Outline of talk

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Shelter Island

- MINOS Beam and Detectors
- Physics potential
- Current status and schedule
- Possible/considered improvements
- ν oscillation future
- Very long baseline approach
- Off-axis or short baseline approach
- Comparisons of various proposals
- Conclusion

Our view of the future of neutrino oscillations.

- A study group is working at BNL. Charge to the study group provided by Tom Kirk.
- Atmospheric Neutrinos $\nu_\mu \to \nu_\tau$ at 1 σ

$$\sin^2 2\theta_{23} > 0.9$$

$$\Delta m^2_{32} = (2.0 - 4.2) \times 10^{-3} eV^2$$

Best fit:$2.6 \times 10^{-3} eV^2$, $\sin^2 2\theta_{23} = 0.92$.

C. K. Jung, T. Kajita, T. Mann, and C. McGrew Annu. Rev. Nucl. Part. Sci. 2001 , Vol. 51: 451-488.

- Solar Neutrinos $\nu_e \to (\nu_\mu, \nu_\tau)$ at 1 σ New results from SNO. A complete fit to all data by the SNO collaboration (nucl-ex/0204008, nucl-ex/0204009)

LMA solution greatly favored.

$$\sin^2 2\theta_{12} = (0.64 - 0.85)$$

$$\Delta m^2_{21} = (3.2 - 12.6) \times 10^{-5} eV^2$$

- Null reactor Exps $\bar{\nu}_e \to \bar{\nu}_e$

$$\sin^2 2\theta_{13} < 0.12$$

- CP violation

  Nothing is known.

  Some additional information

  LSND Sterile neutrinos ?

$$\sin^2 2\theta_{12} \approx \ few \times 10^{-3}$$

$$3 \times 10^{-2} < \Delta m_{21}^2 < 3eV^2$$

  Upward going muons
  No evidence for sterile neutrinos in atmospheric Osc.
  K2K (56 observed with 80 expected) disappearance agrees with ν_μ disappearance hypothesis.

4 GOALS OF NEUTRINO PHYSICS

- Precise determination of Δm^2_{32} and definitive observation of oscillatory behavior.
- Detection of $\nu_\mu \to \nu_e$ in the appearance mode. If $\Delta m^2_{\nu_\mu \to \nu_e} = \Delta m^2_{32}$ then $|U_{e3}|^2$ $(= \sin^2\theta_{13})$ is non-zero.
- Detection of the matter enhancement effect in $\nu_\mu \to \nu_e$. Sign of Δm^2_{32}; i.e. which neutrino is heavier.
- Detection of CP violation in neutrino physics. Phase of $|U_{e3}|$ is CP violating and causes asymmetry in the rates $\nu_\mu \to \nu_e$ versus $\bar{\nu}_\mu \to \bar{\nu}_e$.

$$P(\nu_a \to \nu_b) = \sin^2 2\theta \sin^2 \frac{1.27(\Delta m^2/eV^2)(L/km)}{(E/GeV)}$$

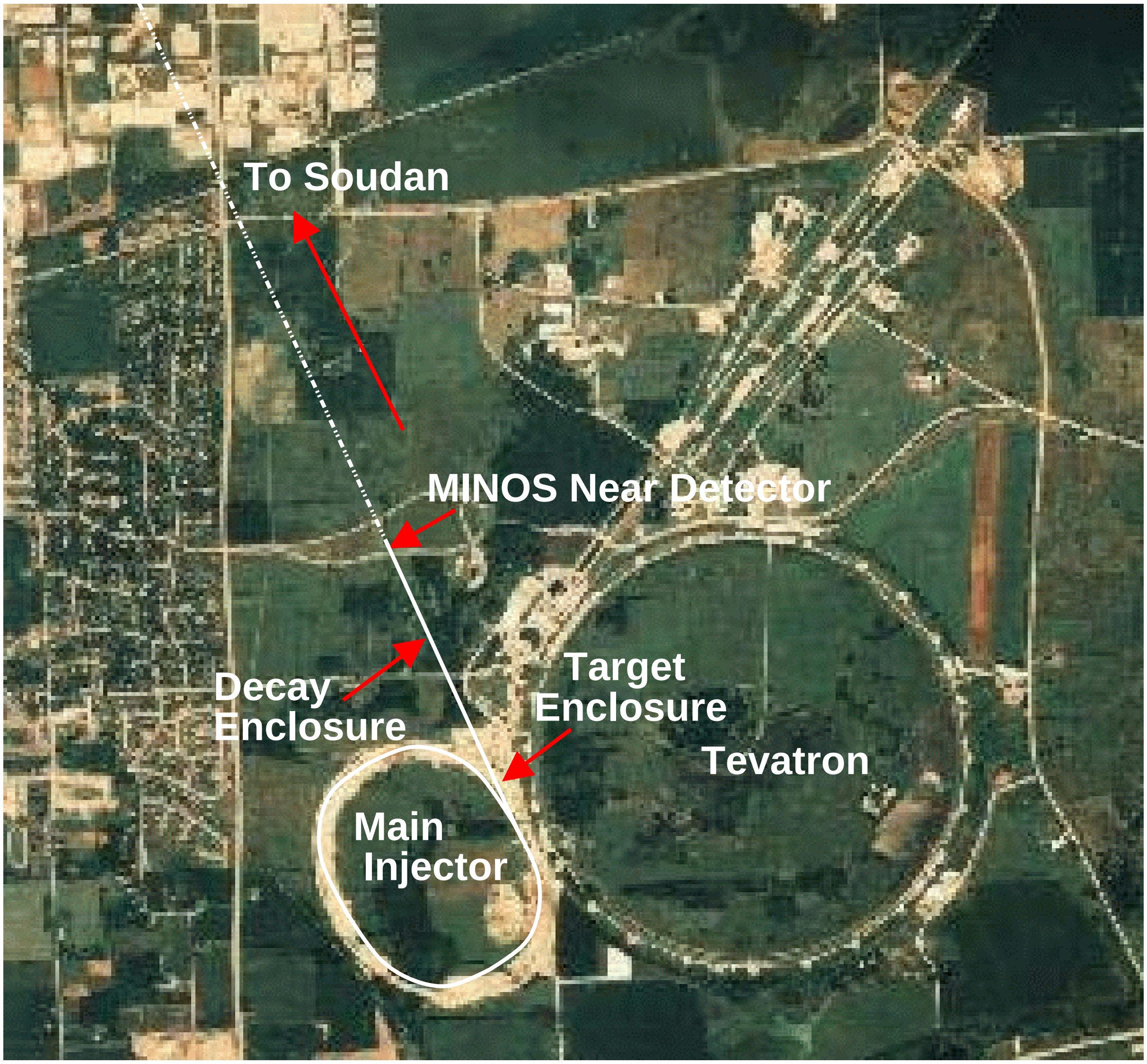
Oscillation nodes at $\pi/2, 3\pi/2, 5\pi/2, \ldots$ $(\pi/2)$: $\Delta m^2 = 0.003 eV^2$, $E = 1 GeV$, $L = 412 km$.

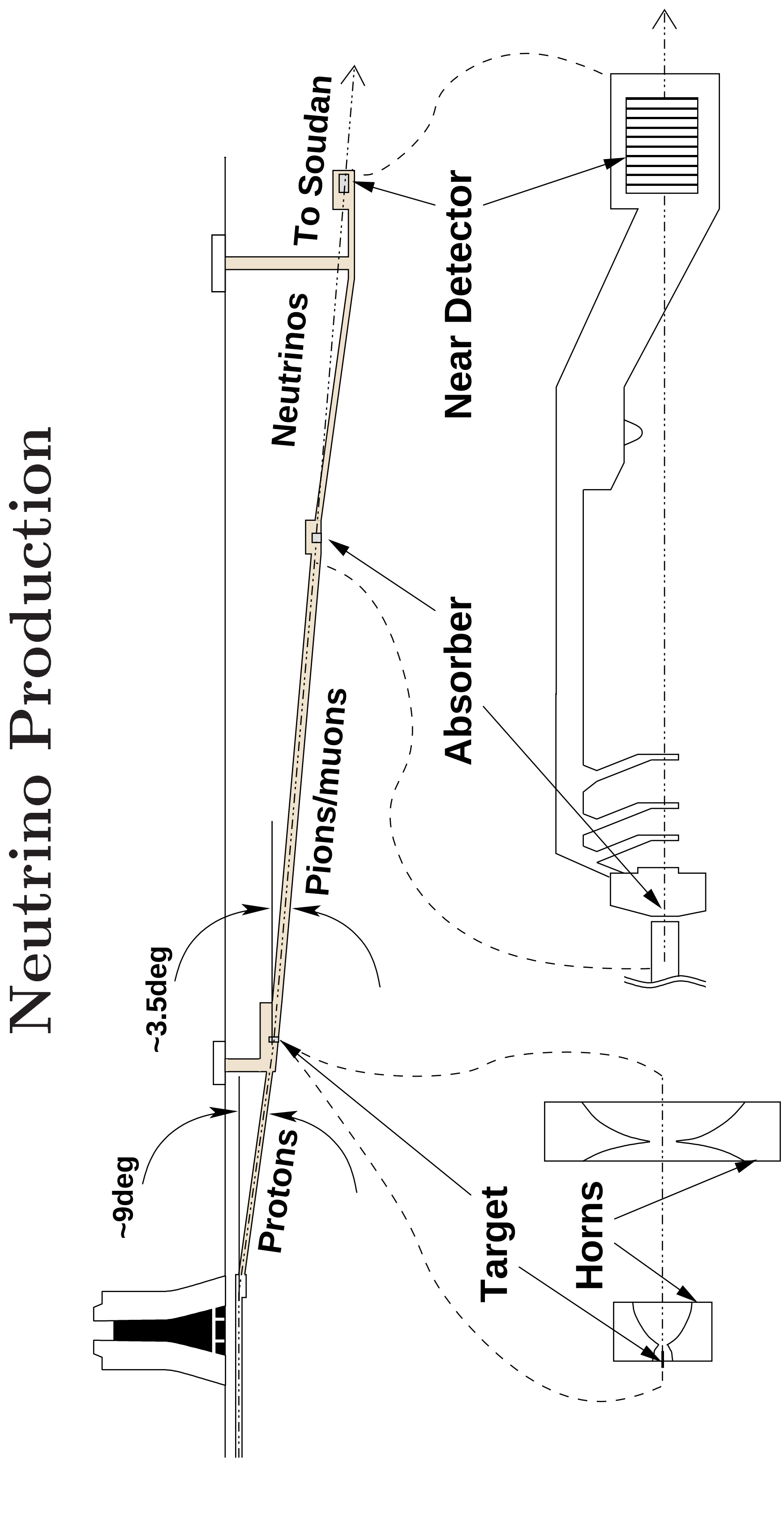
MINOS Overview

MINOS = **M**ain **I**njector **N**eutrino **O**scillation **S**earch

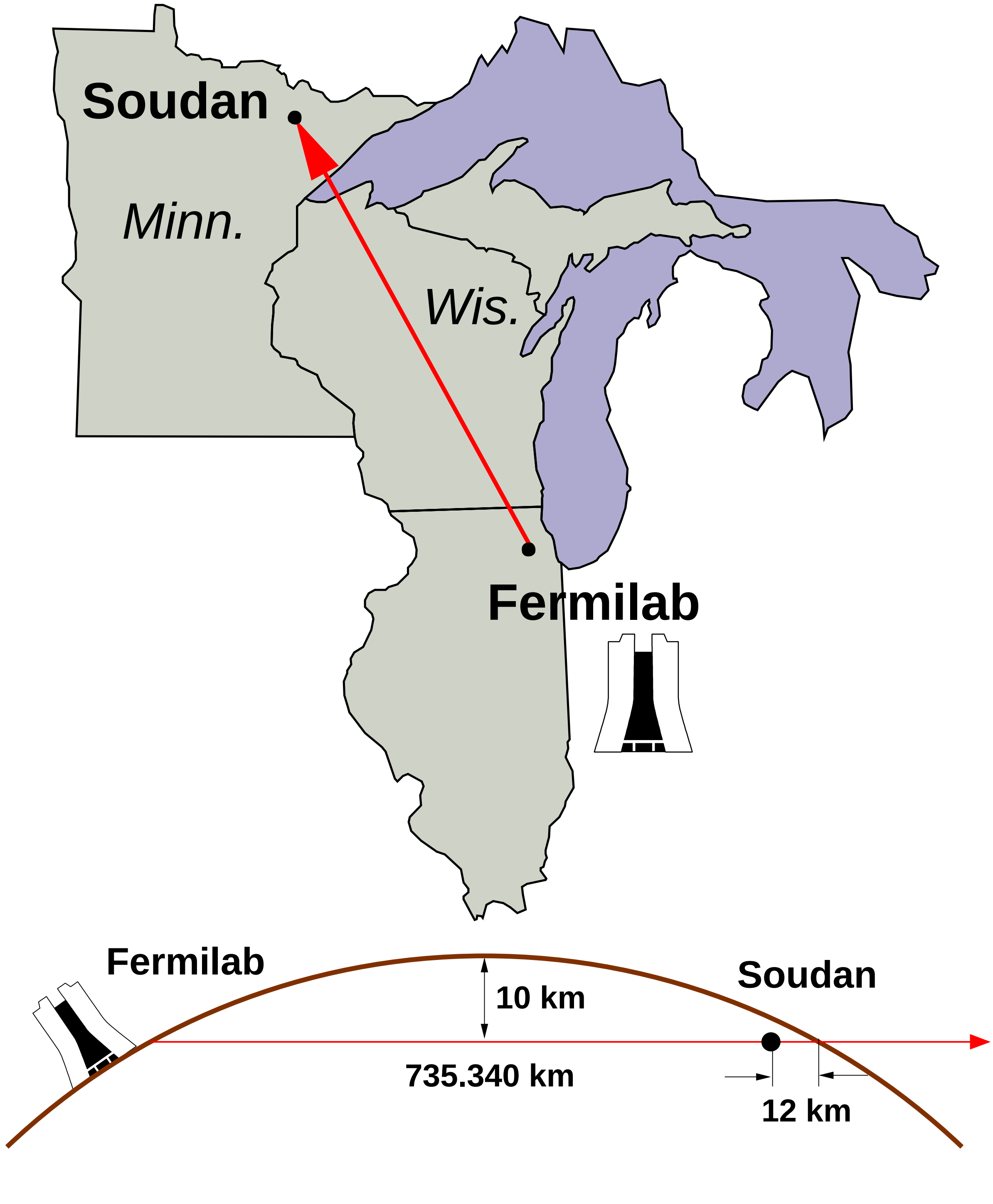
- 120 GeV MI protons on graphite target
  - 5/6 batches ($\bar{p}$/no $\bar{p}$)
  - 84 3-8 ns bunches/batch
  - 8.1 or 9.8 μsec spill every 1.9 sec
  - 4×10^{13} protons/spill (max)
  - 3.8×10^{20} protons/year
- 2 horn pion focusing
- "LE" 1-6 GeV neutrinos w/ tail out to 50 GeV
- 735.340 km baseline.
- Near and Far iron/scintillator detectors
  - Near @ FNAL: 3 events/spill in "target region"
  - Far @ Soudan, MINN: 3000 ν_μ CC events/kt/yr (no osc.)

Aerial View

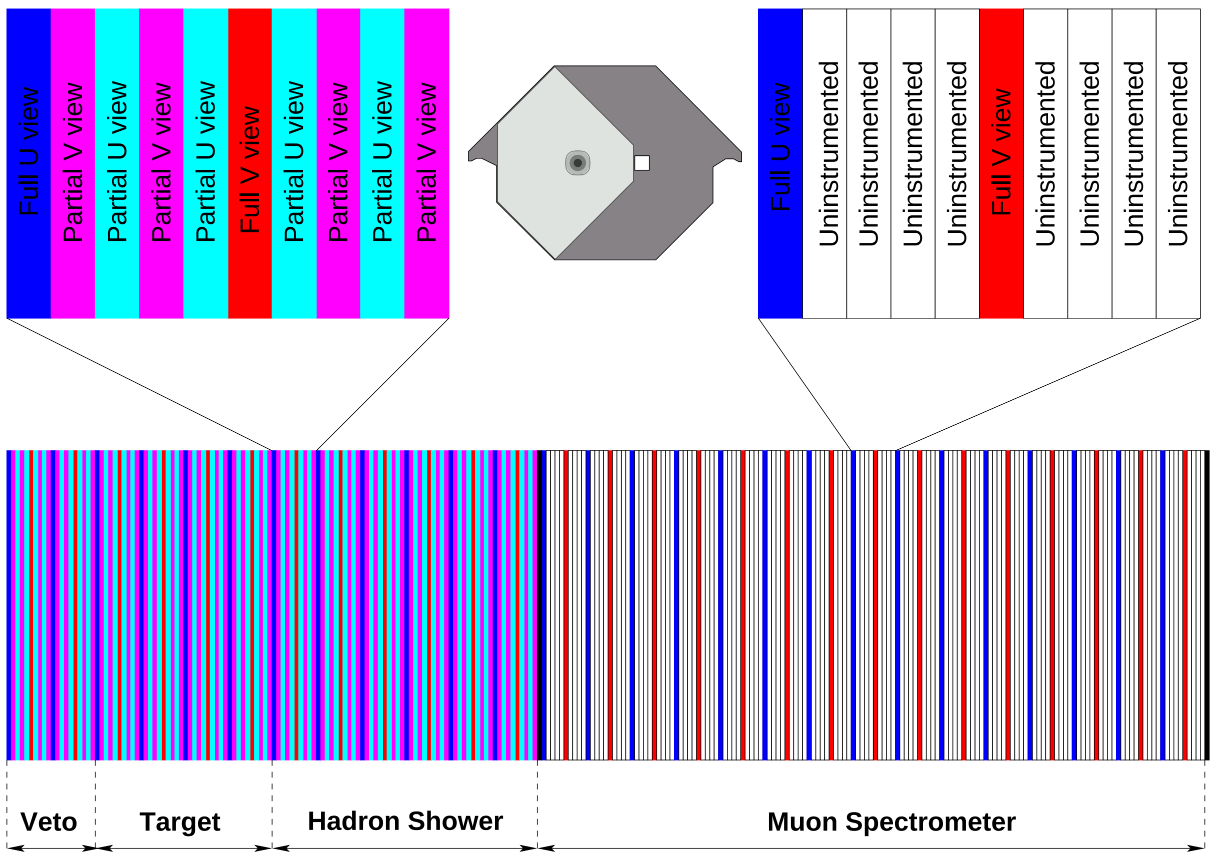

To Soudan
MINOS Near Detector
Decay
Enclosure
Target
Enclosure
Tevatron
Main
Injector


Neutrino Production
To Soudan
Near Detector
Neutrinos
Absorber
Pions/muons
~3.5deg
~9deg
Protons
Target
Horns

Base Line

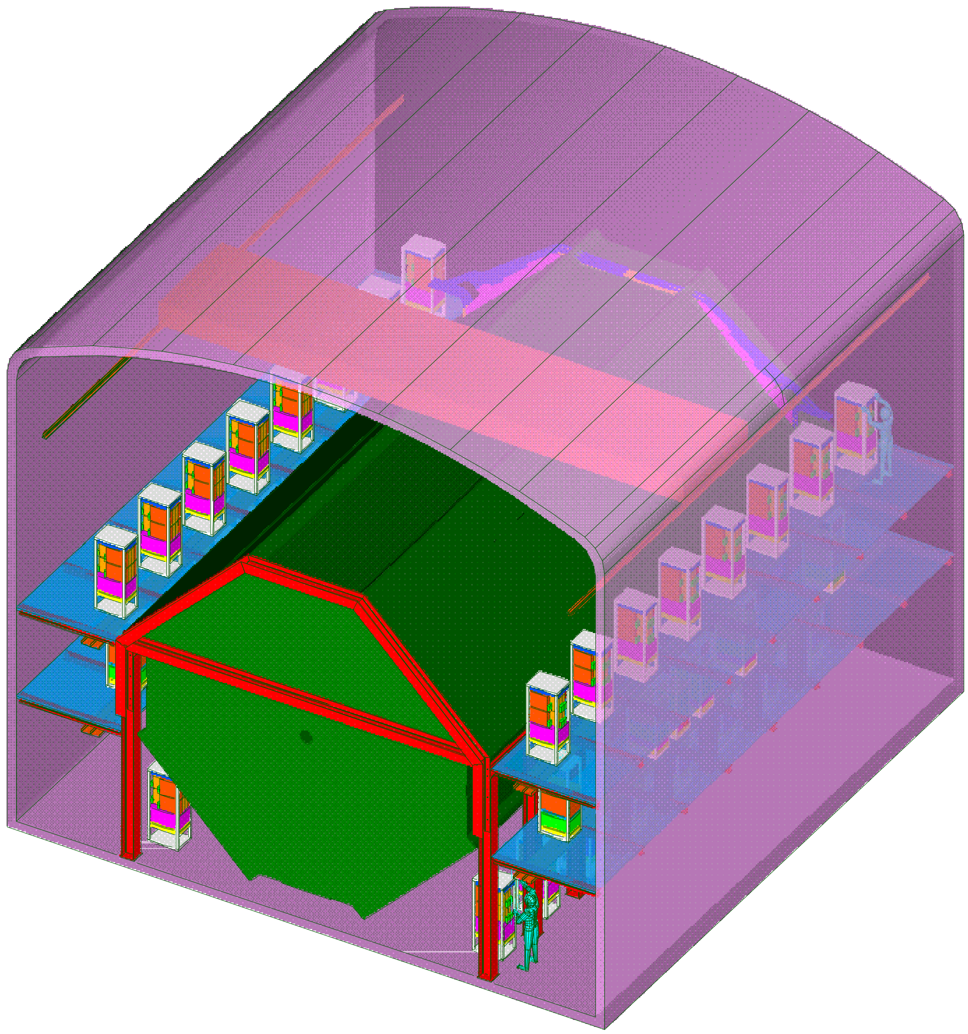

Soudan
Minn.
Wis.
Fermilab
Fermilab
Soudan
10 km
735.340 km
12 km

Near Detector



- 1kt (0.1kt fiducial).
- 282 steel planes
- 153 scintillator planes
- 68 or 96 scintillator strips/plane.
- 1 ended readout, no multiplexing

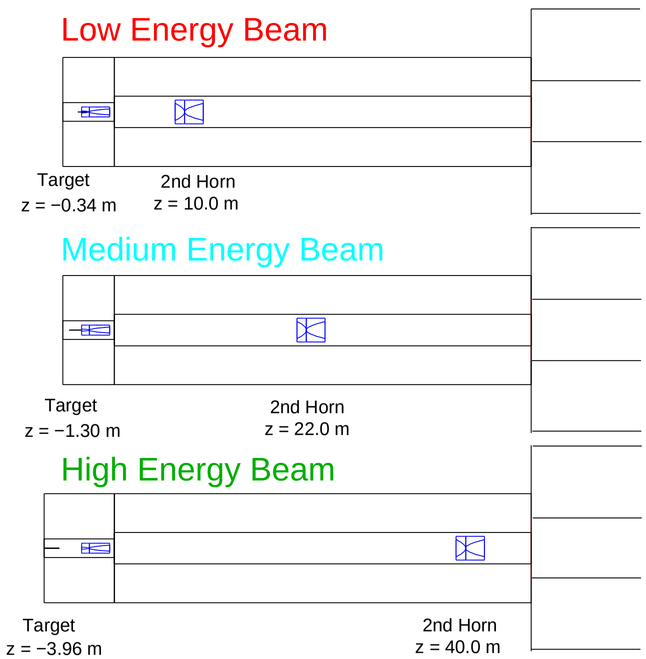
Far Detector

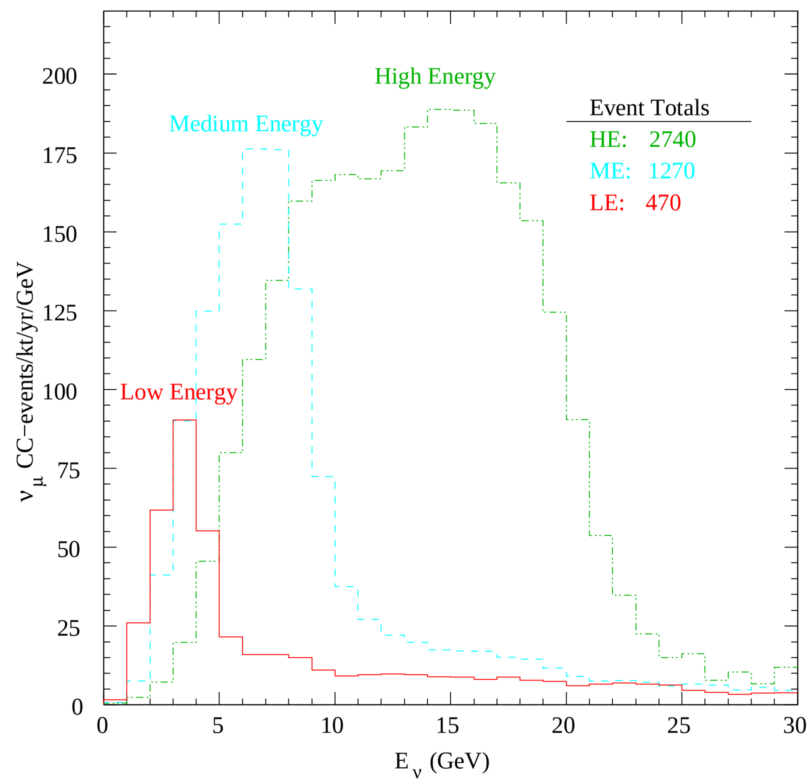


- 5.4kt (3.3kt fiducial)
- 486 steel planes (243/243)
- 484 scintillator planes (242/242)
- 192 scintillator strips/plane.
- 2 ended readout, 8x multiplexing

Expected Far Detector Interaction Spectra

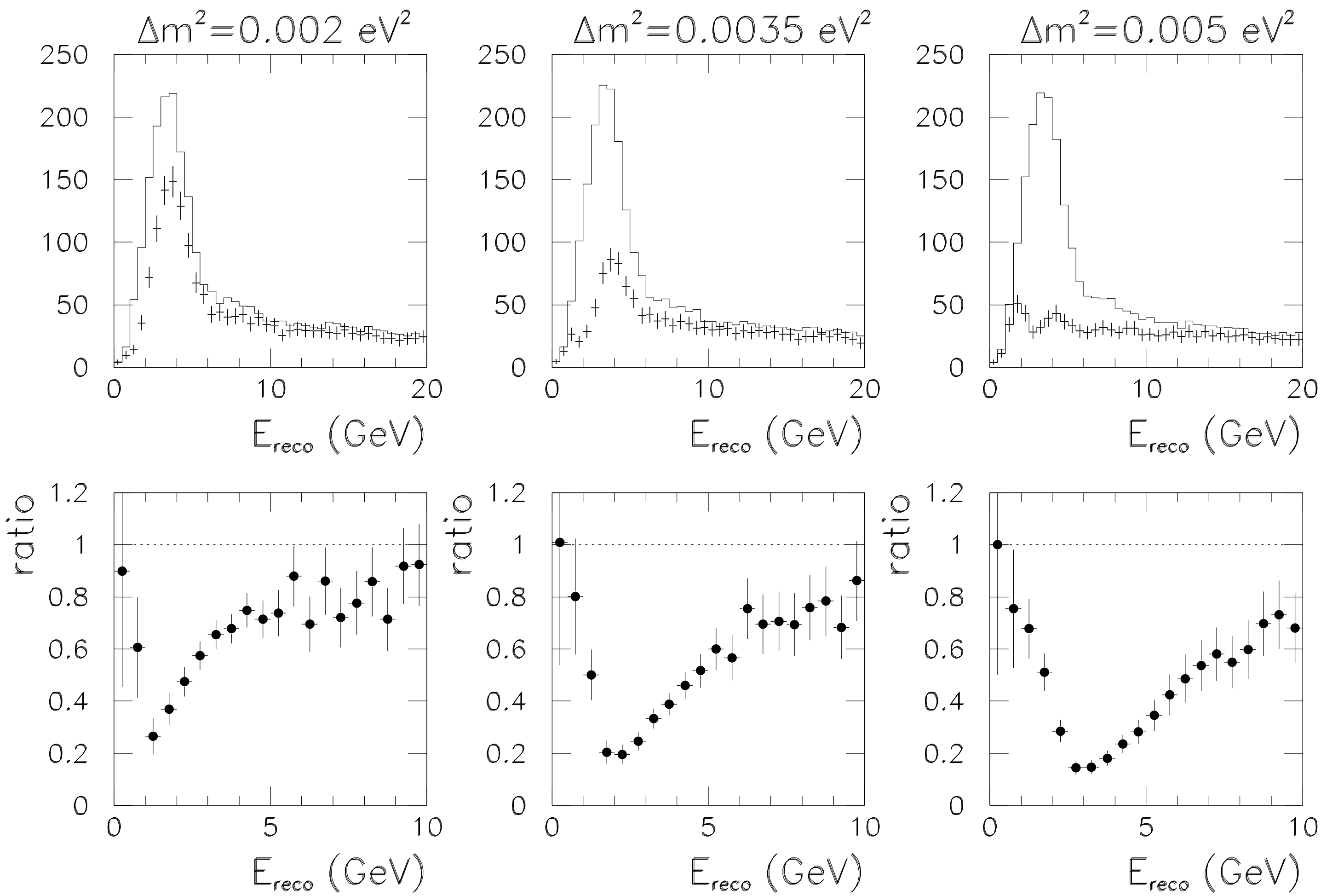
NuMI Beam Lines



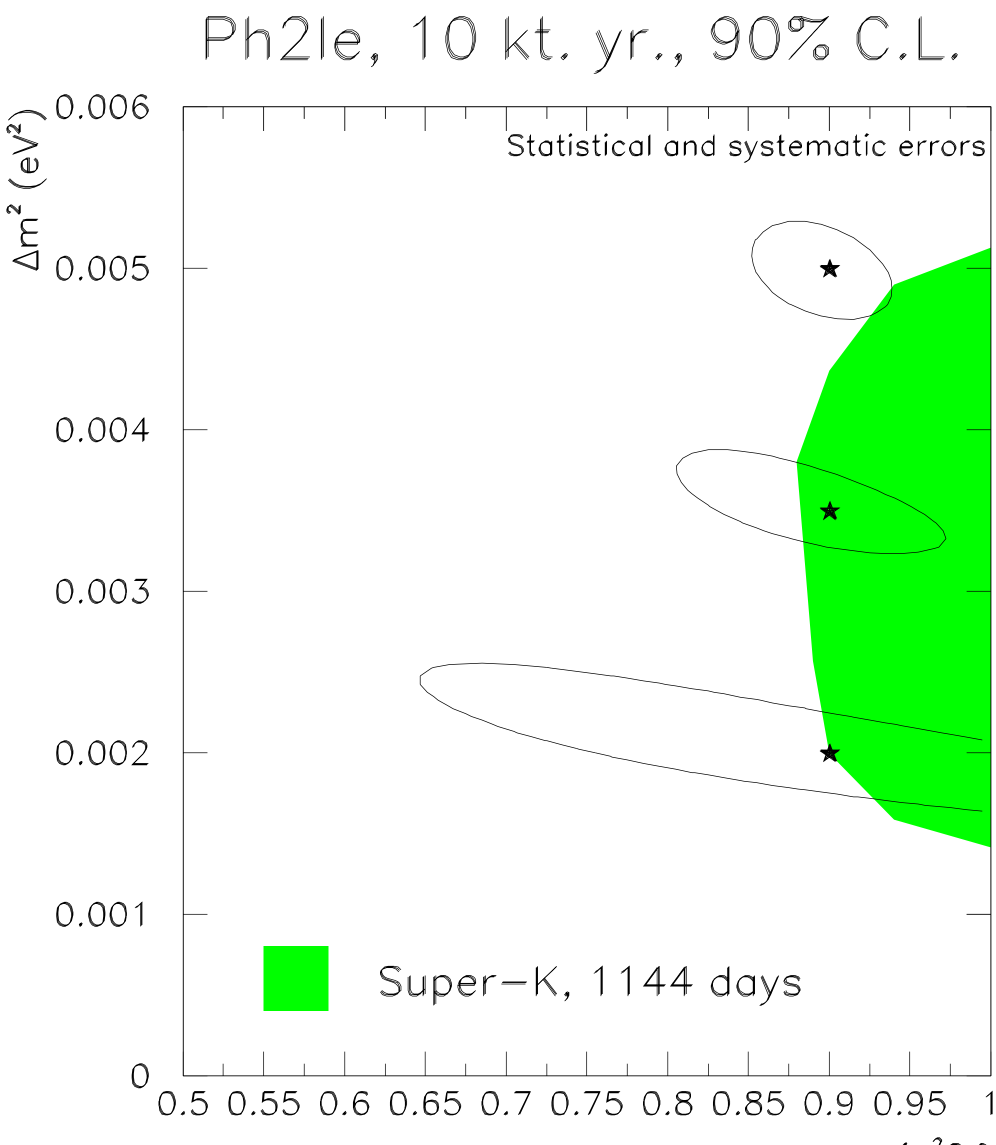


Expected Flux Distribution (ν_μ disappearance)

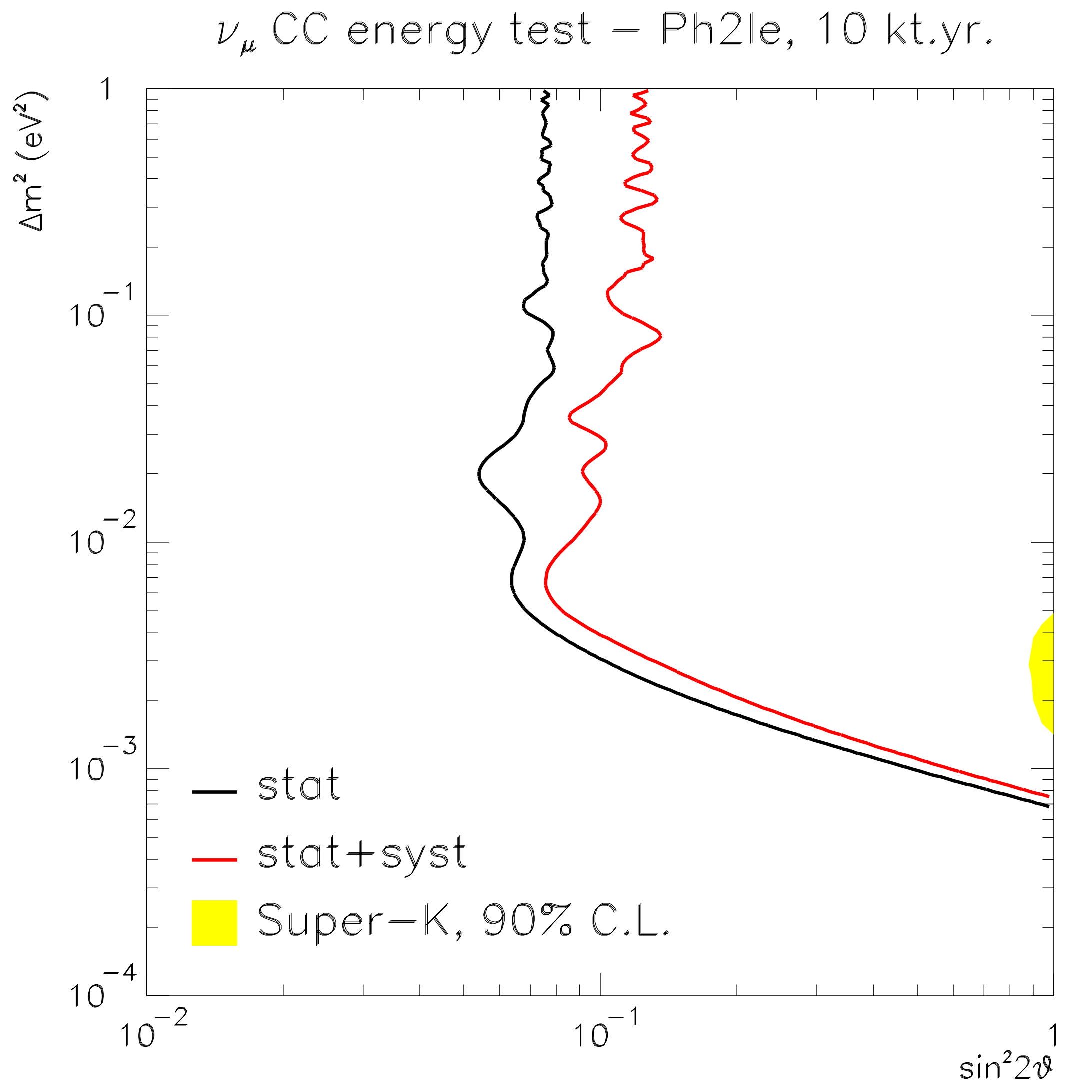
CC energy distributions – Ph2le, 10 kt.yr., $\sin^2(2\vartheta)=0.9$



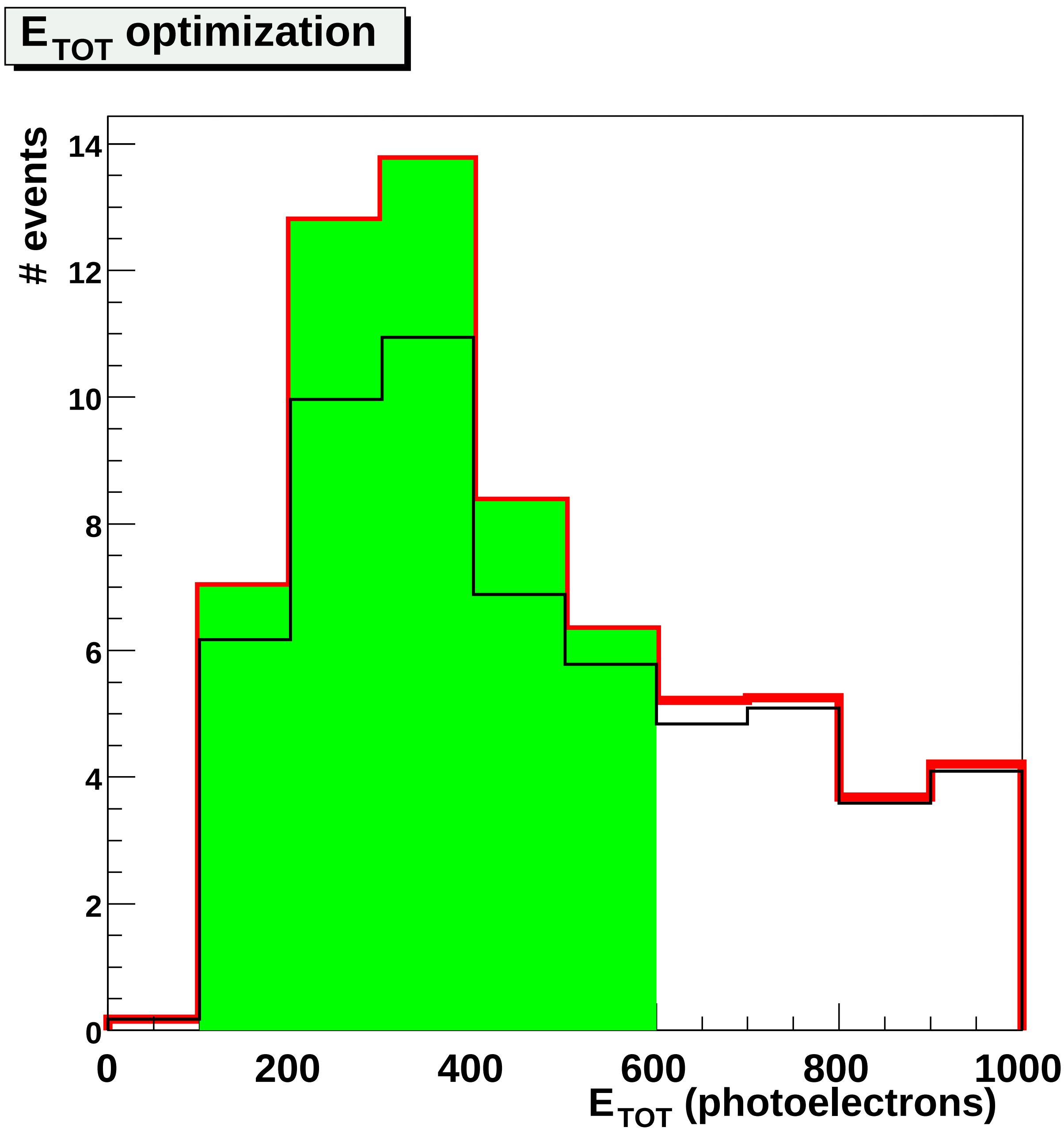
Expected Sensitivities
(ν_μ disappearance)



Expected Limits
(ν_μ disappearance)



Expected Signal/Background (ν_e appearance)



10 kt-yr, $U_{e3}^2 = 0.01$, $\delta m^2 = 0.003\,\mathrm{eV}^2$, $U_{\mu 3}^2 = U_{\tau 4}^2$

Problem for ν_e: NC background

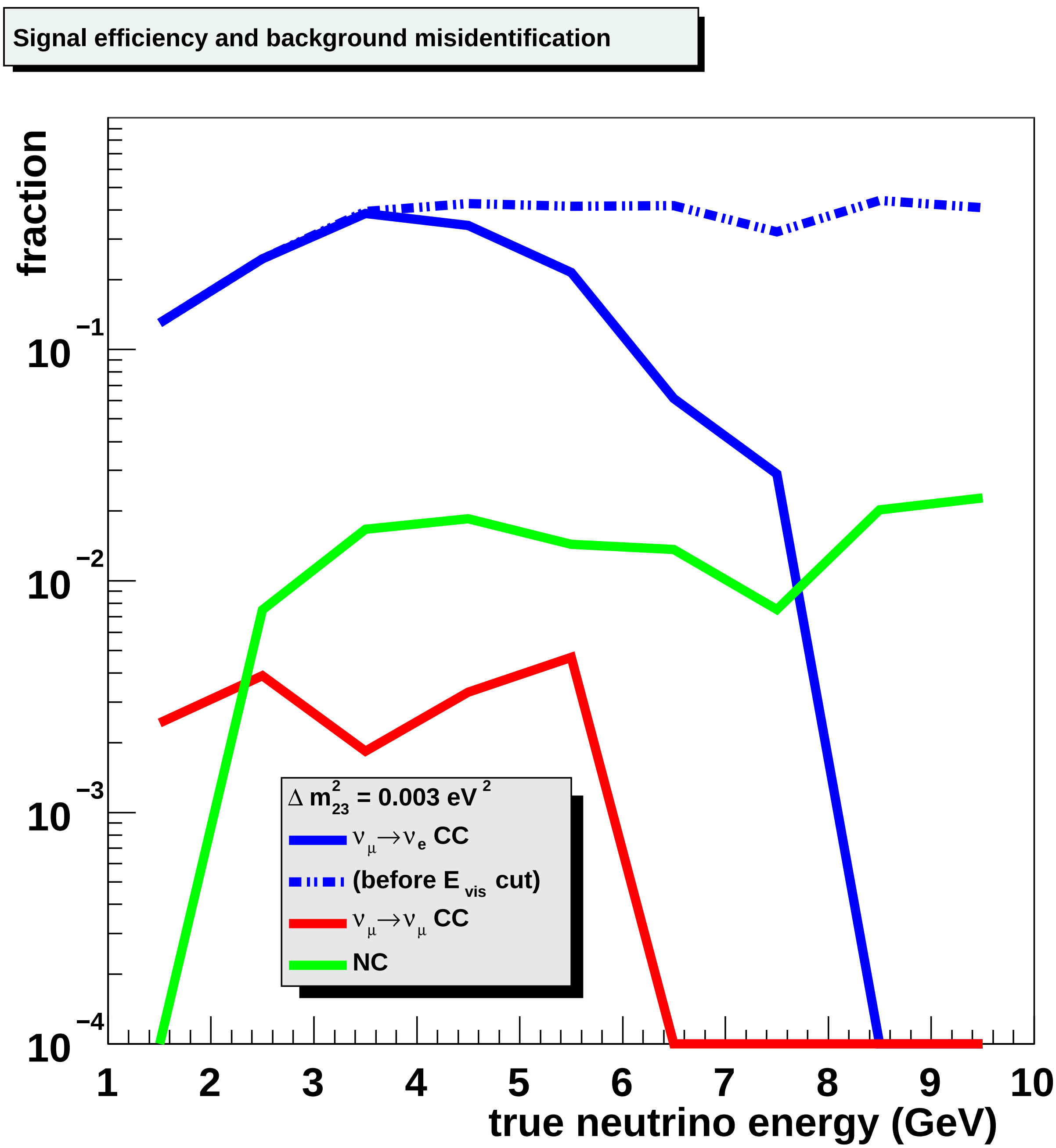
δm^2	signal	ν_e (intrinsic)	ν_μ CC	ν_τ CC	NC (E_ν <10 GeV)	NC (E_ν >10 GeV)
0.002	8	5.6	6.5	0	19	9.2
0.003	8.5	5.6	3.9	3.0	15.7	11.5
0.006	20	5.6	1.0	3.0	6	6.9

At $|U_{e3}|^2 = 0.01$

Baseline LE beam.

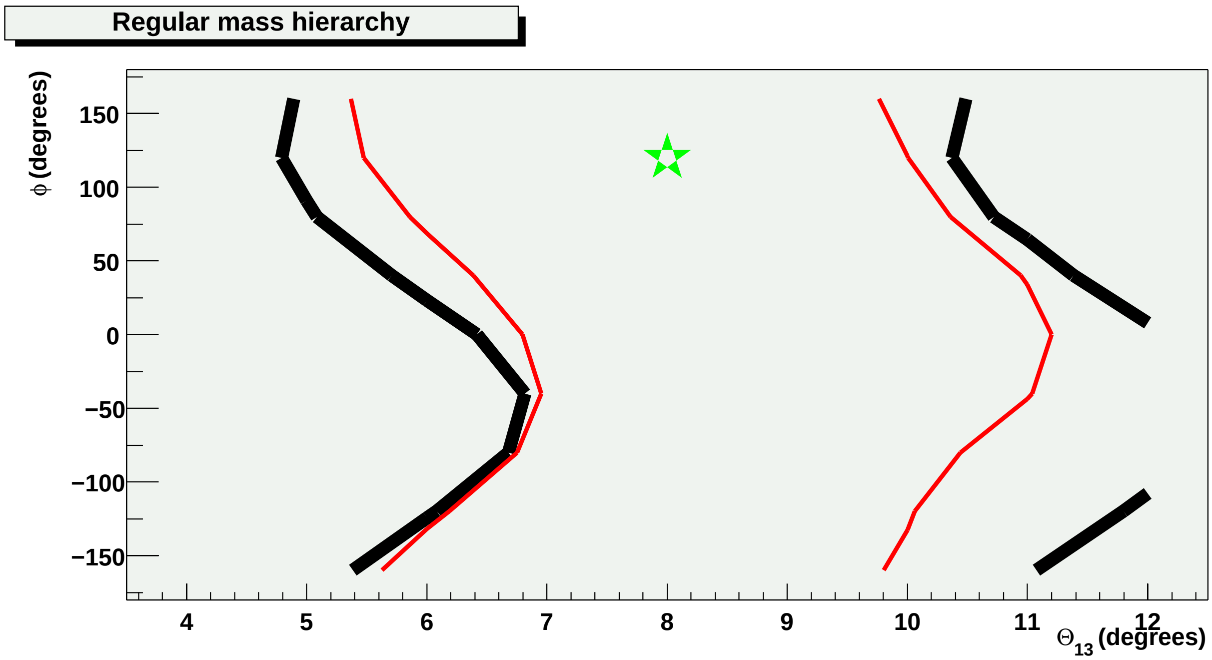
10 kton·years.

Expected Efficiency
(ν_e appearance)



$$\delta m^2 = 0.003\text{eV}^2$$

Expected Sensitivities
(ν_e appearance)

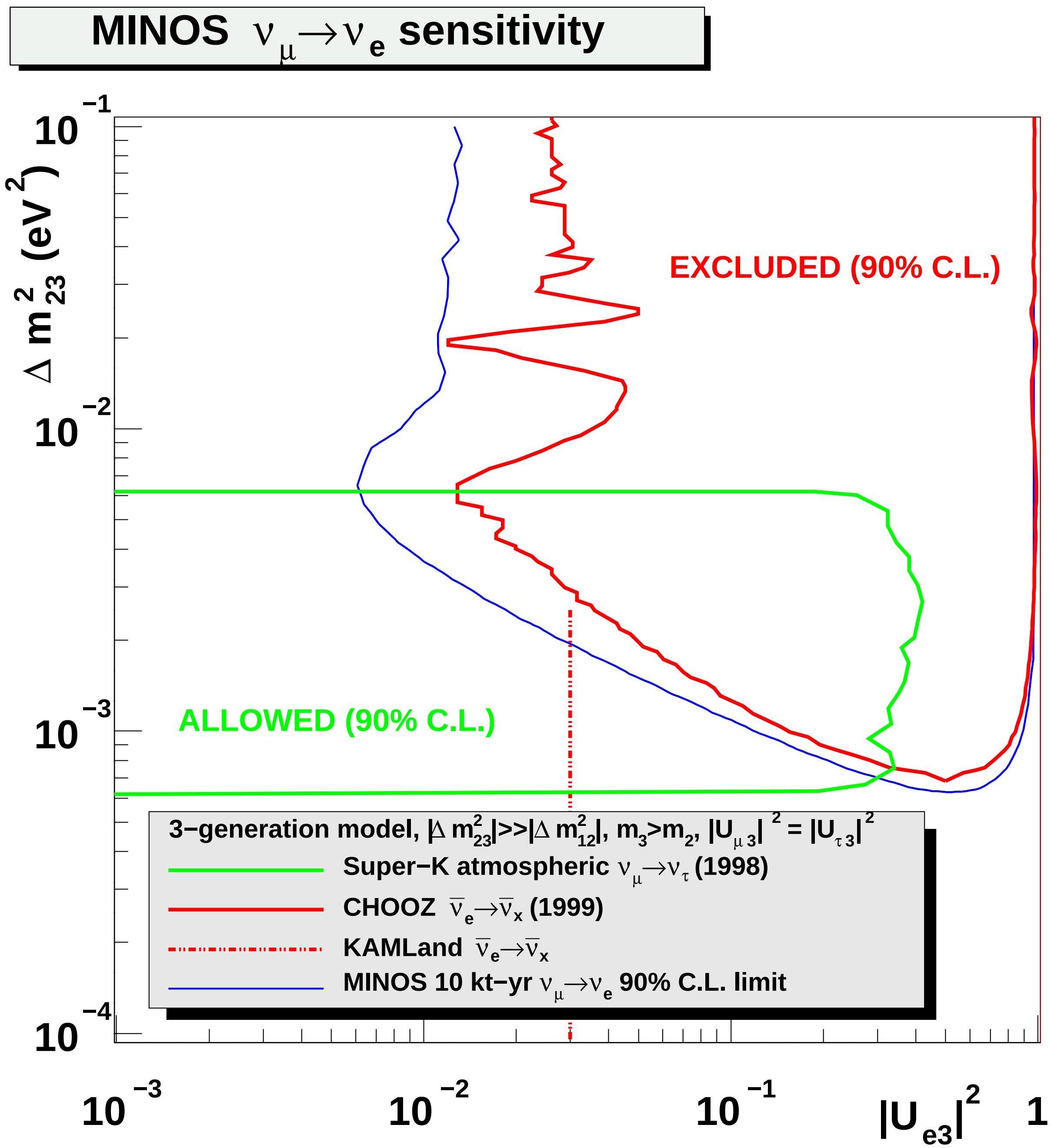


Green test point at $\theta_{13} = .14$, $\theta_{12} = \pi/4$, $\theta_{23} = \pi/4$, $\delta m^2_{12} = 0.0001\text{eV}^2$, $\delta m^2_{23} = 0.003\text{eV}^2$, $\phi = 2\pi/3$.

Black line is 1-σ, 10 kt-yr $\nu_\mu \rightarrow \nu_e$

Red line is 1-σ, 20 kt-yr $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

Expected Limits
(ν_e appearance)



Current Status and Schedule

- Calibration Detector taking data at CERN.
- NuMI turn on: First protons Dec 2004, Fully commissioned Feb 9, 2005.
- Near Detector tunnel finished. Beampipe being installed.
- Far Detector hall finished, 2.2 kT finished. Finish both super-modules: Oct 2003.
- First upward going muon detected.

Future Experimental Approach

- Muon storage ring neutrino factory !
- Send beam over a very long distance ($\sim 3000 km$) so that many oscillation nodes can be covered.
  - Can address all 4 goals.
  - Need much bigger detector.
  - Need an intense new beam.
- Send a narrow band beam to a distance precisely tuned for $\pi/2$ oscillation node.
  - Need to know Δm^2_{32} precisely.
  - Address $\nu_\mu \rightarrow \nu_e$ appearance goal. NEW DETECTOR
  - Probably not the best for matter enhancement study.
  - Use existing NUMI beam by going OFF-AXIS.
  - New intense beam for CP study.
- Send two beams to same detector !

Why go off-axis for neutrino beam ?

- Natural way to get a narrow band beam.
- Beam energy is almost independent of pion energy.
- Pions of a broad energy spectrum contribute to the same neutrino energy bin.
- No sacrifice of flux to get a narrow band beam.

Originally proposed by E889 Collaboration

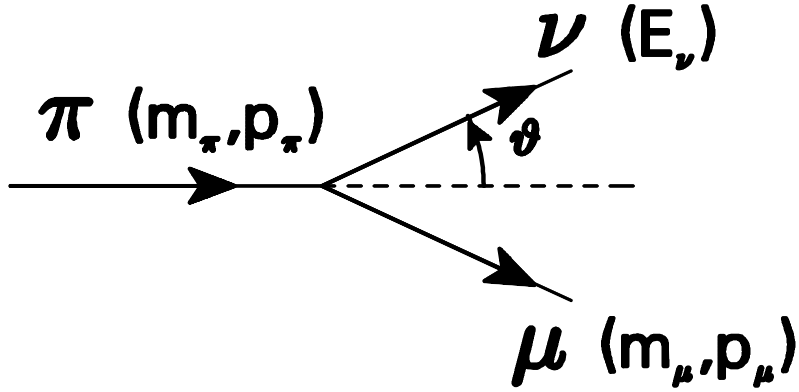
Long Baseline Neutrino Oscillation Experiment, D. Beavis et al., Physics Design Report, BNL 52459. April 1995.

http://minos.phy.bnl.gov/nwg

Now being considered for the JHF-SK proposal.

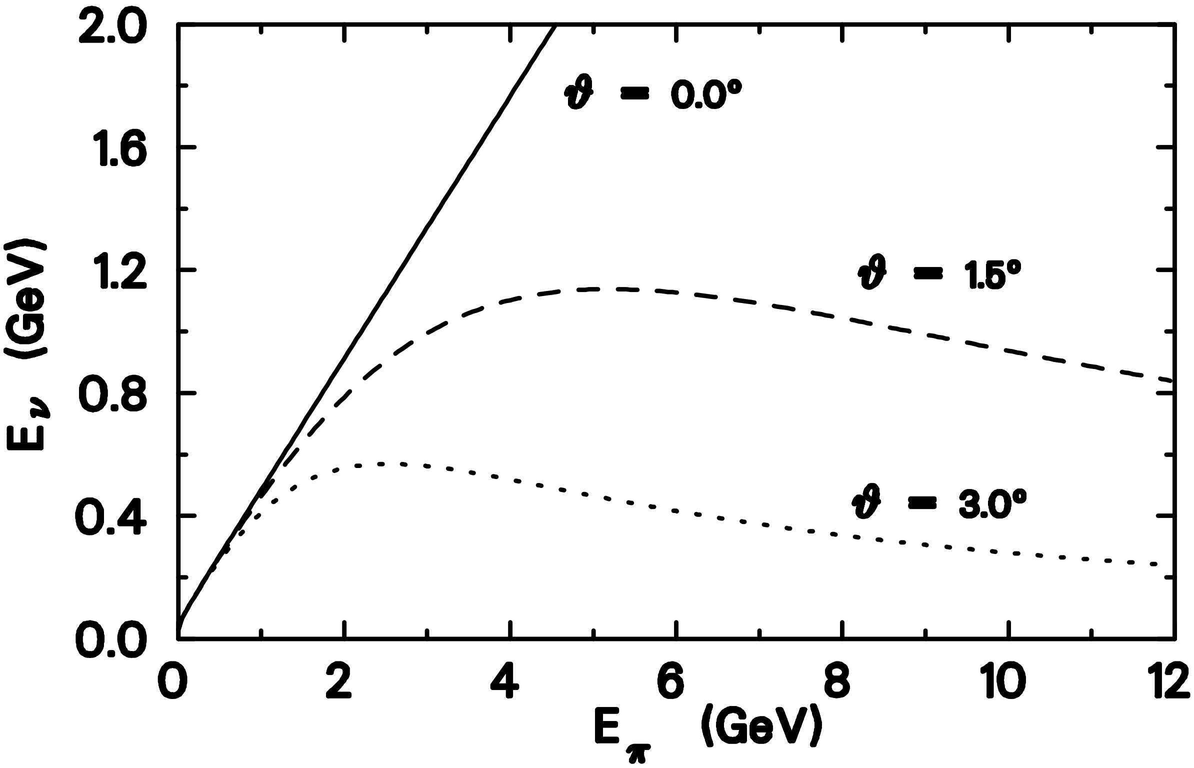
And new initiatives for the NUMI beam.

Workshop May 2 (tomorrow) at FNAL to discuss details.

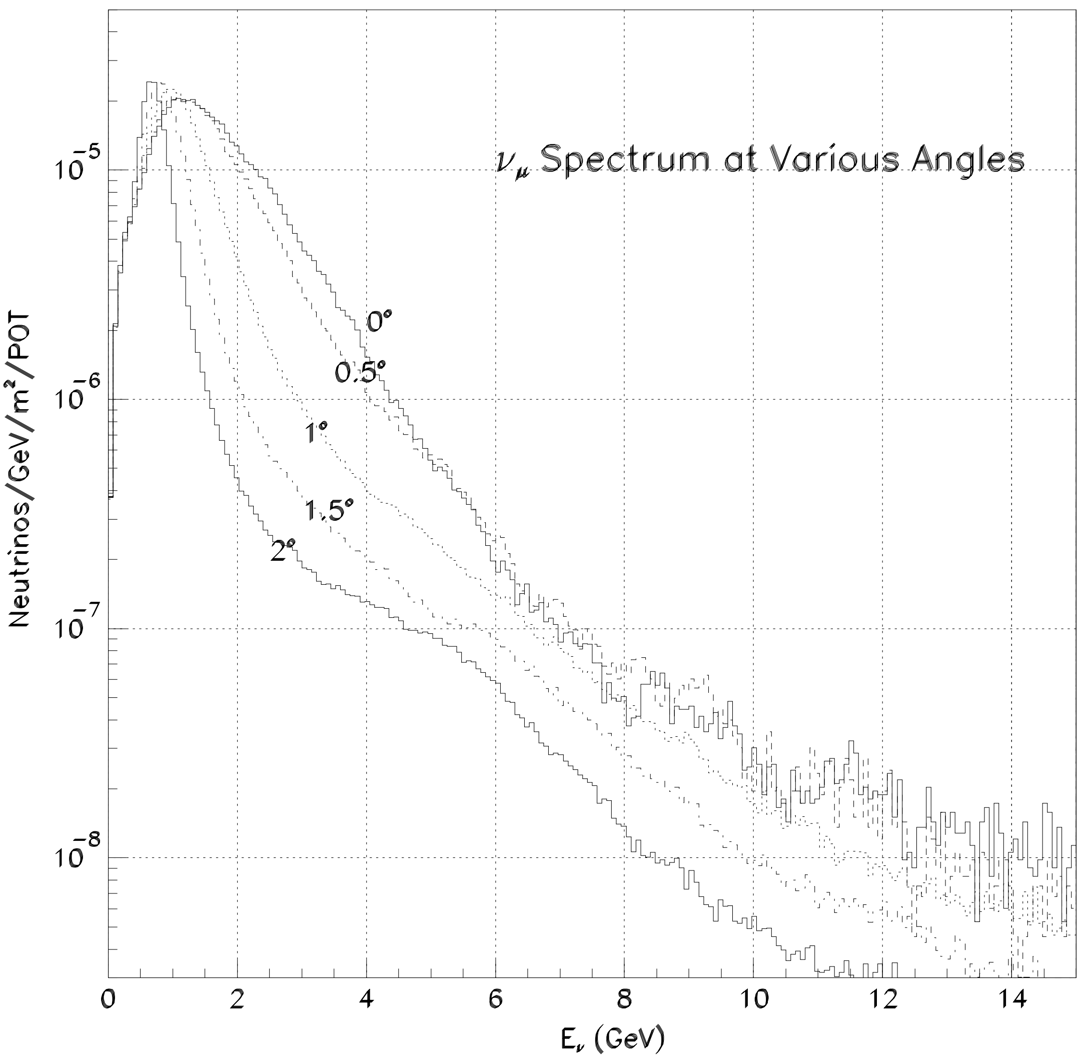


From energy, momentum conservation

$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2(E_\pi - p_\pi \cos\vartheta)}$$



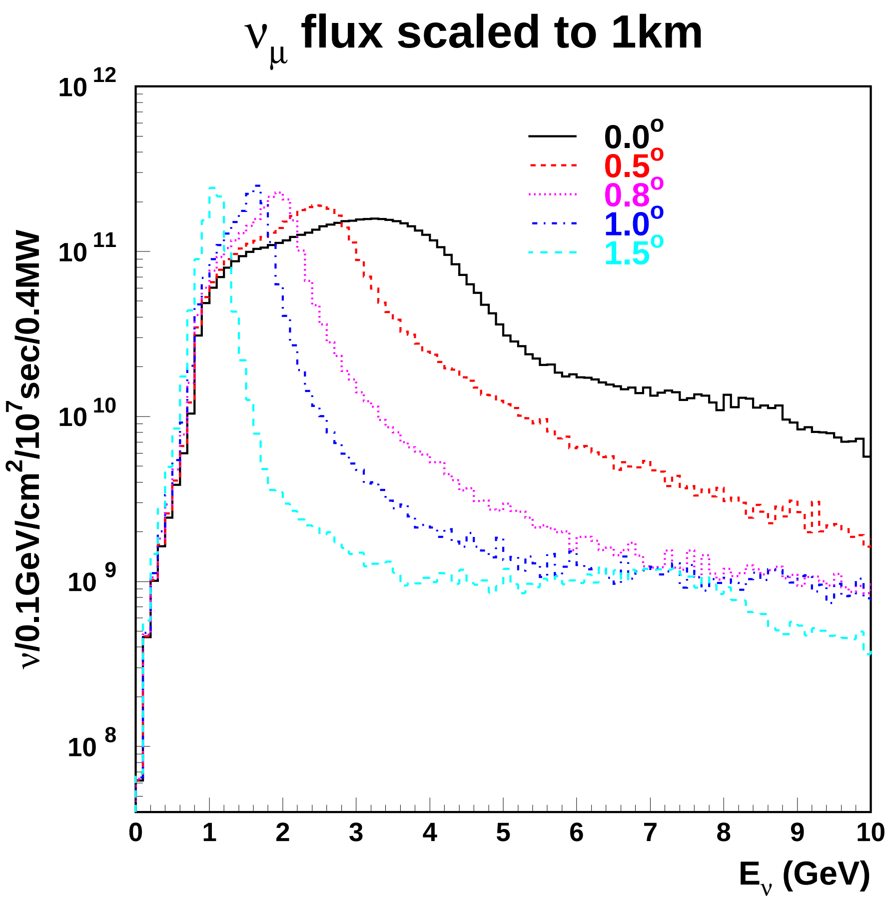
BNL Wideband Beam for E889



Wide band neutrino beam at 1 km designed for the E889 experiment at BNL at various angles.

Decay Tunnel length = 200 m.

FNAL LE beam

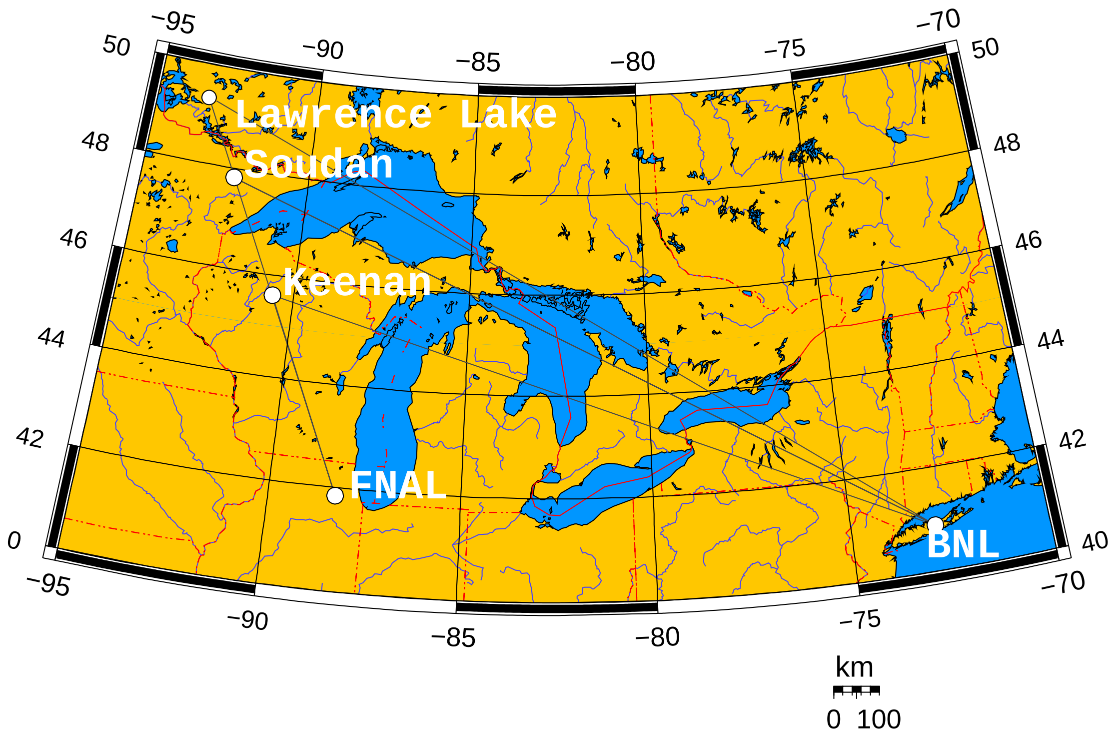


@ $\Delta m^2_{atm} = 2.5 \times 10^{-3}$

Angle (deg)	E_{peak} (GeV)	L_{osc} (km)	
0.0	3.0	1500	
0.5	2.5	1250	
0.8	2.0	1000	(L. Lake)
1.0	1.5	750	(Soudan)
1.5	1.0	500	(Keenan)
2.0	0.7	350	

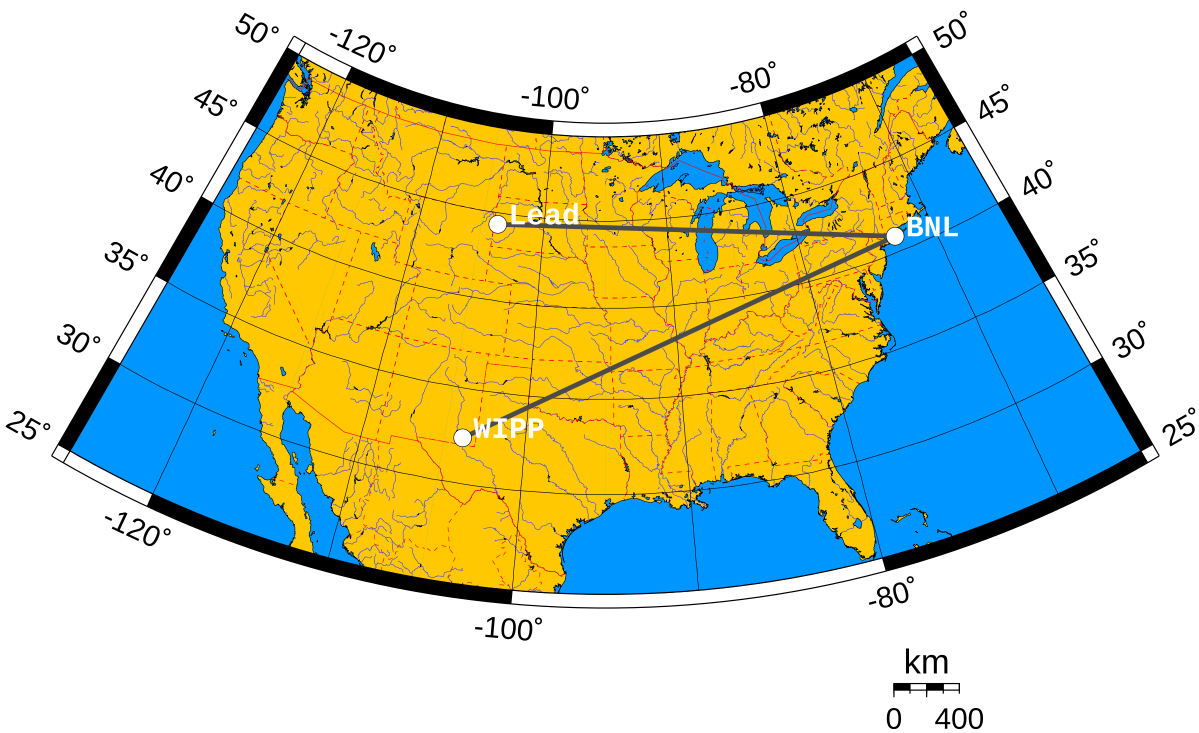
Baselines

	Keenan, WI	Soudan, MN	Lawrence Lake, ON
FNAL	458 km	735 km	911 km
BNL	1522 km	1711 km	1840 km



Very Long Baseline Experiment: BNL to Homestake

- Homestake: 2540 km
- WIPP: 2880 km
- Easily covers the goal of precisely measuring Δm^2_{32}. Can find $\nu_\mu \to \nu_e$ with a large detector.



Beam parameters

- NUMI beam
  - 3.8×10^{20} protons per year
  - 10 kT target (LAr)
  - OFF axis
  - 5 years
- New BNL beam
  - 12×10^{20} protons per year
  - 500 kT target at 2540 km (WaterCer)
  - On axis to get a wide band beam
  - 5 years

Off axis at FNAL

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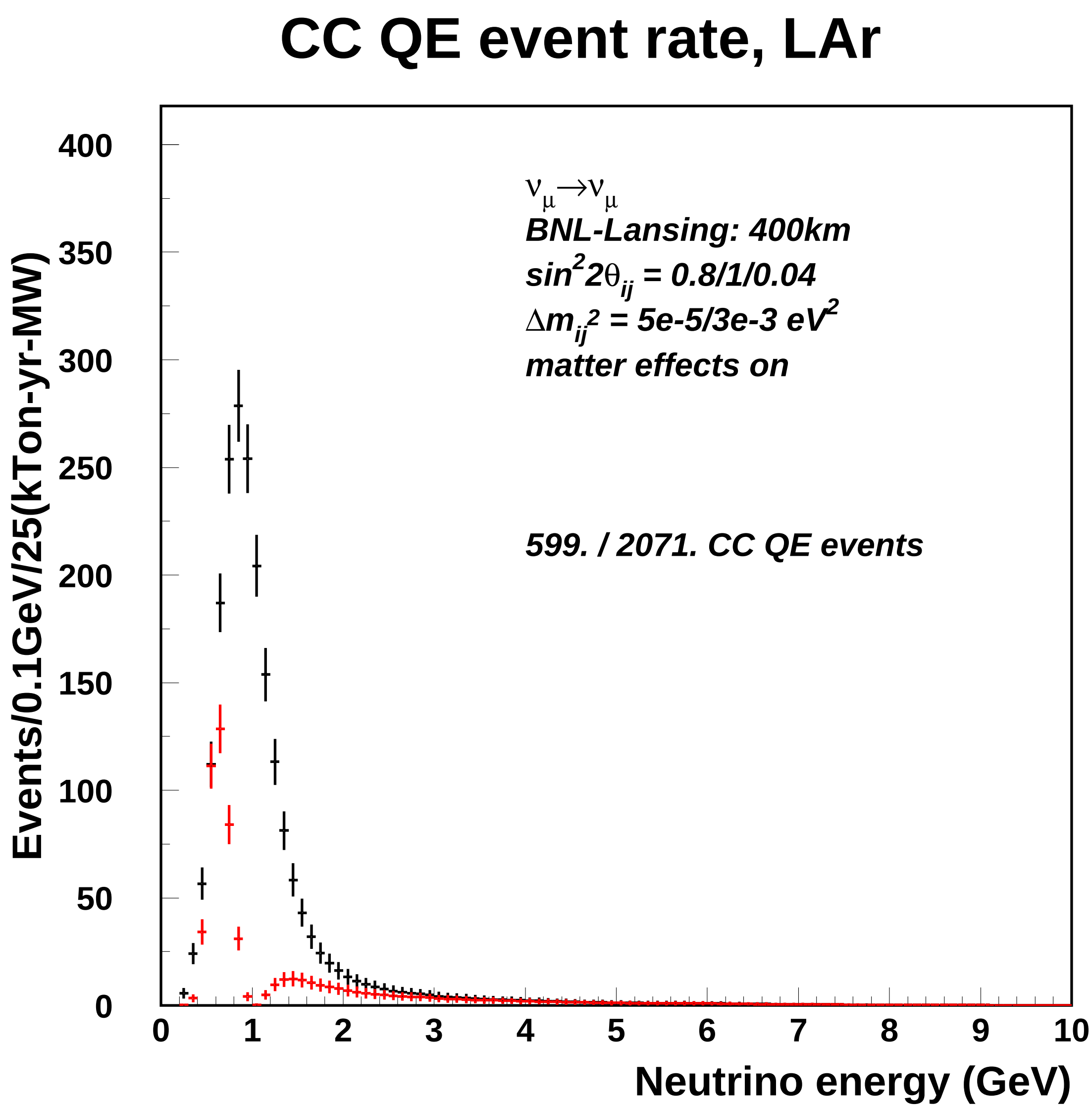
Off axis experiment at BNL



- Event rate: 2071 Q.E. events Total events about 1.5 times larger.
- Electron rate: ~ 40 events for $|U_{e3}|^2 = 0.01$.

Some Equations

Bill Marciano, hep-ph/0108181

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_1 c_3 & s_1 c_3 & s_3 e^{-i\delta} \\ -s_1 c_2 - c_1 s_2 s_3 e^{i\delta} & c_1 c_2 - s_1 s_2 s_3 e^{i\delta} & s_2 c_3 \\ s_1 s_2 - c_1 c_2 s_3 e^{i\delta} & -c_1 s_2 - s_1 c_2 s_3 e^{i\delta} & c_2 c_3 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \quad (1)$$

$$\begin{aligned} P(\nu_\mu \to \nu_e) \quad = \quad & 4(s_2^2 s_3^2 c_3^2 + J_{CP} \sin\Delta_{21}) \sin^2 \frac{\Delta_{31}}{2} \\ & +2(s_1 s_2 s_3 c_1 c_2 c_3^2 \cos\delta - s_1^2 s_2^2 s_3^2 c_3^2) \sin\Delta_{31} \sin\Delta_{21} \\ & +4(s_1^2 c_1^2 c_2^2 c_3^2 + s_1^4 s_2^2 s_3^2 c_3^2 - 2 s_1^3 s_2 s_3 c_1 c_2 c_3^2 \cos\delta - J_{CP} \sin\Delta_{31}) \sin^2 \frac{\Delta}{2} \\ & +8(s_1 s_2 s_3 c_1 c_2 c_3^2 \cos\delta - s_1^2 s_2^2 s_3^2 c_3^2) \sin^2 \frac{\Delta_{31}}{2} \sin^2 \frac{\Delta_{21}}{2} \end{aligned} \quad ($$

$$\begin{aligned}\Delta_{31} &\equiv \Delta m^2_{31} L/2E_\nu \\ \Delta_{21} &\equiv \Delta m^2_{21} L/2E_\nu \end{aligned} \tag{3}$$

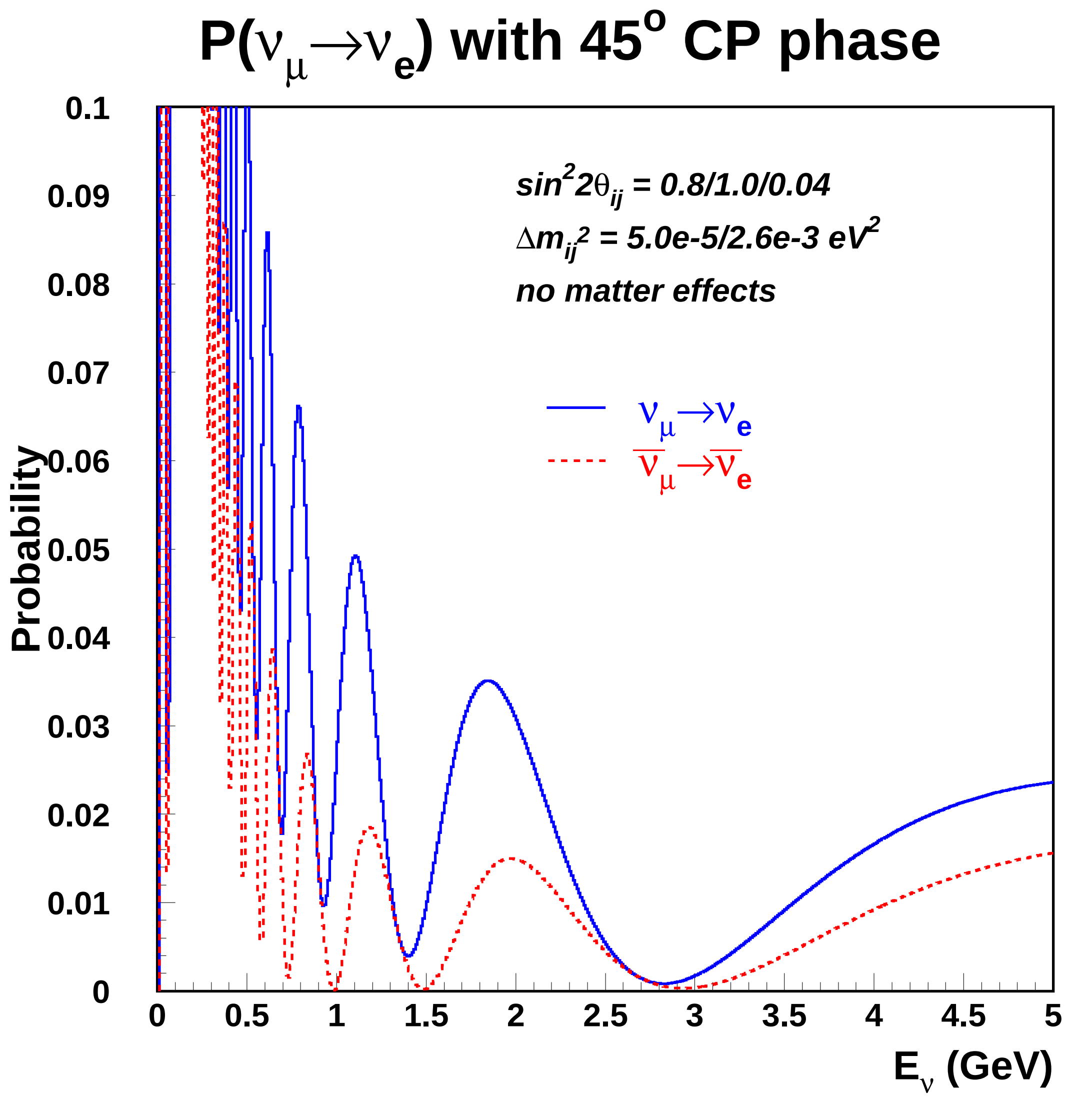
$$J_{CP} \equiv s_1 s_2 s_3 c_1 c_2 c_3^2 \sin\delta \tag{4}$$

$$A \equiv \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \tag{5}$$

To leading order in Δ_{21} (assumed to be small), one finds

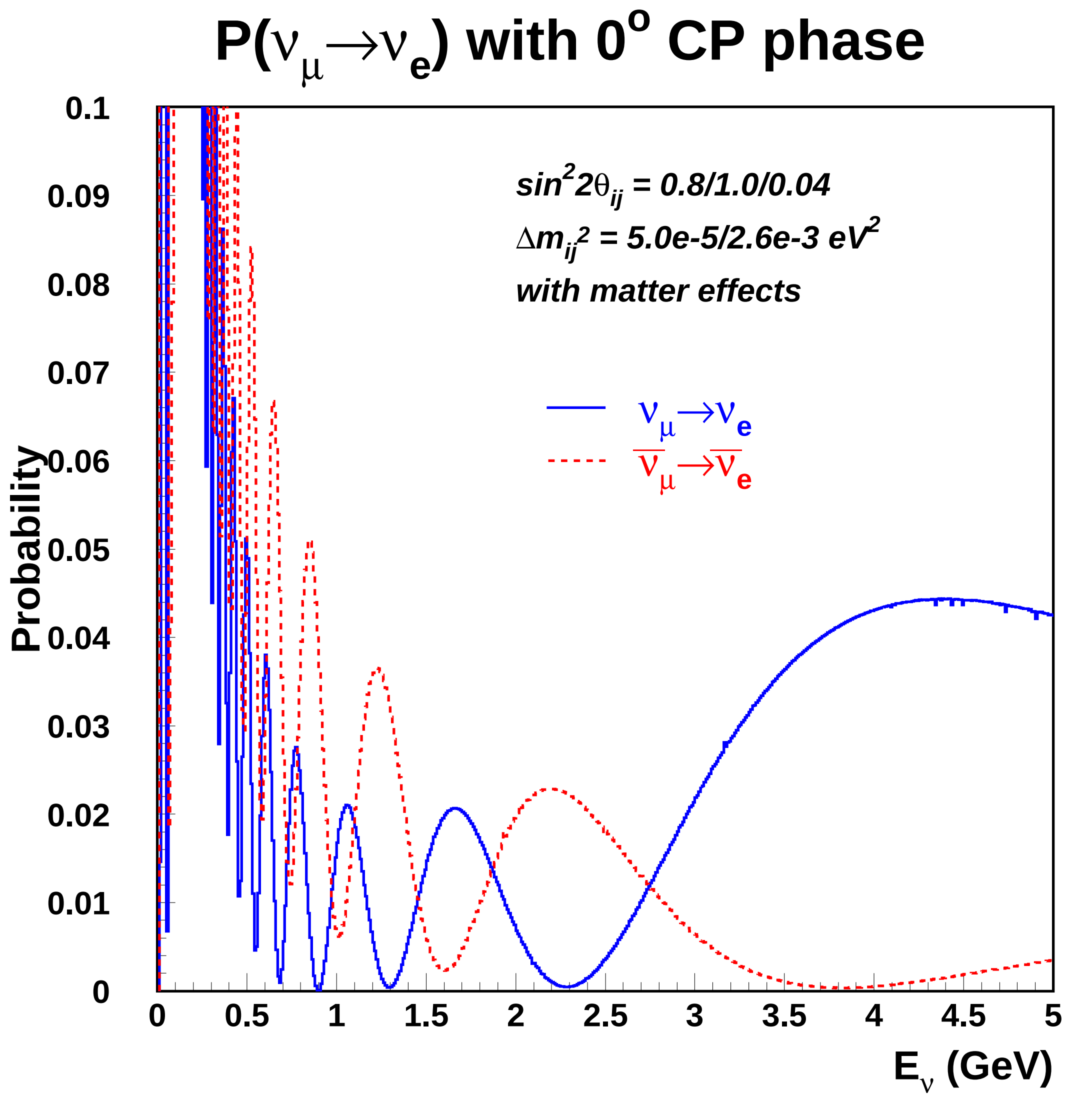
$$P(\nu_\mu \to \nu_e) \simeq 4 s_2^2 s_3^2 c_3^2 \sin^2 \frac{\Delta_{31}}{2} + \mathcal{O}(\Delta_{21}) \tag{12a}$$

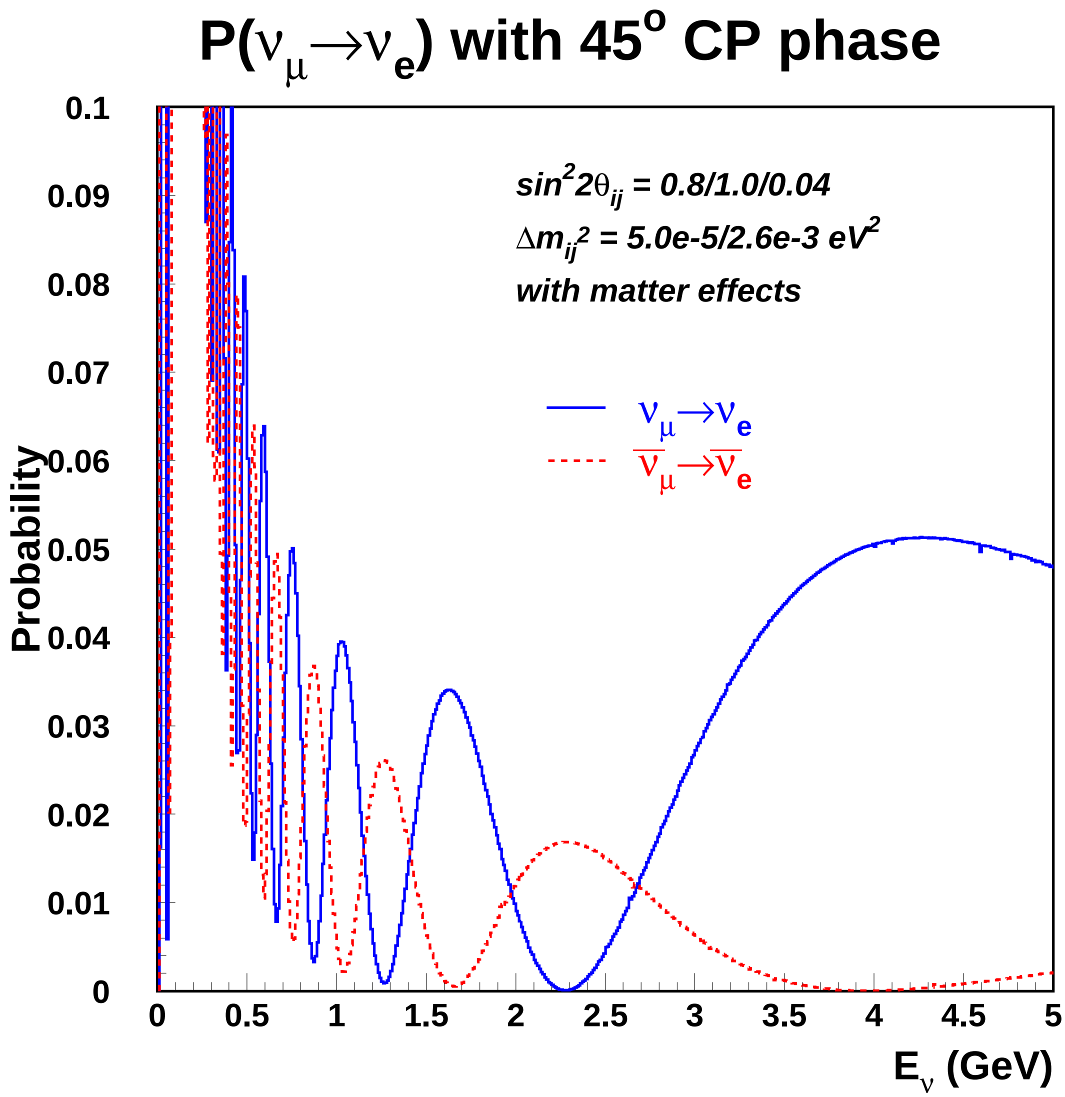
$$A \simeq \frac{J_{CP} \sin\Delta_{21}}{s_2^2 s_3^2 c_3^2} \simeq \frac{2 s_1 c_1 c_2 \sin\delta}{s_2 s_3} \left(\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right) \frac{\Delta m^2_{31} L}{4E_\nu} + \mathcal{O}(\Delta^2_{21}) \tag{12b}$$


P($\nu_\mu \to \nu_e$) with 45^o CP phase
$sin^2 2\theta_{ij}$ = 0.8/1.0/0.04
Δm_{ij}^2 = 5.0e-5/2.6e-3 eV^2
no matter effects
$\nu_\mu \to \nu_e$
$\overline{\nu}_\mu \to \overline{\nu}_e$
Probability
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
E_ν (GeV)

Very Long Baseline Experiment: Matter Effect

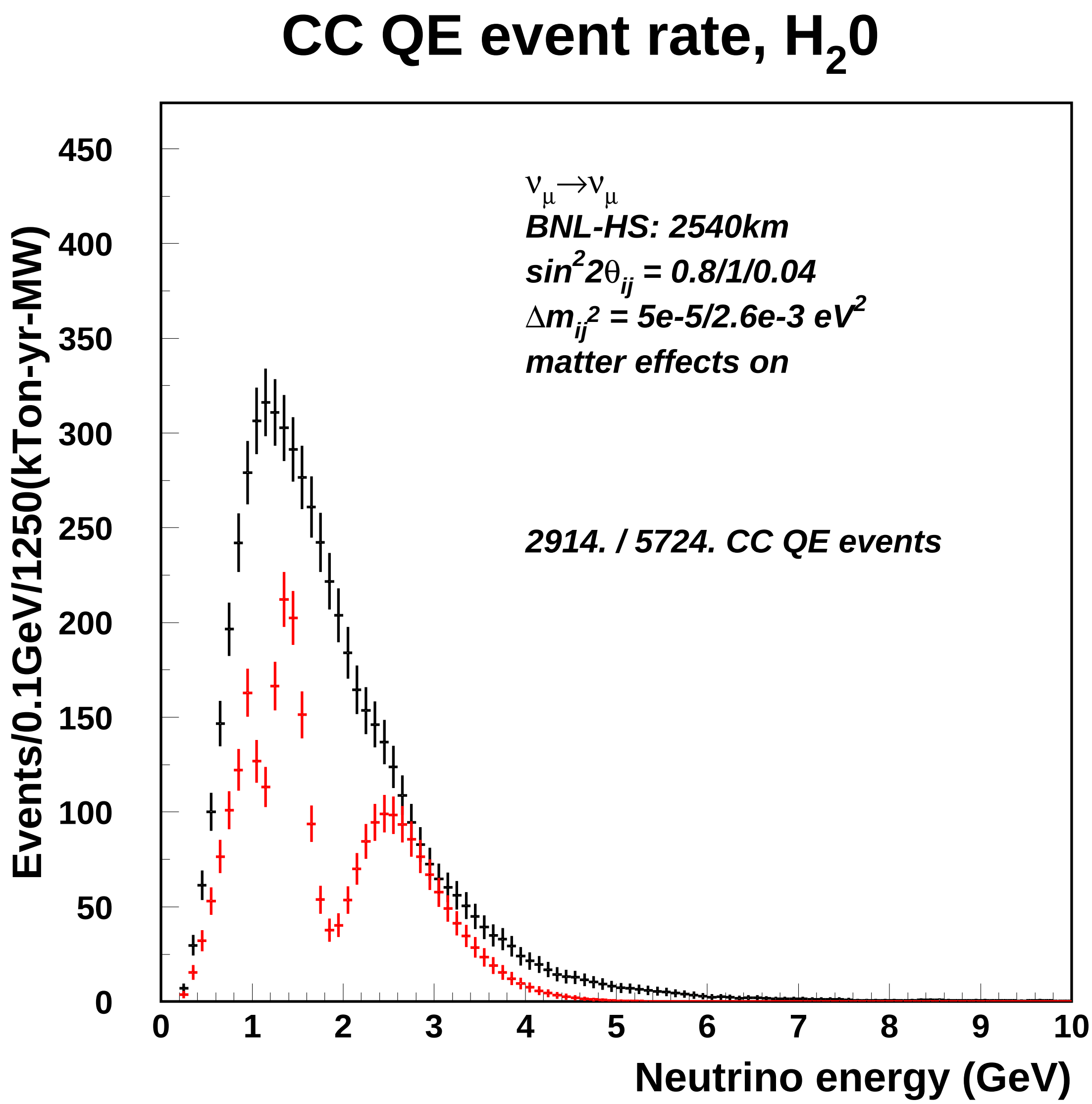
- Effect of matter: enhance the $\pi/2$ peak and shift it to lower energy.
- Opposite on Anti-neutrinos.
- Changes sign if $\Delta m^2_{32} \rightarrow -\Delta m^2_{32}$

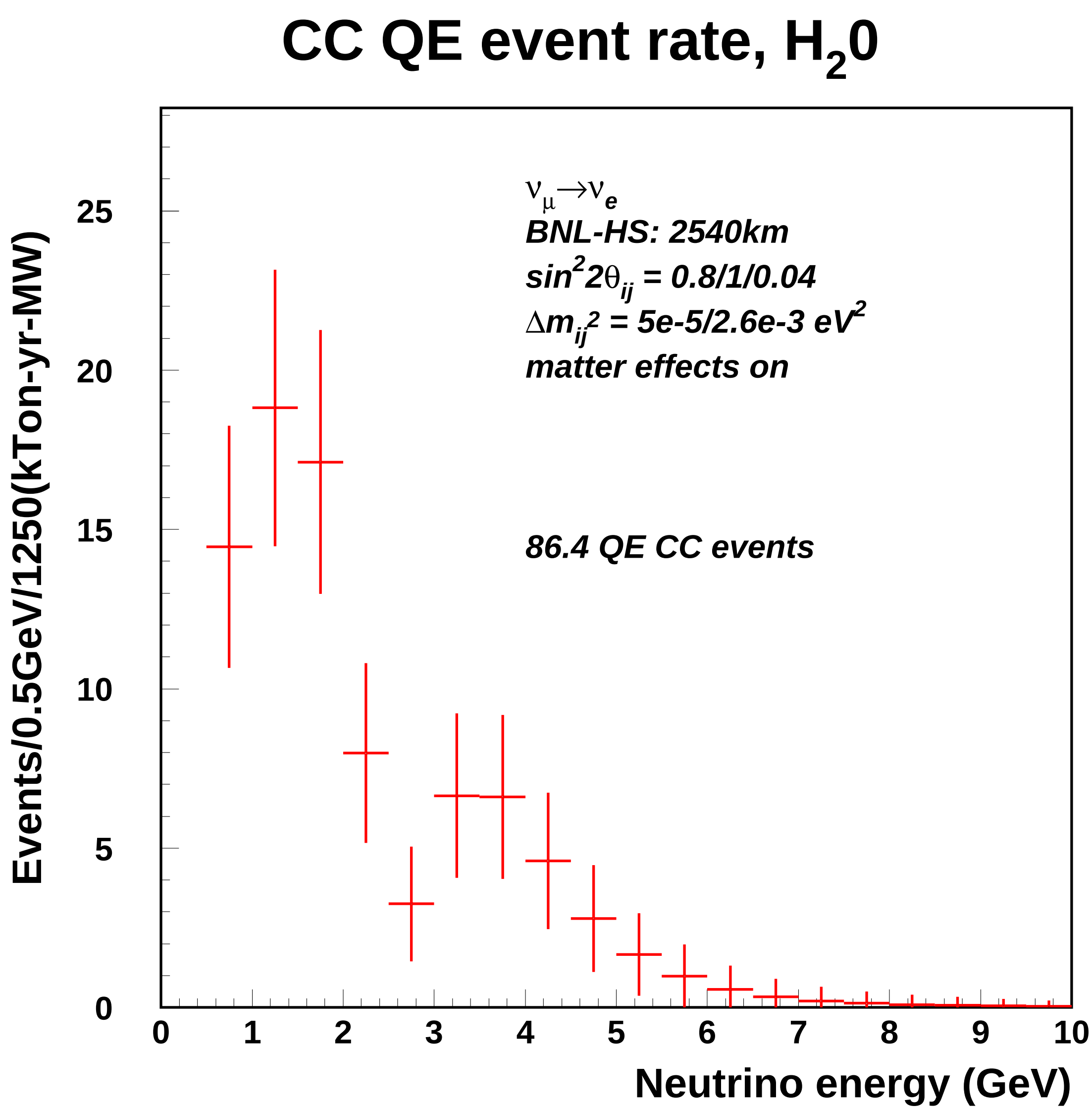

P(νμ→νe) with 0° CP phase
sin²2θij = 0.8/1.0/0.04
Δmij² = 5.0e-5/2.6e-3 eV²
with matter effects
νμ→νe
ν̄μ→ν̄e
Probability
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Eν (GeV)


P(ν_μ→ν_e) with 45° CP phase
sin²2θ_ij = 0.8/1.0/0.04
Δm_ij² = 5.0e-5/2.6e-3 eV²
with matter effects
ν_μ→ν_e
ν̄_μ→ν̄_e
Probability
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
E_ν (GeV)

Very Long Baseline Experiment: Event Rates

- Spectra are for Q.E. events only with resolution effects.
- Resolution of Water Cerenkov for Q.E. well understood by K2K experiment.
- ν_e rates and spectrum are sensitive to solar Δm^2_{21}


CC QE event rate, H20
νμ→νμ
BNL-HS: 2540km
sin²2θij = 0.8/1/0.04
Δmij² = 5e-5/2.6e-3 eV²
matter effects on
2914. / 5724. CC QE events
Events/0.1GeV/1250(kTon-yr-MW)
450
400
350
300
250
200
150
100
50
0
0
1
2
3
4
5
6
7
8
9
10
Neutrino energy (GeV)


CC QE event rate, H20
νμ→νe
BNL-HS: 2540km
sin22θij = 0.8/1/0.04
Δmij2 = 5e-5/2.6e-3 eV2
matter effects on
86.4 QE CC events
Events/0.5GeV/1250(kTon-yr-MW)
Neutrino energy (GeV)
0
5
10
15
20
25
0
1
2
3
4
5
6
7
8
9
10

AGS upgrade path

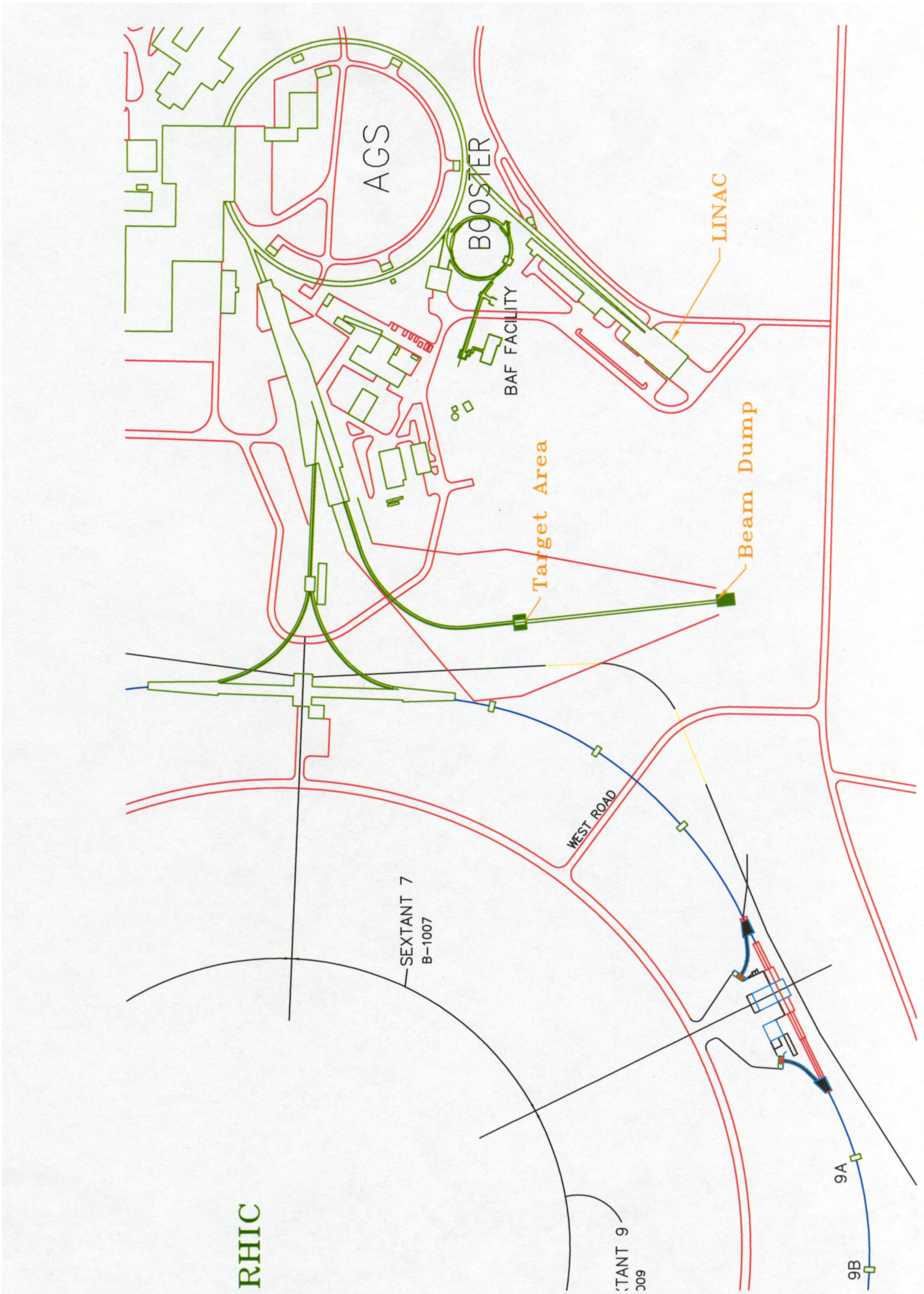
	Now	400 MeV LINAC	2.5 GeV Accumulator 200 MeV LINAC	2.5 GeV Accumulator 400 MeV LINAC	AGS to 2.5 Hz
LINAC Energy (MeV)	200	400	200	400	400
Booster Intensity (ppp)	1.5×10^{13}	2.0×10^{13}	1.5×10^{13}	2.0×10^{13}	2.0×10^{13}
Booster energy (GeV)	1.8	1.8	2.5	2.5	2.5
Booster Cycles	4	4	6	6	6
AGS energy (GeV)	24	28	28	28	28
AGS Intensity (Tp/sec)	36	48	90	120	300
AGS Rep Rate (Hz)	0.6	0.6	1.0	1.0	2.5
AGS Current (μ A)	5.75	7.7	14.4	19.2	48
AGS Intensity (ppp)	6×10^{13}	8×10^{13}	9×10^{13}	12×10^{13}	12×10^{13}
AGS power (kW)	138	215	403	538	1344

AGS Upgrade to 0.5 and 1.3 MW AGS upgrade costs (Bill Weng, BNL):

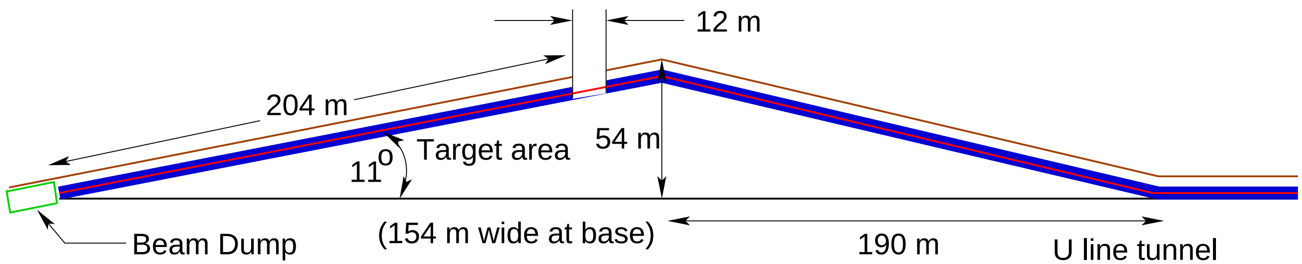
Phase I (AGS at 1 Hz) **538 kW** $\Rightarrow 1.2 \times 10^{21}$ ppp.	$\$10^6$
300 MeV SRF (116 MeV to 400 MeV)	35
2.5 GeV AGS accumulator ring	25
AGS Injection at 2.5 GeV	5
Total for Phase I	**65**
Phase-II (AGS at 2.5 Hz), **1344 kW** $\Rightarrow 2.9 \times 10^{21}$ ppp.	
AGS power supply	32
AGS RF upgrade	8.6
Booster Power Supply	5.5
AGS Collimation and Shielding	8.0
Total for Phase-II	**54.1**

The future of neutrino oscillations

Milind Diwan


AGS
BOOSTER
LINAC
BAF FACILITY
Target Area
Beam Dump
WEST ROAD
SEXTANT 7
B-1007
RHIC
9A
9B

The BNL to Homestake Hill (Mt. Palmer)



Item	basis	200 m	150 m
Proton transport	RHIC injector	\$11.85 M	\$11.85 M
Target/horn	E889	\$3.0 M	\$3.0
Installation/Beam Dump	New	\$2.67 M	\$2.67 M
Decay Tunnel	E889	\$0.45 M	\$0.45 M
Conventional const. (hill)	New	\$8.0 M	\$5.0 M
Conventional const. (other)	E889	\$9.1 M	\$9.1 M
Total		\$35.19	\$32.19

Letter of Intent to Brookhaven National Laboratory. Neutrino Oscillation Experiments for Precise Measurements of Oscillation Parameters and Search for $\nu_\mu \to \nu_e$ Appearance and CP Violation.

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Neutrino Projects

- K2K could confirm atm oscillation signature if enough statistics.
- MINOS will measure Δm^2_{32} with $\sim 10\%$ error. Could get lucky if $\nu_\mu \rightarrow \nu_e$ large.
- JHF-to-SK
- Off-axis NUMI experiment.
  How complementary/competitive to JHF-to-SK ?
- Off-axis BNL experiment
  How complementary/competitive to NUMI or JHF-to-SK ?
- Off-axis NUMI experiment combined with a beam from BNL.
- Conventional JHF beam to very long distance.
- Conventional BNL beam to a very long distance.
- Neutrino Factory ?

Conclusions

- MINOS will measure Δm^2_{32} with $\sim 10\%$ error.
- New initiatives for NUMI beam sought.

  Original idea from BNL-E889 of using an off-axis beam to make a narrow band beam being revived.
- New Letter of Intent for a very long baseline experiment using a new intense BNL beam.
- Very long baseline experiment must be done in the not too distant future.
- Neutrino oscillations and mixing has the same "dignity" as quark mixing and must be understood with the same scale of effort.