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

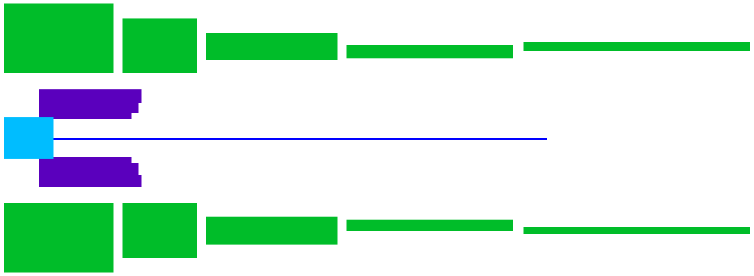
- Upgrade AGS to 1MW Proton Driver:

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 30 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 →

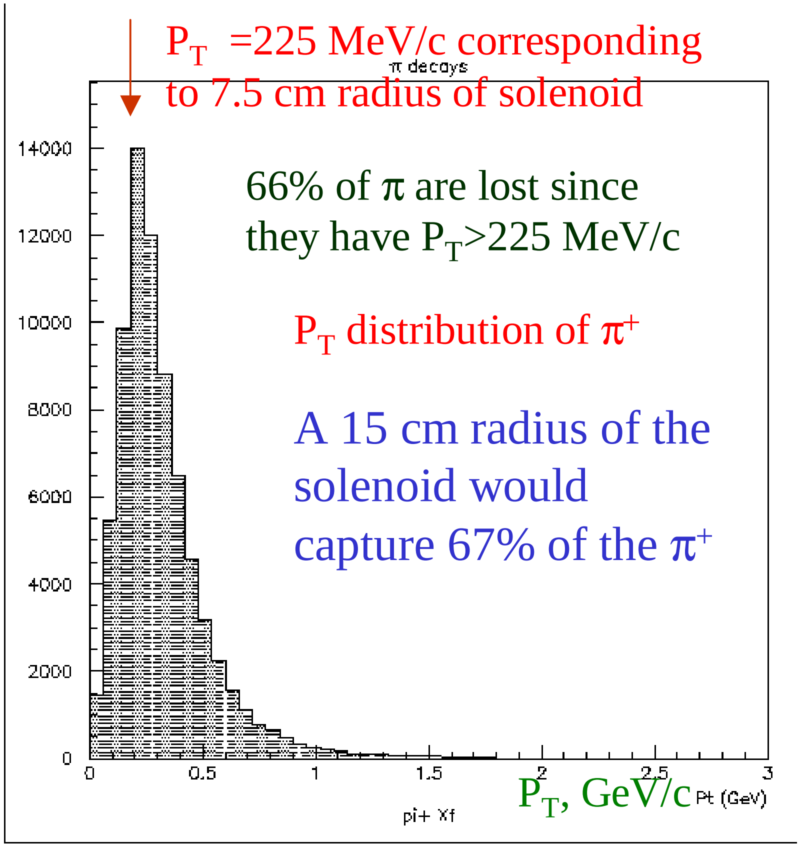


- If only ν and not ν̄ is desired, then a dipole magnet could be inserted between adjacent solenoids above.
- Inserting a dipole also gives control over the mean energy of the neutrino beam.
- Since ν and ν̄ events can be separated with a modest magnetic field in the detector, it will be desirable to 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 $\nu_e\ /\nu_{\mu}$ flux ratios.

Captured Pion Distributions



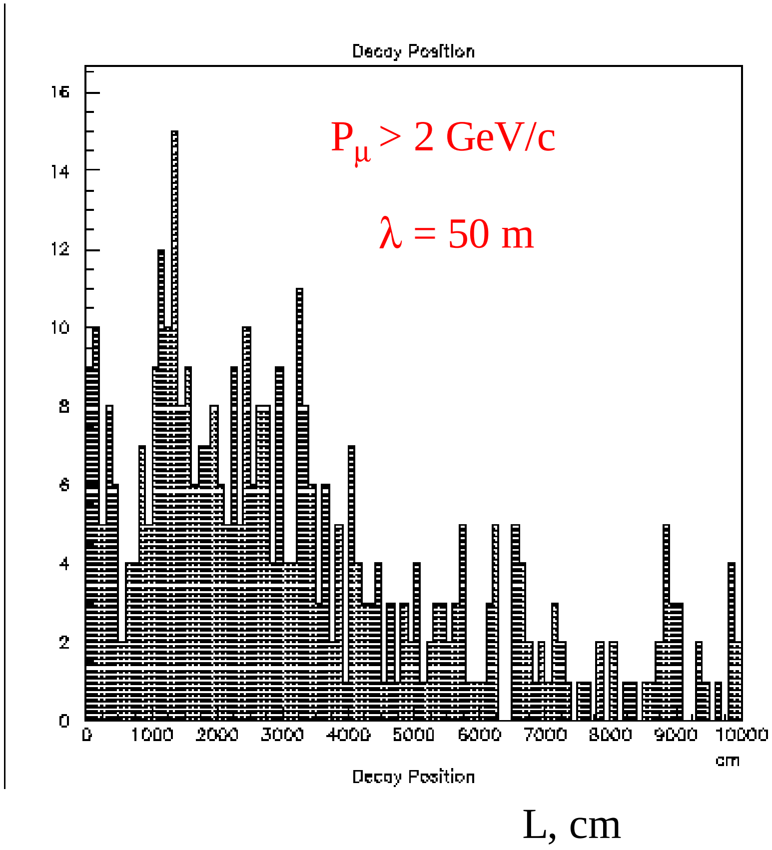
P_T =225 MeV/c corresponding to 7.5 cm radius of solenoid

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

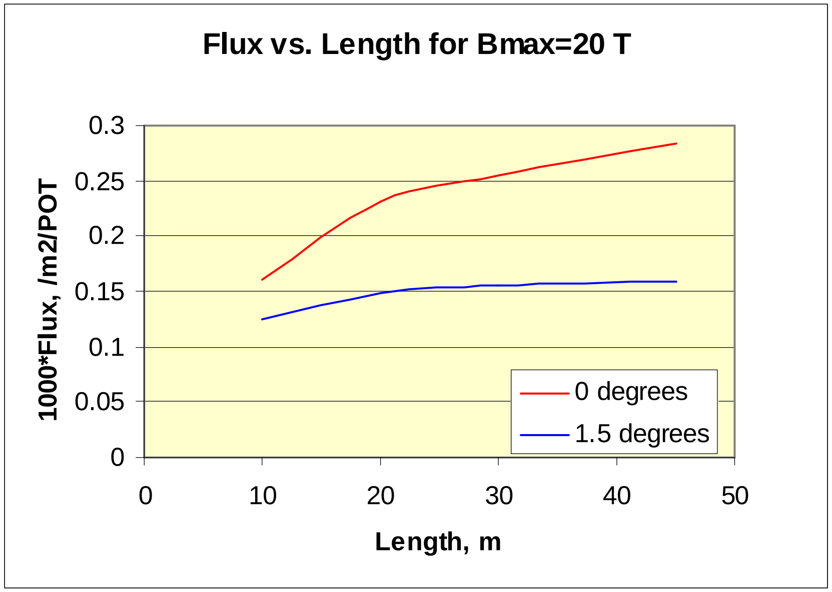


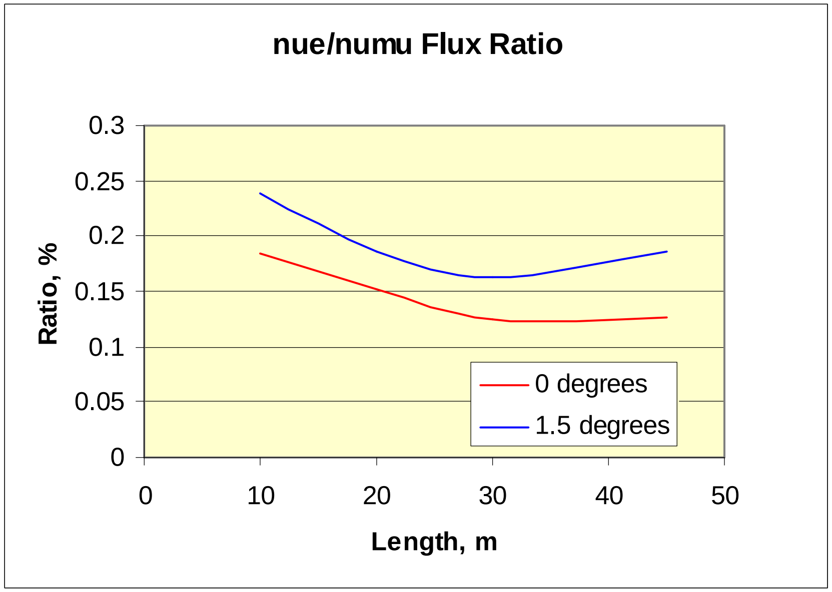
P_μ > 2 GeV/c

λ = 50 m

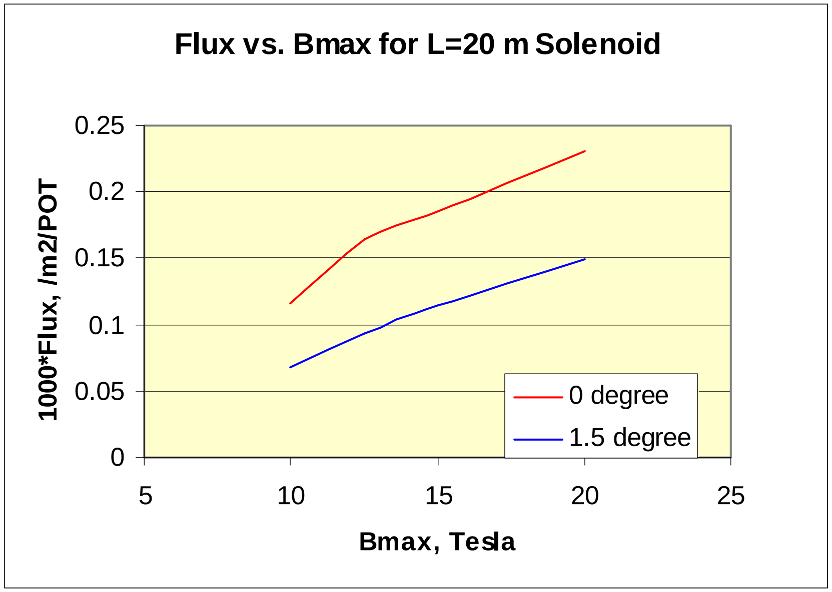
L, cm

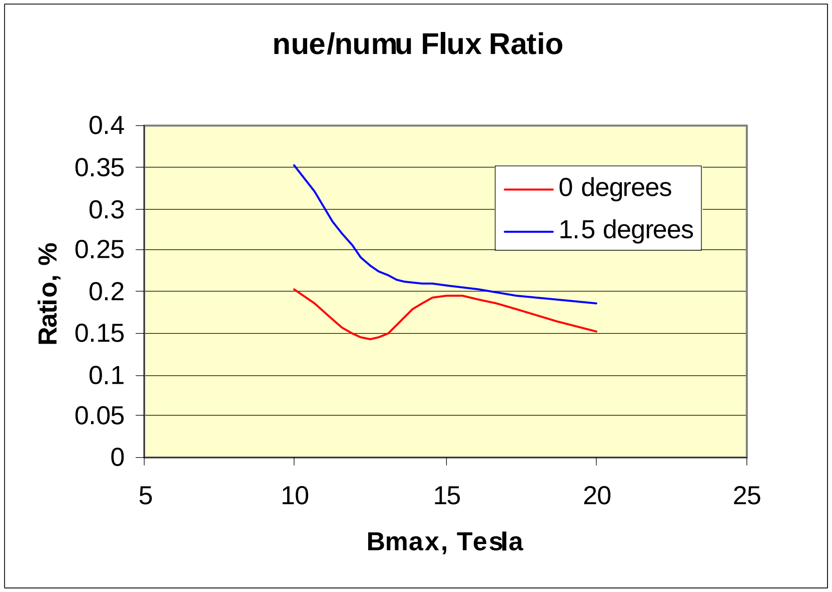
Flux as a function of Solenoid Length





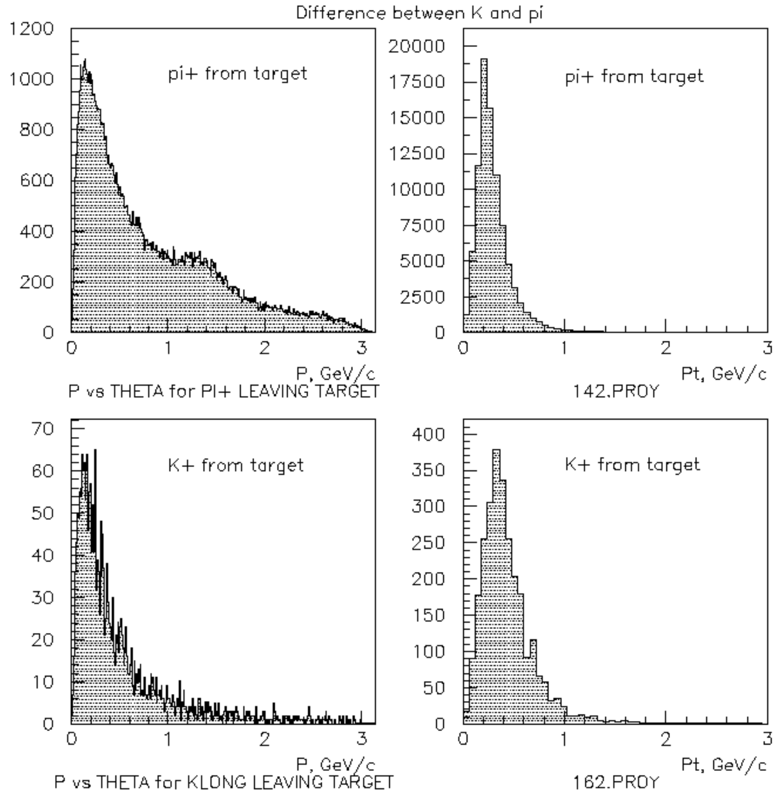
Flux as a Function of Capture Field





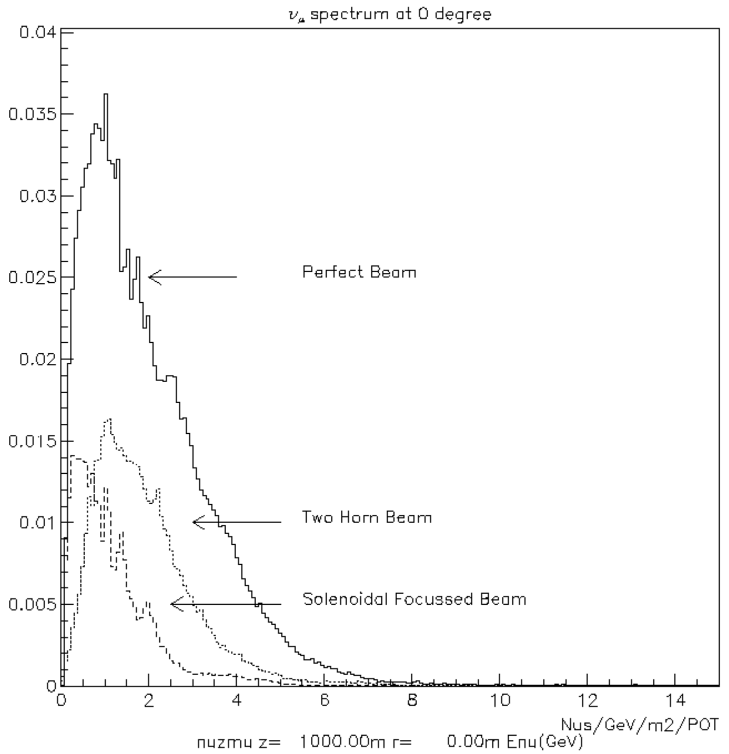
ν_e/ν_μ Ratio

- The solenoid capture system sees a smaller ν_e/ν_μ flux ratio than traditional horn systems.
  - We see $\nu_e/\nu_\mu \approx 0.15\%$ as opposed to the 0.8% in horn beams.
- The solenoid captures a lower E_ν spectrum.
- The P_T of the K^+ are larger than that of the π^+.
  - This can explain only part of it.
- The π distribution is more forward in the center of mass than the K distribution.



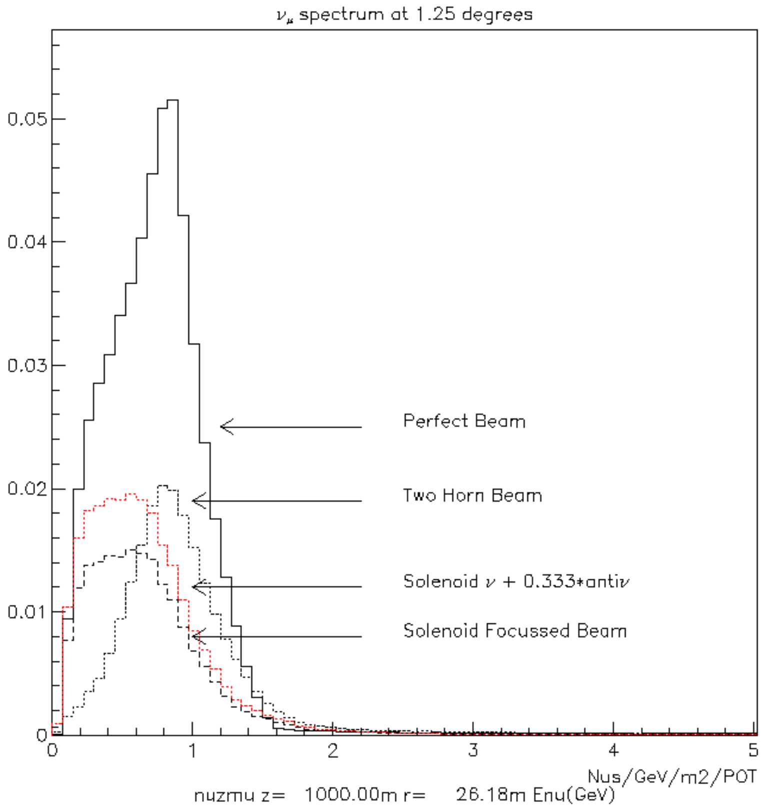
Comparison of Horn and Solenoid Focused Beams

- 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.

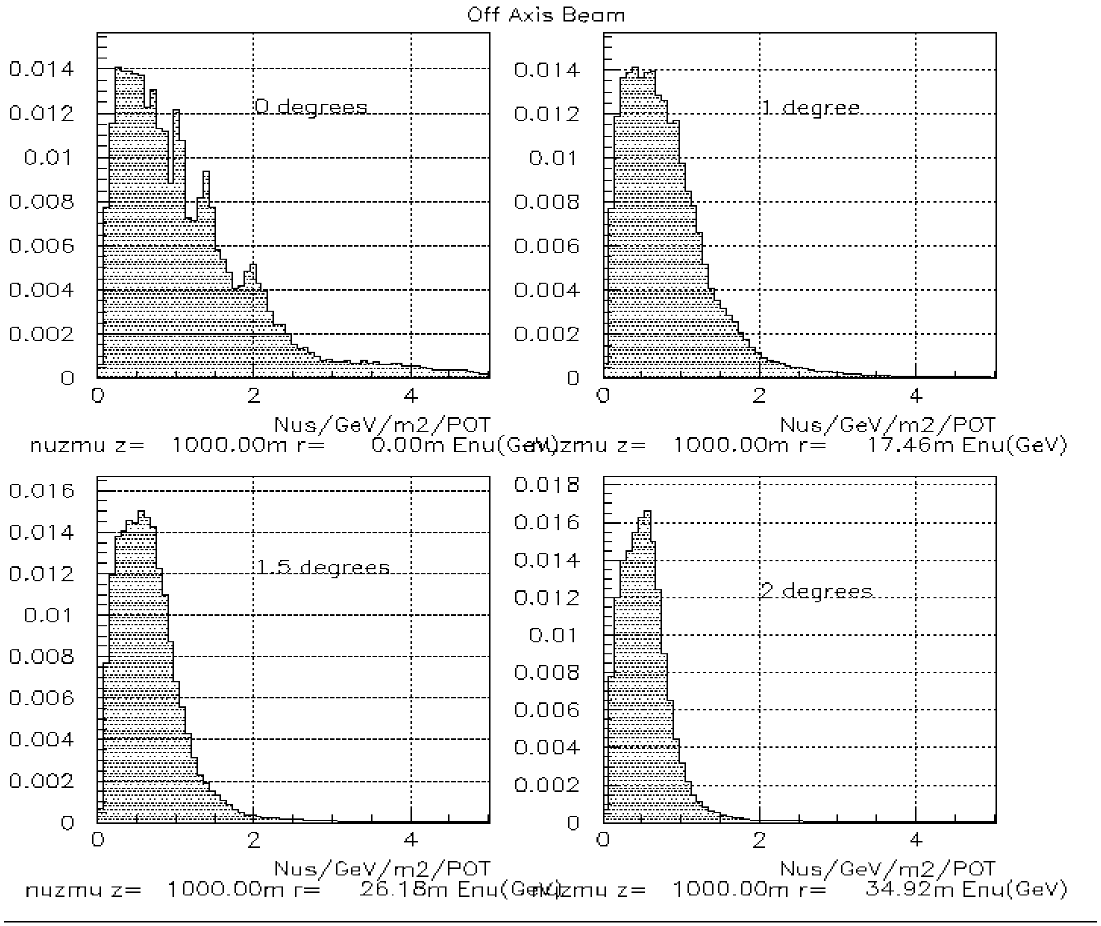


ν Flux Seen at Off-Axis Angles

- 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.



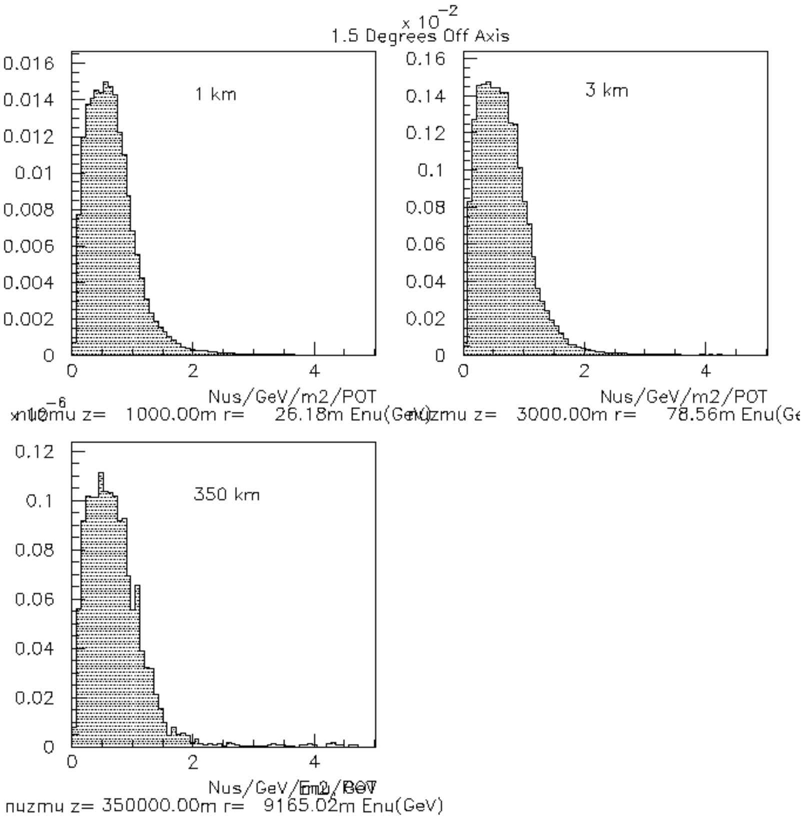
Detector Choices

- 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^o Off ν Beam Axis

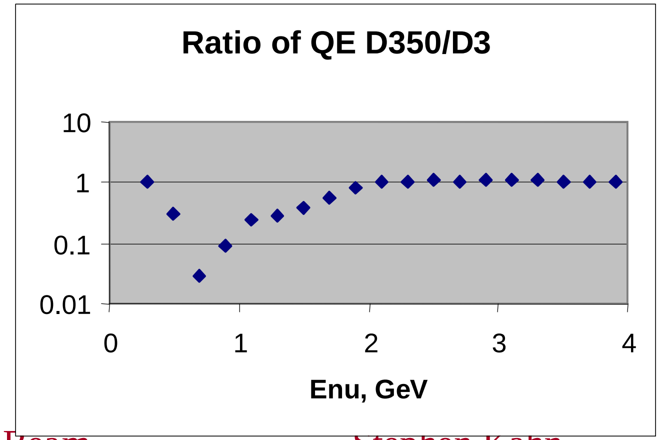
- Placing detectors at a fixed angle off axis provides a similar E_ν profile at all distances.
- It also provides a lower E_ν distribution than on axis.
- μ from π decays are captured by long solenoid channel. They provide low E_ν enhancement.
- Integrated flux at each detector:
  - Units are ν/m^2/POT

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 $P(\nu_\mu \rightarrow \nu_e)$:
  - 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.
  - Terms involving the CP phase δ:
    - There are both CP conserving and violating terms involving δ.
    - The CP violating term can be measured as

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

    - This asymmetry is larger at lower $E_{\nu.}$ 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	9.95×10^4	14978
At 3 km	4.17×10^6	9.44×10^5	4.28×10^5	1.00×10^4	1477
At 350 km	15539	3455	1618	36.7	5.4

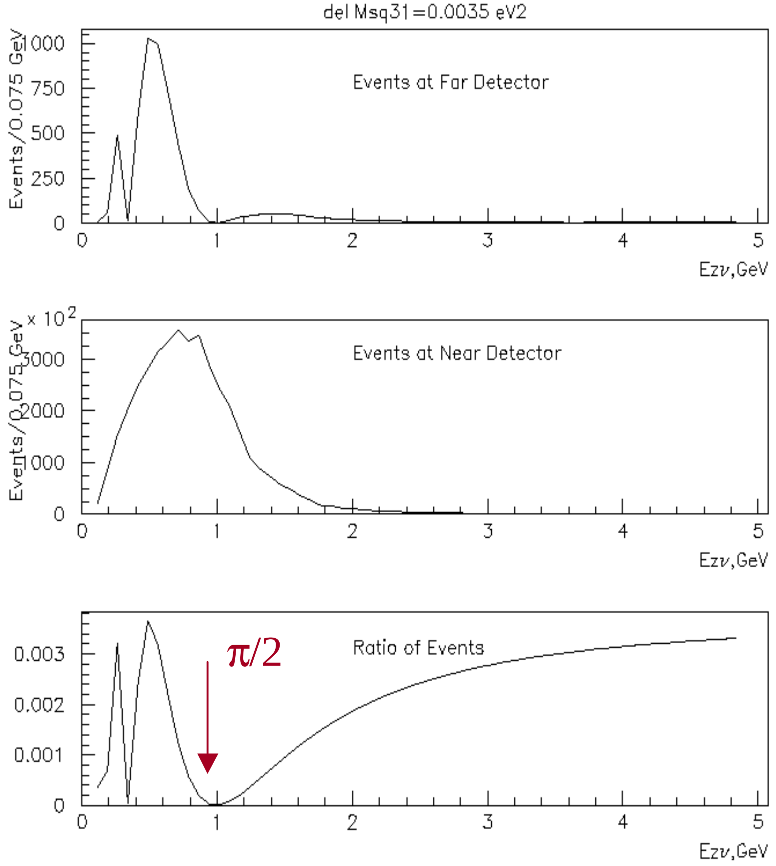
- Estimates with a 4 MW proton driver source would be four times larger.

Determination of Δm^2_{13}

- 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_{13} from

$$1.27\,\Delta m^2_{13} L/E_0=\pi/2$$

Where E_0 is the corresponding null point



Barger, Marfatia and Whisnant Table

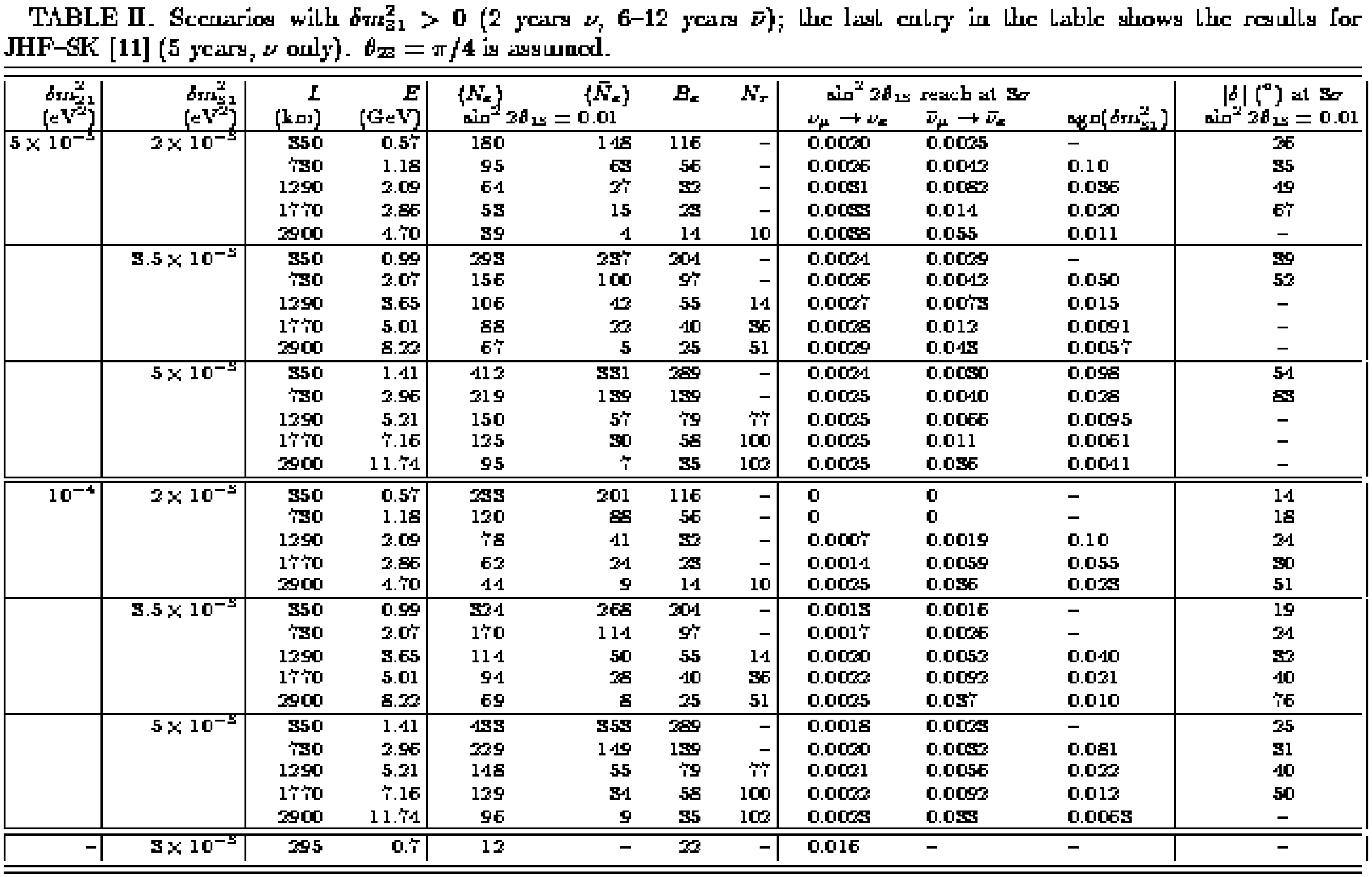


TABLE II. Scenarios with $\delta m^2_{31} > 0$ (2 years ν, 6–12 years $\bar{\nu}$); the last entry in the table shows the results for JHF–SK [11] (5 years, ν only). $\theta_{23} = \pi/4$ is assumed.

δm^2_{31} (eV^2)	δm^2_{21} (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
				$\sin^2 2\theta_{13} = 0.01$				$\nu_\mu \to \nu_e$	$\bar{\nu}_\mu \to \bar{\nu}_e$	$\mathrm{sgn}(\delta m^2_{31})$	$\sin^2 2\theta_{13} = 0.01$
5×10^{-3}	2×10^{-5}	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	27	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^{-5}	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^{-5}	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^{-5}	350	0.57	233	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^{-5}	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	0.021	40
		2900	8.22	69	8	25	51	0.0025	0.037	0.010	76
	5×10^{-5}	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^{-5}	295	0.7	12	–	22	–	0.016	–	–	–

Oscillation Signal

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 miles away.
- Experiment running for 5×10^7 seconds.
- Solenoid capture system with ν_e/ν_μ flux ratio=0.15 %

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		37	3455		5.4
0.002	5065	76	37	1096	18.5	5.4
0.0035	5284	70	37	1283	16.2	5.4
0.005	7722	55	37	1762	13.1	5.4

•For comparison we have 28% of the flux used in Barger et al.

•We use a not necessarily optimum L/E fixed configuration for all cases.

•We use an actual flux distribution, not a monochromatic ν beam (as used in Barger et al.).

•We see a quite significant appearance signal.

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 ~0.15% ν_e/ν_μ flux ratio in the capture configuration that was used in this study. This yields a 0.25% 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!