Semi-Coherent Thoughts on Fermilab's Long Baseline Future

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Overview

- A list of physics issues/questions
- On the way to the proton driver.
  - MINOS
  - NuMI Off Axis
- Long Baseline and the Proton Driver
  - NuMI experiments
  - A new beamline?
- A Neutrino Factory? Too much extrapolation to tell now.

A List of Physics Issues and Questions

- Demonstrate with precision the energy dependence of the oscillations.
  - Just the basic expected energy dependence or perhaps something a bit more subtle?
- Precise measurements of the oscillation parameters:
  - Delta m**2 to a few percent
  - What is the sign of Δm**2? This can only be determined via matter effects in long baseline experiments and only then if θ_{13} is big enough.
  - Sin**2 2θ_{23} to 1% or better
    - How close is this number to 1? Is it "fundamental"?
    - Important to remove ambiguity in θ_{13} measurement.
  - What is the value of θ_{13}? Is it "naturally" big like the other parameters or anomalously small. Is there some heirarchy here trying to teach us something about the fundamental physics involved?
- Is there CP violation in neutrino oscillations? How might this relate to CP violation that may be responsible for leptogenesis?
- What about the possibility of subtle CPT violation? Why shouldn't this be a perfectly good source of matter/anti-matter asymmetry? Could neutrino oscillations be a natural place to first observe such a violation? What quantitative limits might be of interest?
- Are there any light, sterile neutrinos and if so what are the oscillation parameters associated with them? If LSND is correct it increasingly appears that there must be at least one. Oscillation phenomenology will be very complex in this case.

$\nu_\mu \Rightarrow \nu_e$ oscillation experiment

$$P(\nu_\mu \to \nu_e) = P_1 + P_2 + P_3 + P_4$$

$$P_1 = \sin^2\theta_{23}\sin^2\theta_{13}\left(\frac{\Delta_{13}}{B_\pm}\right)^2 \sin^2\frac{B_\pm L}{2}$$

$$P_2 = \cos^2\theta_{23}\sin^2\theta_{12}\left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\frac{AL}{2}$$

$$P_3 = J\cos\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\cos\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}$$

$$P_4 = J\sin\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\sin\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}$$

$$\Delta_{ij} = \frac{\Delta m_{ij}^2}{2E_\nu};$$

$$A = \sqrt{2}G_F n_e;$$

$$B_\pm = \left|A \pm \Delta_{13}\right|;$$

$$J = \cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$$

$$P = f(\sin^2 2\theta_{13}, \delta, \mathrm{sgn}(\Delta m_{13}^2), \Delta m_{12}^2, \Delta m_{13}^2, \sin^2 2\theta_{12}, \sin^2 2\theta_{23}, L, E)$$

3 unknowns, 2 parameters under control L, E, neutrino/antineutrino

Need several independent measurements to learn about underlying physics

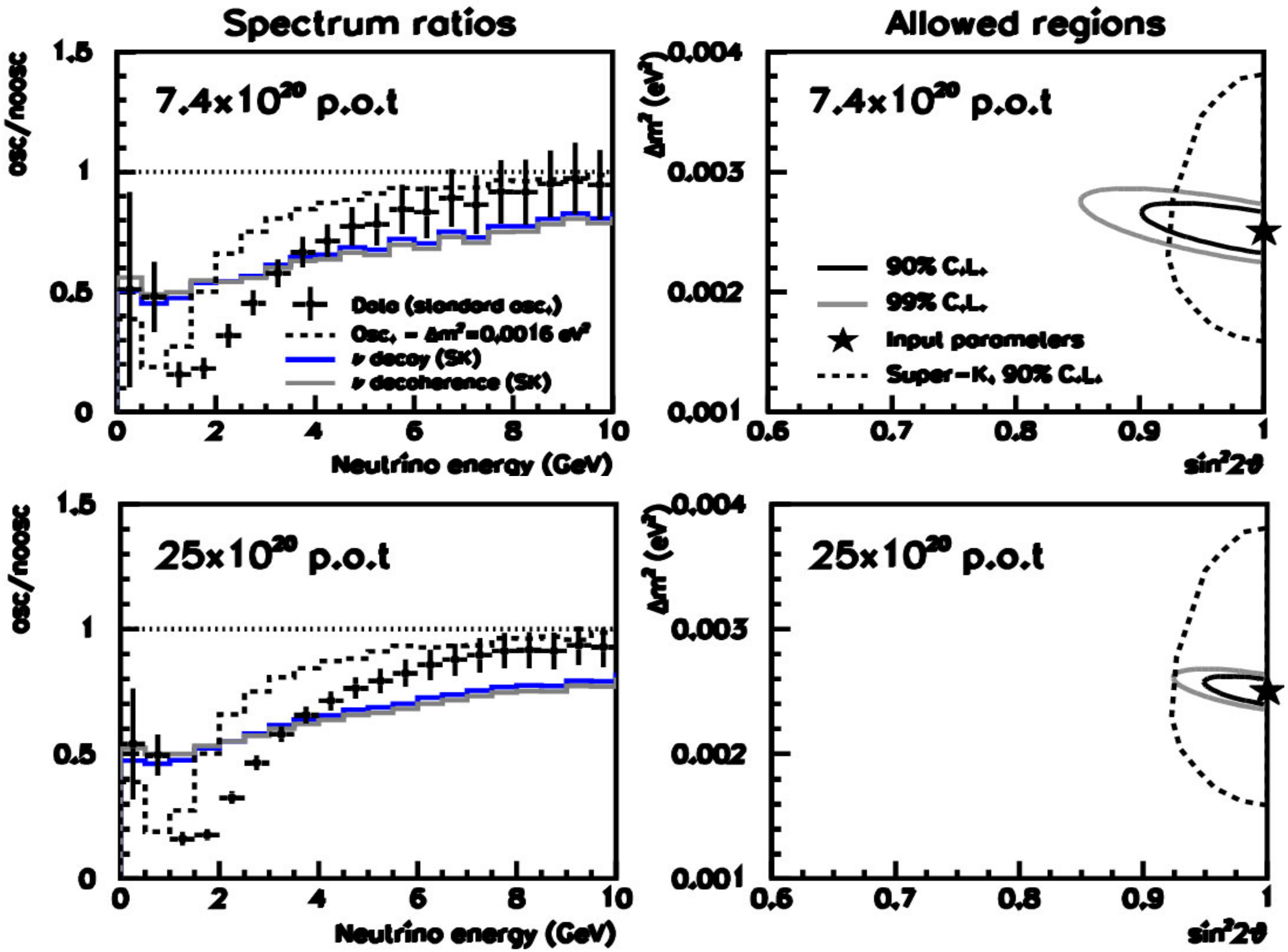
Note, if there are any sterile ν's things can be more complicated!

On the way to the proton driver: MINOS

MINOS Running Plan

- Draft Fermilab Long-Range Plan:
  - NuMI beam commissioning starting in Dec. 2004.
  - 4 years of physics running for MINOS starting in April 2005.
  - Goal for protons on target in first year = 2.5×10^{20}
  - Plans are being developed for increased proton intensity.
- New MINOS Running Request (May 2003)
  - MINOS has submitted a request to Fermilab for 5 years of running with a total of 25×10^{20} protons on target in that time.
  - MINOS has provided updated physics sensitivity curves based on 7.4, 16 and 25 $\times 10^{20}$ total protons on target. (Original MINOS physics sensitivity was based on 7.4×10^{20} pot.)
  - There are several options for providing this number of protons.
- The performance of MINOS has always depended on the NuMI beamline being far more intense than any other.

Measurement of Oscillations in MINOS

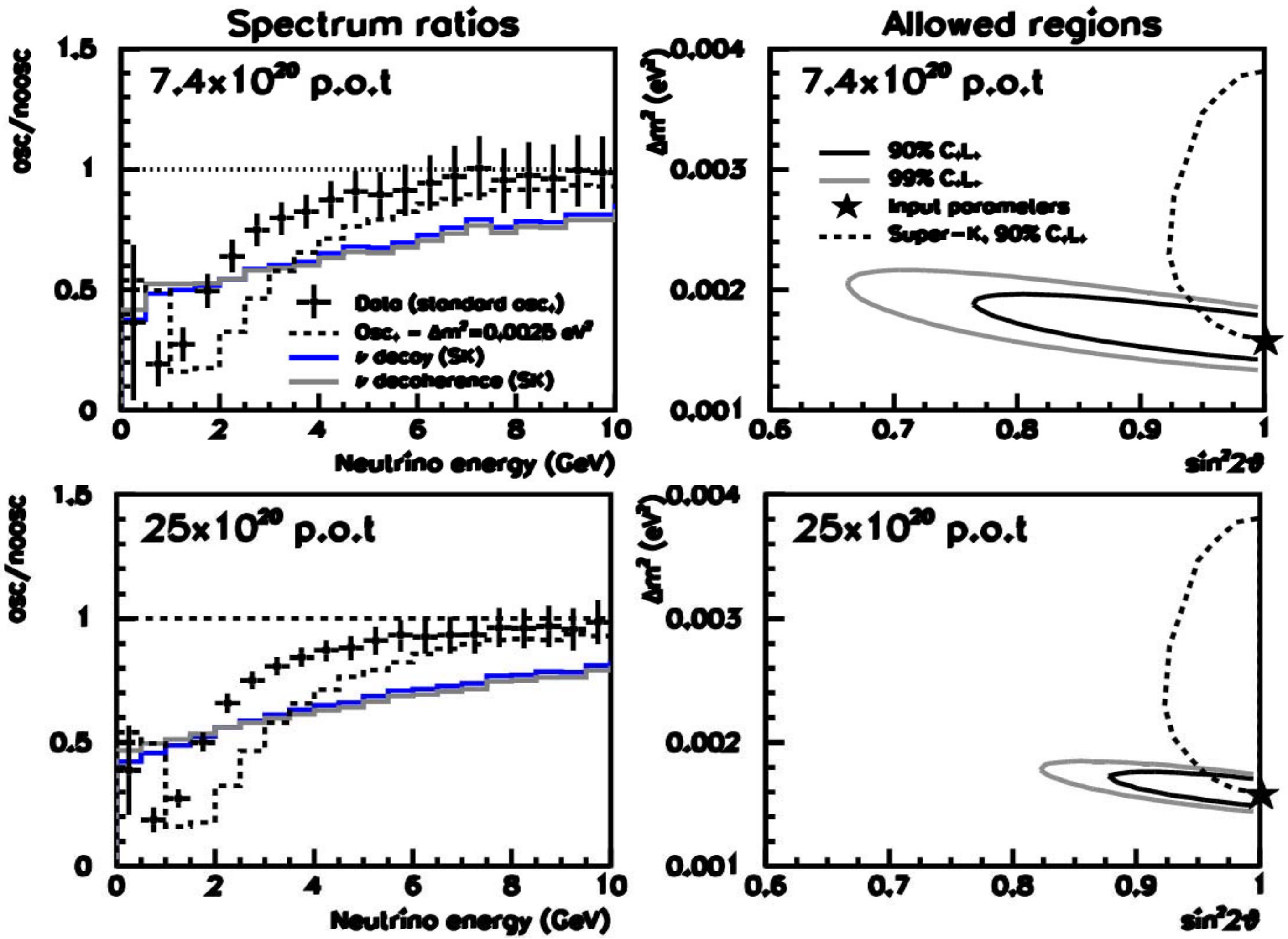


For $\Delta m^2 = 0.0025$ eV^2, $\sin^2 2\theta = 1.0$

Oscillated/unoscillated ratio of number of ν_μ CC events in the far detector vs $E_{observed}$

MINOS 90% and 99% CL allowed oscillation parameter space.

Measurement of Oscillations in MINOS

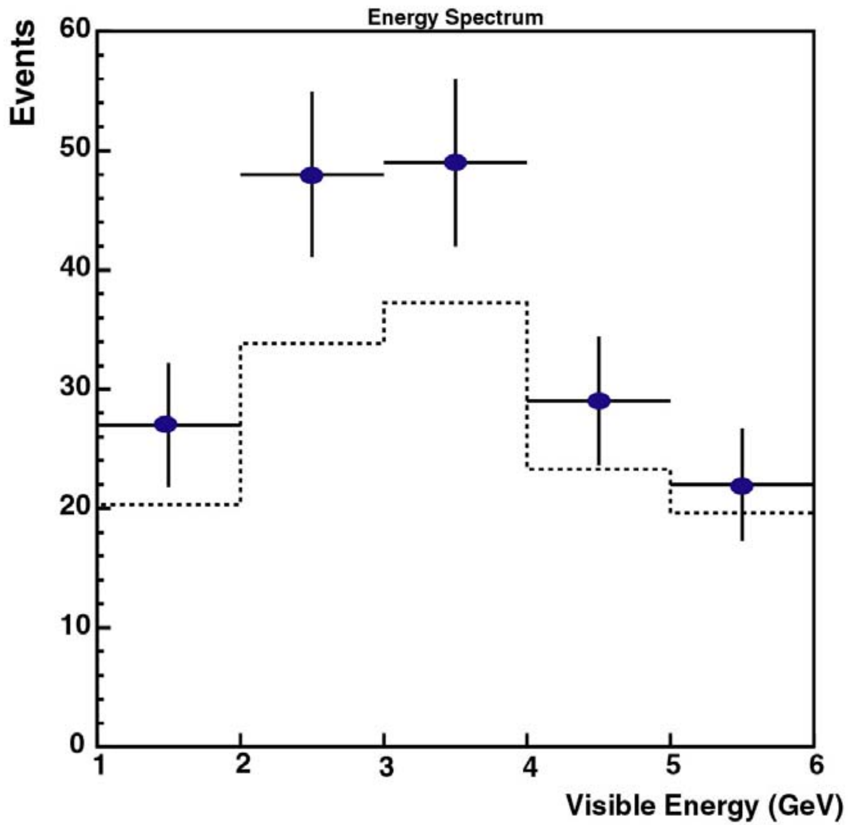


For $\Delta m^2 = 0.0016$ eV^2, $\sin^2 2\theta = 1.0$

Oscillated/unoscillated ratio of number of ν_μ CC events in the far detector vs $E_{observed}$

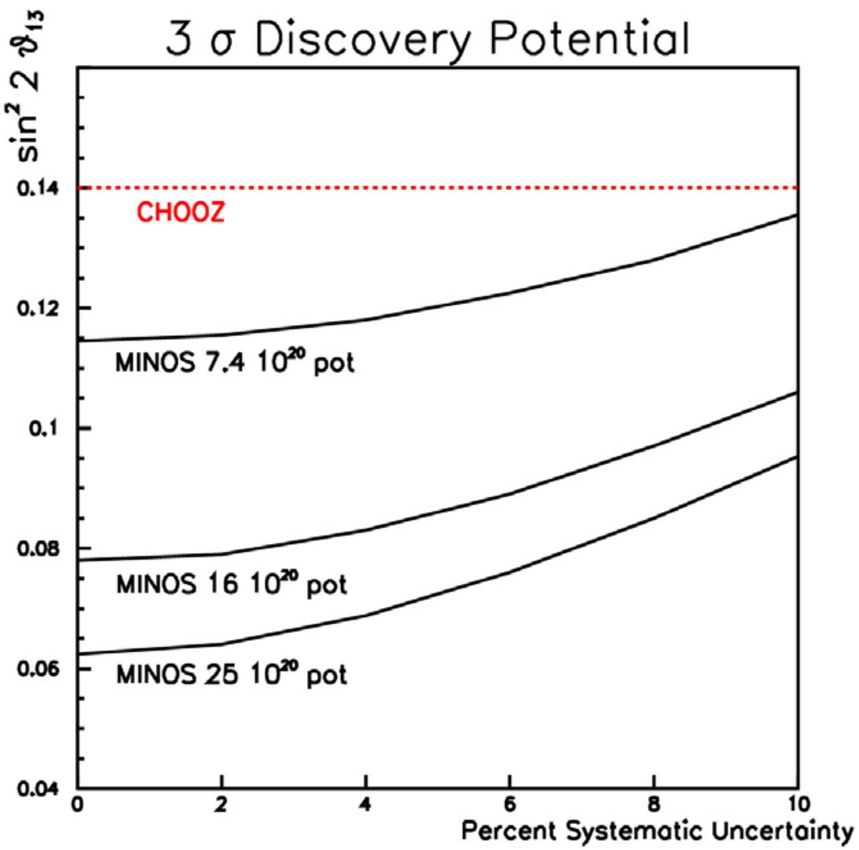
MINOS 90% and 99% CL allowed oscillation parameter space.

Appearance of Electrons



For $\Delta m^2 = 0.0025\ eV^2$, $\sin^2 2\theta_{13} = 0.067$

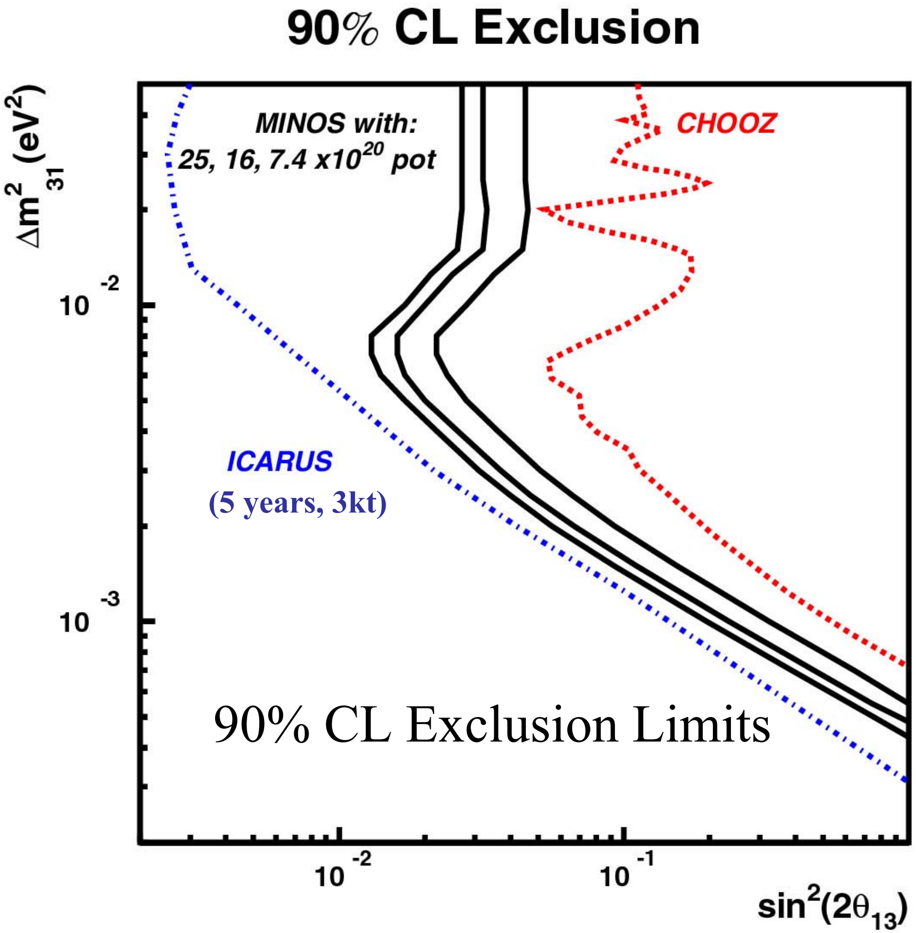
Observed number of events identified as coming from ν_e CC interactions with and without oscillations. 25×10^{20} protons on target.

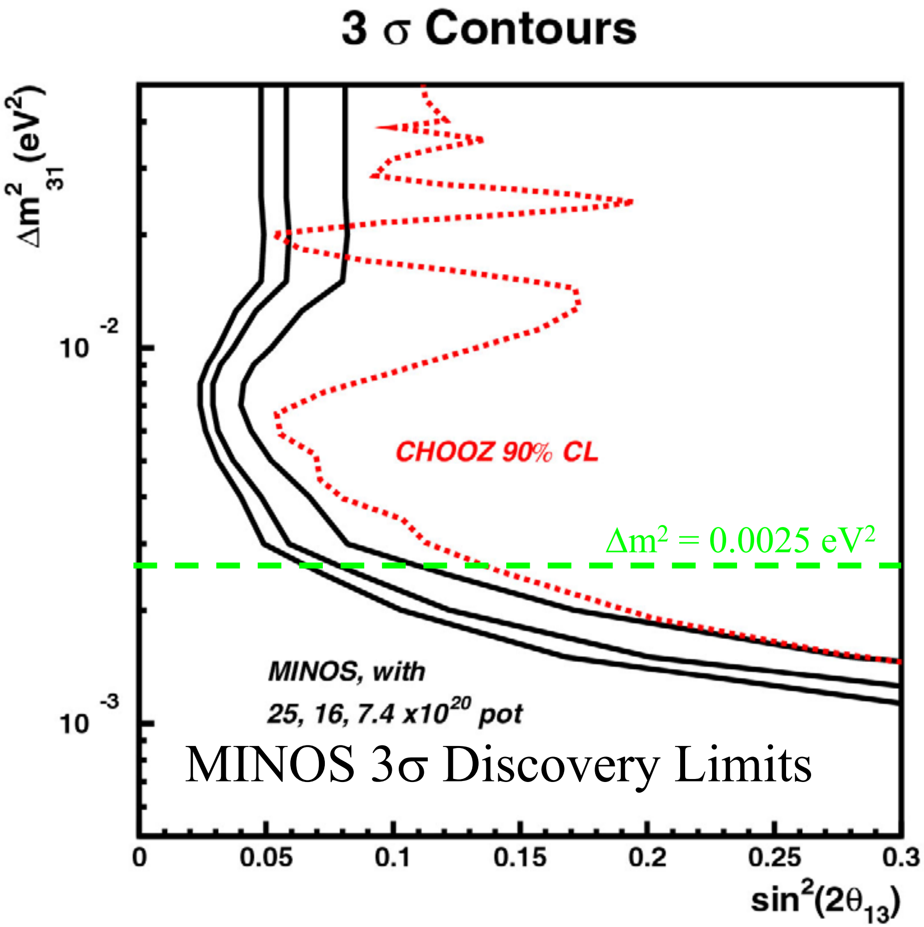


For $\Delta m^2 = 0.0025\ eV^2$

3 σ discovery potential for three different levels of protons on target and versus systematic uncertainty on the background.

Appearance of Electrons





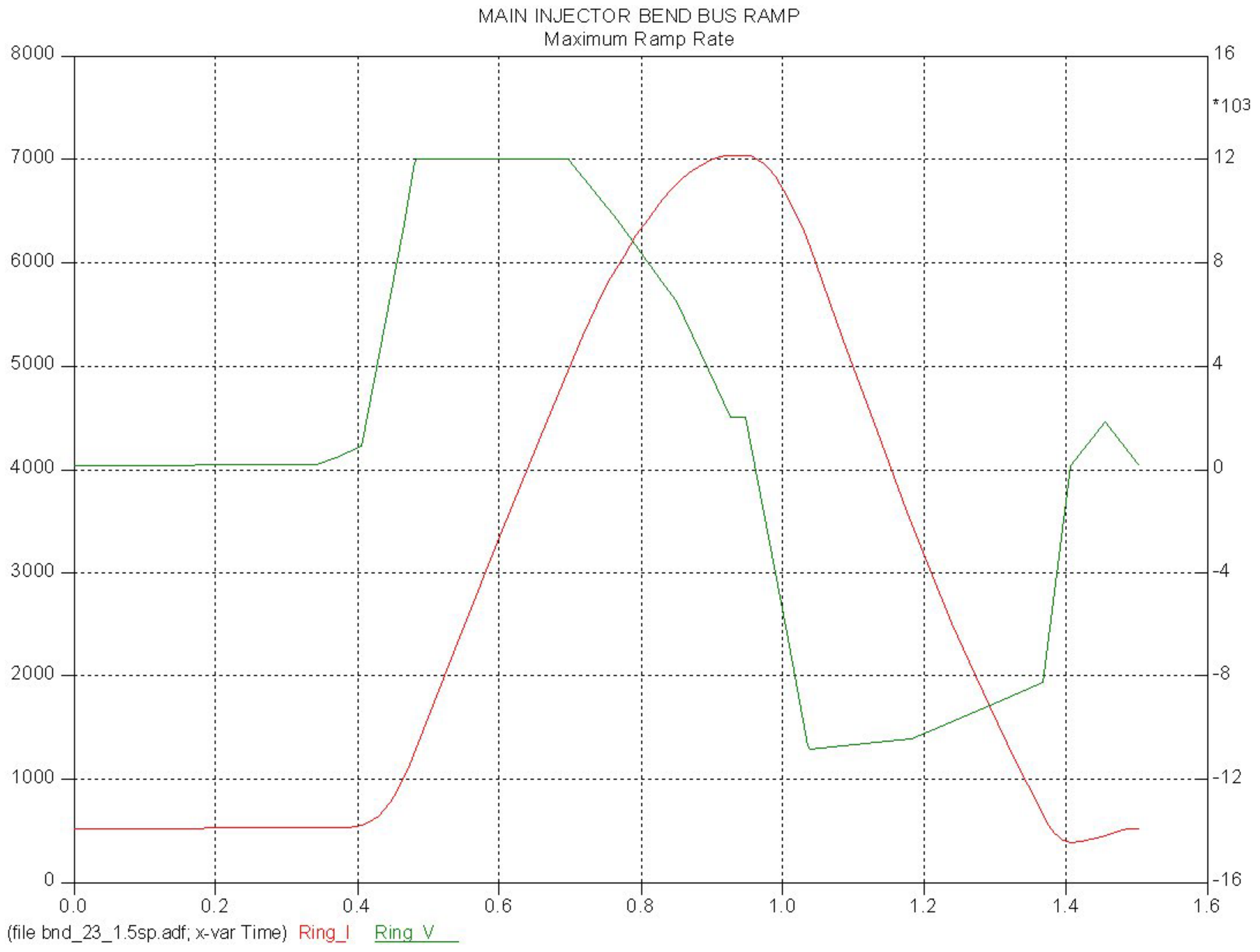
• MINOS sensitivities based on varying numbers of protons on target

25e20? Is this guy a nut?

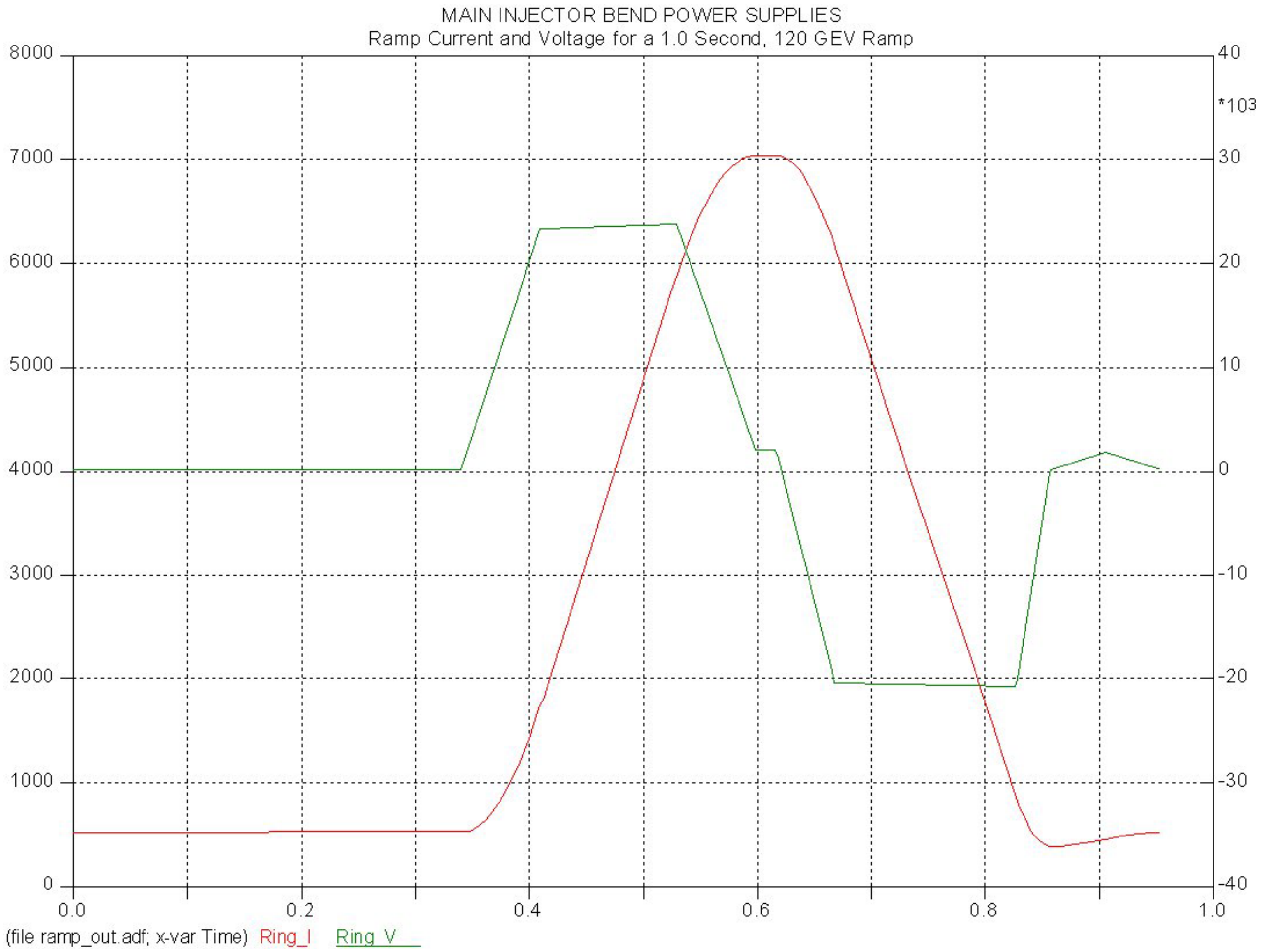
- 10 years at the nominal first year plan
- 5 years if all that is done is just a factor of 2 in the proton intensity… Possible by reducing the MI cycle time.
- Using the Recycler to hide the cycle time of the Booster could be a cost effective means of another 30-50% increase in intensity. Just this and the MI cycle time can yield a 0.8 MW proton source.
- Then squeeze out another 20-30% of improvement through stacking in the Main Injector and/or increase in intensity from the Booster…
- … Perhaps this is the hitch. Can it survive this?

Current Main Injector Ramp

- Bend Ramp



But it can be faster!



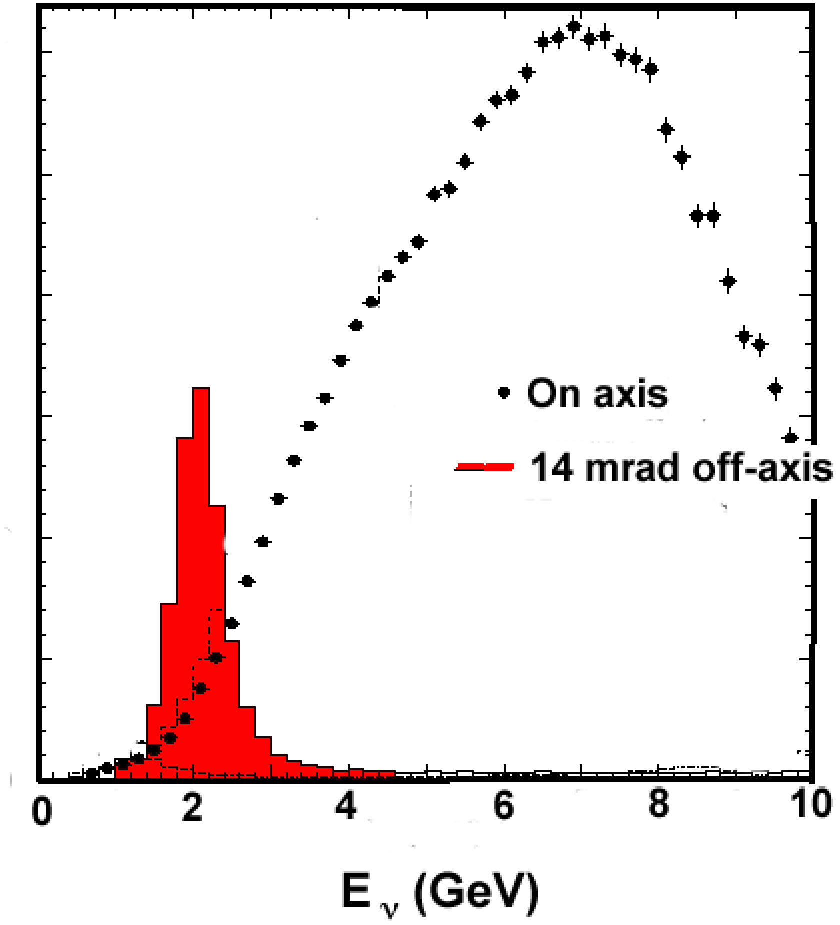
Reducing the MI Cycle Time

- This is one thing that can "work for sure" to deliver more protons. But beware of the pbar cycle time! 2.0 s is lower limit?
- Will be useful before and after completion of a new proton source.
- Some specific studies have been done of what is necessary to set an MI ramp time of 1.17 s and 0.62 s (Proton driver study, Mishra, Wolf, Marriner, others)
  - 1.17 s ramp time may be achievable for very little cost (<$2M?)
  - 0.62 s ramp time costs $25M for magnet power? + $25M for RF? Needs more study.
    - Additional magnet power supplies (and places to put them)
    - Replace some magnets?
    - x2 RF power (Complete overlap with high intensity needs)
    - x2 RF voltage (More cavities and/or higher voltage per cavity (new cavities?), Currently there are 18 cavities. HI requires 20. Depending on the exact intensity and ramp time this requires 20<N<36 equivalent? Use straight section at MI 30 (Marriner))
- Beyond a very first step, additional RF voltage, beyond that available to the cavities will be necessary quickly… New RF cavities. Universities could help make a partial step particularly inexpensive?
- The MI has enough RF power now for 6e13 protons acc to 120 GeV in 1.5s.
- Technically, should be possible by 2008

Off-Axis Rationale

- Want low-energy narrow-band beams at $\Delta m^2_{13} \approx \Delta m^2_{23}$ oscillation maximum:
  - ν_e appearance maximum
  - ν_μ CC disappears
  - – Higher-energy NC disappears
- Want detectors optimized for ν_e detection
- Want increases in beam flux times detector mass
- $\Rightarrow$ Off-axis Experiment Proposal

Off-Axis Spectrum (No oscillations)

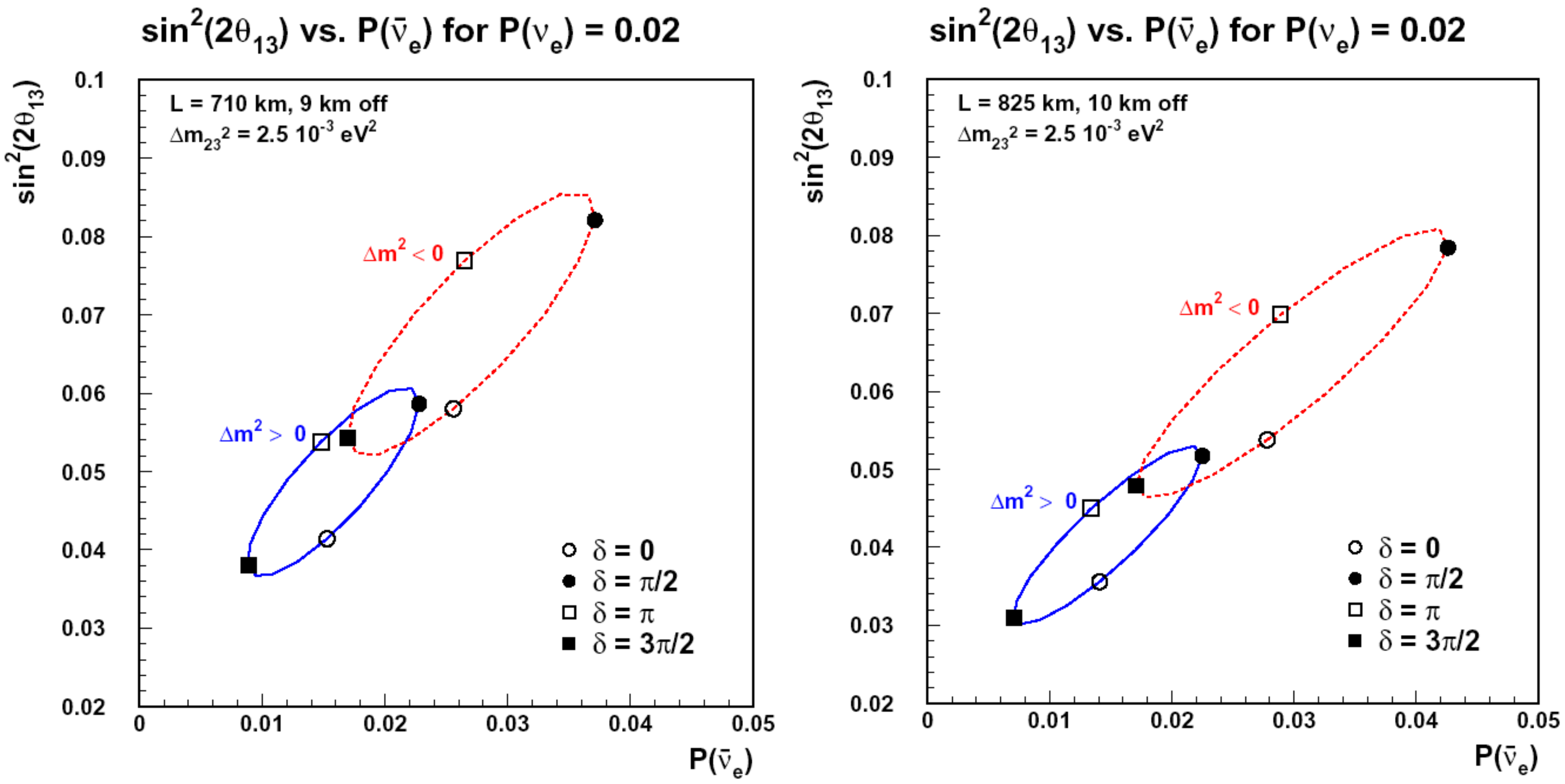


Signal and Backgrounds: NuMI Off-Axis and J-PARC

$\sin^2(2\theta_{13})_{eff} = 0.1$

	NuMI Off-axis 50 kton, 85% eff, 5 years, 4×10^{20} pot/y		JHF to SK Phase I, 5 years	
	all	After cuts	all	After cuts
ν_μ CC (no osc)	28348	6.8	10714	1.8
NC	8650	19.4	4080	9.3
Beam ν_e	604	31.2	292	11
Signal (Δm^2_{23}=2.8/3 x 10^{-3}, NuMI/JHF)	867.3	307.9	302	123
FOM (signal/$\sqrt{}$bckg)		40.7		26.2

$P(\nu_\mu \rightarrow \nu_e) = 0.02$ at 710 and 825 km



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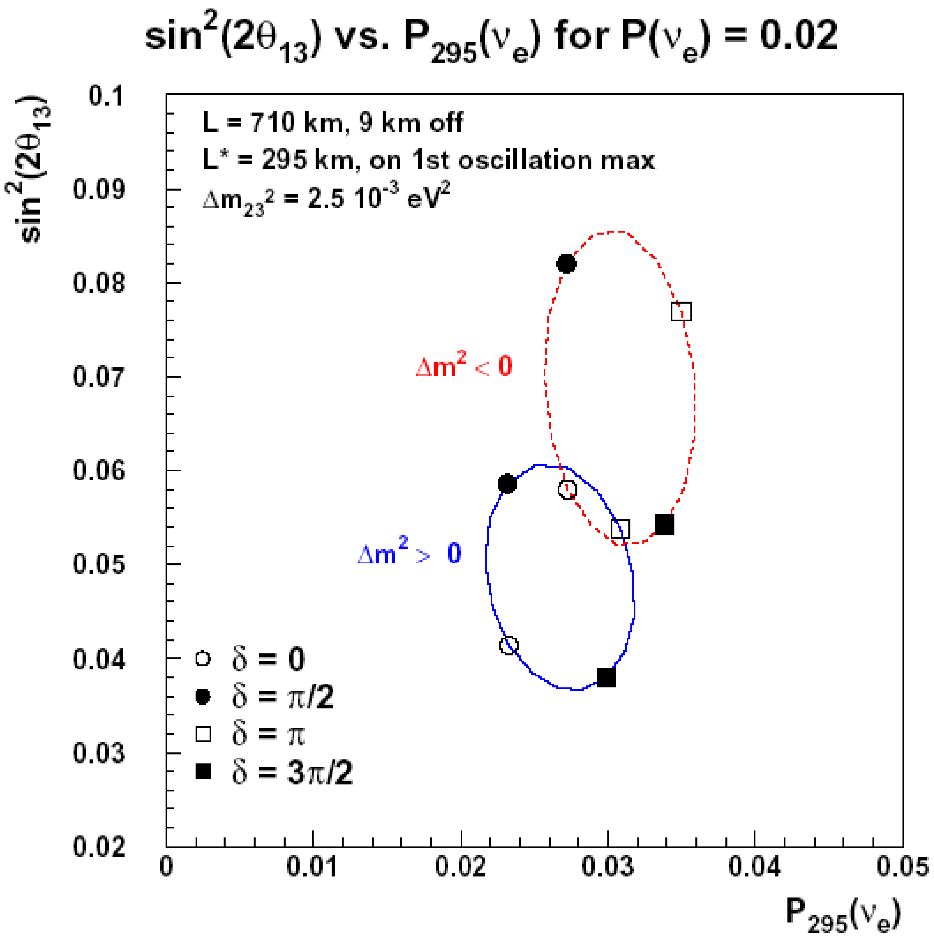
$P(\nu_\mu \rightarrow \nu_e) = 0.02$ at 710 km vs. $P(\nu_\mu \rightarrow \nu_e)$ at 295 km



As warned by Parke et al., hierarchy is not resolved by just neutrino running.

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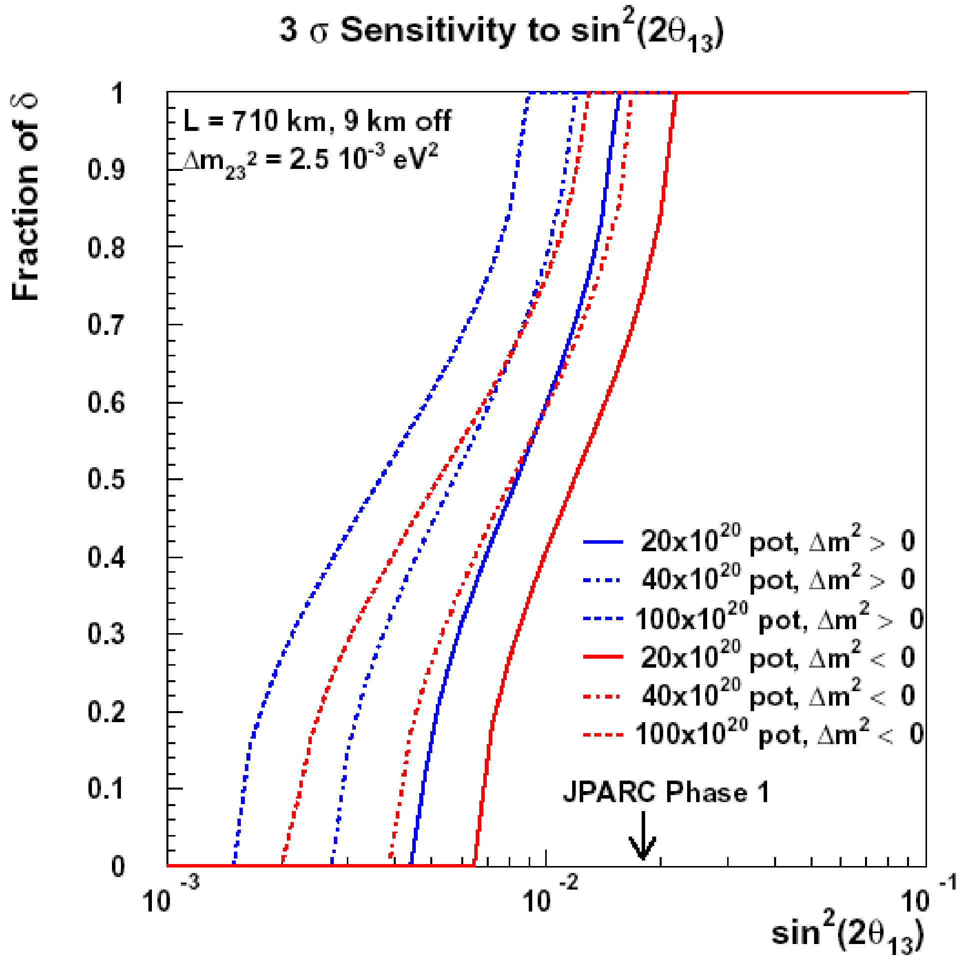
3 σ Discovery Potential for $\nu_\mu \rightarrow \nu_e$



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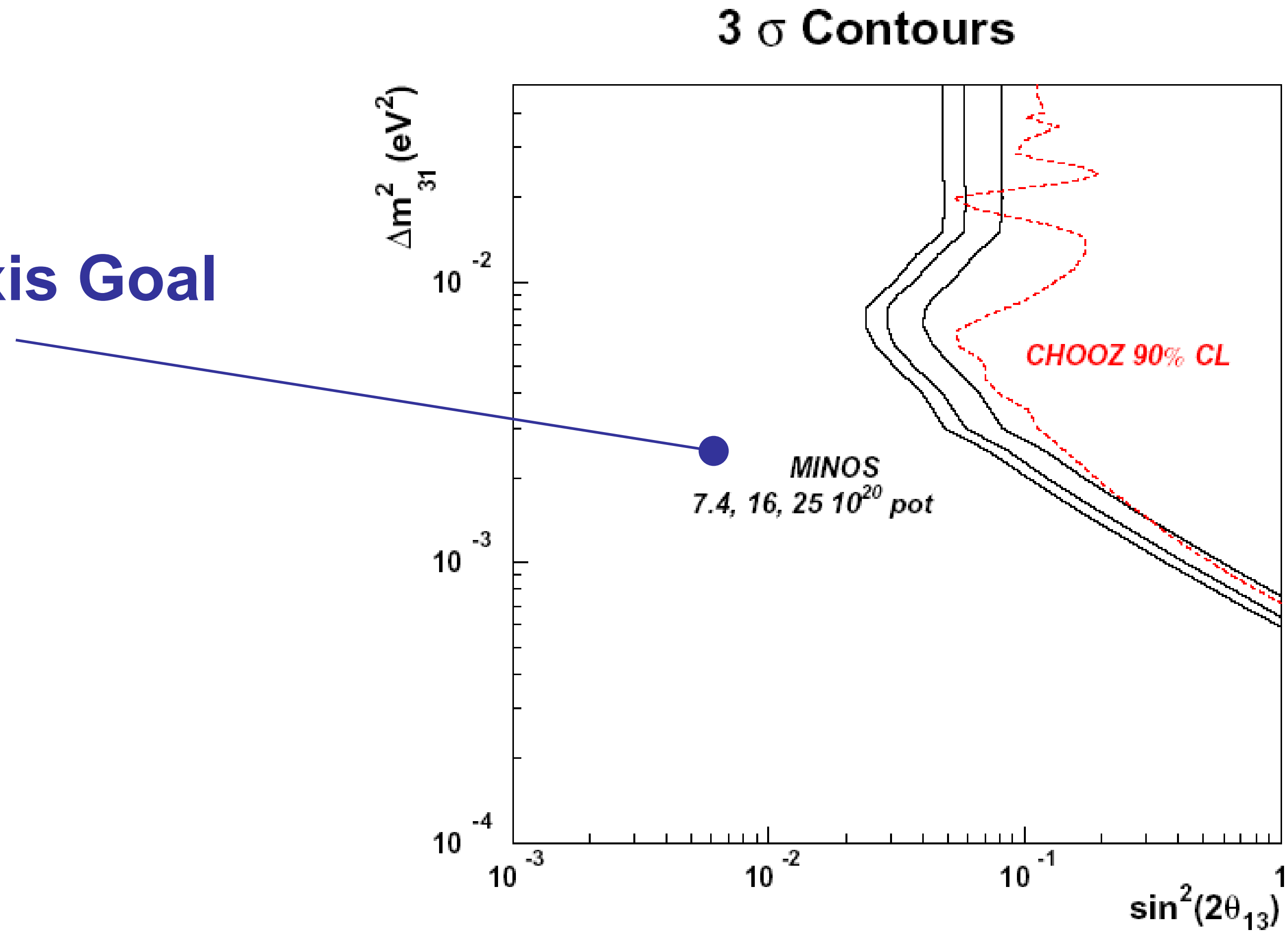
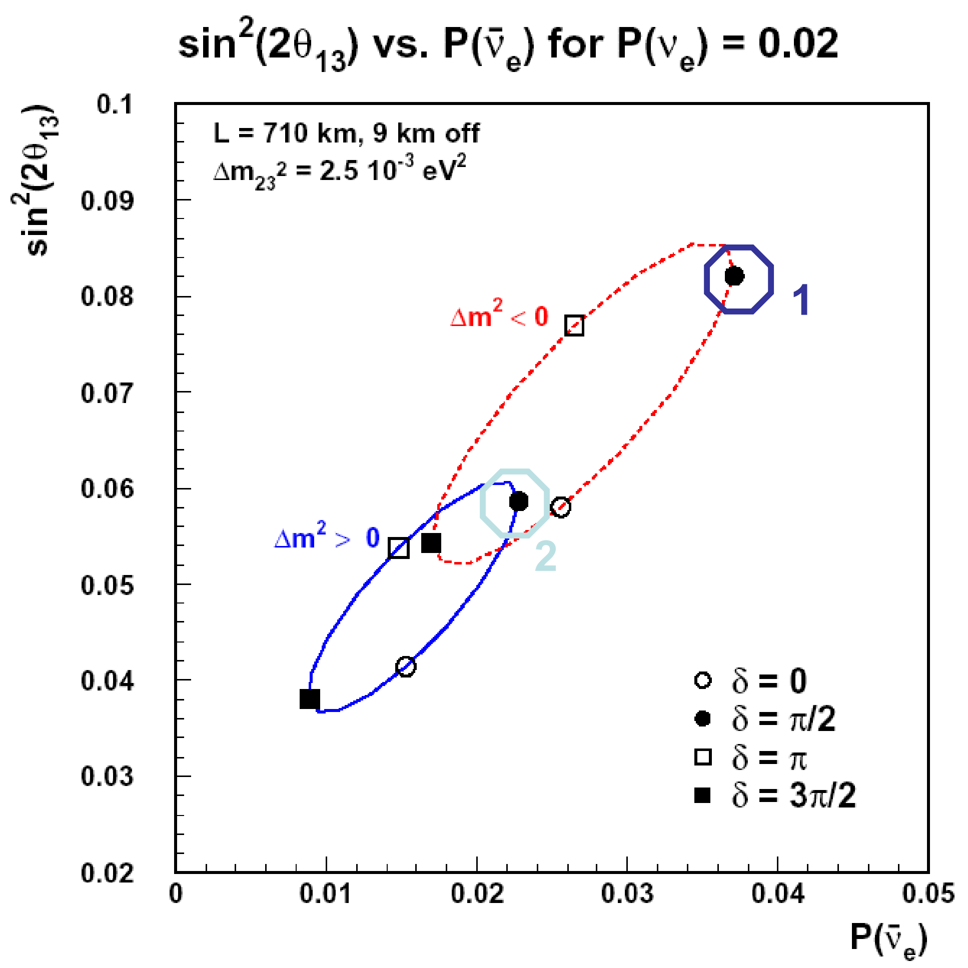
MINOS Sensitivity to $\nu_\mu \to \nu_e$ at 3σ Discovery

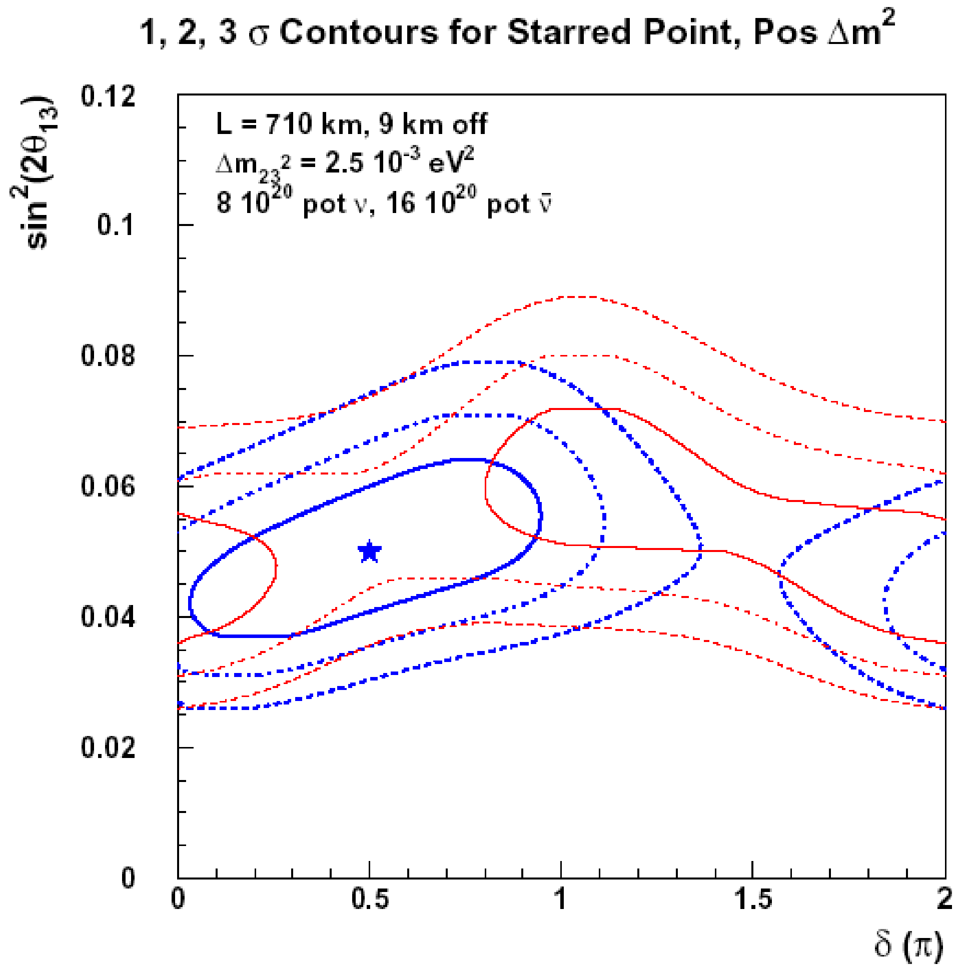
Off-Axis Goal



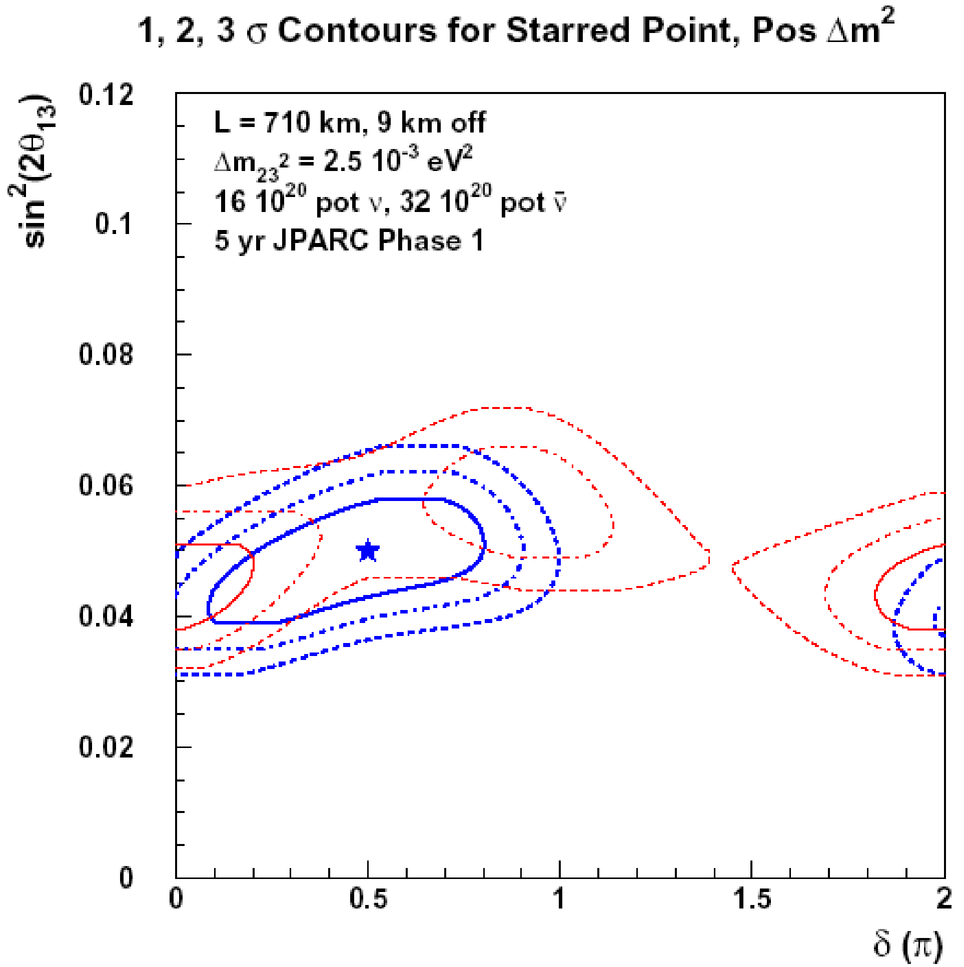
Study Points



Point 2: NuMI 2 yr ν, 4 yr $\bar{\nu}$ $4\ 10^{20}$ pot/yr



NuMI 2 yr ν, 4 yr $\bar{\nu}$, 8 10^{20} pot/yr and JPARC, Phase 1



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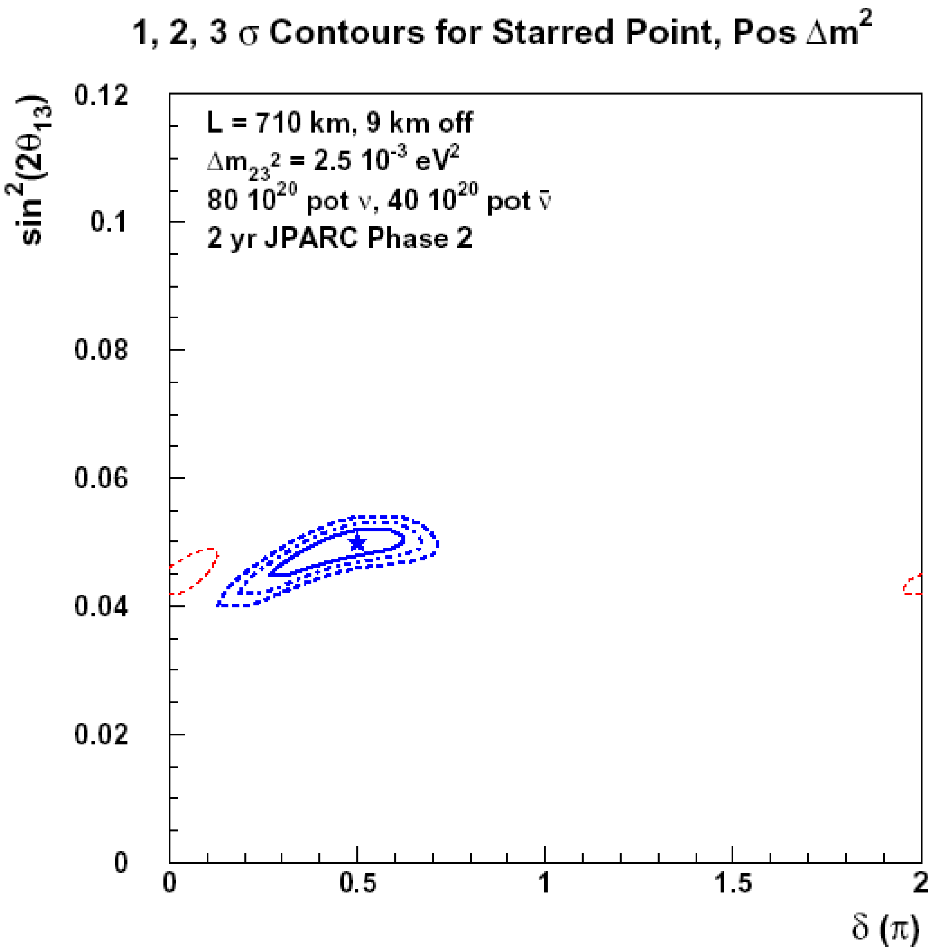
NuMI 4 yr ν, 2 yr $\bar{\nu}$, Proton Driver and JPARC, Phase 2



Hierarchy finally resolvable at > 95% CL with 6 yrs of proton driver.

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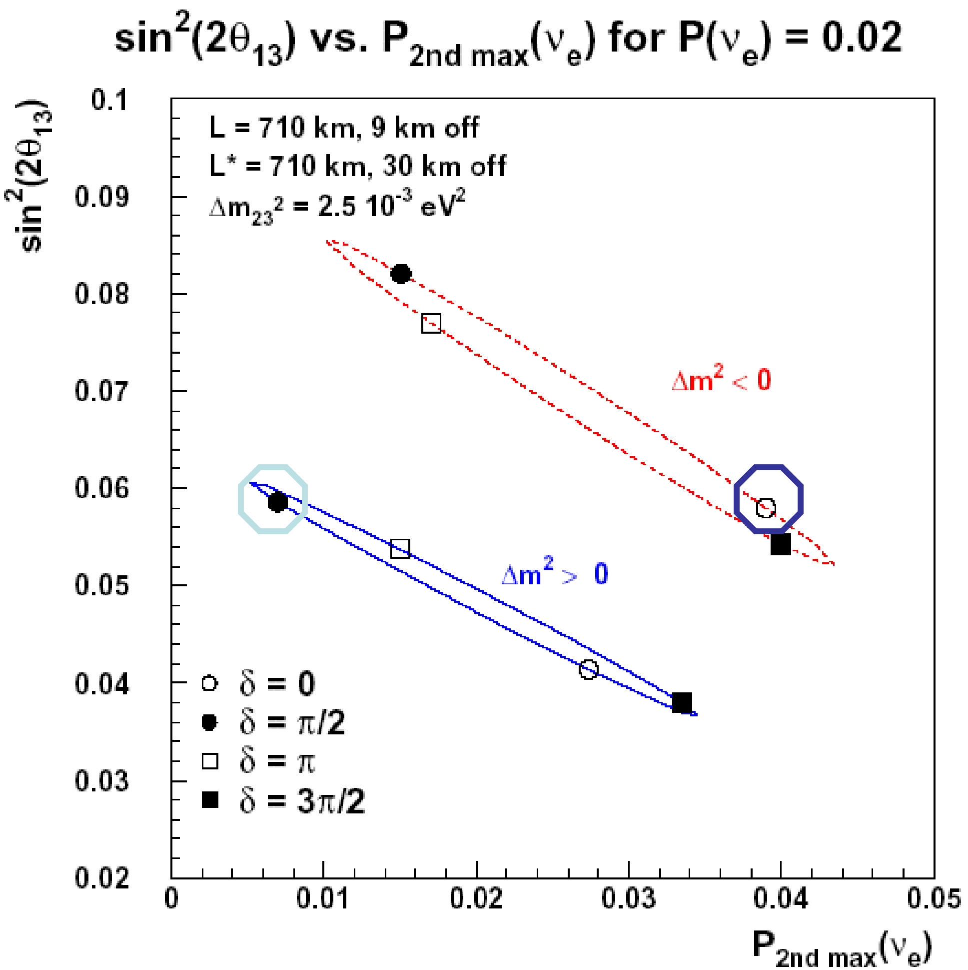
A 2nd Detector at the 2nd Maximum?



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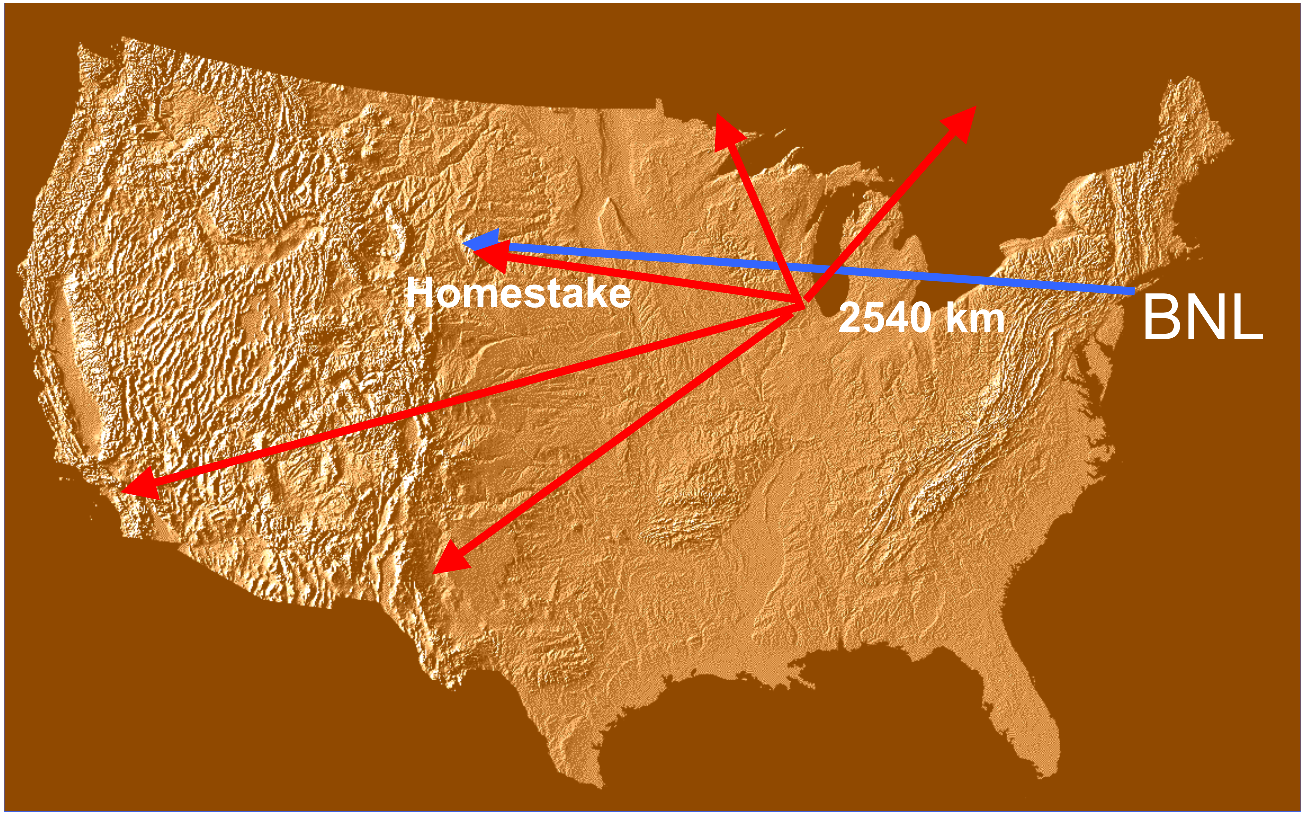
So What about this second oscillation maximum?

BNL → Homestake Super Neutrino Beam



28 GeV protons, 1 MW beam power
500 kT Water Cherenkov detector
5e7 sec of running, Conventional Horn based beam

Could we play this game at Fermilab?

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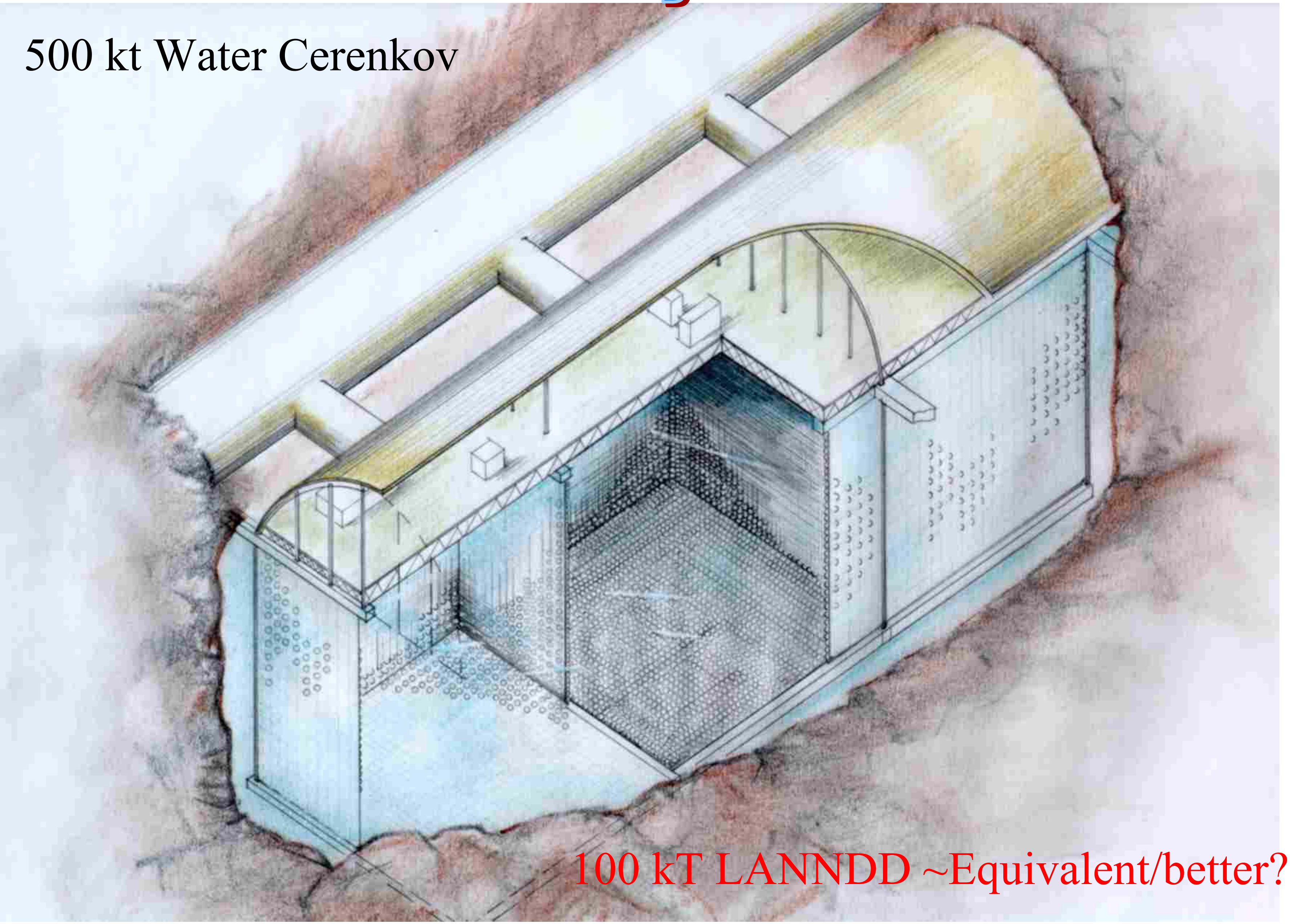
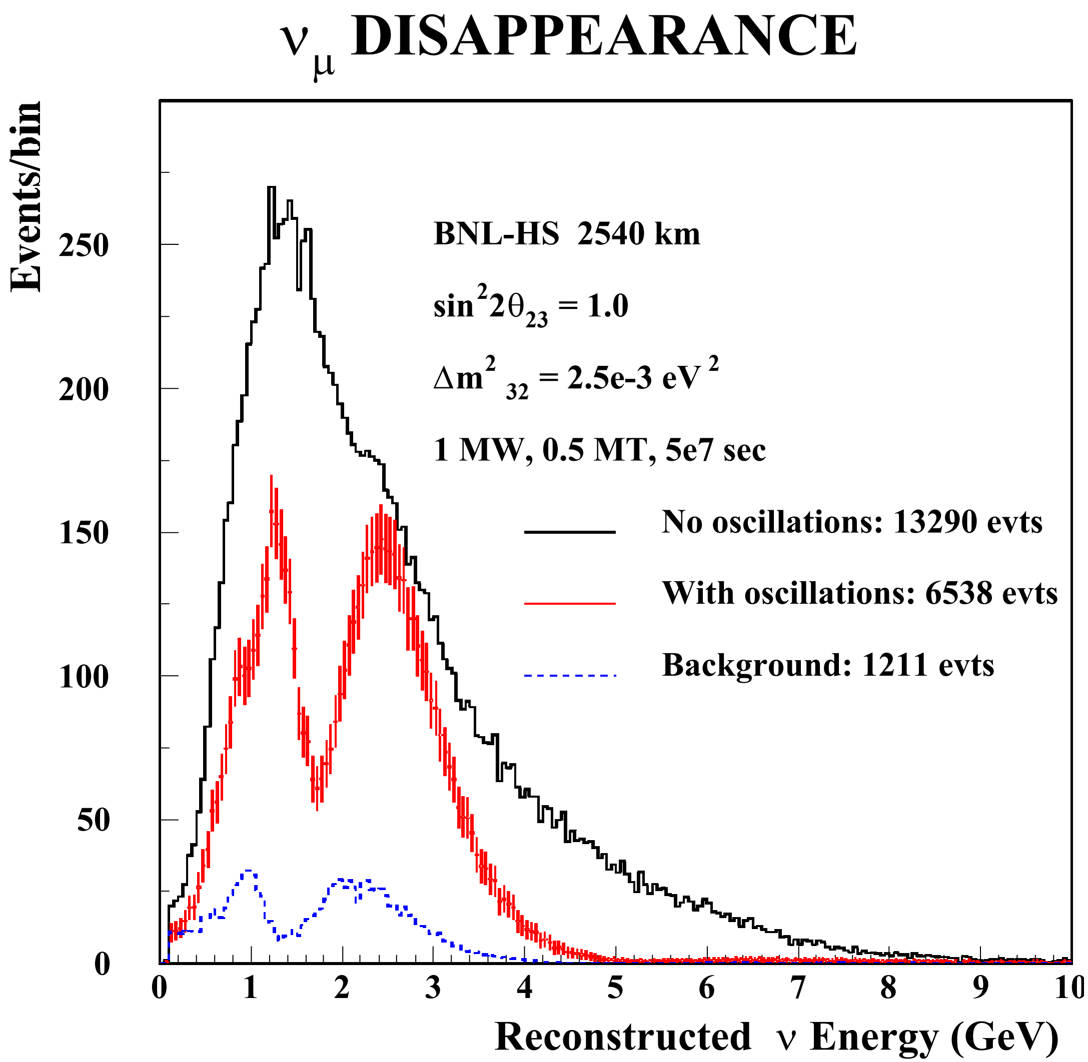
UNO: The Study Baseline



Advantages of a Very Long Baseline



- neutrino oscillations result from the factor $\sin^2(\Delta m_{32}^2\ L / 4E)$ modulating the ν flux for each flavor (here ν_μ disappearance)
- the oscillation period is directly proportional to distance and inversely proportional to energy
- with a *very long baseline* actual oscillations are seen in the data as a function of energy
- the multiple-node structure of the very long baseline allows the Δm_{32}^2 to be precisely measured by a *wavelength* rather than an amplitude (reducing systematic errors)

The problem is that the specific proposed use of water Cerenkov may not work in this energy region

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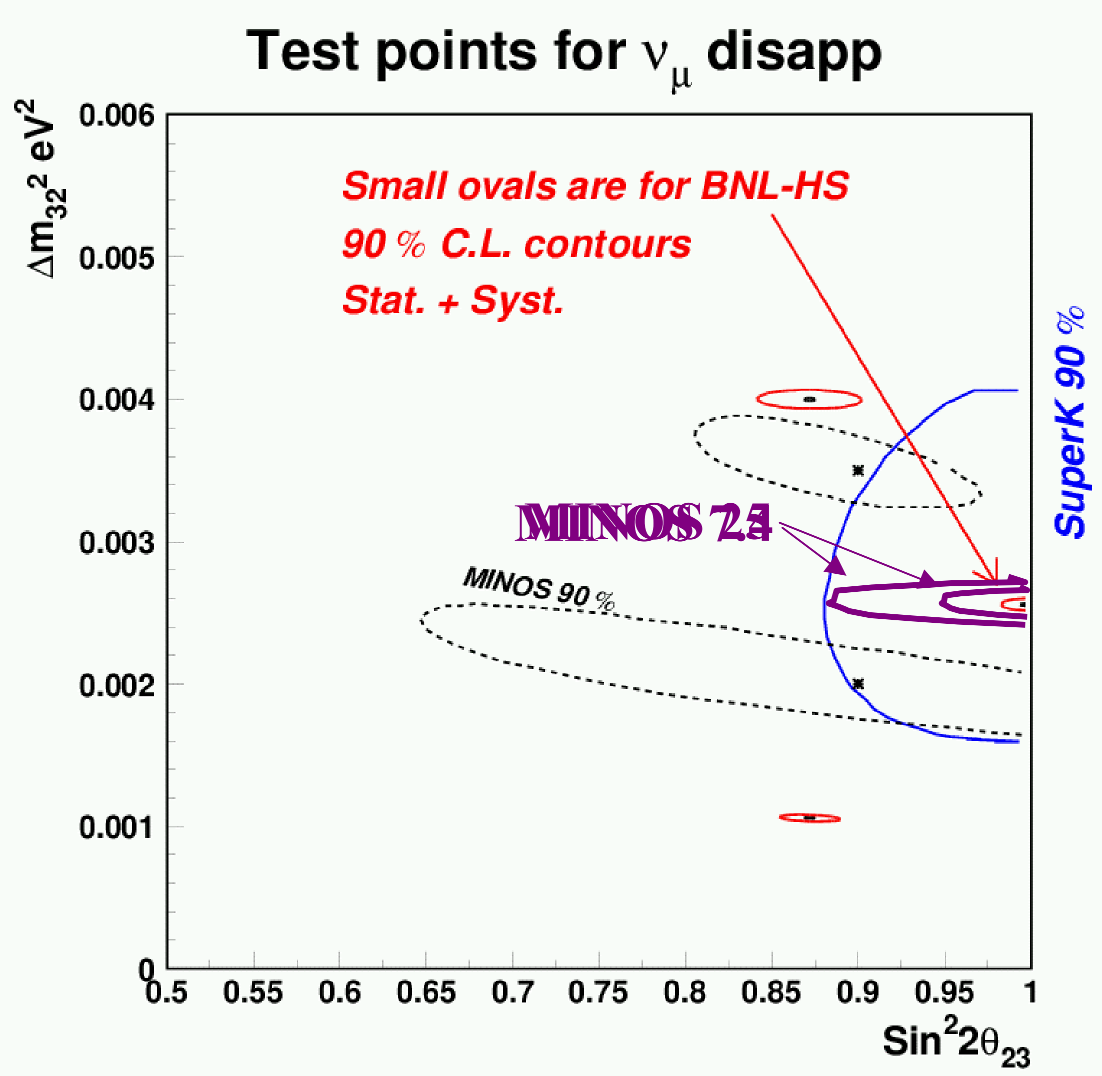
VLB Application to Measurement of Δm_{32}^2



- the multiple node method of the VLB measurement is illustrated by comparing the BNL 5-year measurement precision with the present Kamiokande results and the projected MINOS 3-year measurement precision; all projected data include both statistical and systematic errors
- there is no other plan, worldwide, to employ the VLB method (a combination of target power and geographical circumstances limit other potential competitors)
- other planned experiments can't achieve the VLB precision

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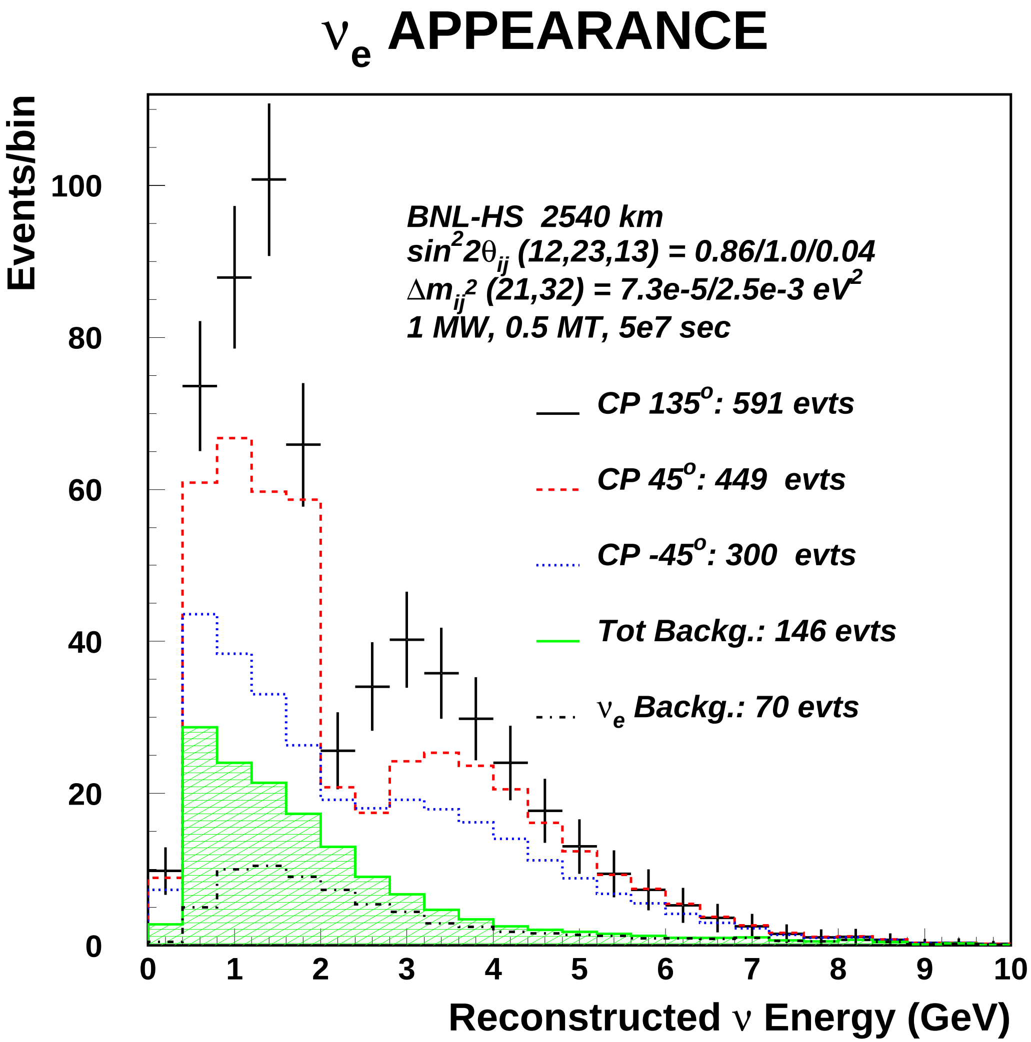
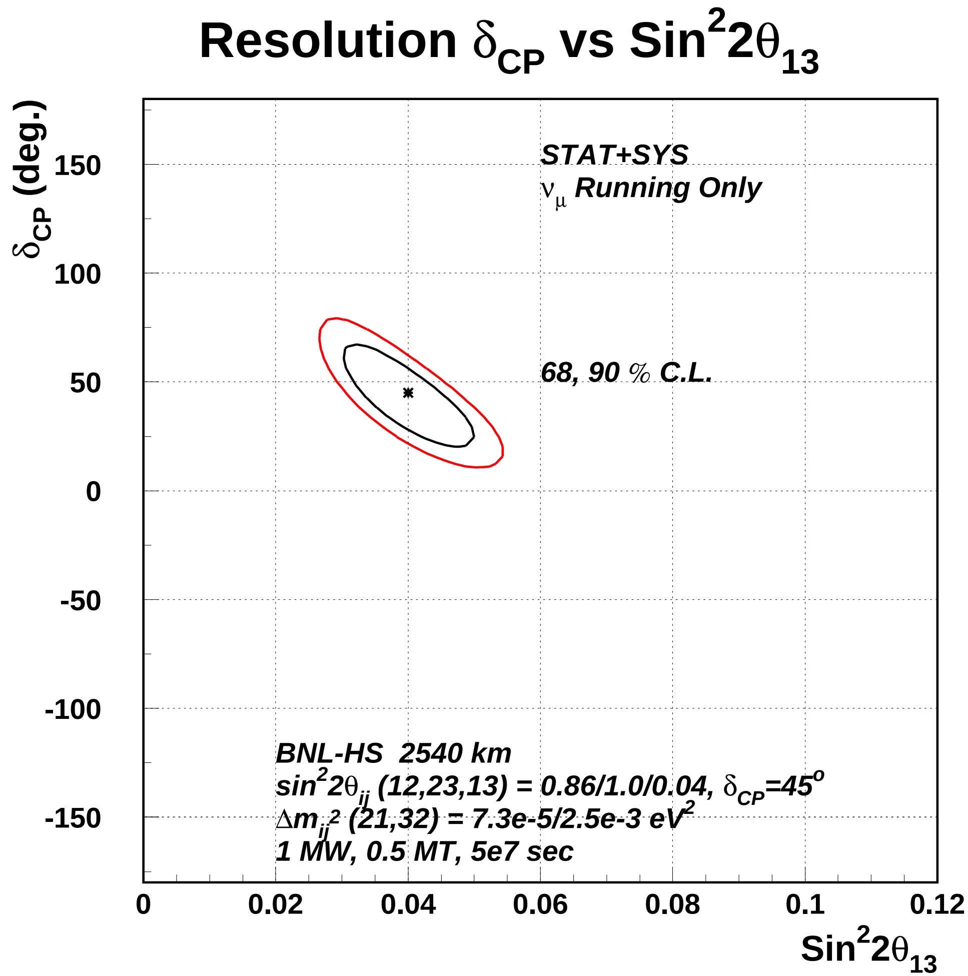
ν_e Appearance Measurements



- a direct measurement of the appearance of $\nu_\mu \rightarrow \nu_e$ is important; the VLB method competes well with any proposed super beam concept
- for values > 0.01, a measurement of $\sin^2 2\theta_{13}$ can be made (the current experimental limit is 0.12)
- for most of the possible range of $\sin^2 2\theta_{13}$, a good measurement of θ_{13} and the CP-violation parameter δ_{CP} can be made by the VLB experimental method

Mass -ordering and CP-violation Parameter δ_{CP}



- the CP-violation parameter δ_{CP} can be measured in the VLB exp. And is relatively insensitive to the value of $\sin^2 2\theta_{13}$
- the mass-ordering of the neutrinos is determined in the VLB exp; $\nu_1 < \nu_2 < \nu_3$ is the natural order but $\nu_1 < \nu_3 < \nu_2$ is still possible experimentally; VLB determines this, using the effects of matter on the higher-energy neutrinos

Comparison of Some Experiments

		F2S	C2GT	JHF2K	JHF2K-II	C2F	C2F+BB	νF	MINOS25	BNL-NUSEL
$< E_\nu >$ [GeV]		2	0.8	1	1	0.3	0.3	10	1-5	1-10
Fiducial mass	Water Cherenkov		1 Mt	22.5 kt	1 Mt	40 kt	1Mt			500 kT
	Iron/scintillator	20 kt						40 kt	5kT	
	Plastic/RPCs	20 kt								100kt LA?
Physics reach	$\sigma(\Delta m^2_{23})$ [eV^2]	1×10^{-4}	3×10^{-5}	1×10^{-4}		1×10^{-4}			2×10^{-4}	1×10^{-4}
	$\sigma(\sin^2 2\theta_{23})$	0.01	0.01	0.01		0.01			0.05	0.01
	$\sin^2\theta_{13}$ [90% CL]	1.5×10^{-3}		1.5×10^{-3}	2.5×10^{-4}	1.5×10^{-3}		2.5×10^{-5}	~0.03	~0.003
	θ_{13} [deg; 90% CL]	2.2		2.2	0.9	2.2		0.3		
	sgn Δm^2_{23}	?	No	No	?	No	No	Yes	?	Yes…
	CP-violation	No	No	No	?	No	?	Yes	No	Yes… But may Need nubar.
Incremental material cost (facility + detector [10^9 US \$])		0.2	0.1	0.2	1.0	0.7	2.0	2.0	0-0.08	1.0
Year of earliest operation		2008	2008		2015		2020		Done 2010	2010-2012?

From NuMI Off-Axis LOI

Conclusions

- We don’t know what the neutrino oscillation future holds.
- Long baseline experiments offer a completeness in measurement capabilities not possible with other techniques
- Protons are the key to these experiments. Don’t bother without making the investment in protons.
- Fermilab cannot delay getting started in increasing the protons. Things which can be done in the existing complex must be done as soon as possible while bringing the proton driver into operation in the next decade.