Unraveling the Mysteries of the Neutrino using Particle Accelerators

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Mary Bishai

mbishai@bnl.gov

Brookhaven National Lab.

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Outline

- A brief history of Neutrinos
- Neutrino oscillations and the Neutrino mixing matrix
- The SuperKamiokande experiment
- The K2K experiment.
- The MINOS experiment.
- Off Axis: The T2K and NOνA experiments
- The case for a wideband super neutrino beam.
- Summary and Conclusions

A BRIEF HISTORY OF THE NEUTRINO

Conception

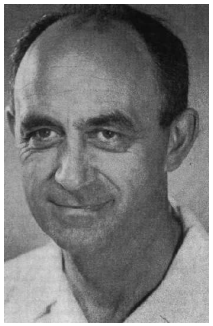
Before 1930's: beta decay spectrum continuous - is this energy non-conservation?

Dec 1930: Wolfgang Pauli's letter to physicists at a workshop in Tubingen proposes that a neutrally charged "neutron" with a mass "$<$ 0.01 proton mass" is emitted in beta-decays.

1932: James Chadwick discovers the neutron - its too heavy - cant be Pauli's particle

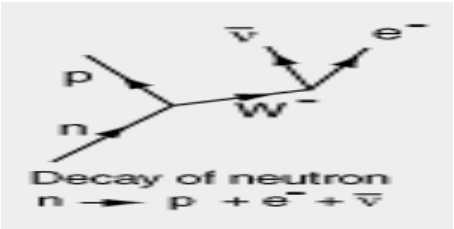
Solvay Conference 1933: Fermi proposes to name Pauli's particle "neutrinos".

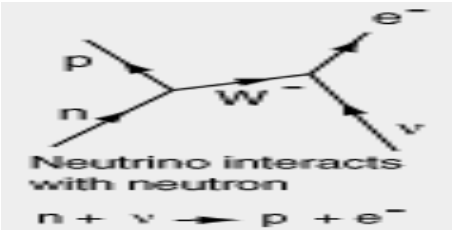
Wolfgang Pauli

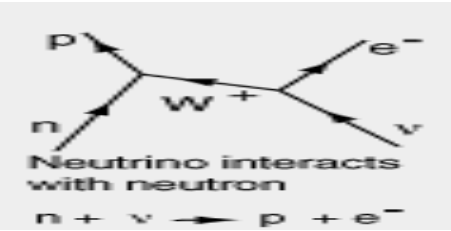


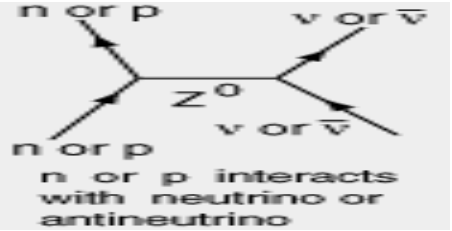
Enrico Fermi

$\geq$ 1933: Fermi builds his theory of weak interactions and beta decay



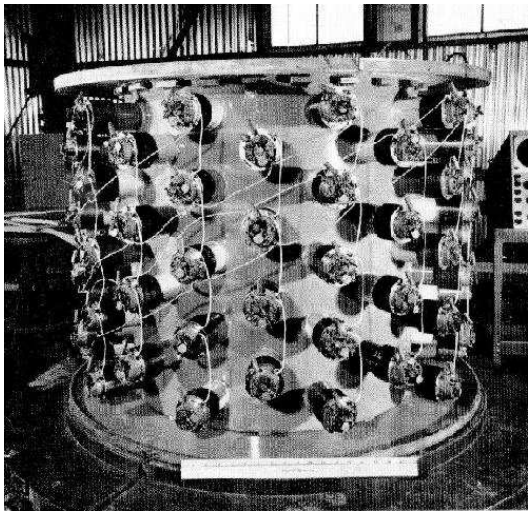






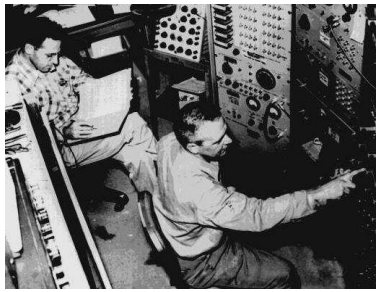
Detecting Neutrinos

1950's: Fred Reines at Los Alamos and Clyde Cowan mounted an experiment at the Hanford nuclear reactor in 1953 and in 1955 at the new Savannah River nuclear reactor. A detector filled with water with $CdCl_2$ in solution was located 11 meters from the reactor center and 12 meters underground.



The detection sequence was as follows:

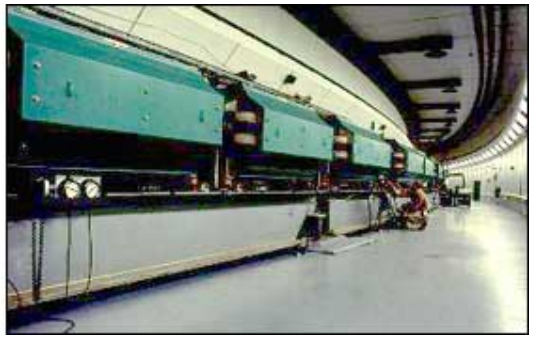
1. $\bar{\nu_e} + p \rightarrow n + e^+$
2. $e^+ + e^- \rightarrow \gamma\gamma$ **(2X 0.511 MeV)**
3. $n +^{108} Cd \rightarrow^{109} Cd* \rightarrow^{109} Cd + \gamma$ **(**$\tau = 5\mu s$**).**



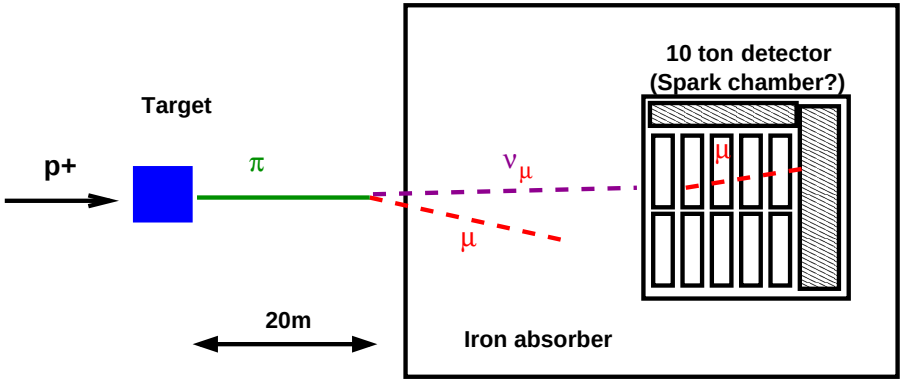
Neutrinos first detected from a reactor!

Neutrinos have flavors

1962: **Leon Lederman, Melvin Schwartz and Jack Steinberger** **use BNL's Alternating Gradient Synchrotron (AGS) to produce a beam of neutrinos using the decay** $\pi^+ \rightarrow \mu^+ \nu_x$

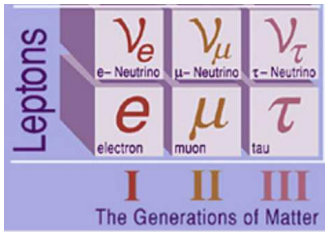


The AGS



Making ν's

Result: **40 neutrino interactions recorded in the detector, 6 of the resultant particles where identified as background and 34 identified as** $\mu \Rightarrow \nu_x = \nu_\mu$



The first accelerator neutrino experiment was at the AGS.

DISCOVERY OF NEUTRINO MASS/MIXING/OSCILLATIONS

The Homestake Experiment

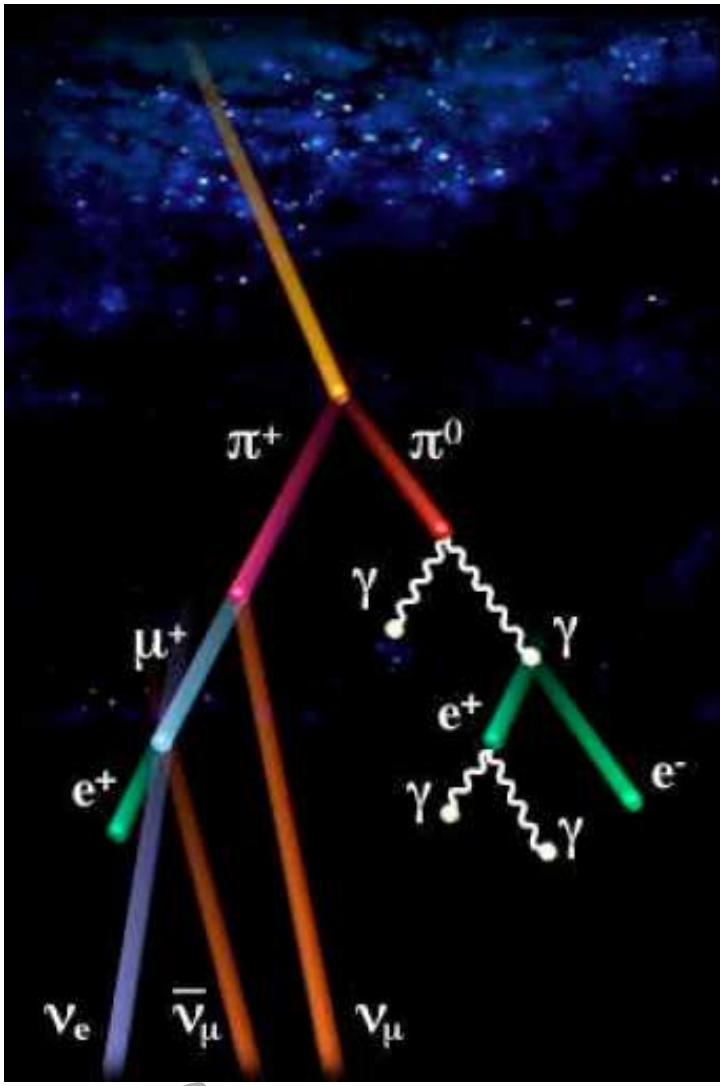
1967: **Ray Davis from BNL installs a large detector, containing 615 tons of tetrachloroethylene (cleaning fluid), 1.6km underground in Homestake mine, SD.**

Ray Davis

1. $\nu_e^{sun} +^{37} CL \rightarrow e^- +^{37} Ar,\ \tau(^{37}Ar) = 35$ **days.**
2. **Number of** Ar **atoms** $=$ **number of** ν_e^{sun} **interactions.**

Results: 1969 - 1993 **Measured** 2.5 ± 0.2 **SNU (1 SNU = 1 neutrino interaction per second for** 10^{36} **target atoms) while theory predicts 8 SNU. This is a** ν_e^{sun} **deficit of 69%.**

The atmospheric neutrino deficit

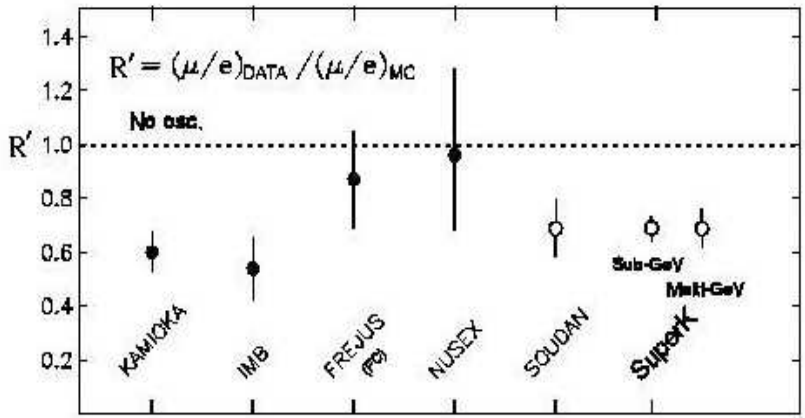


Neutrinos are produced from cosmic ray interactions in the atmosphere. The atmospheric neutrino beam is approx $1/3(\nu_e+\bar{\nu_e})$ and $2/3(\nu_\mu+\bar{\nu_\mu})$. (NB: $E(\nu_e^{sun}) \leq 20$ MeV whereas $E(\nu^{atm}) = \mathcal{O}(\mathrm{GeV}) - \mathcal{O}(\mathrm{TeV})$).

The 80's and 90's: Measurement of the ratio:

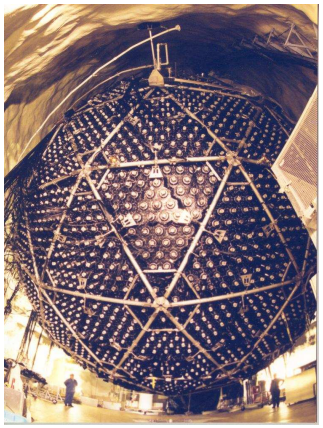
$$R = \frac{(\nu_\mu/\nu_e)_{data}}{(\nu_\mu/\nu_e)_{MC}}$$

in different expts reveals a 40% deficit of ν_μ



Evidence for neutrino oscillations

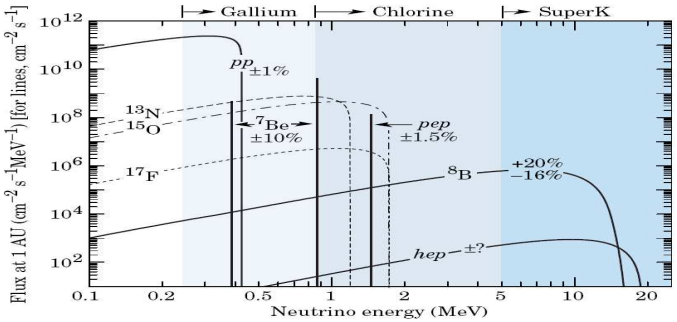
2001-02: Sudbury Neutrino Observatory. Water Čerenkov detector with 1 kT heavy water located 2Km below ground in INCO's Creighton nickel mine near Sudbury, Ontario. Can detect the following ν^{sun} interactions:



1) $\nu_e + d \rightarrow e^- + p + p$ **(CC).**

2) $\nu_x + d \rightarrow p + n + \nu_x$ **(NC).**

3) $\nu_x + e^- \rightarrow e^- + \nu_x$ **(ES).**



SNO measured:

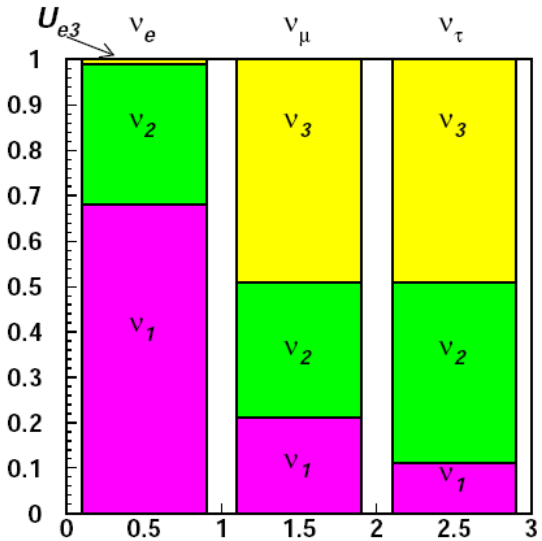
$$\phi^{CC}_{SNO}(\nu_e) = 1.75 \pm 0.07(\text{stat})^{+0.12}_{-0.11}(\text{sys.}) \pm 0.05(\text{theor}) \times 10^6 cm^{-2} s^{-1}$$
$$\phi^{ES}_{SNO}(\nu_x) = 2.39 \pm 0.34(\text{stat})^{+0.16}_{-0.14}(\text{sys.}) \pm \times 10^6 cm^{-2} s^{-1}$$
$$\phi^{NC}_{SNO}(\nu_x) = 5.09 \pm 0.44(\text{stat})^{+0.46}_{-0.43}(\text{sys.}) \pm \times 10^6 cm^{-2} s^{-1}$$

ν_e has changed to ν_x!

Neutrino mixing

In 1962 Maki, Nakagawa, Sakata proposed a 2 flavor mixing matrix. The 3-flavor form now used (attributed to MNS and Pontecorvo) is:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}_{U_{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



BUT: Notable difference with CKM matrix- very large off diagonal terms:

$$U_{PMNS} \sim \begin{pmatrix} 0.8 & 0.5 & ? \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \quad V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.005 \\ 0.2 & 1 & 0.04 \\ 0.005 & 0.04 & 1 \end{pmatrix}$$

Neutrino oscillations

Assume 2 flavors only:

$$\begin{pmatrix} \nu_a \\ \nu_b \end{pmatrix} = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\begin{aligned} \nu_a(t) &= \cos(\theta)\nu_1(t) + \sin(\theta)\nu_2(t) \\ P(\nu_a \to \nu_b) &= |<\nu_b|\nu_a(t)>|^2 \\ &= \sin^2(\theta)\cos^2(\theta)|e^{-iE_2t} - e^{-iE_1t}|^2 \end{aligned}$$

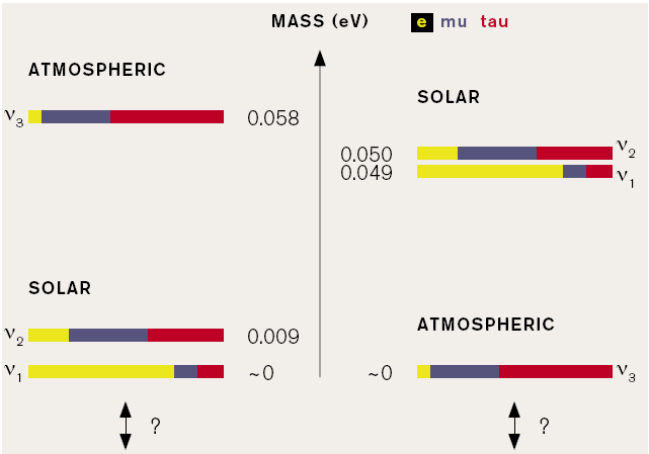
$$P(\nu_a \to \nu_b) = \sin^2 2\theta \sin^2 \frac{1.27((m_2^2 - m_1^2)/eV^2)(L/km)}{(E/GeV)}$$

$$P(\nu_a \to \nu_a) = 1 - \sin^2 2\theta \sin^2 \frac{1.27((m_2^2 - m_1^2)/eV^2)(L/km)}{(E/GeV)}$$

Neutrino Matrix Parameterization

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{Atmospheric } \nu's} \underbrace{\begin{pmatrix} c_{13} & 0 & e^{i\delta_{\rm CP}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{\rm CP}} s_{13} & 0 & c_{13} \end{pmatrix}}_{\text{Reactor } \nu's} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Reactor,Solar } \nu's}$$

where $c_{\alpha\beta} = \cos\theta_{\alpha\beta}$ **and** $s_{\alpha\beta} = \sin\theta_{\alpha\beta}$ **and** $\delta_{\rm CP}$ **is the CP phase.**



Normal **Inverted**

$\sin^2\theta_{13}$: **Amount of** ν_e **in** ν_3

$\tan^2\theta_{23}$: **Ratio of** $\frac{\nu_\mu}{\nu_\tau}$ **in** ν_3

$\tan^2\theta_{12}$: $\frac{\text{Amount of } \nu_e \text{ in } \nu_2}{\text{Amount of } \nu_e \text{ in } \nu_1}$

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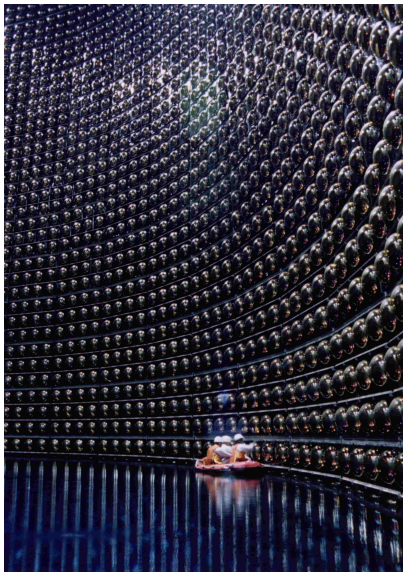
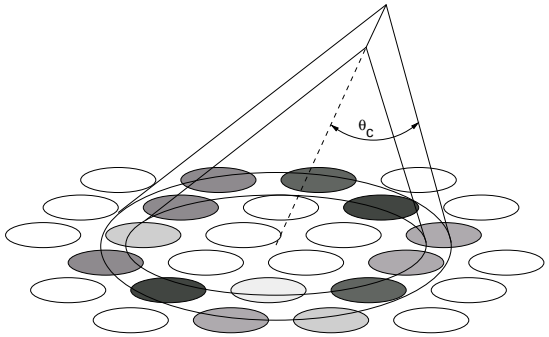
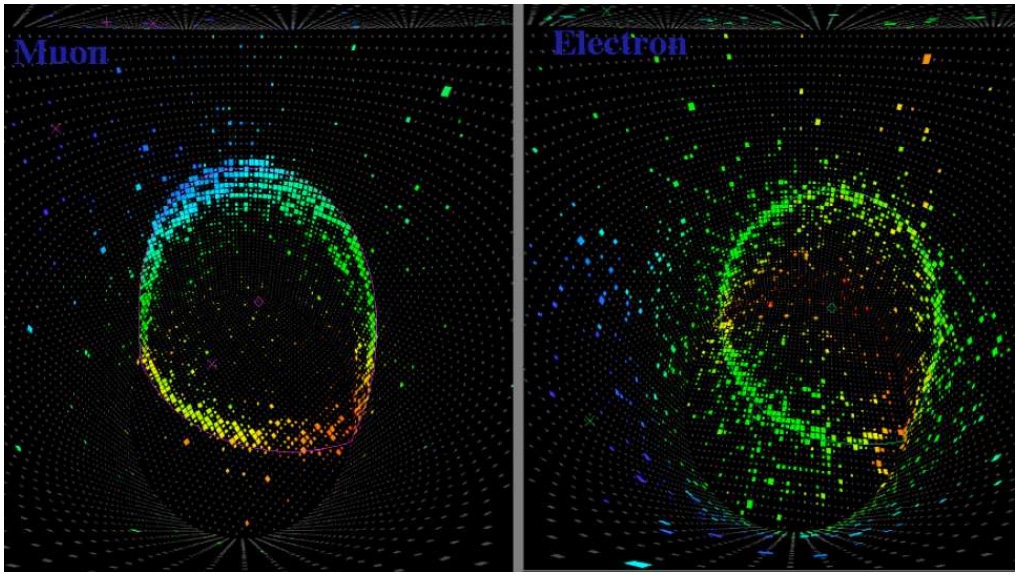
The Super-Kamiokande Detector

A huge 50kT double layered tank of ultra pure water surrounded by 11,146 20” diameter photomultiplier tubes. Located in an old zinc mine 0.6km under Mount Ikena in the Japanese Alps, near the town of Kamioka. The project has been collecting data since 1 April 1996.





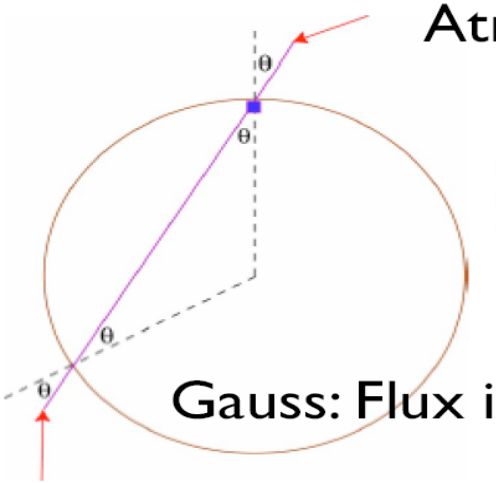
Particle id using rings of Čerenkov light

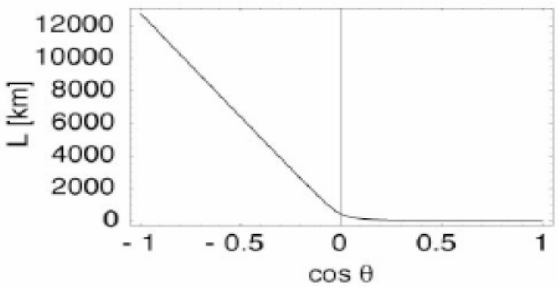


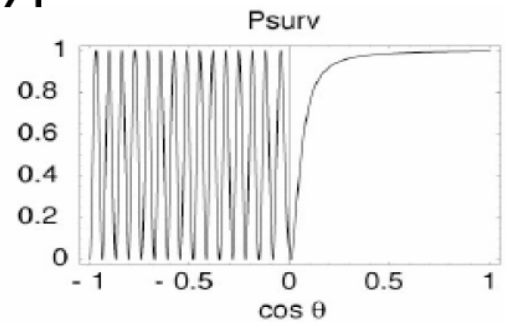
Measurement of ν^{atm} oscillations

Atmospheric neutrinos as a source for oscillation experiments

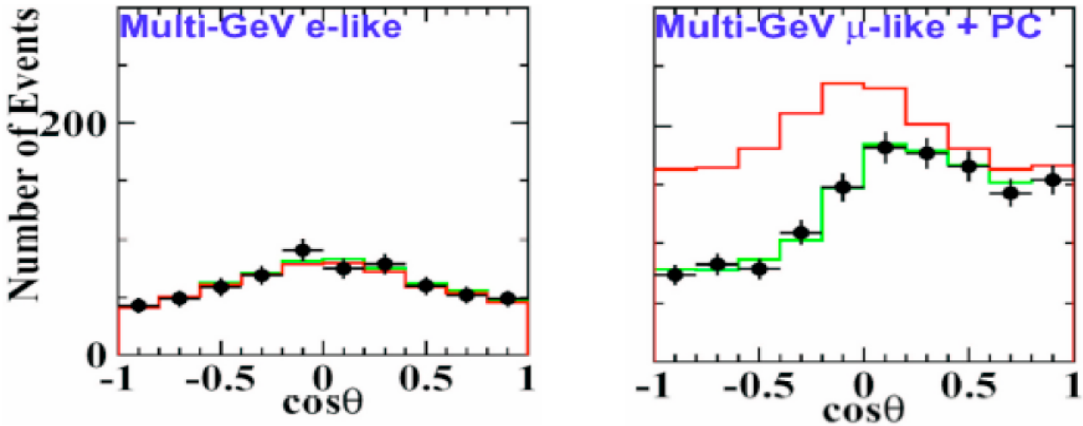
Atm. neutrinos 2:1 mu:e type







Gauss: Flux inside spherical shell isotropic



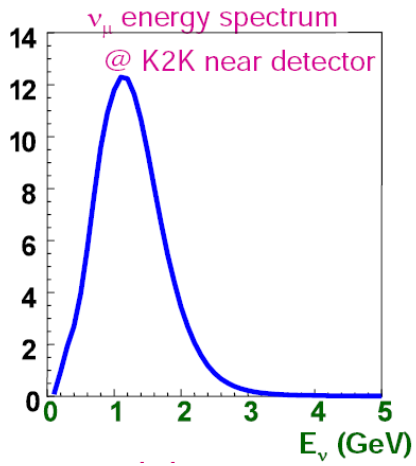
Evidence for neutrino oscillations from SuperK

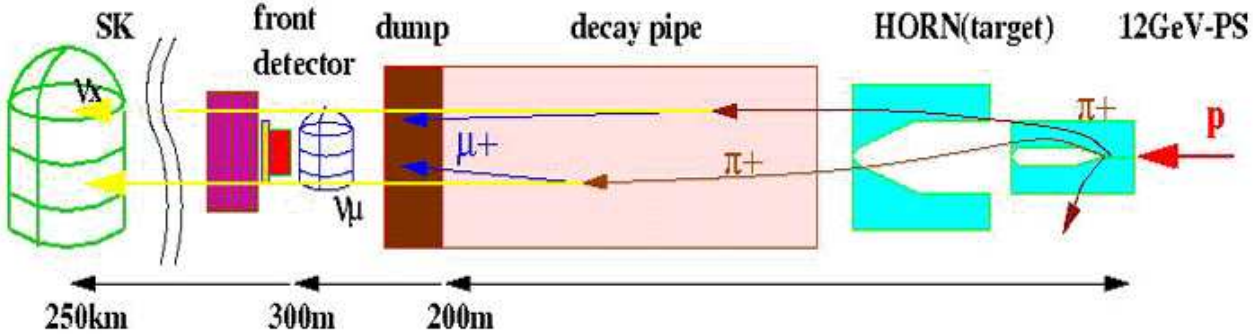
Best fit : $(\sin^2 2\theta_{23}, \Delta m^2_{32}) = (1.02, 2.4 \times 10^{-3} eV^2)$

$\sin^2 2\theta_{23} > 0.90$ **and** $1.9 < \Delta m^2_{32} < 3.0 \times 10^{-3} eV^2$ **at the 90% CL.**

The K2K experiment

Confirm the SK oscillation result using ν_μ beam from KEK. $L = 250$ km.



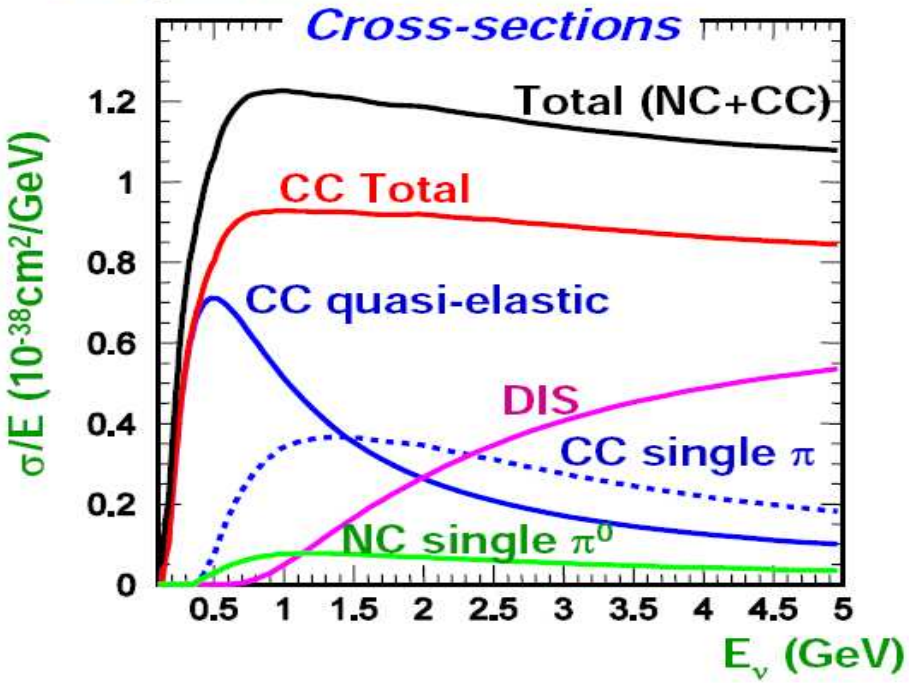


Neutrino interactions - redux

Neutrino interactions around 1GeV region

- Charged current quasi-elastic scattering (CCQE) $\nu_\mu + n \rightarrow \mu^- + p$
- Neutral current elastic scattering $\nu_\mu + N \rightarrow \nu + N$
- Single π, η, K resonance productions $\nu_\mu + N \rightarrow l + N' + \pi\ (\eta, K)$
- Coherent pion productions $\nu_\mu + O \rightarrow l + X + \pi$
- Deep inelastic scattering $\nu_\mu + N \rightarrow l + N' + m\pi\ (\eta, K)$

(*l* : lepton, N,N' : nucleon, m : integer)



It is also important
to take into account
nuclear effects.
Mesons (especially π)
and
protons interactions
in target nucleus.
(Oxygen, Carbon ..)

Yoshinari Hayato

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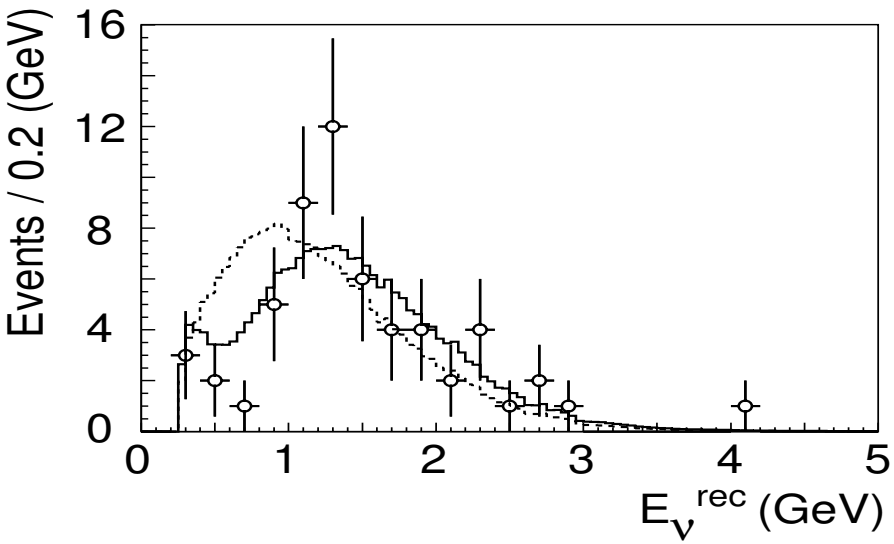
K2K results

"Evidence for muon neutrino oscillation in an accelerator-based experiment" (The K2K Collaboration) PRL 94 (2005) 081802

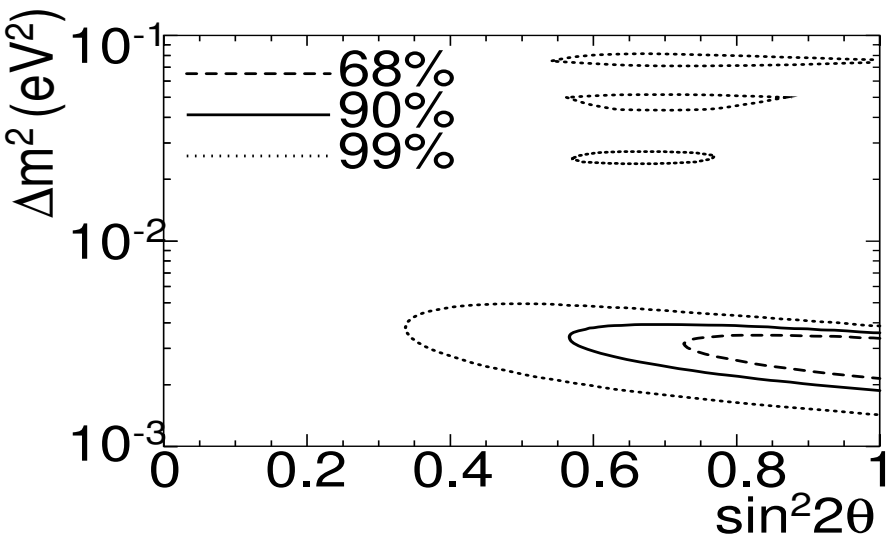
Results: **Using** 8.9×10^{19} **protons-on-target (POT).**

Find 107 fully contained events in SK fiducial volume

Expected $151^{+12}_{-10}(syst)$ **no-osc.**



SK 1-ring μ like



Allowed regions

Best fit : $(\sin^2 2\theta_{23}, \Delta m^2_{32}) = (1.0, 2.8 \times 10^{-3} eV^2)$

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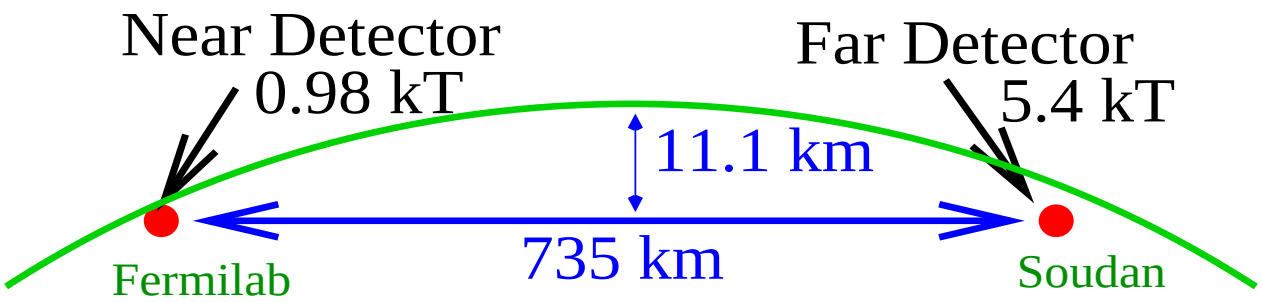
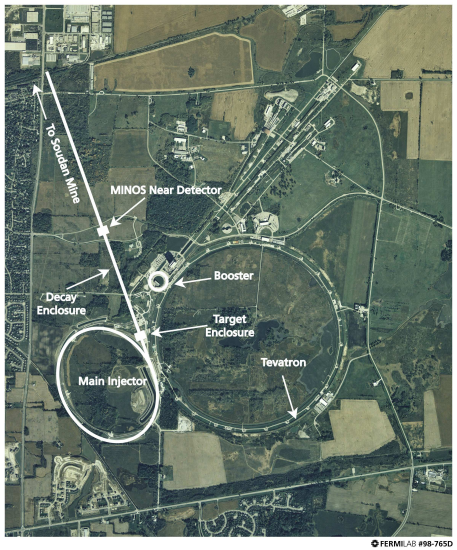
INTRODUCTION TO NuMI/MINOS

NuMI/MINOS Concept



Fermilab's Main Injector, Illinois



Soudan Underground Lab, Minnesota

120 GeV protons, 2.5×10^{13} protons/ 8μsec pulse, 1.9 sec rep rate.

$\Rightarrow$ 0.25 MW

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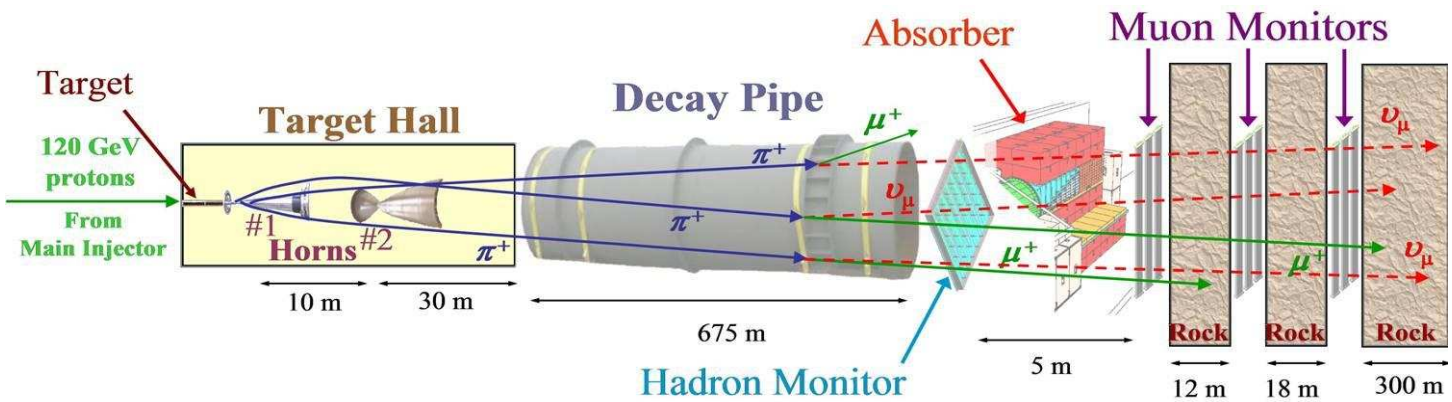
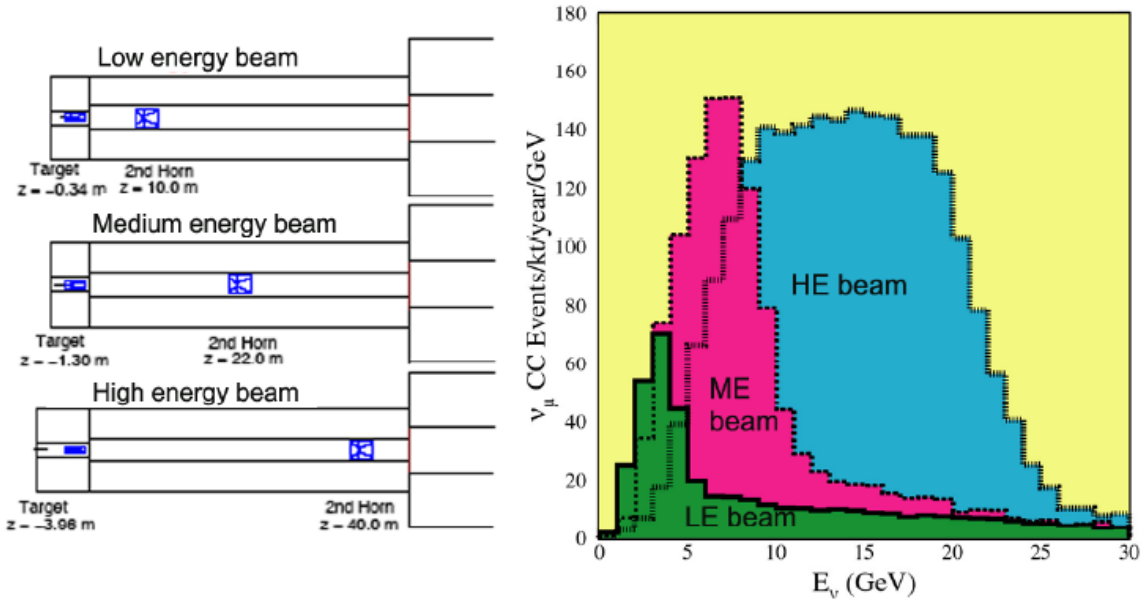
MINOS Beam Spectrum

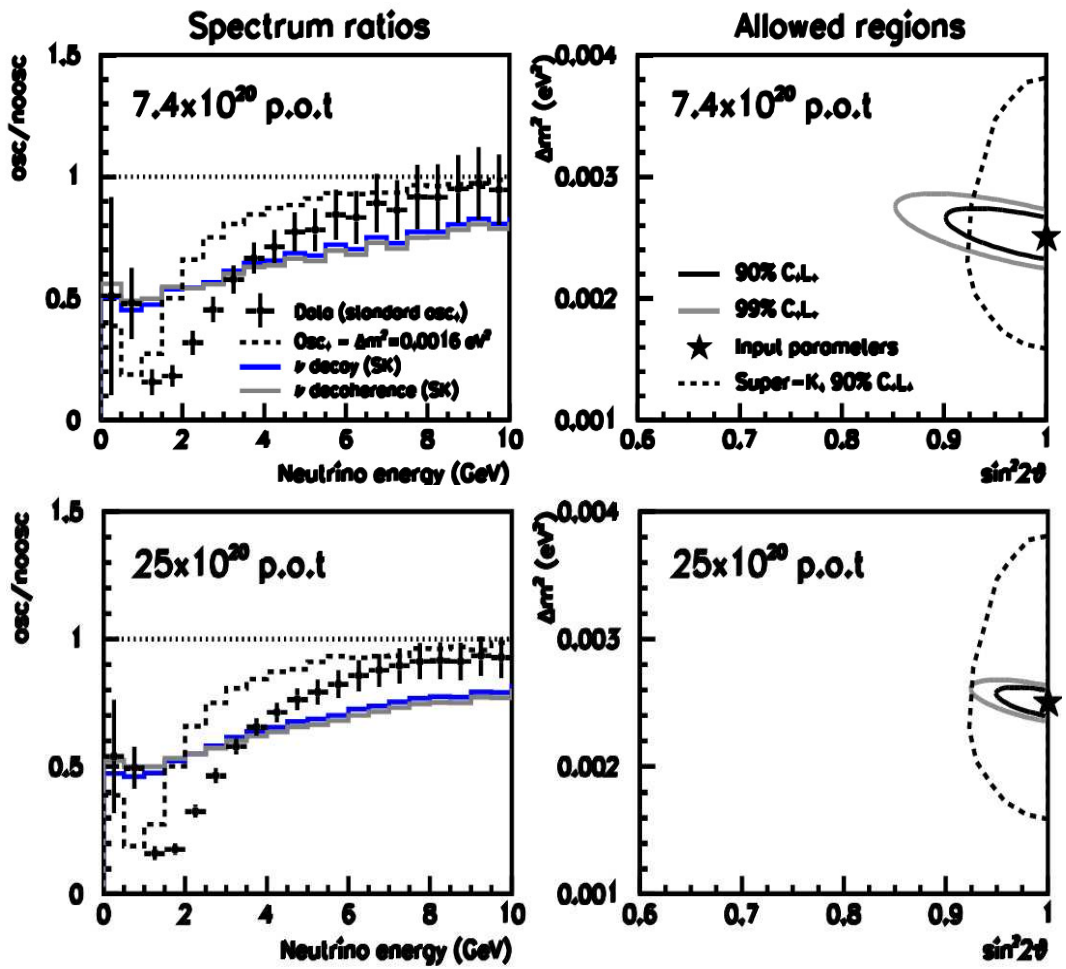




LE beam at 2.5×10^{20} POT/yr $\Rightarrow$ expect 1600 events/yr in FD

MINOS ν_μ Disappearance

- Plot ratio of yield at far det. to expected from near det.
- Location and depth of dip yield δm^2 and $\sin^2 2\theta$
- Assume $\delta m^2 = 0.0025$ eV^2, $\sin^2 2\theta = 1.0$



3 years at nominal intensity (top). Intensity upgrades (bottom)

Determine δm^2 to 10 % Rule out exotic oscillation models

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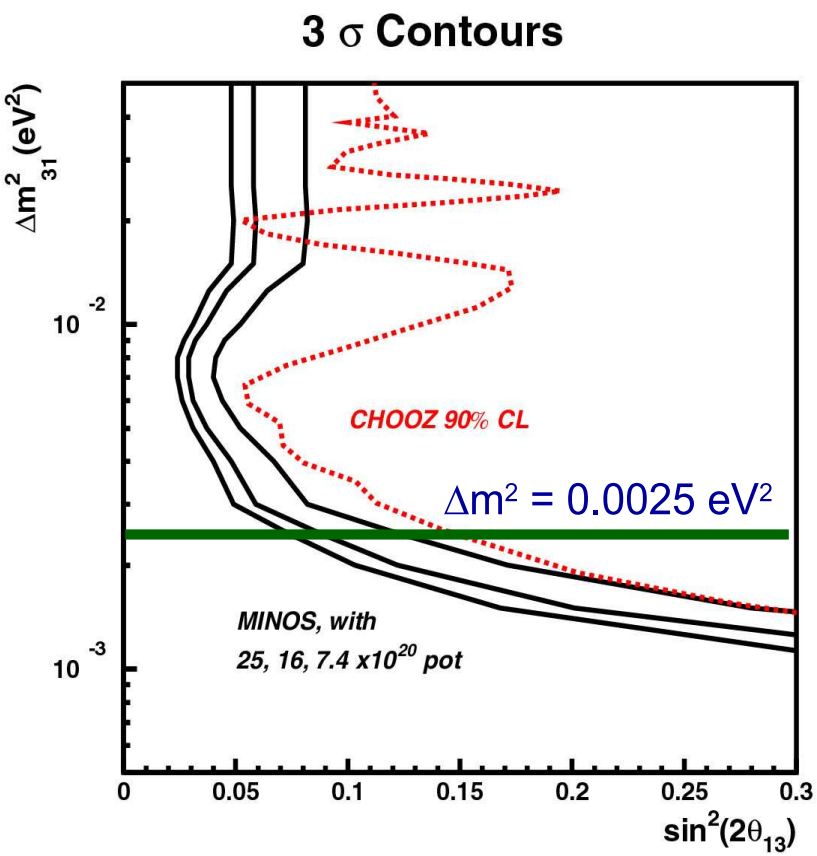
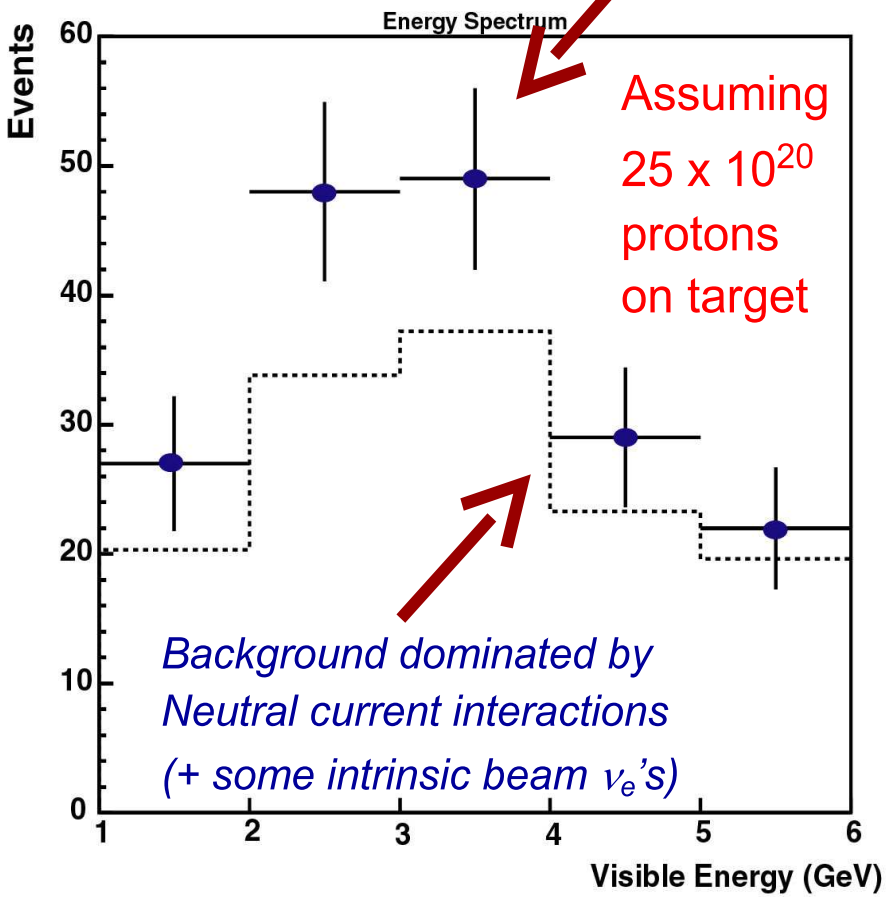
MINOS ν_e Appearance Sensitivity

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





Detection of ν_e at Δm^2_{atm}. Evidence for non-zero θ_{13}

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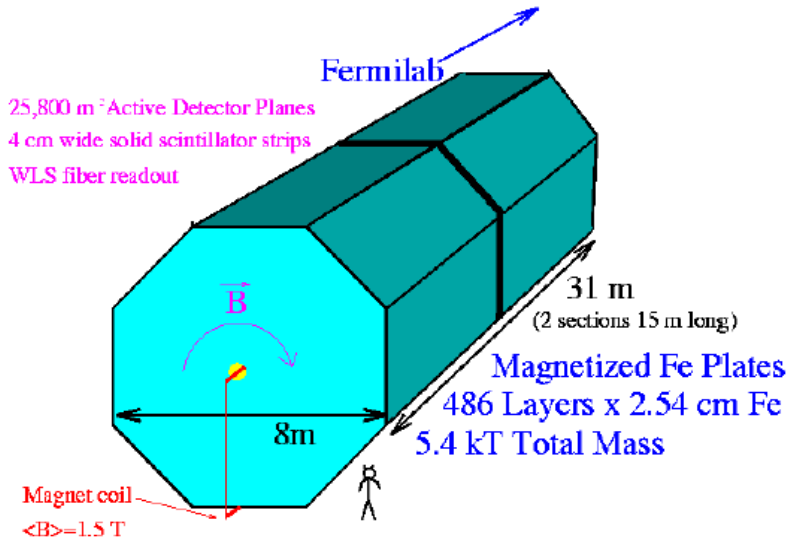
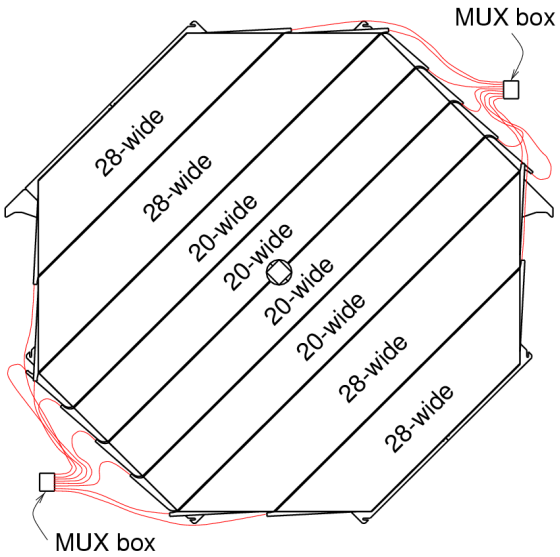
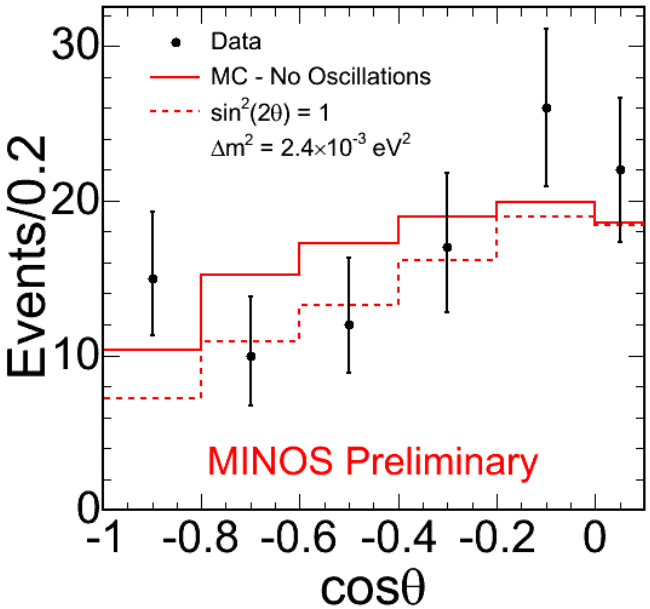
The Far Detector (FD)

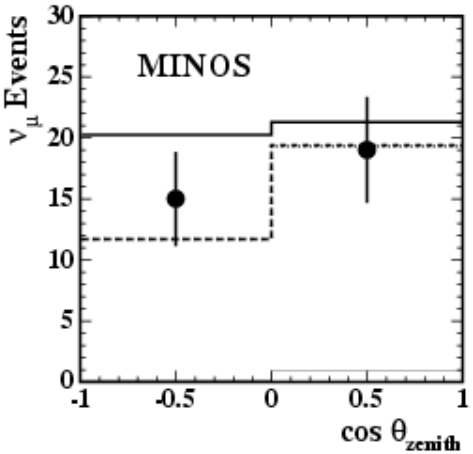


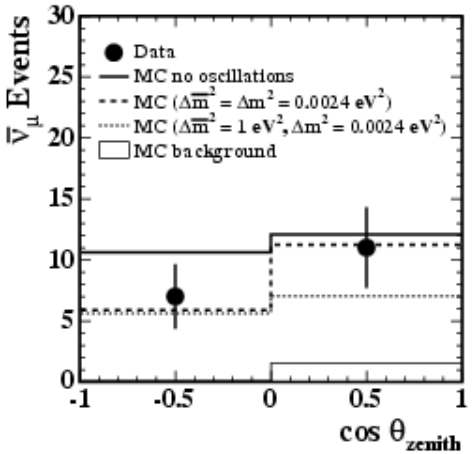
- **8m $\times$ 2.54 cm thick Fe plates**
- $4.1\mathrm{W} \times 1\mathrm{D} \times 800\mathrm{L}$ **cm scintillator strips with WLS fiber readout.** **486 layers $\Rightarrow$ 5.4kTon**
- **Toroidal B-field, 1.3 T at $r = 2$m**
- **Cosmic μ veto shield**



FD ν^{atm} Physics



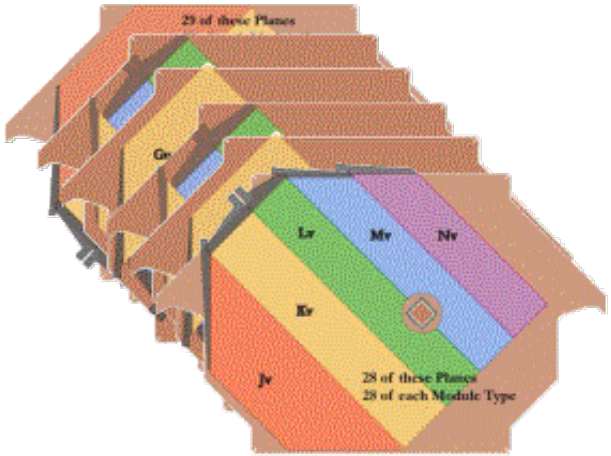




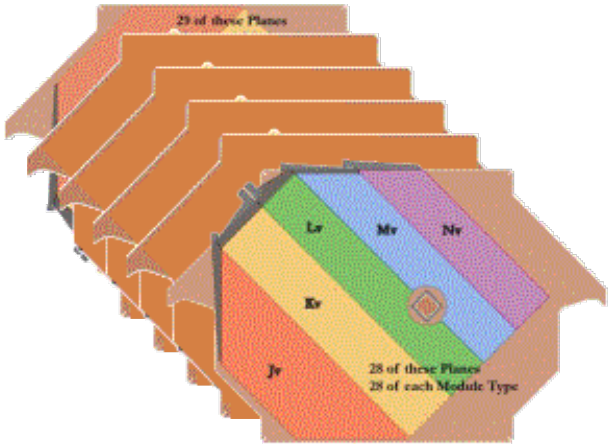
First ν^{atm}, $\bar{\nu}^{atm}$ seperation:

Selection	Data	Expected no oscillations	Expected $\Delta m^2_{23} = 0.0024\,\mathrm{eV}^2$
Low Res.	30	37 ± 4	28 ± 3
Ambig. $\nu_\mu/\overline{\nu}_\mu$	25	26 ± 3	20 ± 2
ν_μ	34	42 ± 4	31 ± 3
$\overline{\nu}_\mu$	18	23 ± 2	17 ± 2

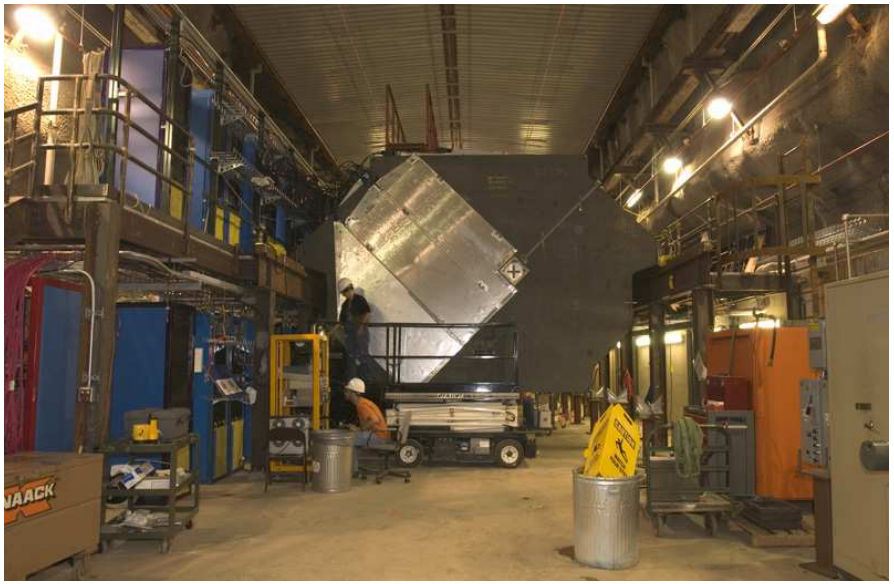
The Near Detector (ND)



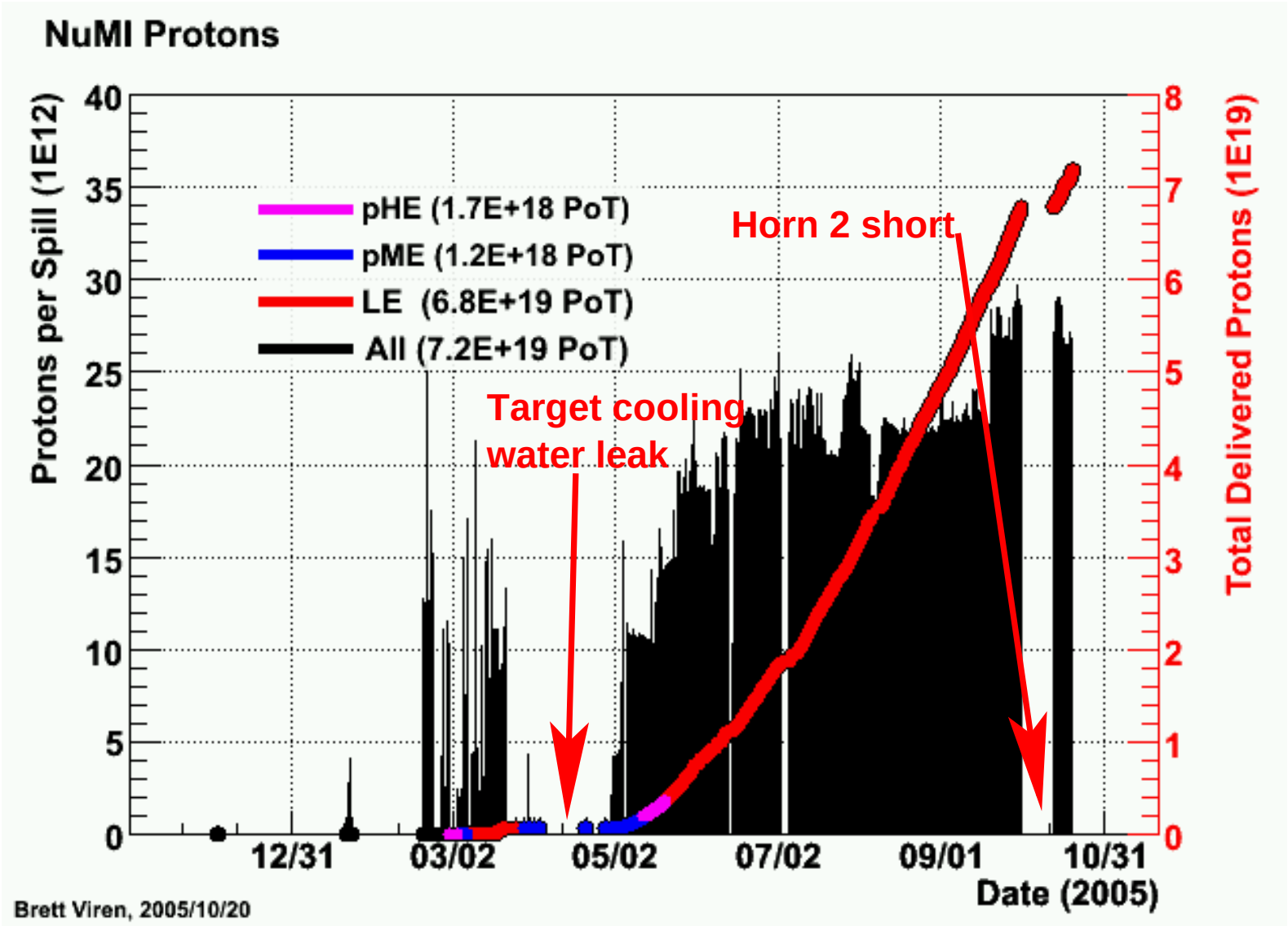
Calorimeter region



Spectrometer region



Beam Performance



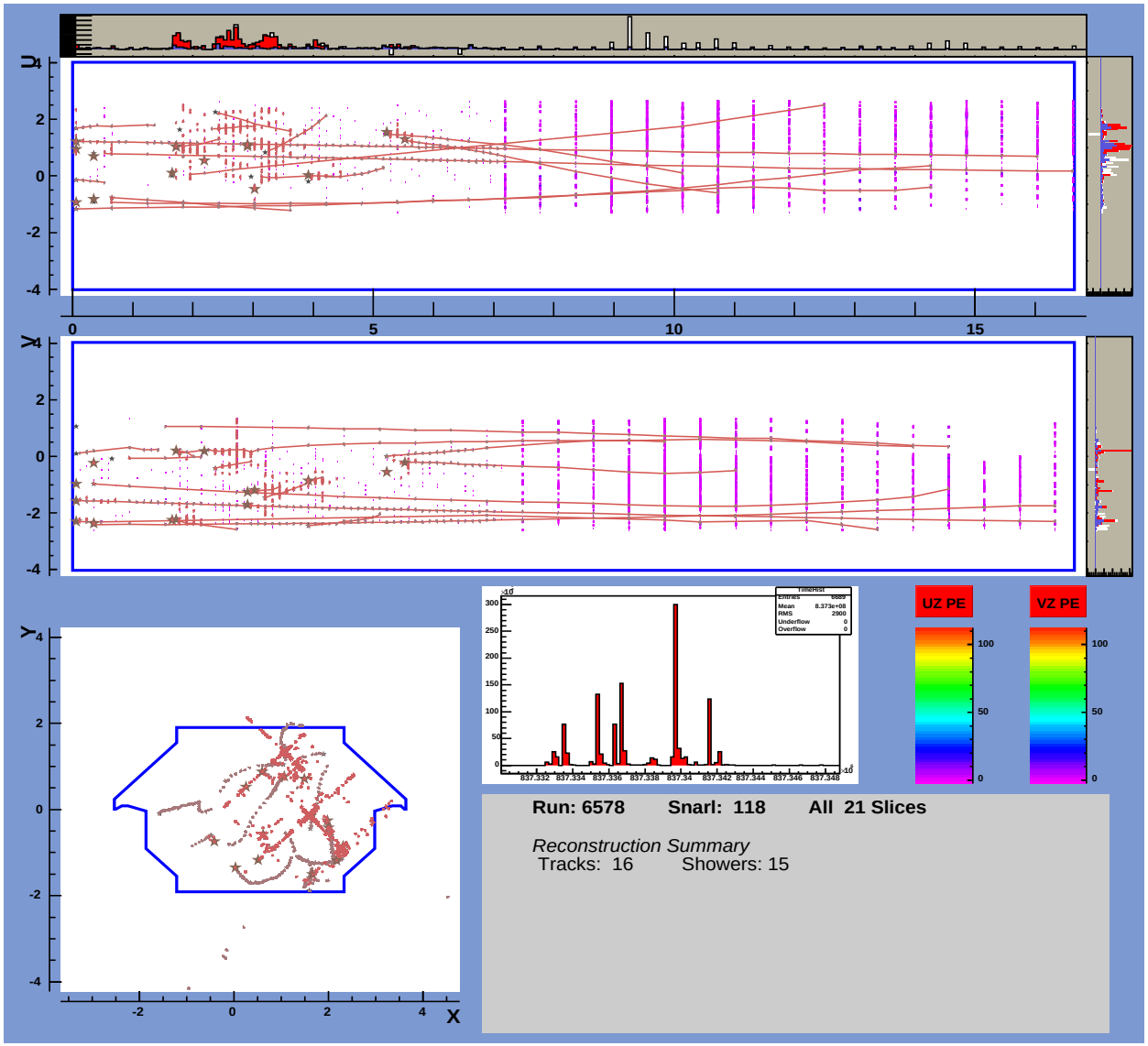
ND Lots and Lots of νs

At 2.5×10^{13} p/spill

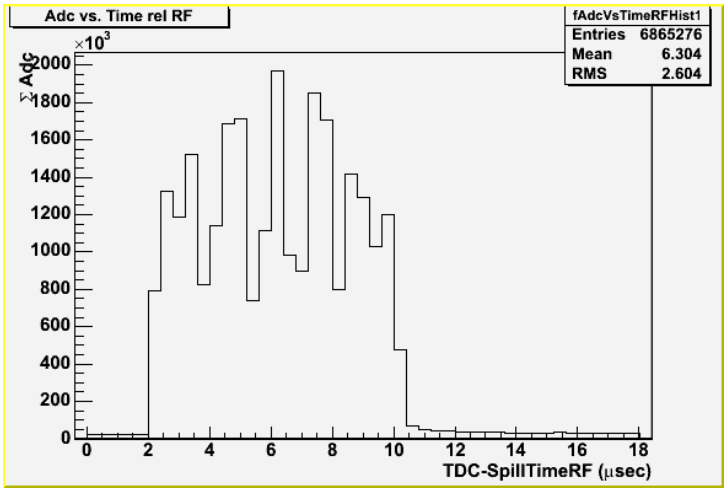
Target is in ME position.

ND scintillator readout has 19ns resolution (same as bunch length).

Timing information is used to separate events.



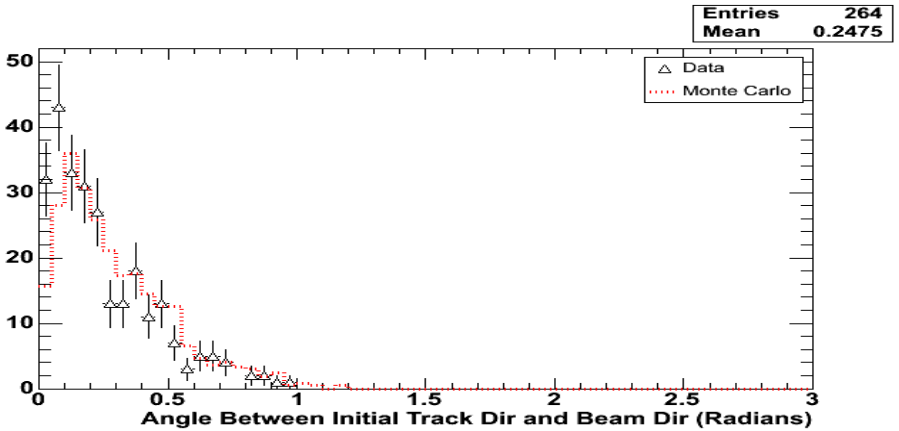
ND Beam Neutrino Properties



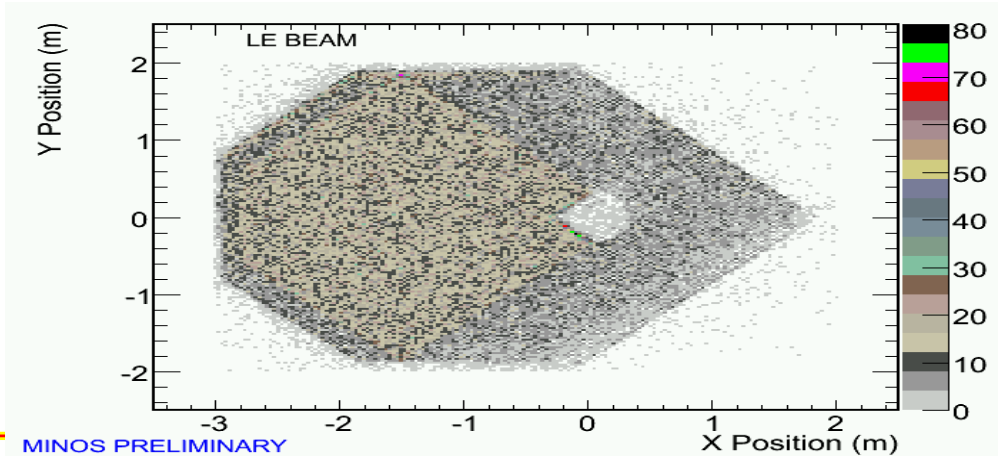
Time difference between ND hits and beam extraction.

NuMI 18.87ns bunches come in 5 batches.

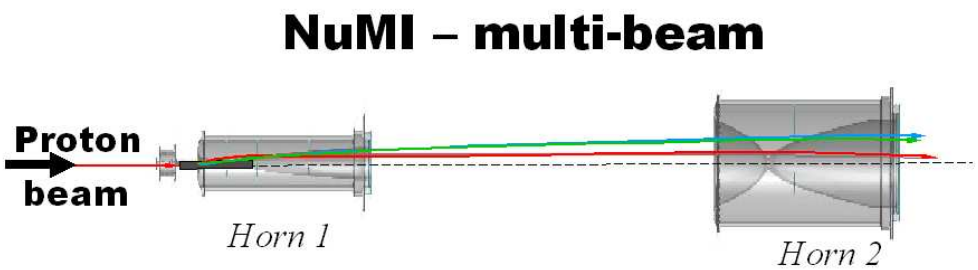
Angle between μ track direction and beam direction:



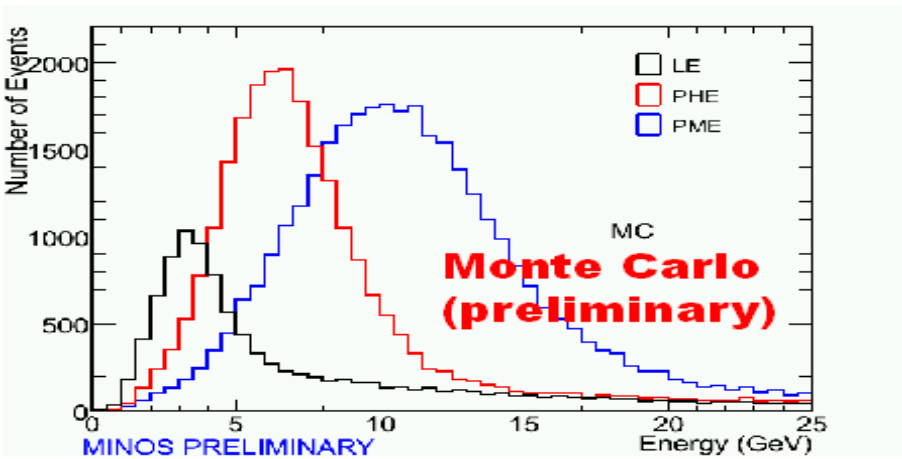
Distribution of LE neutrino interaction vertices

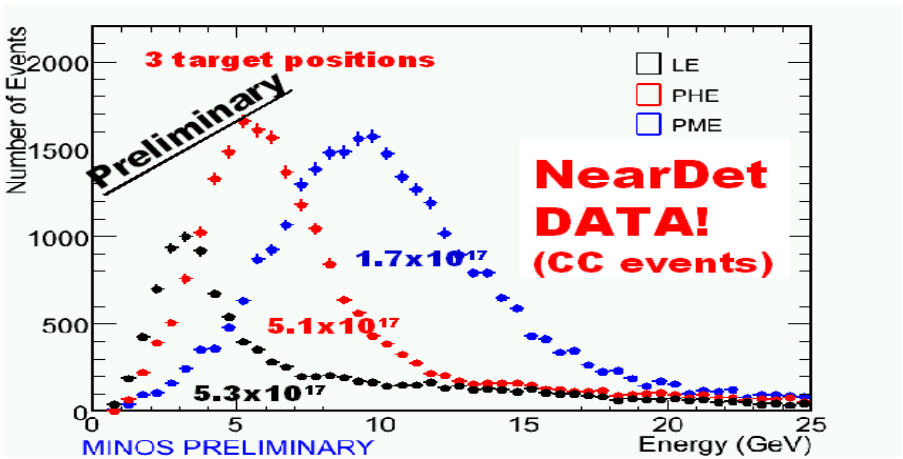


ND Beam Energy Scan



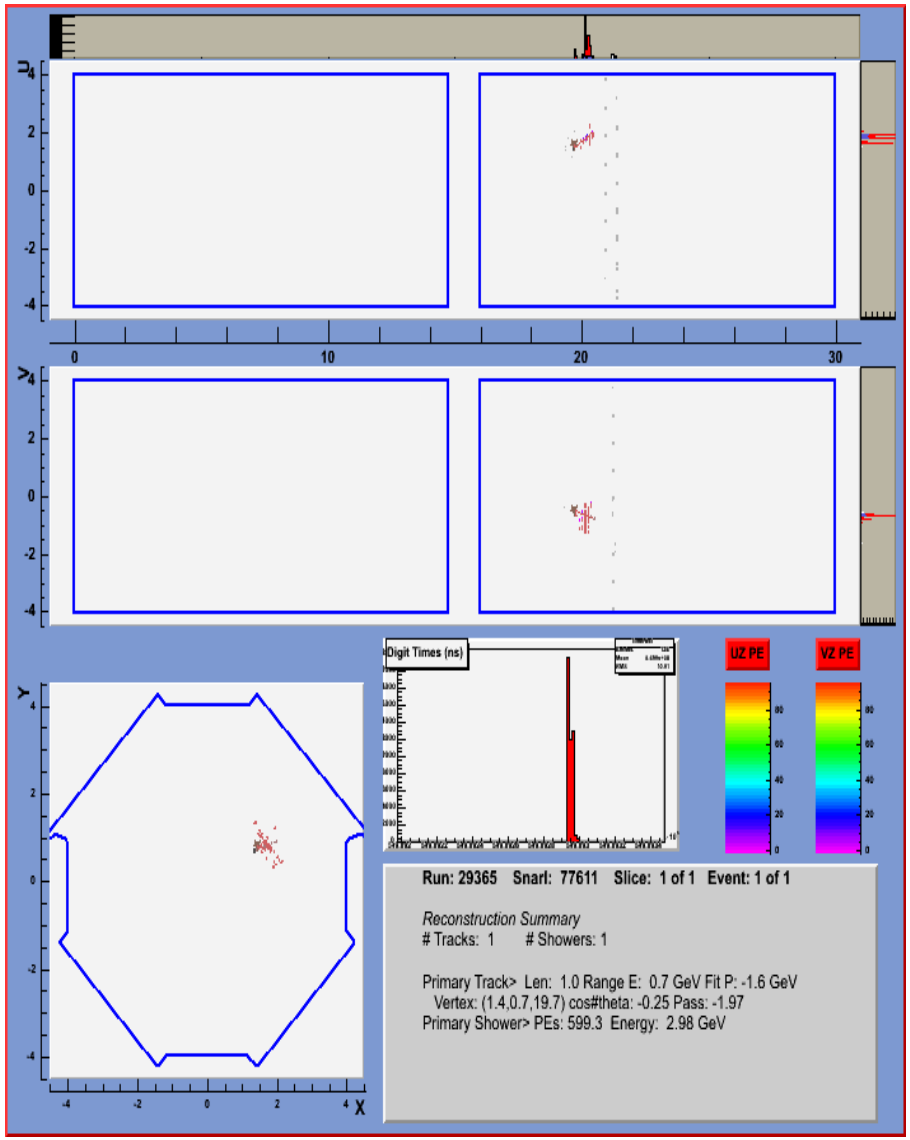
By varying the distance of the target from Horn 1 we get 3 energy spectra: 1) LE: target in Horn1 2) pME': target 1m from Horn 1 3) pHE: target 2.5m from Horn 1.

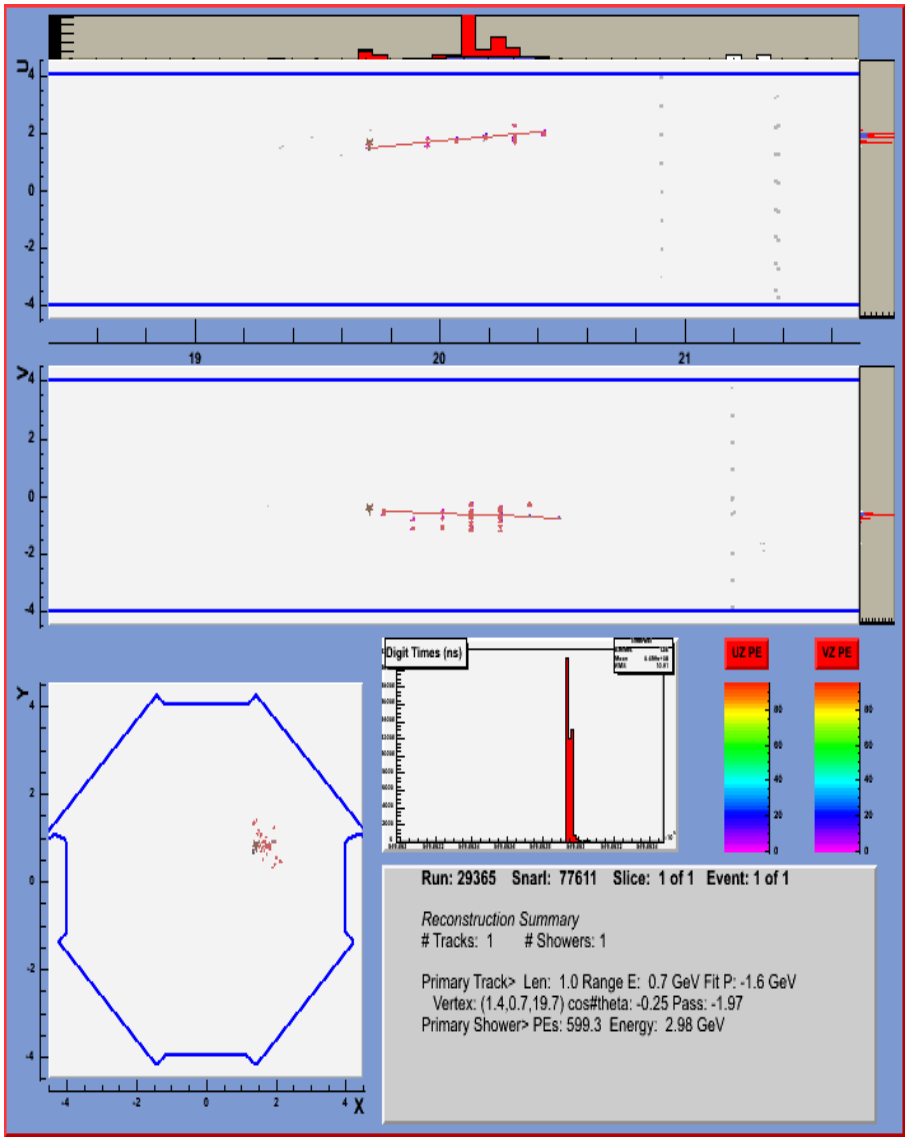




VERY preliminary agreement between data and MC

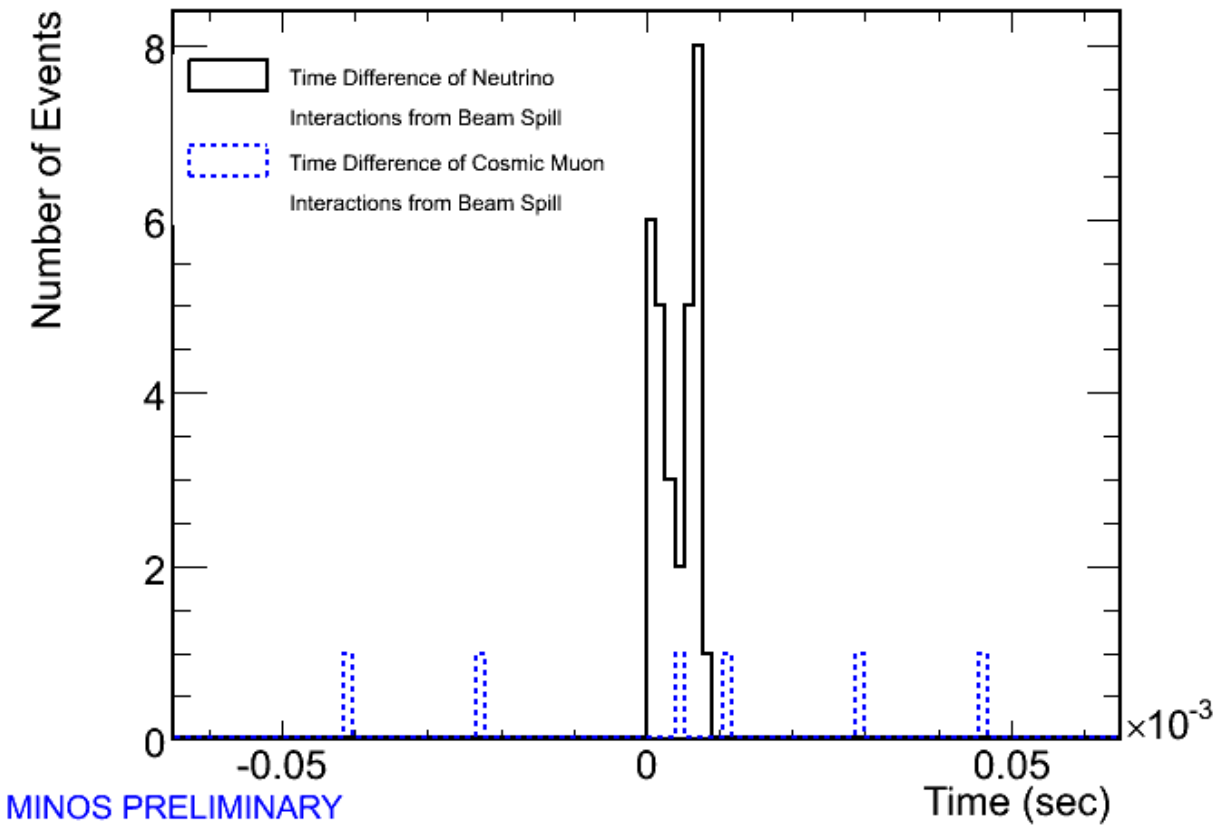
1st FD Beam Neutrino, March 7 ’05





FD Beam Neutrino Properties

The MINOS FD neutrino beam data is blinded. We will open the box $\sim$ early 2006. Some properties of the first unblinded FD events:



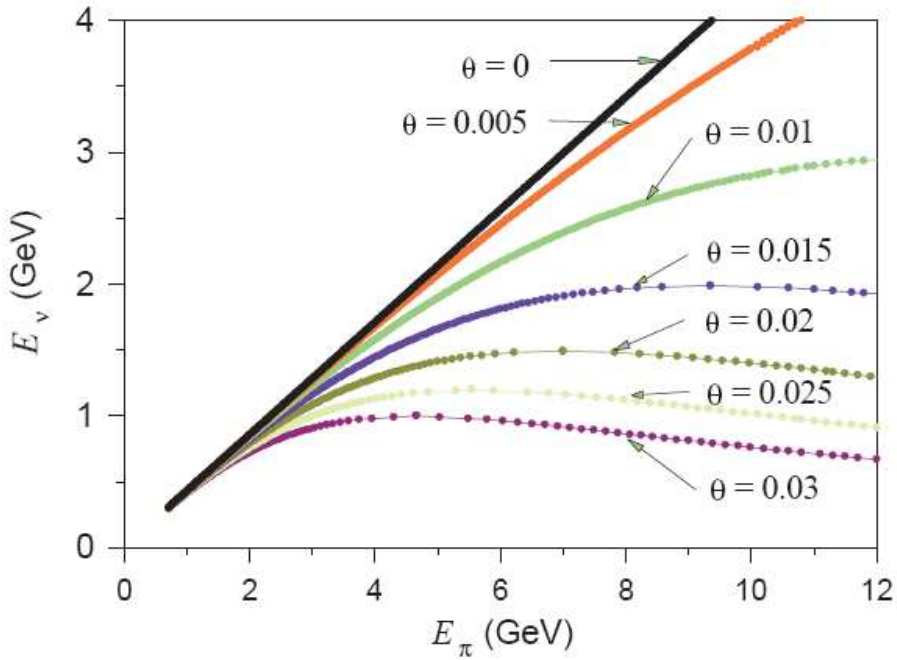
FD events are correlated with beam time

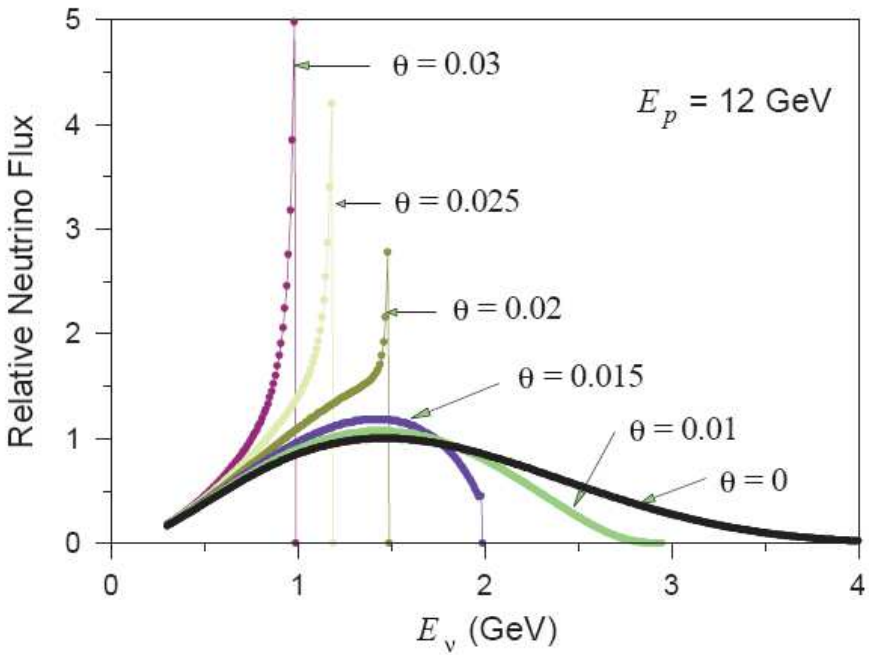
OFF-AXIS NEUTRINO BEAMS

Off-Axis - The Idea

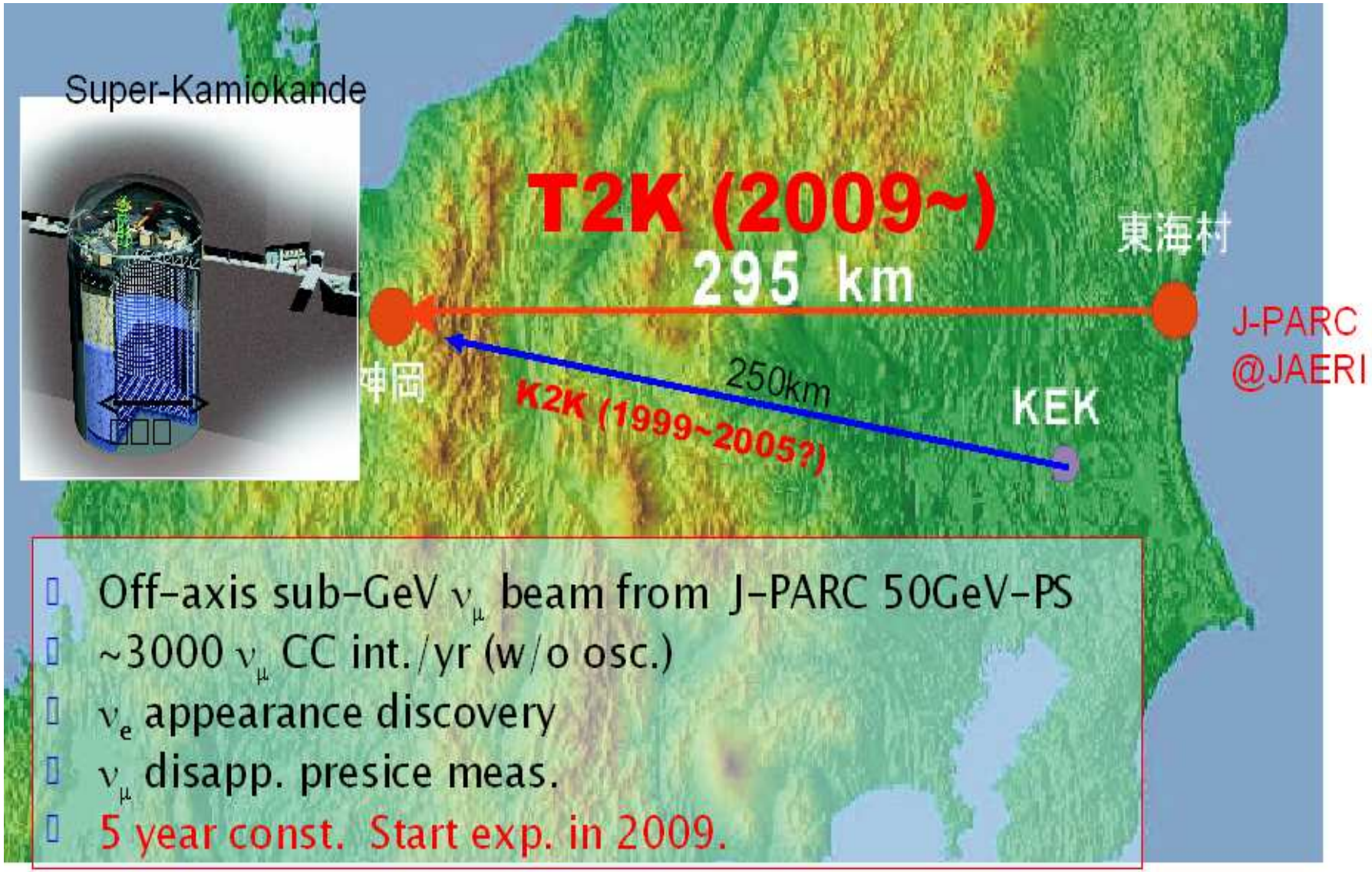
First proposed for BNL E-889 (1995):

In the decay $\pi \rightarrow \mu\nu$ for a given angle θ there is a maximum possible ν energy, as the ν energy approaches this value a large range of π energies contribute to a small range of ν energies.

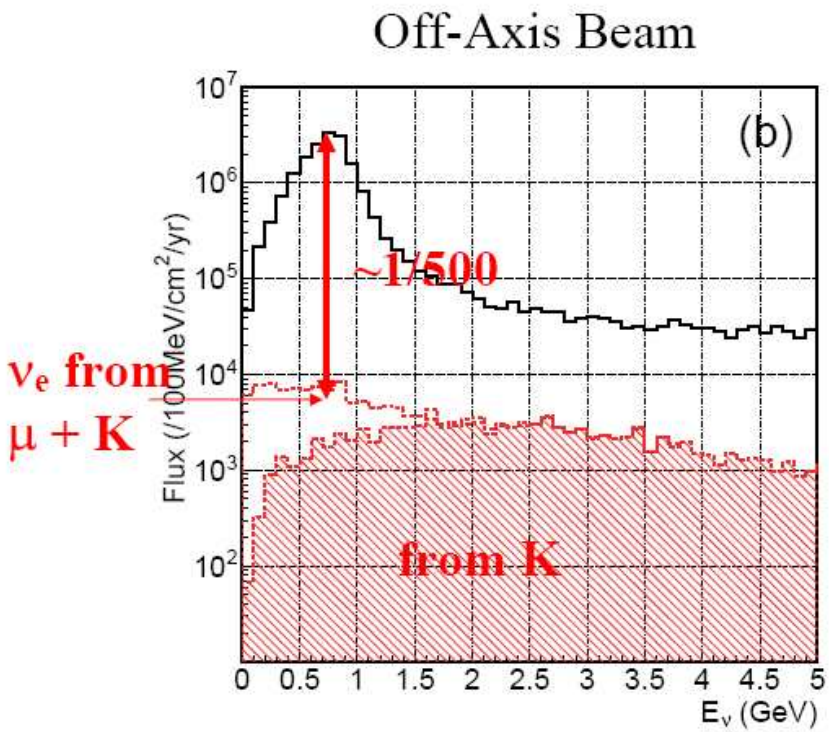


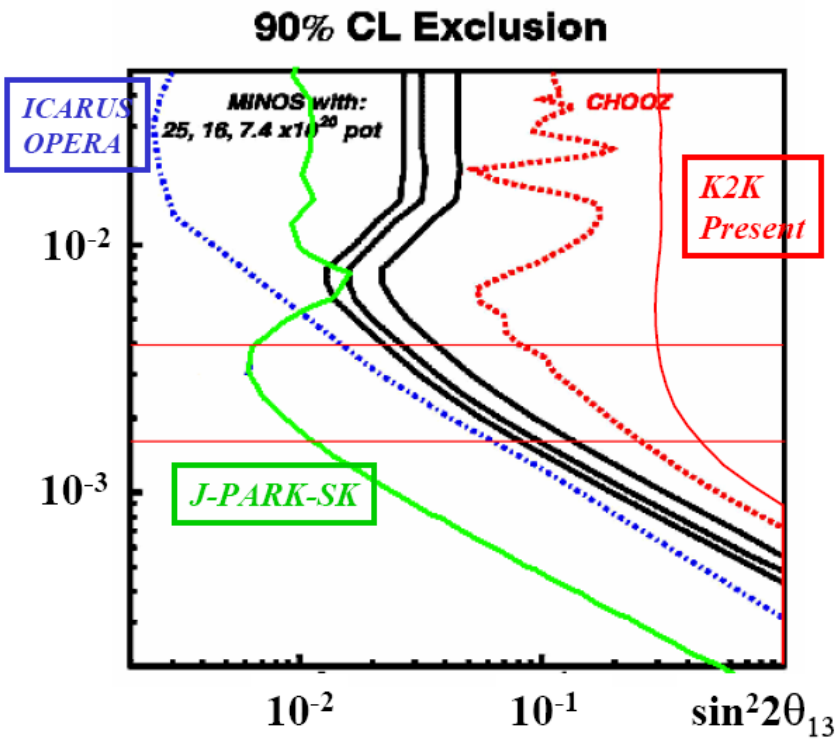


The T2K Experiment



T2K $\nu_\mu \rightarrow \nu_e$ Sensitivity



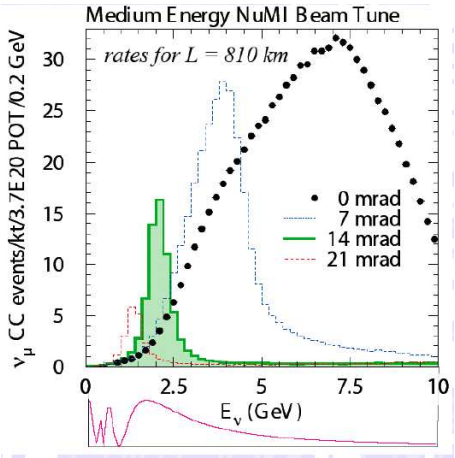


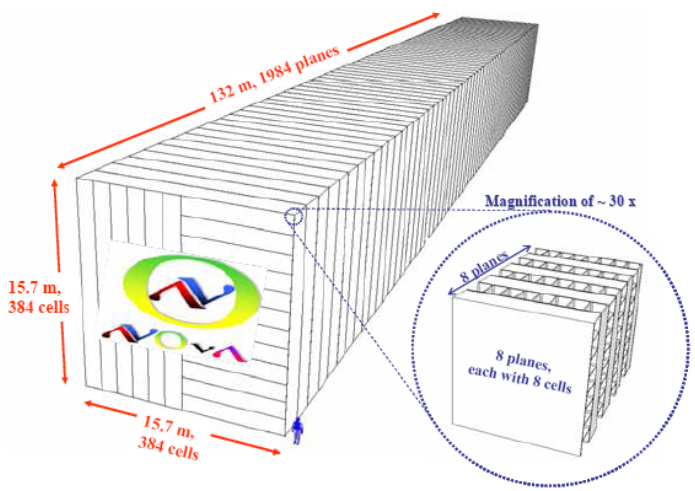
Improve S:B by focusing the ν beam energy at the oscillation maximum.

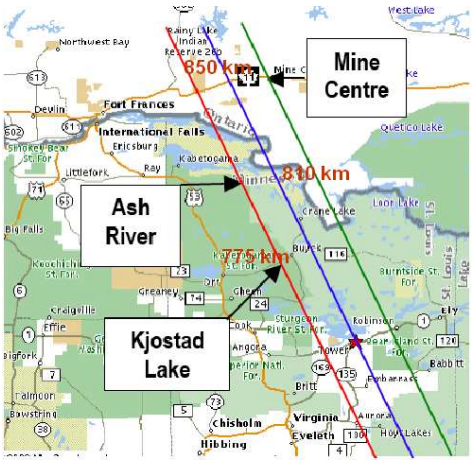
The NOνA Proposal

NuMI Off-axis ν Appearance experiment

A proposed off-axis experiment using the existing NuMI beamline eventually operating at 1-2 MW after upgrades to FNAL accelerator complex (proton driver).







Proposed sites and baselines

Far detector is 30 kT fully active scintillator

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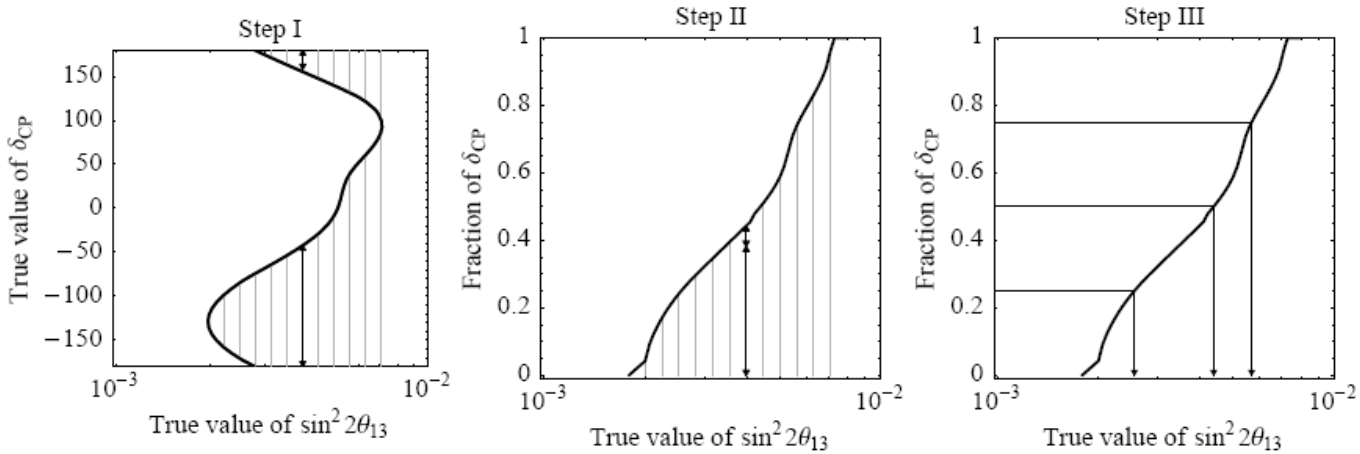
CP fraction

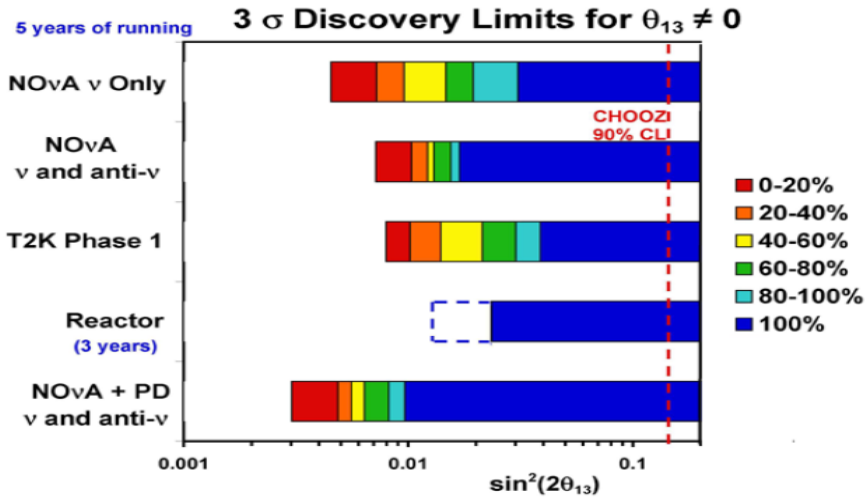
Patrick Huber

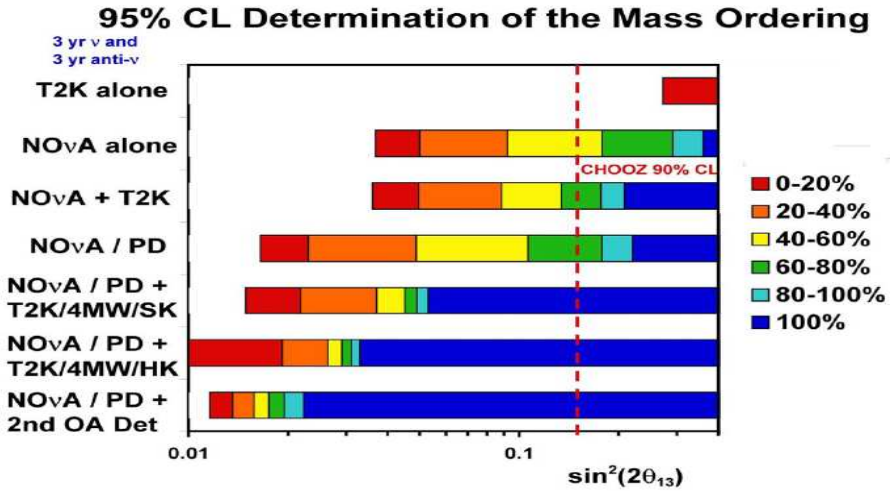


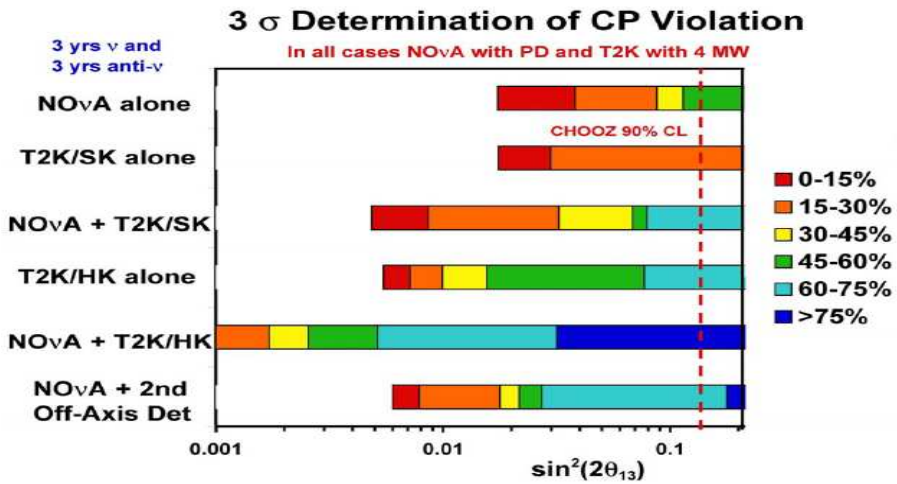
- **Simplifies 2D plot**
- **allows unbiased comparison**
- **allows risk assessment**
- **CPF = 1, worst case - guaranteed sensitivity**
- **CPF = 0, best case**

NOνA/T2K comparisons

Sensitivies of NOνA with an 8GeV proton driver and T2K with 4 MW







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THE CASE FOR A WIDE-BAND+VERY LONG BASELINE SUPER NEUTRINO BEAM

Why a Very Long Baseline?

Sensitivity to atmospheric (Δm^2_{32}) AND solar (Δm^2_{21}) oscillation scales

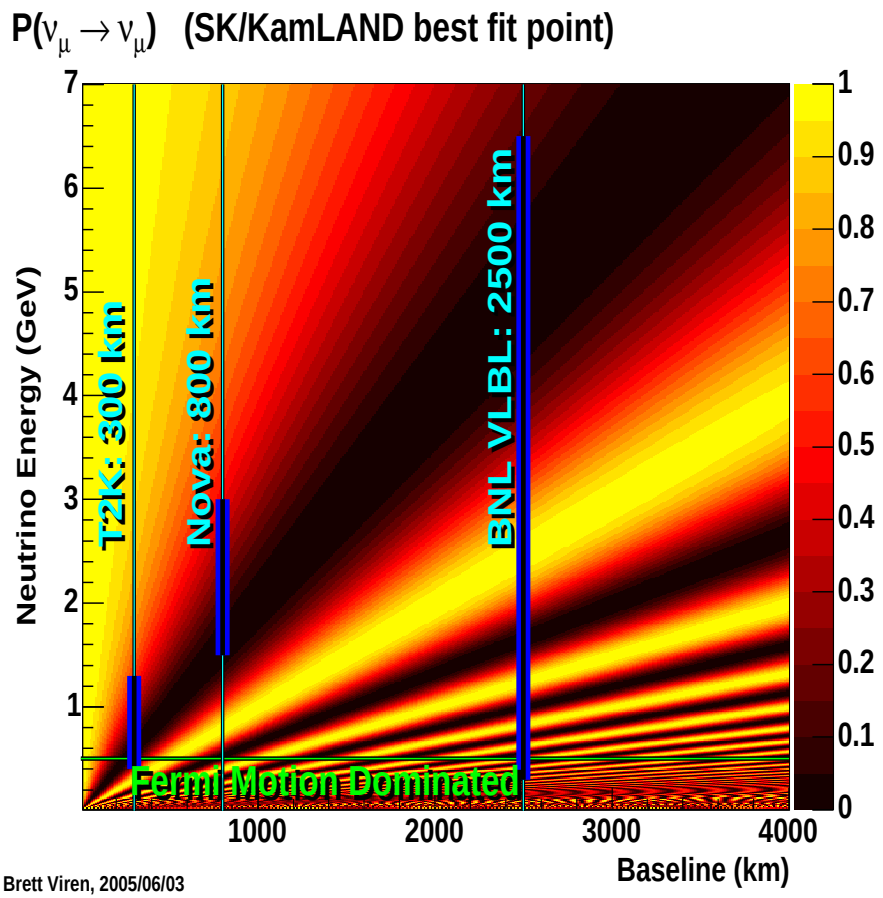
Verify oscillation behaviour by observing multiple nodes

Resolution of $E_{\nu_\mu} < 500$MeV/c^2 dominated by Fermi motion $\Rightarrow$ maximize $L = \mathcal{O}(1000)$ km

Higher energies = larger cross-sections

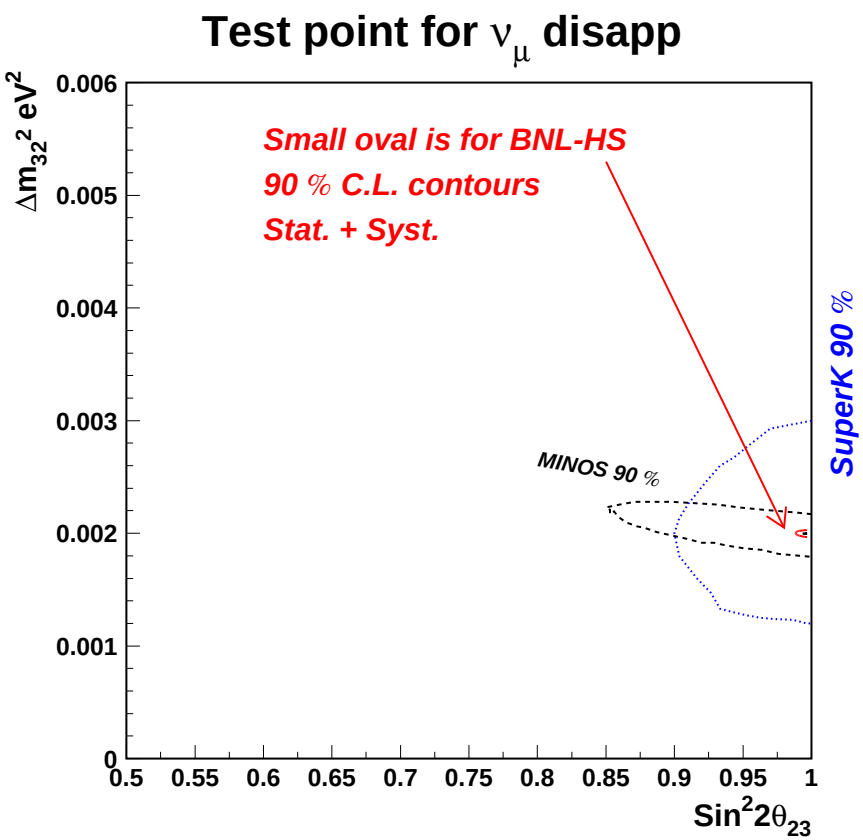
Very long baseline = multiple node pattern is detectible for all Δm^2_{32} range.

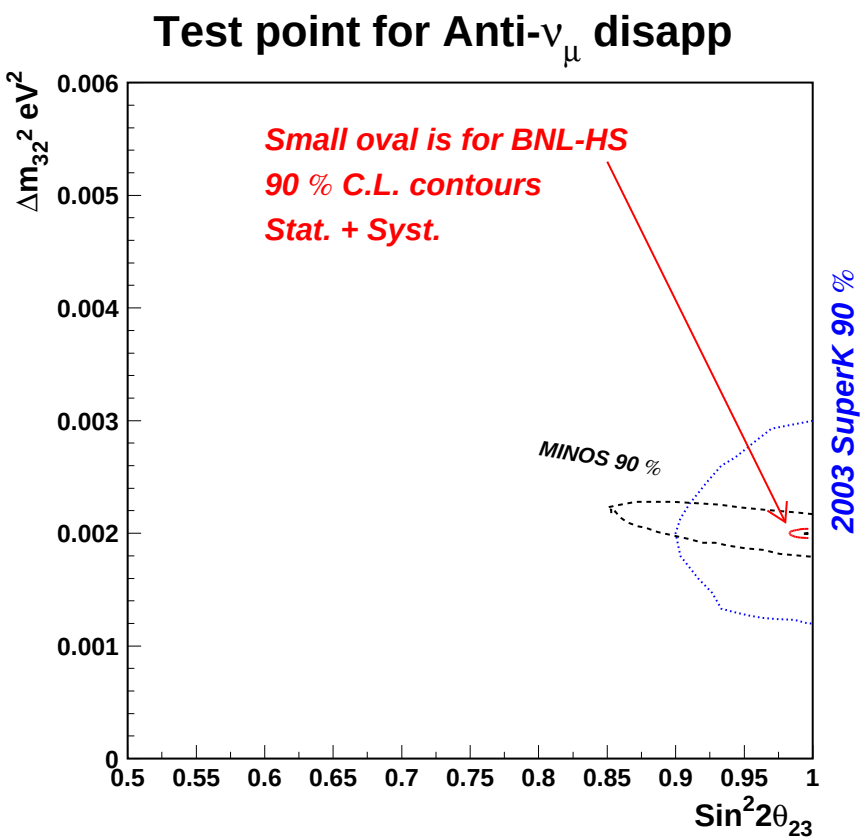
More nodes = higher precision.



VLB Disappearance Sensitivity

For a BNL-Homestake 2540 km baseline:





$\sim 1\%$ **resol on** Δm^2_{32} **and** $\sin^2 2\theta_{23}$ **if detector energy scale uncert** $\sim 1\%$

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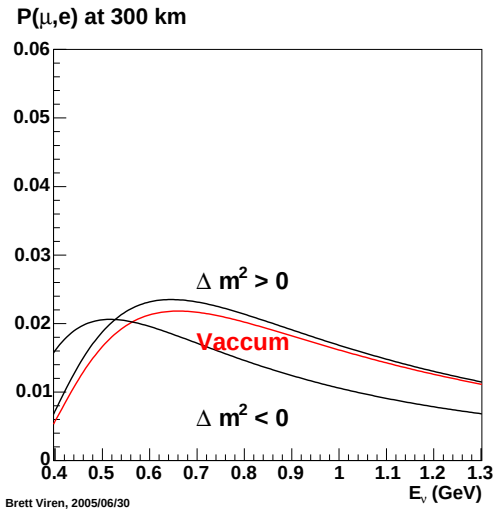
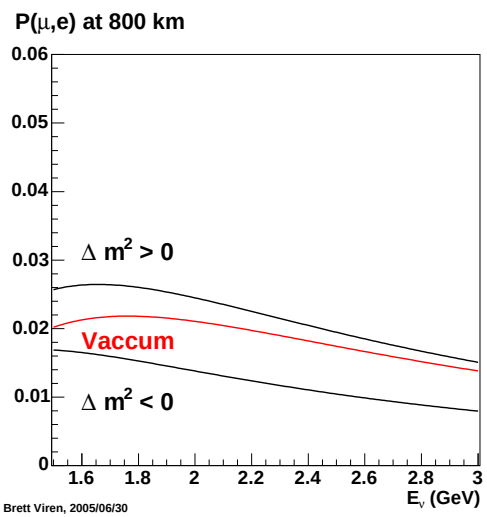
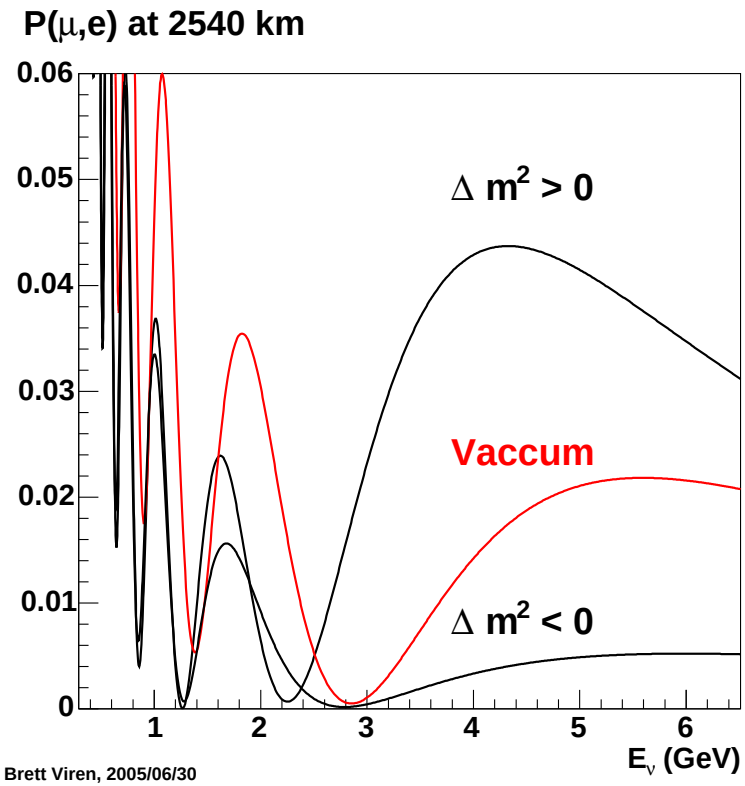
VLB ν_e Appearance Sensitivity

If $\theta_{13} \neq 0$, $\Rightarrow$ matter effects change $P(\nu_\mu \rightarrow \nu_e)$.

More matter = larger effects







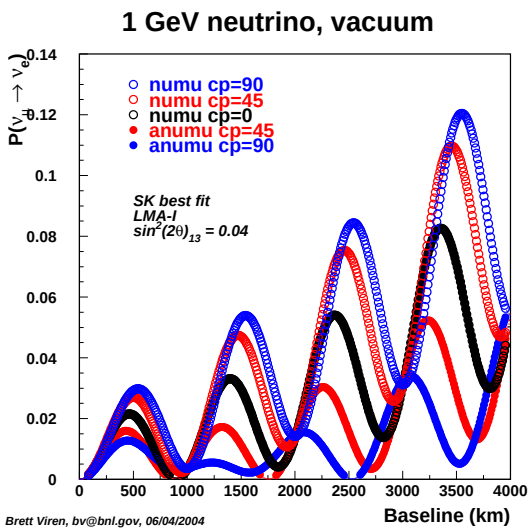
Longer L = better resolution of the Mass hierarchy

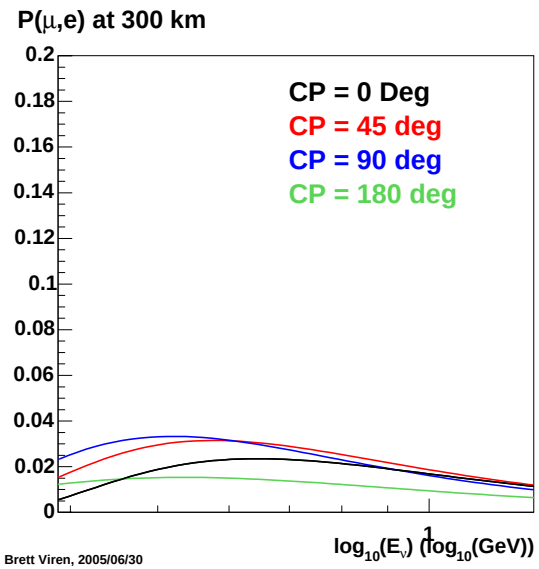
CP Violation Sensitivity

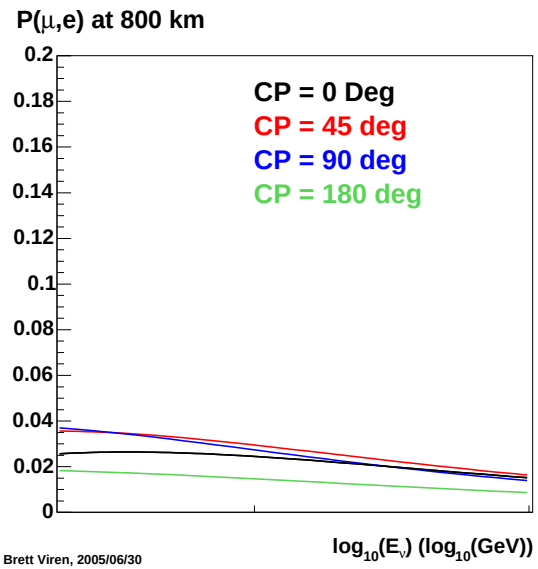
Marciano (hep-ph/0108181):

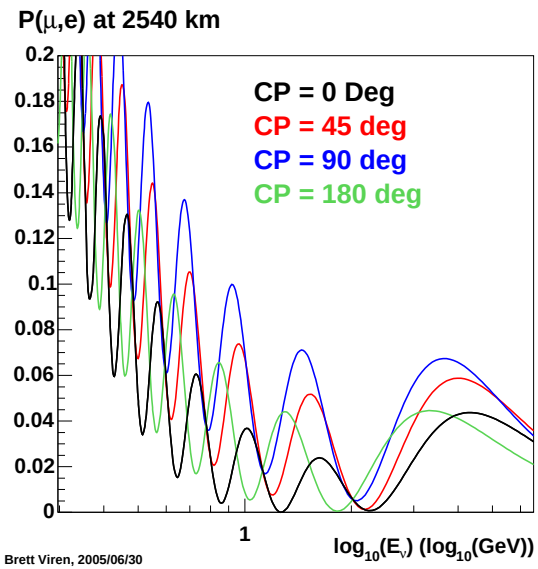
CP asymmetry in $\nu_\mu \to \nu_e$, A, grows with L Flux at far detector goes as $1/L^2$. $\Rightarrow$ FOM $= A^2 N_\nu/(1-A^2)$ is $\sim$ constant

FOM independent of baseline







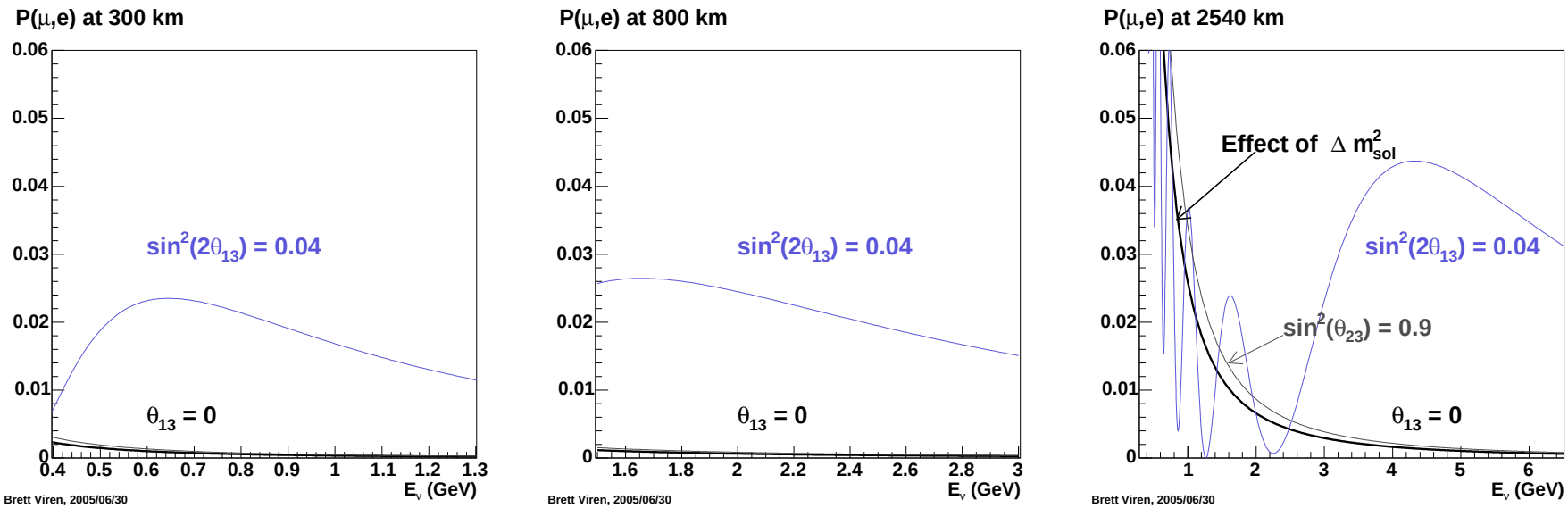


Guaranteed ν_e Appearance

If $\sin^2 2\theta_{13}$ is small $\Rightarrow$ δ_{cp} measurement not possible

BUT observation of ν_e appearance is still possible from the current value of the solar parameters:

$$P(\nu_\mu \to \nu_e) \sim \left(\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right)^2 \sin^2 2\theta_{12} \cos^2 \theta_{23} \frac{\Delta m^2_{31} L}{4E_\nu}$$



Only feasible with the longer baseline (2540 km)

Separating Multiple $\nu_\mu \to \nu_e$ Effects

	energy (GeV)	$\sin^2 2\theta_{13}$ > 0	Δm^2_{32} $(> 0, < 0)$	$\delta_{CP} =$ $(\frac{\pi}{4}, -\frac{\pi}{4})$	θ_{23} $(< \frac{\pi}{4}, > \frac{\pi}{4})$
ν	0–1.2	$\uparrow$	–, –	$\uparrow, \downarrow$	$\Uparrow, \Downarrow$
	1.2–2.2	$\uparrow$	–, –	$\Uparrow, \Downarrow$	$\downarrow, \uparrow$
	$>$ 2.2	$\uparrow$	$\Uparrow, \Downarrow$	$\uparrow, \downarrow$	$\downarrow, \uparrow$
$\bar{\nu}$	0–1.2	$\uparrow$	–, –	$\downarrow, \uparrow$	$\Uparrow, \Downarrow$
	1.2–2.2	$\uparrow$	–, –	$\Downarrow, \Uparrow$	$\downarrow, \uparrow$
	$>$ 2.2	$\uparrow$	$\Downarrow, \Uparrow$	$\downarrow, \uparrow$	$\downarrow, \uparrow$

Need a wideband beam (WBB) with $E_\nu = 1$ to 6 GeV

For 3 generations we do not need $\bar{\nu}$.

$\bar{\nu}$ will resolve reversed hierarchy, sensitive to new physics.

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BNL baselines

The US is $\approx$ 4500 km coast-to-coast. Brookhaven National Lab is located on the eastern coast $\Rightarrow$ ideal for $\mathcal{O}(2000)$ km baselines.

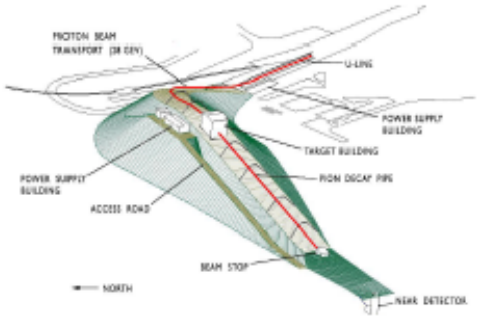
BNL-Homestake mine = 2540 km **BNL-Henderson mine = 2700 km**

BNL Conceptual Design Report

BNL-73210-2004-IR available at http://raparia.sns.bnl.gov/nwg_ad/

October 1, 2004 BNL-73210-2004-IR

The AGS-Based Super Neutrino Beam Facility
Conceptual Design Report



Brookhaven National Laboratory
Upton, NY 11973
October 1, 2004

October 1, 2004 BNL-73210-2004-IR

The AGS-Based Super Neutrino Beam Facility
Conceptual Design Report

Editor: W. T. Weng, M. Diwan, and D. Raparia

Contributors and Participants

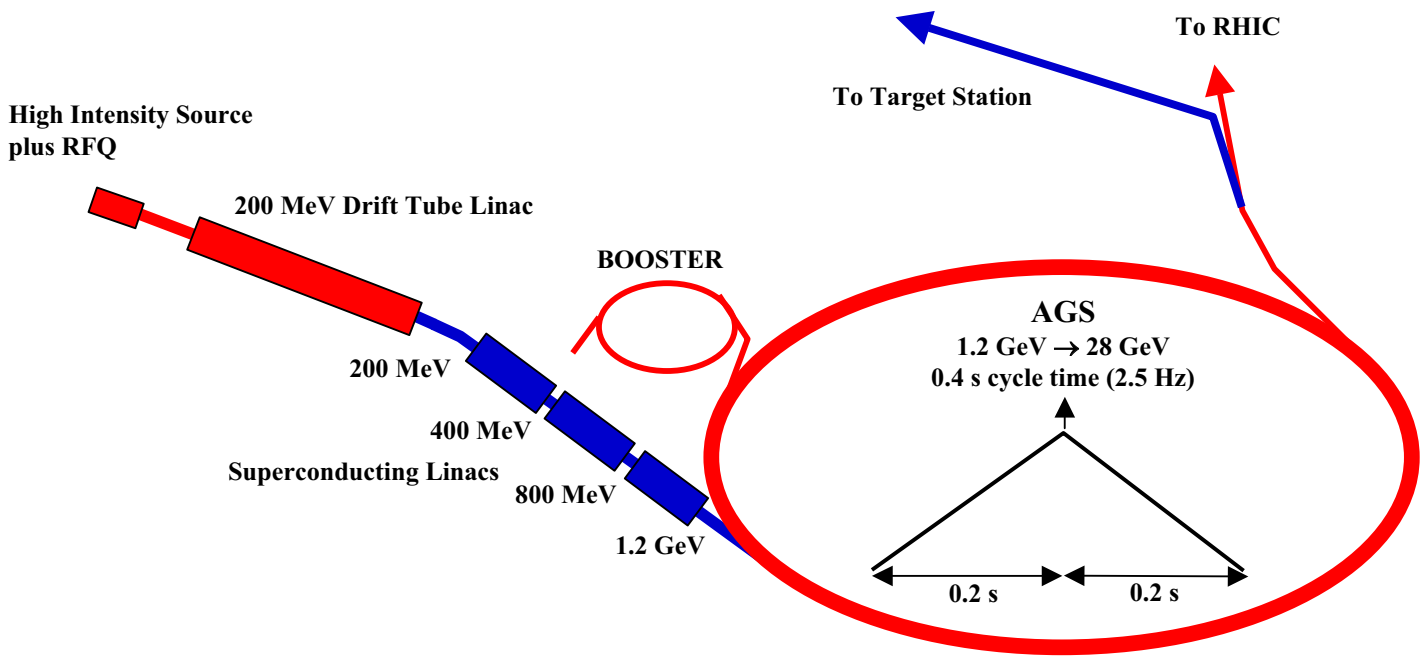
J. Alessi, D. Barton, D. Beavis, S. Bellavia, I. Ben-Zvi, J. Brennan, M. Diwan, P. K. Feng, J. Gallardo, D. Gassner, R. Hahn, D. Hseuh, S.Kahn, H. Kirk, Y. Y. Lee, E. Lessard, D. Lowenstein, H. Ludewig, K. Mirabella, W. Marciano, I. Marneris, T. Nehring, C. Pearson, A. Pendzick, P. Pile, D. Raparia, T. Roser, A. Ruggiero, N. P. Samios, N. Simos, J. Sandberg, N. Tsoupas, J. Tuozzolo, B. Viren, J. Beebe-Wang, J. Wei, W. T. Weng, N. Williams, P. Yamin, K. C. Wu, A. Zaltsman, S. Y. Zhang, Wu Zhang

Brookhaven National Laboratory
Upton, NY 11973
October 1, 2004

Total *estimated* cost is FY 04 $ 406.9 M (including 30% contingency)

AGS MW Beam Upgrade

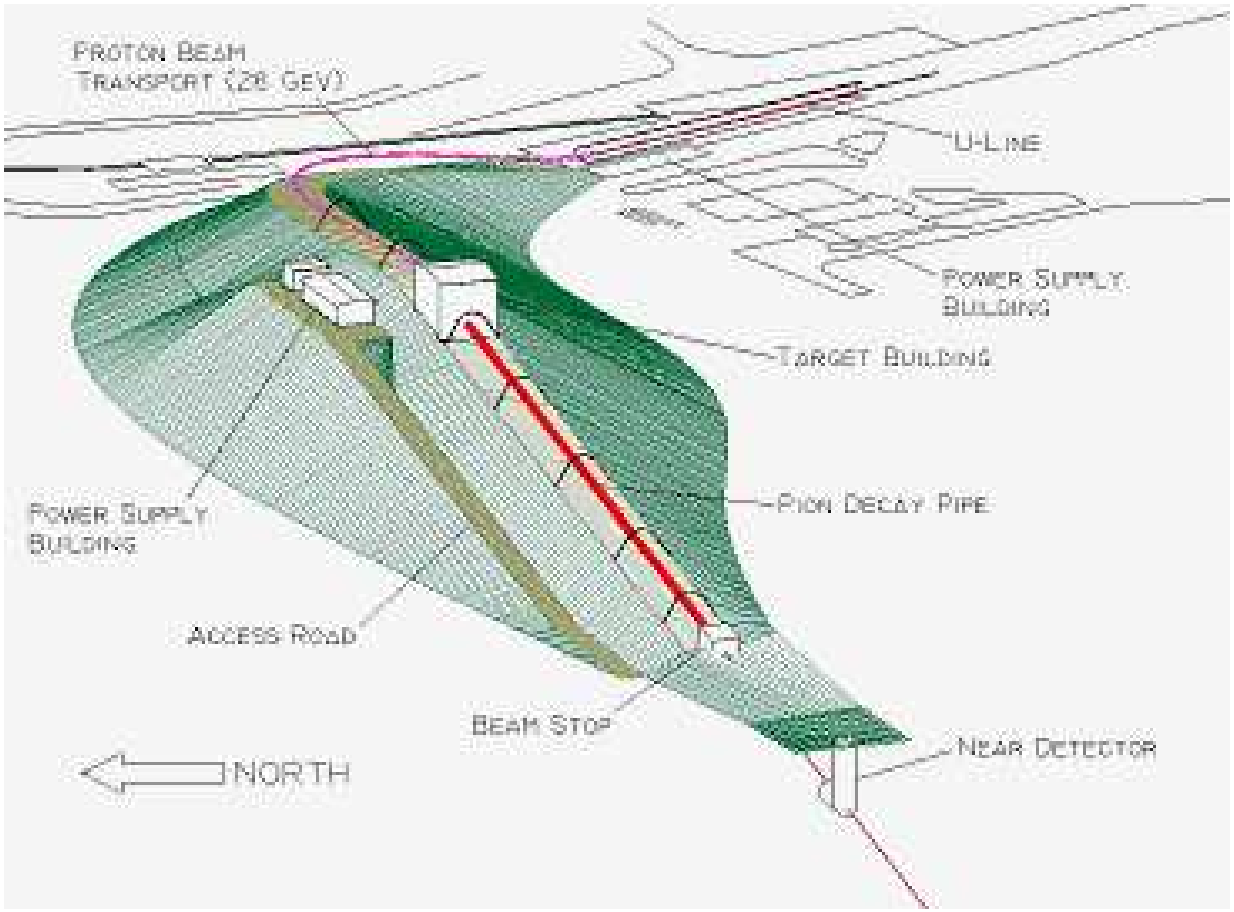
Very long baseline = low ν flux at the far detector $\Rightarrow$ need 1-2 MW beam and megaton detectors To increase rep rate from 0.5 - 2.5 $\Rightarrow$ replace booster.



Linac design is driven by lenght constrain = 120m. We need a 1.2-1.5 GeV linac to replace booster.

A 1 GeV proton SCL for the Spallation Neutron Source has already been built

Getting the beam to Homestake



Beam needs to point downwards at 11.3° to reach detector at 2540 km

Build a hill instead of a tunnel! = hadrons above water

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PHYSICS SENSITIVIES OF L=1290,2540 km WIDEBAND VERY LONG BASELINE EXPT.

M. Diwan, “The Case for a Super Neutrino Beam”. Conference proceedings of Heavy Quarks and Leptons, San Juan, Puerto Rico, June 1-June 5, 2004, hep-ex/0407047.

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Raw Event Counts

1 (2) MW ν ($\bar{\nu}$), 500 kT, L=2540km, 5×10^7 sec.

CC $\nu_\mu N \to \mu^- X$	51800 (30050)	NC $\nu_\mu N \to \nu_\mu X$	18323 (11540)
CC $\nu_e N \to e^- X$	380 (106)		
QE $\nu_\mu n \to \mu^- p$	11767 (11868)	NC elastic	4575 (3882)
QE $\nu_e n \to e^- p$	84 (80)		
CC Single π	22053 (11872)	NC Single π	7741 (5074)
CC Two π	10143 (3336)	NC Two π	3557 (1630)
CC $> 2\,\pi$	4882 (500)	NC $> 2\,\pi$	1729 (560)
CC $\nu_\tau N \to \tau^- X$	~ 110 (40)	(depends on Δm^2)	

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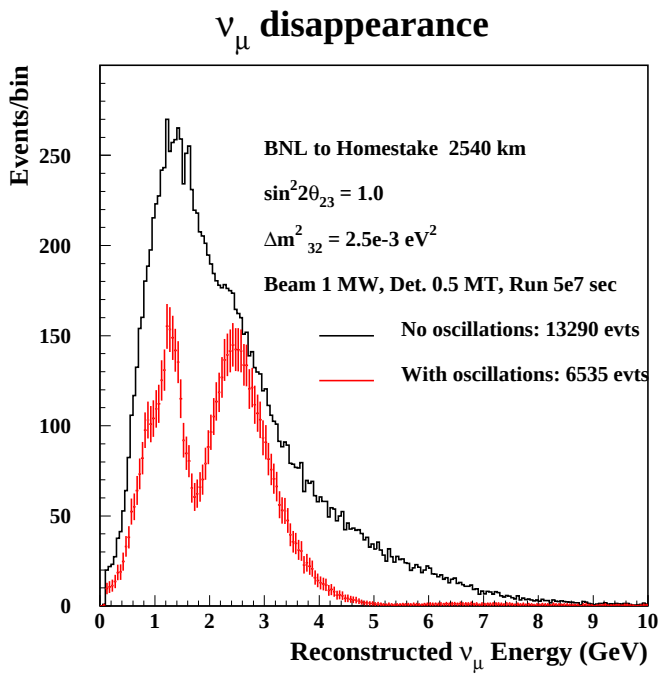
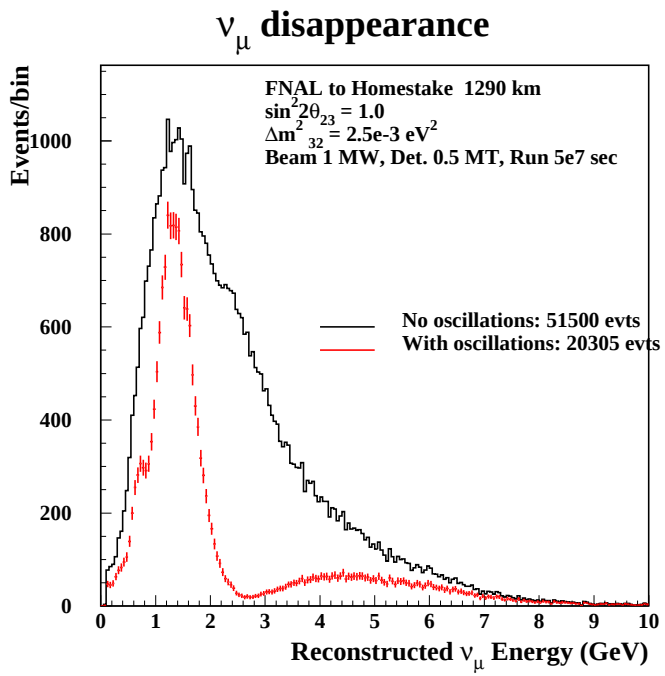
ν_μ Disappearance

Results for clean QE μ. MC includes fermi motion, detector resolution and non-QE backgrounds





Oscillation pattern in spectrum = low sensitivity to flux normalization

Both baselines will determine Δm^2_{32} and $\sin^2 2\theta_{32}$ to ~ 1%

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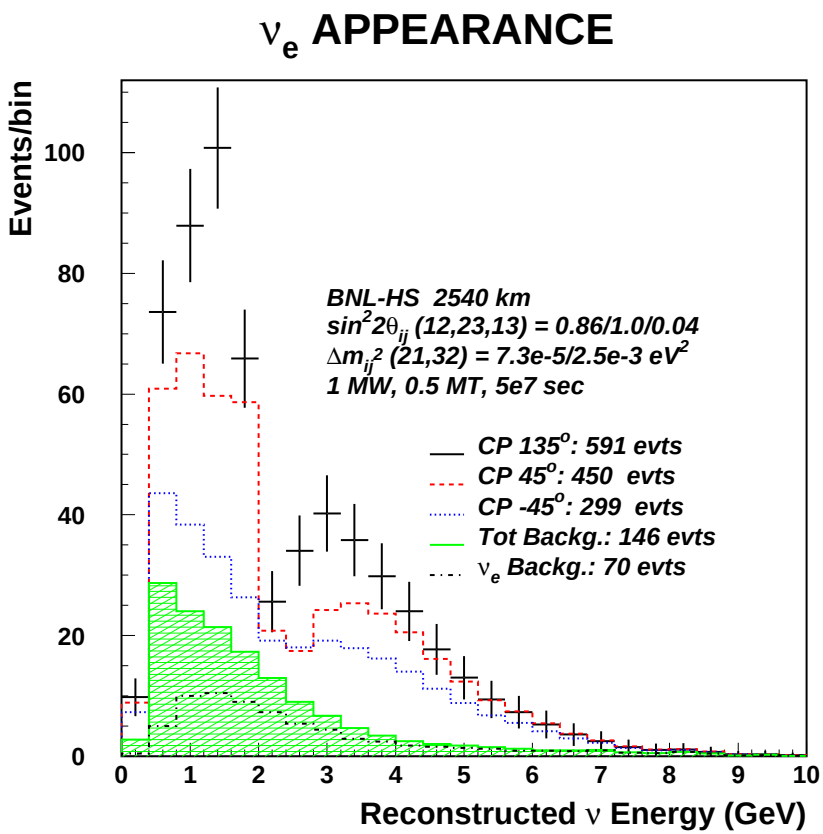
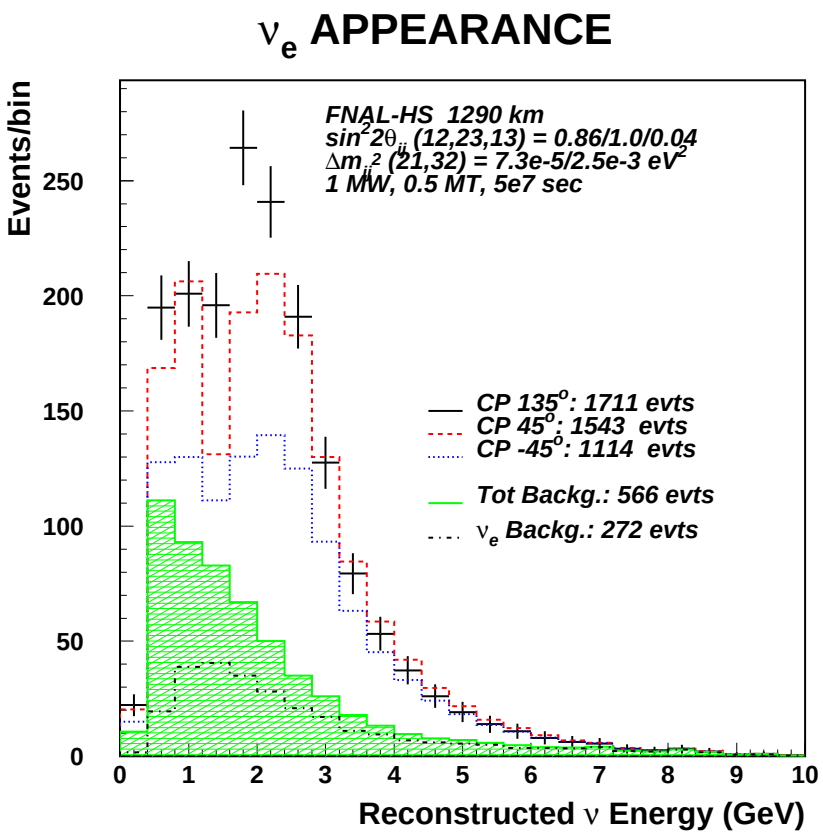
ν_e appearance (normal hierarchy)

Longer baseline $\Rightarrow$ oscillation visible





Already assuming 10% background uncertainty

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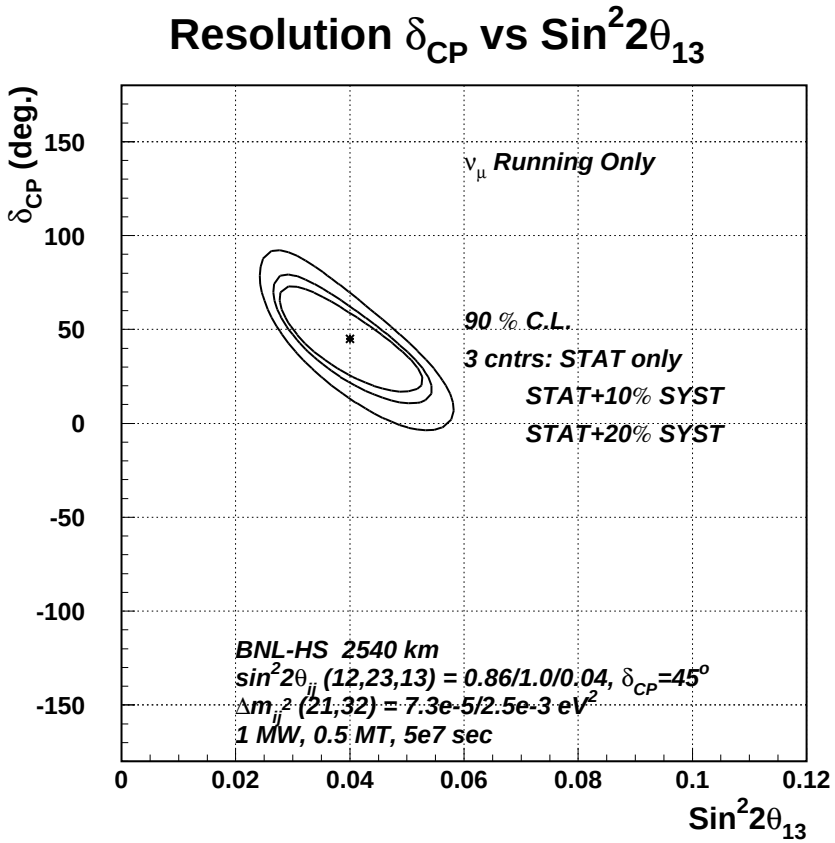
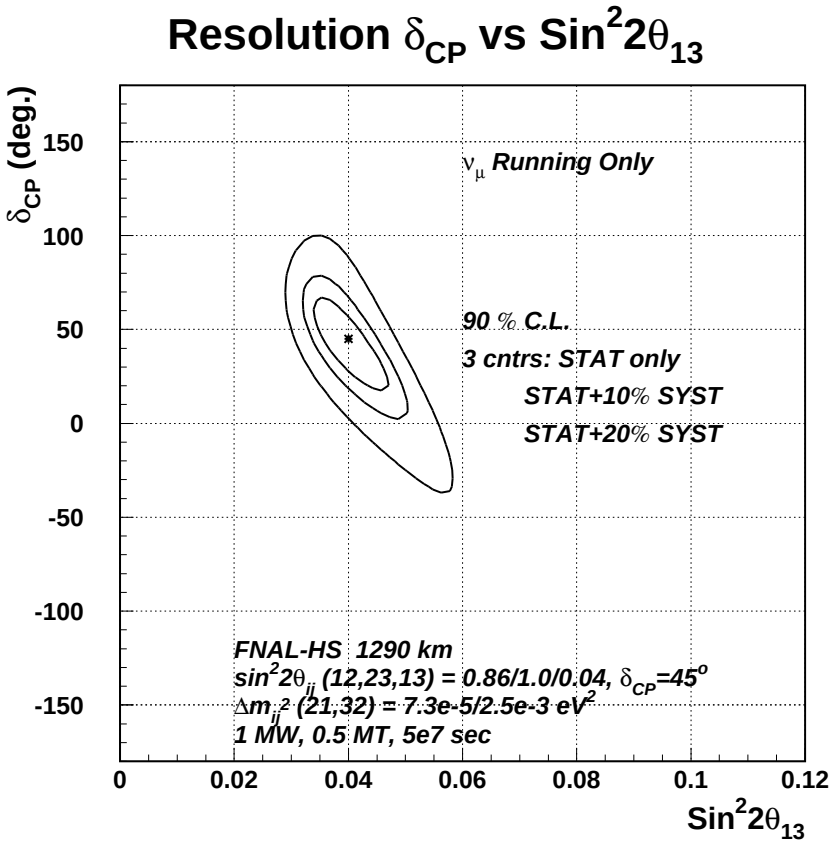
Sensitivity to δ_{cp} (normal heirarchy)





Although CP resolution is $\approx$ independent of baseline

Shorter baseline = systematics limited

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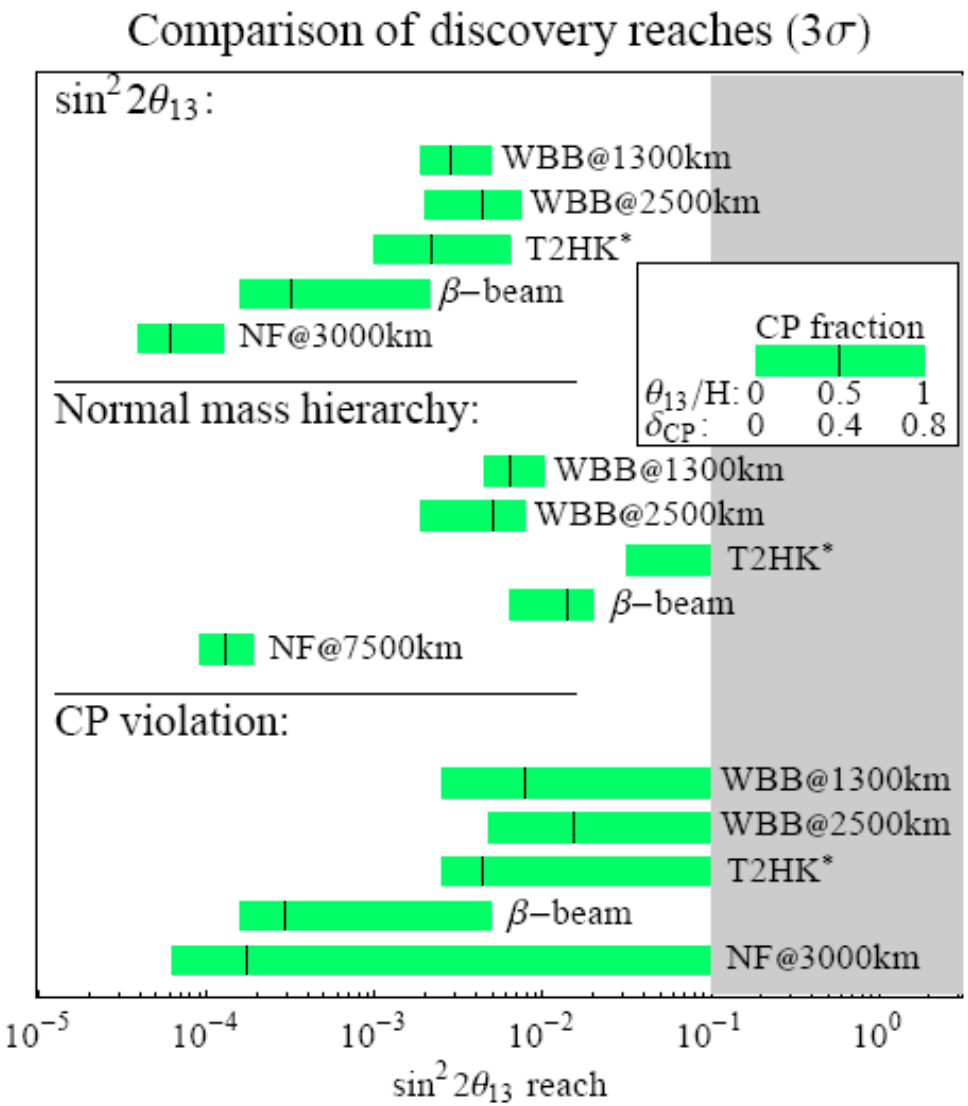
WBB discovery reaches

Patrick Huber



SUMMARY AND CONCLUSIONS

Summary and Conclusions

Accelerators played a key role in understanding ν properties at the discovery phase.

In recent and near-future experiments like MINOS and T2K, accelerator based ν experiments will provide the best precision on the measurement of $\sin^2 2\theta_{23}$ and Δm^2_{32}.

Off-axis experiments such as T2K will further constrain the measurement of $\sin^2 2\theta_{13}$ at a level that is competitive with reactor experiments.

For the next generation of accelerator experiments, a wide-band, very long baseline (> 1200Km) experiment is the optimal choice of expt. to provide precision measurements of the other unknowns in the neutrino sector: the mass hierarchy, CP violation in the lepton sector, is θ_{13} =0?, the sign of θ_{23}, sensitivity to new physics....

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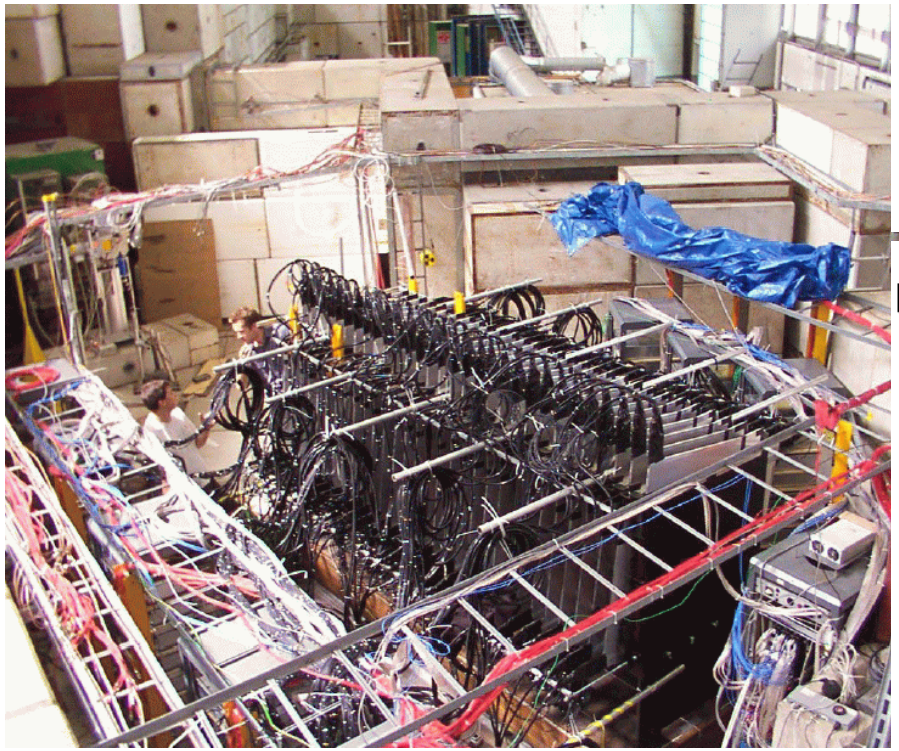
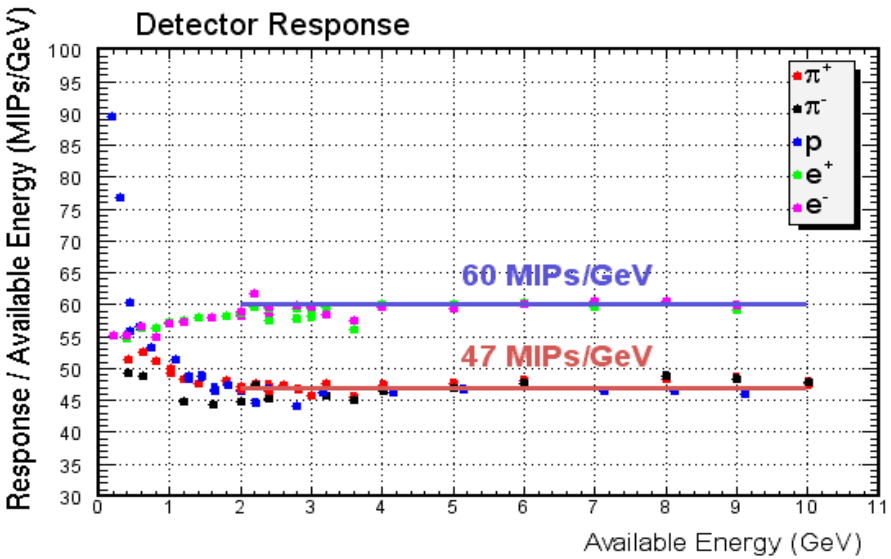
BACKUP

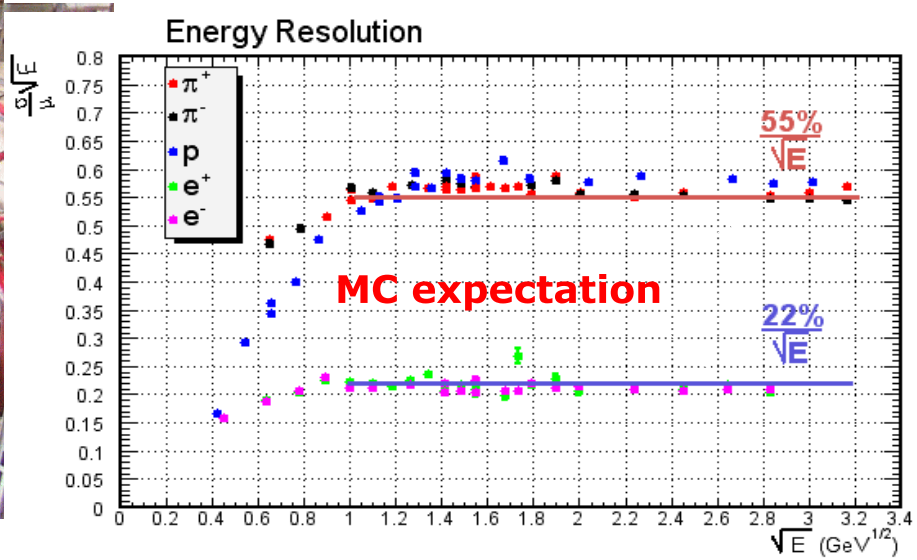
The Calibration Detector

60-plane 'micro - MINOS'

-- has taken data at T7 & T11 test beam lines at CERN during 2001, 2002, 2003

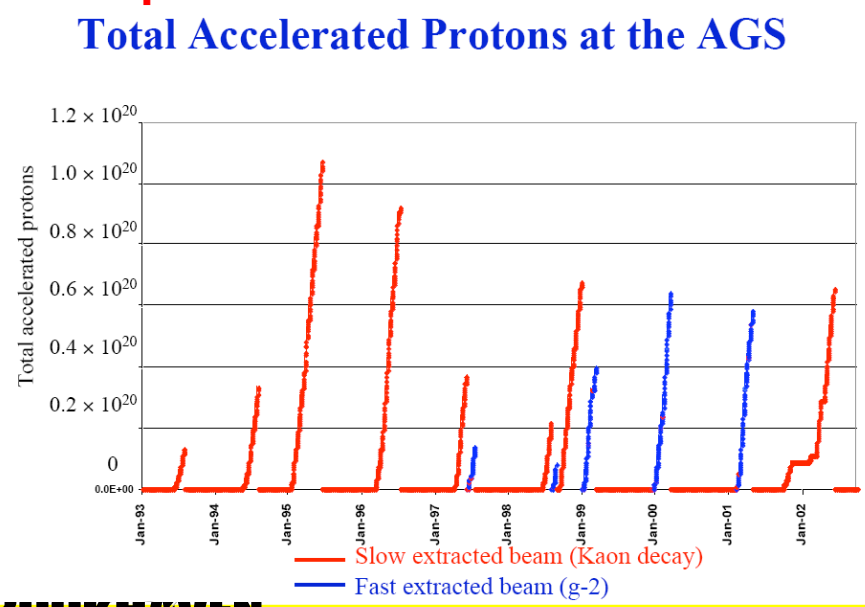


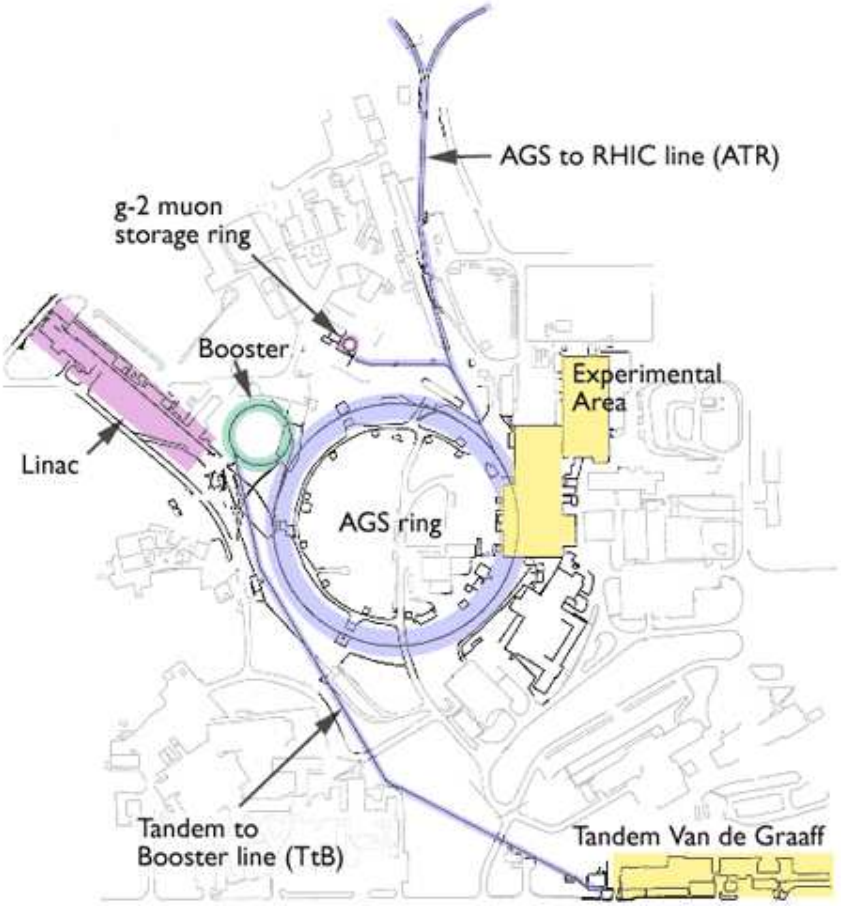




The AGS as a proton source

The *Alternating Gradient Synchrotron* at BNL accelerates 1.5 GeV/c protons from the Booster up to 33 GeV/c. **Typical intensity achieved for slow extracted beam is 6.7×10^{13} protons at a rep rate of 0.5 Hz $\Rightarrow$ the most intense proton beam in the world**





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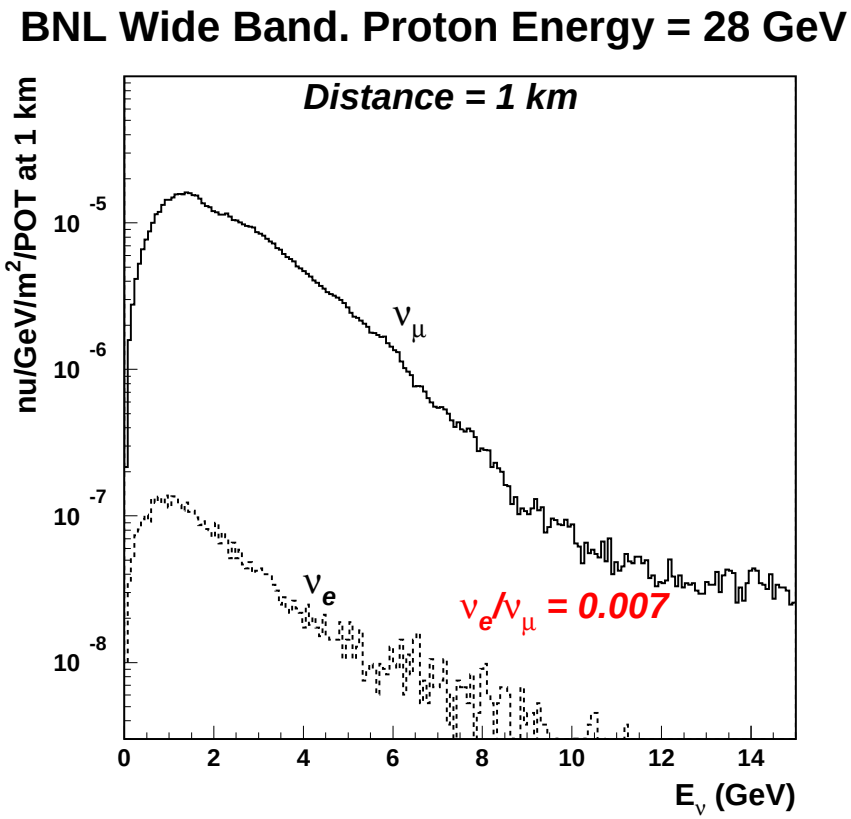
BNL ν beam spectrum

Detailed simulation of a 28 GeV proton beam on a graphite target with a wideband focusing horn.

Beam can be run in either neutrino or anti-neutrino mode.

A combination of neutrino and anti-neutrino running will constrain $\sin^2\theta_{13} \sim 0.003$.



AGS 28 GeV protons will produce a spectrum of $E_\nu = 1$ to 10 GeV/c^2

Well matched to baseline $\sim$ 2000 km

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BNL 1MW ν beam cost estimate

Cost Estimate of the AGS Super Neutrino Beam Facility

Construction Phase - Direct FY04 Dollars

1.0 AGS Super Neutrino Beam Facility	EDIA	M&S	Labor	Total
1.1 The Linac System	**6,879,116**	**98,556,970**	**16,783,762**	**122,219,848**
1.1.1 Front End and RT Linac Upgrade	313,000	2,383,000	856,000	3,552,000
1.1.2 SCL Accelerating Cavity System	954,240	22,254,200	11,040,000	34,248,440
1.1.3 SCL RF Source	3,620,988	51,668,800	402,332	55,692,120
1.1.4 SCL Cryogenic System	370,000	13,700,000	2,200,000	16,270,000
1.1.5 SCL Vacuum System	641,598	3,474,570	1,148,378	5,264,546
1.1.6 SCL Instrumentation	460,957	1,390,400	409,061	2,260,418
1.1.7 SCL Magnet and Power Supply	518,332	3,686,000	727,991	4,932,324
1.2 The AGS Upgrade	**10,406,245**	**53,619,159**	**6,472,590**	**70,587,994**
1.2.1 AGS Main Magnet Power Supply	503,959	28,200,000	1,342,337	30,046,296
1.2.2 AGS RF System Upgrade	6,082,625	9,850,000	675,847	16,608,472
1.2.3 AGS Injection/Extraction	644,000	6,437,066	1,668,330	8,749,396
1.2.4 Beam Transport to Target	1,636,771	7,852,241	2,637,290	12,126,302
1.2.5 Control System	1,628,890	1,279,852	148,786	3,057,528
1.3 The Target and Horn System	**664,742**	**3,417,152**	**1,208,338**	**5,290,232**
1.3.1 The Target System	127,008	229,284	50,130	406,422
1.3.2 The Horn System	454,524	2,358,568	656,224	3,469,316
1.3.3 Shielding and Remote Handling	83,210	809,300	125,300	1,017,810
1.3.4 Target & Horn Physics Support	0	20,000	376,684	396,684
1.4 The Conventional Facility	**7,550,300**	**60,090,300**	**1,210,700**	**68,851,300**
1.4.1 Linac Tunnel/Klystron Gallery	2,253,000	11,529,000	230,000	14,012,000
1.4.2 AGS Power Supply Building	2,024,000	13,347,000	432,000	15,803,000
1.4.3 Beam Transport and Target Area	1,674,300	25,091,000	172,500	26,937,800
1.4.4 The Decay Tunnel and Beam Stop	184,000	1,225,300	115,200	1,524,500
1.4.5 Site Utilities & Roads	1,088,000	6,820,000	140,000	8,048,000
1.4.6 Modifications for AGS RF System	327,000	2,078,000	121,000	2,526,000
1.5 ES&H	**104,652**	**275,211**	**437,355**	**817,218**
1.5.1 ES&H	20,000	105,000	270,000	395,000
1.5.2 Access Controls.	84,652	170,211	167,355	422,218
1.6 Project Support	**1,148,681**	**384,109**	**4,096,963**	**5,629,753**
1.6.1 Project Management	0	100,000	1,178,000	1,278,000
1.6.2 Technical Support	1,148,681	214,109	2,146,963	3,509,753
1.6.3 Project Controls	0	70,000	772,000	842,000
AGS Super Neutrino Beam Facility Project Total	**26,843,736**	**216,342,901**	**30,209,709**	**273,396,345**

Total <u>direct</u> cost is FY 04 $ 273.4 M.

Total *estimated* cost is FY 04 $ 406.9 M (including 30% contingency)

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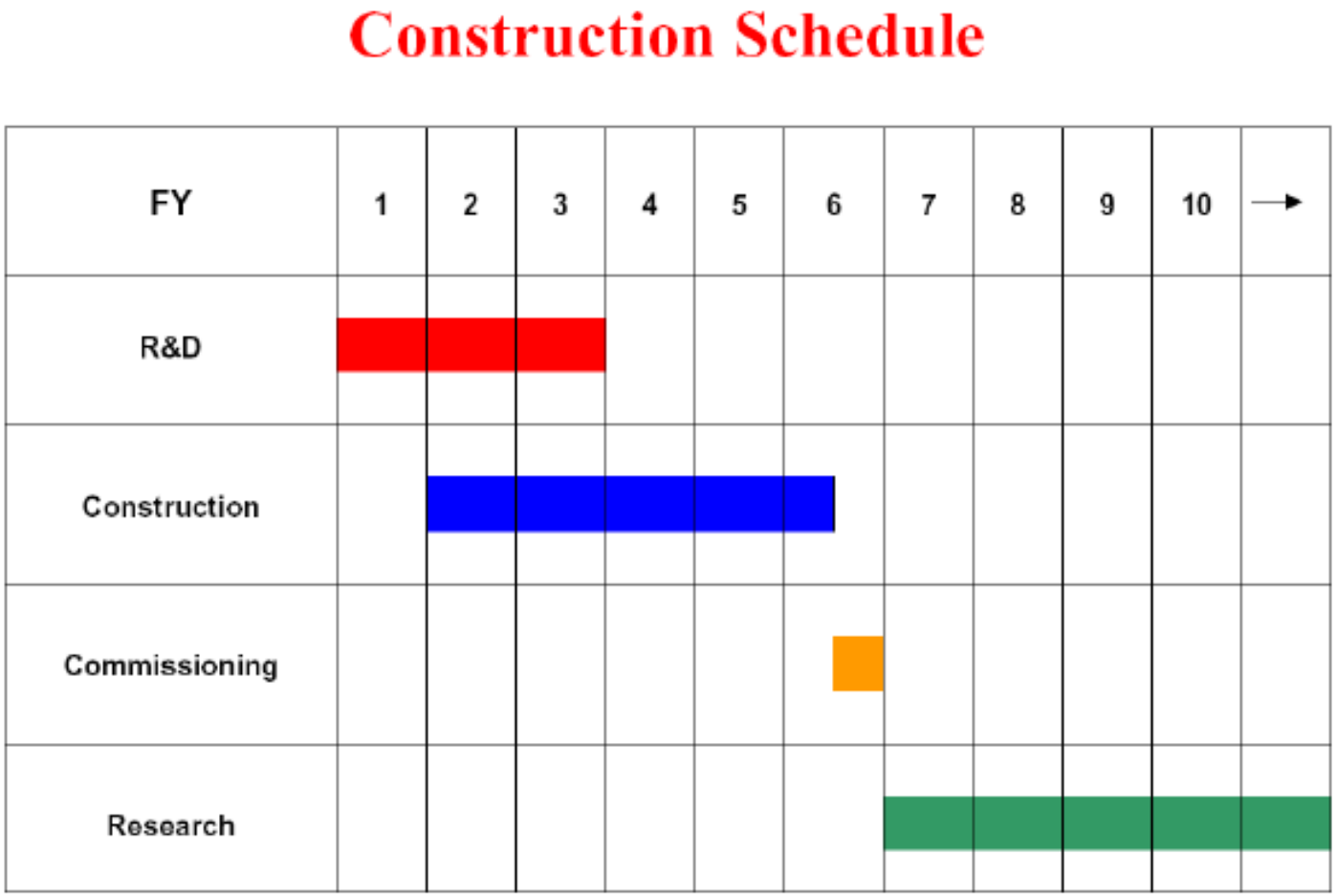
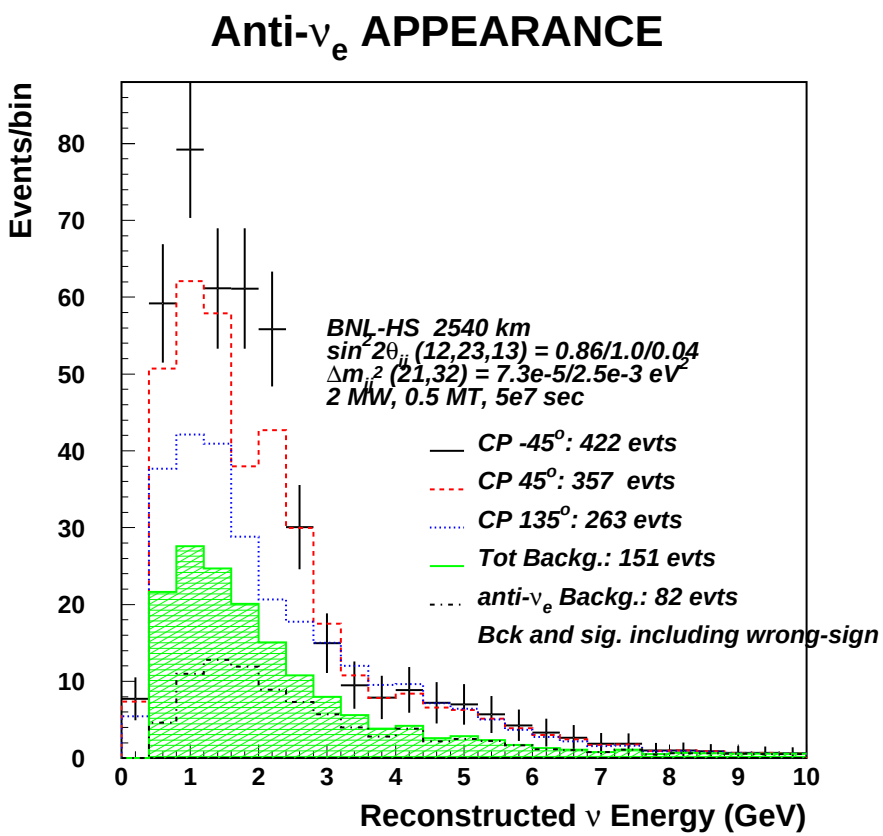
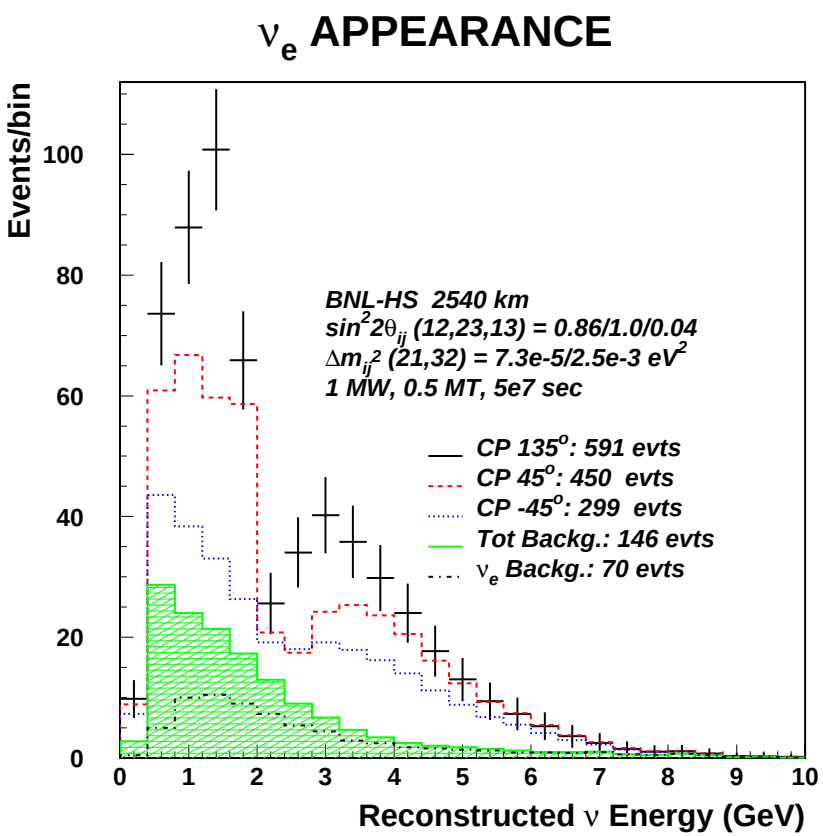
Construction Schedule



$\bar{\nu}_e$ appearance (normal hierarchy)

Lower cross-sections $\Rightarrow$ need 2 MW beam





Mass hierarchy resolved to better than $10\,\sigma$ after $\nu\ \bar{\nu}$ running.

Sensitive to new physics

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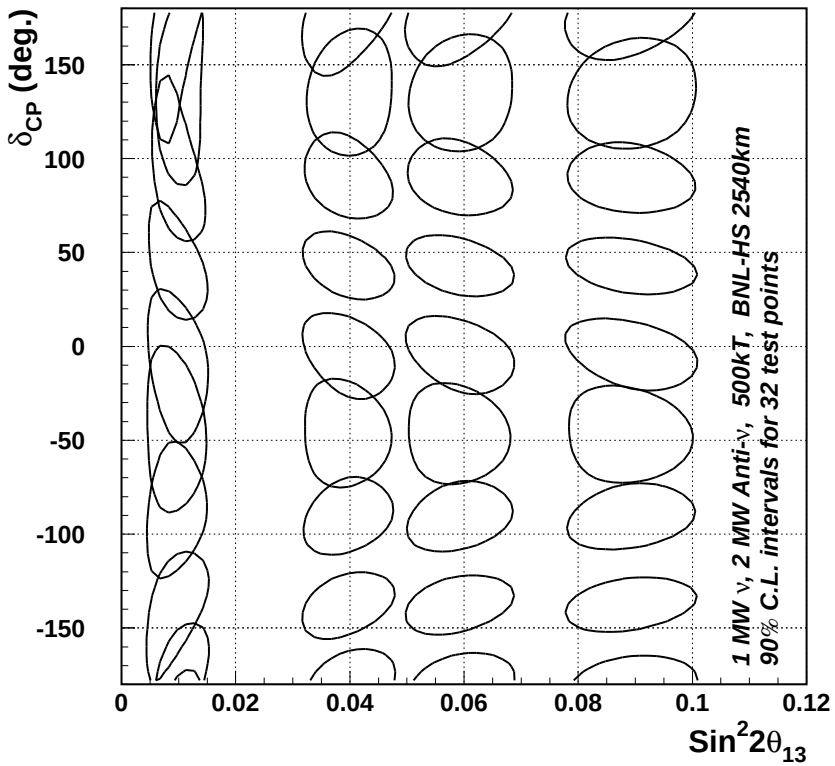
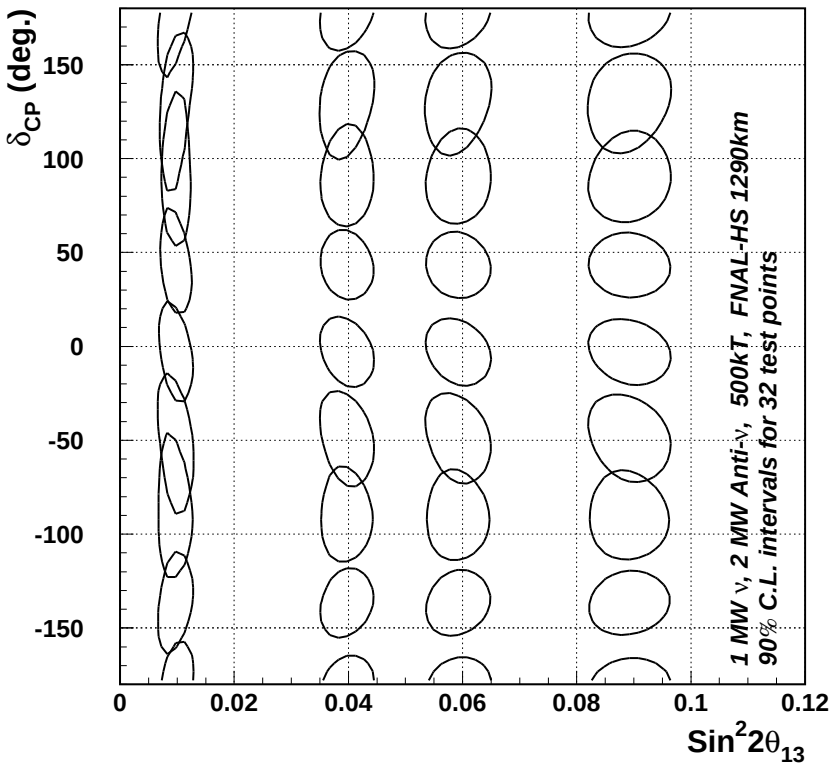
Limits after $\bar{\nu}$ running

90% confidence level error contours with statistical and 10% systematic errors:

Regular hierarchy ν and Antiν running



Regular hierarchy ν and Antiν running



If no $\nu_e \Rightarrow$ observed $\Rightarrow$ limit $\sin^2 2\theta_{13} \sim 0.003$