NEUTRINO OSCILLATIONS WITH

MINOS & NOνA

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WHEPP 2006, IOP, Bhubaneswar, 3rd–14th January, 2006

IN MEMORIAM

THIS TALK IS DEDICATED IN MEMORY OF MY COLLEAGUE FOR FIVE YEARS AT CALTECH AND COLLABORATOR ON

MACRO, MINOS & NOνA

DOUG MICHAEL

WITHOUT WHOSE LEADERSHIP MINOS WOULD NOT HAVE BEEN POSSIBLE. HE PASSED AWAY CHRISTMAS NIGHT, 2005. MAY HIS SOUL REST IN PEACE.

PLAN OF THE TALK

1. Neutrino Oscillation – The Present Situation
2. Neutrino Oscillation – Open Questions in context of MINOS & NOυA
3. What would we like to know from Long-baseline in next 15 yrs (before ν factory)
4. MINOS - Where are we and what can we hope to measure in next 5 - 7 yrs?
   - ✓ MINOS Motivation and Physics Goals
   - ✓ MINOS Detector
   - ✓ NuMI Beam
   - ✓ Results from Atmospheric υ_μ and $\bar{\upsilon}_\mu$ Events
5. NOυA – Why, What & When ? - A neutrino road map for next 15 yrs.
   - ➢ NOυA – Motivation
   - ➢ NOυA – Detector
   - ➢ NOυA – Physics
   - ➢ NOυA – Timeline
6. Summary and Conclusions

ATMOSPHERIC NEUTRINO OSCILLATION – PRESENT SITUATION

- From L/E Measurement of Super- K – PRL 93, 101801 (2004)
  - ✓ Best Fit value (Physical Region) $\Rightarrow$ $\Delta m^2_{23} = 2.4 \bullet 10^{-3}$ eV^2, $\sin^2 2\theta_{23} = 1.00$
  - ✓ @90% CL $\Rightarrow$ $1.9 \bullet 10^{-3} < \Delta m^2_{23} < 3.0 \bullet 10^{-3}$ eV^2, $\sin^2 2\theta_{23} > 0.90$
- Super- K – 1489 Day Exposure – PRD 71, 112005 (2005)
  - ✓ Best Fit value (Physical Region FC, PC, & $\uparrow$thru μ's of)
  - ✓ $\Rightarrow \Delta m^2_{23} = 2.1 \bullet 10^{-3}$ eV^2, $\sin^2 2\theta_{23} = 1.00$
  - ✓ @90% CL $\Rightarrow$ $1.5 \bullet 10^{-3} < \Delta m^2_{23} < 3.4 \bullet 10^{-3}$ eV^2, $\sin^2 2\theta_{23} > 0.92$
- New analysis of Super-K with finer binning in zenith angle – finer energy bins for multi-GeV are sensitive to oscillation analysis - Talk by Y. Suzuki at TAUP 9/2005, Zaragoza, Spain
  - ✓ Best Fit value (Physical Region) $\Rightarrow \Delta m^2_{23} = 2.5 \bullet 10^{-3}$ eV^2, $\sin^2 2\theta_{23} = 1.00$
  - ✓ @90% CL $\Rightarrow$ $2.0 \bullet 10^{-3} < \Delta m^2_{23} < 3.0 \bullet 10^{-3}$ eV^2, $\sin^2 2\theta_{23} > 0.93$
- K2K - Y. Suzuki at TAUP 9/2005 with 9.22X10^{19} POT –
  - ✓ Best Fit value (Physical Region) $\Rightarrow \Delta m^2_{23} = 2.76 \bullet 10^{-3}$ eV^2, $\sin^2 2\theta_{23} = 1.00$
  - ✓ @90% CL $\Rightarrow$ $1.88 \bullet 10^{-3} < \Delta m^2_{23} < 3.48 \bullet 10^{-3}$ eV^2 @ $\sin^2 2\theta_{23} = 1.0$

PRESENT SITUATION - SUMMARY

1. Atmospheric neutrino related parameters are not well measured.
2. Error on measured parameters are of the order of 20%:
   1. $\delta(\text{Sin}^2 2\theta_{23}) \sim 0.2$,
   2. $\delta(\Delta m^2_{23}) \sim 0.4 \bullet 10^{-3}$ eV^2.
   3. The central value of Δm^2_{23} itself moves around a lot.
3. The value of θ_{23} at 99% CL varies from ~36^0 to ~54^0.

1. Solar parameters are relatively well measured.
2. Present limit on θ_{13} is dependent on atmospheric Δm^2_{23}.
3. Limit on θ_{13} for various atmospheric Δm^2_{32} values (95% CL) –
   a. $\text{Sin}^2 2\theta_{13} < 0.14$ for $\Delta m^2_{23} = 2.5 \bullet 10^{-3}$ eV^2
   b. $\text{Sin}^2 2\theta_{13} < 0.18$ for $\Delta m^2_{23} = 2.0 \bullet 10^{-3}$ eV2
   c. Maximum appearance probabilty of $\upsilon_e \rightarrow \upsilon_{\mu/\tau}$ ranges from ~7-9%. At 99% CL, θ_{13} is < 10^0.
4. We don't know about hierarchy. Need to figure out via matter effect.
5. We have no idea about CP violation in the lepton sector.

NEUTRINO OSCILLATION – OPEN QUESTIONS

1. Does ν_μ exclusively oscillate into ν_τ?
2. Does ν_μ at all oscillate to ν_s?
3. What fraction of ν_μ oscillates to ν_e?
4. What is the precise value of Δm^2_{23} ?
5. What is the precise value of θ_{23}?
6. Is θ_{23} maximal ($\theta_{23} = 45^0$)?
7. What is the value of θ_{13}? Is it different from ZERO?
8. How is neutrino mass hierarchy structured?
9. Is there CP violation in the lepton sector?

WHAT WE WOULD LIKE TO KNOW FROM LBL IN NEXT 15 YRS.

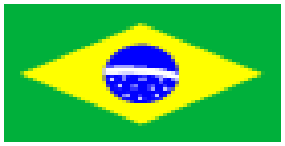
1. Atmospheric Sector – Long baseline – Next 5 -7 years
   - ✓ Observation of L/E (or should I say confirmation of L/E ?)
   - ✓ Precision measurement of Δm^2_{23}
   - ✓ Precision measurement of $Sin^2 2\theta_{23}$ (??)
   - ✓ Is θ_{23} maximal ? (??)
   - ✓ Better limit on θ_{13}
   - ✓ Exclusion of non-oscillation hypothesis like neutrino decay, decoherence, extra-dimensions etc.
2. Atmospheric Sector – Long baseline – Next 10-15 years
   - ✓ Very precise measurement of Δm^2_{23} and $Sin^2 2\theta_{23}$
   - ✓ Measure θ_{13}
   - ✓ Determine hierarchy via "matter effect", and
   - ✓ Measure CP Violation in the lepton sector

How MINOS & NOυA will contribute in finding answers to these open questions ?

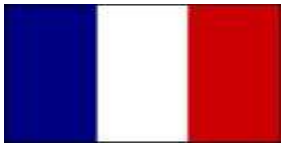
MINOS COLLABORATION

ANL, U. Athens, Benedictine U., BNL, Caltech, U. Cambridge, U. Estadual de Campinas, FNAL, College de France, Harvard U., IIT, Indiana U. - Bloomington, ITEP-Moscow, Lebedev Intitute, LLNL, U. Minnesota - Minneapolis, U. Minnesota-Duluth, U. Oxford, U. Pittsburgh, Protvino, RAL, U. Sao Paulo, U. South Carolina, Stanford U., U. Sussex, TAMU, UT-Austin, Tufts U., UCL, Western Washington U., College of William & Mary, & U. Wisconsin – Madison

Brazil - 2



France - 1

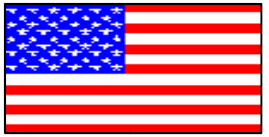


Greece - 1

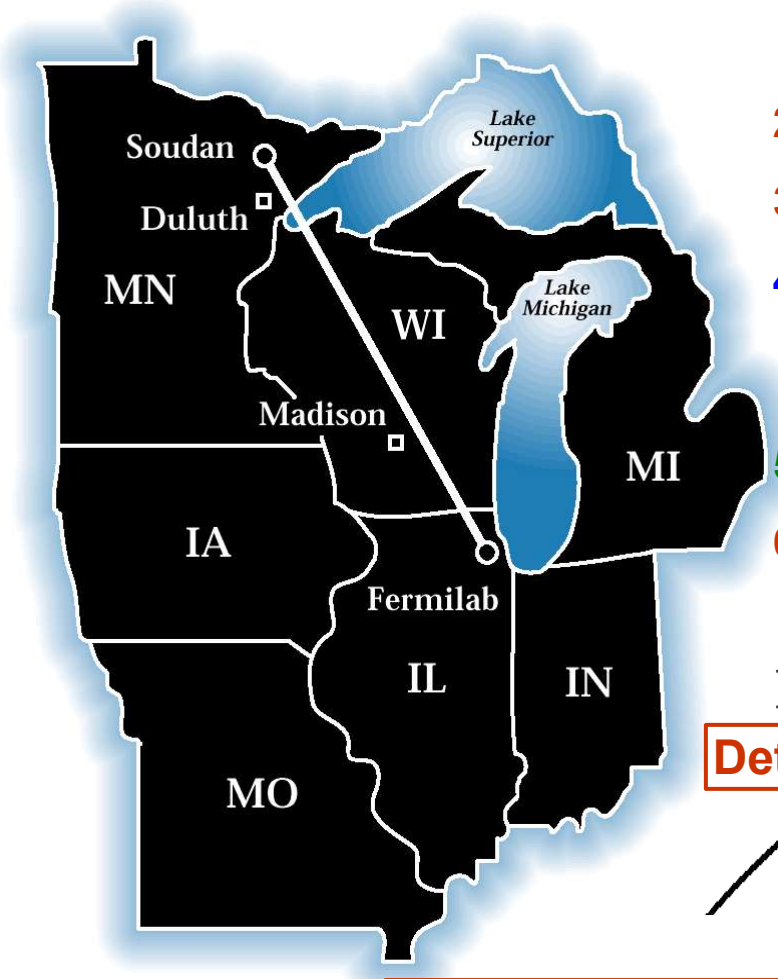
Russia - 3

U.K - 5

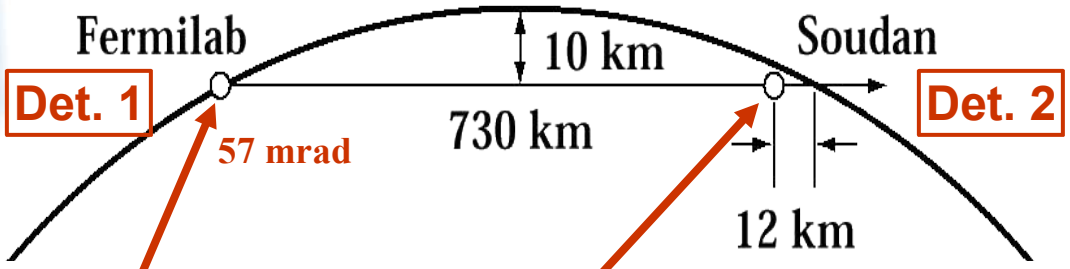
U.S.A – 20



THE MINOS EXPERIMENT



1. Motivation – Precision measurement of atmospheric neutrino parameters with υ_μ beam and two detectors.
2. 120 GeV protons from Fermilab MI.
3. Beam cycle time ~ 2.0 – 3.0 Sec.
4. At present - up to $3.0X10^{13}$ protons/pulse.
   Average beam power 170KW (0.17MW).
   Maximum beam power 270KW (0.27MW).
5. $1.0X10^{20}$ POT – On Dec. 6, 2005.
6. First beam data result expected very soon - may be as early as this month.



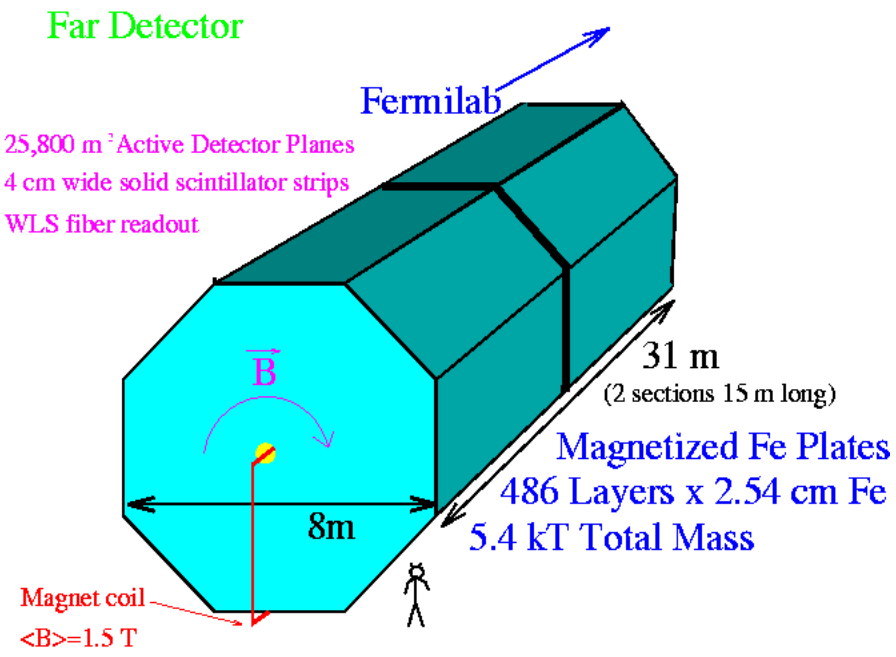
Near Detector: 980 Tons – 1Km

Far Detector: 5,400 Tons

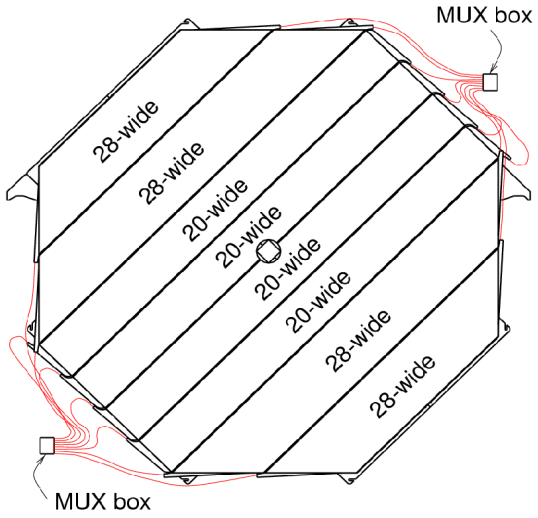
MINOS PHYSICS GOALS

- **Demonstrate flavor oscillation behavior of neutrino data**
  - ✓ Measure CC interaction rate. Measure CC energy distribution.
  - ✓ Measure NC/CC rate ratio. Measure NC energy distribution.
- **Precisely measure oscillation parameters from CC energy distribution**
  - ❑ $\Delta m^2_{23} \sim 10\%$,
  - ❑ $\mathrm{Sin}^2 2\theta_{23}$ - of the same order or slightly better than the present measurement
- **Provide high statistics L/E discrimination against non-oscillation alternate models:**
  - Neutrino Decay
  - Decoherence
  - Extra-Dimensions and others
- **Search for sub-dominant $\upsilon_\mu \rightarrow \upsilon_e$**
  - ❖ Possible first measurement of θ_{13} or a factor of 2 or better limit compared to CHOOZ.
- **MINOS is the first large underground magnetized detector - First direct measurement of υ_μ and $\bar{\upsilon}_\mu$ oscillations from atmospheric neutrino data**
  - ➔ **hep-ex/05012036 – "First Observation of Separated Atmospheric υ_μ and $\bar{\upsilon}_\mu$ Events in the MINOS Detector" – Submitted to PRD – 15.Dec.2005**

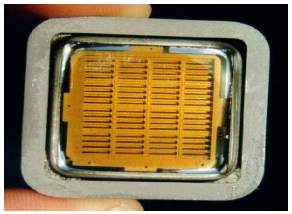
MINOS FAR DETECTOR



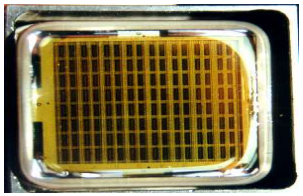
- ✓8m wide octagonal scintillator & fiber based tracking calorimeter
- ✓486 layers of 2.54 cm magnetized Fe plates (1.3 Tesla or 15.2 kA)
- ✓2 supermodules, each ~15m long
- ✓Veto shield against entering cosmic rays
- ✓Completed June 2003



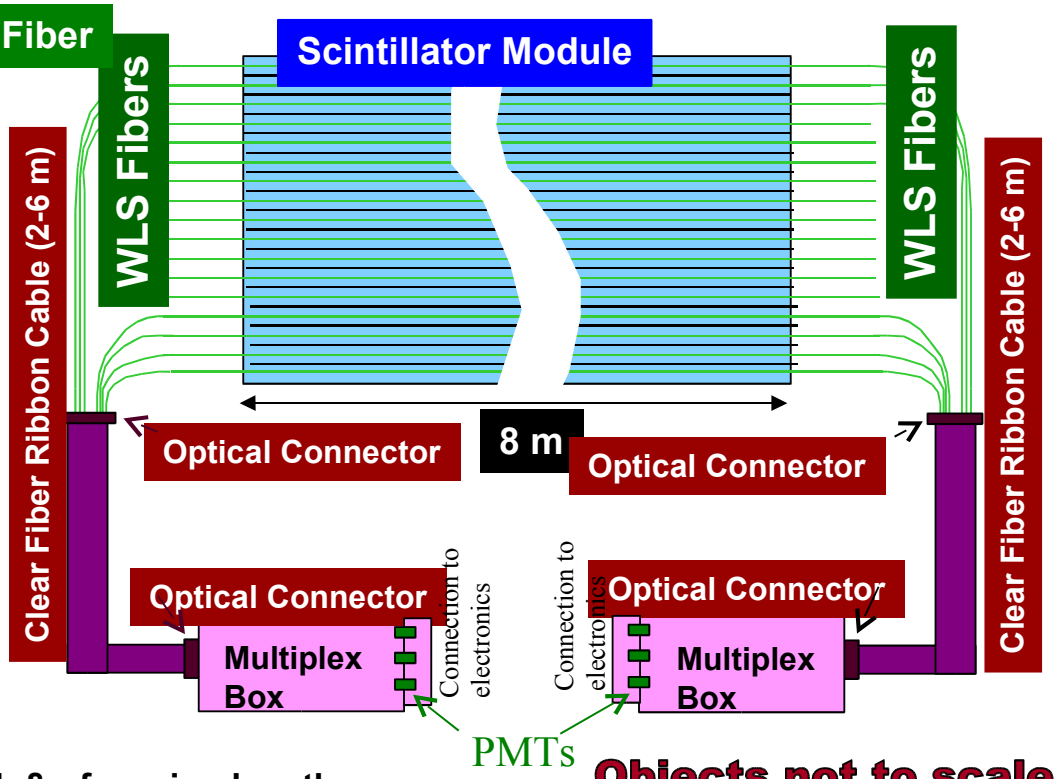
SCHEMATIC VIEW OF THE MINOS FD SCINTILLTOR SYSTEM



Far Detector:
Hamamatsu
M16 MAPMT



Near Detector:
Hamamatsu
M64 MAPMT

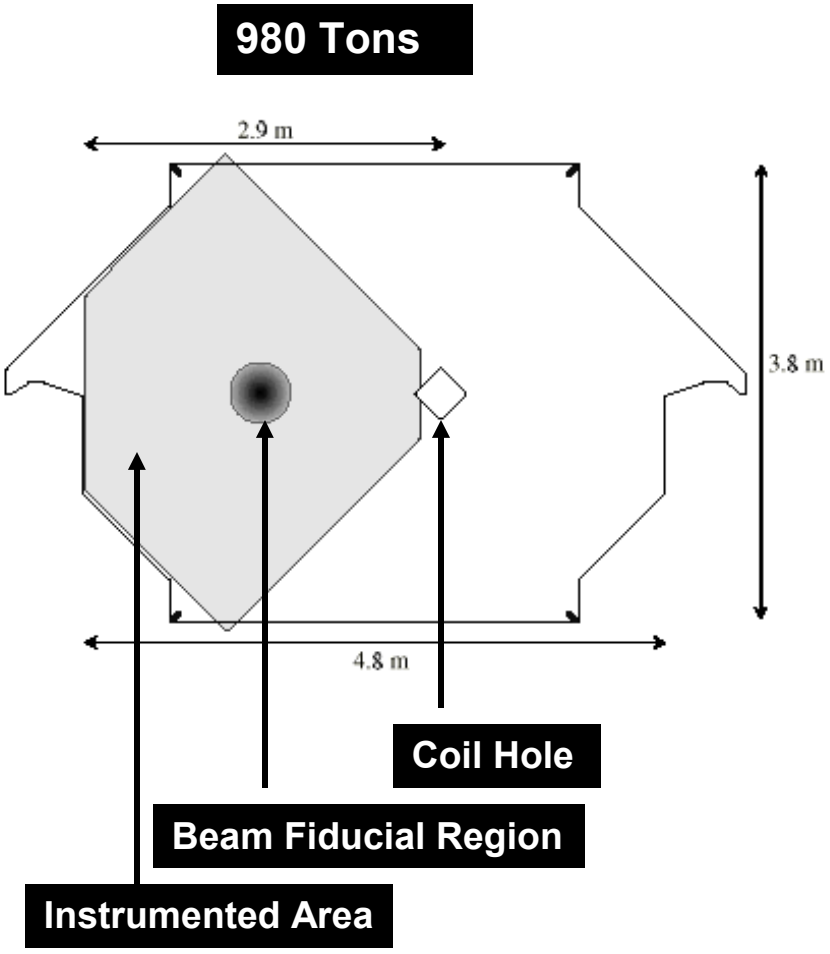


- Extruded scintillator, 41mm wide, 10mm thick & of varying length
- Two-ended WLS fiber readout
- Strips assembled into 20 or 28-wide modules
- WLS fibers routed to optical connectors.
- Light routed from modules to PMTs via clear fibers.
- 8 Fibers/PMT pixel in far detector. Fibers separated by ~1m in a single plane.
- 1 Fiber/PMT pixel in near detector (avoids overlaps).
- Multi-pixel PMTs Hamamatsu M16 for FD and Hamamatsu M64 for ND.

MINOS NEAR DETECTOR

Emulates the Far Detector in absorber, active planes and the B-field

- ➢ Located in cavern – 90m below ground
- ➢ Cavern is 46m long, 10m high
- ➢ Access is by a 6.5m diameter shaft
- ✓ 280 single steel squashed octagons
- ✓ Detector is ~16.5m long & weighs 980T
- ✓ Each planes is 3.8m X 4.8m
- ✓ Divided in veto(20), target (40), shower (60) & muon section (120)
- ❑ Forward section: 120 planes
  - ✓ 4/5 partially instrumented
  - ✓ 1/5 fully instumented
- ❑ Spectrometer section:160 planes
  - ✓ 4/5 planes not instrumented
  - ✓ 1/5 planes fully instrumented
- ● Magnetic Field <B> = 1.3T

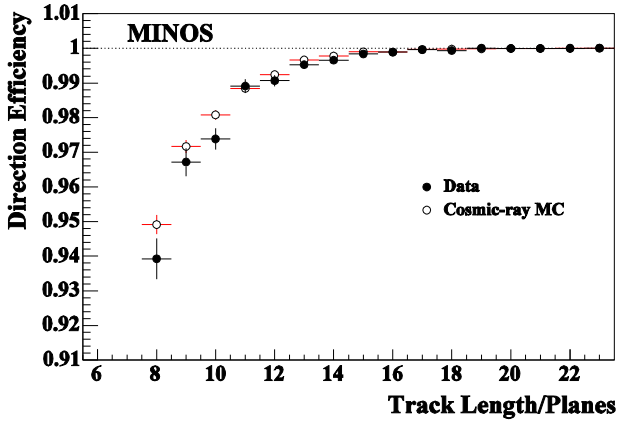


MINOS DETECTOR CAPABILITIES

1. **Muon Tracking:**
   a. **Muon charge sign from magnetic field**
   β. $\sigma^2_{1/p} = [0.10^2 + (0.3/p)^2]\ GeV^{-2}$ (p in GeV/c) (Curvature)
   c. $(\sigma_p/p)^2 = [0.06^2 + (0.045/p)^2]$ (p in GeV/c) (Muon range)
2. **EM shower detection:** $\sigma_E/E \sim 0.22/E^{1/2}$, E in GeV
3. **Hadronic shower:** $\sigma_E/E \sim 0.55/E^{1/2}$, E in GeV
4. **Single hit timing resolution:** $\sigma \sim 2.3$ ns
5. **Veto shield rejection of cosmic rays**

Measurement of:

- (1,2,3) → Neutrino event ID, E_ν measurement
- (1,4) → particle direction
- (1,4) → up/down neutrino/antineutrino



CALIBRATION DETECTOR

MINOS
NUMI

A Small MINOS like Detector

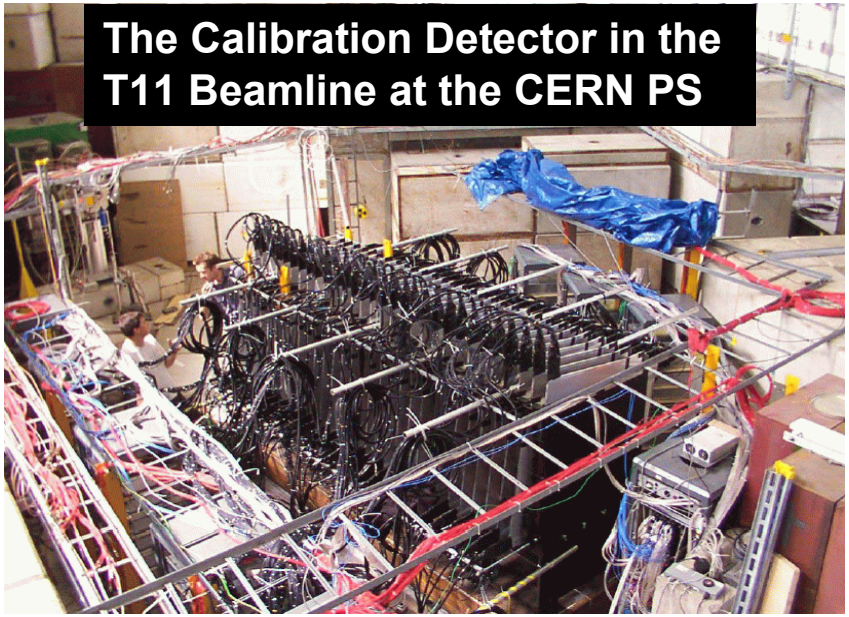
1mX1m – 60 planes thick – 3.7m long

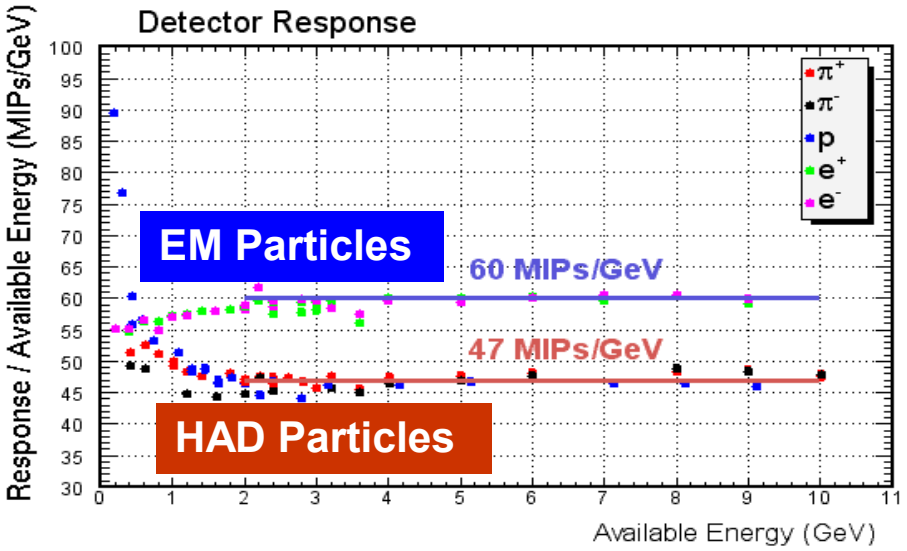
2.54cm Fe + Scintillator + WLS Fiber

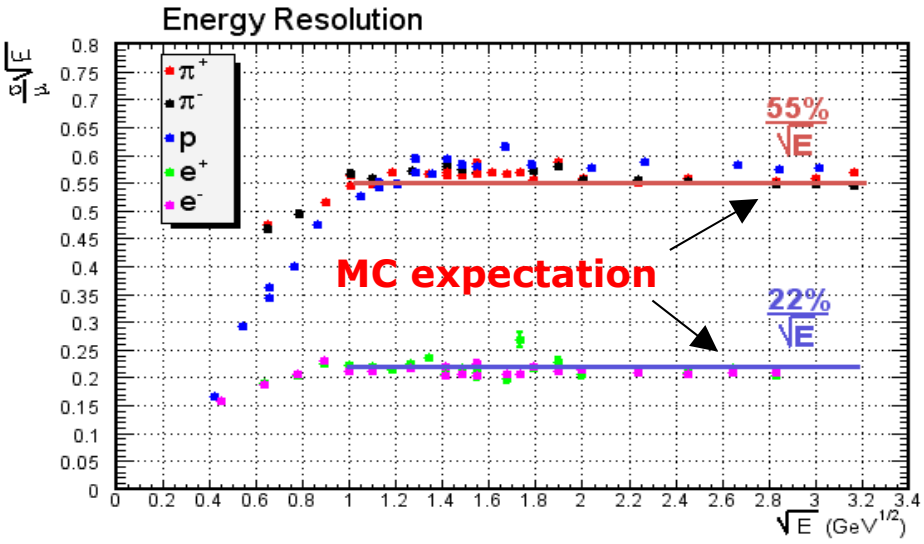
M64+IDE chip (FD) & M16+QIE chip (ND)

Collected data at T7 and T11 test beam @CERN in 2001, 2002 & 2003

The Calibration Detector in the T11 Beamline at the CERN PS

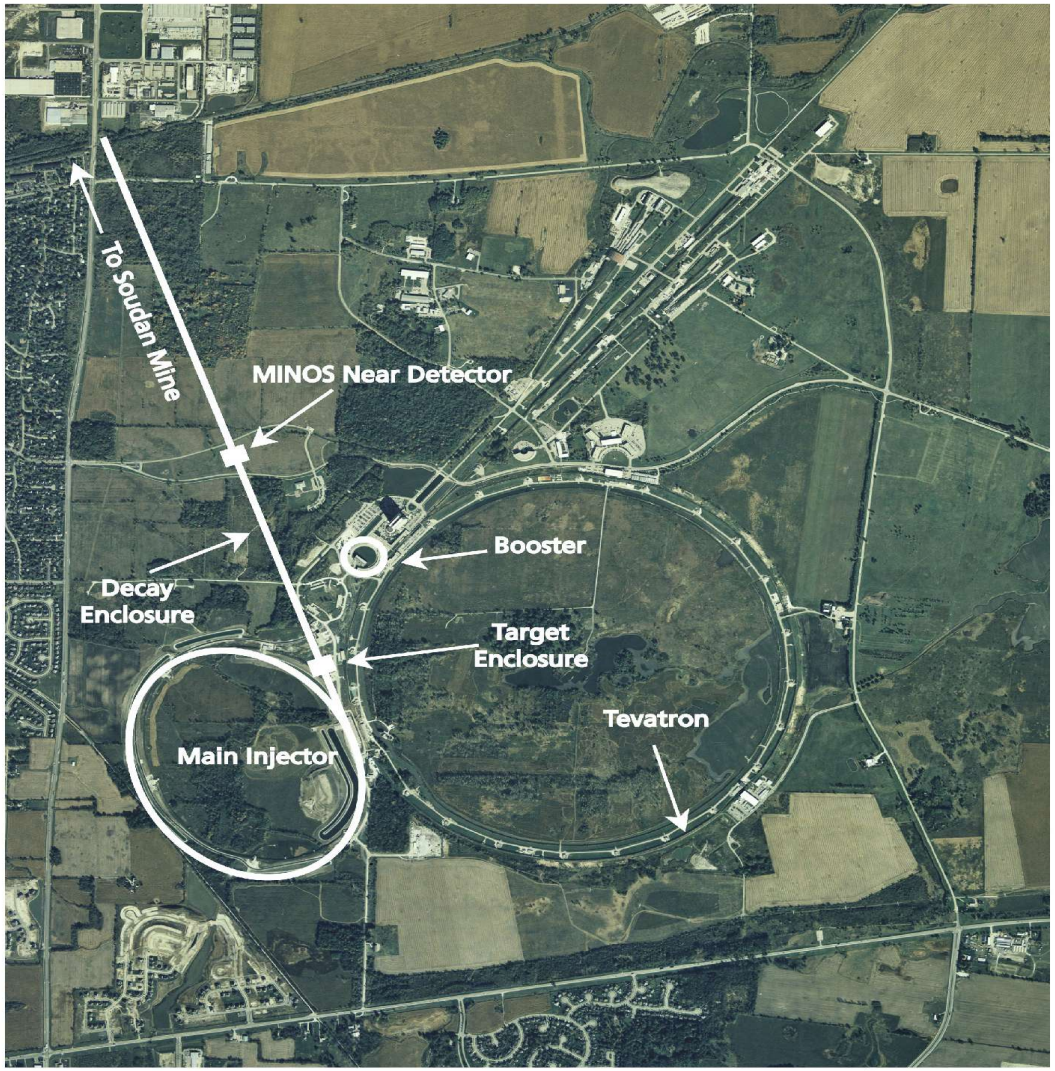






- ✓ **Calibrate Far-Near differences**
- ✓ **Obtain energy scale calibration**
- ✓ **Excellent test bed for exercising and testing calibration methods**

FERMILAB MAIN INJECTOR & NuMI BEAMLINE



Fermilab Main Injector:

- ✓ 120 GeV protons
- ✓ Upto 3.0×10^{13} protons/pulse
- ✓ 2.0-3.0 sec rep rate
- ✓ ~8 to 9.6 μsec spill
- ✓ ~0.17 MW to 0.27 MW

NuMI Beam:

- ➢ Graphite target
- ➢ Two magnetic horns
- ➢ 675 m vacuum decay pipe
- ➢ Hadron absorber
- ➢ Designed for 4 x 10^{13} ppp

Beam Monitoring:

- ▪ Beam line monitors
- ▪ Muon detectors
- ▪ Hadron detectors
- ▪ + Near Detector

120 GeV protons hit target

π^+ ("pions") produced at wide range of angles

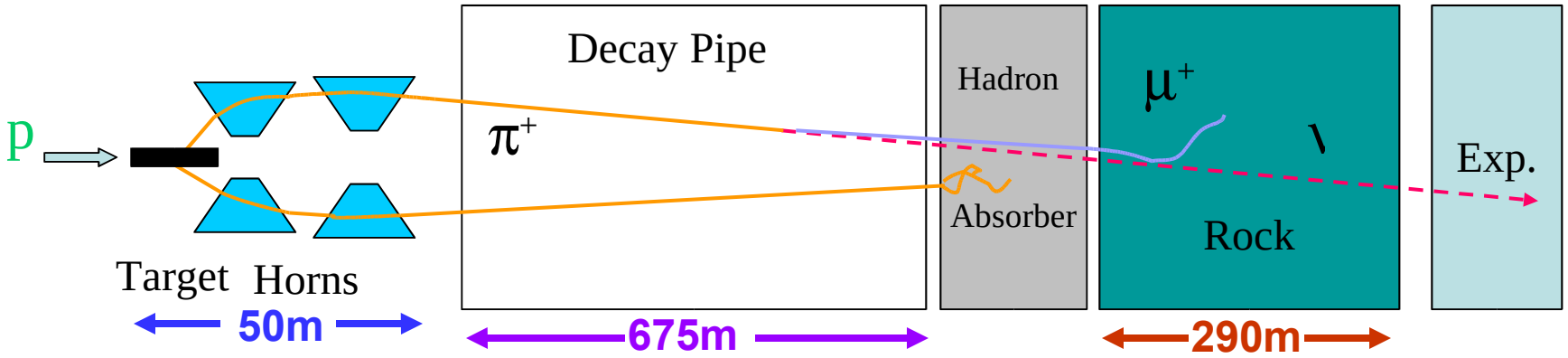
Magnetic horns to focus π^+

π^+ decay to $\mu^+\nu$ in long evacuated pipe

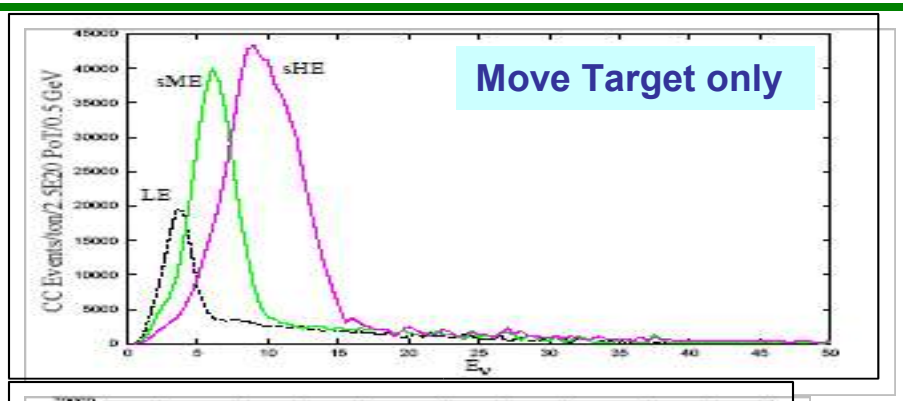
Left-over hadrons shower in hadron absorber

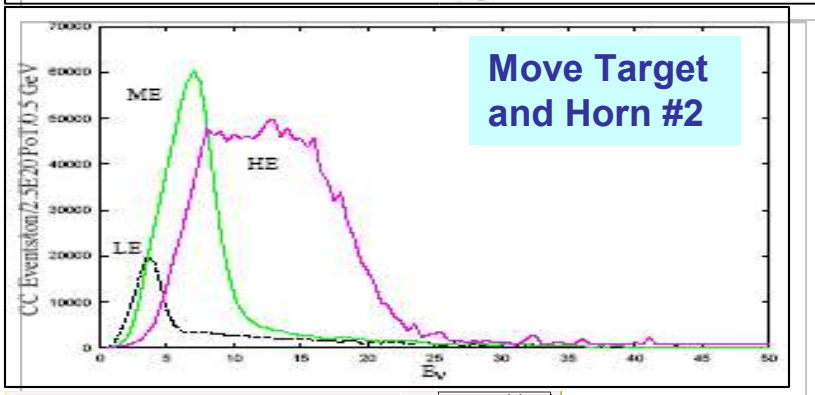
Rock shield ranges out μ^+

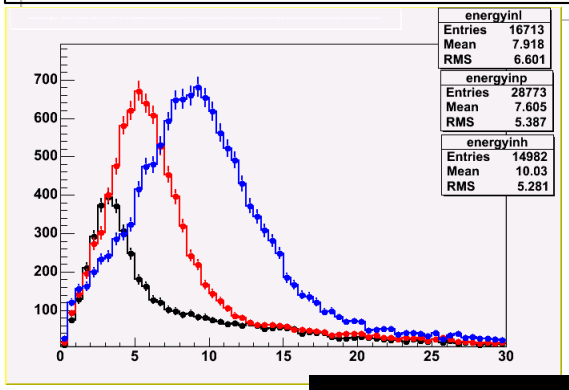
ν beam travels through earth to the experiment



HOW TO GET VARYING ENERGY BEAM @ NuMI







Reconstructed E_ν (GeV)

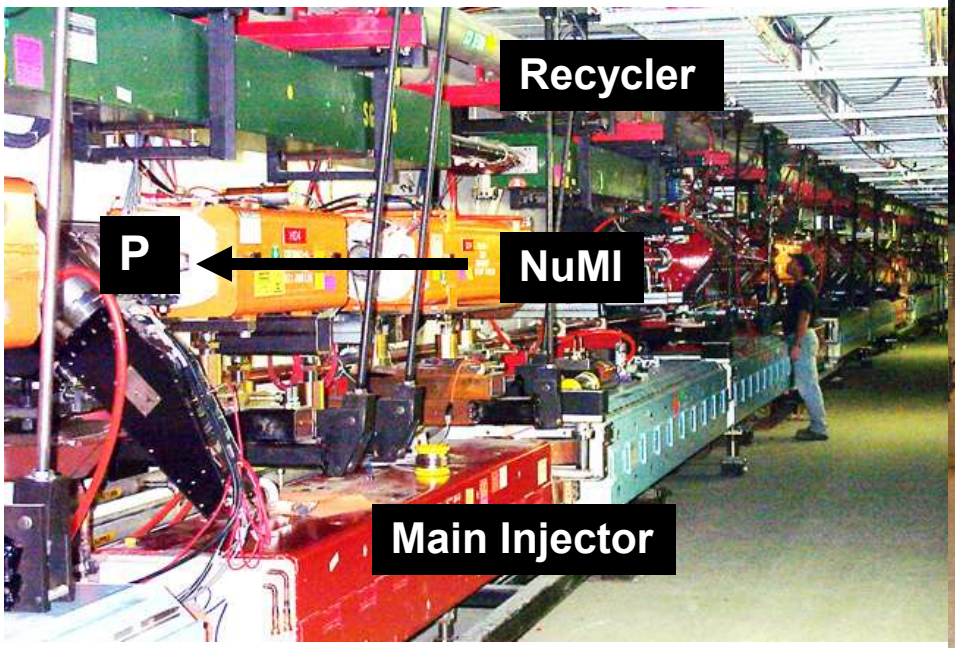
- Movable target in the beam direction
- Target position and 2- horn positions can be adjusted for neutrinos of different energy ranges

ν_μ CC Events in MINOS 5.4kt Detector (for 2.5×10^{20} POT/yr)

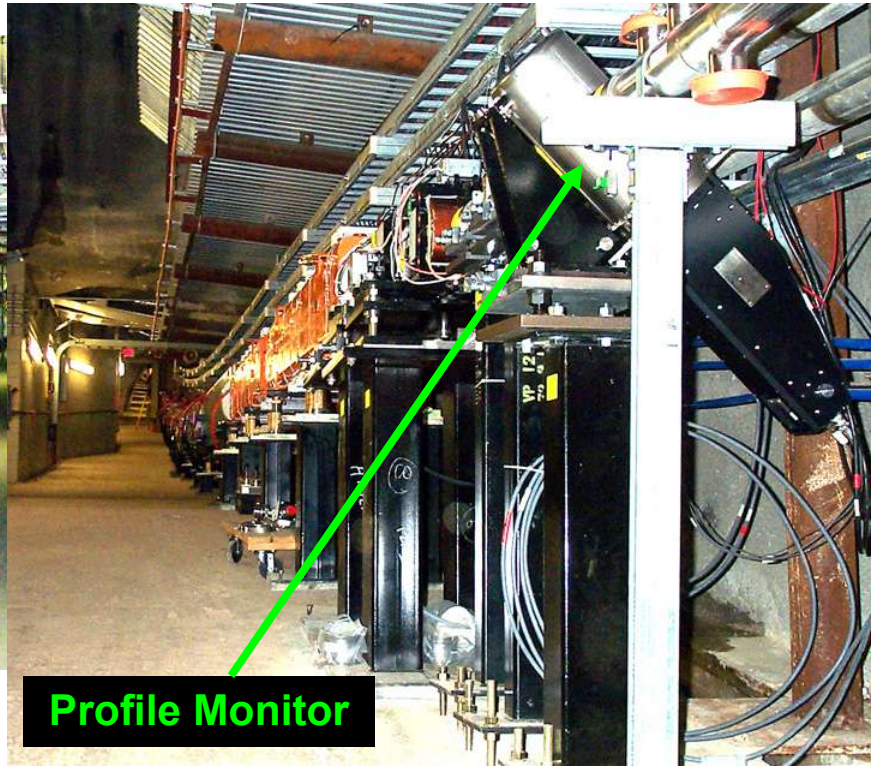
Low	~ 1600/yr
Medium	~ 4300/yr
High	~ 9250/yr

NuMI/MINOS run has collected most of the data with low energy beam to accommodate $\Delta m^2_{23} \sim 2X10^{-3}\ eV^2$

PRIMARY BEAMLINE & THE MAIN INJECTOR

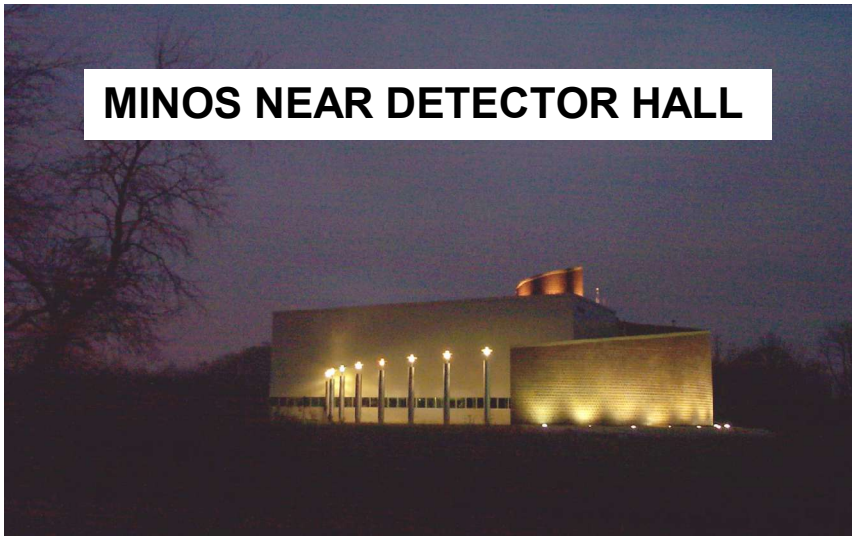


Main Injector tunnel showing the Recycler overhead and the NuMI beamline coming out of page.



NuMI Beamline descending towards the pre-target and then moving up towards the target – out of page.

SHAFTS & BUILDINGS



WHERE ARE WE IN MINOS?

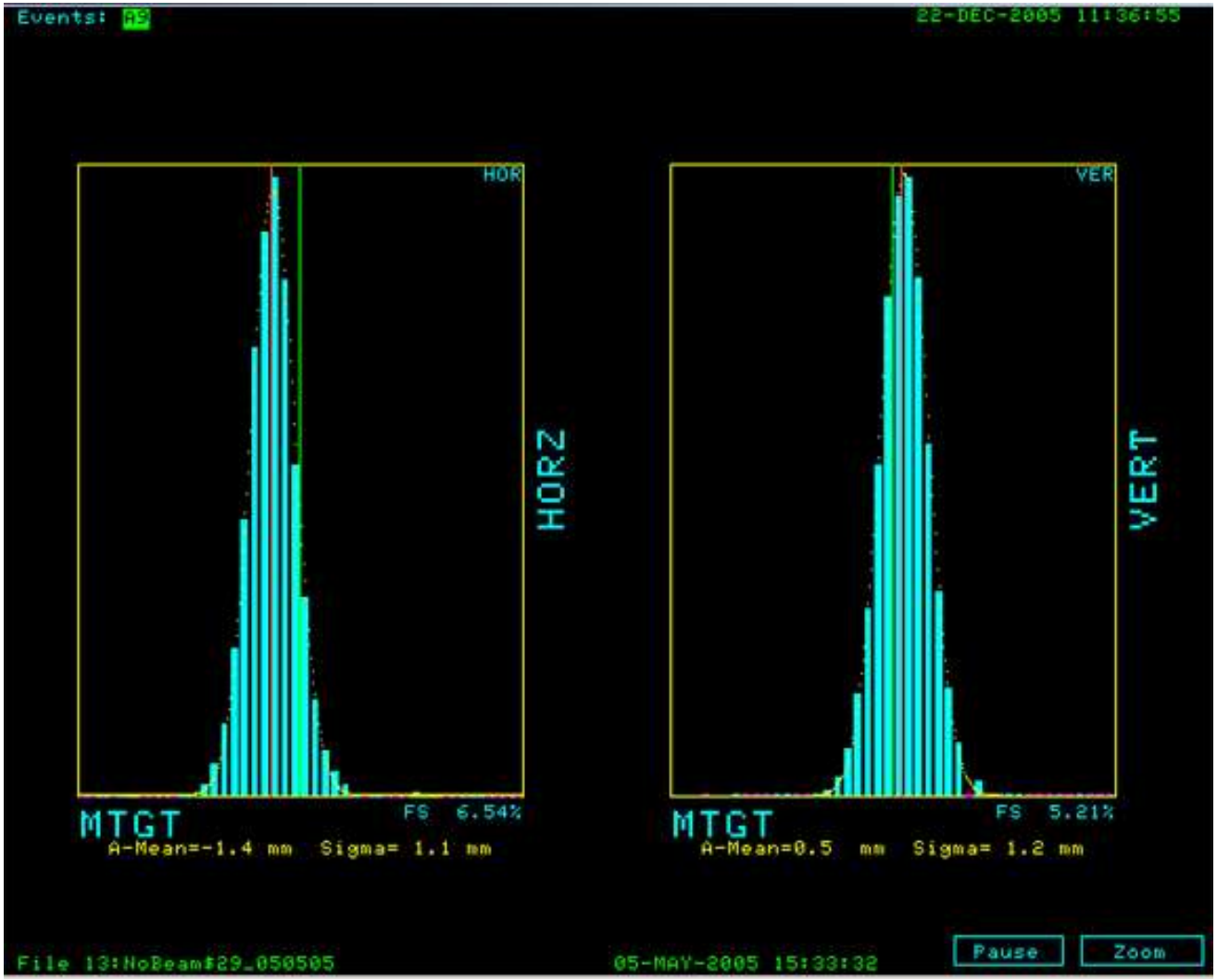
- MINOS FD completed in July 2003. Magnetic Field since August 2003.
- Atmospheric neutrino data collected for ~500+ days equivalent.
- Results on atmospheric neutrinos submitted to PRD with 418 days equivalent of live time (6.18 KTon Exposure – 4.54 KTon Fiducial).
- MINOS ND completed and commissioned by Dec. 2004.

- ✓ NuMI beam commissioned in March 2005.
- ✓ Consistent physics quality data since May.
- ✓ NuMI beam has already delivered $1X10^{20}$ protons on target.

- MINOS ND has accumulated high statistics neutrino interactions.
- MINOS FD has been recording neutrino interactions.

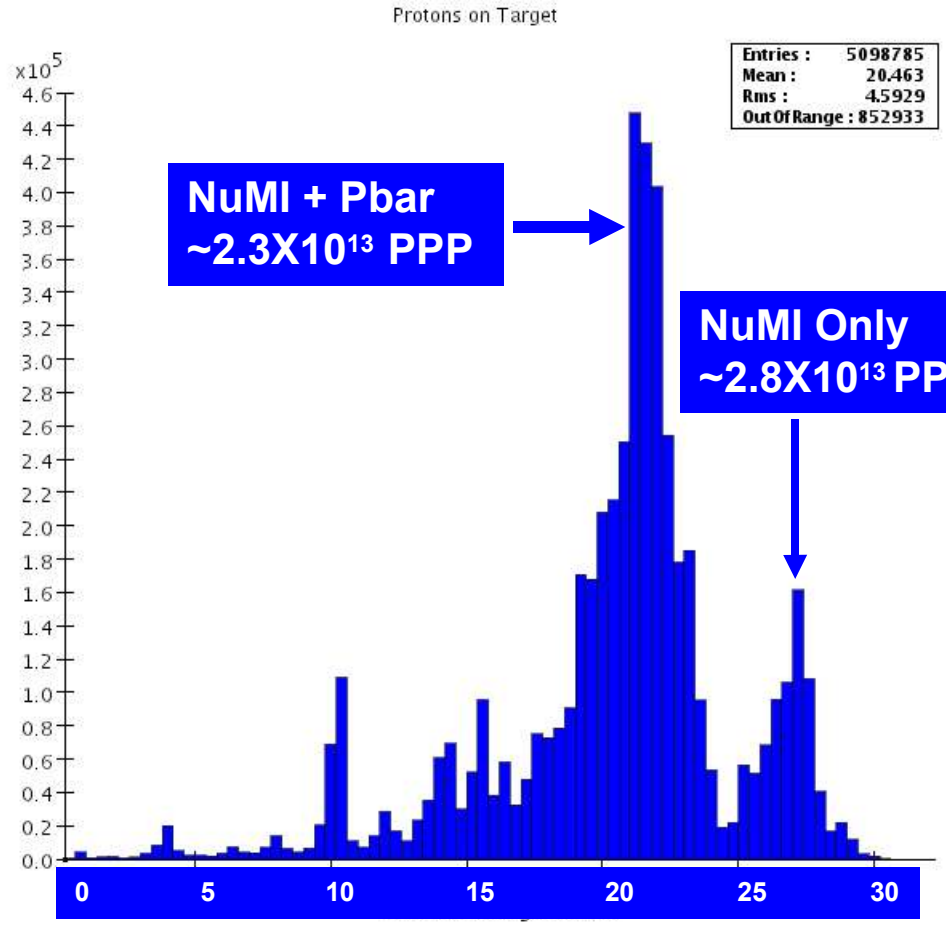
- Blind analysis method is being used.
- Physics analysis in progress.
- Result based on $1X10^{20}$ POT expected soon.

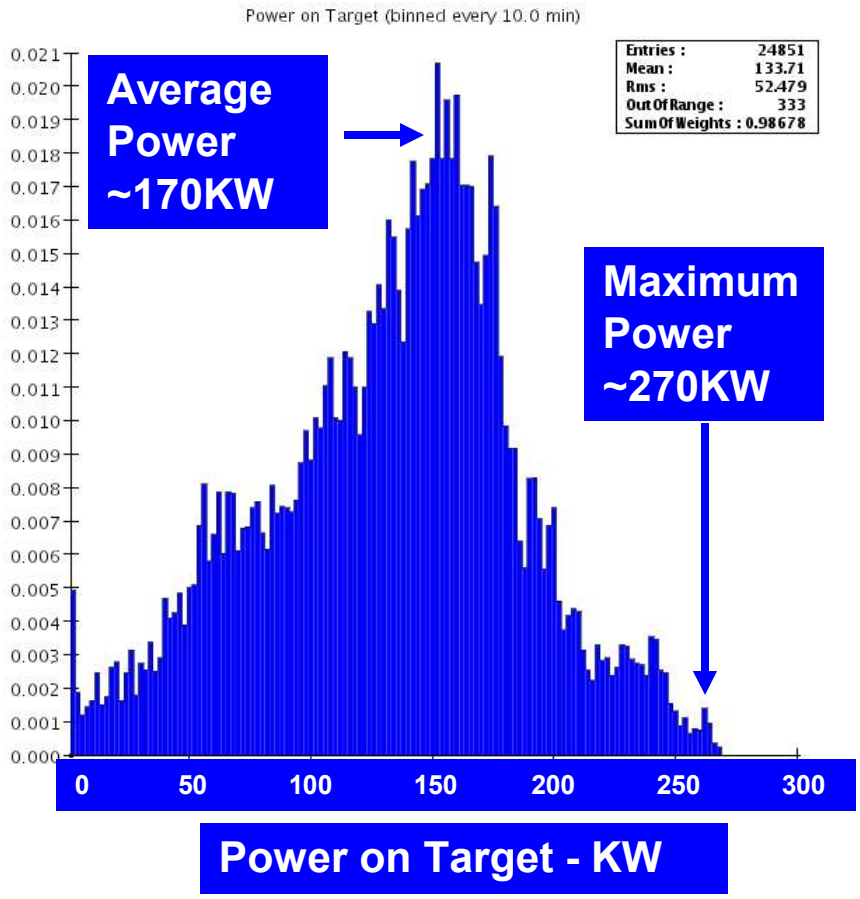
THE BEAM IS ON



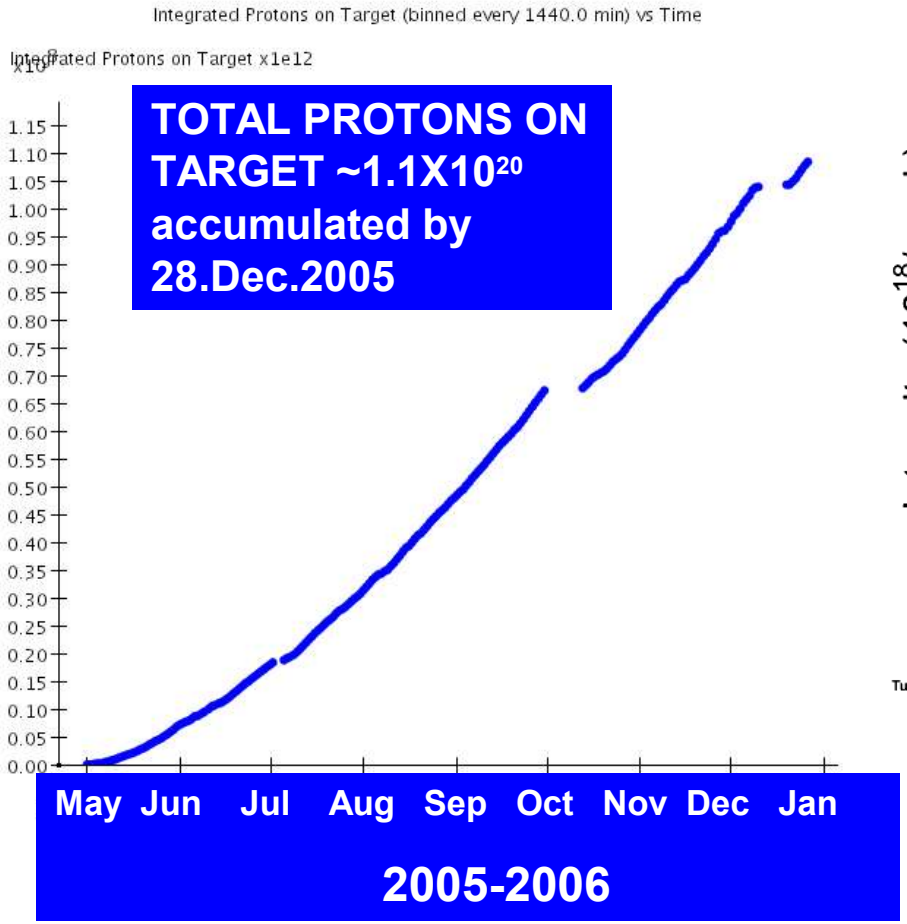
BEAM POSITION ON MINOS TARGET

PROTONS PER PULSE & TOTAL BEAM POWER

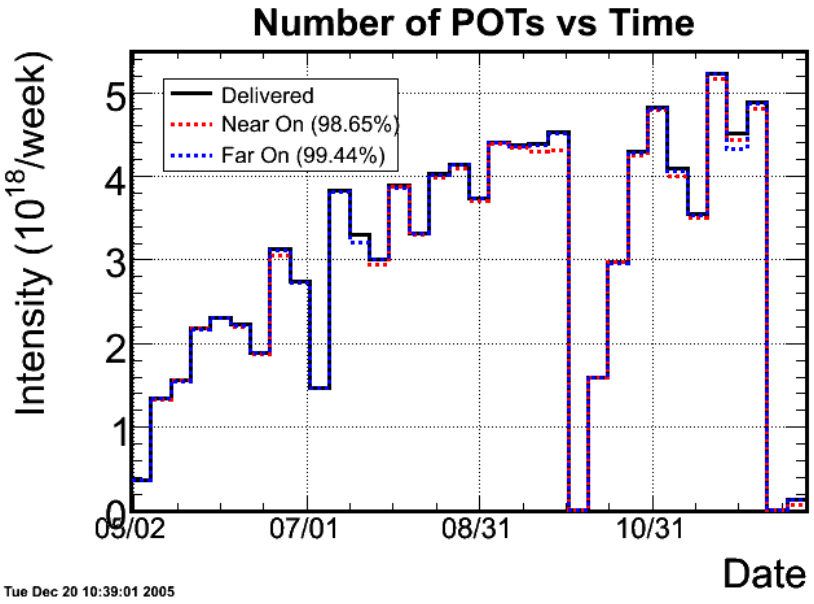




TOTAL PROTON ON TARGET, DETECTOR UP TIME & POT/WEEK



TOTAL PROTONS ON TARGET ~1.1X10^{20} accumulated by 28.Dec.2005

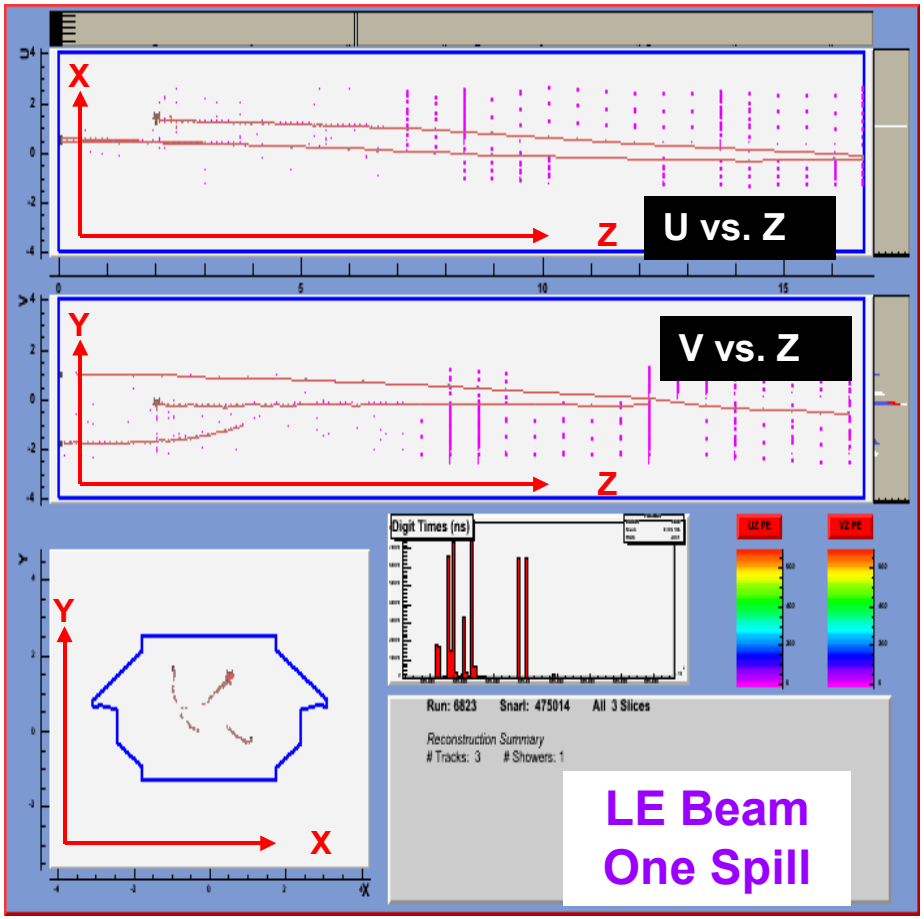


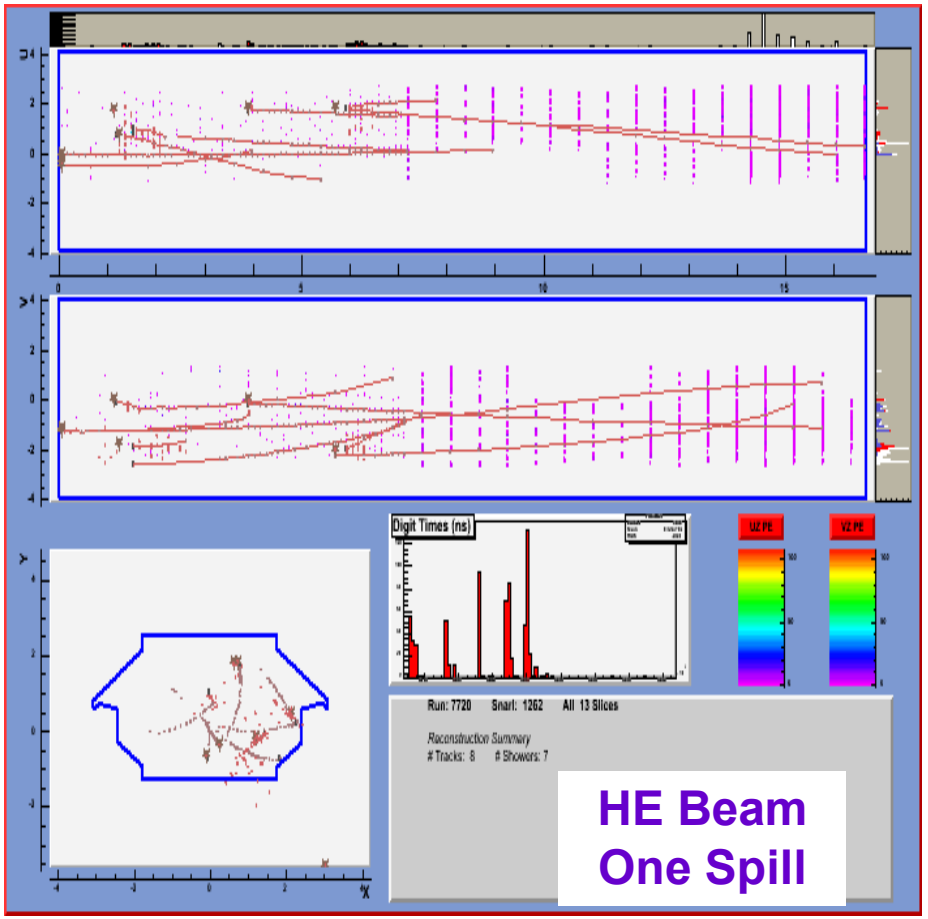
FD Uptime ~ 99.5%

ND Uptime ~ 98.7%

Ave. POT/Week ~ 5X10^{18}

BEAM NEUTRINOS IN A SINGLE SPILL @ ND



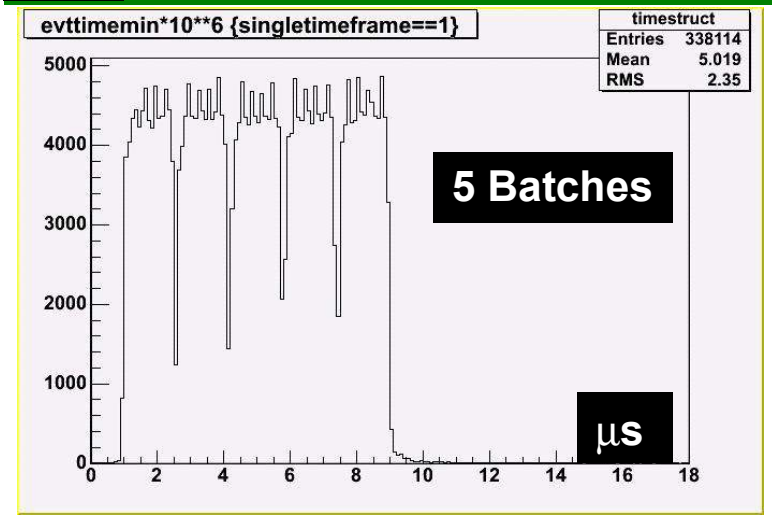


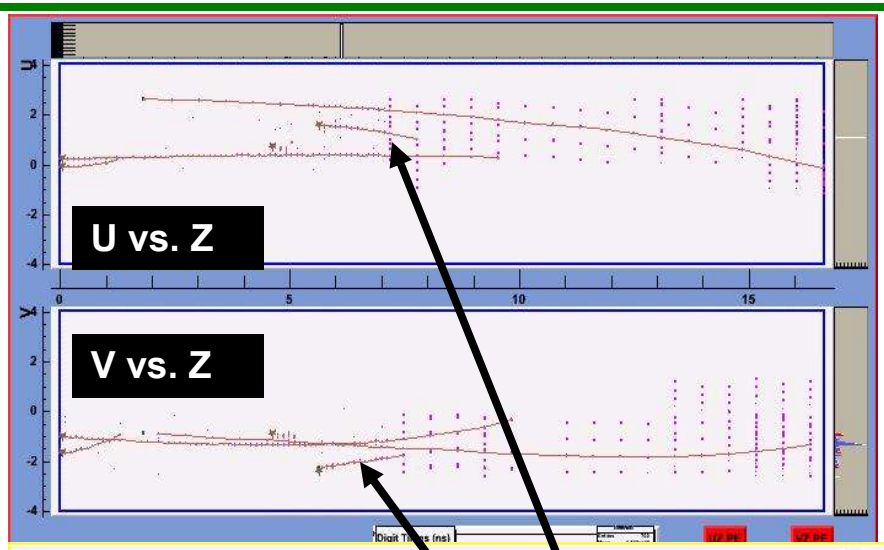
Beam spill length is 8-10μs, 5-6 batches of beam each ~1.6μs long.

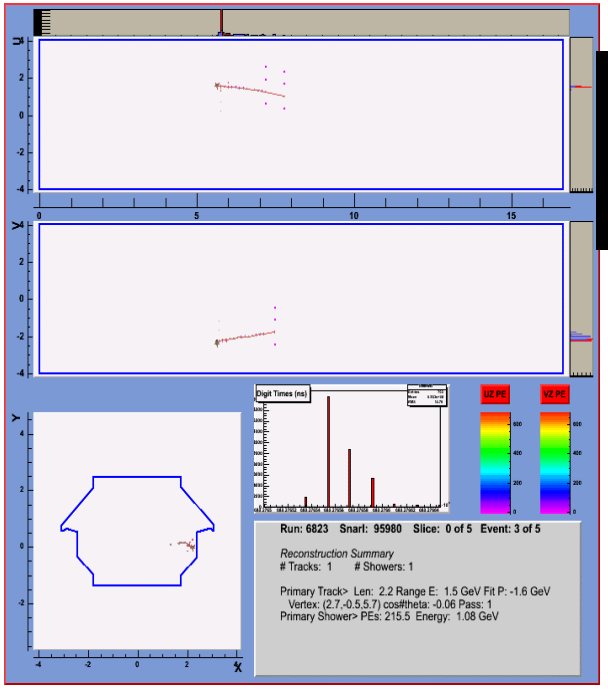
Continuous readout for 18ms.

Several neutrino interactions/spill – separate events by time slicing – 18.9ns resolution.

ISOLATING A SINGLE EVENT – CONTAINED CC EVENT

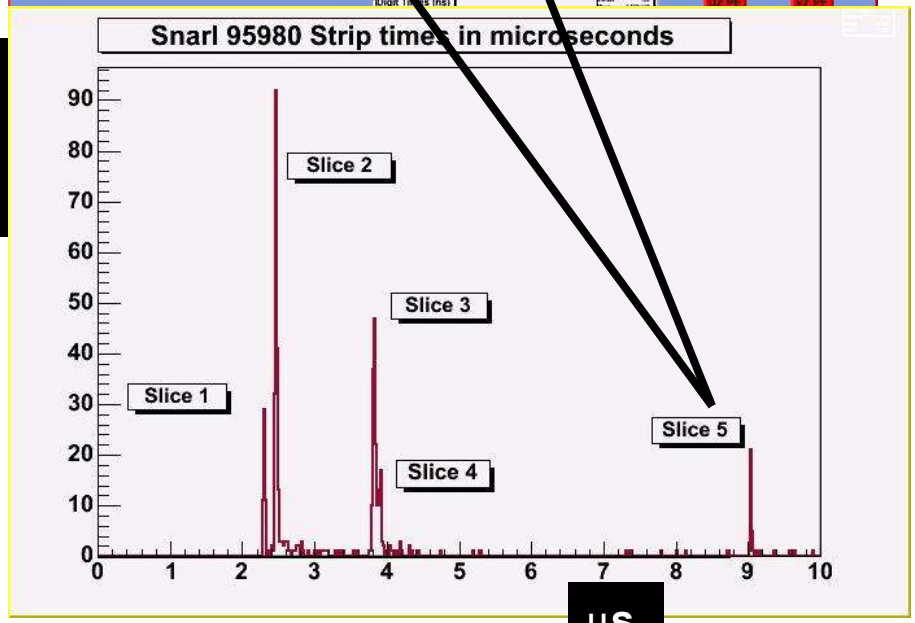




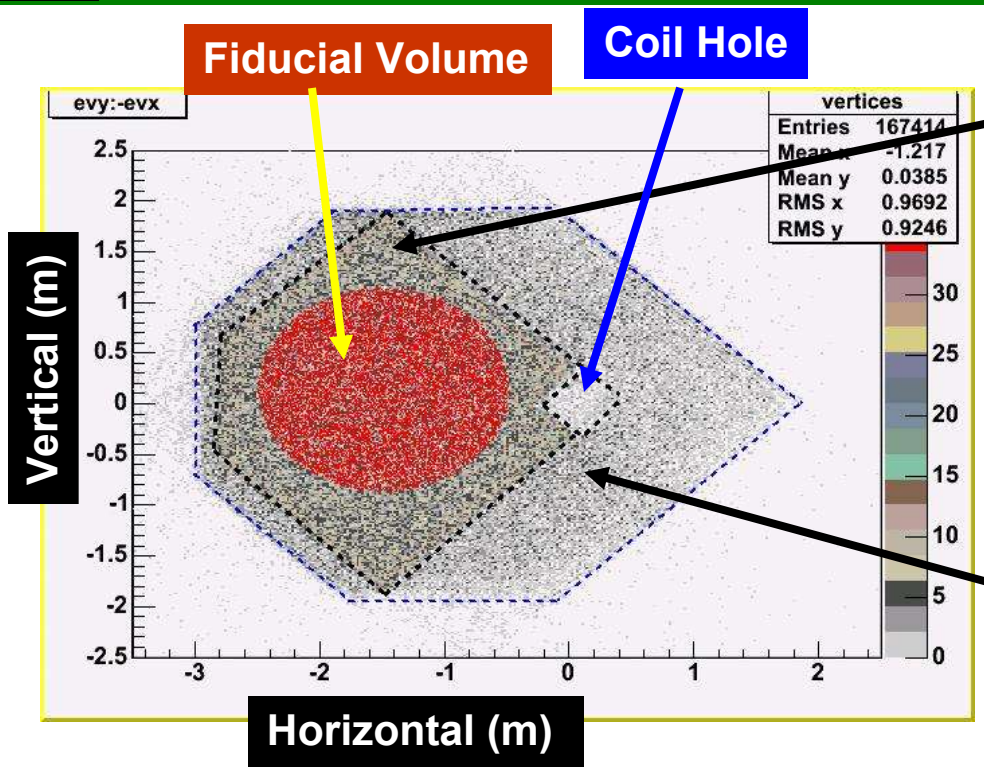


~1.5 GeV/c μ

~1.1 GeV shower



BEAM NEUTRINO EVENTS IN THE NEAR DETECTOR



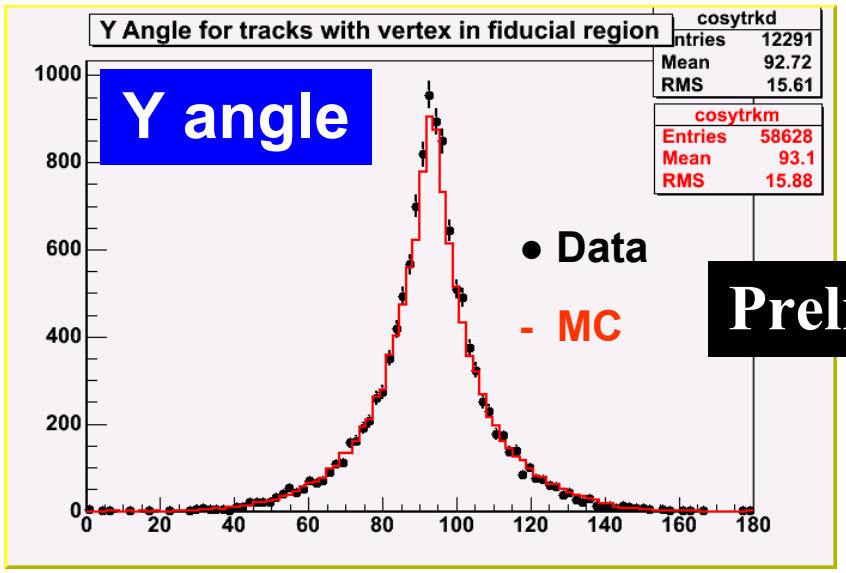
- Multiple Interactions/Spill
- High Statistics sample in the ND
- Enough data in one month to observe detector structures
- Expect 1X10^{7} ν interactions in a fiducial region of 1m radius and 4 m length for 2.5X10^{20} POT

NuMI BEAM POINTING TO THE FAR DETECTOR

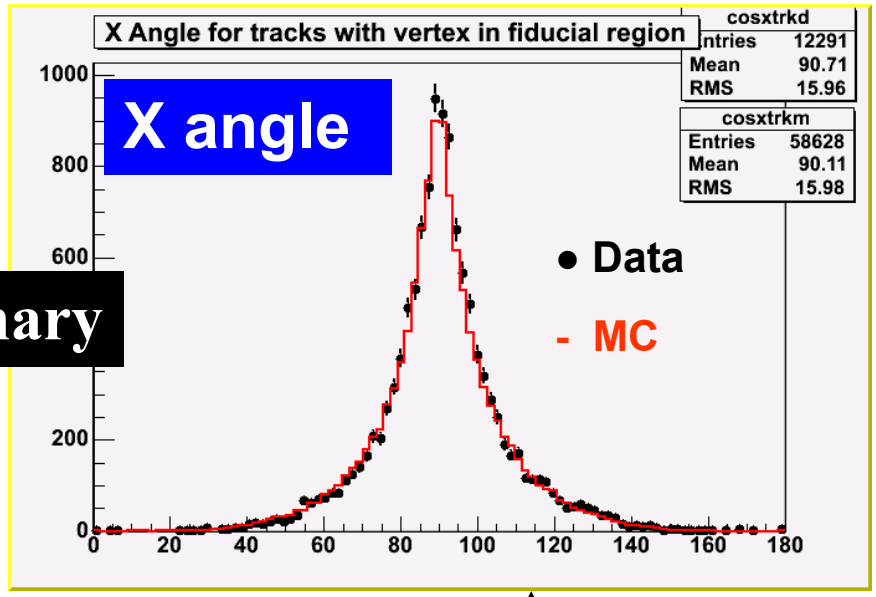
Y-angle must be 3.3 deg down, i.e, 93 deg.

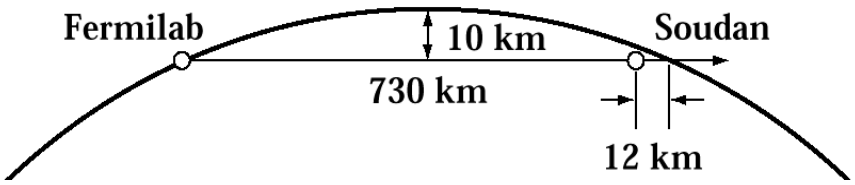
Shown below: Muon track direction.

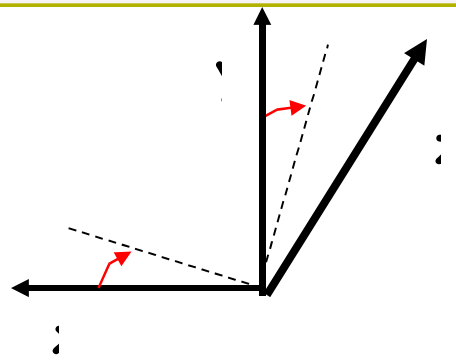
In good agreement with expectation.



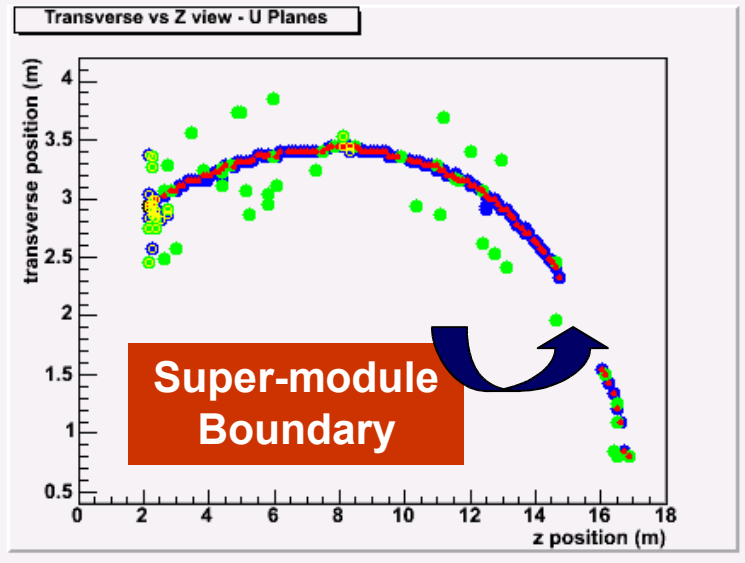
Preliminary

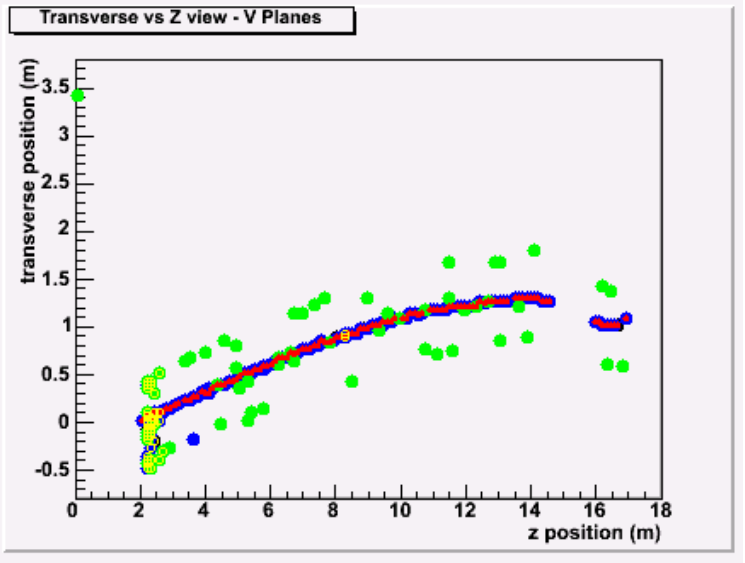






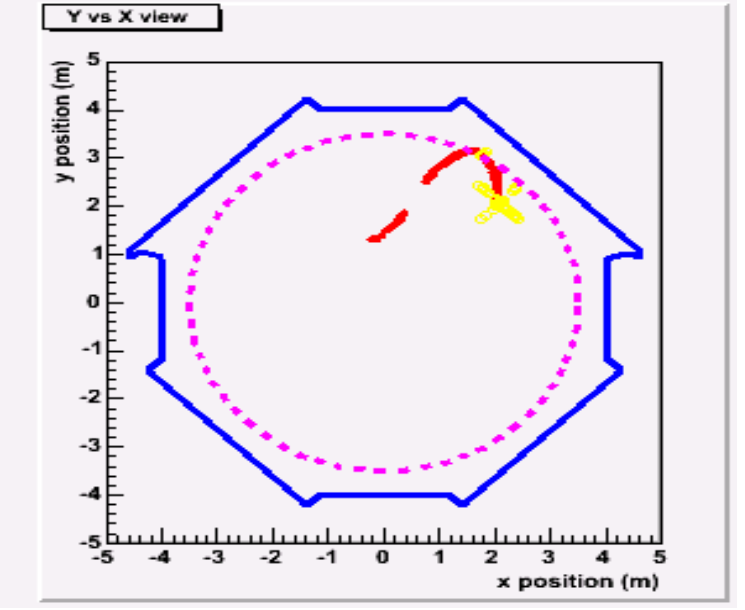
FAR DETECTOR - ν_μ CHARGED CURRENT EVENT





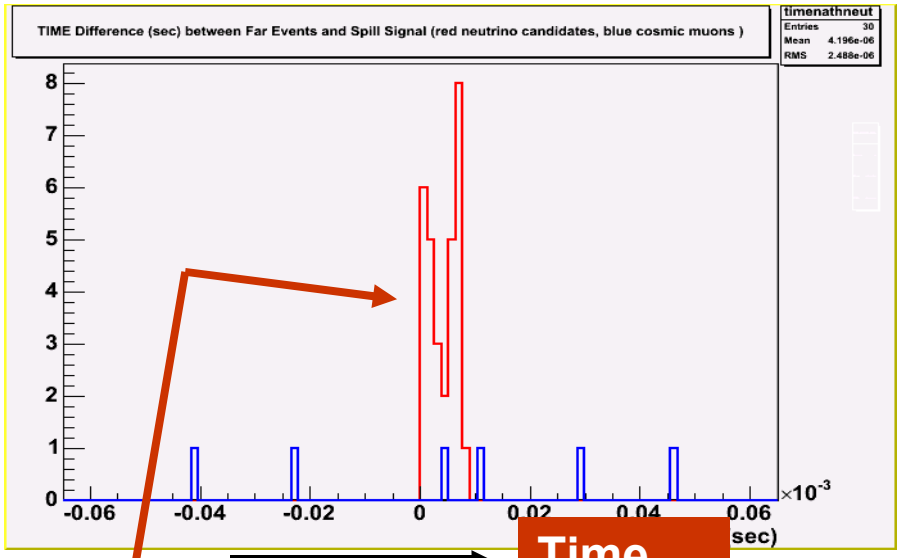
HE Beam Run

14.7 GeV Neutrino Interaction



Fiducial cut of 50cm along the edges – 74% Fiducial Area

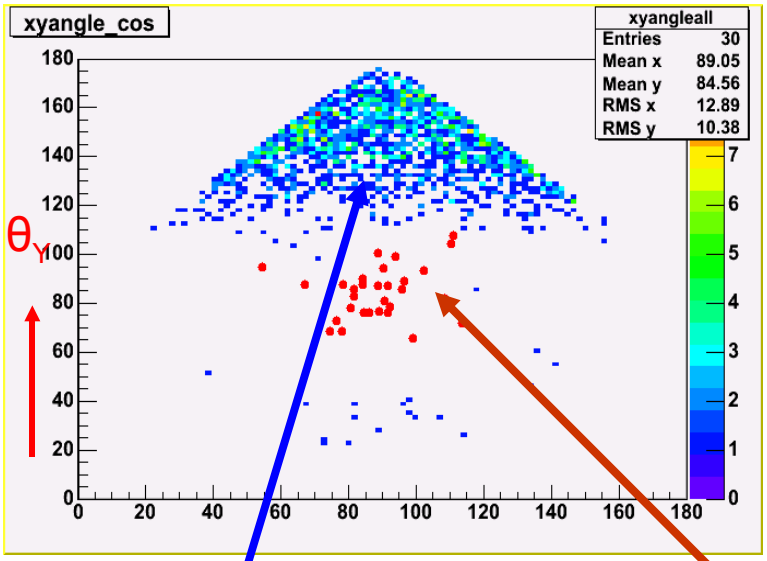
NEUTRINO EVENT SELECTION IN THE FAR DETECTOR



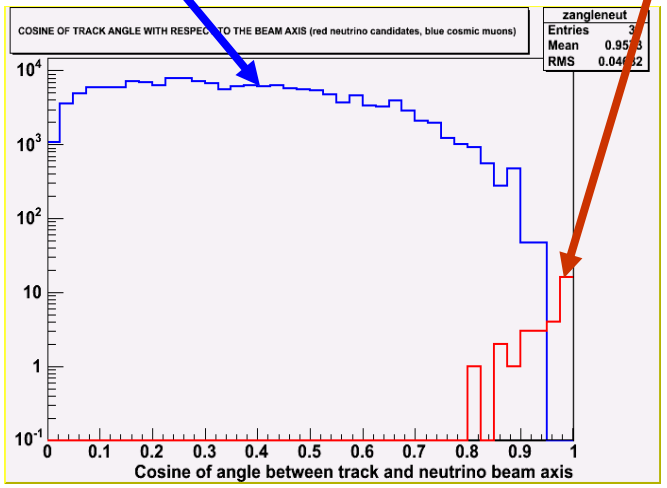
Time

Timing:

Beam events occur in a 10 μs interval

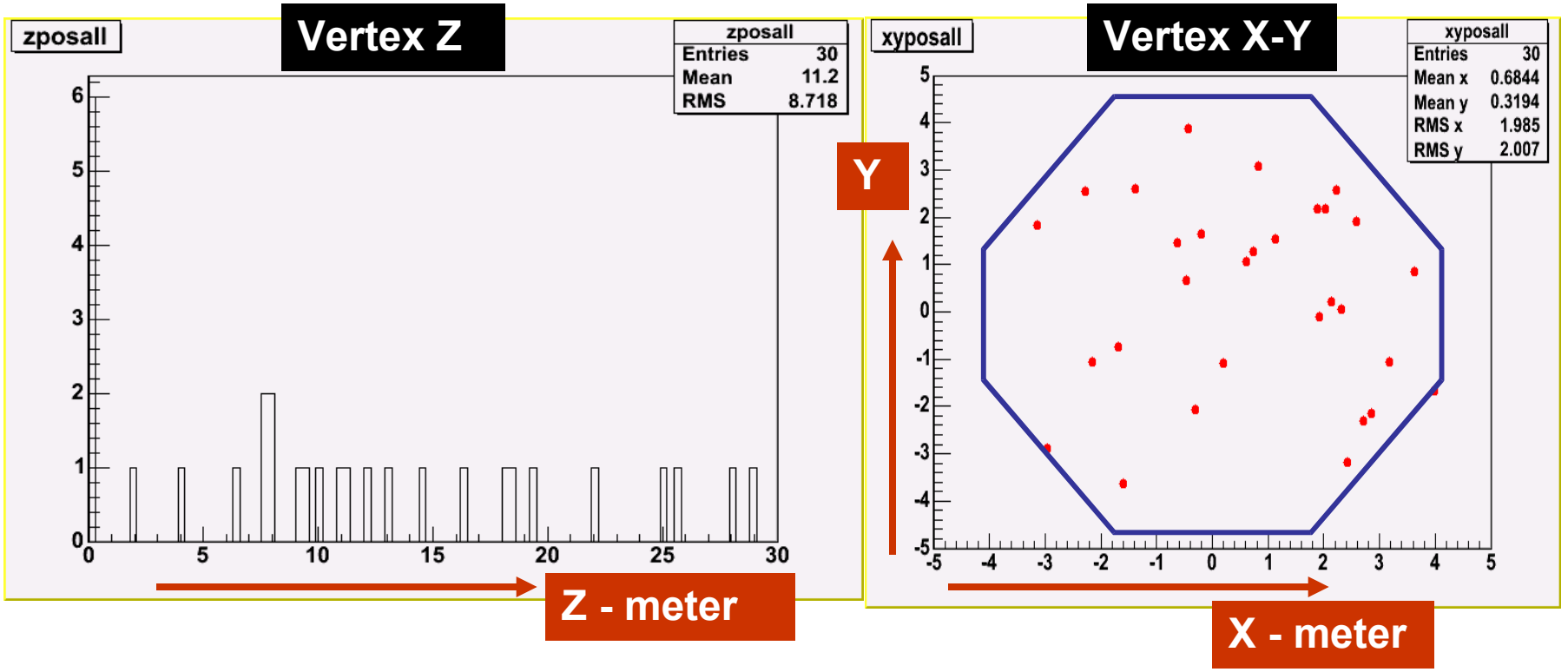


Cosmic Rays → θ_X → **ν Interactions**



Distinguish between Beam events and Cosmic Rays based on different directions as well as beam spill timing

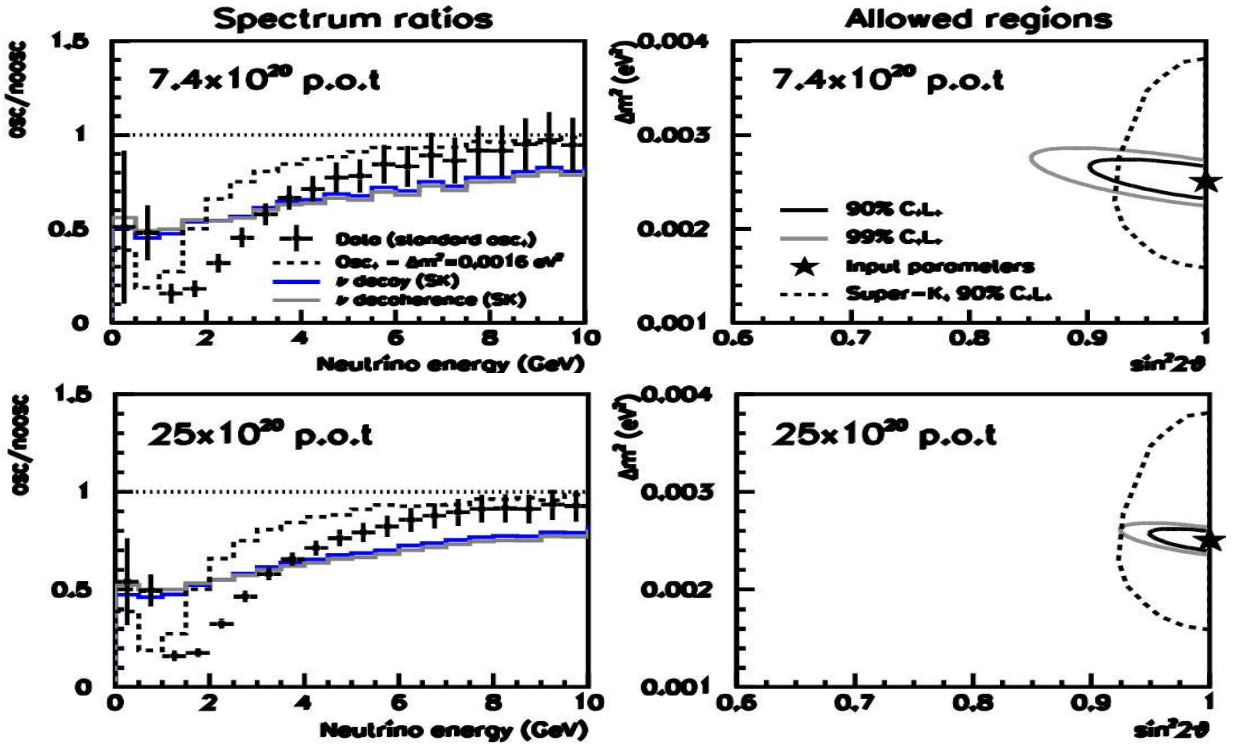
NEUTRINO EVENT SELECTION IN THE FAR DETECTOR



Event characteristics are in agreement with expectations

MINOS CC SENSITIVITY FOR Δm^2_{23} & $Sin^2 2\theta_{23}$

MC Prediction for Δm^2_{23} = 2.5X10^{-3} eV^2, $sin^2\ 2\theta_{23}$ = 1.0

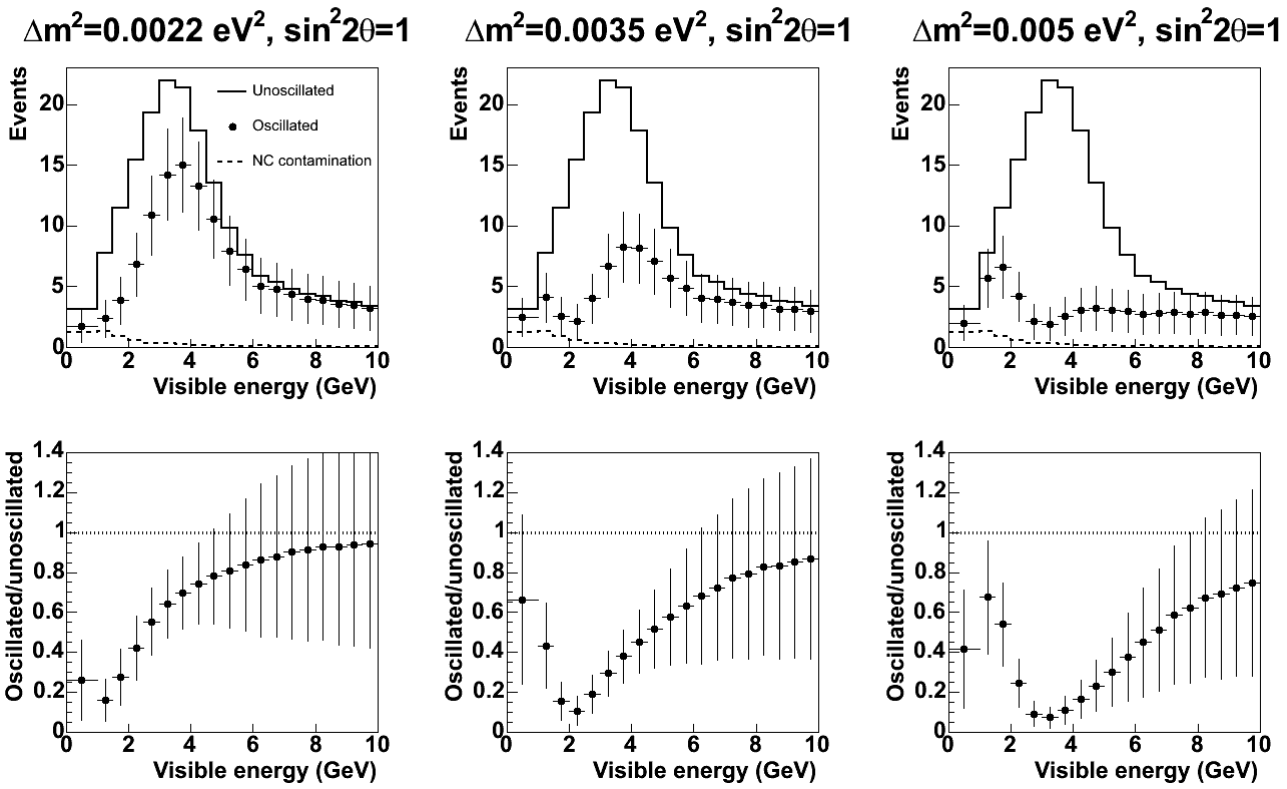


By mid 2008

By mid 2012 - Estimate

- ✓ Minos will improve existing measurements.
- ✓ Will discriminate against alternative hypothesis.
- ✓ With additional protons – continued improvement in Δm^2_{23} & $Sin^2 2\theta_{23}$.

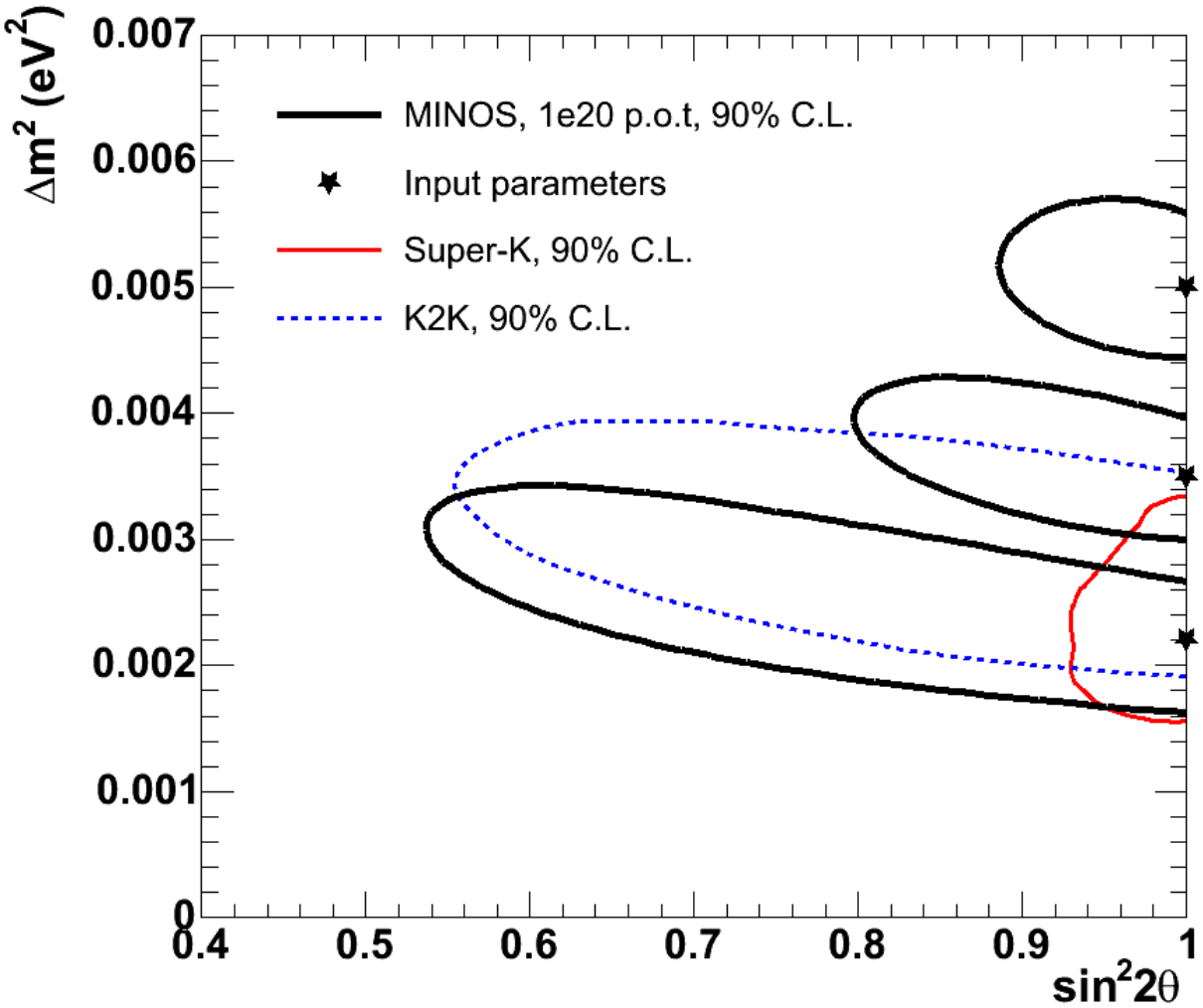
MINOS ν_μ CC SENSITIVITY FOR 1X10^{20} POT



- ✓ **Fully reconstructed events generated with GMINOS and NEUGEN ν generator.**
- ✓ **Events selected using a likelihood method based on reconstructed event qualities.**
- ✓ **Includes statistical and systematic error. Systematic error includes a 4% ν flux uncertainty, 2% energy scale uncertainty, & 10% uncertainty on NC background.**

MINOS ν_μ CC SENSITIVITY FOR 1X10^{20} POT

MINOS sensitivity, Δm^2=0.0022,0.0035,0.005 eV^2, sin$^2 2\theta$=1



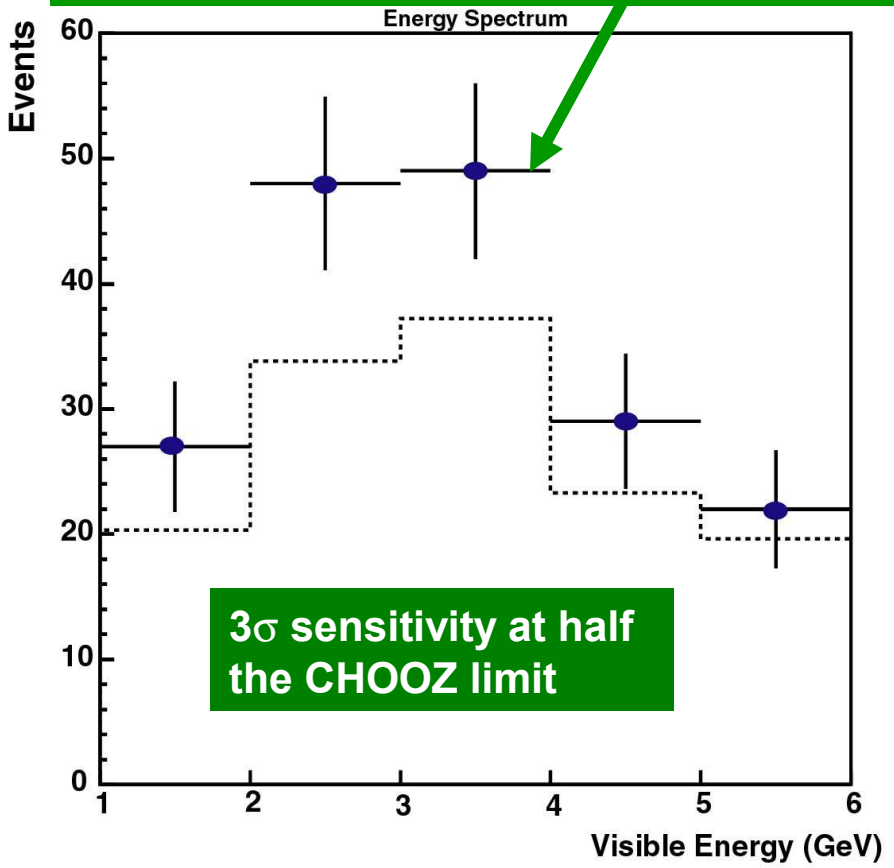
Super-K limit from hep-ex/0501064

K2K limit from T. Nakadaira's talk at La Thuile, 2005.

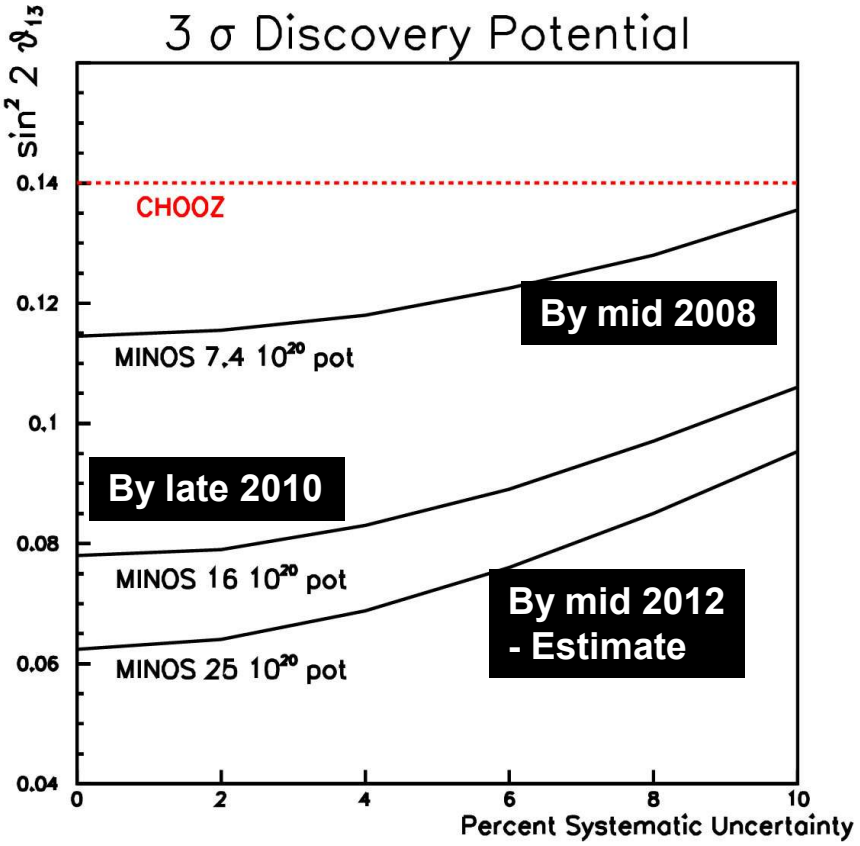
Even with 1X10^{20} POT MINOS will have a competitive or better limit on Δm^2_{23} compared to Super-K.

MINOS ν_e CC SENSITIVITY FOR 25X10^{20} POT

For Δm^2_{23} = 2.5X10^{-3} eV^2, Sin^2 2θ_{13}= 0.067



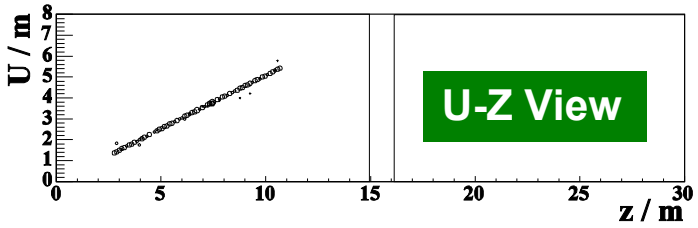
For Δm^2_{23} = 2.5X10^{-3} eV

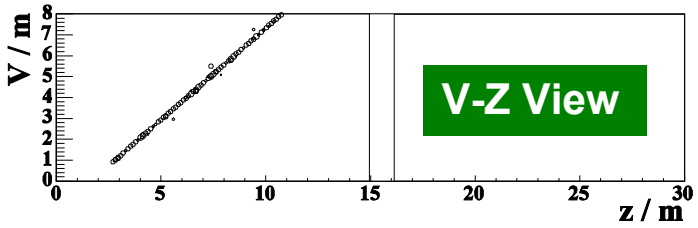


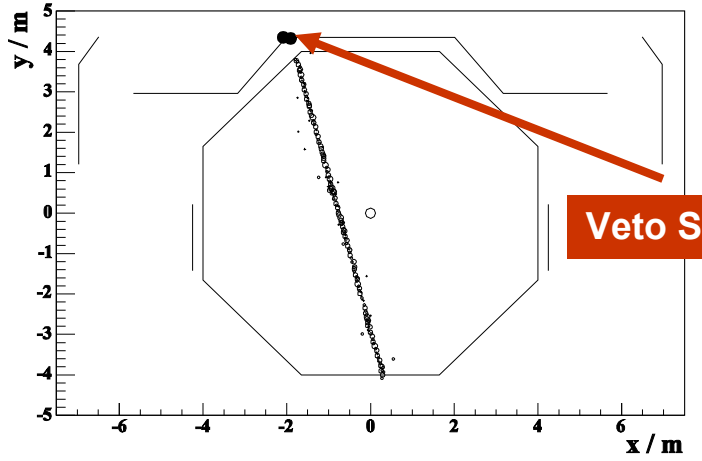
Observed number of events identified as coming from ν_e CC interactions with and without oscillations. Backgrounds dominated by NC interactions and some beam ν_e's.

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

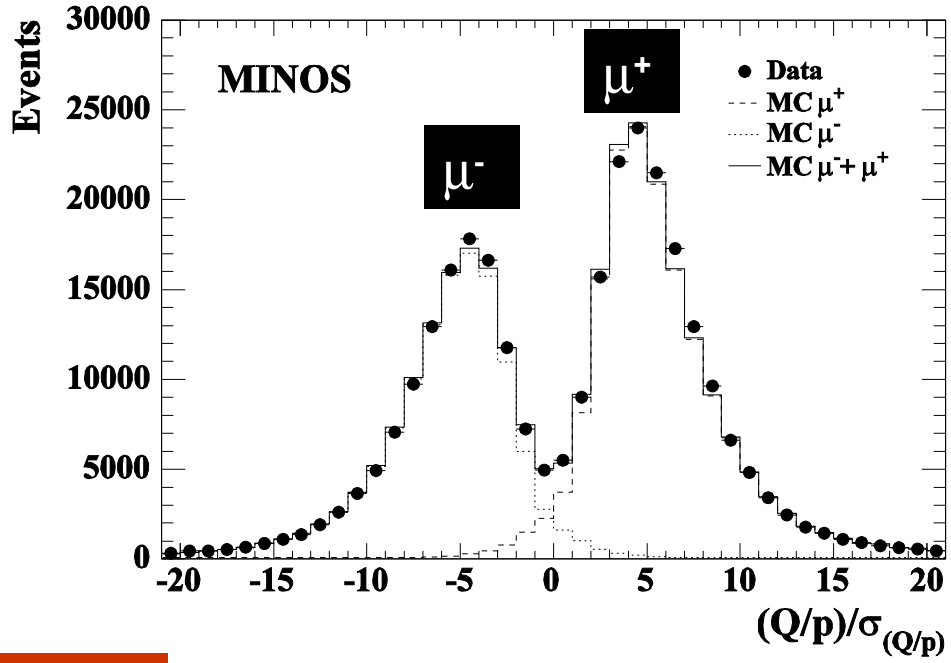
MUONS FROM SKY IN MINOS





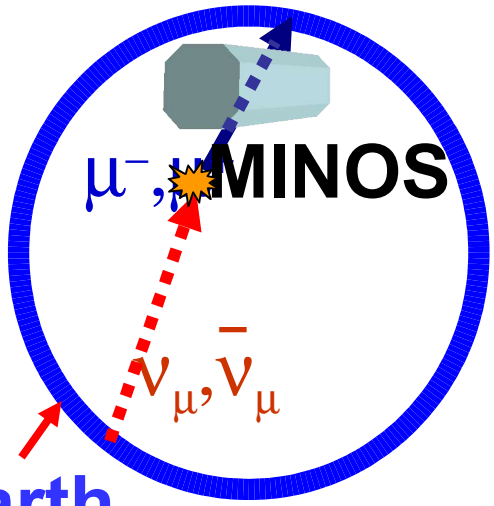


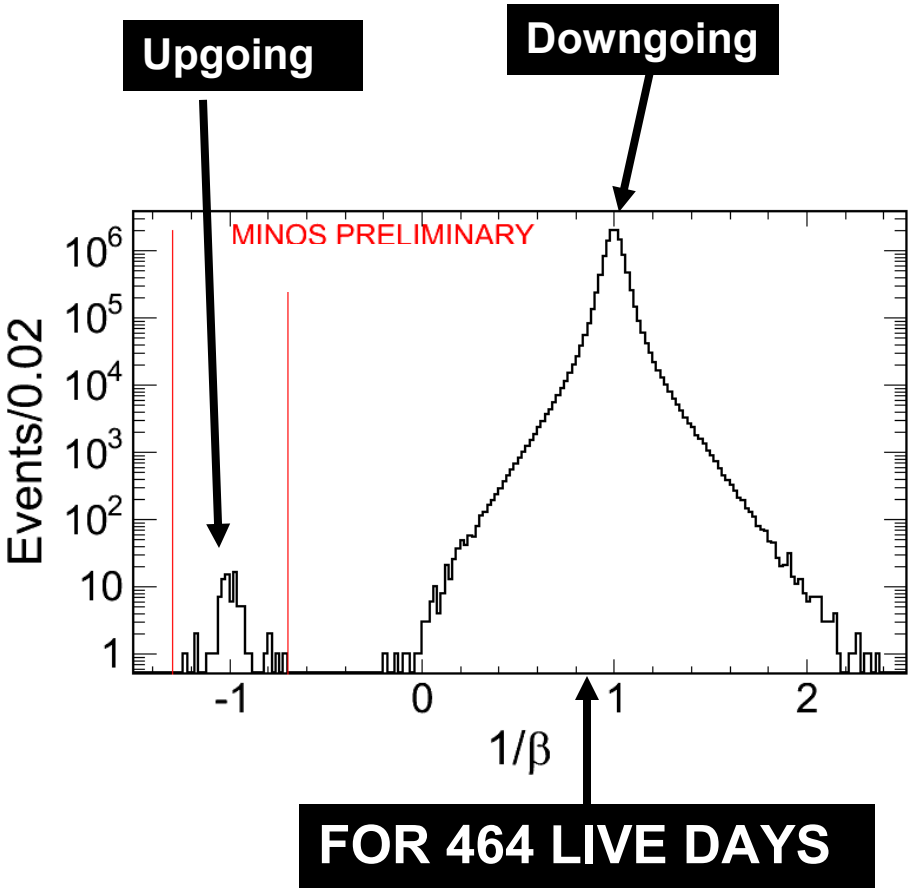
Through going Cosmic Ray Muon

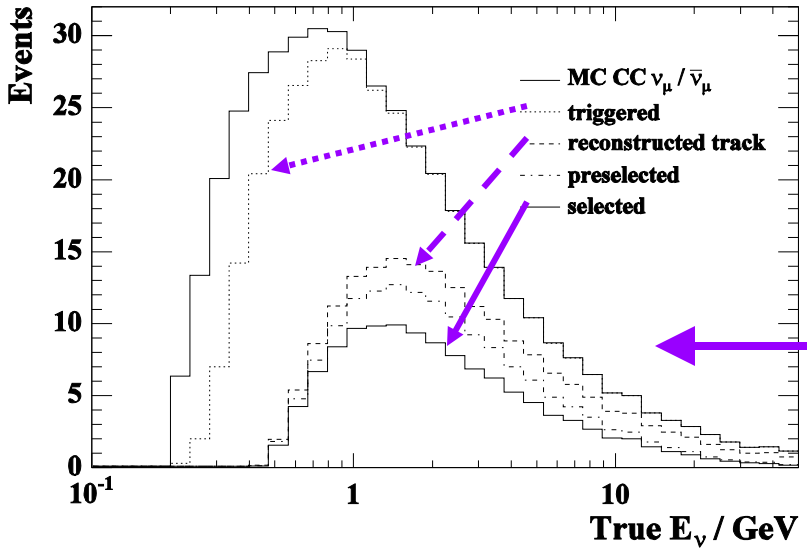


Charge Separation for Stopping Cosmic Muons in the MINOS Detector

NEUTRINO INDUCED UPGOING MUONS



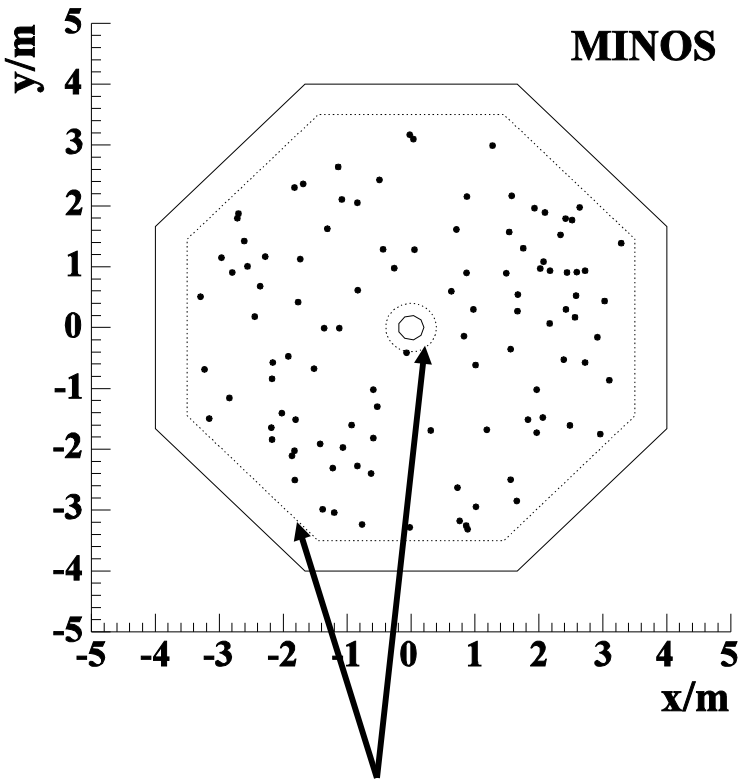




CC $\nu_\mu/\bar{\nu}_\mu$ events at different selection stages in MINOS FD detector for 418 days of exposure. Eν thres ~ 500 MeV

ATMOSPHERIC ν INDUCED FC+PC MUONS - RESULTS

Vertex X-Y Plot



Fiducial Cuts

Selection	Data	Expected with No Oscillation	Expected Δm^2_{23}=0.0024 eV² & $Sin^2 2\theta_{23}$ =1.0
Good timing	77	90 ± 9	68 ± 7
Low Resolution (Dir. Uncertain)	30	37 ± 4	28 ± 3
All Events	107	127 ± 13	96 ± 10

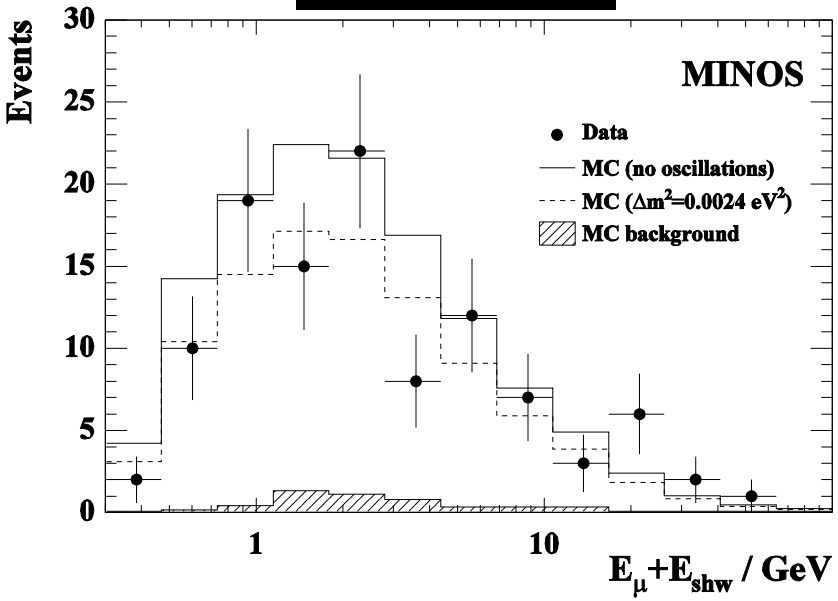
FC	69
PC Down	25
PC up	13
Total	107

Backgrounds

CR Muons (from data)	4.4±0.5
NC + ν_e/ $\bar{\nu}_e$ CC (Estimated)	4.5±0.5

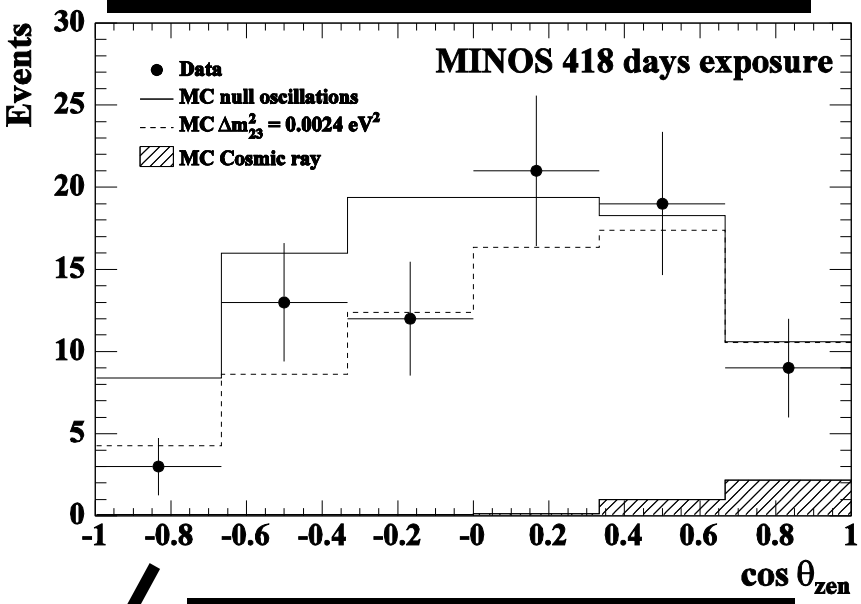
ATMOSPHERIC FC +PC EVENTS – ENERGY & ANGLE

ALL EVENTS



Reconstructed Neutrino Energy – 107 Events

EVENTS W/GOOD TIMING ONLY



Zenith Angle – 77 Events

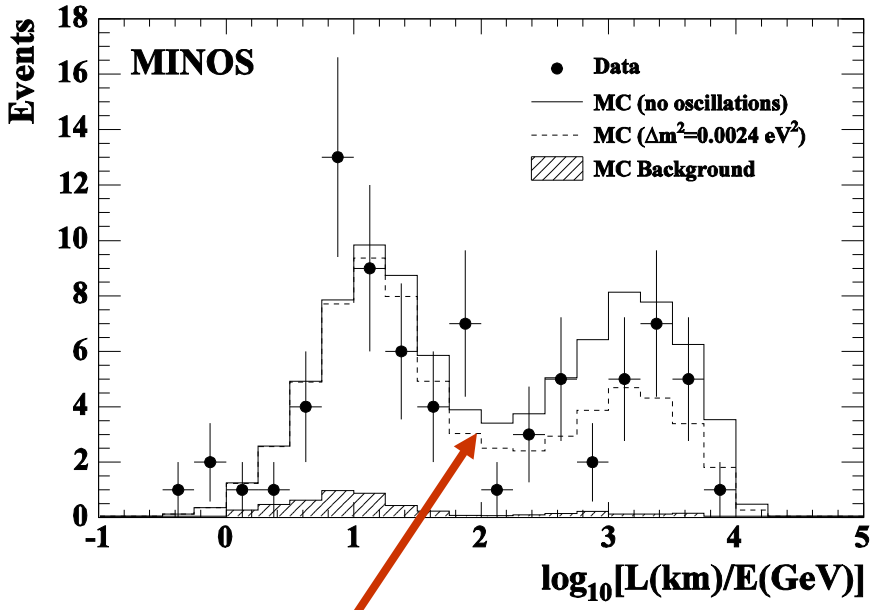
Upward-going/Downward-going Double Ratio

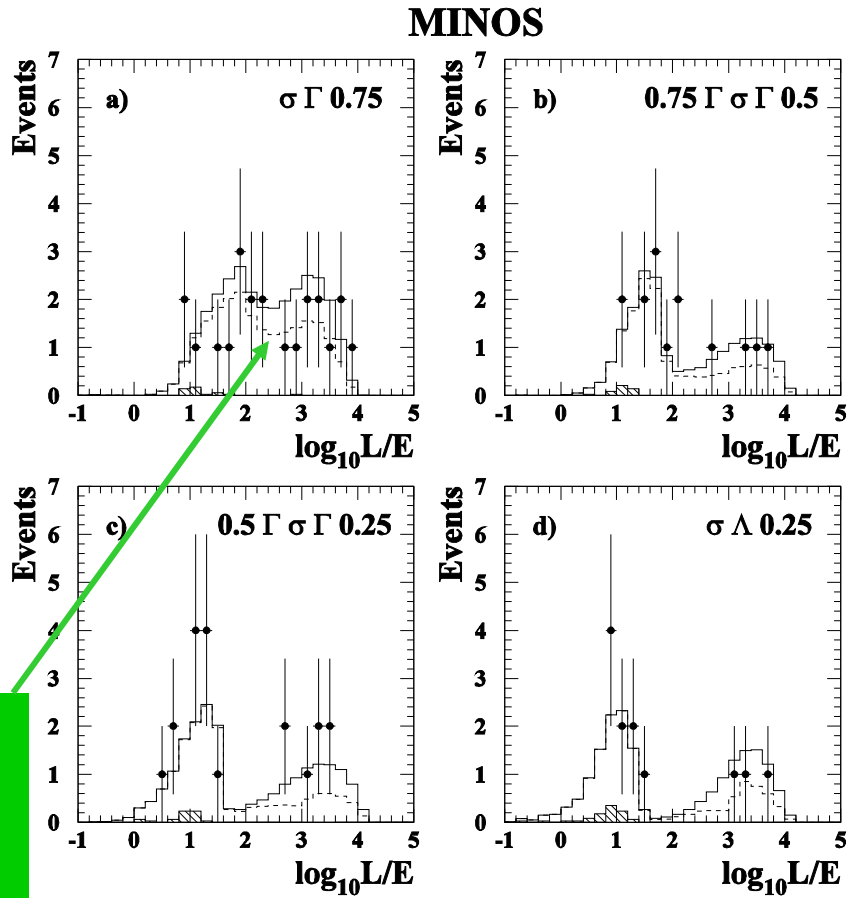
$$R^{\text{Data}}_{\text{Up/down}} / R^{\text{MC}}_{\text{Up/down}} = 0.62^{+0.19}_{-0.14}\ (stat) \pm 0.02 (sys.)$$

ATMOSPHERIC L/E ANALYSIS & LIMITS

Oscillation Probability: $P(\nu_\mu \rightarrow \nu_\mu) = 1.0 - \sin^2 2\theta_{23} \sin^2\left(1.27\Delta m^2_{23}\frac{L}{E}\right)$,

$where: \Delta m^2_{23}[eV^2],\ L[km],\ E[GeV]$

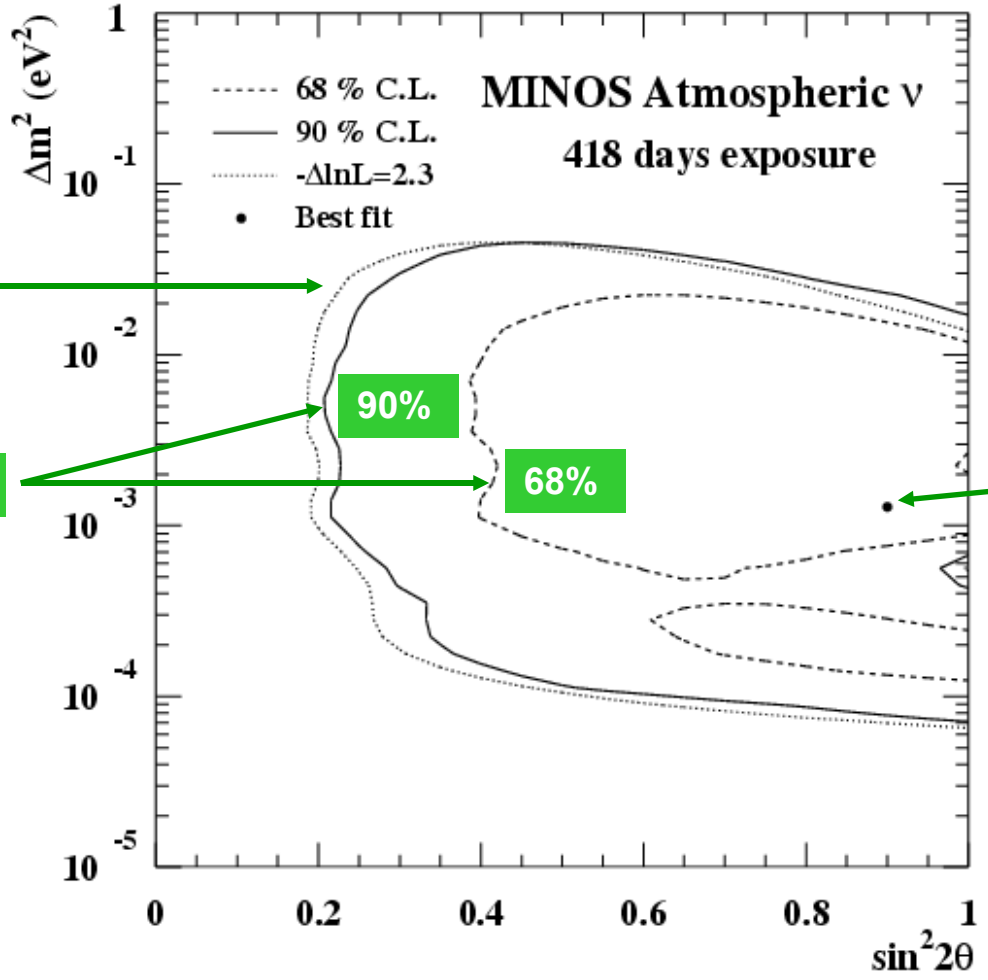




MC Oscil: $\nu_\mu \leftrightarrow \nu_\tau$
$\sin^2 2\theta_{23} = 1.0$
$\Delta m^2_{23} = 2.4 \times 10^{-3}\ eV^2$

Maximum Likelihood Fit:
$\nu_\mu \leftrightarrow \nu_\tau$ **(Best Fit Values)**
$\sin^2 2\theta_{23} = 0.90$
$\Delta m^2_{23} = 1.3 \times 10^{-3}\ eV^2$

MINOS ATMOSPHERIC – OSCILLATION LIMITS



−ΔlnL = 2.3

90%

Feldman - Cousins

68%

Best Fit

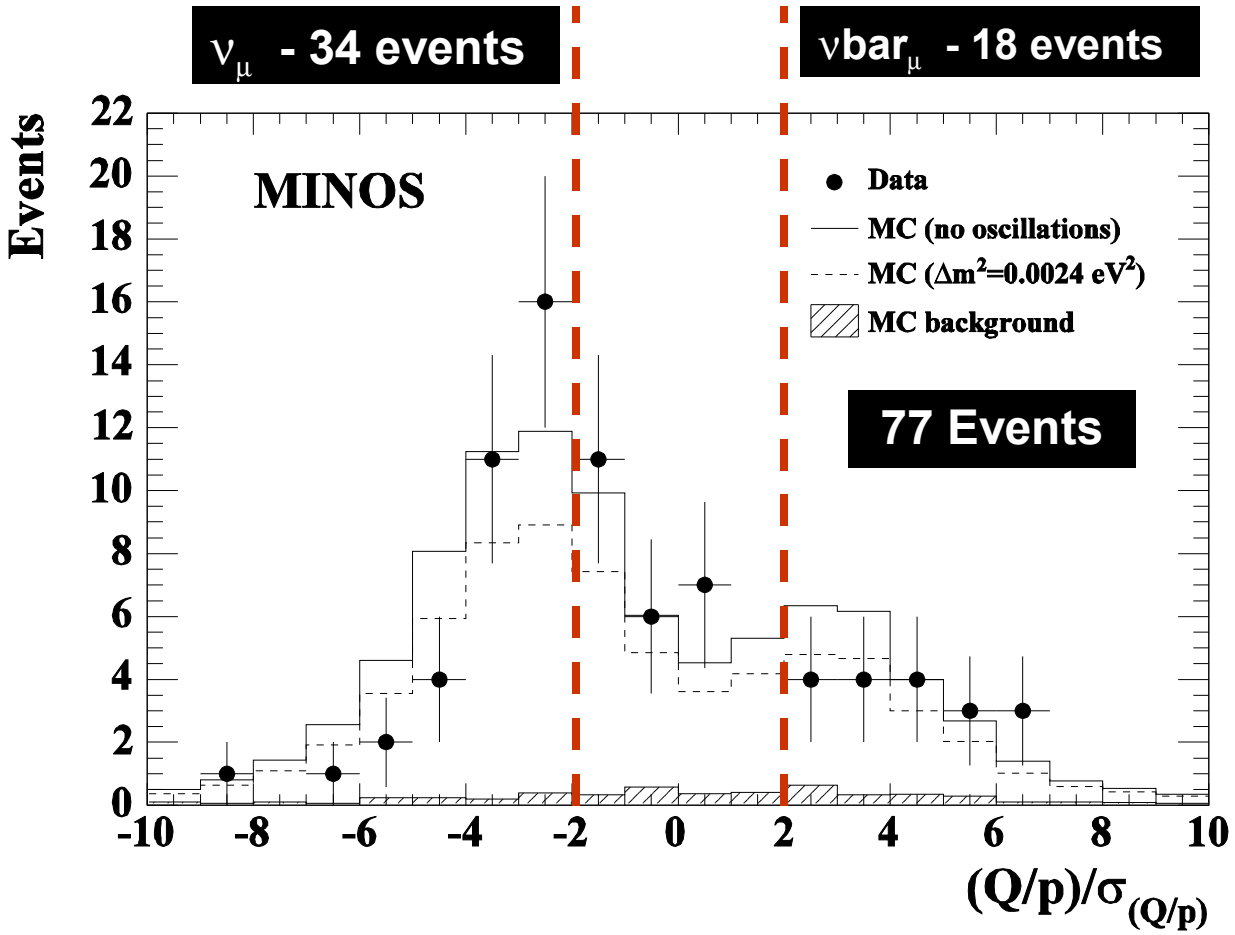
$\nu_\mu \leftrightarrow \nu_\tau$

$\sin^2 2\theta_{23} = 0.90$

$\Delta m^2_{23} = 1.3 \times 10^{-3}$ eV^2

MINOS ATMOSPHERIC – CHARGE RATIO

ν_μ versus $\bar{\nu}_\mu$

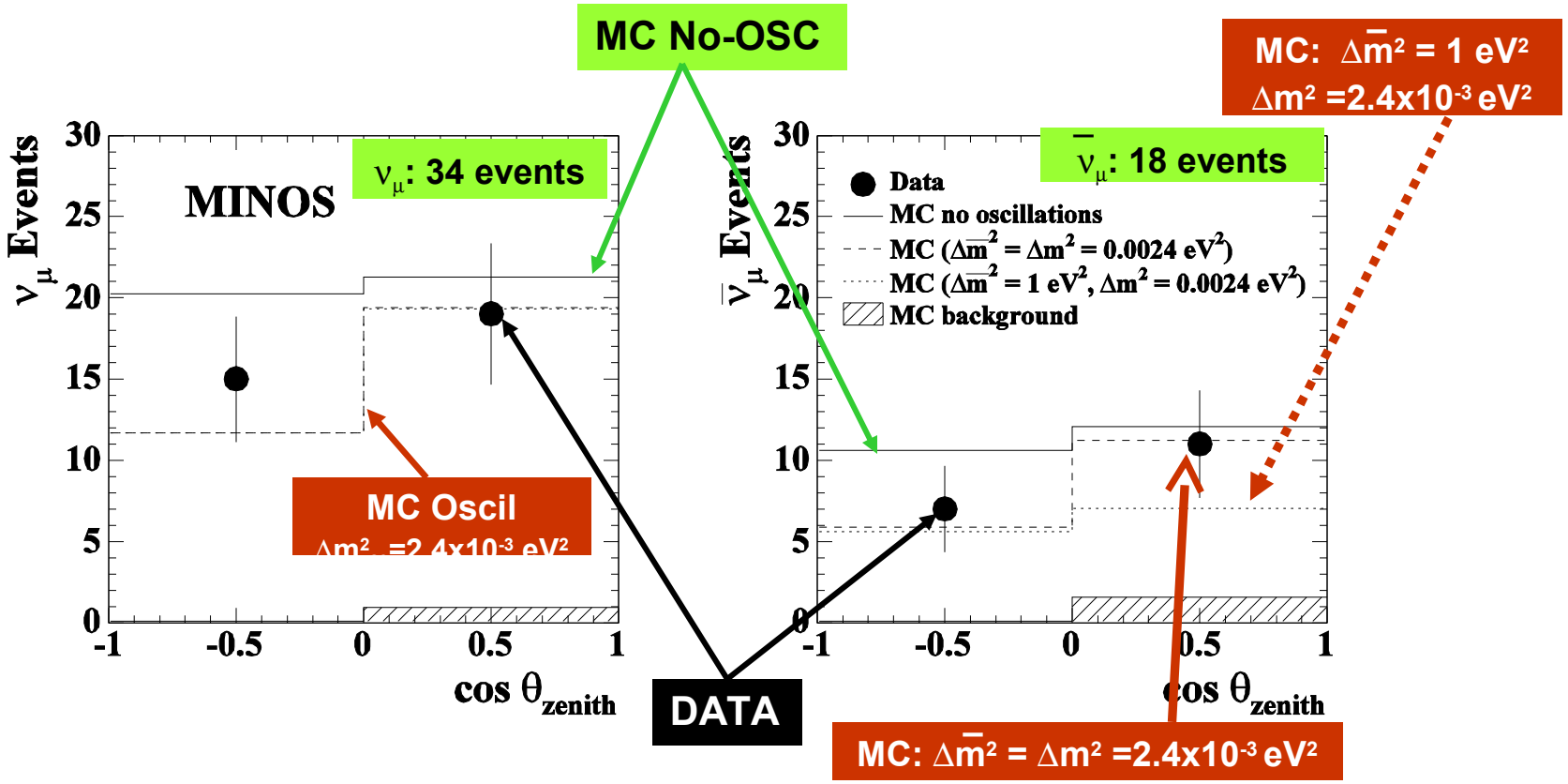


MC $\nu_\mu \leftrightarrow \nu_\tau$ $\sin^2 2\theta_{23} = 1.0$ $\Delta m^2_{23} = 2.4 \times 10^{-3}$ eV^2

$$R^{Data}_{\bar{\nu}_\mu/\nu_\mu} / R^{MC}_{\bar{\nu}_\mu/\nu_\mu} =$$

$$0.96^{+0.38}_{-0.27}\ (stat.) \pm 0.15 (sys.)$$

ATMOSPHERIC CHARGE SEPARATED UP/DOWN DISTRIBUTIONS



- Data consistent with ν_μ and $\bar{\nu}_\mu$ oscillating with same parameters.
- CPT violating scenarios with large Δm^2_{23} not excluded with current data.

CONCLUSIONS FOR MINOS SECTION

1. MINOS Far Detector commissioned in July 2003, Near Detector in December 2004 & NuMI beam in January 2005.
2. Atmospheric Neutrino Results with 4.54 KTon-yrs submitted to PRD. Results consistent with standard atmospheric oscillation.
3. Fermilab Main Injector consistently provides between $2.3X10^{13}$ to $3.0X10^{13}$ protons every 2s~3s for neutrino beam.
4. MINOS has already collected $1X10^{20}$ Protons On Target.
5. MINOS Near Detector is accumulating high statistics.
6. Blind analysis is in progress for Far Detector data.
7. First Beam results expected soon.
8. Very soon MINOS will provide the most precise measurement of $\Delta m^2 2\theta_{23}$.

NuMI OFF-AXIS υ_e APPEARANCE EXPERIMENT

MINOS NUMI

Proposal to Build a 30 Kiloton Off-Axis Detector to Study $\nu_\mu \rightarrow \nu_e$ Oscillations in the NuMI Beamline

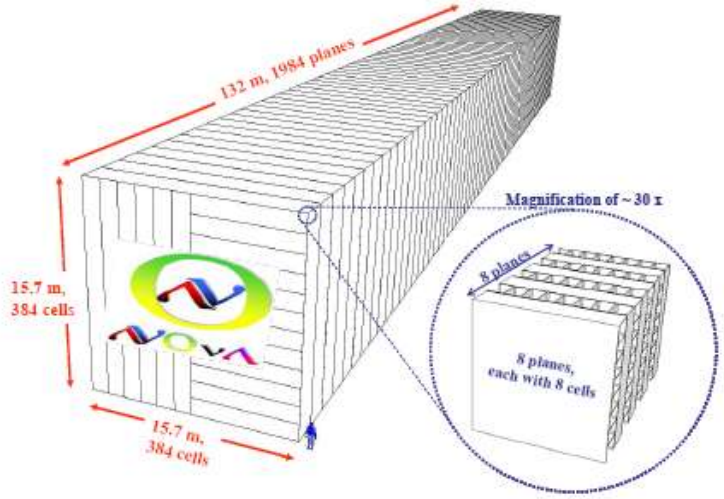
NOνA

NuMI Off-Axis ν_e Appearance Experiment

March 21, 2005

The NOνA Collaboration

Argonne, Athens, Caltech, UCLA, Fermilab, College de France, Harvard, Indiana, ITEP, Lebedev, Michigan State, Minnesota/Duluth, Minnesota/Minneapolis, Munich, Stony Brook, Northern Illinois, Ohio, Ohio State, Oxford, Rio de Janeiro, Rutherford, South Carolina, Stanford, Texas A&M, Texas/Austin, Tufts, Virginia, Washington, William & Mary



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NOυA is a major Fermilab and USA DOE effort in HEP.

It is an open collaboration.

Fermilab is interested in further International Participation.

YOU ARE MOST WELCOME TO JOIN.

~ 25 Institutions

~ 140 Collaborators

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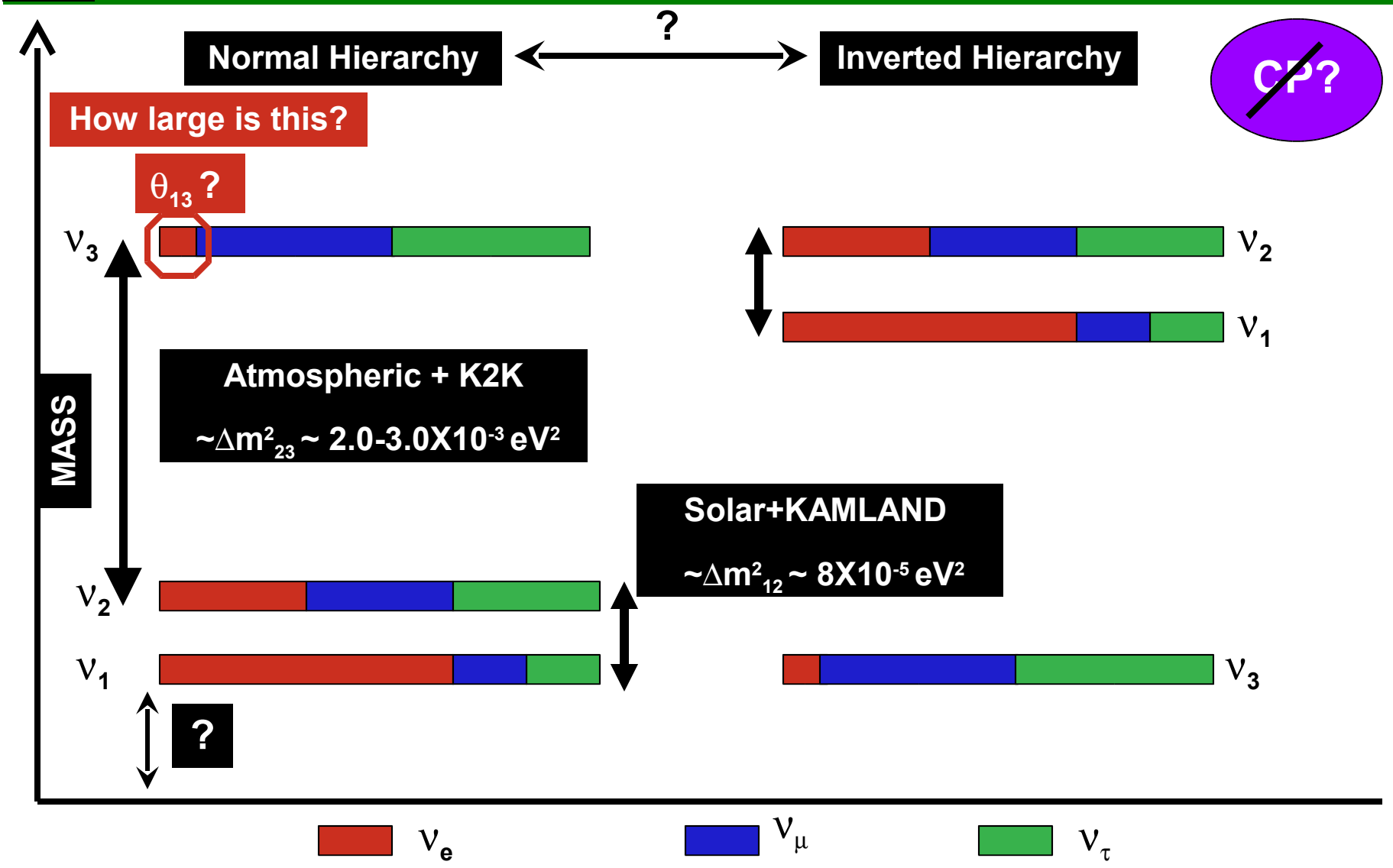

Normal Hierarchy
?
Inverted Hierarchy
CP?
How large is this?
θ_{13} ?
ν_3
ν_2
ν_1
MASS
Atmospheric + K2K
$\sim\Delta m^2_{23} \sim 2.0\text{-}3.0 \times 10^{-3}\ eV^2$
Solar+KAMLAND
$\sim\Delta m^2_{12} \sim 8 \times 10^{-5}\ eV^2$
ν_2
ν_1
ν_3
?
ν_e
ν_μ
ν_τ

$P(\nu_\mu \rightarrow \nu_e)$ IN VACUUM

- $P(\nu_\mu \rightarrow \nu_e) = P_1 + P_2 + P_3 + P_4$
  - $P_1 = \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2(1.27\ \Delta m^2_{23}\ L/E)$ "Atmospheric"
  - $P_2 = \pm J \sin(\delta) \sin(1.27\ \Delta m^2_{23}\ L/E)$ } Atmospheric - Solar Interference
  - $P_3 = J \cos(\delta) \cos(1.27 \Delta m^2_{23}\ L/E)$
  - $P_4 = \cos^2(\theta_{23}) \sin^2(2\theta_{12}) \sin^2(1.27\ \Delta m^2_{12}\ L/E)$ "Solar"

where

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

$\sin(1.27\ \Delta m^2_{23}\ L/E) \sin(1.27\ \Delta m^2_{12}\ L/E)$

+ for νbar and – for ν

HIERARCHY THROUGH $P(\nu_\mu \rightarrow \nu_e)$ IN MATTER

In addition P is also sensitive to the type of hierarchy.

Why?

In LBL experiment the neutrino beam traverses through the Earth and the electron neutrinos goes through forward coherent scattering through the charged current interactions in the matter. The modifies the mixing angle and enhances (suppresses) the probability of conversion for ν (νbar) for normal hierarchy and vive-versa for inverted hierarchy.

In a 3-ν mixing case for the LBL experiment the probability P gets modified. For a 2 GeV neutrino of energy, matter effect gives

About $\pm$30% effect for NuMI

About $\pm$11% effect for T2K.

By measuring $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$, we are sensitive to θ_{13}, δ, and the type of hierarchy (or sign of Δm^2_{23}).

NOνA MOTIVATION

- **Main Motivation:**
  - ✓ Sensitivity to $Sin^2 2\theta_{13}$ up to ~ 0.01
  - ✓ Resolve mass hierarchy via "Matter Effect"
    - Either by neutrino and anti-neutrino running
    - Or with another experiment
    - Or with a Second Detector
    - Or all of them
  - ✓ Begin to study/measure CP violation in the Neutrino Sector

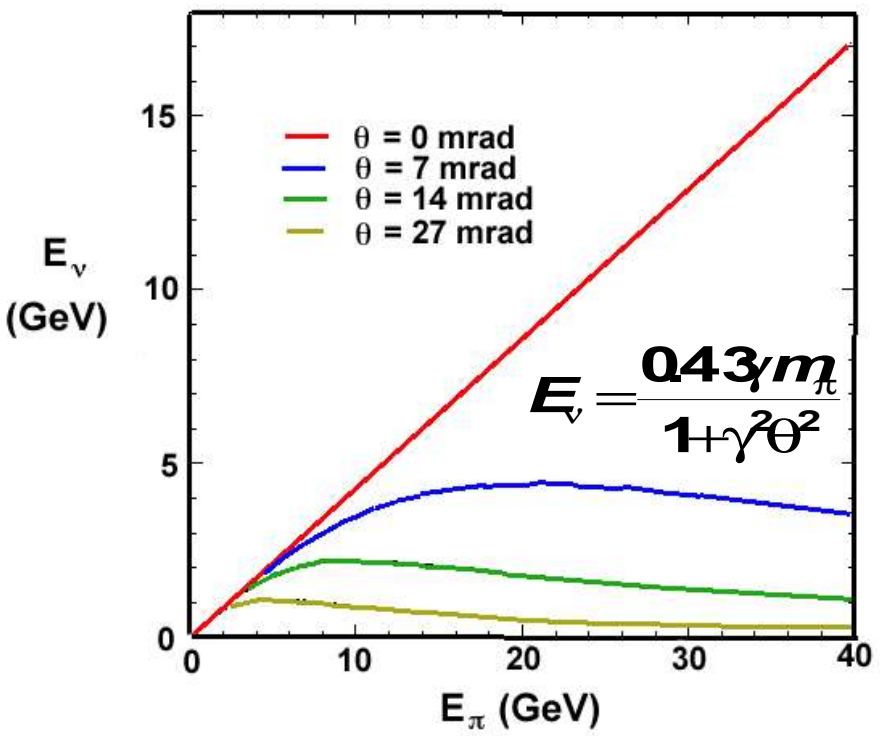
L = 810 Km MATTERS

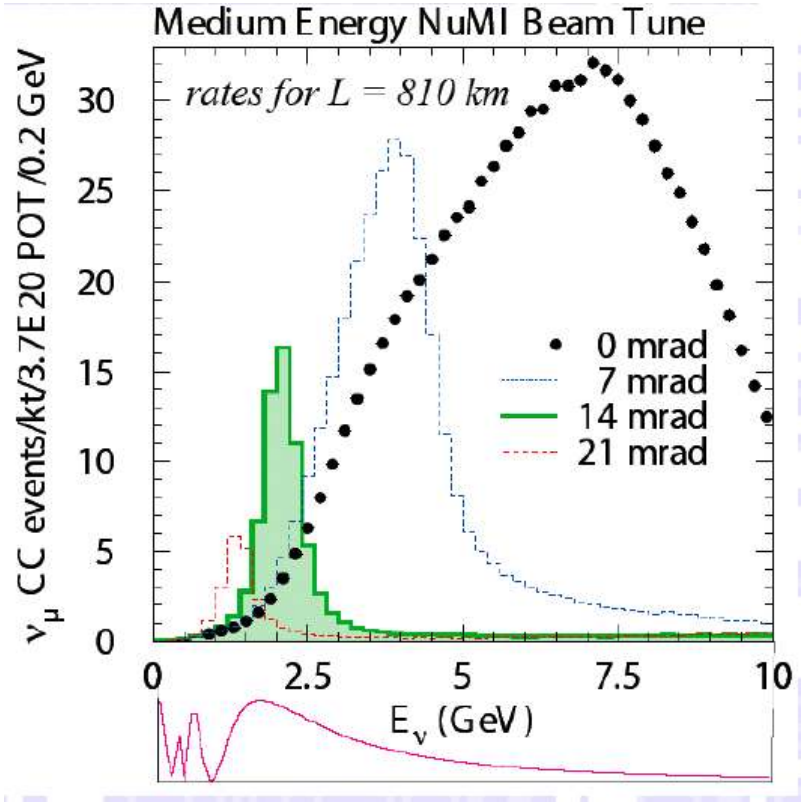
- **Other Measurements:**
  - ✓ Δm^2_{23} ~ 10^{-4} eV^2
  - ✓ $Sin^2 2\theta_{23}$ ~ 1 to 2%.
  - ✓ Check maximality of θ_{23} (Is $\theta_{23} = 45^0$?)
  - ✓ $\nu_\mu \rightarrow \nu_\mu$ vs. $\nu_\mu \rightarrow \nu_\mu$ gives a measurement of CPT
- **Study MiniBooNE Signal**
- **Study Galactic Super-NOνA**

HOW NOνA WILL DO IT ?

- Off-Axis neutrino beam is by default a narrow band beam
  - ✓ Main ν peak comes almost from π decays
  - ✓ Spectrum largely insensitive to K/π production ratio
- Move to ~12-14 Km (~14-17 mrad) off-axis of the NuMI beam at a distance of about ~810Km from Fermilab
  - ✓ Have a narrow band beam with E_ν (peak) ~ 2.0 GeV
  - ✓ Maximize neutrino events in the energy range of oscillation
  - ✓ Minimize/Reduce NC background
- 30KTon Mass Detector (~5.5 times more massive than MINOS) – **Mass can be further increased (beyond 30KTon) (a possibility)**
  - 80% of NOνA detector mass is active
  - Longitudinal sampling every 0.15 X_0
- With neutrinos measure $\nu_\mu \rightarrow \nu_e$ (or θ_{13})
- With neutrino & anti-neutrino, or neutrino, anti-neutrino and a 2nd detector or their combination measure hierarchy and CP violation.

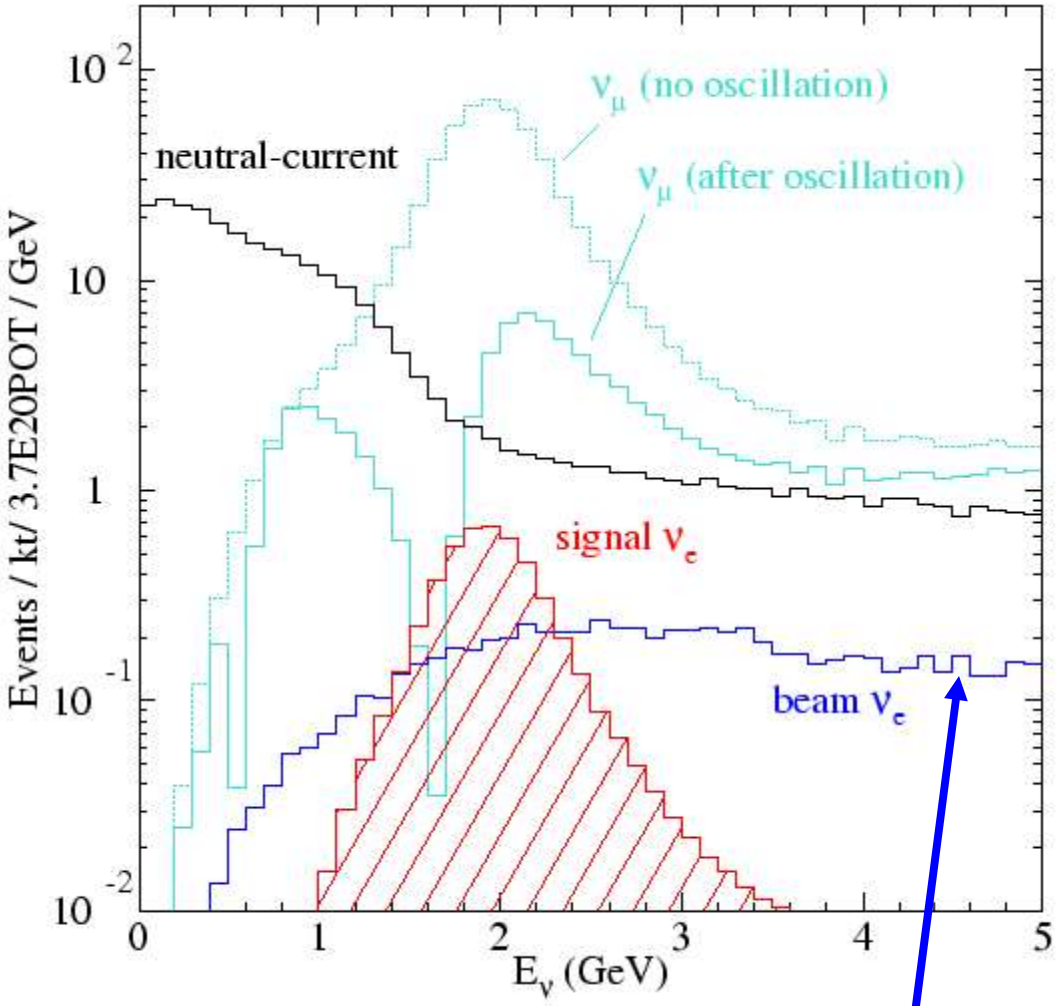
NuMI OFF-AXIS BEAM & NEUTRINO SPECTRA





- ✓NuMI ME beam tune at 14mrad - Peaks at ~2GeV and has ~20% width
- ✓High energy tail is suppressed – reducing the NC backgrounds
- ✓Sits just above the oscillation maximum (ex. shown Δm^2_{23}=2.5X10^{-3} eV^2)

EVENT RATES OFF NuMI BEAM AXIS



Mostly from μ and K_{e3} decays

L = 810 Km

Off-Axis Distance = 12 Km

$\Delta m^2 2\theta_{23} = 2.5X10^{-3}$ eV^2

$Sin^2 2\theta_{23} = 1.0$

$Sin^2 2\theta_{23} = 0.01$

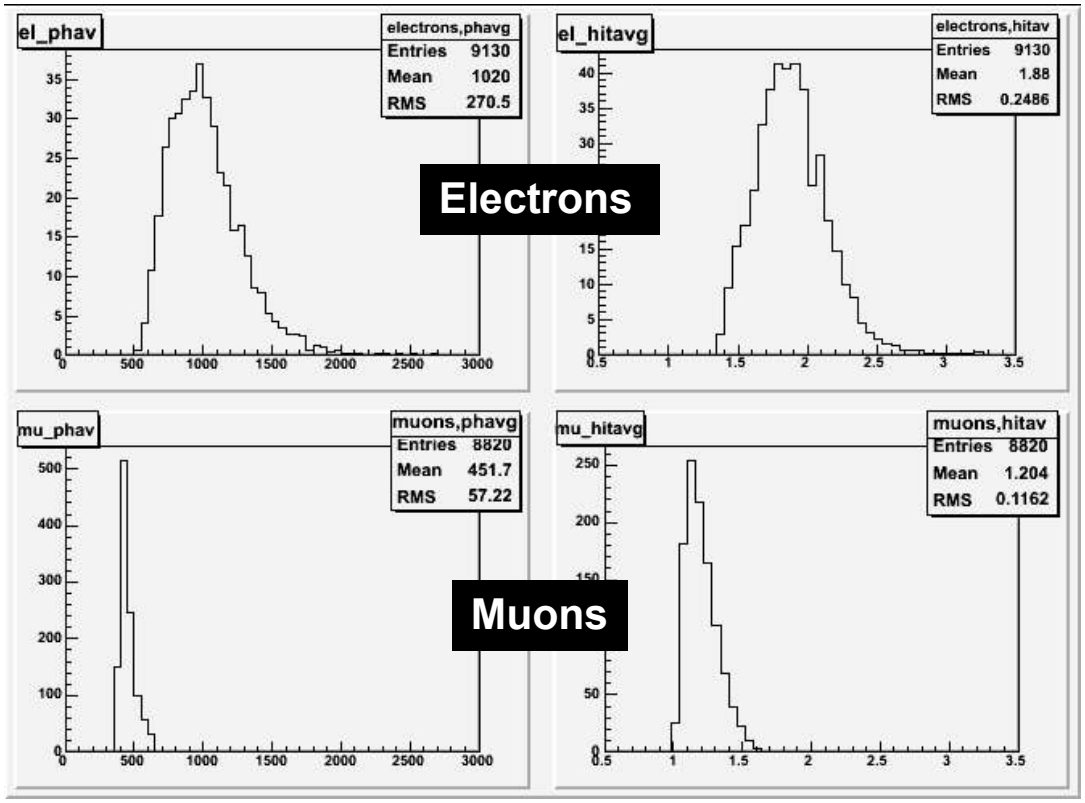
GOALS FOR THE DETECTOR

Most ν_μ oscillate away - Need only 50:1 ν_μ CC rejection

For NC background
- Need 100:1 rejection
-Fine grained low density detector does the job

To reject beam ν_e – Good detector energy resolution

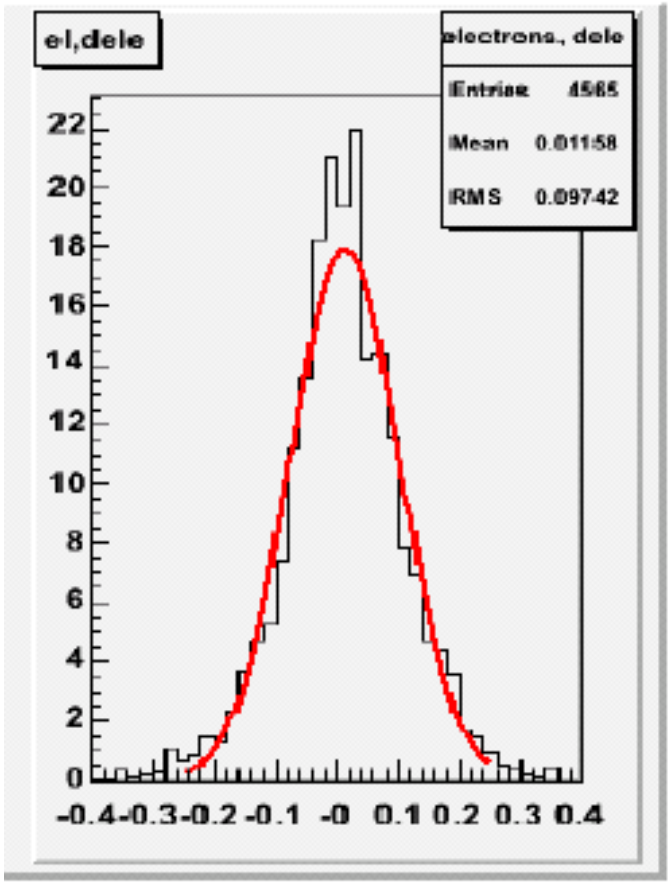
ELECTRON IDENTIFICATION & ENERGY RESOLUTION



Average Pulse Height/Plane

Average # of Hits/Plane

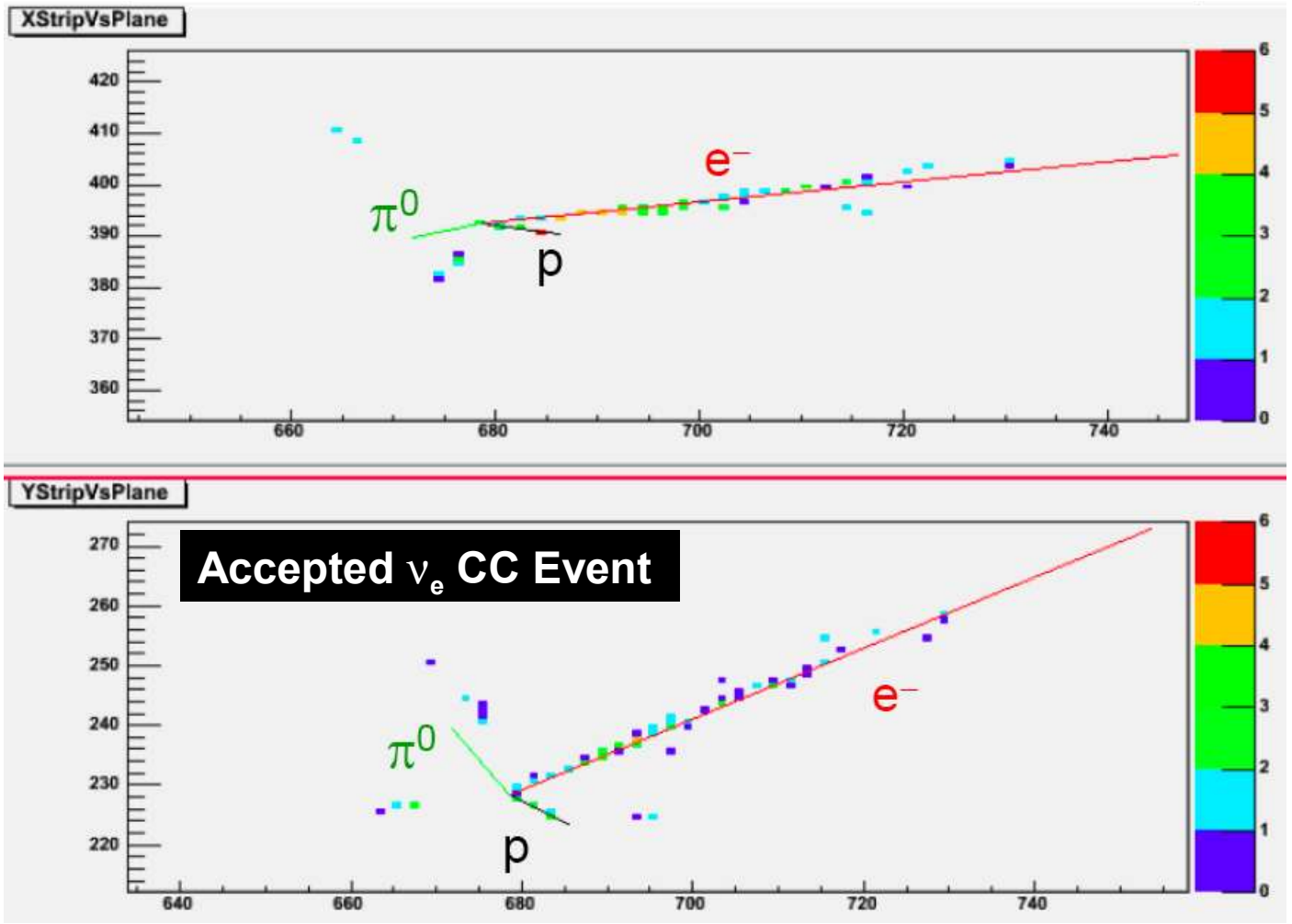
One can also use average pulse height/plane, ave. # of hits/plane, RMS of pulse height/plane, gaps, and energy cuts to distinguish between muons & electrons.



$\Delta E/E(\sigma) \sim 10\%/E^{1/2}$

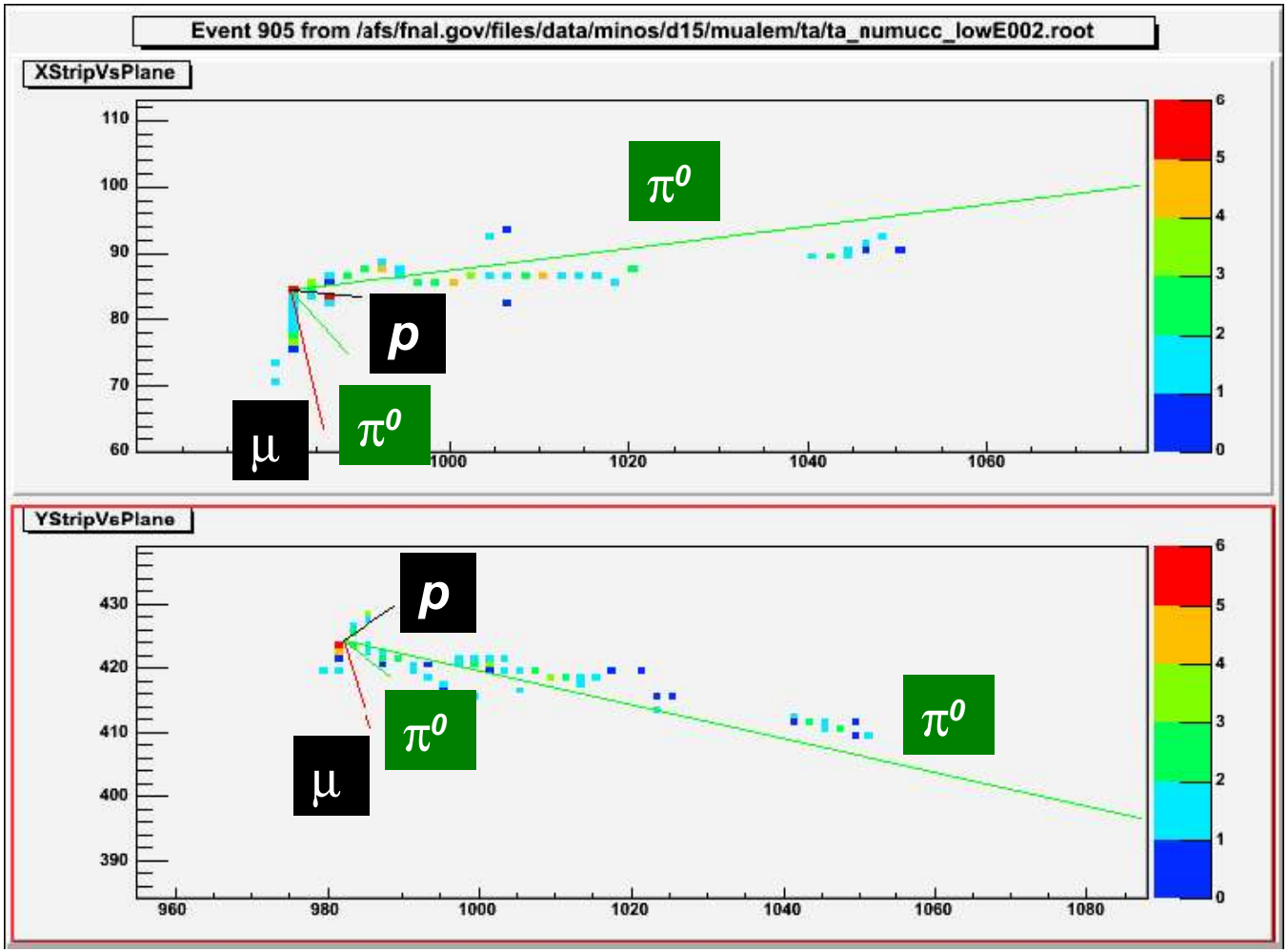
For a 2 GeV ν_e event energy measured to ~7%.

1.65 GeV $\nu_e N \rightarrow e p \pi^0$



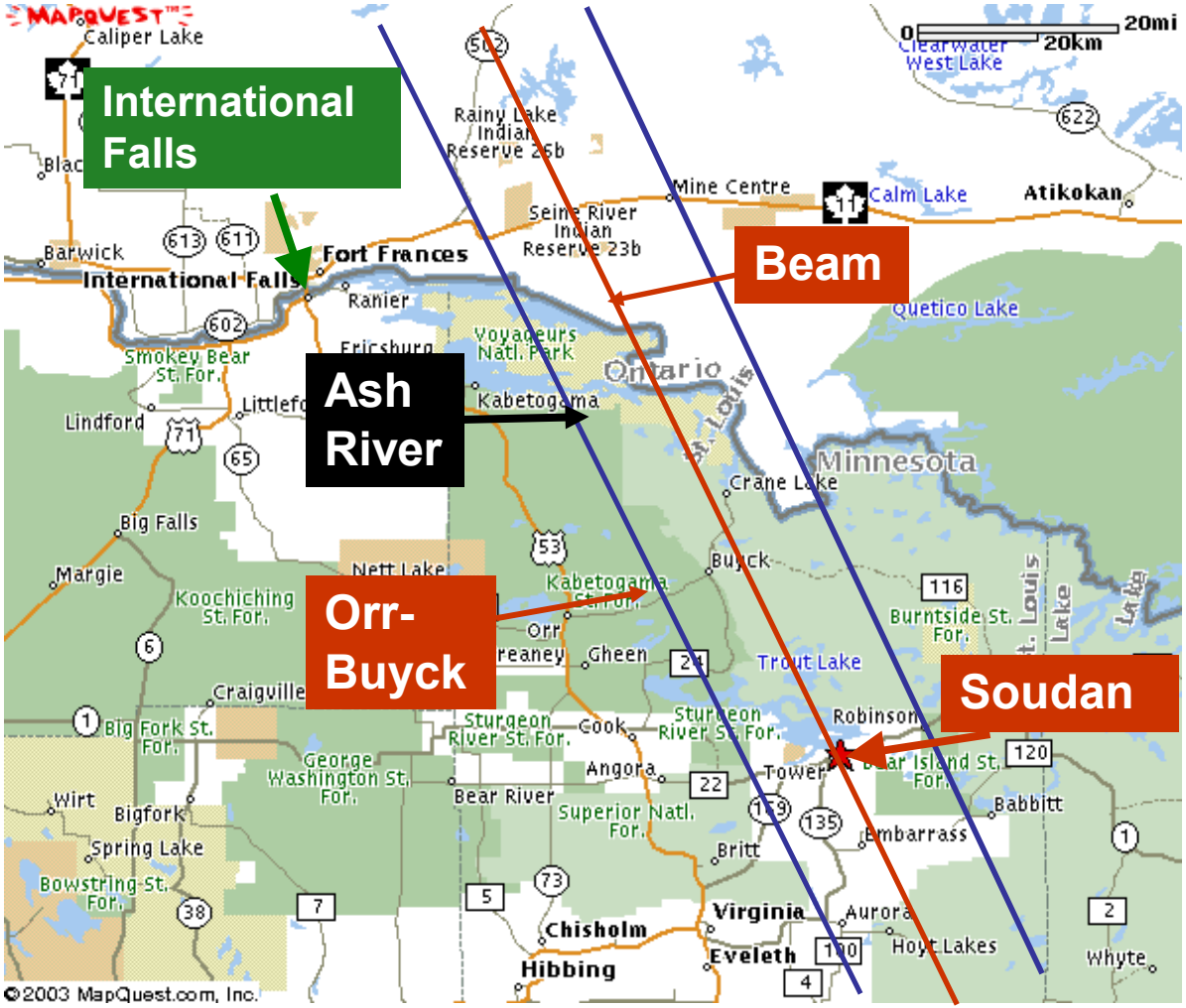
NEUGEN3 Neutrino Interaction Generator
GEANT3 Detector Simulation

1.70 GeV $\nu_\mu N \rightarrow p\mu\pi^0\pi^0$



Background ν_μ CC Event

WHERE WILL BE THE NOνA FAR DETECTOR?



- **Main Site - Ash River - 810 Km**
  - ✓ Needs Power Upgrade
  - ✓ 3.6 Miles Access Road
- **Backup Site – Orr/Buyck Road - 775 Km**
  - ✓ More Available Power
  - ✓ ~1mile access Road

Can fly to International Falls – an hour drive

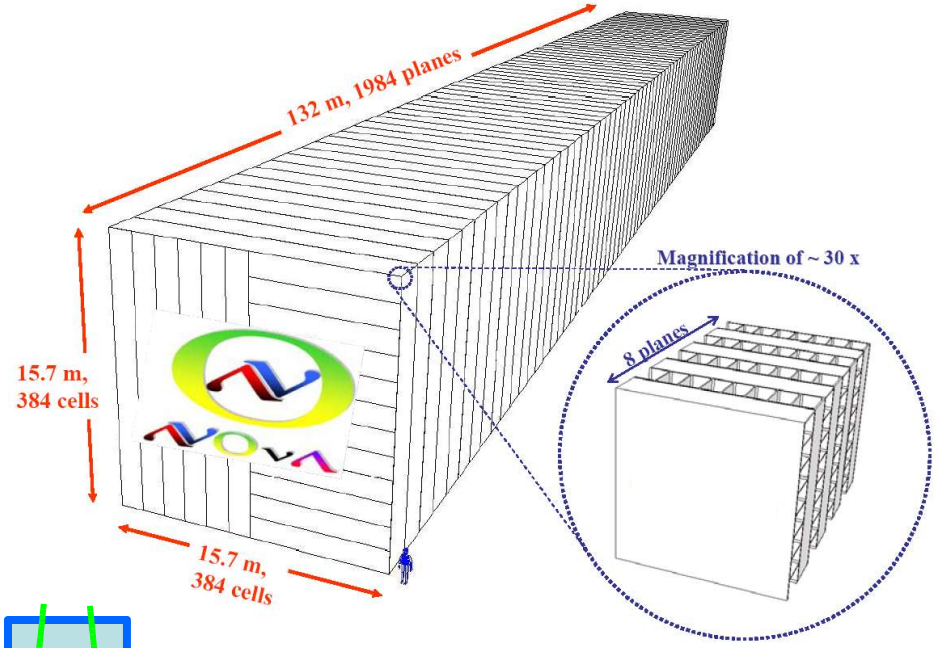
Many sites available with varying angle from 14 to 17 mrad off-axis.

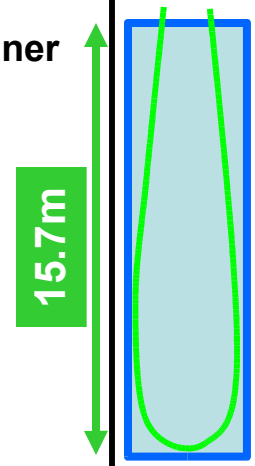
NOνA FAR DETECTOR

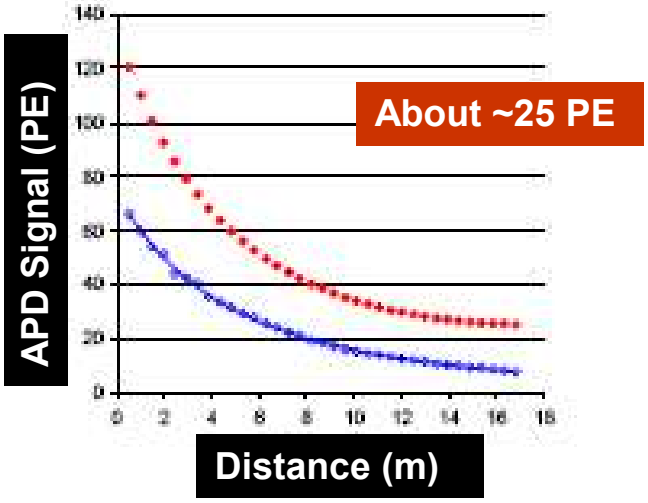
MINOS NUMI

NOνA is an approved Fermilab proposal and has CD0 from US DOE

- Totally Active Liquid Scintillator Detector
  - Total Mass – 30 KTons
  - Mass of Scintillator – 24 KTons
  - Mass of RPVC Extrusions – 6 KTons
- Number of layers - 1984
- Alternate horizontal & Vertical Cells
- Cell size 3.87cm X 6.0 cm X 15.7 m
- Cell wall thickness 3mm outer, 2mm inner
- Total number of cells 761,856
- Number of Extrusions 23,808
- Readout by
  - U-shaped WLS fiber – 0.8mm dia.
  - Fiber length – 26 Million meters
  - Fiber Mass 13.5 Tons
  - APD's with ~80% QE
- ~~Readout Channels – 762K~~



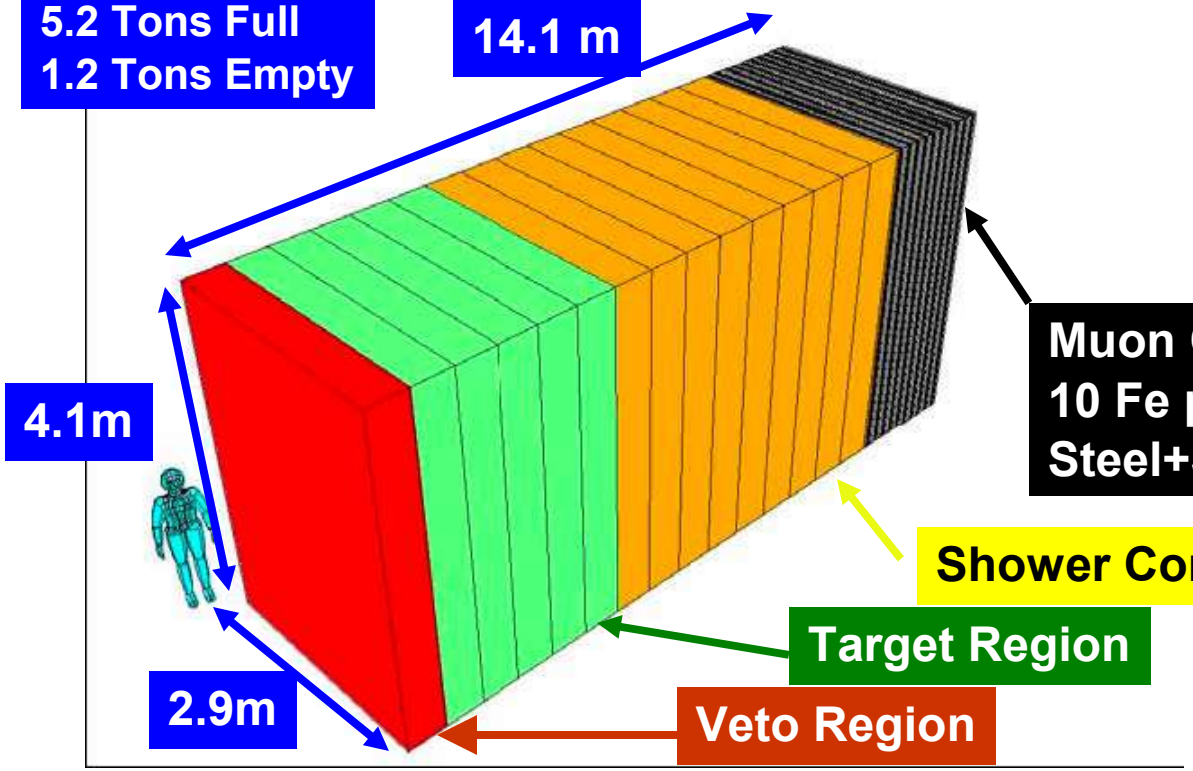




NOνA NEAR DETECTOR

MINOS NUMI

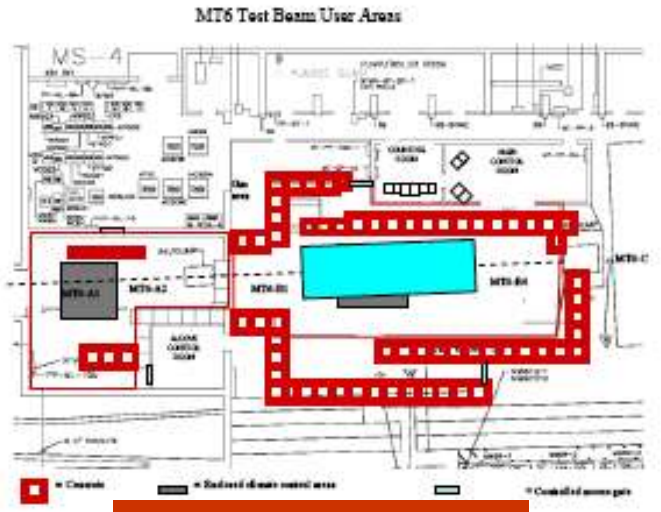
8-plane Block
5.2 Tons Full
1.2 Tons Empty



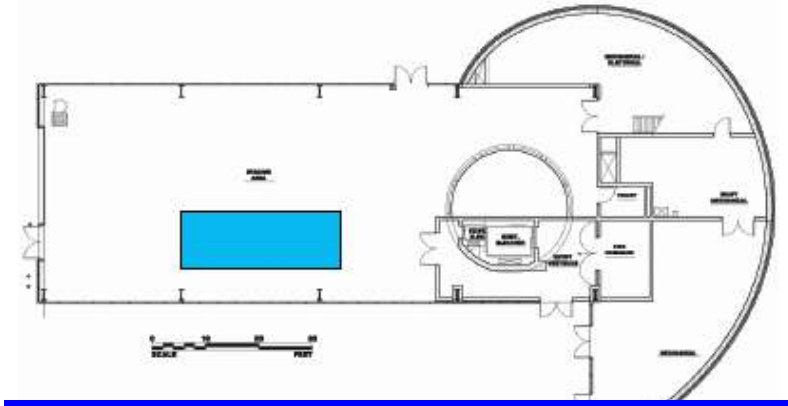
212 Tons
124 Tons Totally Active
21.1 Tons Fiducial
202 Planes
101 H + 101 V
16,160 Channels

- ✓ ND will measure ν_e content of the beam at Fermilab
- ✓ Characterize the detector response to neutrino events, &
- ✓ Perform the crucial background studies

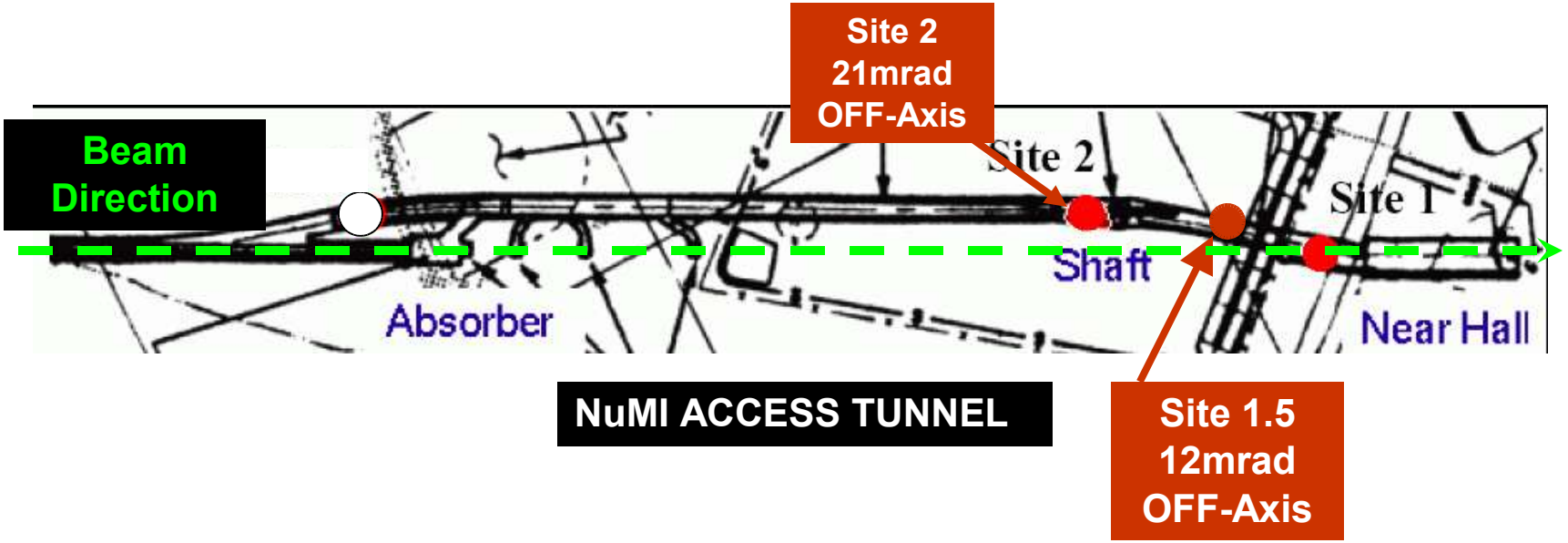
NOνA PROTOTYPE OR ND SECTIONS – WE CAN MOVE IT AS WE LIKE



FNAL TEST BEAM

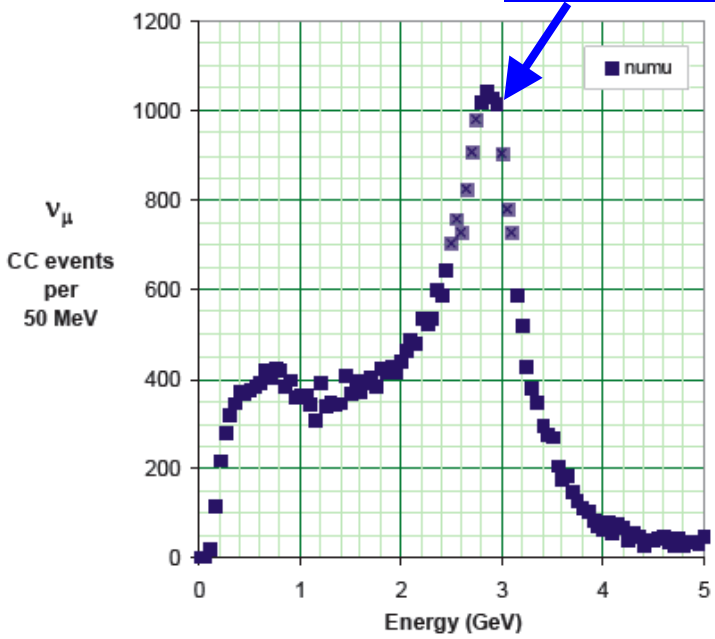


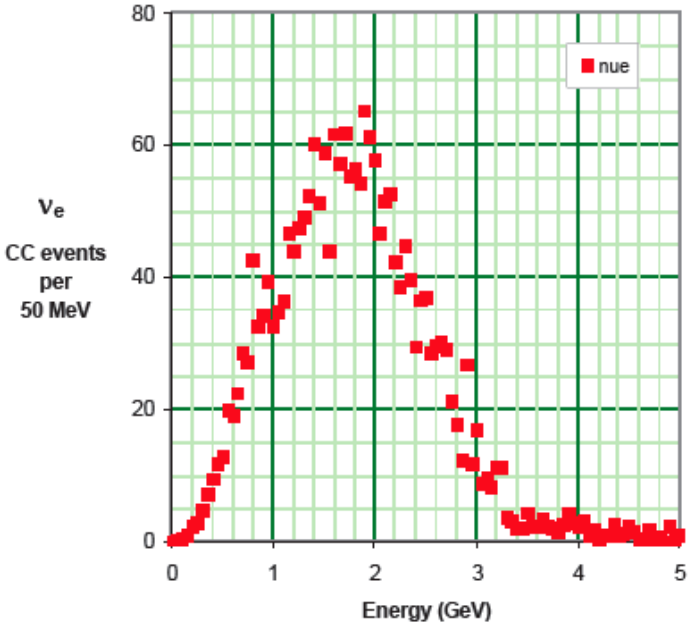
MINOS SURFACE BUILDING -75 mrad OA
NOνA Detector in High Bay Area



6.5 x 10^{20} POT in 75 mrad off-axis beam

Kaon peak





45,000 ν_μ CC events

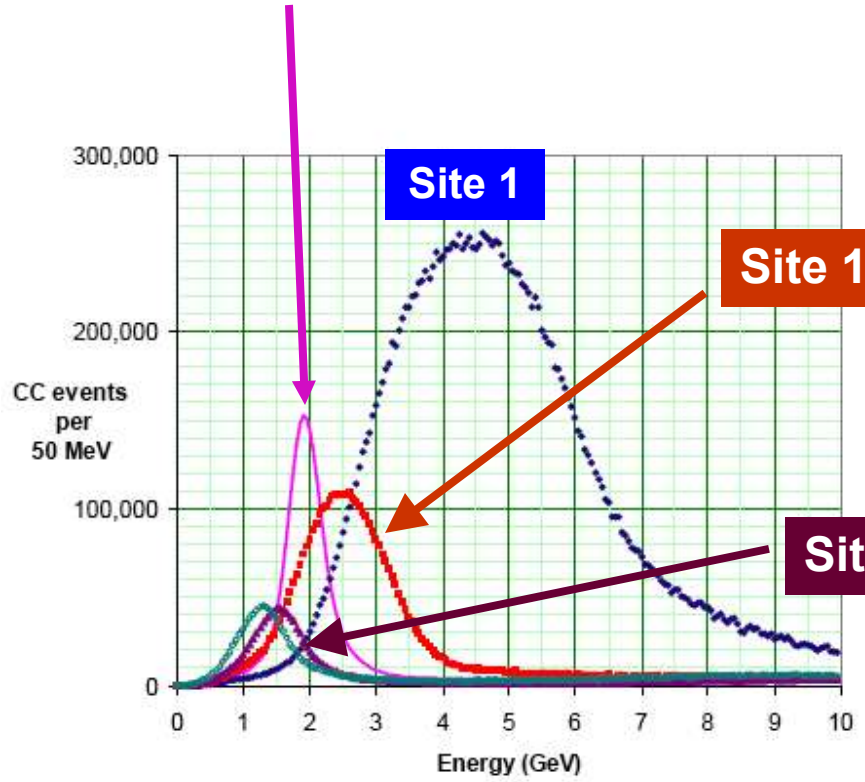
2,200 ν_e CC events

ν_e/ν_μ ratio in 1-2 GeV range is = 10-15%.

Kinematics of $K \rightarrow \mu\nu_\mu$ vs. K_{e3} allows one to cross correlate ν_μ and ν_e energy distribution

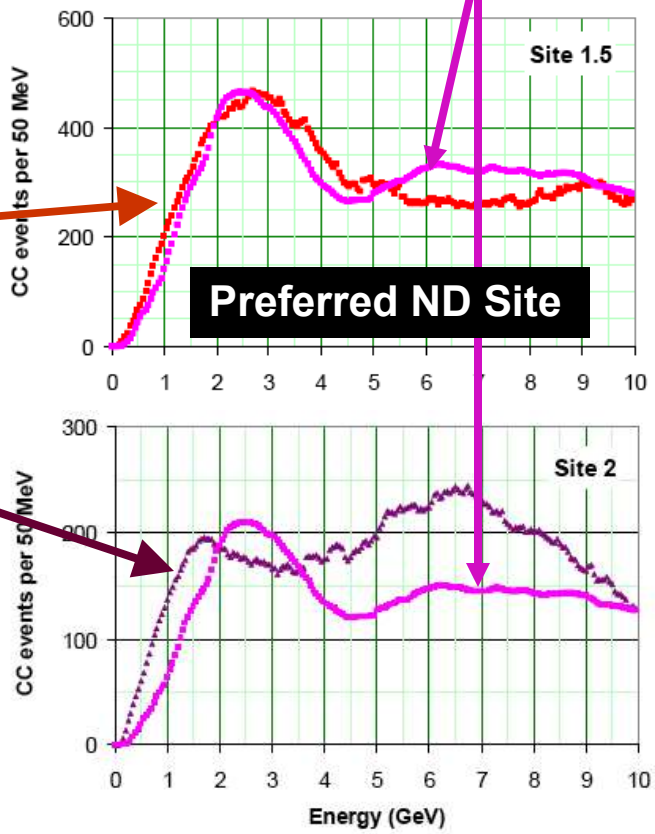
MINOS NUMI

Un-oscillated FD ν_μ Spectrum X 800



ν_μ CC Events

FD un-oscillated ν_e Normalized at ~2 GeV



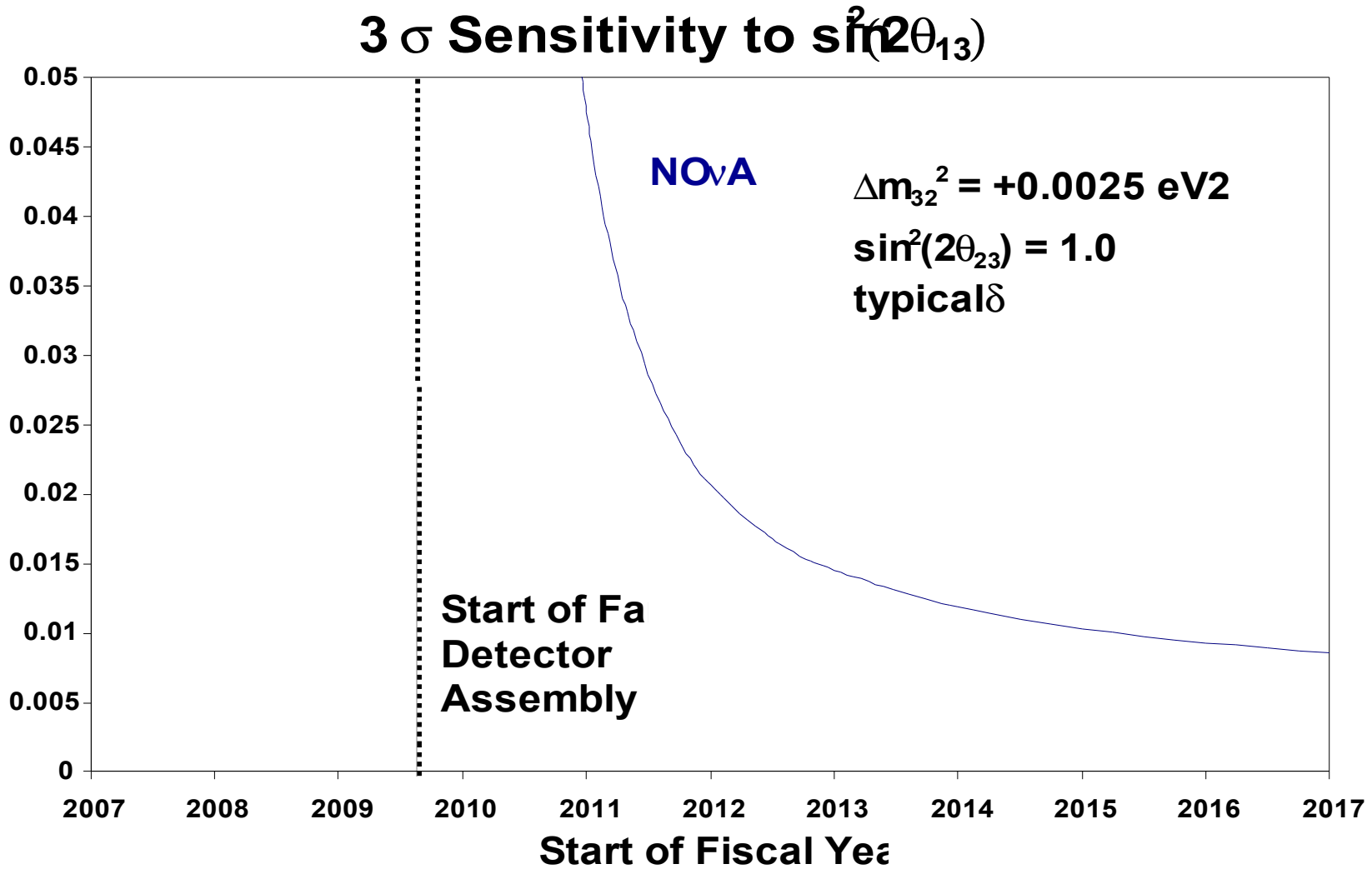
Beam ν_e CC Events

6.5 x 10^{20} POT – NuMI ME Configuration

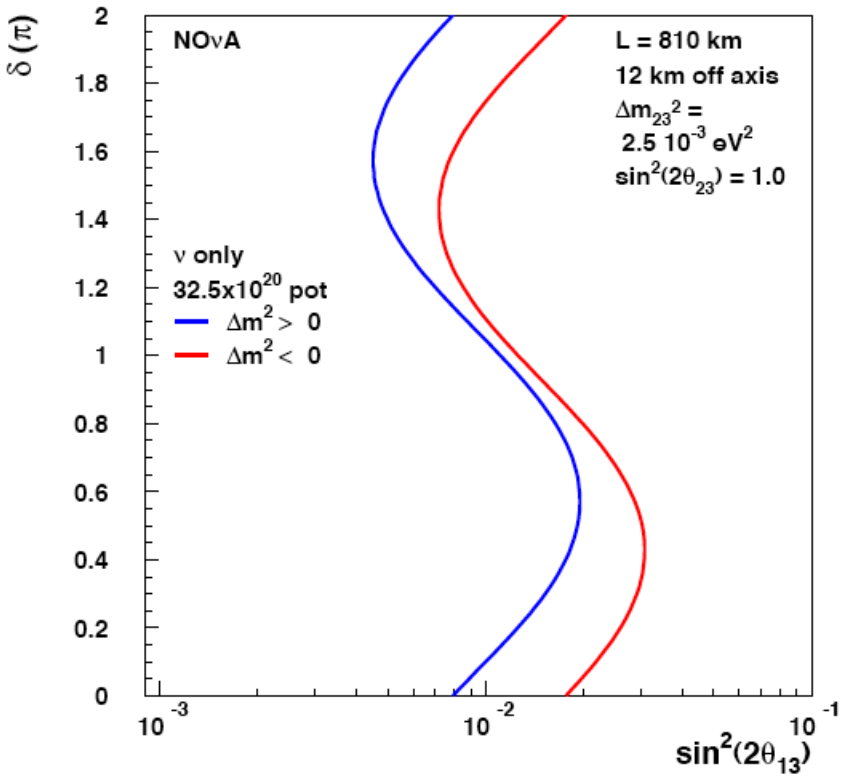
YOU WANT NEUTRINOS – GOT TO HAVE PROTONS

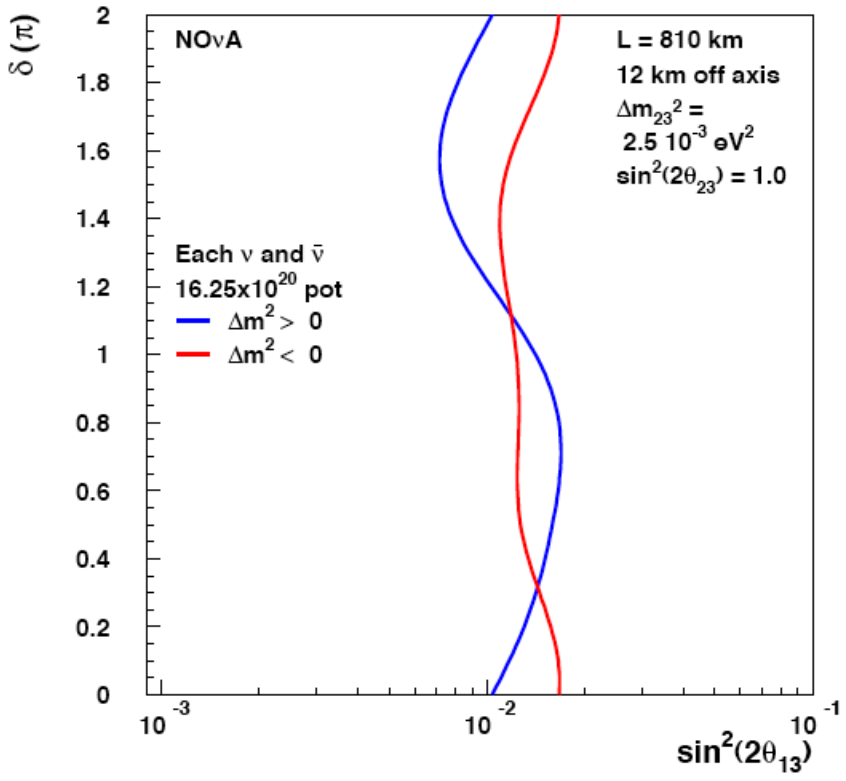
- At present we get upto $3X10^{13}$ protons/pulse every 2.0-3.0 sec
- Proton for MINOS While Tevatron Runs (Upto 2009)
  - ✓ In 2006 – Try to slip stack 9 out of 11 Booster batches for neutrinos
  - ✓ Each Batch is ~$5.5X10^{12}$ protons
  - ✓ Repetition rate = 0.8s (Booster) + 1.4s (Ramp) = 2.2s
  - ✓ Collider shot setup (10% timeline) + Pbar transfer (5% Timeline)
  - ✓ $\Rightarrow$ $3.4X10^{20}$ POT/YEAR (340KW)
- Protons for MINOS+NOνA in Post Tevatron Era (After 2009)
  - ✓ All 11 Booster batches for Neutrinos – Gain 11/9 = 1.22 factor
  - ✓ Hide Booster filling Time in Recycler $\Rightarrow$ 0.8s $\rightarrow$ 0.067s
  - ✓ 2.2 s becomes 1.467 s = 1.50 factor
  - ✓ Save 10% for shot setup and 5% for Pbar transfer = 1.17 factor
  - ✓ Total = ($3.4X10^{20}$ POT/yr) X (1.22) X (1.50) X (1.17) = $7.3X10^{13}$ POT/year
  - ❖ *Even with 90% efficiency we have $\Rightarrow$ $6.5X10^{13}$ POT/year (650KW)*
- With Further Upgrade of the present system one can go upto 1.0+MW
- With proton Driver – $25X10^{20}$ POT/Year (2+ MW)

SENSITIVITY vs. TIME



NOVA 3σ SENSITIVITY TO $\theta_{13} \neq 0$

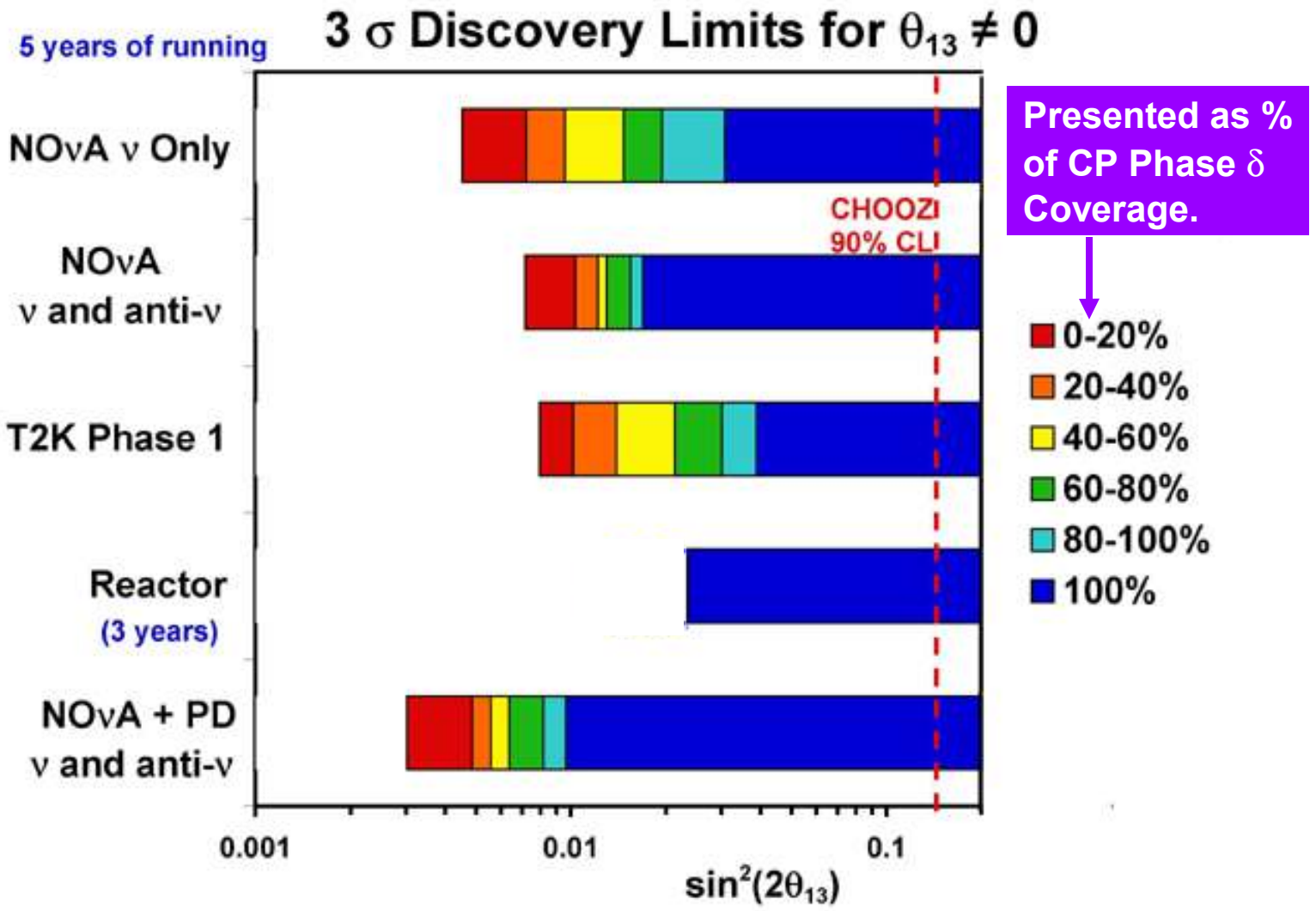




5 YEAR ν ONLY RUN

2.5 YEAR EACH ν & νbar RUN

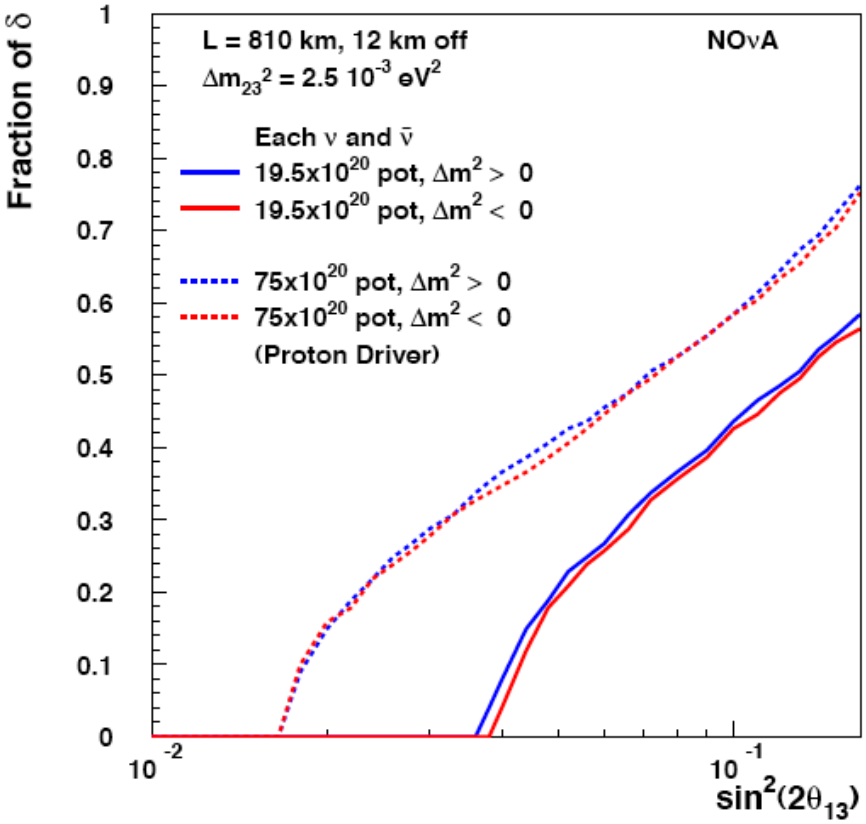
NOVA θ_{13} SENSITIVITY

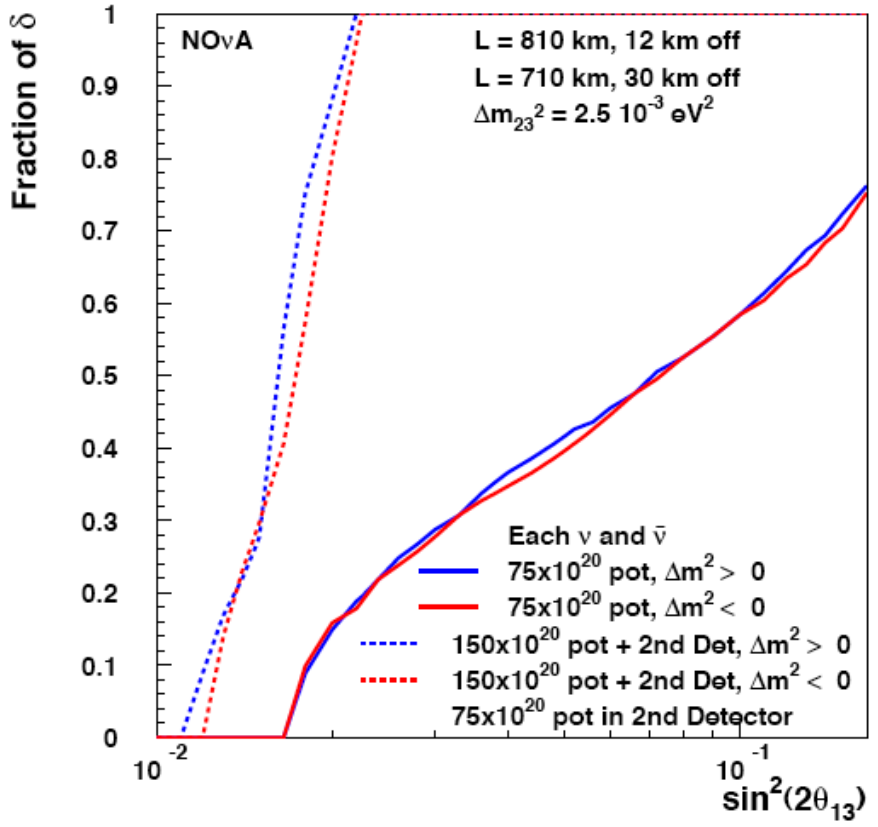


NOνA MASS ORDERING DETERMINATION

- ✓ The mass ordering can only be resolved by matter effects in the earth over long baselines.
- ✓ NOνA at NuMI is the only proposed neutrino experiment with a sufficient long baseline to resolve the hierarchy problem.
- ✓ The NOνA Far Detector off-axis angle and distance has been optimized for this measurement.
- ✓ NOνA FD and ND are the first step in a phased program that can resolve the mass ordering in the region accessible to conventional neutrino beams.
- ✓ Mass ordering resolution is needed to study the CP violation, since it contributes an apparent CP violation that must be corrected.

NOνA MASS ORDERING DETERMINATION





3 yrs each with ν & νbar

95% CL Resolution of the Mass Ordering

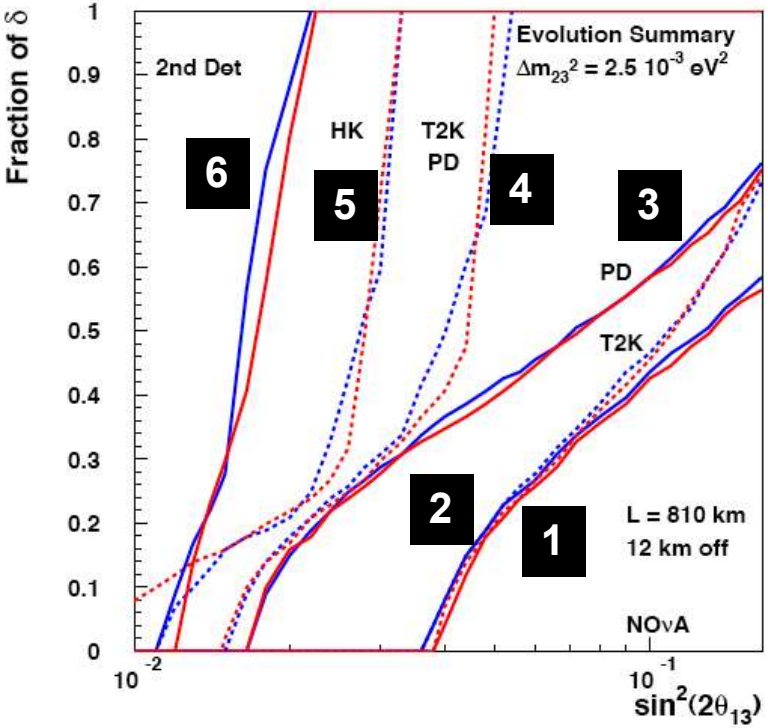
2 yrs of ν Run with PD

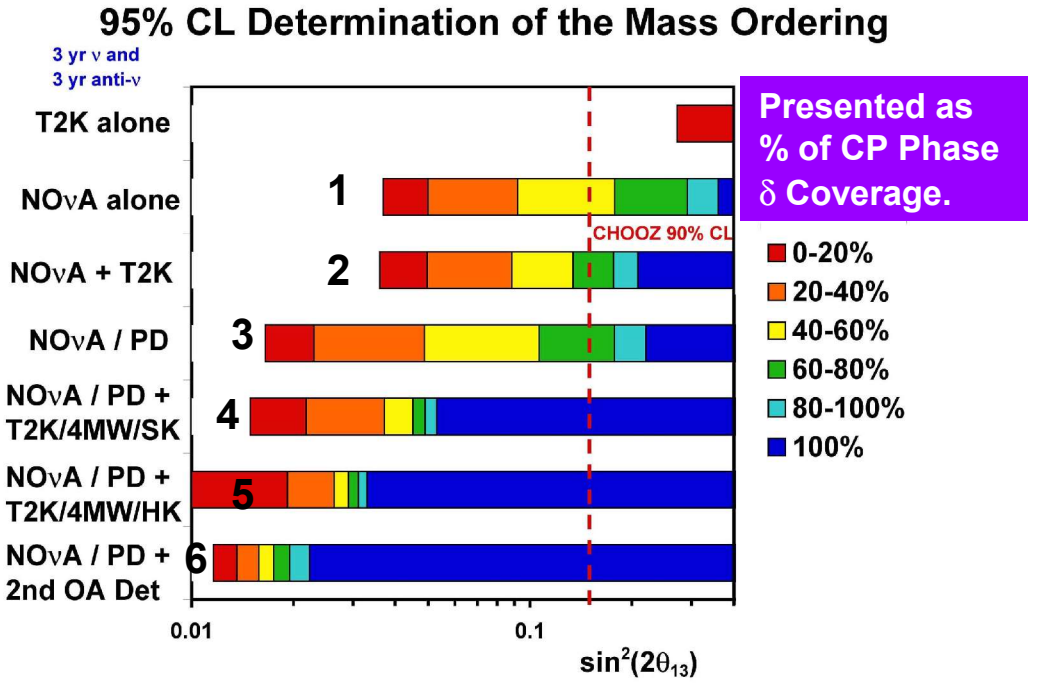
Build a 50KTon 2nd Off-Axis Detector in 4 yrs – 30Km Off-Axis at 710Km at 2nd Osc. Max.

Additional 6 years with both Detectors

12 years with Proton Driver

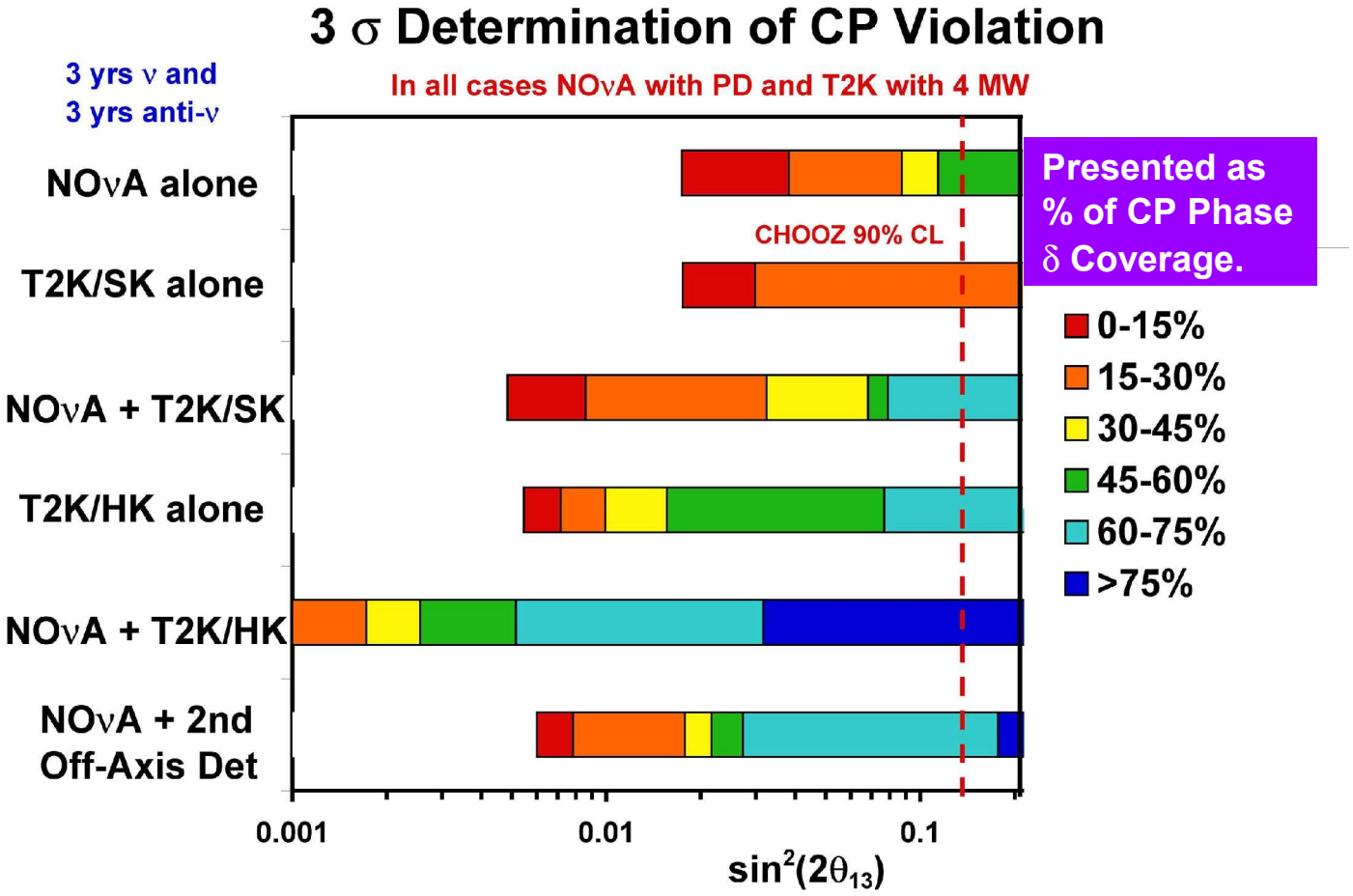
NOνA MASS ORDERING DETERMINATION





95% CL Resolution of the Mass Ordering

A SECOND OFF-AXIS INTERMEDIATE DISTANCE DETECTOR IS REQUIRED TO RESOLVE MASS ORDERING FOR ALL δ UPTO $Sin^2 2\theta_{13} = 0.02$



FOR MEASURING CPV PHASE δ SEVERAL MW POWER IS NEEDED.

ACCELERATOR UPGRADE IS A MUST EITHER IN USA OR IN JAPAN.

HYPER-K IN JAPAN or 2nd OFF-AXIS DETECTOR IN USA IS NEEDED.

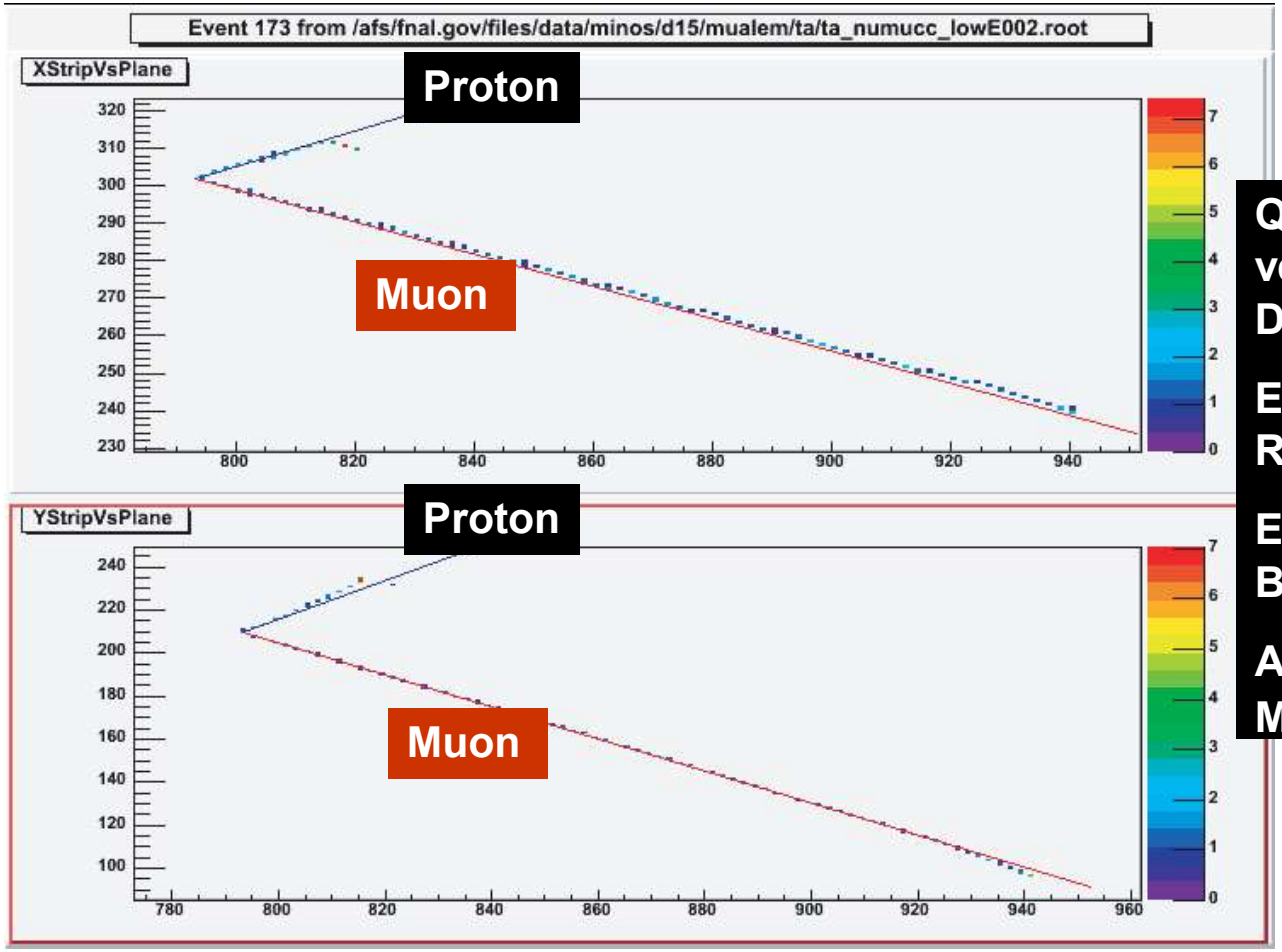
MORE ON NOνA

1. **Super-NOνA: A long-baseline neutrino experiment with two off-axis detectors – PRD 72, 053002 (2005)**
2. **Determining the Neutrino Mass Hierarchy and CP-Violation in NOνA with a Second Off-Axis Detector – hep-ph/0510182 v1**

   By Olga Mena, Sergio Palomares-Ruiz and Silvia Pascoli

- ✓ **Two off-axis detectors.**
- ✓ **The Far off-axis detector is same as the present NOνA detector.**
- ✓ **The intermediate distance (200km or 434km) off-axis detector is chosen such that L/E is the same for both the detectors.**
- ✓ **Intermediate distance off-axis detector is either Liqid Argon or Water Cerenkov of varying mass according to parameter one wishes to measure.**
- ✓ **They CONCLUDE that NOνA can resolve the hierarchy problem with an intermediate detector at the same L/E as the far detector, with neutrino running only. NO anti-Neutrino running is required.**

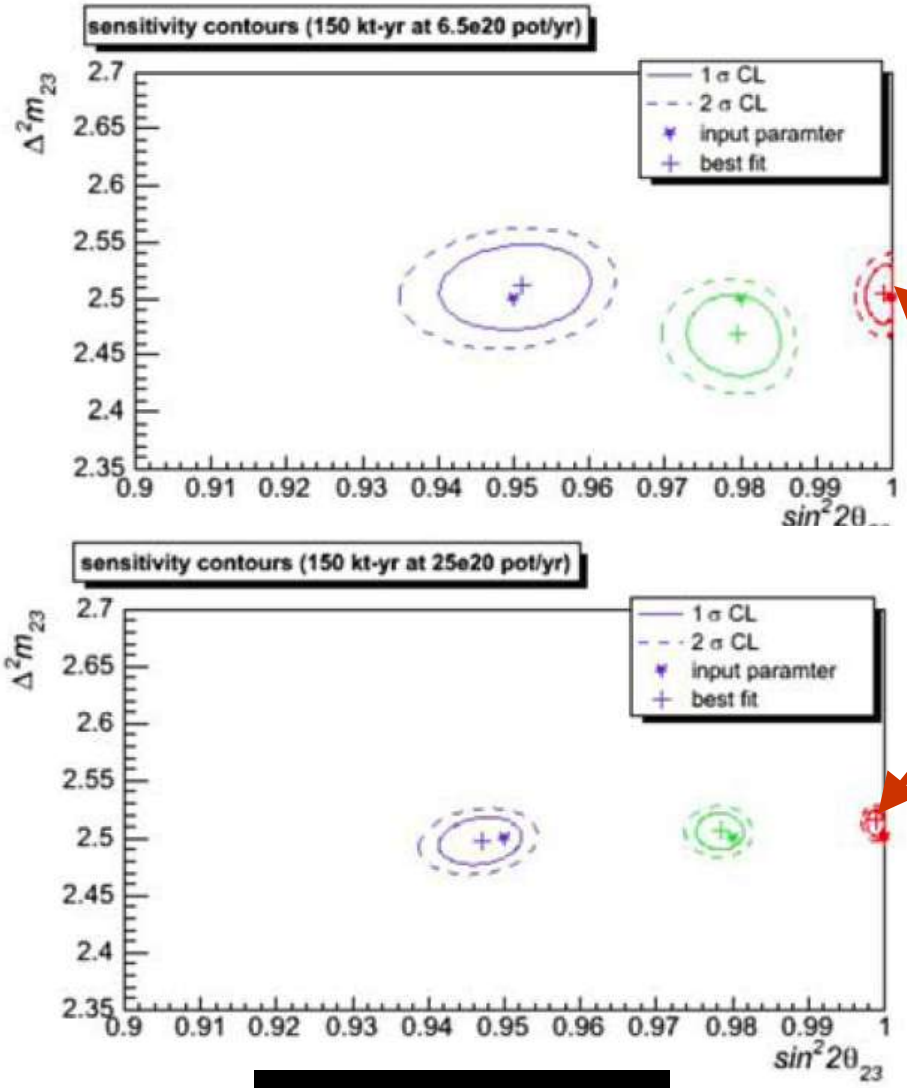
SIMULTANEOUS MEASUREMENT OF Δm^2_{23} & $Sin^2 2\theta_{23}$



- Quasi-elastic Events are very clean in the Detector
- Excellent Energy Resolution
- Essentially no NC Background
- Allows for Clean Measurement of $Sin^2 2\theta_{23}$

$$\nu_\mu N \rightarrow \mu + P$$

SIMULTANEOUS MEASUREMENT OF Δm^2_{23} & $Sin^2 2\theta_{23}$



1σ & 2σ Contours

5-year ν run with 6.5X10^{20} POT/Year

For Maximal Mixing

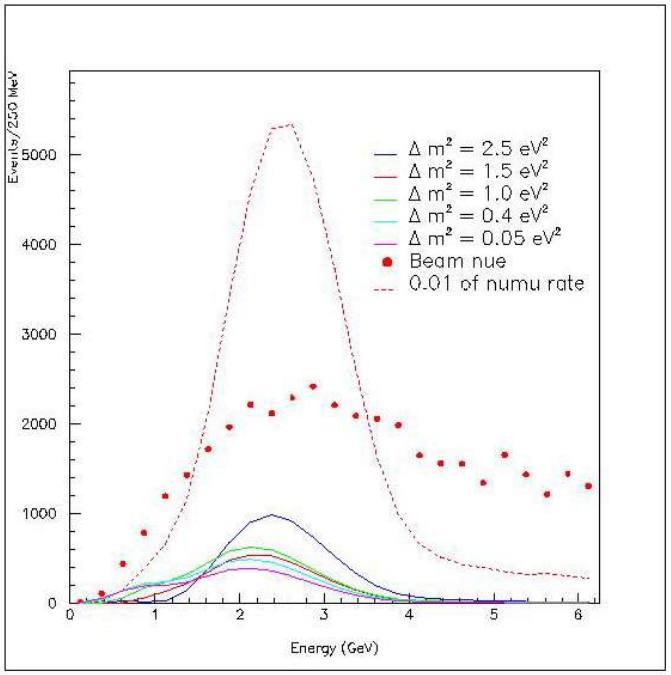
$\delta(Sin^2 2\theta_{23}) = 0.004$

$\delta(Sin^2 2\theta_{23}) = 0.002$

With energy resolution of 2-4%.

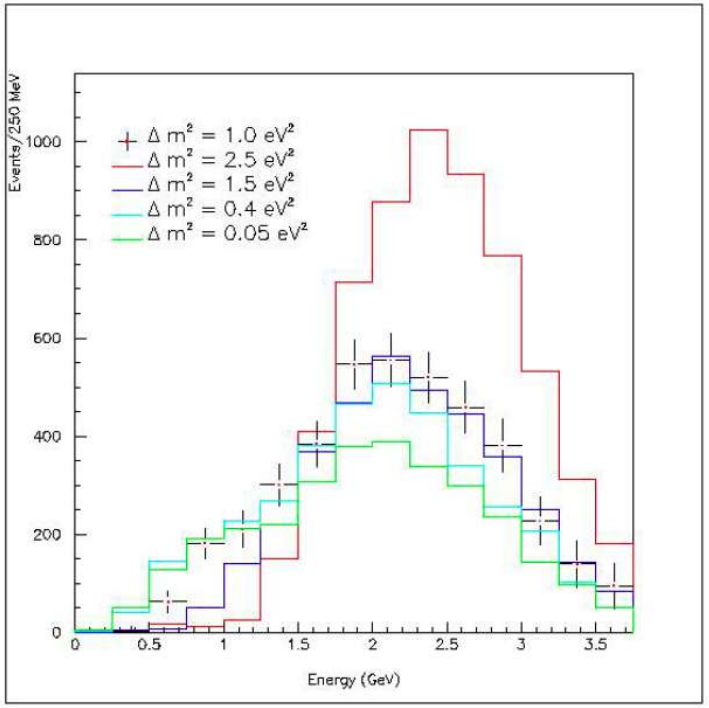
5-year ν run with 25X10^{20} POT/year. PROTON DRIVER

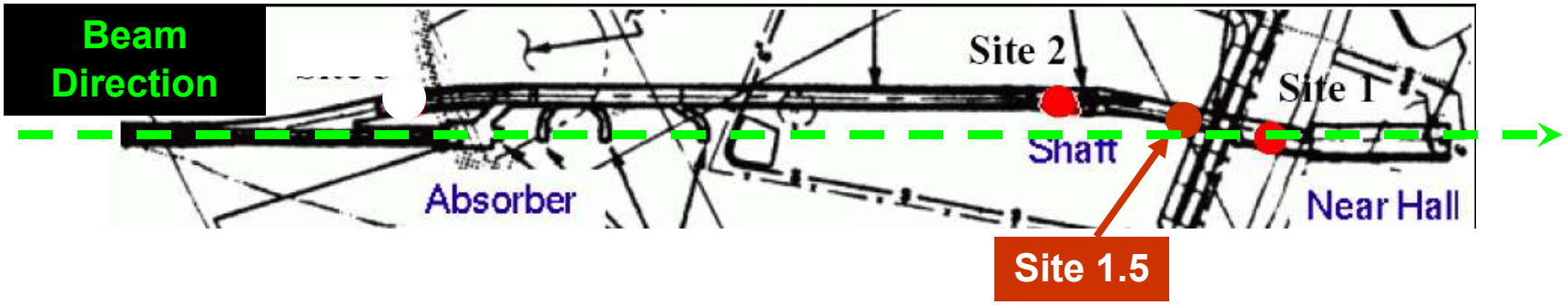
STUDY MiniBooNE SIGNAL



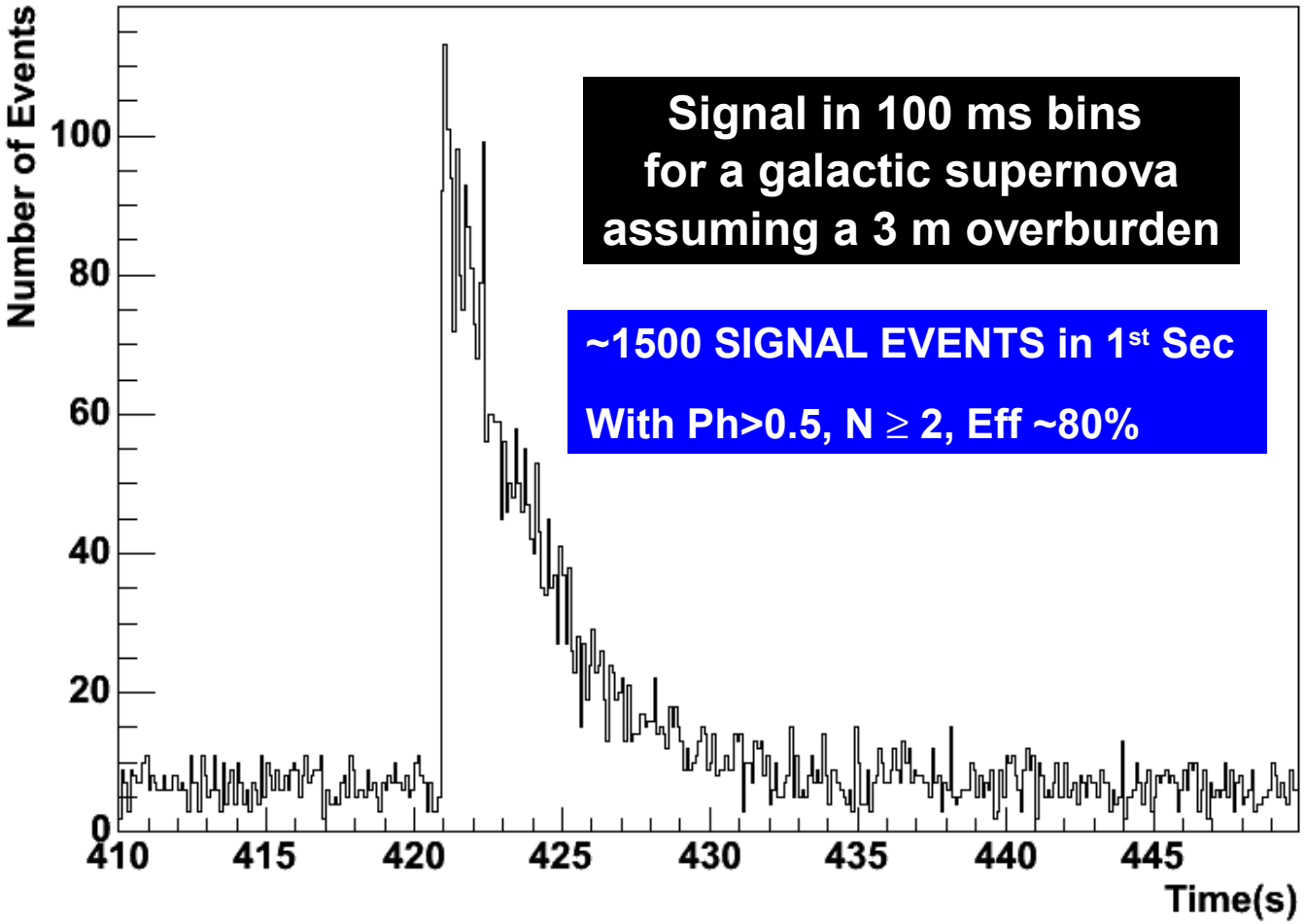
Site 1.5

1-year ν run





SENSITIVITY TO A GALACTIC SUPER-NOνA @ 10KPSecs



NOνA TIMELINE & COST

- ✓ Project Begins – October 2007.
- ✓ Start Construction of Far Detector – Mid 2009.
- ✓ First 5 KTon Operational – Spring- Summer 2010.
- ✓ Full 30 KTon Operational – Mid to End 2011.

➔ NOνA COST - (From Proposal) - $165M (2004$).

COST ESTIMATE UNDER REVIEW

Assumes Full DOE APPROVAL by OCTOBER 2007.

SUMMARY & CONCLUSIONS

1. NOνA is a major Fermilab and US DOE HEP effort.
2. NOνA has CD0 approval from US DOE.
3. NOνA provides a flexible approach to measure θ_{13}, matter hierarchy, and CP violation in the lepton sector.
4. A long baseline approach is crucial to measure all the parameters of neutrino oscillation in context of the world neutrino program.
5. NOνA is a staged program – Each stage of the experiment could be planned according to what we learn from the previous stage.
6. NOνA's physics reach is greater than other neutrino experiments being contemplated in pre neutrino factory era.

MINOS & NOνA EXPERIMENTS ARE ALL SET TO ANSWER MOST OF THE QUESTIONS RELATED WITH ATMOSPHERIC NEUTRINOS, MEASURE θ_{13}, HIERARCHY & CPV IN LEPTON SECTOR IN PHASED MANNER.