Horn and Solenoid Capture Systems for a BNL Neutrino Superbeam

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Types of Capture/Focus Systems Considered

- Traditional Horn Focus System
  - Uses *toroidal* magnetic field.
  - Focuses efficiently
    - $B_\phi \perp p_\parallel$
  - 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

Super Neutrino Beam from Solenoid Capture

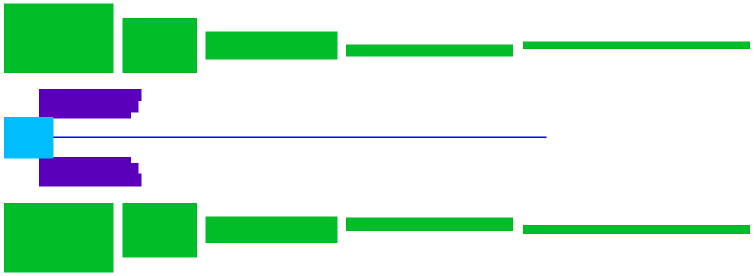
- Upgrade AGS to 1MW Proton Driver:

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 JHF 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.

Solenoid Capture

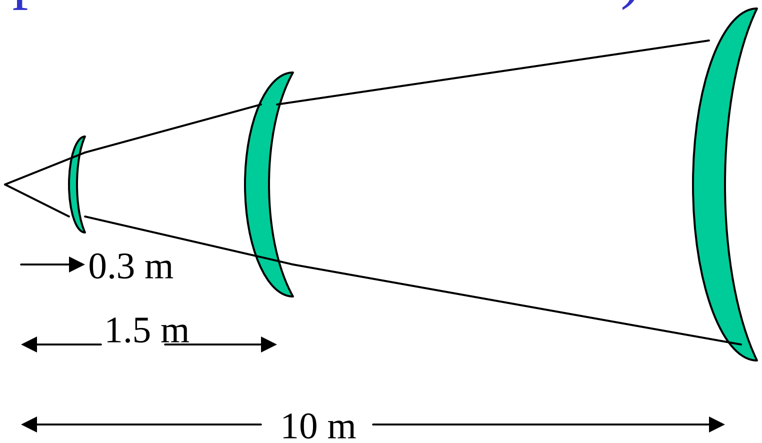
Sketch of solenoid arrangement for Neutrino Factory →



- 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.

A Solenoid as a Horn

- A horn system can be imagined as 3 thin lenses. (Simplistic Model of course.)



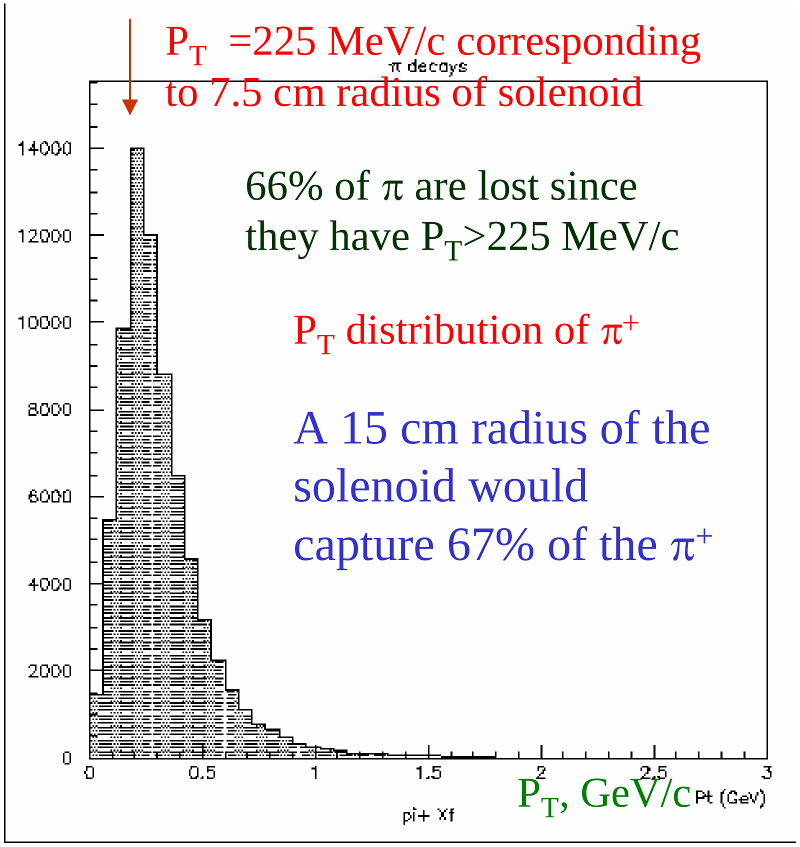
The first 2 lenses form the 1st horn and the 3rd lens forms the 2nd horn.

- A similar arrangement could be made using multiple short solenoids as thin lenses.
  - This is being investigated. We do not have results yet.

Simulations to Calculate Fluxes

- Model Solenoid/Horn Magnet in GEANT.
  - 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.

Captured Pion Distributions



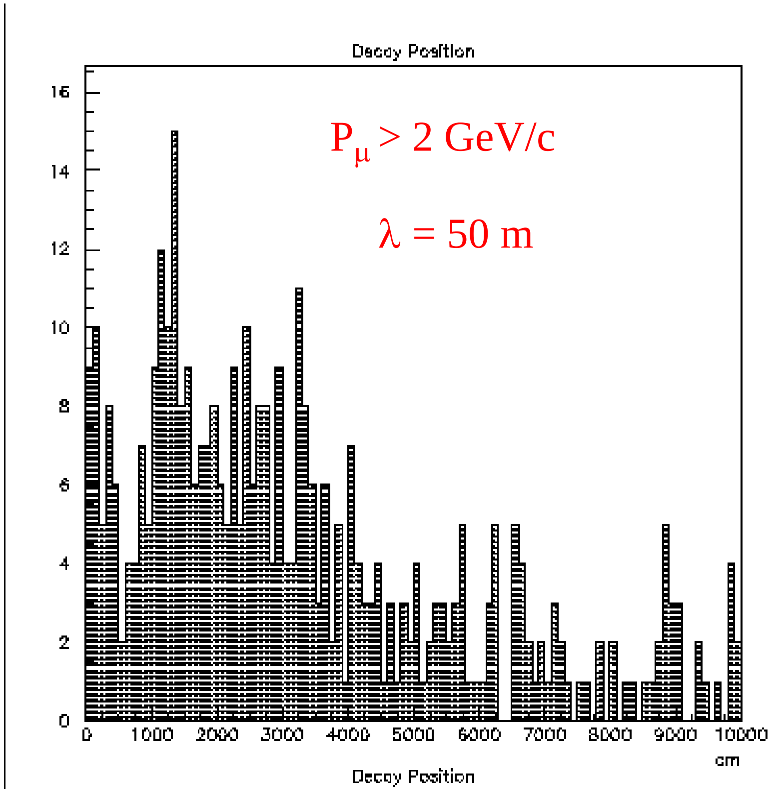
P_T =225 MeV/c corresponding to 7.5 cm radius of solenoid

66% of π are lost since they have P_T>225 MeV/c

P_T distribution of π^+

A 15 cm radius of the solenoid would capture 67% of the π^+

P_T, GeV/c

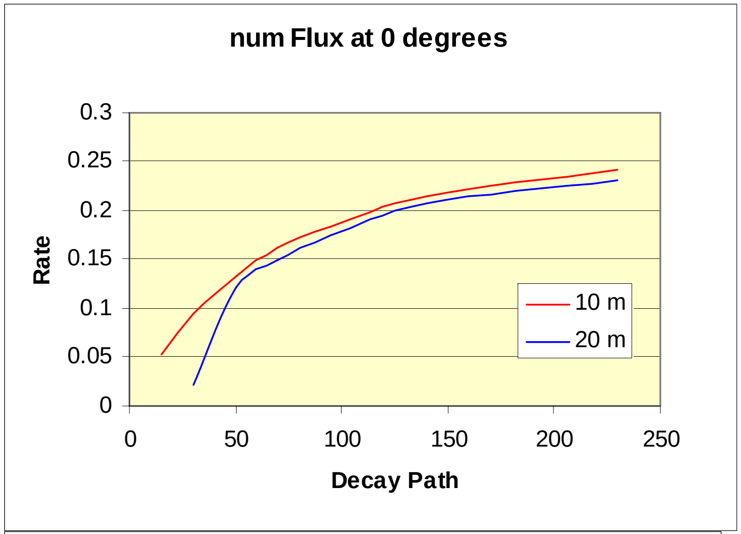


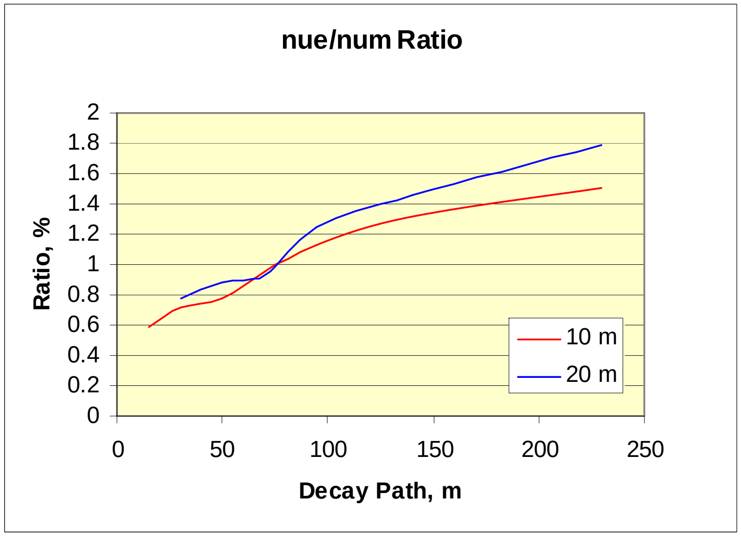
P_μ > 2 GeV/c

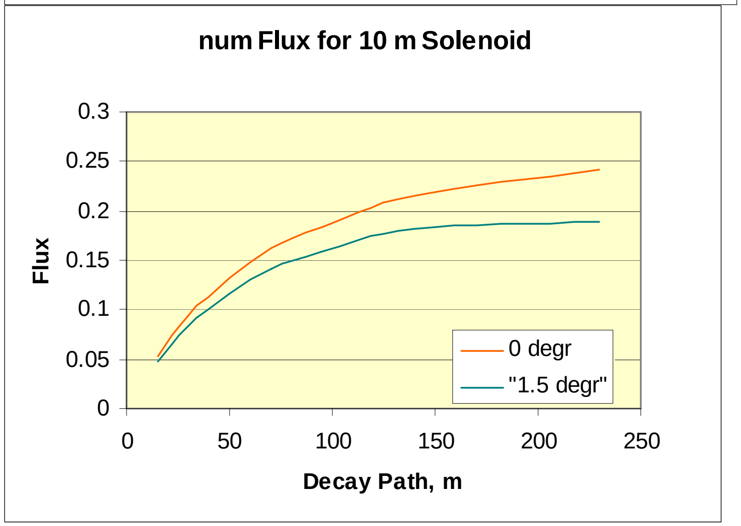
λ = 50 m

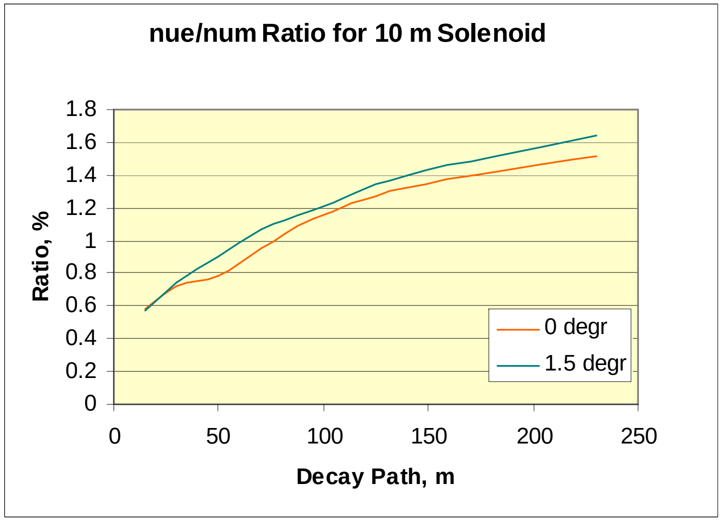
L, cm

Rate and ν_e/ν_μ as a function of Decay Tunnel Length for a Solenoid Capture System


num Flux at 0 degrees

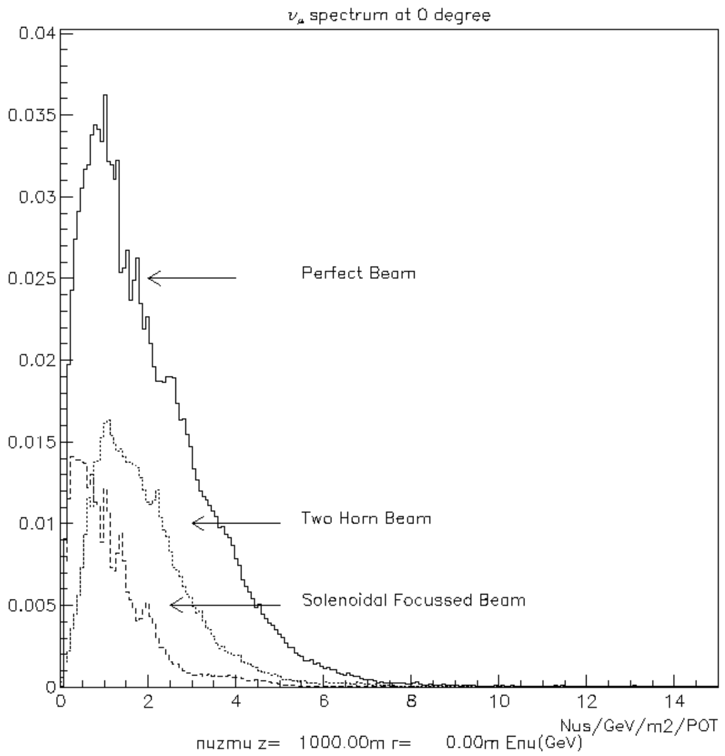

nue/num Ratio


num Flux for 10 m Solenoid


nue/num Ratio for 10 m Solenoid

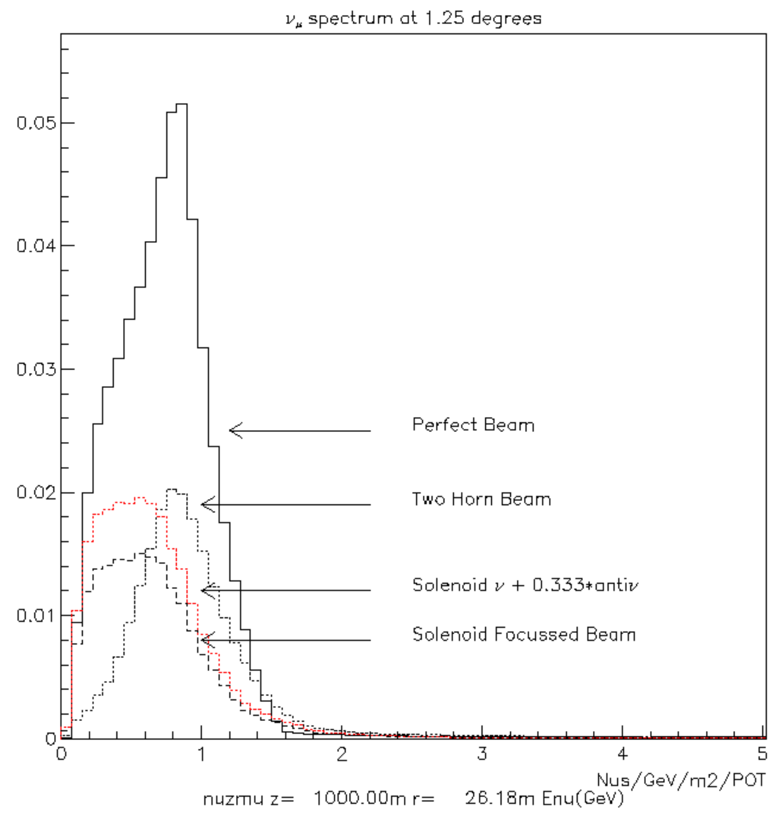
Comparison of Horn and Solenoid Focused Beams

- The Figure shows the spectra at 0° 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



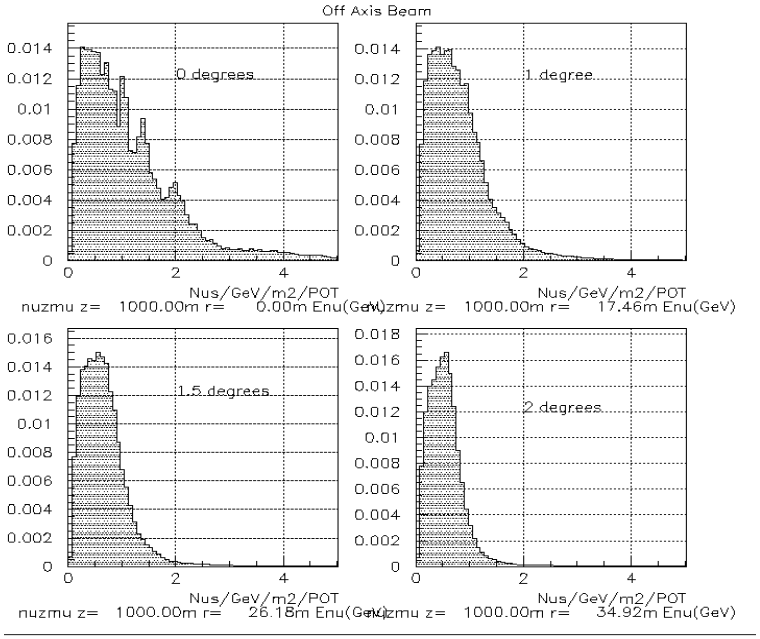
Horn and Solenoid Comparison (cont.)

- 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

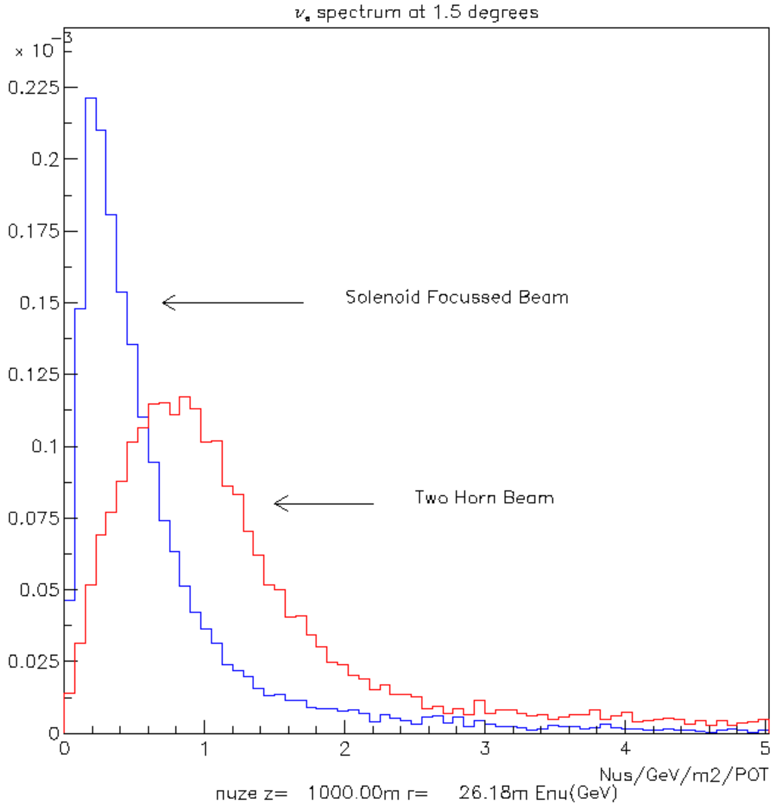
- We desire to have *Low Energy* ν beam.
- We also desire to have a narrow band beam.
- I have chosen 1.5° off-axis for the calculations.



Angle	Solenoid ν_μ QE evts	Solenoid ν_μ QE Events	Horn ν_μ QE evts	Horn ν_μ 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

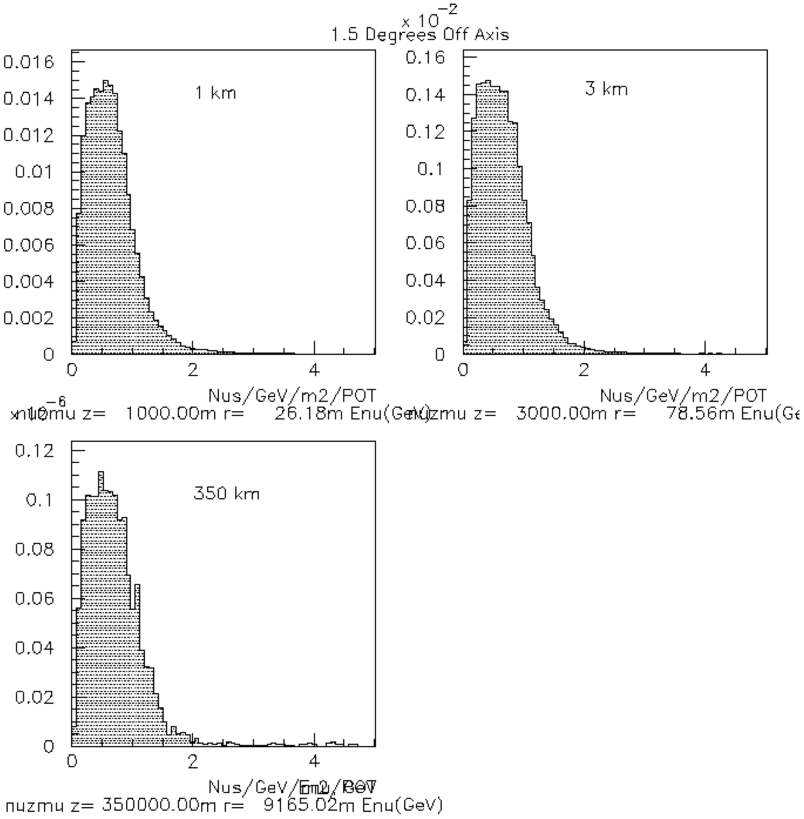
- The figure shows the ν_e flux spectrum for the solenoid focused and horn beams.
- The horn focused beam has a higher energy ν_e spectrum that is dominated by $K\rightarrow\pi^o e\nu_e$
- The solenoid channel is effective in capturing and holding π and μ.
  - The ν_e spectrum from the solenoid system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



Detectors Are Placed 1.5º Off ν Beam Axis

- Placing detectors at a fixed angle off axis provides a similar E_ν profile at all distances.
- It also provides a lower E_ν distribution than on axis.
- μ from π decays are captured by long solenoid channel. They provide low E_ν enhancement.
- Integrated flux at each detector:
  - Units are ν/m²/POT

Detector Position	ν_μ	Anti ν_μ	ν_e	Anti ν_e
At 1 km	1.40×10^{-5}	1.22×10^{-5}	2.40×10^{-8}	1.33×10^{-8}
At 3 km	1.49×10^{-6}	1.30×10^{-6}	2.42×10^{-9}	1.31×10^{-9}
At 350 km	1.10×10^{-10}	9.39×10^{-11}	1.78×10^{-13}	9.62×10^{-14}



Event Estimates Without Oscillations

- Below is shown event estimates expected from a solenoid capture system
  - The near detectors are 1 kton and the far detector is 50 kton.
  - The source is a 1 MW proton driver.
  - The experiment is run for 5 Snowmass years. This is the running period used in the JHF-Kamioka neutrino proposal.
  - These are obtained by integrating the flux with the appropriate cross sections.

Detector Position	$\nu_\mu n \to \mu^- p$	$\nu_\mu p \to \mu^+ n$	$\nu N \to \nu N \pi^o$	$\nu_e n \to e^- p$	$\nu_e p \to e^+ n$
At 1 km	3.87×10^7	8.82×10^6	3.87×10^6	1.32×10^6	3.18×10^5
At 3 km	4.17×10^6	9.44×10^5	4.28×10^5	1.31×10^5	3.20×10^4
At 350 km	15539	3455	1618	455	150

- Estimates with a 4 MW proton driver source would be four times larger.

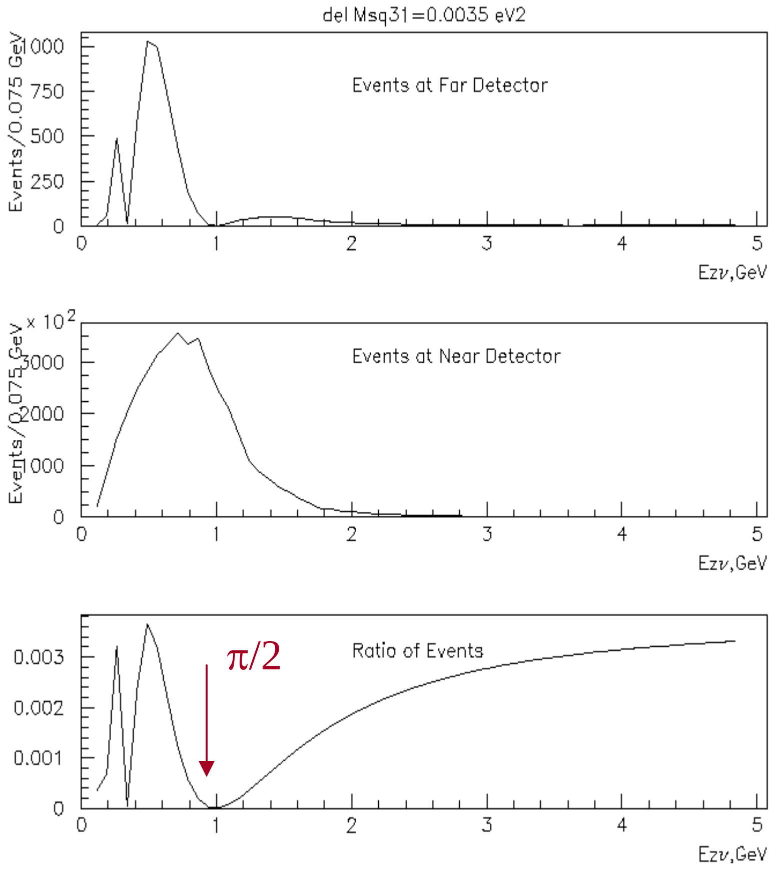
Determination of Δm^2_{23}

- Consider a scenario where
  - $\Delta m^2_{12}=5\times10^{-5}\ \mathrm{eV}^2$
  - $\theta_{23}=\pi/4$
  - $\Delta m^2_{31}=0.0035\ \mathrm{eV}^2$ (unknown)
  - $\mathrm{Sin}^2\ 2\theta_{13}=0.01$ (unknown)
  - This is the Barger, Marfatia, and Whisnant point Ib.
- $\langle E_\nu \rangle$ =0.8 GeV is *not* optimum since I don’t know the true value in advance.
- I can determine Δm^2_{23} from

$$1.27\ \Delta m^2_{23} L/E_0=\pi/2$$

Where E_0 is the corresponding null point

- Note that these figures ignore the effect of Fermi motion in the target nuclei.
  - This would smear the *distinct* $3\pi/2$ minimum.



Solenoid Capture System with 230 m Decay Tunnel

Table 1: Oscillation Signal:

- Consider $\Delta m^2_{12}=5\times10^{-5}$ eV^2, $\theta_{23}=\pi/4$ and $\sin^2 2\theta_{13}=0.01$
- Using a 1 MW proton driver and a 50 kton detector 350 kilometers away.
- Experiment running for 5×10^7 seconds.
- Solenoid capture system with ν_e/ν_μ flux ratio=1.9 %

ν_μ ν_e Signal ν_e BG $\overline{\nu_\mu}$ $\overline{\nu_e}$ signal $\overline{\nu_e}$ BG

Δm^2_{13} eV^2	ν_μ	ν_e signal	ν_e background	Anti ν_μ	Anti ν_e signal	Anti ν_e BG
No Oscillation	15539		455	3455		150
0.002	5065	76	455	1096	18.5	150
0.0035	5284	70	455	1283	16.2	150
0.005	7722	55	455	1762	13.1	150

Ignores ν_e BG oscillations

Significance:

ν_e signal: 3.3 s.d.

$\overline{\nu_e}$ signal: 1.3 s.d.

Solenoid Capture System with 100 m Decay Tunnel

Table 1: Oscillation Signal:

- Consider $\Delta m^2_{12}=5\times10^{-5}$ eV^2, $\theta_{23}=\pi/4$ and $\sin^2 2\theta_{13}=0.01$
- Using a 1 MW proton driver and a 50 kton detector 350 kilometers away.
- Experiment running for 5×10^7 seconds.
- Solenoid capture system with ν_e/ν_μ flux ratio=1.1 %

	ν_μ	ν_e signal	ν_e BG	$\bar{\nu}_\mu$	$\bar{\nu}_e$ signal	$\bar{\nu}_e$ BG
Δm^2_{13} eV^2	ν_μ	ν_e signal	ν_e background	Anti ν_μ	Anti ν_e signal	Anti ν_e BG
No Oscillation	10582		249	2560		47
0.002	3600	58	249	878	14.4	47
0.0035	4282	50	249	1090	12.3	47
0.005	5283	43	249	1303	10.6	47

Ignores ν_e BG oscillation

Significance:

ν_e signal: 3.2 s.d.

$\bar{\nu}_e$ signal: 1.8 s.d.

Horn Beam 200 m Decay Tunnel

E889 Horn Design

Table 1: Oscillation Signal:

- Consider $\Delta m^2_{12}=5\times10^{-5}\ eV^2$, $\theta_{23}=\pi/4$ and $\sin^2 2\theta_{13}=0.01$
- Using a 1 MW proton driver and a 50 kton detector 350 kilometers away.
- Experiment running for 5×10^7 seconds.
- Horn capture system with ν_e/ν_μ flux ratio=1.08 %

	ν_μ	ν_e Signal	ν_e BG	$\overline{\nu}_\mu$	$\overline{\nu}_e$ signal	$\overline{\nu}_e$ BG
Δm^2_{13} eV^2	ν_μ	ν_e signal	ν_e background	Anti ν_μ	Anti ν_e signal	Anti ν_e BG
No Oscillation	21645		272	228		5.4
0.002	8317	83	272	115	1	5.4
0.0035	5165	95	272	84	1	5.4
0.005	9966	69	272	90	1	5.4

Ignores ν_e BG oscillations

Significance:

ν_e signal: 5.8 s.d.

Anti ν Horn Beam 200 m Decay Tunnel

E889 Horn Design

Table 1: Oscillation Signal:

- Consider $\Delta m^2_{12}=5\times10^{-5}\,\mathrm{eV}^2$, $\theta_{23}=\pi/4$ and $\sin^2 2\theta_{13}=0.01$
- Using a 1 MW proton driver and a 50 kton detector 350 kilometers away.
- Experiment running for 5×10^7 seconds.
- Horn capture system with ν_e/ν_μ flux ratio=1.04 %

ν_μ ν_e Signal ν_e BG $\bar{\nu}_\mu$ $\bar{\nu}_e$ signal $\bar{\nu}_e$ BG

Δm^2_{13} eV^2	ν_μ	ν_e signal	ν_e background	Anti ν_μ	Anti ν_e signal	Anti ν_e BG
No Oscillation	691		19	4354		65
0.002	506	4	19	1576	19.7	65
0.0035	305	4.7	19	1018	17.8	65
0.005	331	4.5	19	2074	13.9	65

Ignores ν_e BG oscillations

Significance:

$\bar{\nu}_e$ signal: 2.2 s.d.