Comparison of Solenoid and Horn Focusing Systems

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27 July 2006

Introduction

- We have been using a solenoid capture system for capturing pions off the target since we started looking at neutrino factories.
  - The neutrino physicists (that we were talking to) seemed more enamored with *Superbeams.*
  - We had looked at using a solenoid in the place of horns for a superbeam, since we had thought that we could build a neutrino factory as a later stage of an existing superbeam facility.
- At the right is a PAC paper showing one of the early studies.

Proceedings of the 1999 Particle Accelerator Conference, New York, 1999

A Solenoidal Capture System For Neutrino Production *

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Abstract

This paper describes the use of a high field solenoidal magnet to capture secondary pions from the production target. The captured pions subsequentially decay to produce the neutrino beam. A pion capture system using a high field solenoid magnet has been proposed for the muon collider[1]. This technology would also be available for neutrino beam production. It will be shown that a high field solenoid would produce a larger flux of neutrinos with energy, $E_\nu < 1.3\,GeV$, than a neutrino beam produced with a horn system. The $\nu_e, \bar{\nu}_e$ flux contamination in the solenoid neutrino beam is only 0.15%.

1 INTRODUCTION

The recent paper from the Super Kamiokande Collaboration[2] [3] indicating evidence for oscillations of atmospheric neutrinos has created interest in verifying the results with an accelerator based neutrino experiment. The probability of oscillation of one species of neutrino into another is proportional to $sin^2[\frac{1.27\Delta m^2 L}{E_\nu}]$. For oscillations in the small Δm^2 region it is advantageous to have either or both a long distance or small E_ν. A high field solenoid can capture all pions produced from proton interactions on a target up to a transverse momentum, P_T, determined by the field, B_s, and the solenoidal radius, R_s. The pion capture solenoid (currently) proposed for the muon collider has $B_s = 20\ tesla$ and $R_s = 8\ cm$. These parameters would limit the capture to pions with $P_T < 0.225\ GeV/c$ which would keep only 33% of the pions. Since muons from low P_T pions can be more efficiently cooled, these parameters are reasonable for a muon collider. For neutrino production a larger solenoid aperture is preferred.

The solenoid field is 20 tesla in the vicinity of the target. The gradient of field, as it falls off moving away from the target, provides focussing by increasing the longitudinal momentum while decreasing the transverse momentum. The form of the field along the longitudinal axis is

$$B_s(z) = \frac{B_o}{1. + az} \qquad (1)$$

where B_o is the nominal field at the target and a is a parameter that determines $\nabla\vec{B}$ and consequently the focussing. A solenoid tends to focus low momentum pions better than high momentum pions. The ν flux from solenoidally captured pions will dominate the ν flux from a horn beam at low neutrino energy. There is an additional contribution of $\bar{\nu}$ from a solenoid since the solenoid does not sign select as a horn does.

* Work performed under Contract No. DE-AC02-76CH00016 with the U.S. Department of Energy.

2 SIMULATION

A simulation study of solenoid focussed pion beam for ν production was made using GEANT[4]. The GEANT model used in the (now defunct) BNL long baseline experiment[5] was used as a basis. The two horn system in the GEANT model was replaced by the high field solenoid. The solenoid is 20 meters long with the radius varying as

$$R(z) = R_o\sqrt{1 + az} \qquad (2)$$

where R_o is the radius of the solenoid in the vicinity of the target. $R_o = 16\ cm$ is chosen so that all πs with $P_T < 0.45\ GeV/c$ are kept. This aperture will capture 75% of the πs produced. a is chosen to give the proper focussing. Choosing $a = 0.05\ cm^{-1}$ will give a radius of 160 cm at the far end of the solenoid.

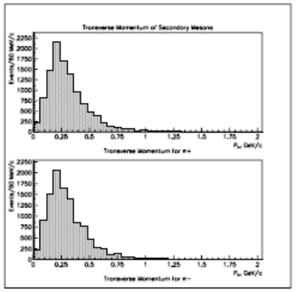


Figure 1: Transverse momentum distribution of secondary pions from the target using the FLUKA option in GEANT. P_T is in GeV/c.

The solenoid for computational purposes is described by a sequence of 100 current rings with radius given by Eq 2 and spacing between the rings as approximately inversely proportional to the field strength. The current in the rings is varied so as to obtain the desired field on the axis. The magnetic field is obtained by summing the contribution from each ring where the field from each ring is calculated from an analytic expression[6]. This procedure for field computation is accurate and manifestly satisfies Maxwell's equation. It does not suffer from the descretation errors that would be present in using a field map for a 20 meter long

0-7803-5573-3/99/$10.00@1999 IEEE. 3023

First Phase Super Neutrino Beam

- Upgrade AGS to 1MW Proton Driver:

Machine	Power	Proton/Pulse	Repetition Rate	Protons/SSC year
Current AGS	0.17 MW	6×10^{13}	0.625 Hz	3.75×10^{20}
AGS Proton Driver	1 MW	1×10^{14}	2.5 Hz	2.5×10^{21}
Japan Hadron Facility	0.77 MW	3.3×10^{14}	0.29 Hz	9.6×10^{20}
Super AGS Prot Driver	4 MW	2×10^{14}	5.0 Hz	1.0×10^{22}

  – Both BNL and JParc have eventual plans for their proton drivers to be upgraded to 4 MW.
- Build Solenoid Capture System:
  – 20 T Magnet surrounding target. Solenoid field falls off to 1.6 T in 20 m.
  – This magnet focuses both π^+ and π^-. Beam will have both ν and $\bar{\nu}$
  – A solenoid is more robust than a horn magnet in a high radiation.
    - A horn may not function in the 4 MW environment.
    - A solenoid will have a longer lifetime since it is not pulsed.

Types of Capture/Focus Systems Considered

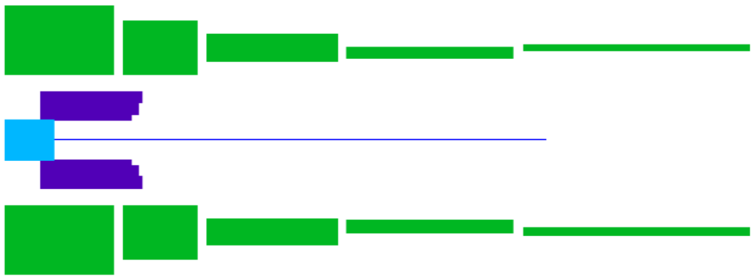
- Traditional Horn Focus System
  - Uses *toroidal* magnetic field.
  - Focuses efficiently
    - $B_\phi \perp p_z$
  - Conductor necessary along access.
    - Concern for radiation damage.
    - Cannot be superconducting.
  - Pulsed horn may have trouble surviving ~10^9 cycles that a 1-4 MW system might require.
- Solenoid Capture System similar to that used by Neutrino Factory
- Solenoid Horn System

Simulations to Calculate Fluxes

- Model Solenoid/Horn Magnet in GEANT. (Geant 3.21)
  - Use Geant/Fluka option for the particle production model.
  - Use 30 cm Hg target (2 interaction lengths.)
    - No target inclination.
      - We want the high momentum component of the pions.
      - Re-absorption of the pions is not a problem.
  - Solenoid Field profile on axis is $B(z)=B_{max}/(1+a\ z)$
    - Independent parameters are B_{max}, B_{min} and the solenoid length, L.
  - Horn Field is assumed to be a toroid.
  - Pions and Kaons are tracked through the field and allowed to decay.
  - Fluxes are tallied at detector positions.
    - The following plots show ν_μ flux and ν_e / ν_μ flux ratios.

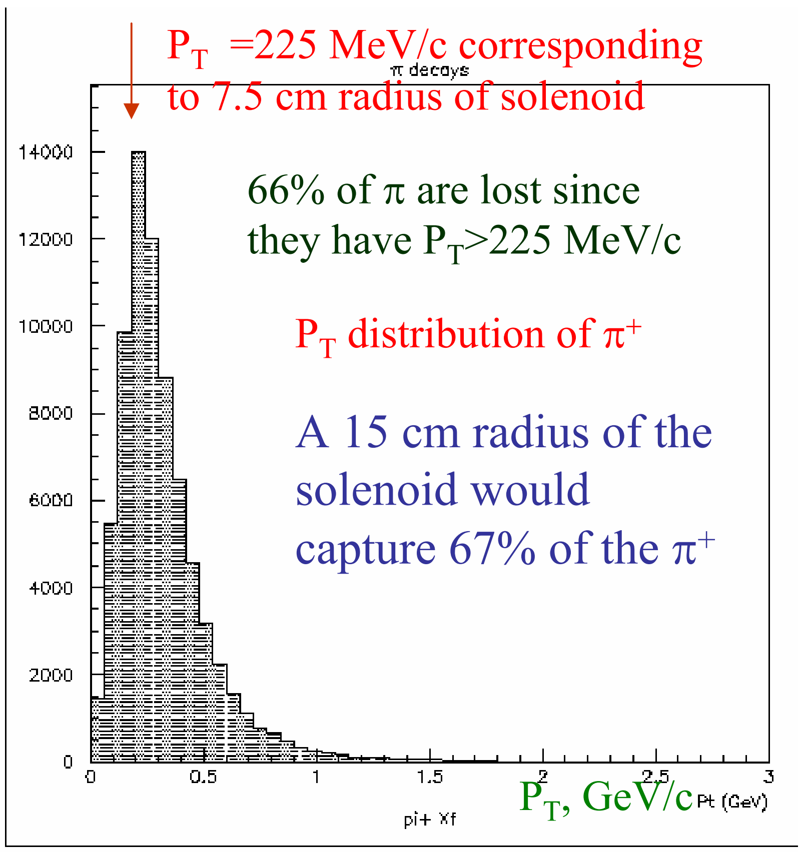
Solenoid Capture

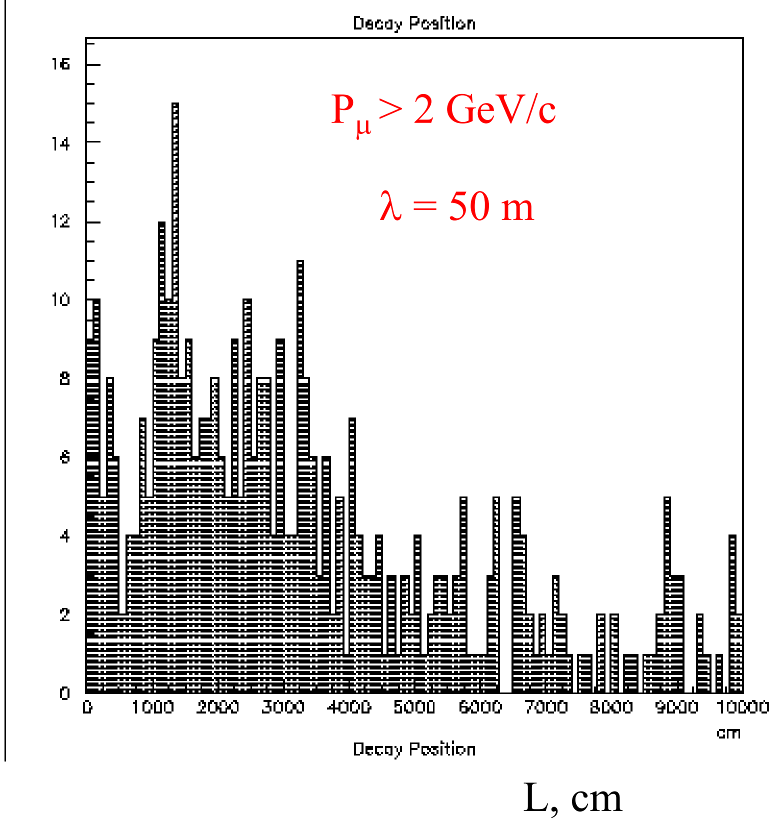
Sketch of solenoid arrangement for Neutrino Factory



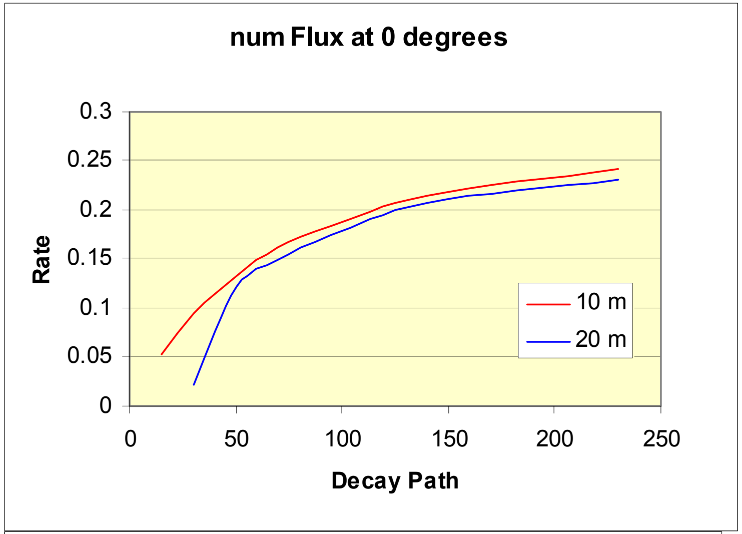
- If only ν and not $\bar{\nu}$ is desired, then a dipole magnet could be inserted between adjacent solenoids above.
- Inserting a dipole also gives control over the mean energy of the neutrino beam.
- Since ν and $\bar{\nu}$ events can be separated with a modest magnetic field in the detector, it will be desirable to collect both signs of ν at the same time.

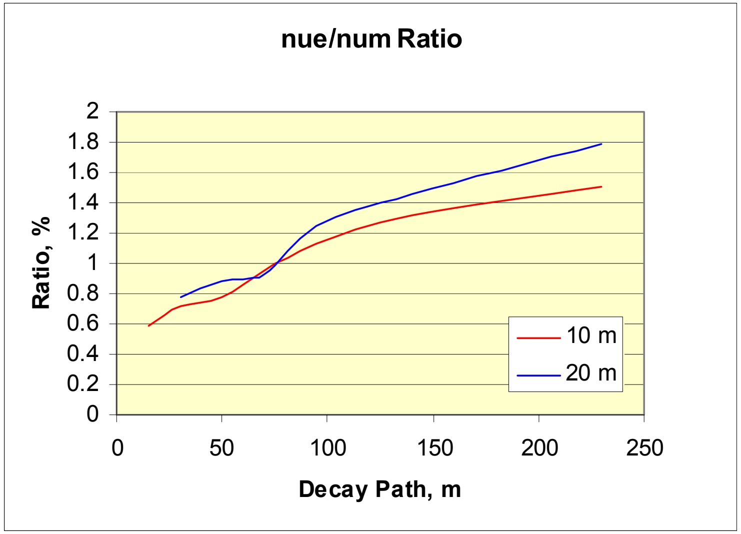
Captured Pion Distributions

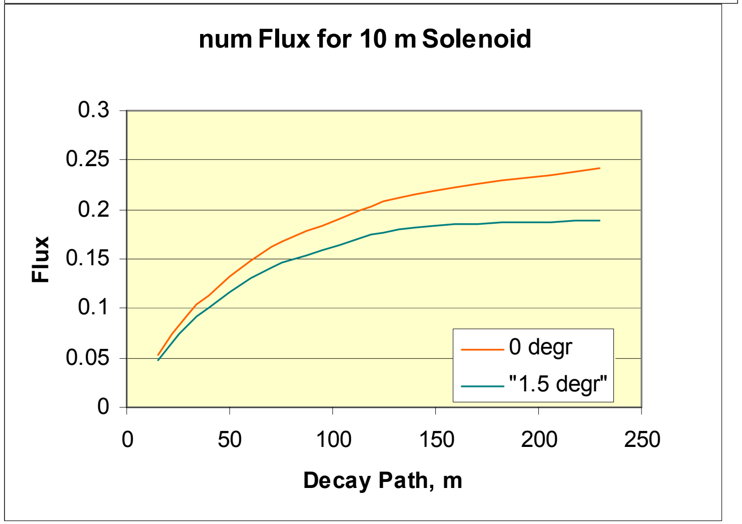


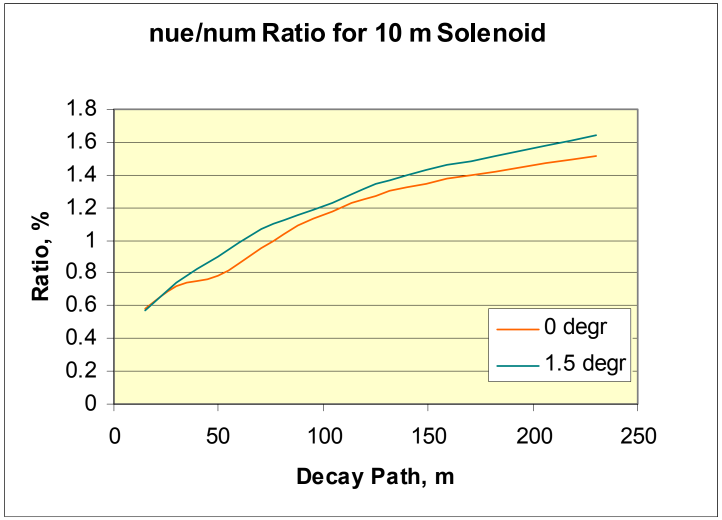


Rate and ν_e/ν_μ as a function of Decay Tunnel Length



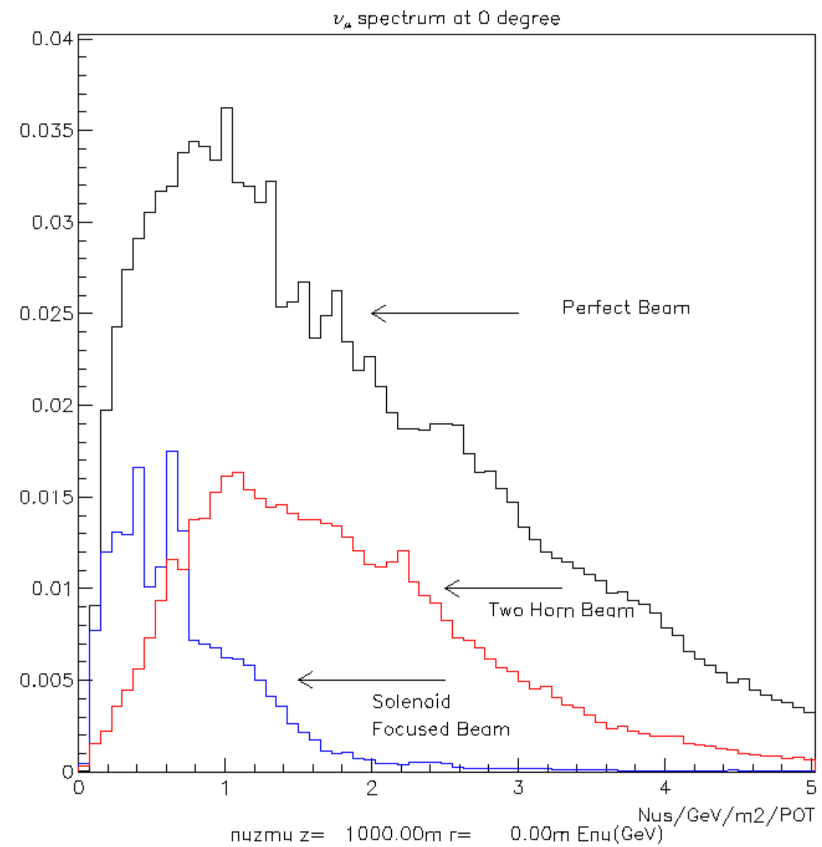






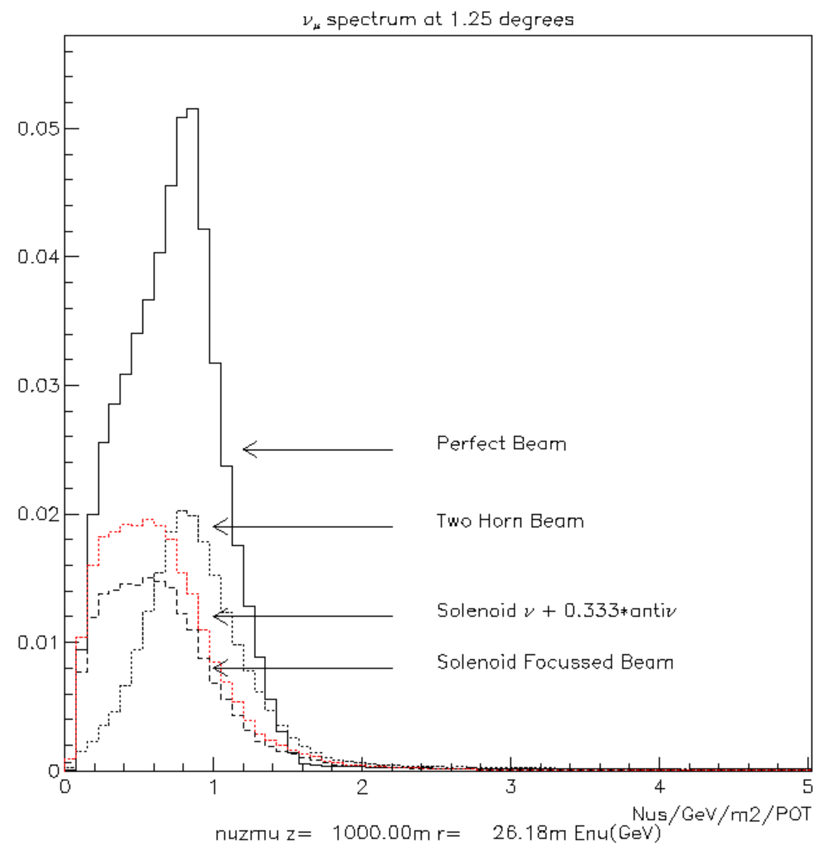
Comparison of Horn and Solenoid Focused Beams

- The Figure shows the spectra at 0º at 1 km from the target.
  - Solenoid Focused Beam.
  - Two Horned Focused Beam designed for E889.
  - So-called *Perfect Focused* beam where every particle leaving the target goes in the forward direction.
    - The perfect beam is not attainable. It is used to evaluate efficiencies.
- A solenoid focused beam selects a lower energy neutrino spectrum than the horn beam.
  - This may be preferable for CP violation physics



Horn and Solenoid Comparison (cont.)

- This figure shows a similar comparison of the 1 km spectra at 1.25° off axis.
  - The off axis beam is narrower and lower energy.
- Also a curve with the ν flux plus 1/3 the anti-ν flux is shown in red.
  - Both signs of ν are focused by a solenoid capture magnet.
    - A detector with a magnetic field will be able to separate the charge current ν and anti-ν.

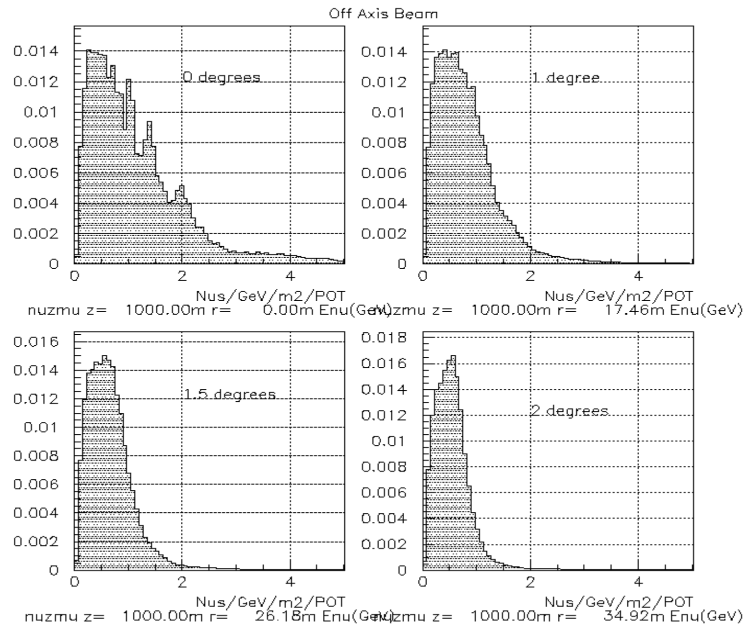


ν Flux Seen at Off-Axis Angles

- We desire to have *Low Energy* ν beam.

- We also desire to have a narrow band beam.

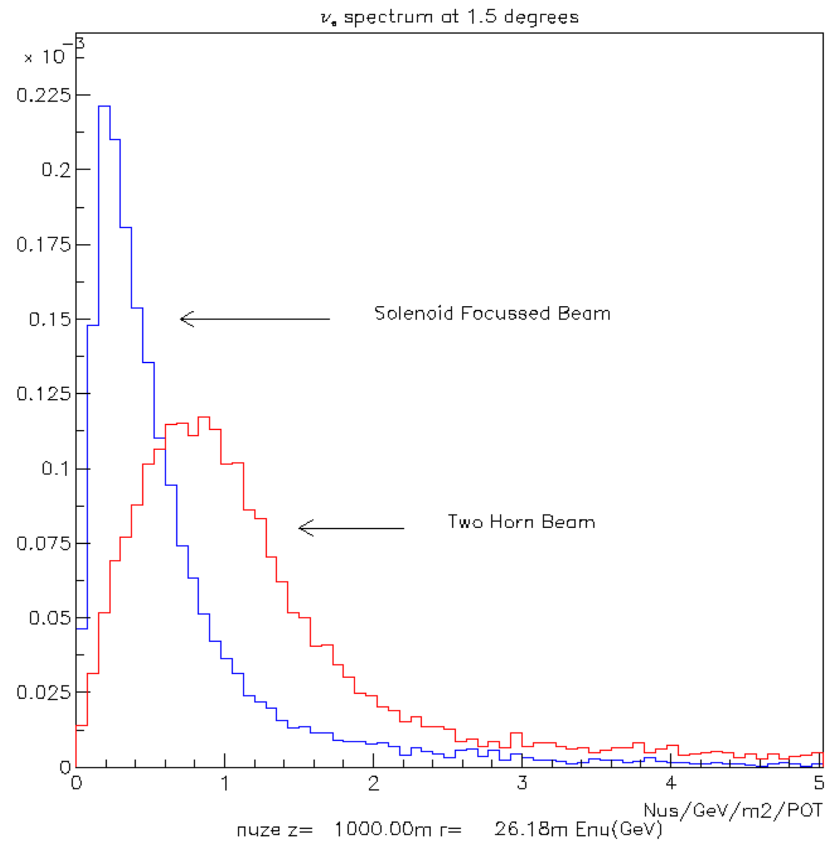
- I have chosen 1.5º off-axis for the calculations.



Angle	*Solenoid ν_μ QE evts*	*Solenoid $\bar{\nu}_\mu$ QE Events*	*Horn ν_μ QE evts*	*Horn $\bar{\nu}_\mu$ evts*
0	4.21×10^6	9.86×10^5	1.38×10^7	1.20×10^5
¼	4.11×10^6	9.56×10^5	1.32×10^7	1.06×10^5
½	4.10×10^6	9.46×10^5	1.18×10^7	1.05×10^5
1	3.80×10^6	8.83×10^5	8.69×10^6	8.27×10^4
1.5	3.36×10^6	7.89×10^5	5.98×10^6	7.53×10^4
2	2.88×10^6	6.80×10^5	4.01×10^6	4.76×10^4
3	1.94×10^6	4.64×10^5	1.93×10^6	3.31×10^4
4	1.31×10^6	3.20×10^5	1.02×10^6	2.35×10^4

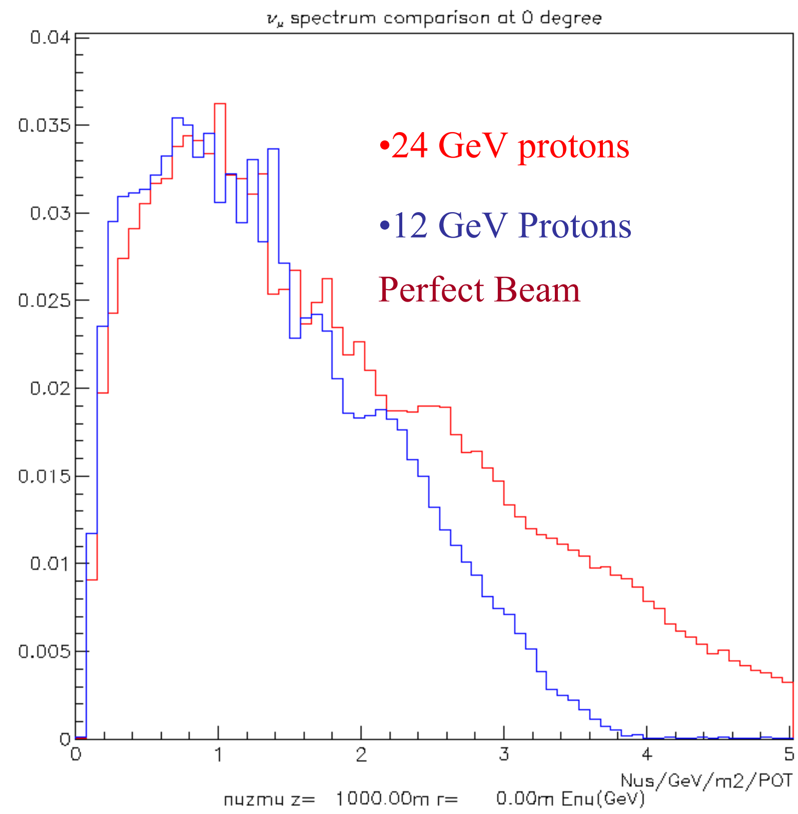
ν_e/ν_μ Ratio

- The figure shows the ν_e flux spectrum for the solenoid focused and horn beams.
- The horn focused beam has a higher energy ν_e spectrum that is dominated by $K \rightarrow \pi^o e \nu_e$
- The solenoid channel is effective in capturing and holding π and μ.
  - The ν_e spectrum from the solenoid system has a large contribution at low energy from $\mu \rightarrow \nu_\mu \nu_e e$.
  - The allowed decay path can be varied to reduce the $\nu_e/\overline{\nu}_\mu$ ratio at the cost of reducing the ν_μ rate.
- We expect the ν_e/ν_μ ratio to be ~1%

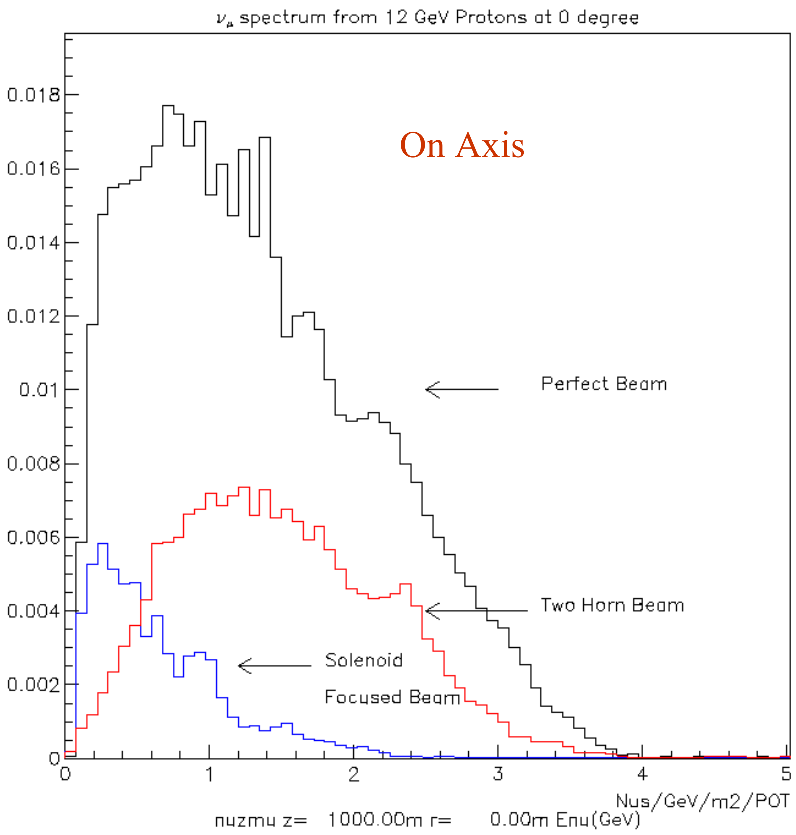


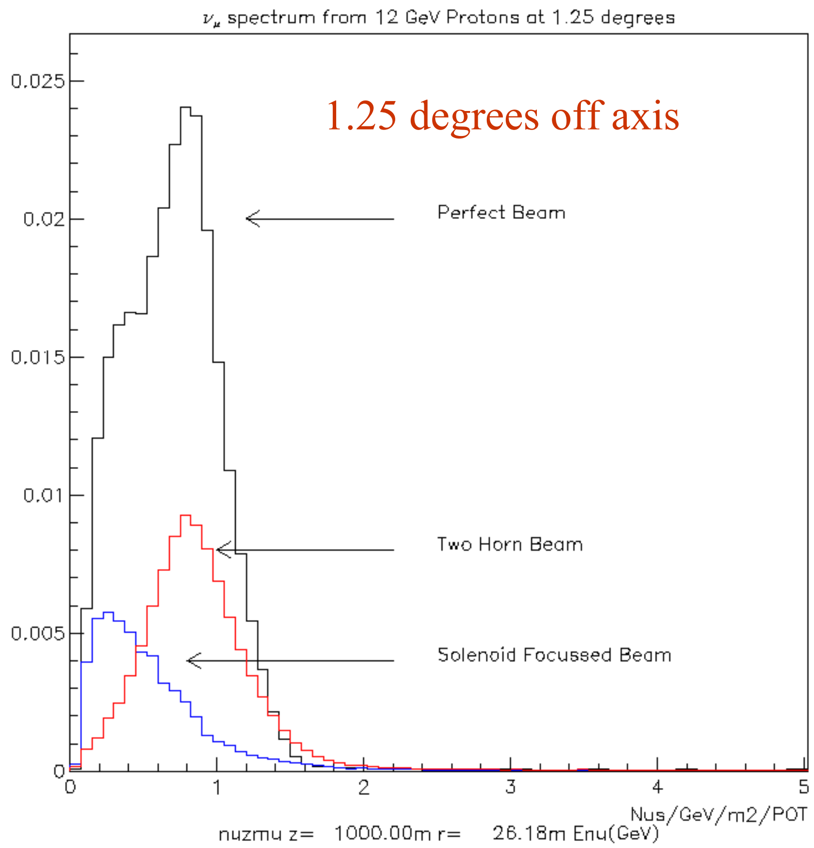
Running the AGS with 12 GeV Protons

- We could run the AGS with a lower energy proton beam.
- If we keep the same machine power level we would run at a 5 Hz repetition rate.
  - This would work for a conventional beam since we are not concerned with merging bunches.
- Figure shows *Perfect Beam* for 12 and 24 GeV incident protons.
  - 12 GeV profile is multiplied by 2 for the higher repetition rate.



12 GeV Protons (cont.)





Conclusions

- Most of this work had been done on and off between 1999 and 2001.
- We had appreciated that making long solenoid channels would be an effective way to hold pions until they decayed.
  - We were concerned about the cost of these long solenoid channels since horns were relatively cheap.
- We were not successful keeping the beam focused after we left the solenoid.
- Horns were reasonably efficient in capturing pions particularly the high part of the spectrum.
  - There was not much room for enormous gain.
- This talk should provide an introduction into Harold Kirk's talk which discusses more recent work that has been done on this subject.