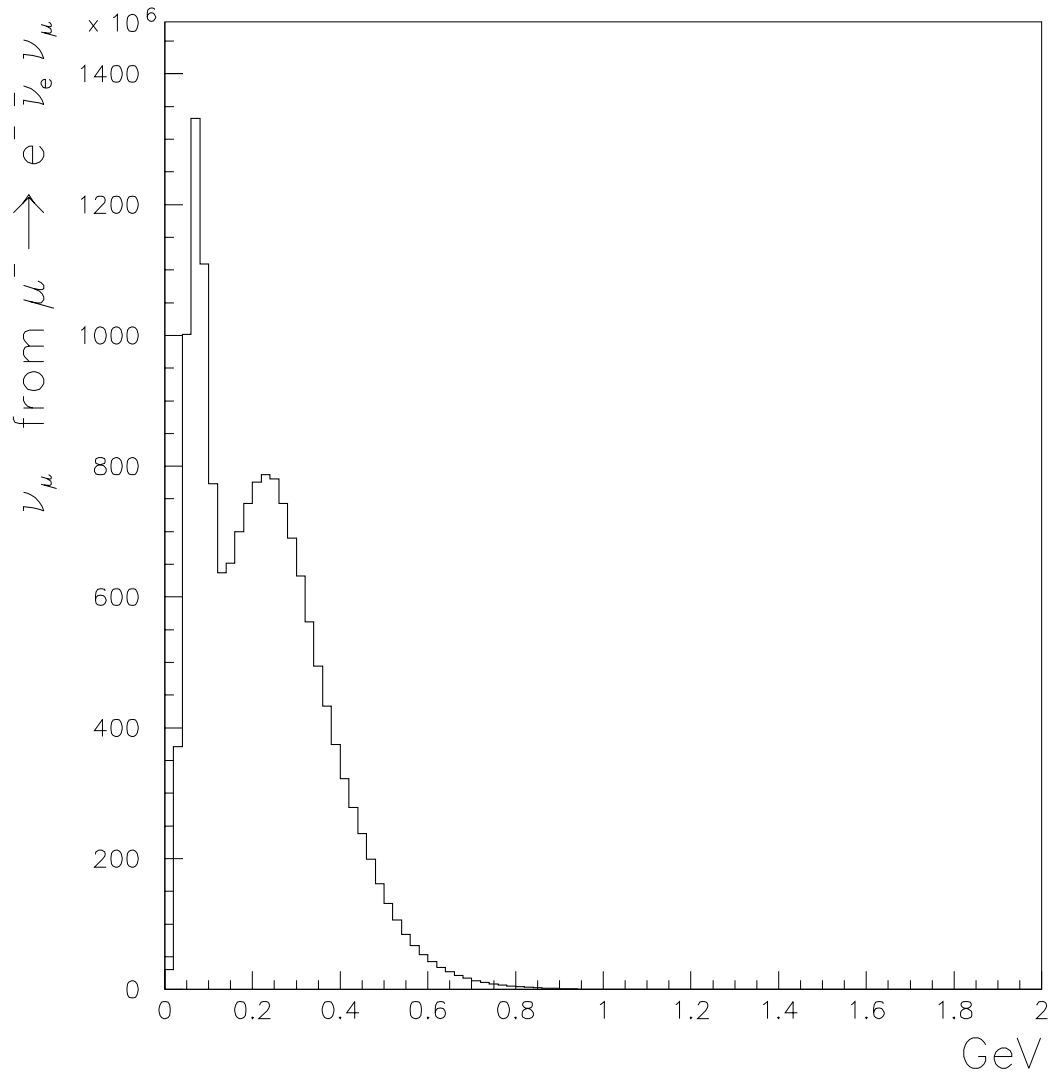


Figure 7:  $\nu_\mu$  from muon decay ( $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$ ). Flux of neutrinos reaching a  $100 \text{ m}^2$  detector situated at 50 km from the target for a decay tunnel of 30 m length, and a proton beam of 2.2 GeV kinetic energy impinging on a Hg target. The flux of neutrinos per 20 MeV bin is given for  $10^{23}$  protons.

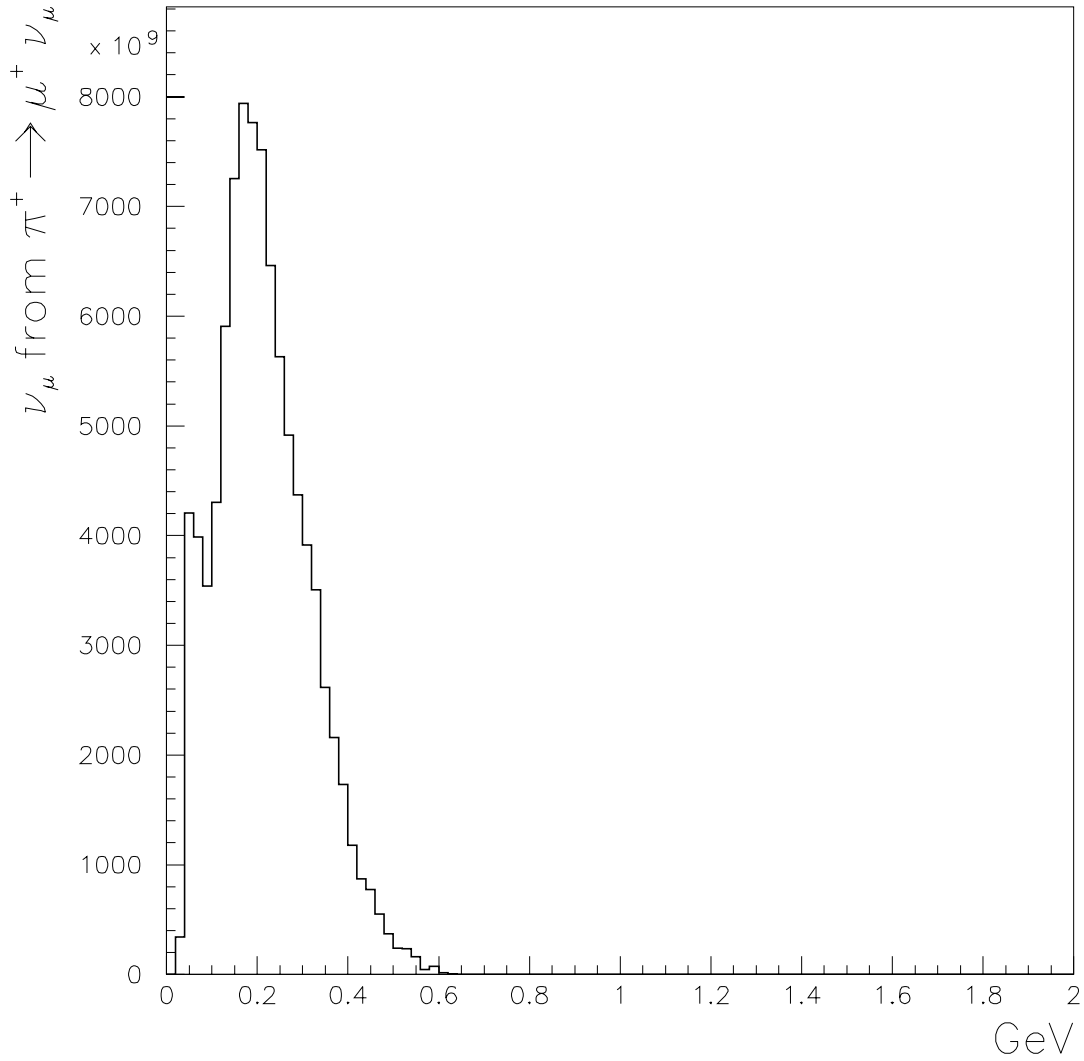


Figure 8:  $\nu_\mu$  from pion decay ( $\pi^+ \rightarrow \mu^+ \nu_\mu$ ). Flux of neutrinos reaching a 100 m<sup>2</sup> detector situated at 50 km from the target for a decay tunnel of 5 m length, and a proton beam of 2.2 GeV kinetic energy impinging on a Hg target. The flux of neutrinos per 20 MeV bin is given for  $10^{23}$  protons.

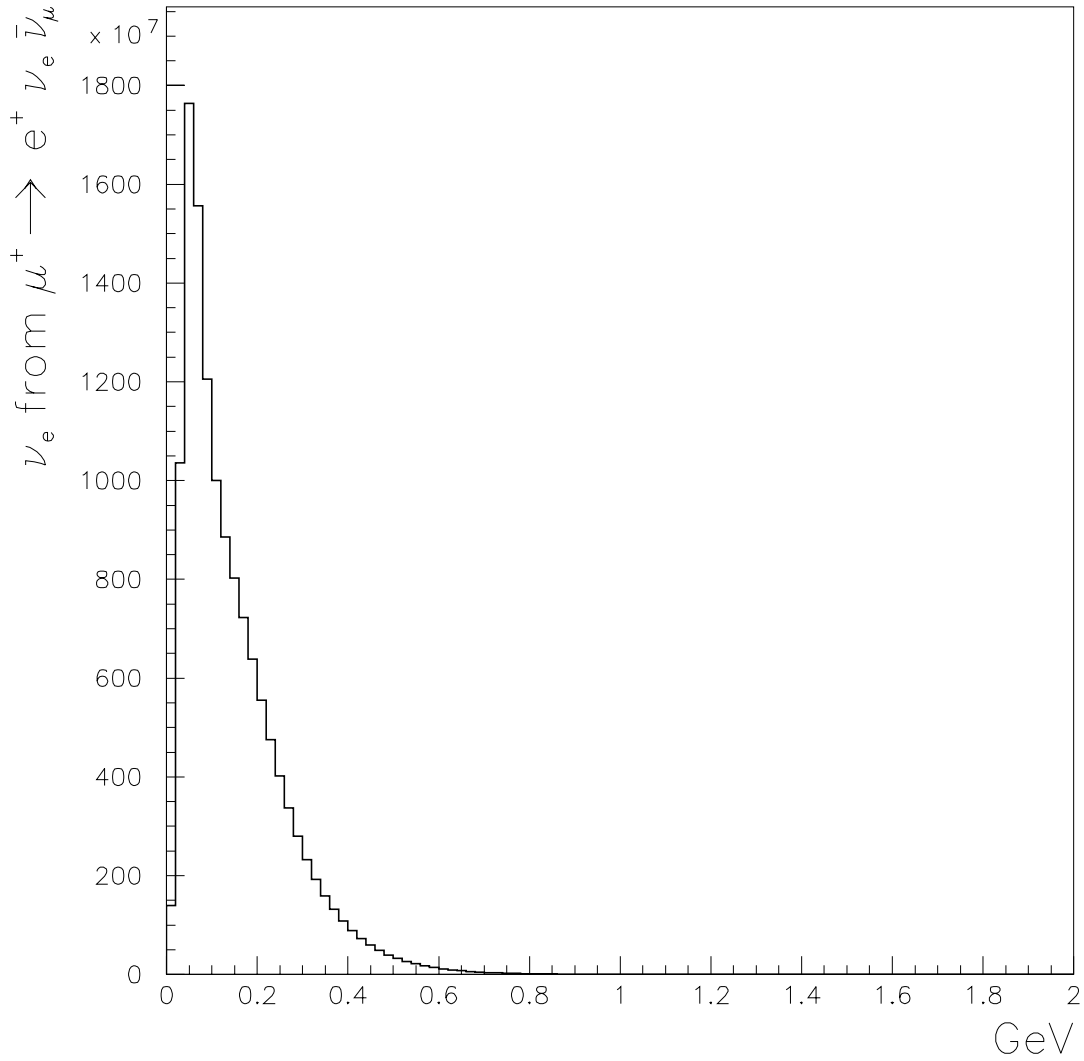


Figure 9:  $\nu_e$  from muon decay ( $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ ). Flux of neutrinos reaching a  $100 \text{ m}^2$  detector situated at 50 km from the target for a decay tunnel of 5 m length, and a proton beam of 2.2 GeV kinetic energy impinging on a Hg target. The flux of neutrinos per 20 MeV bin is given for  $10^{23}$  protons.

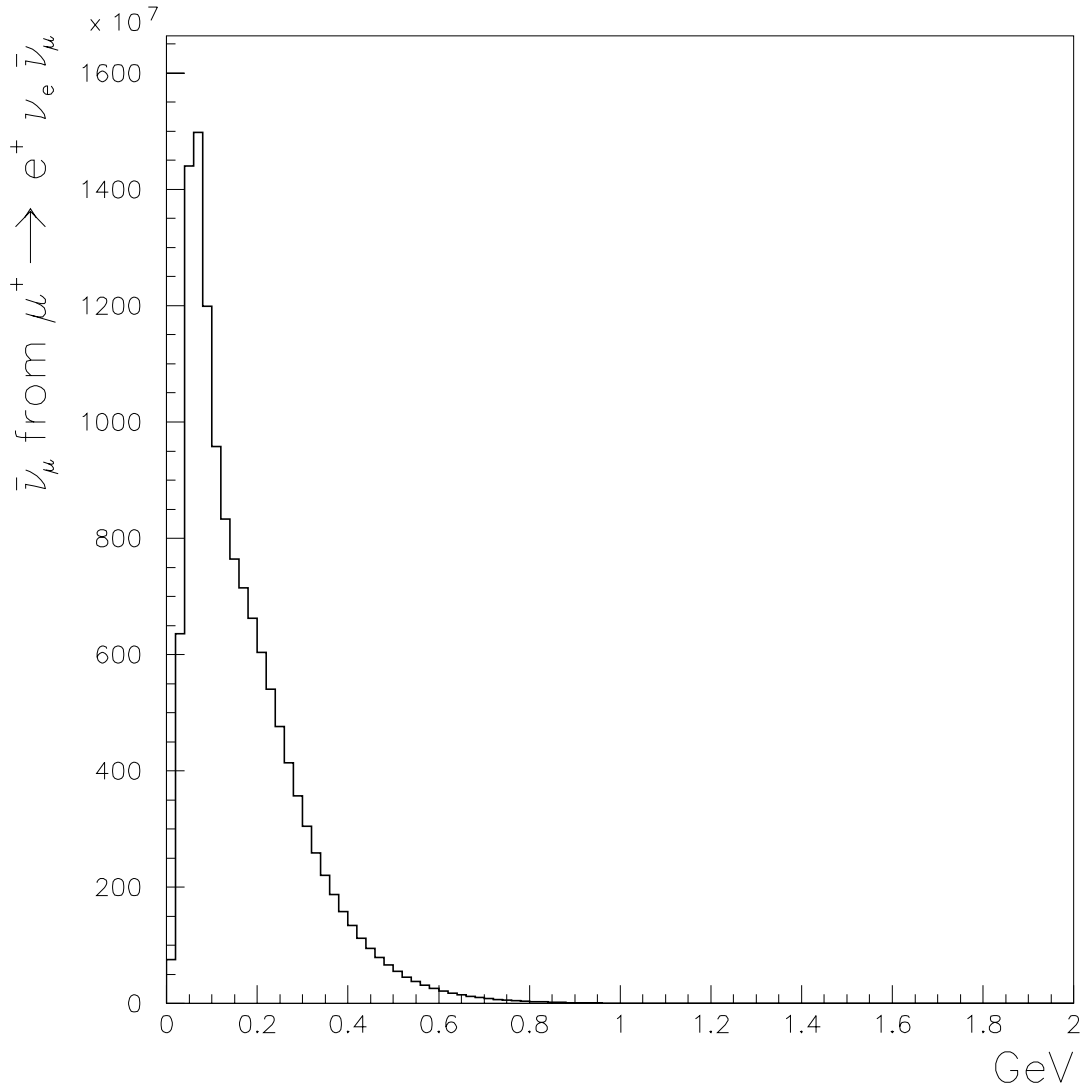


Figure 10:  $\bar{\nu}_\mu$  from muon decay ( $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ ). Flux of neutrinos reaching a  $100 \text{ m}^2$  detector situated at 50 km from the target for a decay tunnel of 5 m length, and a proton beam of 2.2 GeV kinetic energy impinging on a Hg target. The flux of neutrinos per 20 MeV bin is given for  $10^{23}$  protons.

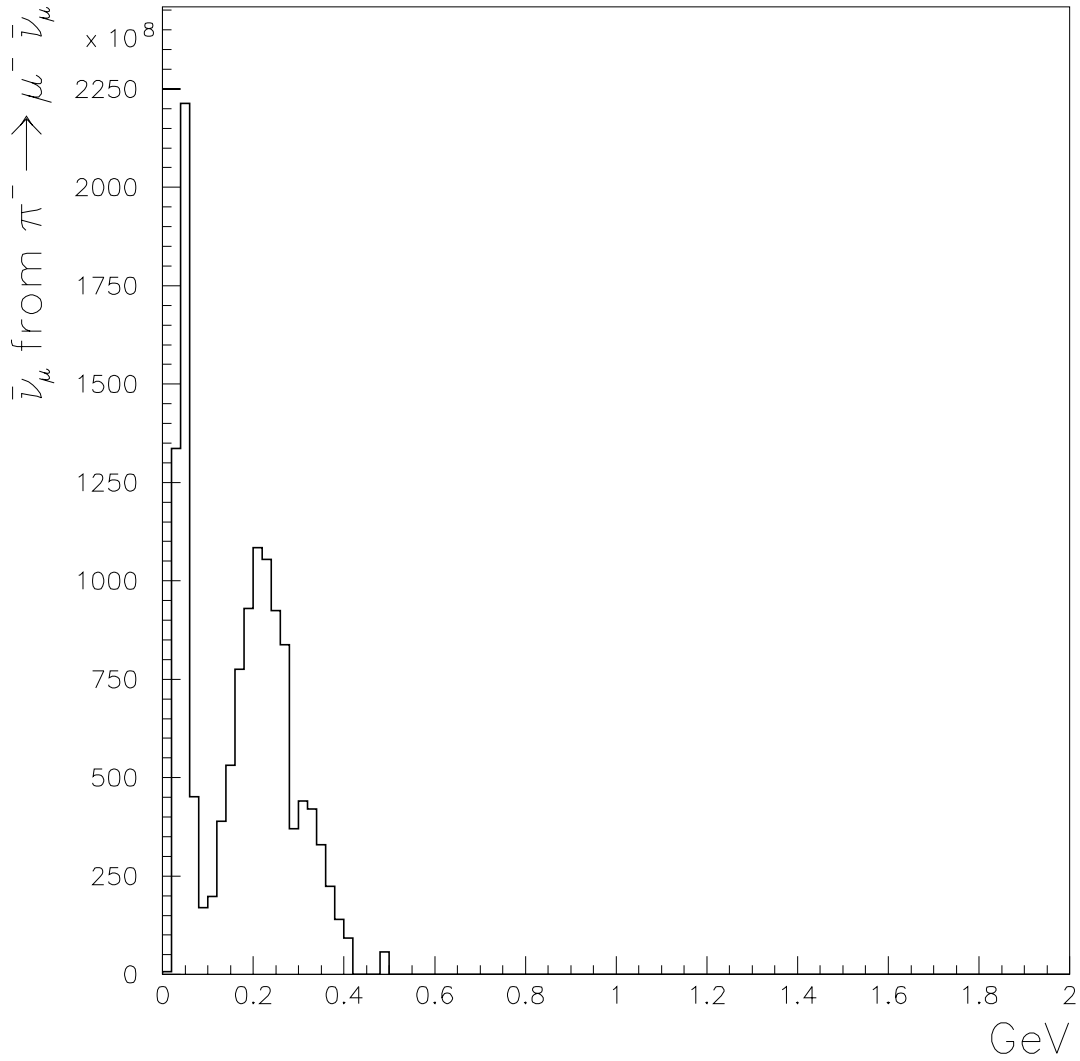


Figure 11:  $\bar{\nu}_\mu$  from pion decay ( $\pi^- \rightarrow \mu^- \bar{\nu}_\mu$ ). Flux of neutrinos reaching a 100 m<sup>2</sup> detector situated at 50 km from the target for a decay tunnel of 5 m length, and a proton beam of 2.2 GeV kinetic energy impinging on a Hg target. The flux of neutrinos per 20 MeV bin is given for  $10^{23}$  protons.

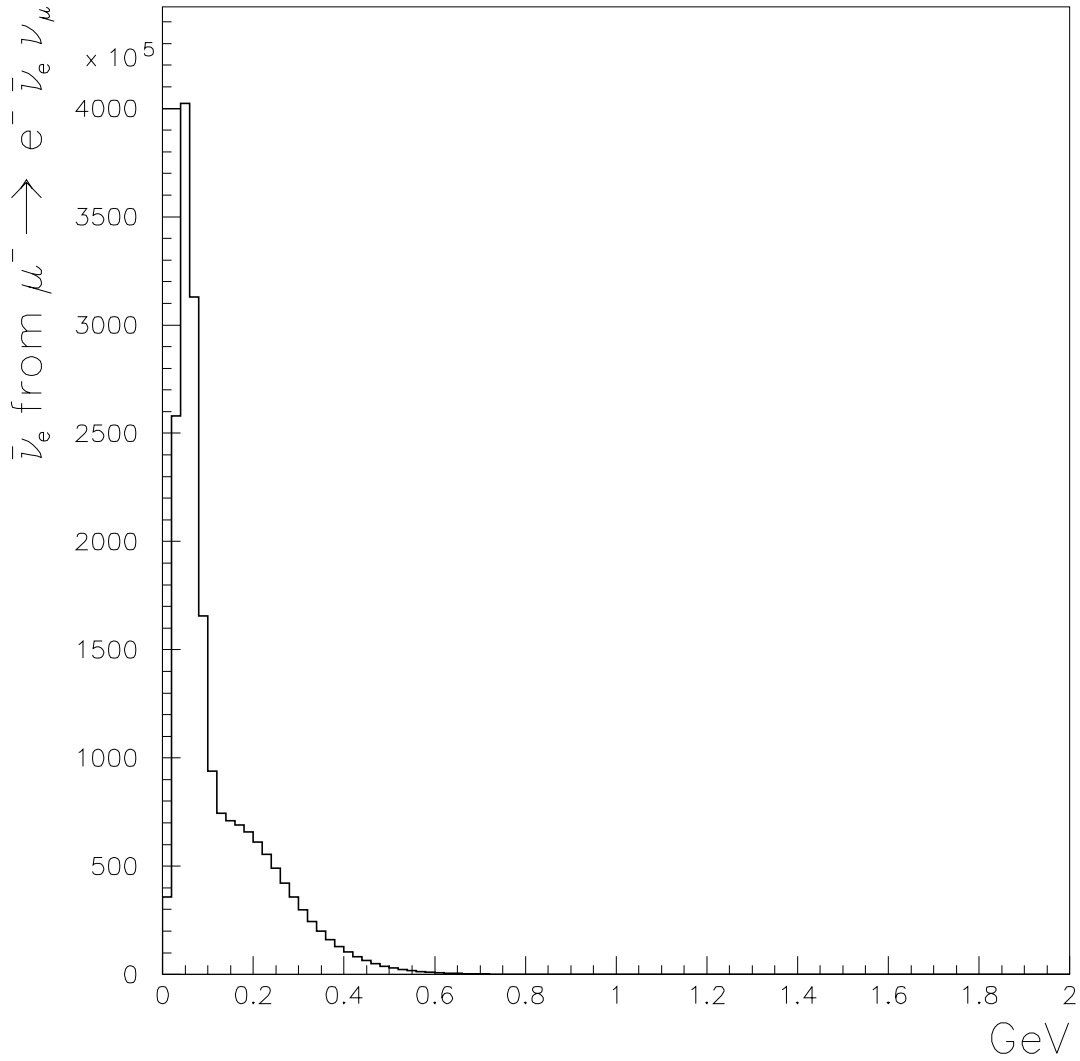


Figure 12:  $\bar{\nu}_e$  from muon decay ( $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$ ). Flux of neutrinos reaching a  $100 \text{ m}^2$  detector situated at 50 km from the target for a decay tunnel of 5 m length, and a proton beam of 2.2 GeV kinetic energy impinging on a Hg target. The flux of neutrinos per 20 MeV bin is given for  $10^{23}$  protons.



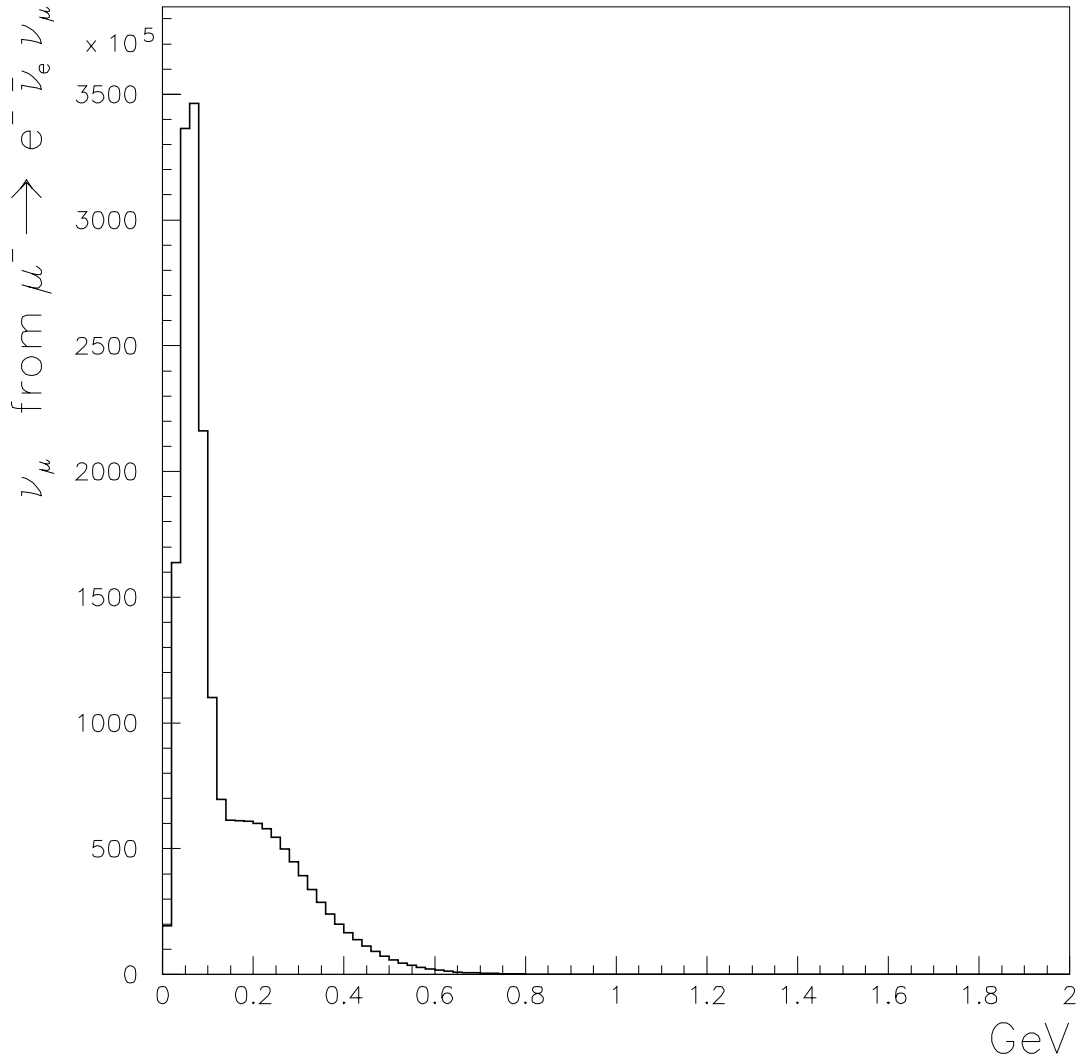


Figure 13:  $\nu_\mu$  from muon decay ( $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$ ). Flux of neutrinos reaching a  $100 \text{ m}^2$  detector situated at 50 km from the target for a decay tunnel of 5 m length, and a proton beam of 2.2 GeV kinetic energy impinging on a Hg target. The flux of neutrinos per 20 MeV bin is given for  $10^{23}$  protons.

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