Brookhaven Super-Neutrino Beam Scenario

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Representing Ideas of

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Staging a Neutrino Factory

- Two feasibility studies for a **Neutrino Factory** have been concluded.
  - These studies indicate a cost of 2-2.5 B$.
    - This *does not* include contingency and overhead.
    - This kind of money may not be available in the current climate
  - They indicate an optimistic turn-on date of 2012.
    - We might like to do some physics before that.
- A staged approach to building a Neutrino Factory maybe desirable.
  - First Phase: Upgrade AGS to create a 1 MW *Proton Driver* and target station.
  - Second Phase: Build phase rotation and part of cooling system.
  - Third Phase: Build a pre-acceleration Linac to raise beam momentum to 2.5 GeV/c
  - Fourth Phase: Complete the Neutrino Factory.
  - Fifth Phase: Upgrade to entry-level Higgs Factory Muon Collider.
- Each phase can support a physics program.

First Phase Super Neutrino Beam

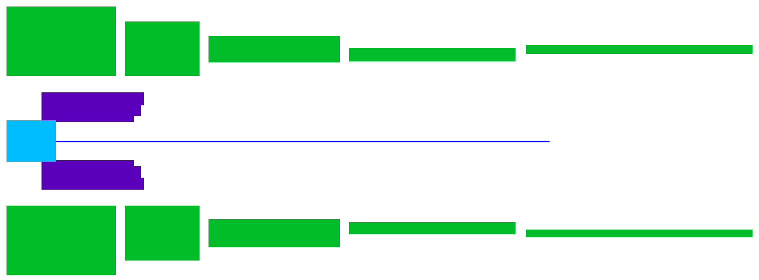
- Upgrade AGS to 1MW Proton Driver:

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 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 $\overline{\nu}$
  - 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 →

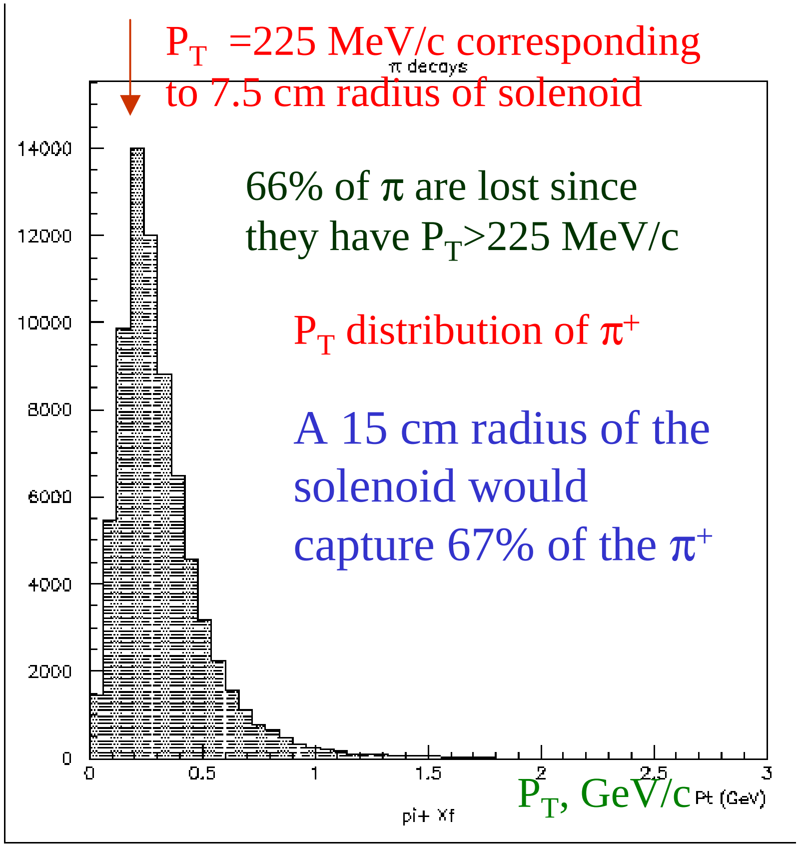


- If only ν and not $\bar{\nu}$ is desired, then a dipole magnet could be inserted between adjacent solenoids above.
- Inserting a dipole also gives control over the mean energy of the neutrino beam.
- Since ν and $\bar{\nu}$ events can be separated with a modest magnetic field in the detector, it will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

Solenoid Design Simulation

- Model Solenoid 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.
  - Field profile on axis is $B(z)=B_{max}/(1+a\ z)$
    - Independent parameters are B_{max}, B_{min} and the solenoid length, L.
  - 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



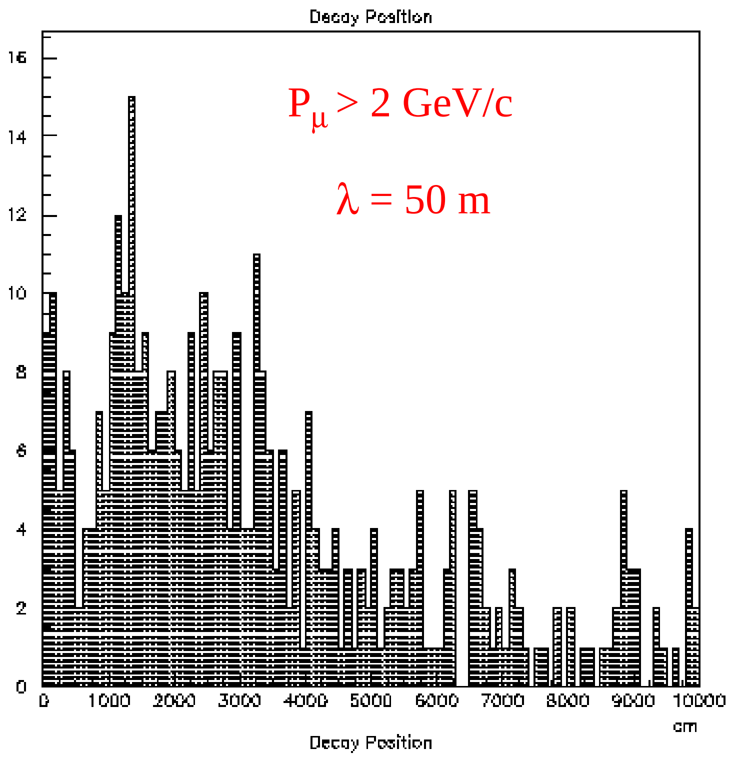
P_T =225 MeV/c corresponding to 7.5 cm radius of solenoid

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

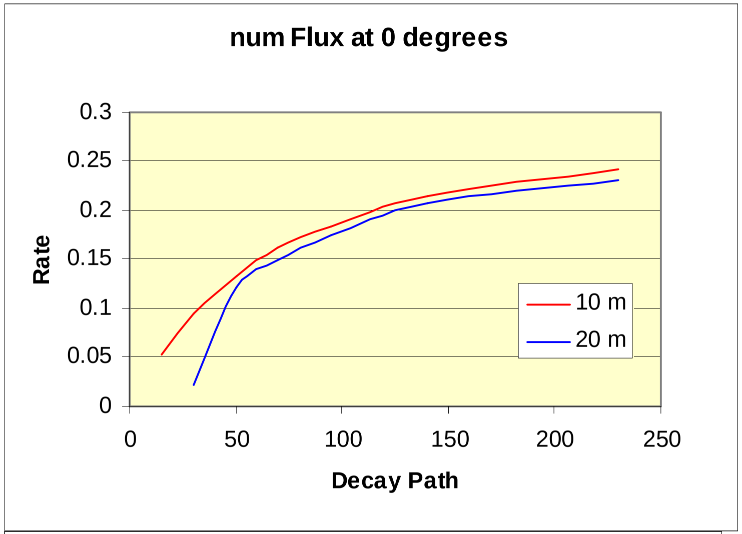


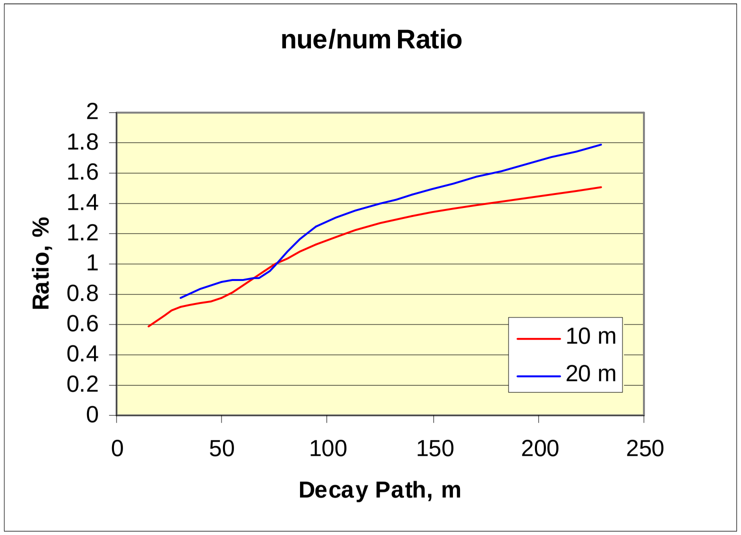
P_μ > 2 GeV/c

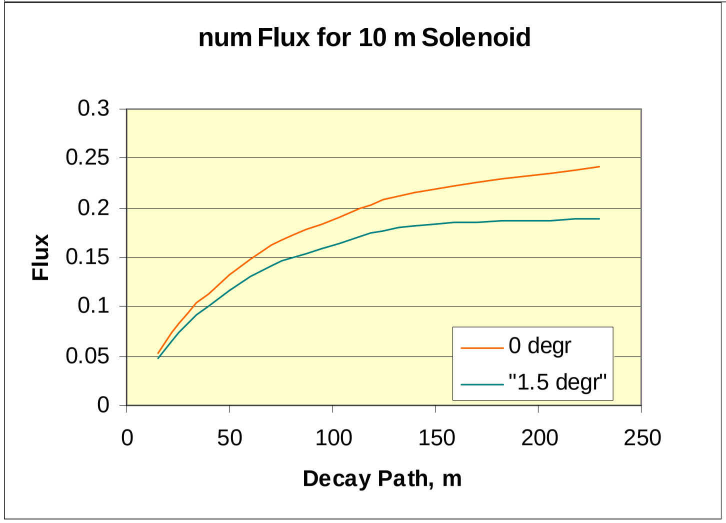
λ = 50 m

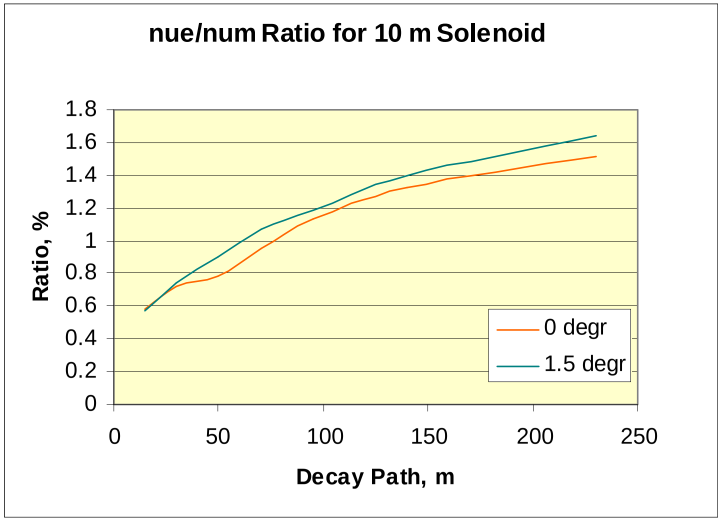
L, cm

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



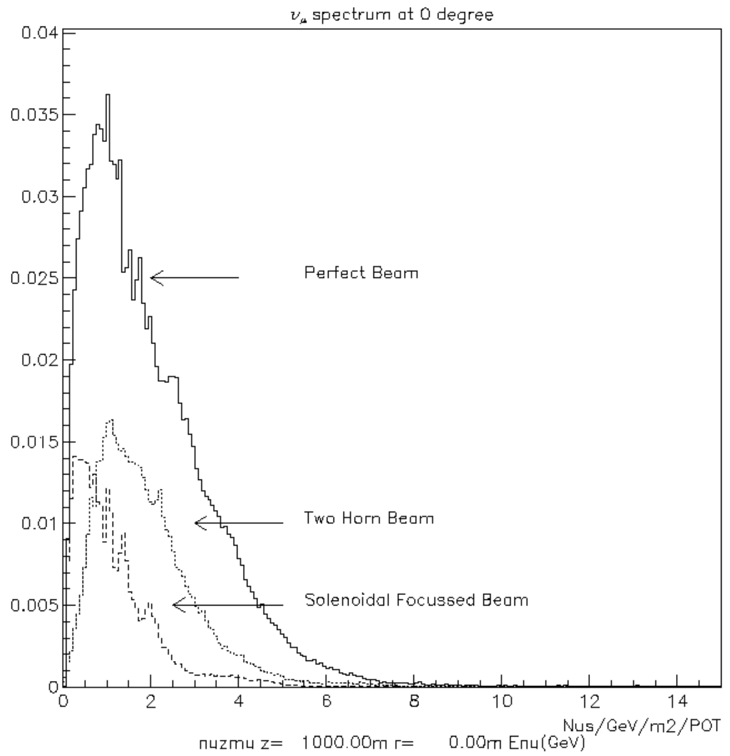






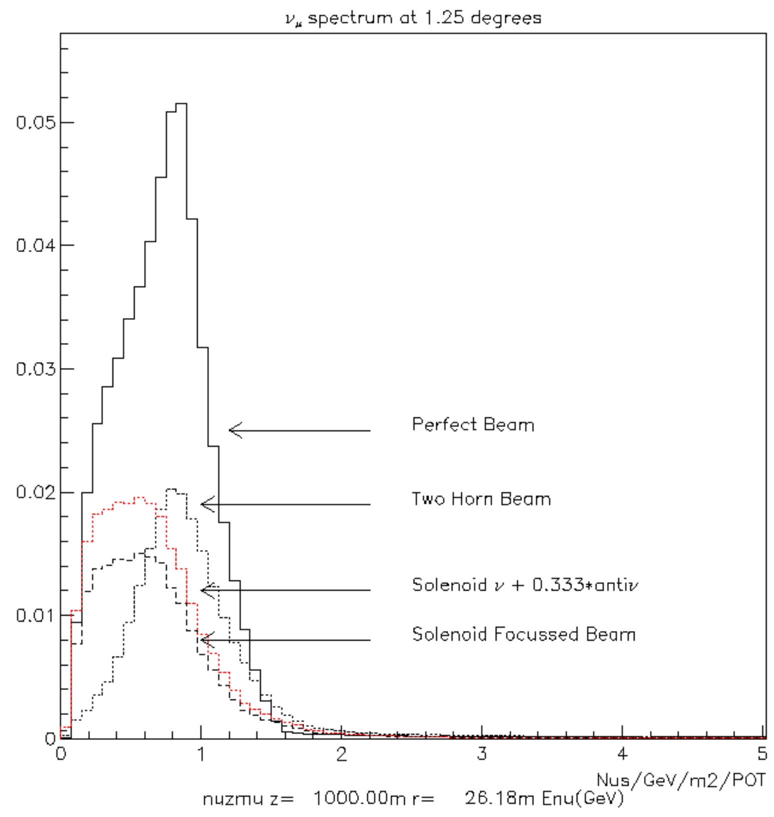
Comparison of Horn and Solenoid Focused Beams

- 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.

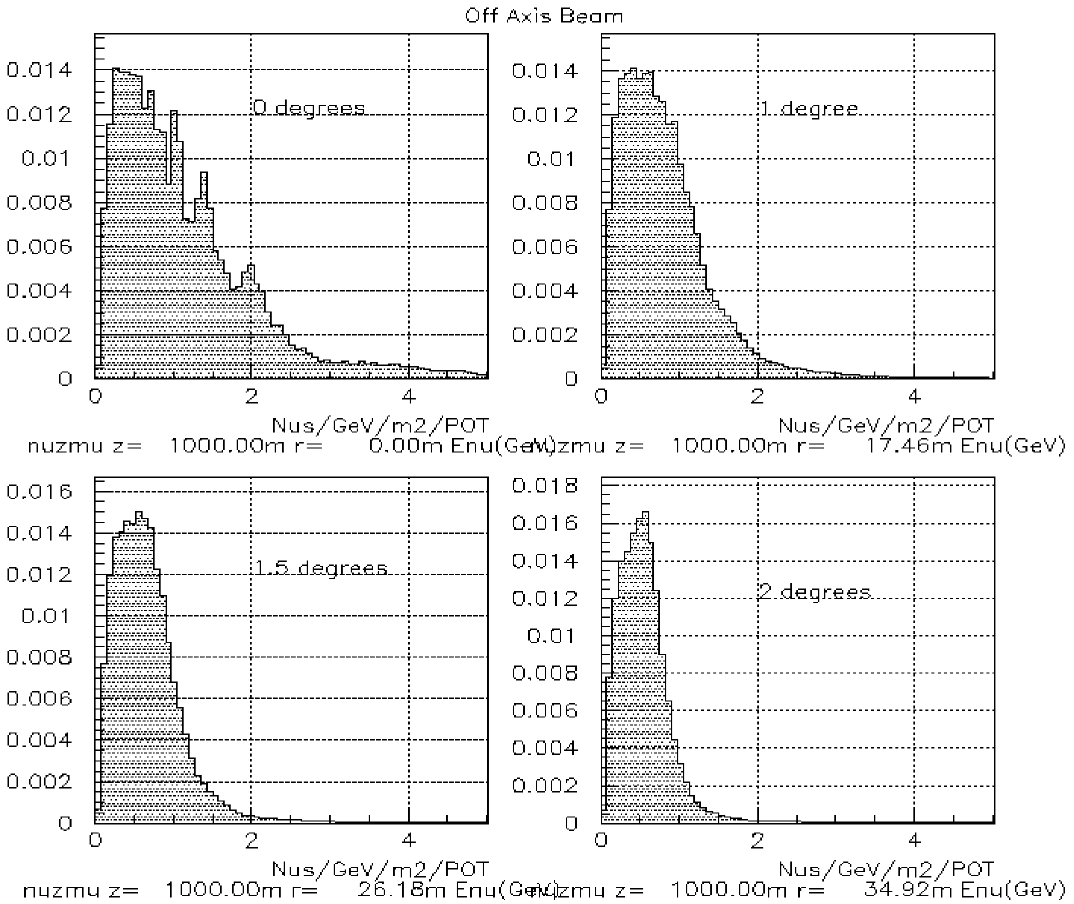


ν Flux Seen at Off-Axis Angles

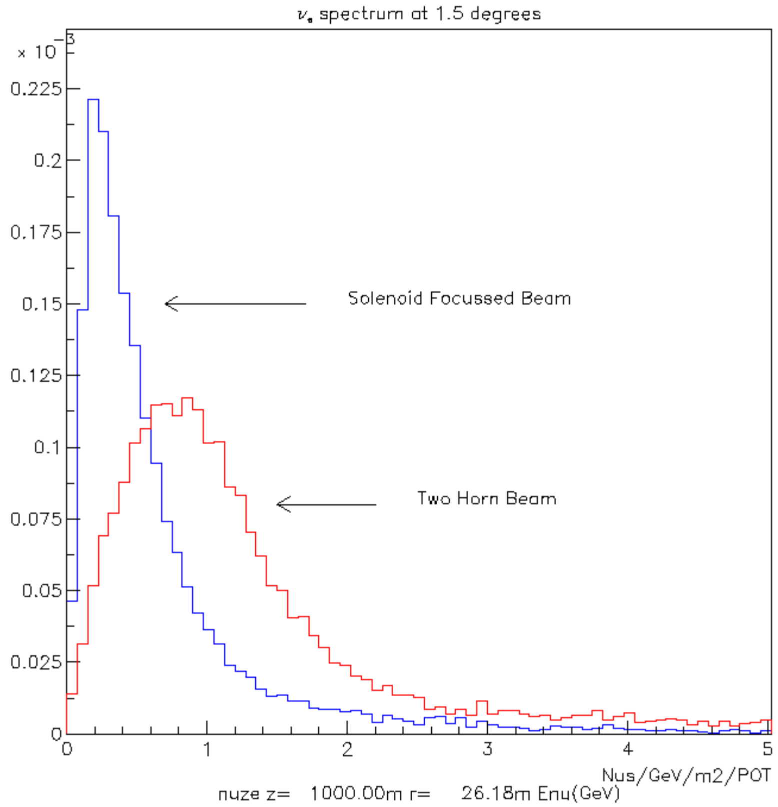
- We desire to have *Low Energy* ν beam.

- We also desire to have a narrow band beam.

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



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%

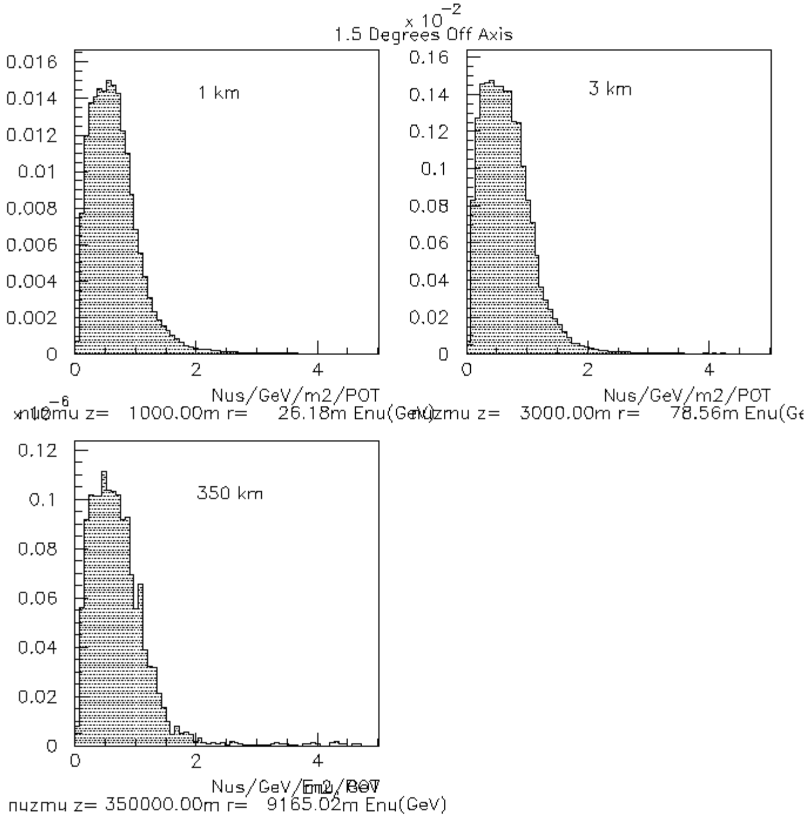
Detector Choices

- The far detector would be placed 350 km from BNL (near Ithica, NY).
  - There are salt mines in this area. One would put the detector 600 m below ground.
- We are favoring Liquid Ar TPC similar to *Icarus*. The far detector would have 50 ktons fiducial volume (65 ktons total.)
  - Provides good electron and π^o detection.
  - The detector will sit between dipole coils to provide a field to determine the lepton charge.
- Close in 1 kton detectors at 1 km and/or 3 km.
  - 1 km detector gives ν beam alignment and high statistics for detector performance.
  - 3 km detector is far enough away that ν source is a point.

Detectors Are Placed 1.5° Off ν Beam Axis

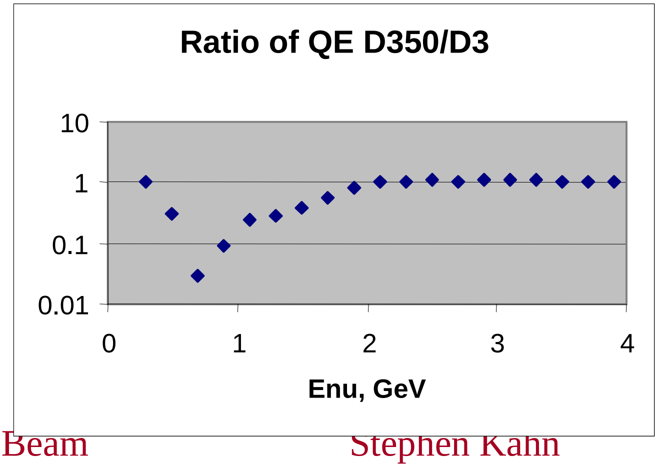
- Placing detectors at a fixed angle off axis provides a similar E_ν profile at all distances.
- It also provides a lower E_ν distribution than on axis.
- μ from π decays are captured by long solenoid channel. They provide low E_ν enhancement.
- Integrated flux at each detector:
  - Units are ν/m^2/POT

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}



Neutrino Oscillation Physics

- The experiment would look at the following channels:
  - – ν_μ disappearance -- primarily $\nu_\mu \rightarrow \nu_\tau$ oscillations.
    - Sensitive to Δm_{23}^2 and θ_{23}
    - Examine ratio of $\nu n \rightarrow \mu p$ (QE) at 350 km detector to 3 km detector as a function of E_ν.
  - – $\nu N \rightarrow \nu \pi^o N$ events
    - These events are insensitive to oscillation state of ν
    - Can be used for normalization.
  - – ν_e appearance
    - (continued on next transparency)



ν_e Appearance Channel

- There are several contributions to $P(\nu_\mu \to \nu_e)$:
  - Solar Term: $P_{solar}=\sin^2 2\theta_{12} \cos^2\theta_{13} \cos^2\theta_{23} \sin^2(\Delta m^2_{sol} L/4E)$
    - This term is very small.
  - Tau Term: $P_\tau=\sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2 (\Delta m^2_{atm} L/4E)$
    - This is the dominant term.
    - This term is sensitive to θ_{13} and would allow us to measure it with the 1 MW proton driver.
  - Terms involving the CP phase δ:
    - There are both CP conserving and violating terms involving δ.
    - The CP violating term can be measured as

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \approx \frac{\Delta m^2_{12} L}{4E_\nu} \frac{\sin 2\theta_{12}}{\sin \theta_{13}} \sin \delta$$

    - This asymmetry is larger at lower E_ν. This could be ~25% of the total appearance signal at the optimum E_ν
    - The 4 MW proton driver would be necessary for this asymmetry

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.

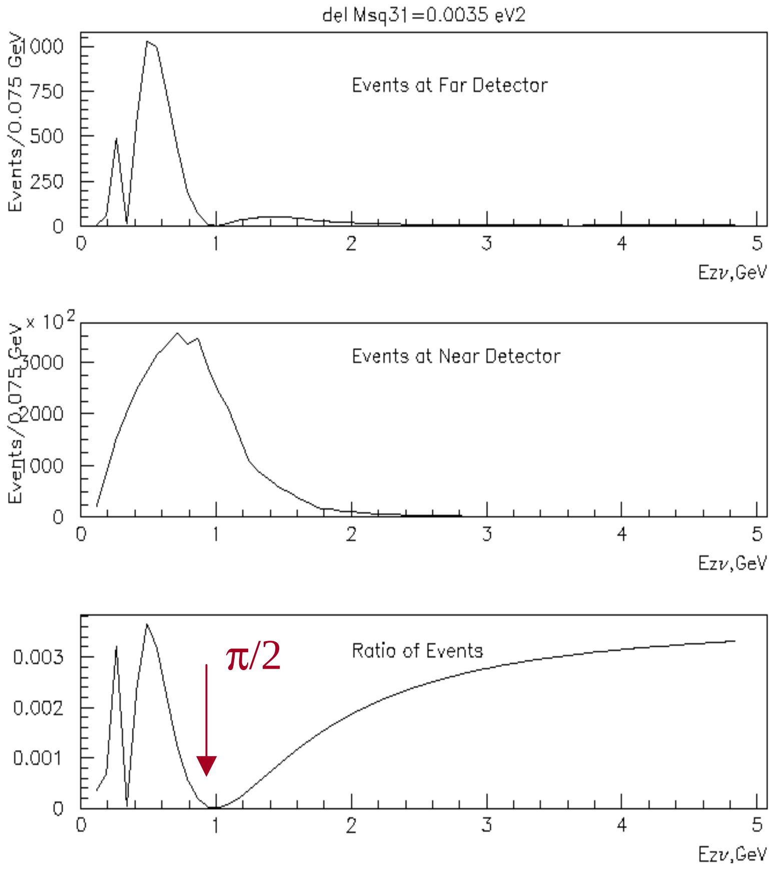
Determination of Δm^2_{23}

- Consider a scenario where
  - $\Delta m^2_{12}=5\times10^{-5}$ eV^2
  - $\theta_{23}=\pi/4$
  - $\Delta m^2_{31}=0.0035$ eV^2 (unknown)
  - $\sin^2 2\theta_{13}=0.01$ (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.



Barger, Marfatia and Whisnant Table

TABLE II. Scenarios with $\delta m^2_{31} > 0$ (2 years ν, 6–12 years $\bar{\nu}$); the last entry in the table shows the results for JHF–SK [11] (5 years, ν only). $\theta_{23} = \pi/4$ is assumed.

δm^2_{21} (eV^2)	δm^2_{31} (eV^2)	L (km)	E (GeV)	$\langle N_e \rangle$	$\langle \bar{N}_e \rangle$	B_e	N_τ	$\sin^2 2\theta_{13}$ reach at 3σ			$\lvert\delta\rvert$ (°) at 3σ
				$\sin^2 2\theta_{13} = 0.01$				$\nu_\mu \to \nu_e$	$\bar{\nu}_\mu \to \bar{\nu}_e$	sgn(δm^2_{31})	$\sin^2 2\theta_{13} = 0.01$
5×10^{-5}	2×10^{-3}	350	0.57	180	148	116	–	0.0020	0.0025	–	26
		730	1.18	95	63	56	–	0.0026	0.0042	0.10	35
		1290	2.09	64	37	32	–	0.0031	0.0082	0.036	49
		1770	2.86	53	15	23	–	0.0033	0.014	0.020	67
		2900	4.70	39	4	14	10	0.0038	0.055	0.011	–
	3.5×10^{-3}	350	0.99	293	237	204	–	0.0024	0.0029	–	39
		730	2.07	156	100	97	–	0.0026	0.0042	0.050	52
		1290	3.65	106	42	55	14	0.0027	0.0073	0.015	–
		1770	5.01	88	22	40	36	0.0028	0.012	0.0091	–
		2900	8.22	67	5	25	51	0.0029	0.043	0.0057	–
	5×10^{-3}	350	1.41	412	331	289	–	0.0024	0.0030	0.098	54
		730	2.96	219	139	139	–	0.0025	0.0040	0.028	83
		1290	5.21	150	57	79	77	0.0025	0.0066	0.0095	–
		1770	7.16	125	30	58	100	0.0025	0.011	0.0061	–
		2900	11.74	95	7	35	102	0.0025	0.036	0.0041	–
10^{-4}	2×10^{-3}	350	0.57	283	201	116	–	0	0	–	14
		730	1.18	120	88	56	–	0	0	–	18
		1290	2.09	78	41	32	–	0.0007	0.0019	0.10	24
		1770	2.86	62	24	23	–	0.0014	0.0059	0.055	30
		2900	4.70	44	9	14	10	0.0025	0.036	0.023	51
	3.5×10^{-3}	350	0.99	324	268	204	–	0.0013	0.0016	–	19
		730	2.07	170	114	97	–	0.0017	0.0026	–	24
		1290	3.65	114	50	55	14	0.0020	0.0052	0.040	32
		1770	5.01	94	28	40	36	0.0022	0.0092	0.031	40
		2900	8.22	69	8	25	51	0.0025	0.037	0.010	76
	5×10^{-3}	350	1.41	433	353	289	–	0.0018	0.0023	–	25
		730	2.96	229	149	139	–	0.0020	0.0032	0.081	31
		1290	5.21	148	55	79	77	0.0021	0.0056	0.022	40
		1770	7.16	129	34	58	100	0.0022	0.0092	0.012	50
		2900	11.74	96	9	35	102	0.0023	0.033	0.0063	–
–	3×10^{-3}	295	0.7	12	–	22	–	0.016	–	–	–

Oscillation Signal

- The following transparencies will show Quasi-Elastic event numbers for Solenoid and Horn capture systems. They assume:
  - 1 MW Proton Driver
  - 50 kton detector at 350 km with charge determination (Liquid Ar)
  - 5×10^{7} second running period.
- For comparison we have 28% of the flux used in Barger et al.
- We do not use a necessarily optimum L/E fixed configuration for all cases since the *true* oscillation parameters are not known in advance.
- We use the actual flux distribution, not a monochromatic ν beam (as used in Barger et al.).
- The size of the ν_e appearance signal will give a θ_{13} measurement since $\Delta m_{13}^2 \approx \Delta m_{23}^2$ is measured independently by the ν_μ disappearance.

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 $\Delta m^2_{12}=5\times10^{-5}\,\mathrm{eV}^2$, $\theta_{23}=\pi/4$ 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.
- 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	$\bar{\nu}_e$ 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	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 $\Delta m^2_{12}=5\times10^{-5}\,eV^2$, $\theta_{23}=\pi/4$ 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	$\overline{\nu_\mu}$	$\overline{\nu_e}$ 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:

$\overline{\nu_e}$ signal: 2.2 s.d.

Cosmic Ray Background

- This table shows the cosmic ray rates for a detector placed on the surface.
  - The rate reduction factors come from the E889 proposal.
  - The events shown are scaled to the 350 km detector mass and 5 Snowmass year running period.

	Muons	Neutrons
Raw Rate (kHz)	81.7	2.7
Beam Time Correlation Reduction	2.5×10^{-7}	2.5×10^{-7}
Passive/Active Shielding	0.001	0.18
Energy Cuts	0.47	0.26
Vertex and Direction Info	0.0033	0.062
Total Reduction	3.9×10^{-13}	7.2×10^{-10}
Background in 5×10^{7} sec	34	2280

- The detector will be placed 600 m below ground in a mine.
  - The residual cosmic ray background would be ~0.002 events.

Backgrounds to ν_e Appearance Signal

- The largest backgrounds to the $\nu_\mu \rightarrow \nu_e$ signal are expected to be:
  - ν_e contamination in the beam.
    - This was ~1% ν_e/ν_μ flux ratio in the capture configuration that was used in this study. This yields a ~2% in the event ratio.
  - Neutral Current $\nu\pi^o N$ events where the π^o are misidentified as an electron.
    - If a γ from the π^o converts close to the vertex (Dalitz decay) and is asymmetric.
    - The magnetic field and dE/dx will be helpful in reducing this background. Simulation study is necessary.
    - I estimate (guess) that this background is ~0.001 of the $\nu\pi^o N$ signal.

Conclusions

- A high intensity neutrino super beam maybe an extremely effective way to study neutrino oscillations.
  - In particular the 4 MW version of the super beam may be the only way to observe CP violation in neutrino oscillations without a *Muon Ring Neutrino Factory*.
- This experiment is directly competitive with the JHF-Kamioka neutrino project.
  - Do we need two such projects? I will not answer that!