NEUTRINO OSCILLATION WITH

NOνA & INO

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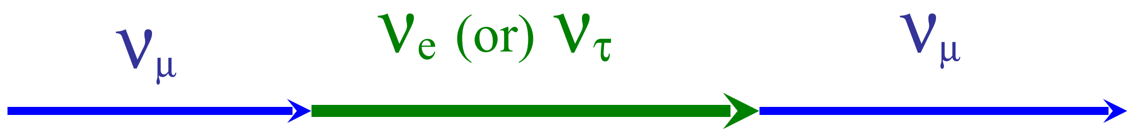
PLAN OF THE TALK

1. Neutrino Oscillation – A Brief Introduction
2. Neutrino Oscillation - Where are we today?
3. Neutrino Oscillation – Open questions
4. What would we like to know in next 20+ years?
   a. **With Conventional Beam & Atmospheric Neutrinos – Next 15 yrs**
   b. **With a Neutrino Factory – If time permits - Very briefly in context of INO ???**
5. NOνA – Why, What and When? A Neutrino roadmap for & from USA
6. A brief history of Cosmic Ray & Atmospheric ν in India
7. INO – What, Why and When?
8. Summary and Conclusions

WHAT ARE NEUTRINO OSCILLATIONS?

Neutrino oscillations is a phenomenon in which neutrinos of one flavor transforms, as it travels through space or matter, into a neutrino of another flavor and then back again.



Neutrino oscillations can occur when the neutrino mass eigenstates are mixed with respect to the flavor eigenstates. A necessary condition for them to occur is that neutrinos have to have mass.

Neutrinos are always produced with a definite flavor. The corresponding mixture of mass states propagate with different velocities. As the relative phase of the mass state shifts, the observed flavor of the neutrino will change accordingly.

MIXING OF THREE NEUTRINOS – PMNS MATRIX

Flavor Eigenstates

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

Mass Eigenstates

$$\Delta m^2_{32} = (m_3^2 - m_2^2), \quad \Delta m^2_{21} = (m_2^2 - m_1^2)$$

$$P(\alpha \rightarrow \beta) = \delta_{\alpha\beta} - 4 \Sigma\Sigma\, U_{\alpha i} U_{\beta i} U_{\alpha j} U_{\beta j} \sin^2[(m_i^2 - m_j^2)L/4E]$$

Three flavor neutrino oscillations are described by two mass squared difference Δm^2_{32}, Δm^2_{21}, three mixing angles θ_{12} (solar), θ_{23} (atmospheric), θ_{13}, and one complex phase δ_{CP}. Sterile neutrinos not taken into account. Lets ignore LSND at this point of time. The phase δ could be CP-violating.

MIXING OF THREE NEUTRINOS – PMNS MATRIX

The mixing matrix can be specified by 3 angles and one complex phase:

$$U = \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix}}_{\text{Atmospheric: } \nu_\mu \leftrightarrow \nu_\tau} \times \underbrace{\begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix}}_{\text{Cross-Mixing: } \nu_e \leftrightarrow \nu_\mu, \nu_\tau} \times \underbrace{\begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{\text{Solar: } \nu_e \leftrightarrow \nu_\mu, \nu_\tau}$$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$(c_{ij} \equiv \cos\theta_{ij}, \quad s_{ij} \equiv \sin\theta_{ij})$

The first term dominates the atmospheric neutrino oscillations. The last term dominates the solar neutrino flavor change and the cross-mixing term involves angles θ_{13} which is constrained by upper limits from reactor data (CHOOZ) to $\leq 7\text{-}9^0$ at atmospheric Δm^2_{23}. The cross-mixing term also contains the CP-violating phase δ, which if not 0^0 & 180^0, leads to CP-violating difference between the probabilities for corresponding neutrino and anti-neutrino oscillations. But δ enters neutrino mixing only in combination with $\sin\theta_{13}$. Thus, the CP violating effects of δ depends on θ_{13}.

OSCILLATION FORMALISM

- ✓ **We have compelling evidence of neutrino oscillation from solar, reactor, atmospheric, and accelerator based experiments.**
- ✓ **The approximate formula describing Oscillations for two neutrino formalism is given by :**

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \, \sin^2(1.27 \, \Delta m^2 \, L/4E)$$

L (Source to Detector Distance) and

E (Neutrino Energy) are experimental parameters

2θ (Mixing Angle) and

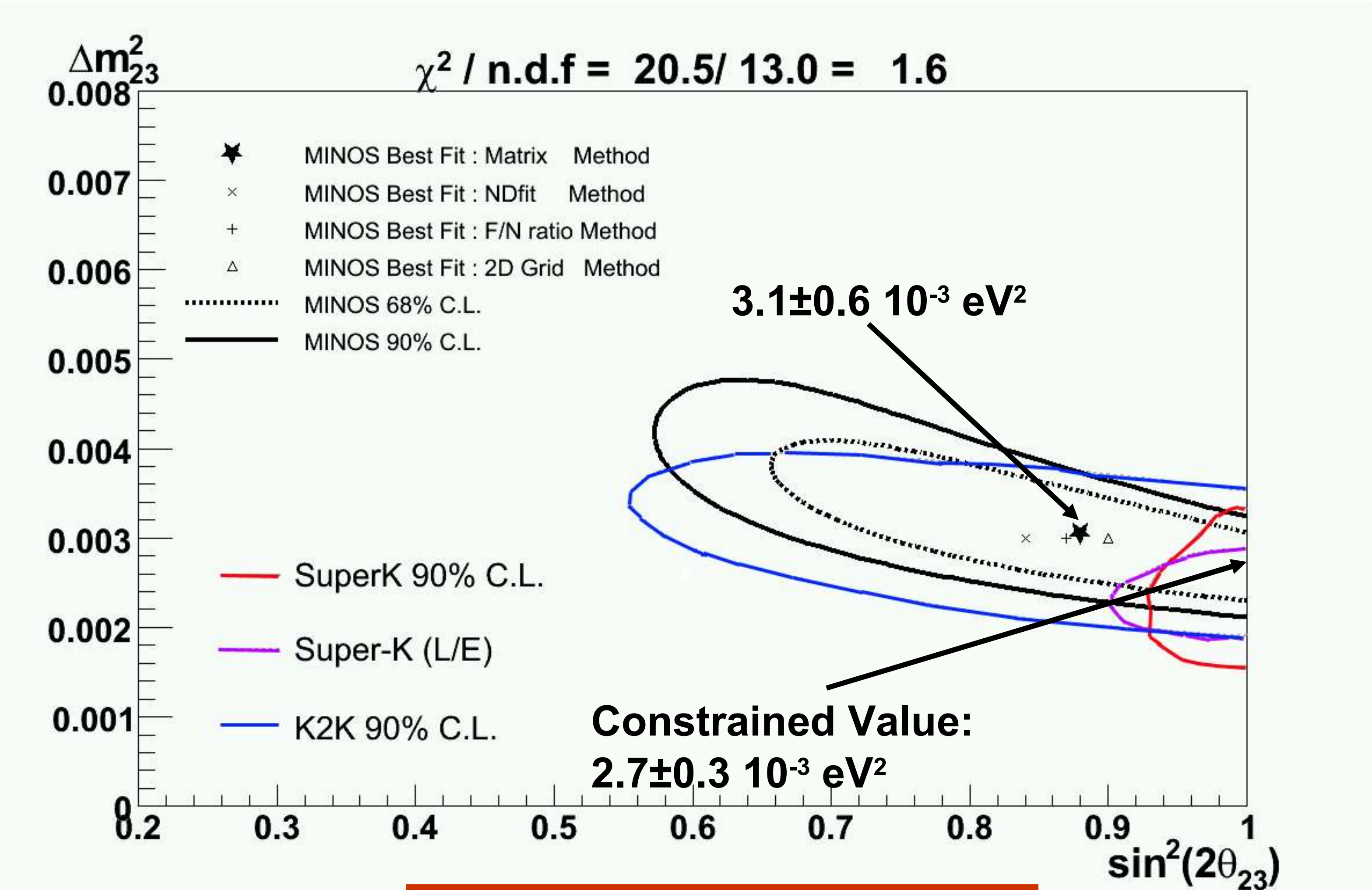
Δm^2 (Mass Squared difference) are oscillation parameters.

- ✓ ***Neutrino Oscillation requires $\Delta m^2 \neq 0$ and $\theta \neq 0$.***

Super-K + K2K NEUTRINO OSCILLATION – PRESENT SITUATION

- From L/E Measurement of Super- K – PRL 93, 101801 (2004)
  - ✓ Best Fit value (Physical Region) ⇒ $\Delta m^2_{23} = 2.4 \bullet 10^{-3}\ eV^2$, $Sin^2 2\theta_{23} = 1.00$
  - ✓ @90% CL ⇒ $1.9 \bullet 10^{-3} < \Delta m^2_{23} < 3.0 \bullet 10^{-3}\ eV^2$, $Sin^2 2\theta_{23} > 0.90$
- Super- K – 1489 Day Exposure – PRD 71, 112005 (2005)
  - ✓ Best Fit value (Physical Region FC, PC, & ↑thru μ's of)
  - ✓ ⇒ $\Delta m^2_{23} = 2.1 \bullet 10^{-3}\ eV^2$, $Sin^2 2\theta_{23} = 1.00$
  - ✓ @90% CL ⇒ $1.5 \bullet 10^{-3} < \Delta m^2_{23} < 3.4 \bullet 10^{-3}\ eV^2$, $Sin^2 2\theta_{23} > 0.92$
- 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) ⇒ $\Delta m^2_{23} = 2.5 \bullet 10^{-3}\ eV^2$, $Sin^2 2\theta_{23} = 1.00$
  - ✓ @90% CL ⇒ $2.0 \bullet 10^{-3} < \Delta m^2_{23} < 3.0 \bullet 10^{-3}\ eV^2$, $Sin^2 2\theta_{23} > 0.93$
- K2K - Y. Suzuki at TAUP 9/2005 with $9.22 X 10^{19}$ POT –
  - ✓ Best Fit value (Physical Region) ⇒ $\Delta m^2_{23} = 2.76 \bullet 10^{-3}\ eV^2$, $Sin^2 2\theta_{23} = 1.00$
  - ✓ @90% CL ⇒ $1.88 \bullet 10^{-3} < \Delta m^2_{23} < 3.48 \bullet 10^{-3}\ eV^2$ @ $Sin^2 2\theta_{23} = 1.0$

MINOS RESULTS



$$\Delta m^2_{23} = 3.05^{+0.60}_{-0.55}(stat) \pm 0.12(syst) \times 10^{-3} eV^2$$

$$\sin^2 2\theta_{23} = 0.88^{+0.12}_{-0.15}(stat) \pm 0.06(syst)$$

SUMMARY OF OSCILLATION MEASUREMENTS

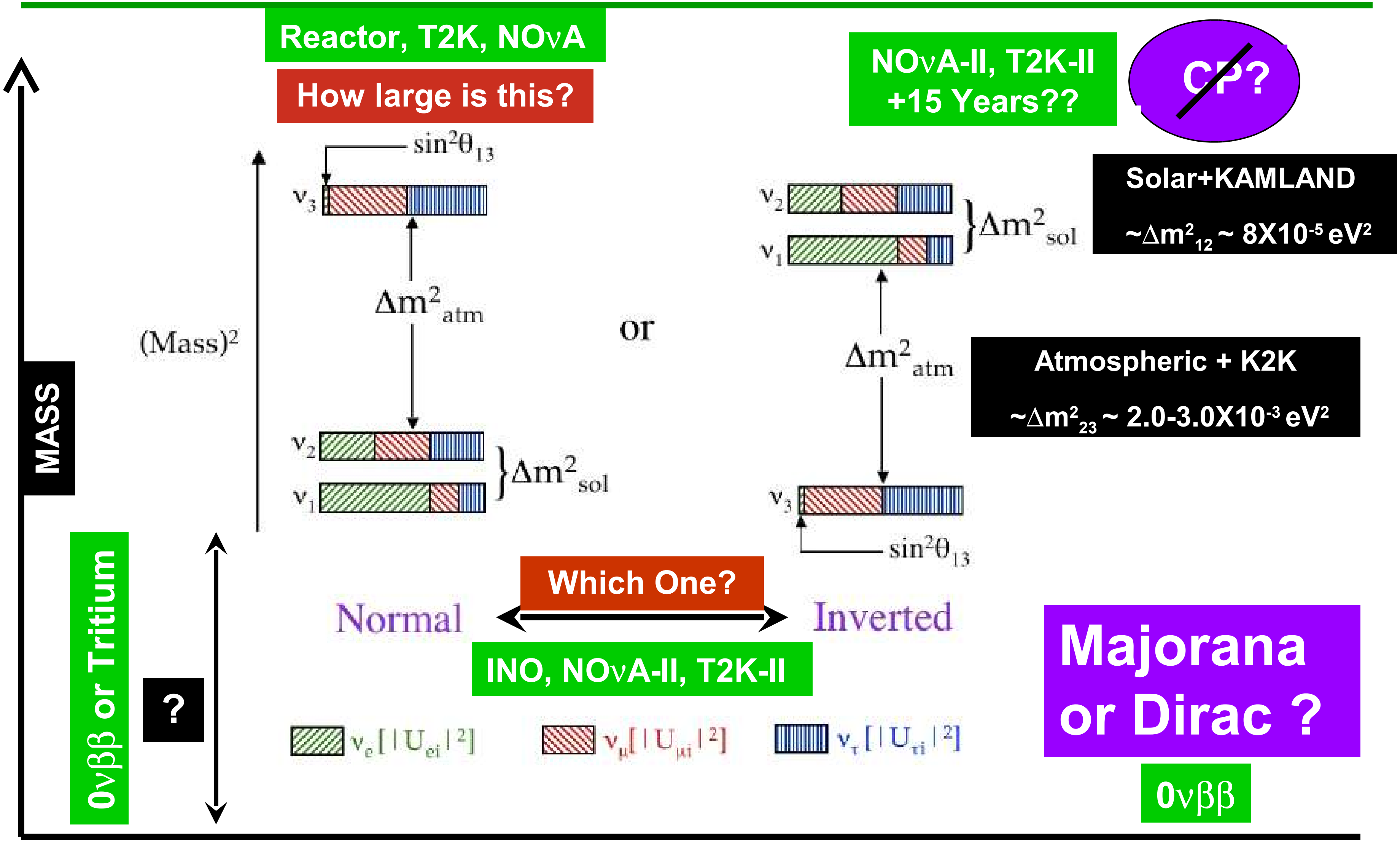
1. Atmospheric neutrino related parameters are not well measured.
2. Error on measured parameters are of the order of 20%:
   1. $\delta(\mathrm{Sin}^2 2\theta_{23}) \sim 0.2$,
   2. $\delta(\Delta m^2_{23}) \sim 0.4 \bullet 10^{-3}\ eV^2$.
   3. The central value of Δm^2_{23} itself moves around a lot.
3. The value of θ_{23} at 90% CL varies from $\sim 37^0$ to $\sim 53^0$.

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. $\mathrm{Sin}^2 2\theta_{13} < 0.14$ for $\Delta m^2_{23} = 2.5 \bullet 10^{-3}\ eV^2$
   b. $\mathrm{Sin}^2 2\theta_{13} < 0.18$ 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 $< 10^0$.

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 value of θ_{13}? Is it different from ZERO?
5. What is the precise value of Δm^2_{23}?
6. What is the precise value of θ_{23}? Is θ_{23} maximal ($\theta_{23} = 45^0$)?
7. How is neutrino mass hierarchy structured? What is the sign of Δm^2_{23}?
8. Is there CP violation in the lepton sector?

WHAT WE KNOW, WHAT WE DON'T KNOW, & WHAT WOULD WE LIKE TO KNOW?



WHAT WE WOULD LIKE TO KNOW FROM LBL + ATM ν IN NEXT 15 YRS?

1. **Atmospheric Sector – Long baseline – Next 5 -7 years (MINOS)**
   - ✓ Observation of L/E (or should I say confirmation of L/E ?)
   - ✓ Precision measurement of Δm^2_{23}
   - ✓ Better limit on θ_{13}
   - ✓ Exclusion of non-oscillation hypothesis, ex: neutrino decay, decoherence, extra-dimensions etc.
2. **Atmospheric Sector – Long baseline – Next 10-15 years**
   - ✓ Very precise measurement of Δm^2_{23} and $Sin^2 2\theta_{23}$ **(T2K, NOνA, INO)**
   - ✓ **Measure θ_{13} (NOνA, T2K) + *REACTOR***
   - ✓ **Determine hierarchy via "matter effect" (INO, NOνA-II + T2K-II), and**
   - ✓ Measure CP Violation in the lepton sector **(NOνA-II + T2K-II)**

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

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

  (P2 and P3:) Atmospheric - Solar Interference
  - $P_4 = \cos^2(\theta_{23}) \sin^2(2\theta_{12}) \sin^2(1.27\, \Delta m^2_{12}\, L/E)$ "Solar"

where

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

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

+ for νbar and – for ν

MATTER EFFECT

- In LBL experiment the neutrino beam traverses through the Earth and the neutrino goes through forward coherent scattering through the interactions in the matter.
- In matter ν_e interacts differently compared to other flavors.
  - ✓ ν_e have charged-current interactions with electrons in the matter
  - ✓ ν_e, ν_μ, and ν_τ have neutral-current interactions with the matter
  - ✓ ν_s has no interaction at all
- Matter can change the oscillation probability due to an effective mass difference which is generated between different types of neutrinos.
- This modifies the mixing angle, enhancing the probability of conversion for ν and suppressing for νbar, or vice-versa depending on the sign of Δm^2_{23}.

MATTER EFFECT

- In matter the effective mixing is given by:

$$\sin^2 2\theta_{matter} = \sin^2 2\theta / (\cos 2\theta - A/\Delta m^2)$$

where $A = +\text{-}2\ \mathrm{sqrt}(2)\ G_F\ Y\ n_B\ E_\nu$

n_B = Baryon Density

$Y = -2Y_n + 4Y_e$ for ν_e (Y_n = neutrons/baryons)

$Y = -2Yn$ for $\nu\mu$ (Y_e = electrons/baryons)

$Y = 0$ for ν_s

- This enhances (suppresses) the probability of conversion for ν (νbar) to normal hierarchy and vice –versa for inverted hierarchy
- For a 2 GeV neutrino of energy, matter effect gives
  - ✓ About ±30% effect for NuMI & about ±11% effect for T2K
- By measuring $P(\nu_\mu \to \nu_e)$ and $P(\nu_\mu \to \nu_e)$, we are sensitive to θ_{13}, δ, and the type of hierarchy (or sign of Δm^2_{23})
- And this is what NOνA will do.

NOνA - NuMI OFF-AXIS ν_e APPEARANCE EXPERIMENT & COLLABORATION

- ✓ **NOνA is a proposed 2nd generation experiment on the NuMI beamline. Its Far Detector will be a 25 kT totally active, tracking liquid scintillator calorimeter located near Ash River, MN, 810 km from Fermilab and 11.77 km off the center (14.52 mr off-axis) of the NuMI beamline.**
- ✓ **Its main physics goal will be the study of $\nu_\mu \rightarrow \nu_e$ oscillations at the atmospheric oscillation length.**
- ✓ **Its unique characteristic is its long baseline, which allows access to matter effects, which can be used to determine the ordering of the neutrino mass states and CPV.**
- **The NOνA Collaboration consists of 142 physicists and engineers from 28 institutions:**
  - *Argonne, Athens, Caltech, College de France, Fermilab, Harvard, Indiana, ITEP, Michigan State, Minnesota-Twin Cities, Minnesota-Duluth, Northern Illinois, Ohio, Ohio State, Oxford, Rutherford, Rio de Janeiro, South Carolina, SMU, Stanford, Texas, Texas A&M, Tufts, UCLA, Virginia, Washington, William and Mary*
- **Five Italian universities with about 20 senior physicists are actively discussing joining NOνA.**

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 (+T2K)
    - Or with a Second Detector
    - Or all of them
  - ✓ Begin to study/measure CP violation in the Neutrino Sector

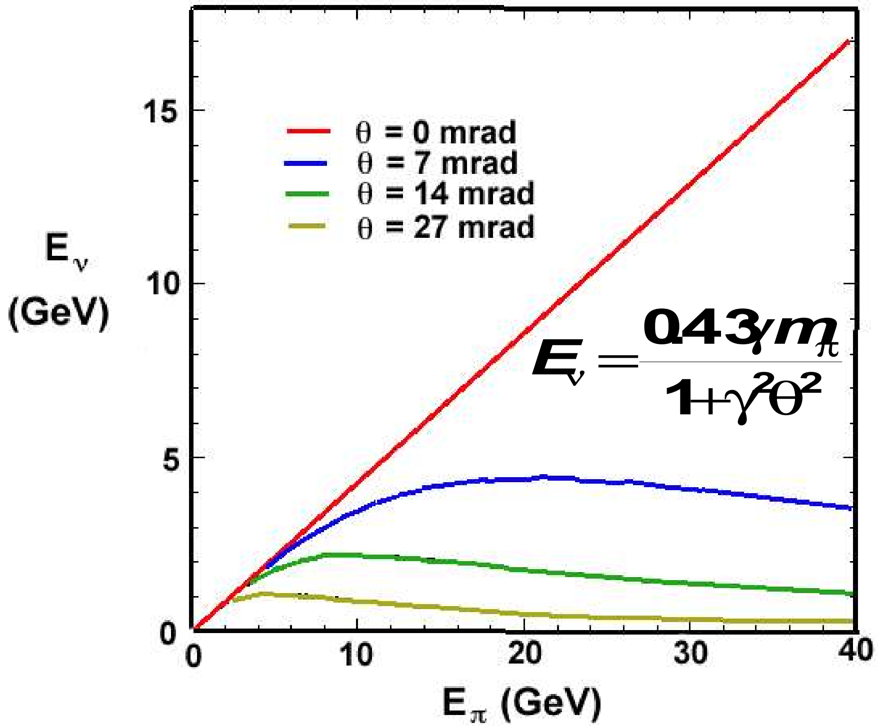
L = 810 Km MATTERS

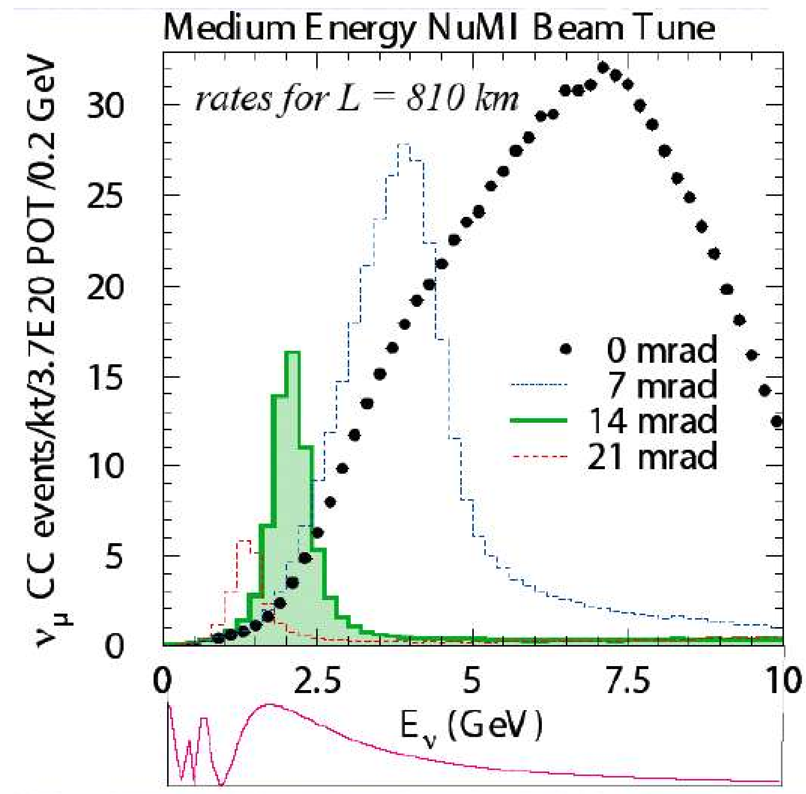
- **Other Measurements:**
  - ✓ Δm^2_{23} ~ 10^{-4} eV^2
  - ✓ $\sin^2 2\theta_{23}$ ~ 1 to 2%.
  - ✓ Check maximality of θ_{23} (Is $\theta_{23} = 45^0$?)
  - ✓ $\nu_\mu \rightarrow \nu_\mu$ vs. $\nu_{\mu bar} \rightarrow \nu_{\mu bar}$ gives a measurement of CPT
- **Study MiniBooNE Signal**
- **Study 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
- 25KTon Mass Detector (~5 times more massive than MINOS) – Mass can be further increased beyond 25KTon - a possibility
  - 73% 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



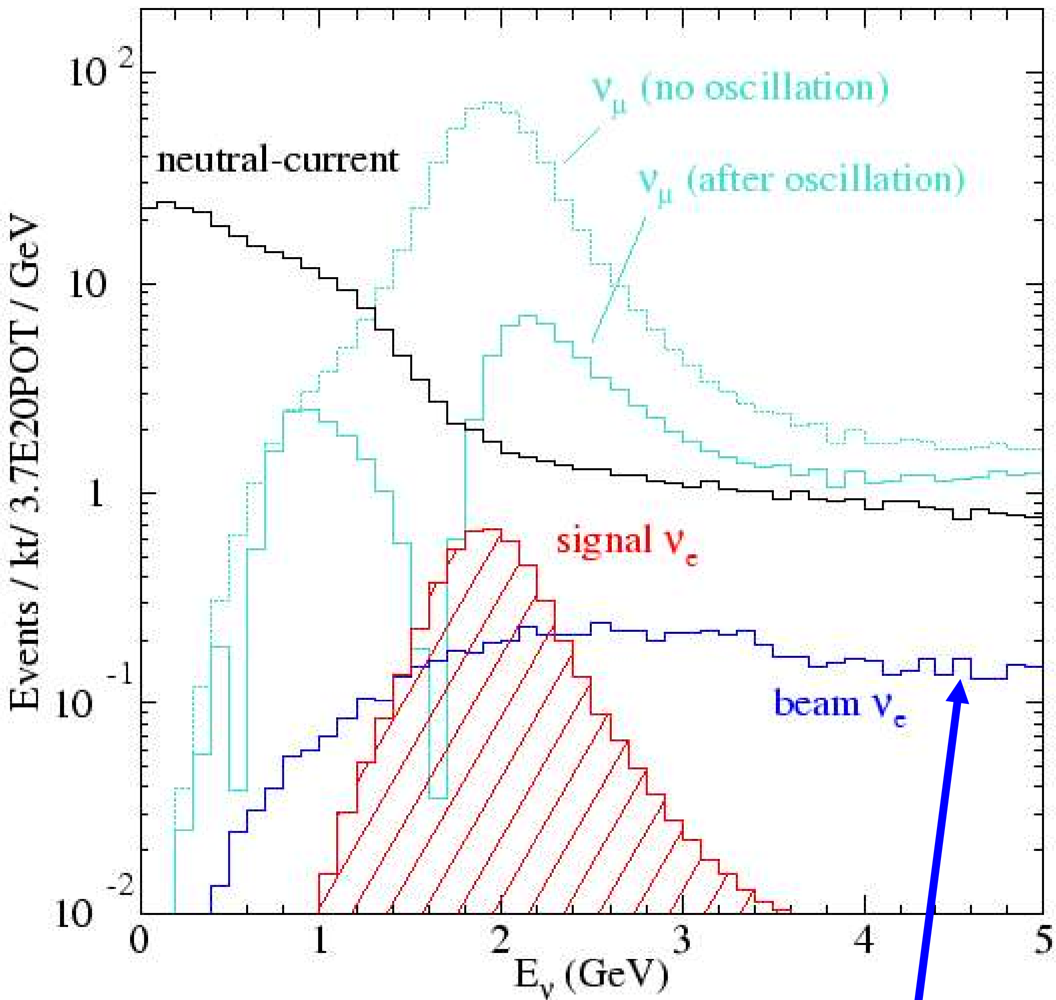


✓NuMI ME beam tune at 14mrad - Peaks at ~2GeV and has ~20% width

✓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

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

$Sin^2 2\theta_{13} = 0.04$

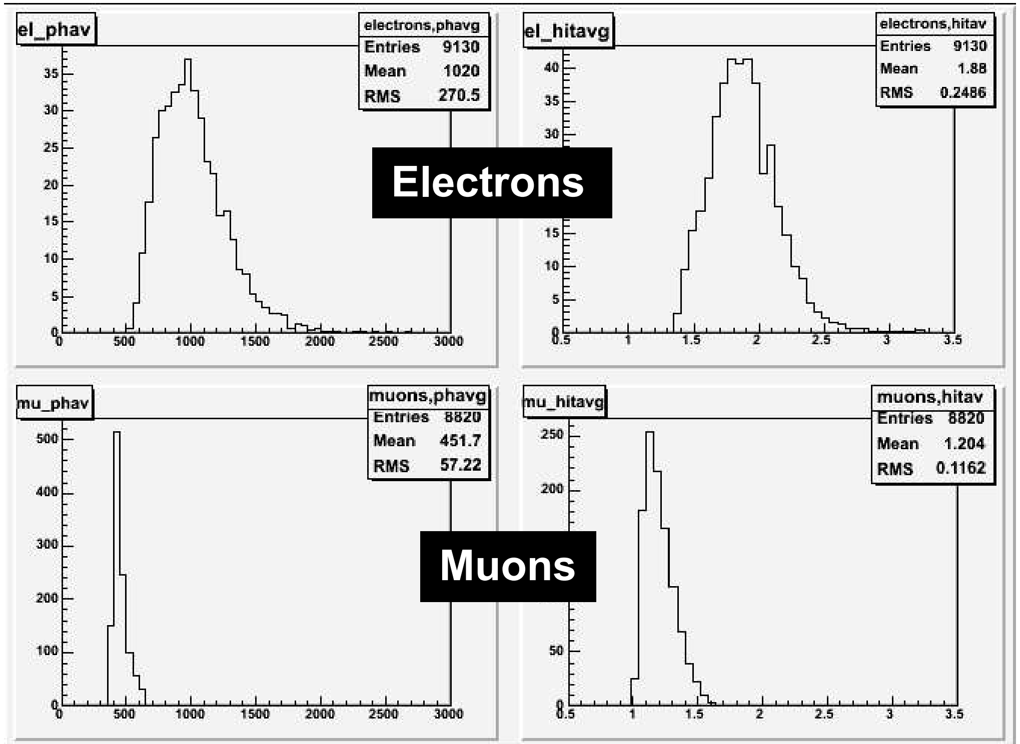
GOALS FOR THE DETECTOR

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

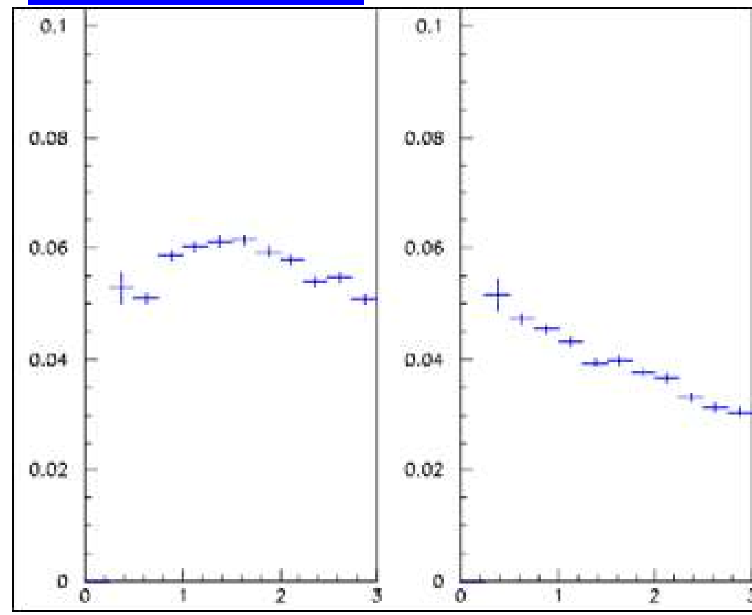
To reject beam ν_e – Good detector energy resolution

ELECTRON IDENTIFICATION & ENERGY RESOLUTION



Average Pulse Height/Plane | **Average # of Hits/Plane**

All ν_e events | **QE events only**



Energy E in GeV

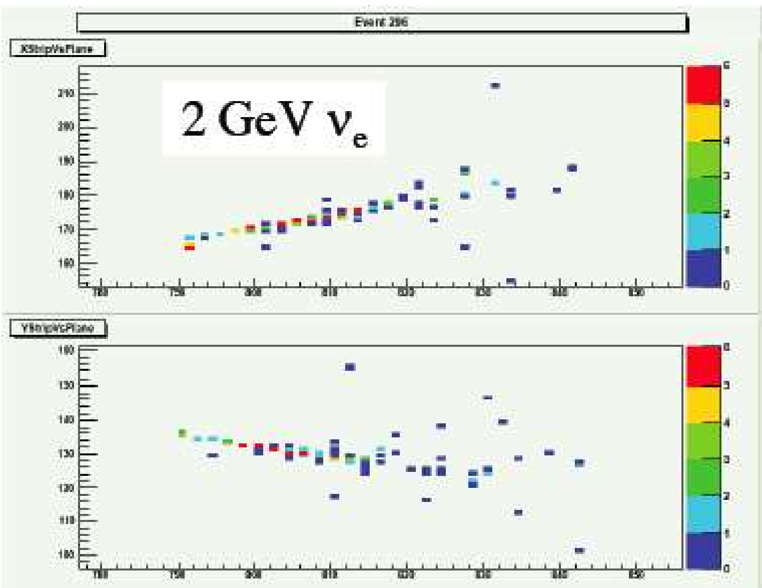
$\Delta E/E(\sigma)$ ~8%/$E^{1/2}$

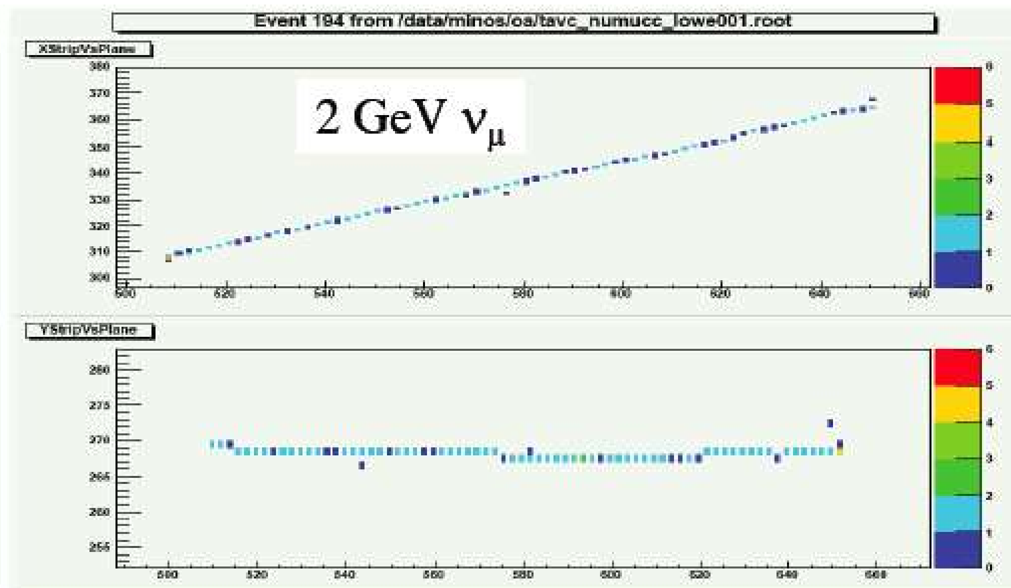
One can also use average pulse height per plane, ave. # of hits/plane, RMS of pulse height per plane, gaps, and energy cuts to distinguish between muons & electrons.

For a 2 GeV ν_e event energy measured to ~6%.

NOνA EVENT QUALITY

Longitudinal sampling is $0.15X_0$, which gives excellent μ-e separation.

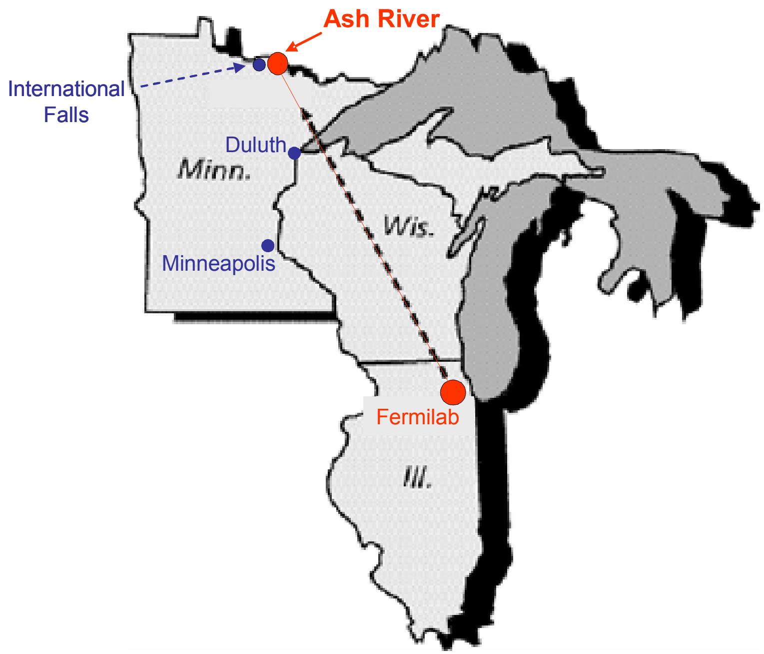


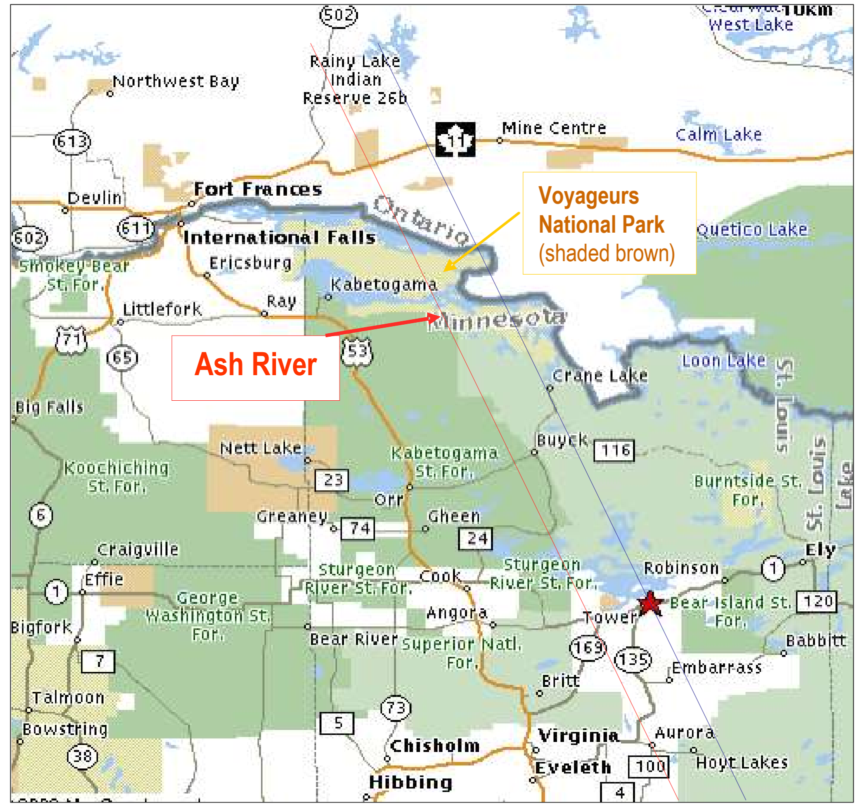


A 2-GeV ν_e is ~30-40 planes long.

A 2-GeV muon is ~100+ planes long.

WHERE WILL BE THE NOνA FAR DETECTOR?





Inside USA the Ash River site is the furthest available site at 810Km from Fermilab along the NuMI beamline. This maximizes NOνA's sensitivity to the mass ordering. It needs power upgrade and 3.6 miles of access road.

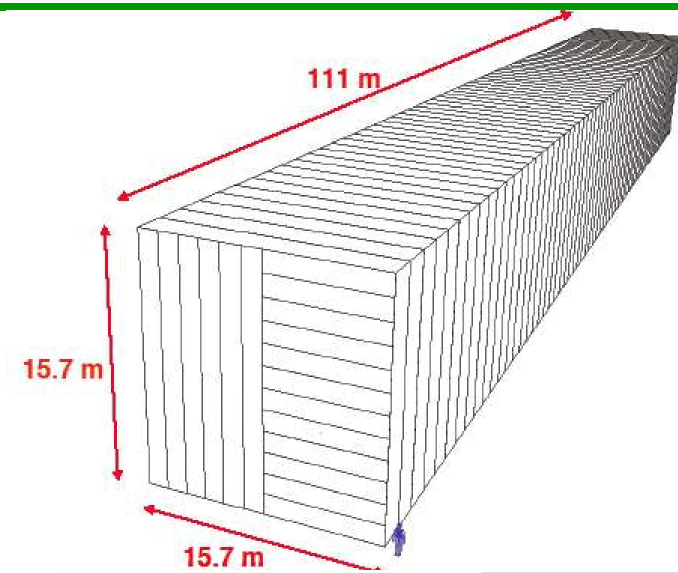
One can fly to International Falls – an hour drive

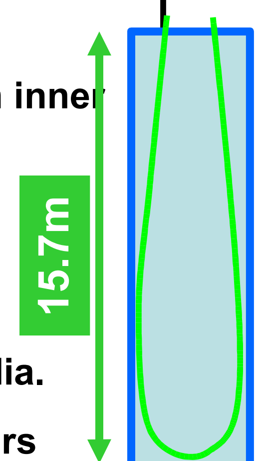
Many sites were available with varying angle from 14 to 17 mrad off-axis.

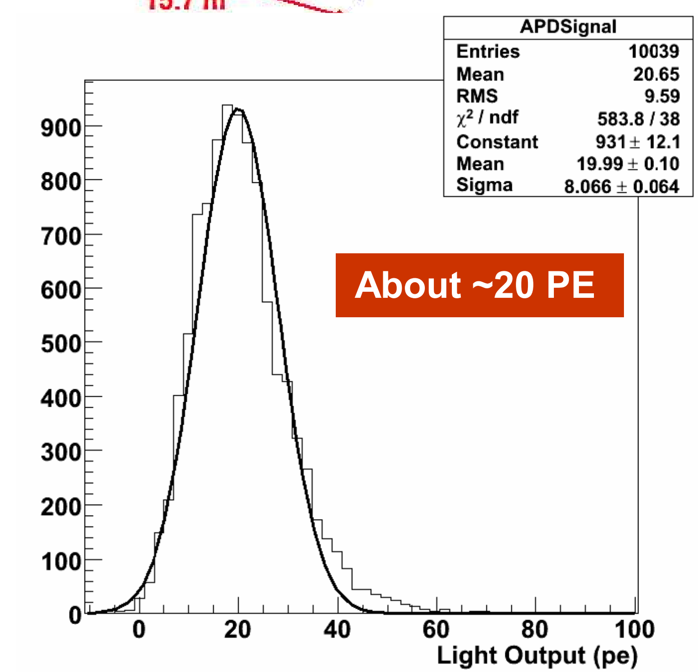
NOνA FAR DETECTOR

NOνA is an approved Fermilab proposal and has CD1 from US DOE

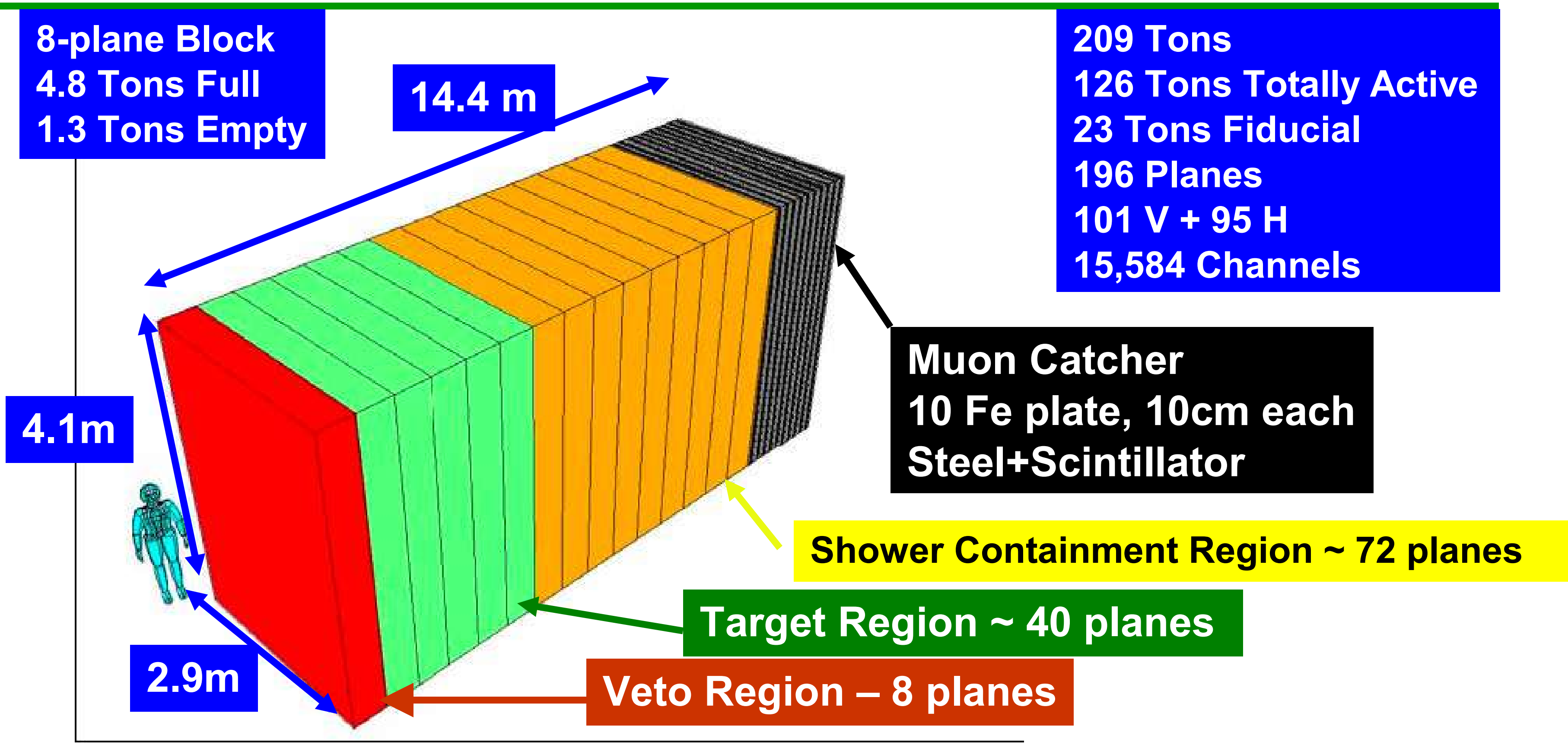
- Totally Active Liquid Scintillator Detector
  - Total Mass – 25.4 KTons
  - Mass of Scintillator ~18.5 KTons
  - Mass of RPVC Extrusions ~6.8 KTons
- Number of planes – 1674 in 54 blocks of 31 plane each, beginning & ending in vertical plane with horizontal in between
- Cell size 3.87cm X 6.0 cm X 15.7 m
- Cell wall thickness 3mm outer, 2mm inner
- Total number of cells 642,816
- Number of Extrusions 20,088
- Readout by
  - U-shaped WLS fiber – 0.8mm dia.
  - Fiber length ~21.6 Million meters
  - Fiber Mass 13.8 Tons
  - APD's with ~85% QE for 520-550 nm
- Readout Channels – 643K (~20K APD's)







NOνA NEAR DETECTOR

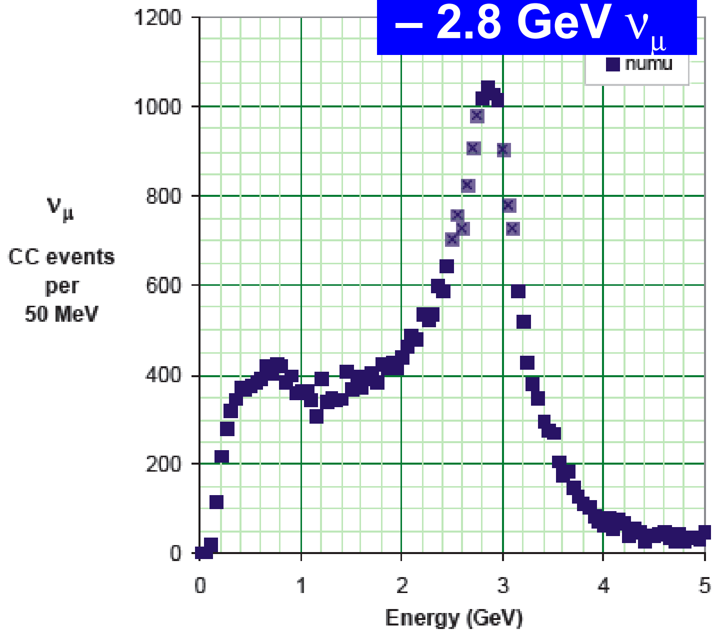


- ✓ ND will measure ν_e content of the beam at Fermilab
- ✓ Characterize the detector response to neutrino events, &
- ✓ Perform the crucial background studies
- ✓ **NOνA ND can be moved to FNAL on-axis test beam, MINOS surface building at 75 mr off-axis, inside NuMI access tunnel and the MINOS ND hall at various off-axis angles from 4mr to 21mr.**

NOνA NEAR DETECTOR – IN MINOS SURFACE BUILDING - ASAP

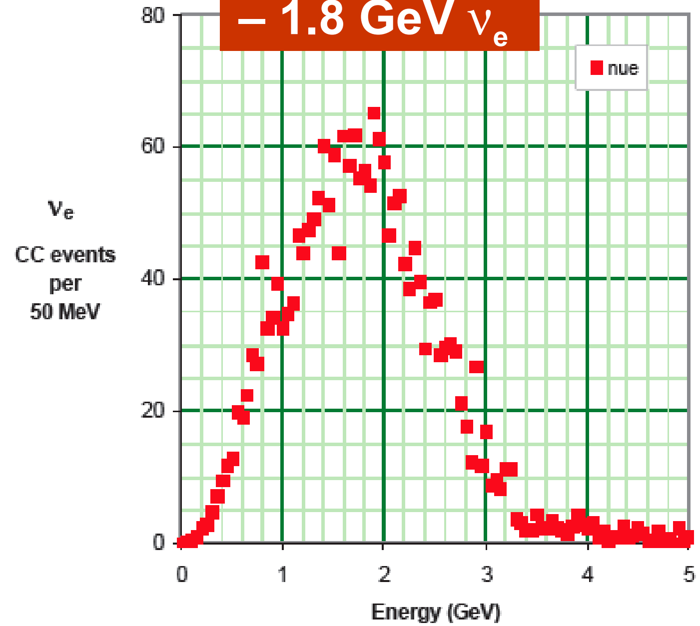
6.5 x 10^{20} POT in 75 mrad off-axis beam

Kaon peak – 2.8 GeV ν_μ



45,000 ν_μ CC events

Kaon peak – 1.8 GeV ν_e



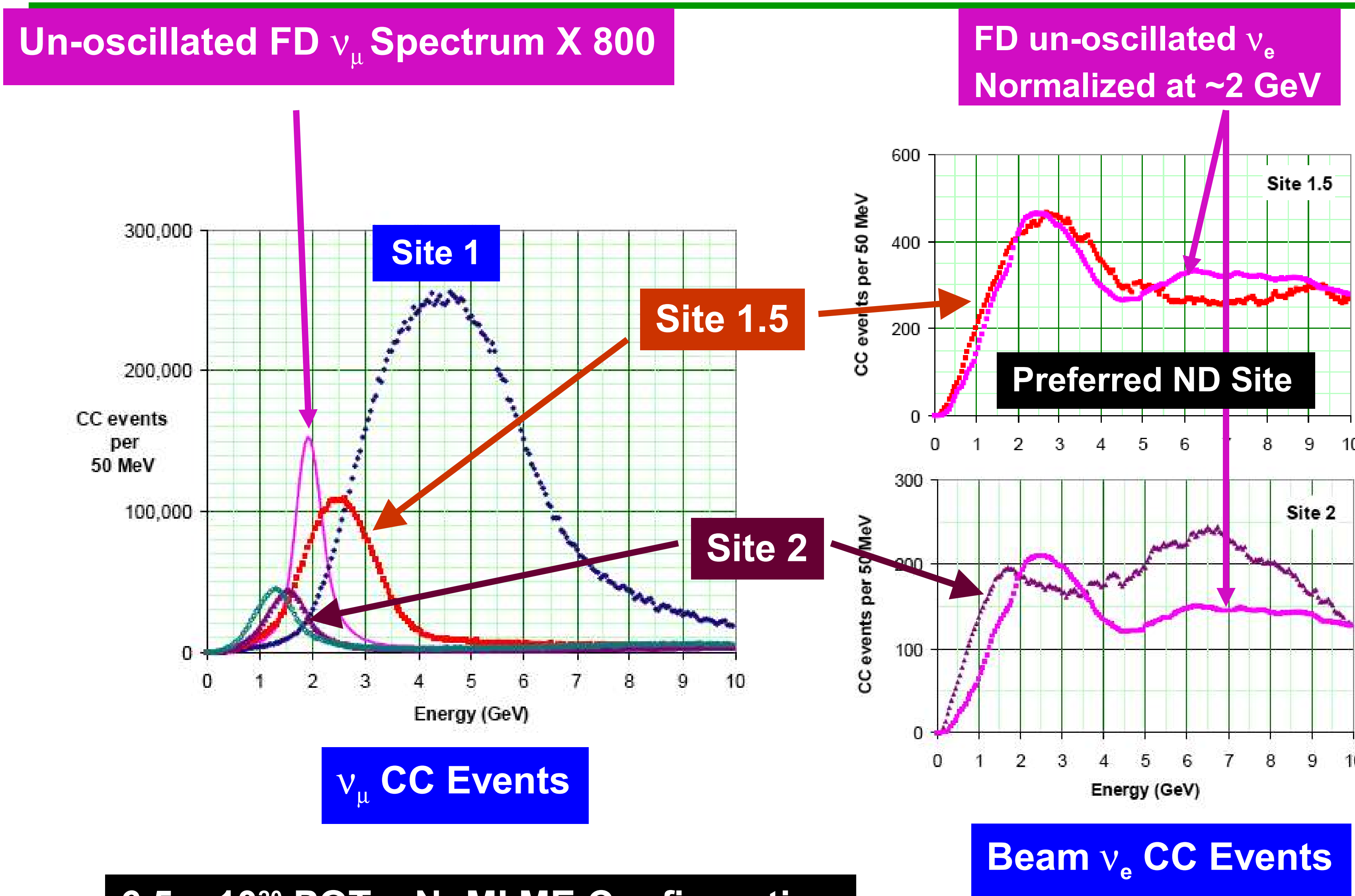
2,200 ν_e CC events

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

Prototype hopefully in MINOS building by late 2007

NOνA NEAR DETECTOR – IN THE NuMI ACCESS TUNNEL



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
- The average power achieved at Fermilab NuMI/MINOS is ~170KW
- The maximum power achieved so far is ~270KW
- Power for NuMI while Tevatron runs (till 2009) with modest upgrade
  - ✓ ⇒ ***$3.4X10^{20}$ POT/YEAR (340KW)***
- Protons for MINOS+NOνA in Post Tevatron Era (After 2009)
  - ✓ ⇒ ***Even with 90% efficiency we have ⇒ $6.5X10^{13}$ POT/yr (650KW)***

✓ ***With Further upgrade one can go upto 1.0+MW***

✓ FY2011 : 44 weeks – 400KW to 700KW

✓ FY2012 : 38 weeks – 700KW to 1MW

✓ FY2013 & beyond: 44 weeks @ 1MW

Recycler & Accumulator as proton stackers

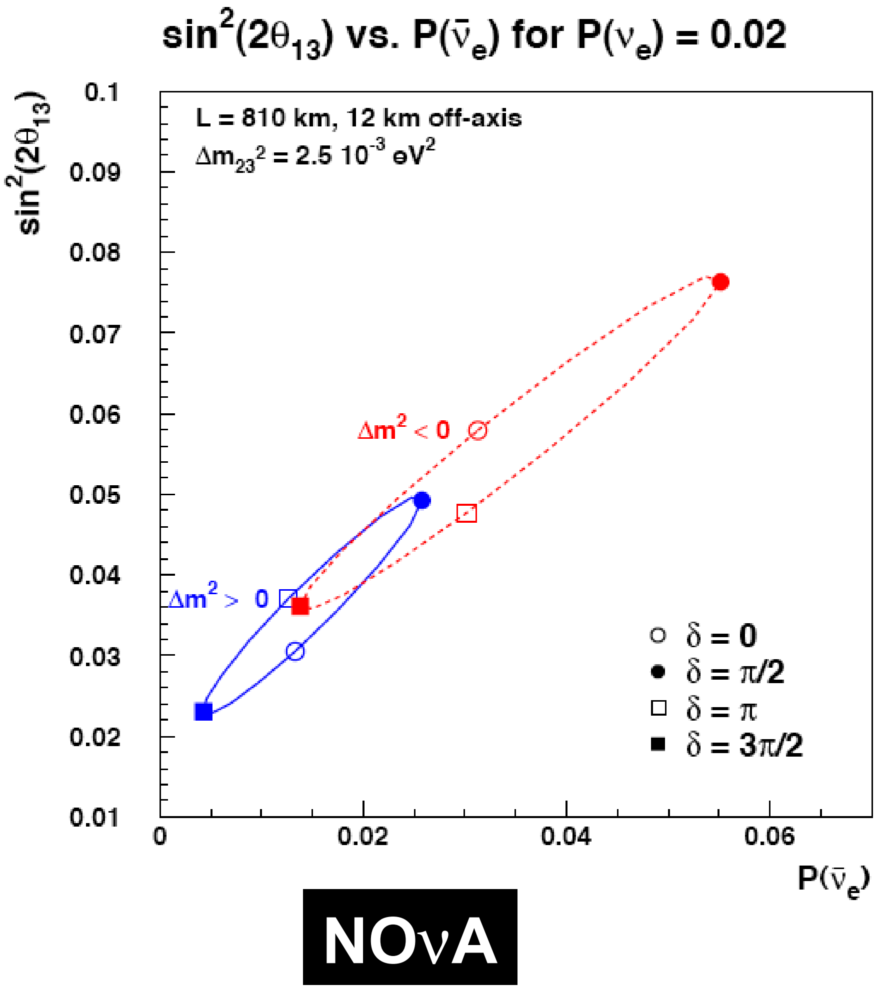
New Booster-Accumulator & Accumulator-Booster Lines

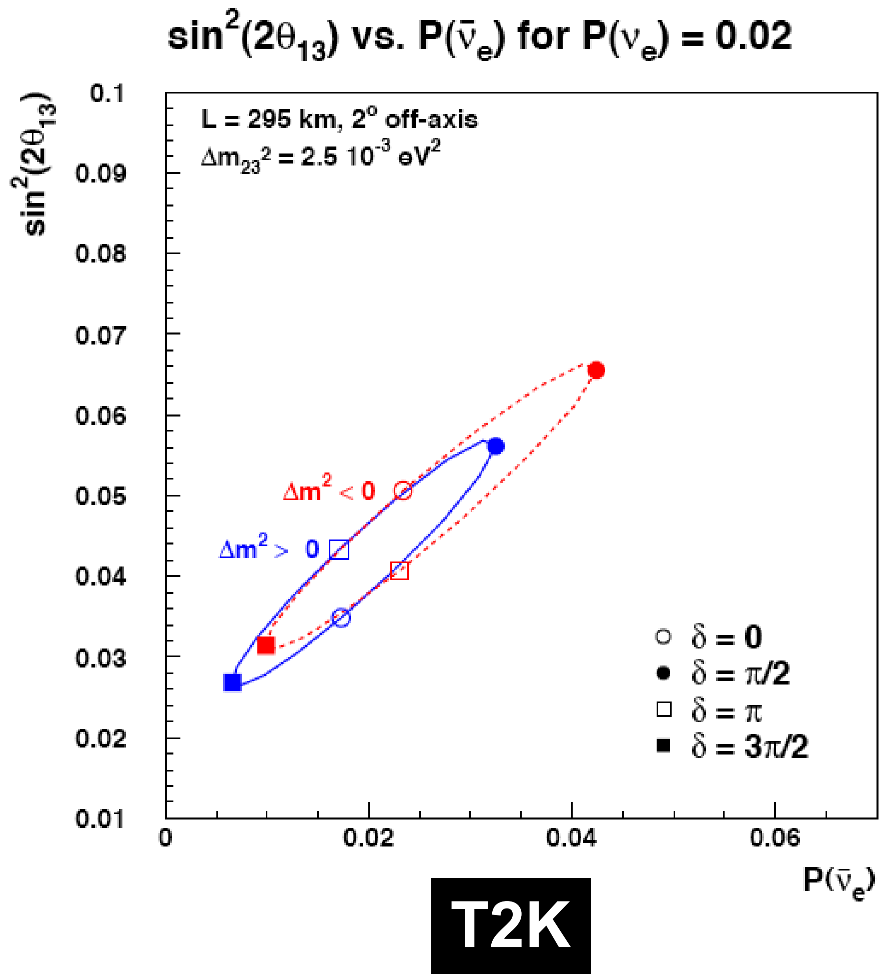
MI RF Upgrade

NuMI Target Upgrade

✓ ***NOνA in ~6 years will accumulate ~$60X10^{20}$ POT.***

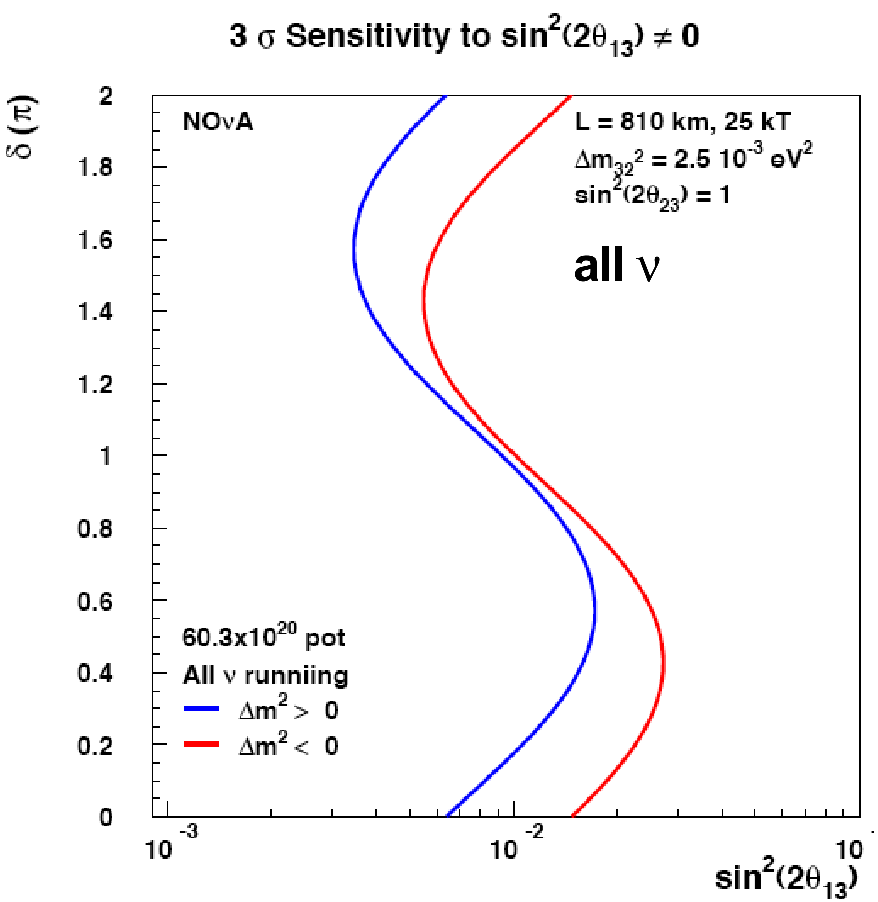
PARAMETERS CONSISTENT WITH A 2% $\nu_\mu \rightarrow \nu_e$ OSCILLATION

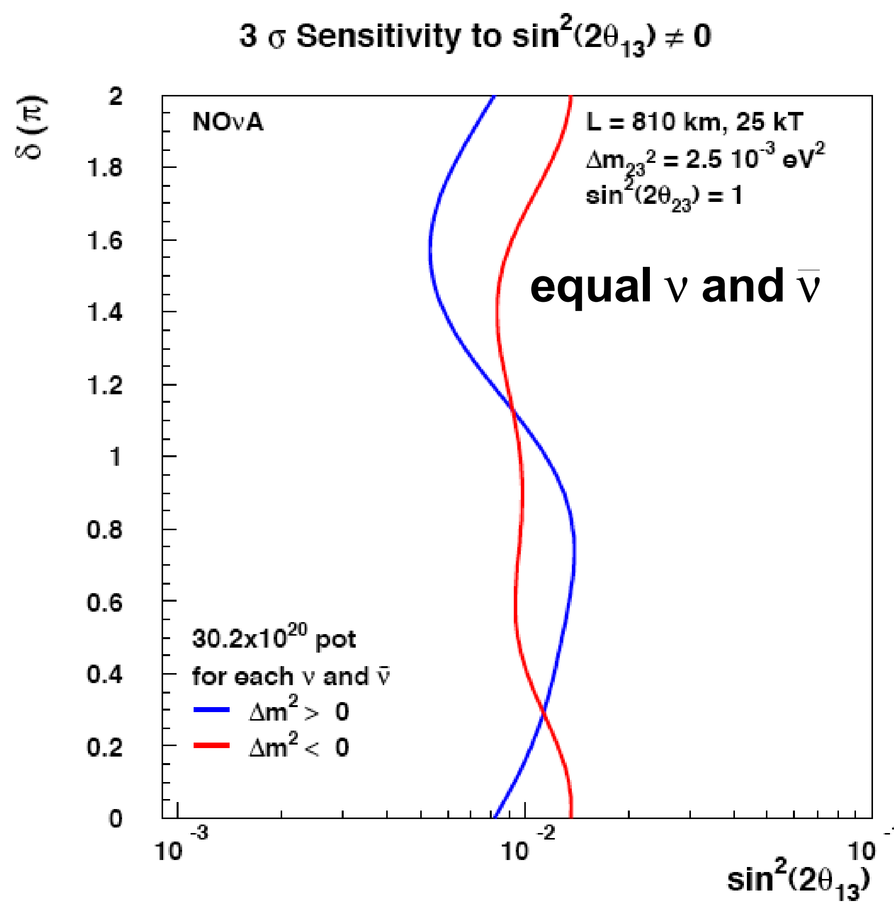




Irreducible. Can't fix the problem with higher statistics. One needs an additional baseline.

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

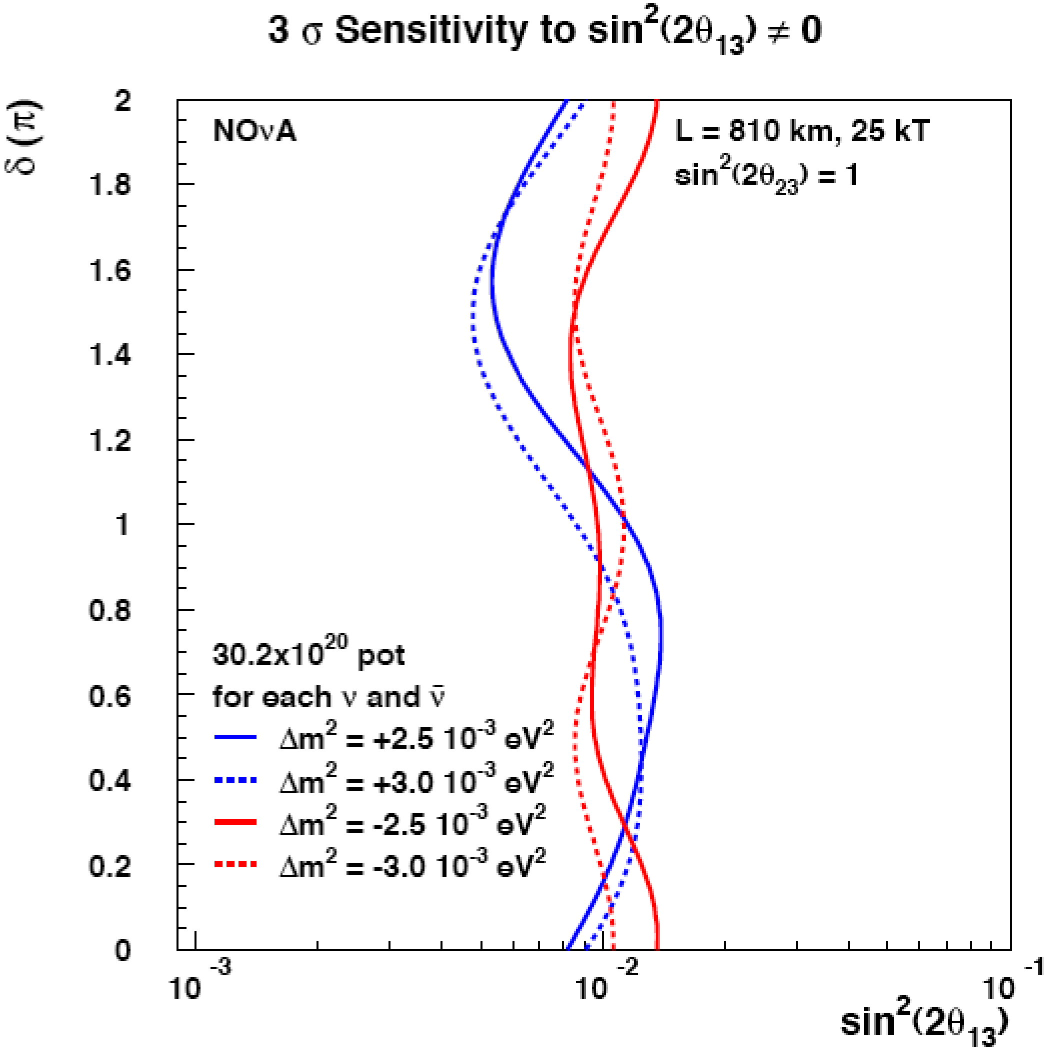




6 YEAR ν ONLY RUN

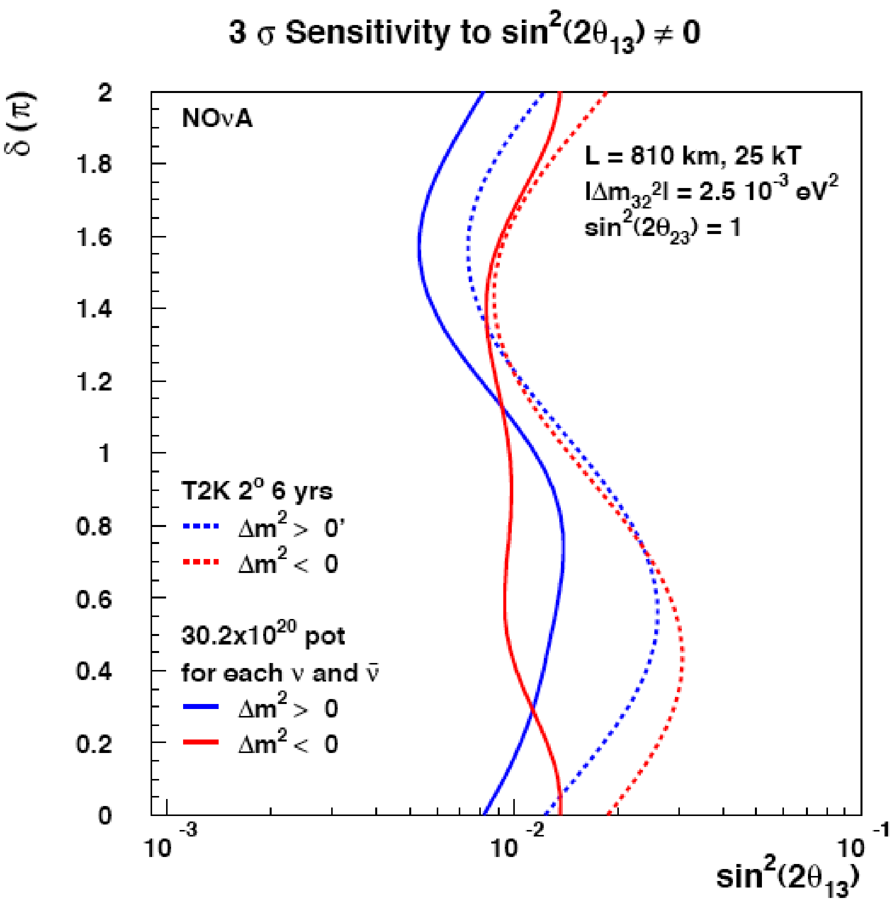
3 YEAR EACH ν & νbar RUN

NOVA 3σ SENSITIVITY TO $\theta_{13} \neq 0$ FOR $\Delta m^2_{23}=2.5\times10^{-3}$ & 3.0×10^{-3} eV^2

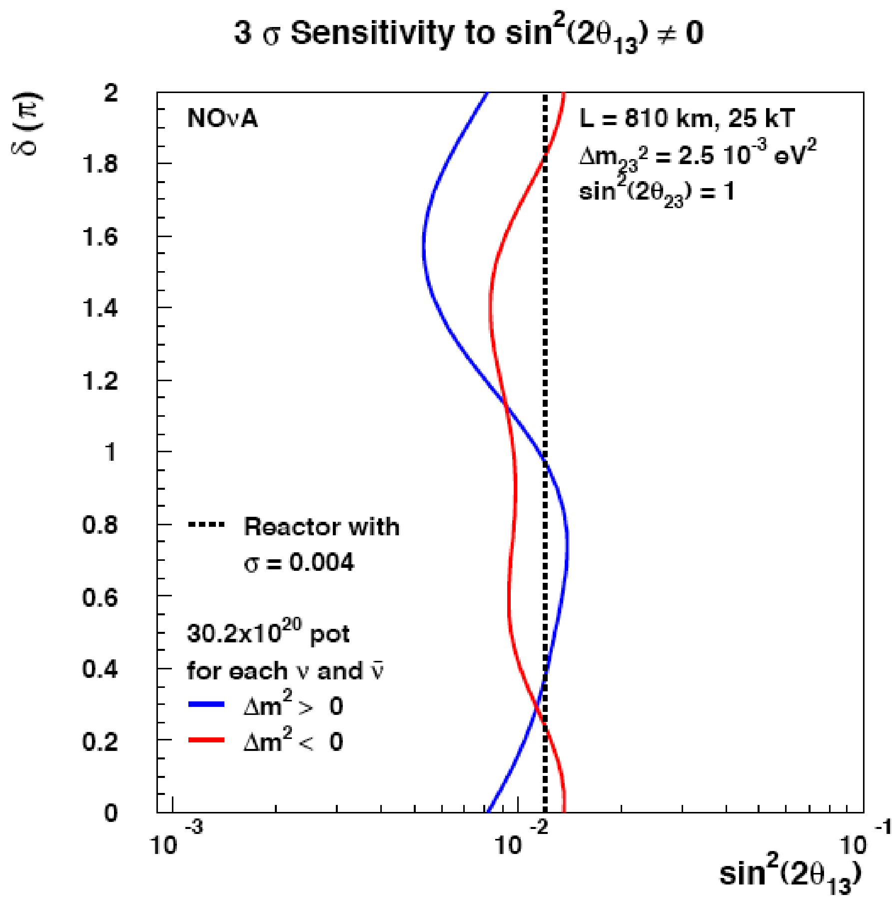


Sensitivity to $\sin^2 2\theta_{13}$ is not much different for these two values of Δm^2_{23}

COMPARISON WITH T2K AND A REACTOR EXPERIMENT



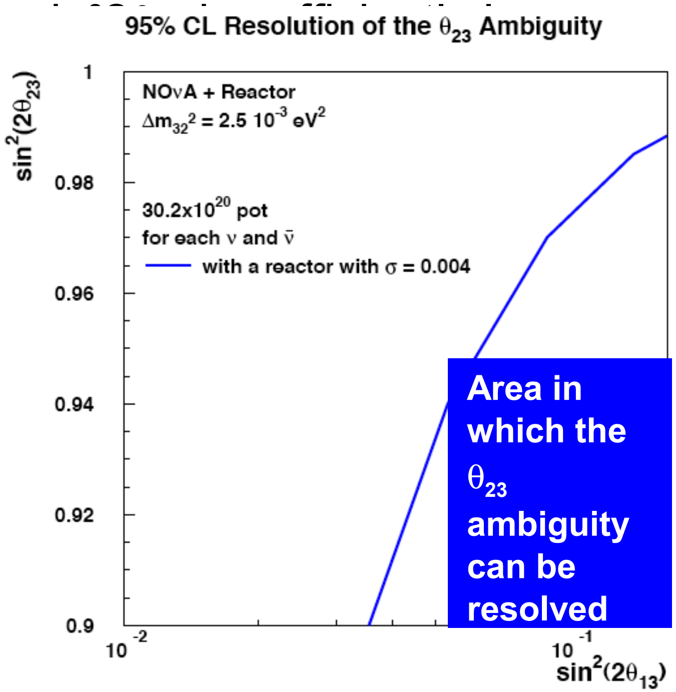
T2K



Reactor

95% CL RESOLUTION OF THE θ_{23} AMBIGUITY

- If θ_{23} is non-maximal then there will be an ambiguity in comparing the results on θ_{13} from accelerator and reactor experiments.
  - Reactor experiments are sensitive to $\sin^2 2\theta_{13}$
  - Accelerator experiments are sensitive to $\sin^2\theta_{23}\sin^2 2\theta_{13}$
- Resolving this ambiguity is the main complementarity between the two types of experiments. It can be done if the θ_{23} mixing is sufficiently non-maximal and

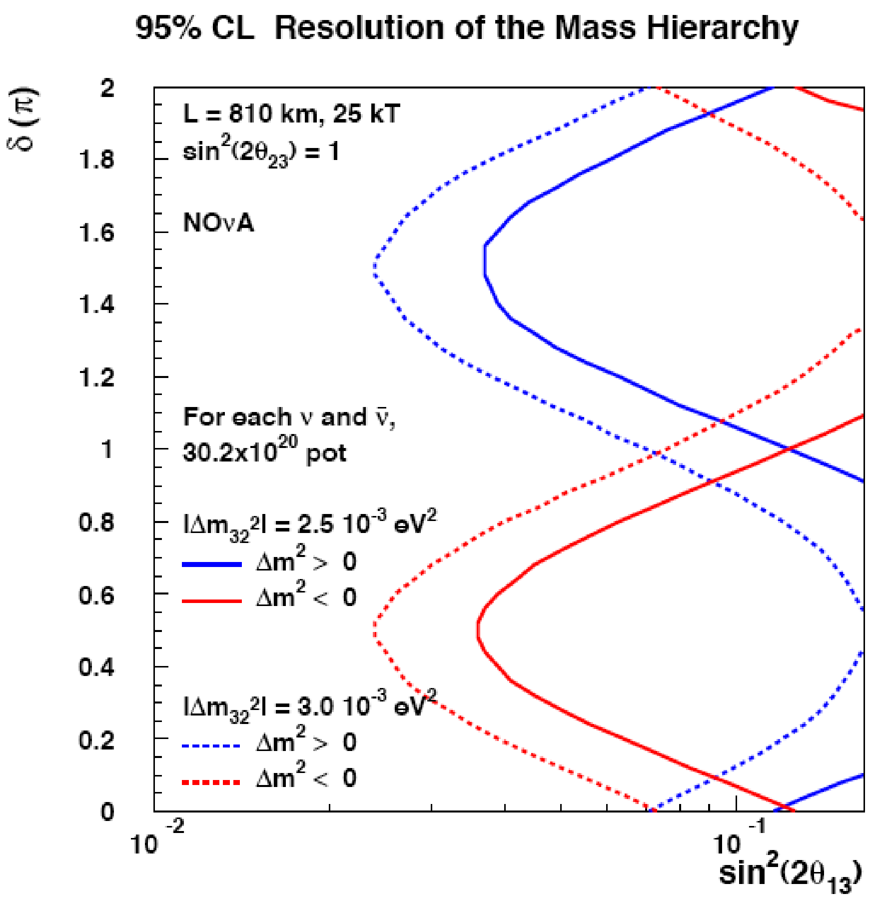


There is some sensitivity to the mass ordering and δ. The blue line represents an average over these parameters.

IMPORTANCE OF MASS ORDERING DETERMINATION & NOνA

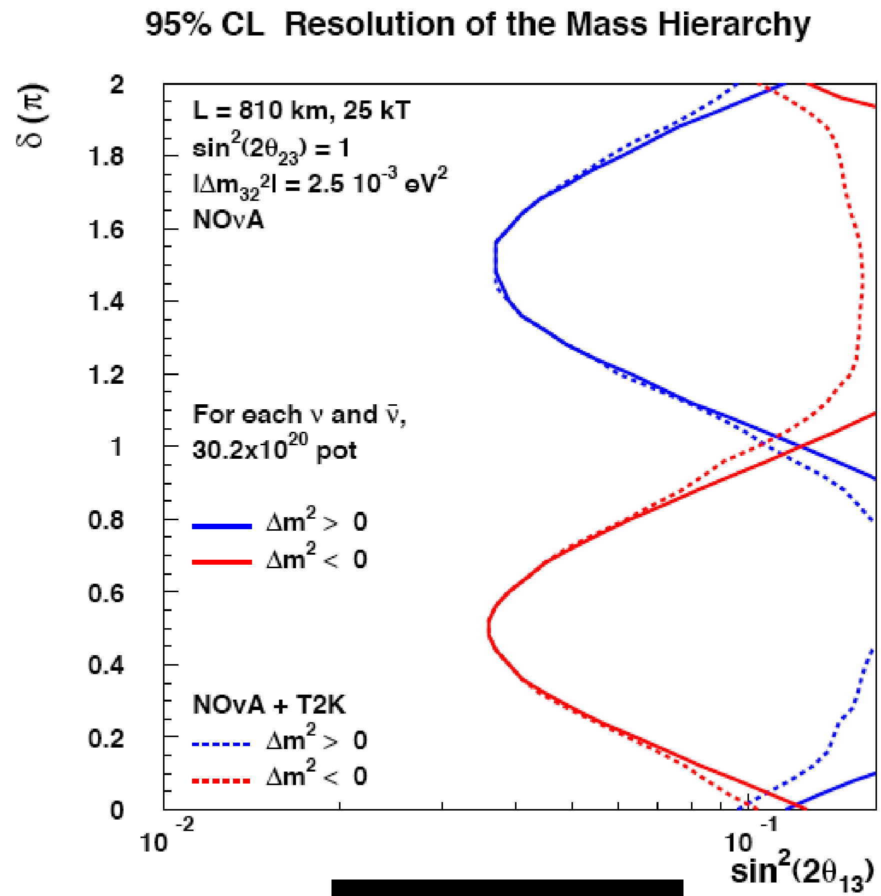
- ✓ The mass ordering can only be resolved by matter effects in the earth over long baselines.
- ✓ If we establish the inverted ordering, then the next generation of $0\nu\beta\beta$ experiment can decide whether the neutrino is its own antiparticle. However, if the normal ordering is established, a negative result from these experiments will be inconclusive.
- ✓ 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.

95% CL RESOLUTION OF THE MASS ORDERING



NOνA ONLY

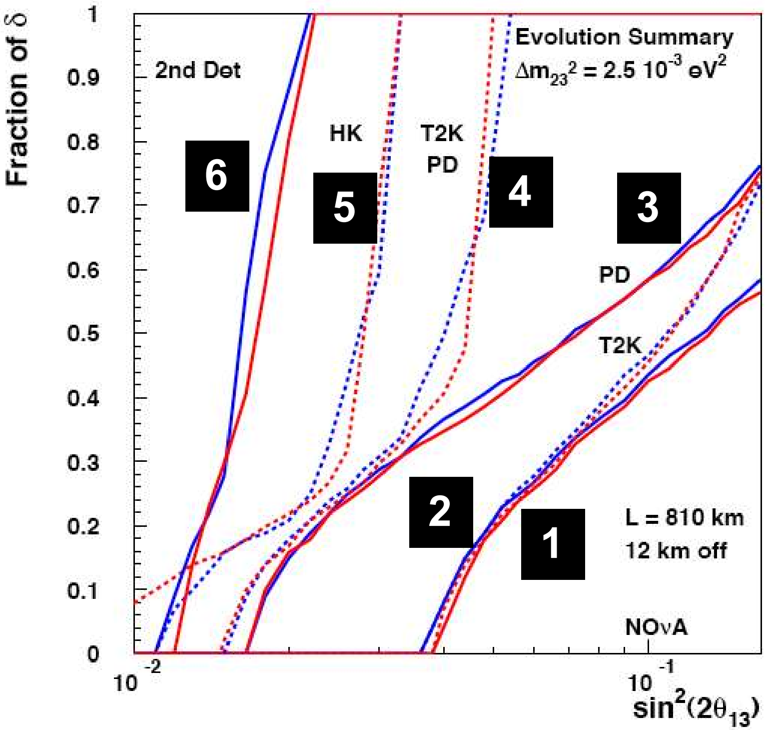
Δm^2_{23} = 2.5x10^{-3} eV^2 &
Δm^2_{23} = 3.0X10^{-3} eV2

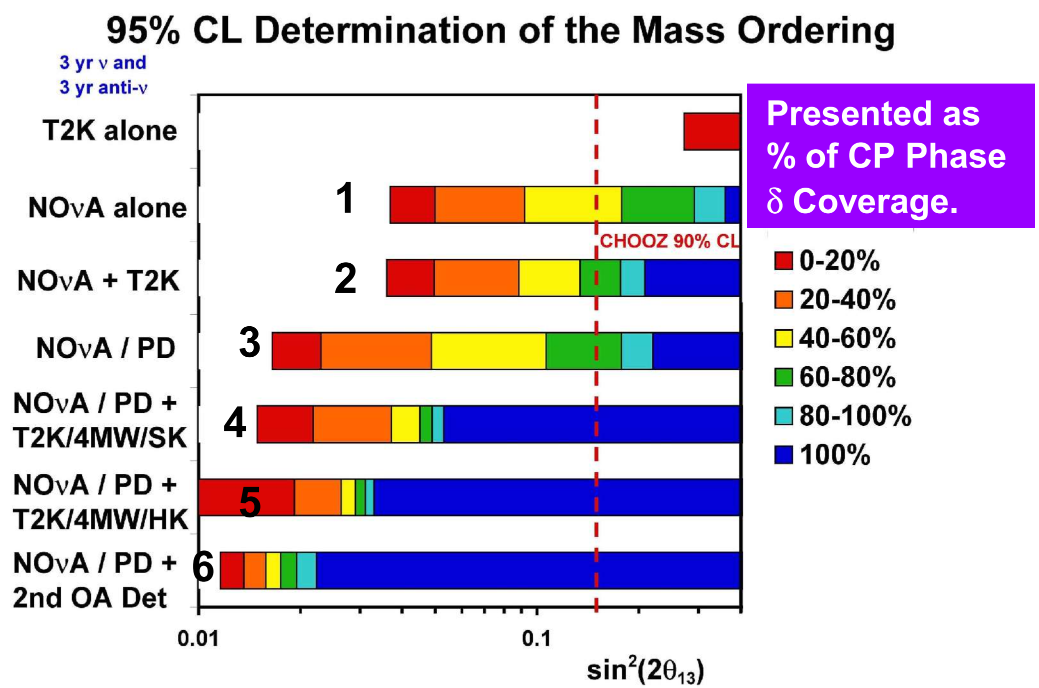


NOνA + T2K

Δm^2_{23} = 2.5x10^{-3} eV^2

NOνA MASS ORDERING DETERMINATION

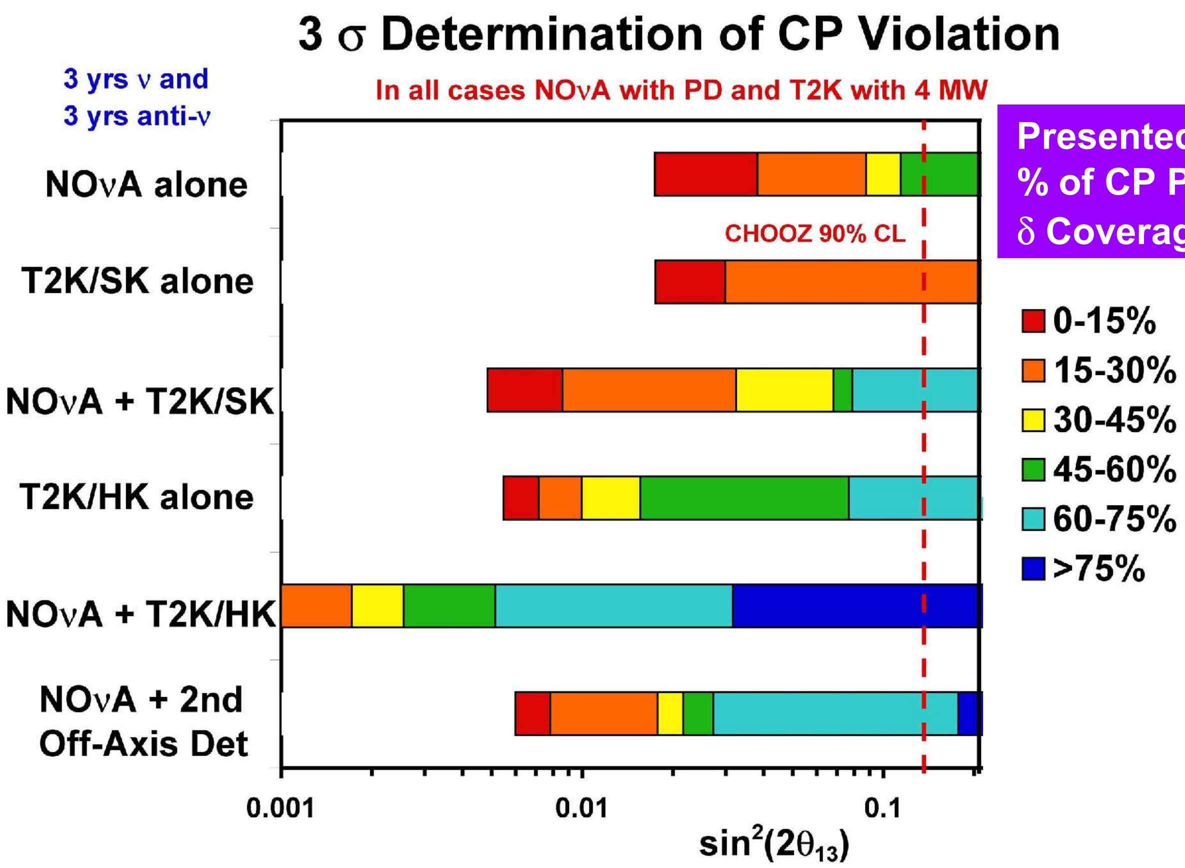




95% CL Resolution of the Mass Ordering

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

NOνA & CP VIOLATION



Presented as % of CP Phase δ Coverage.

FOR MEASURING CPV PHASE δ SEVERAL MW POWER IS NEEDED.

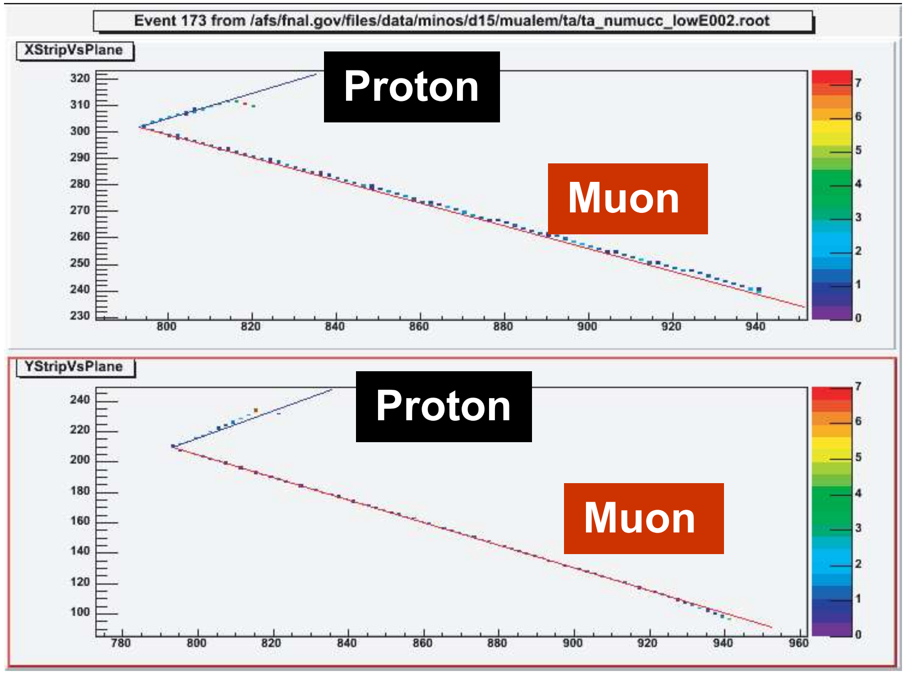
ACCELERATOR UPGRADE IS A MUST EITHER IN USA OR IN JAPAN.

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

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

- ✓ Whether the atmospheric mixing is maximal is an important question both practically (comparison of reactor and accelerator measurements) and theoretically (Is there a symmetry that induces maximal mixing?).

- ✓ The combination of the narrow-band beam and NOνA's excellent energy resolution allows it to do a high-precision measurement of $\sin^2(2\theta_{23})$ by measuring quasi-elastic ν_μ CC events.



Quasi-elastic Events are very clean in the Detector

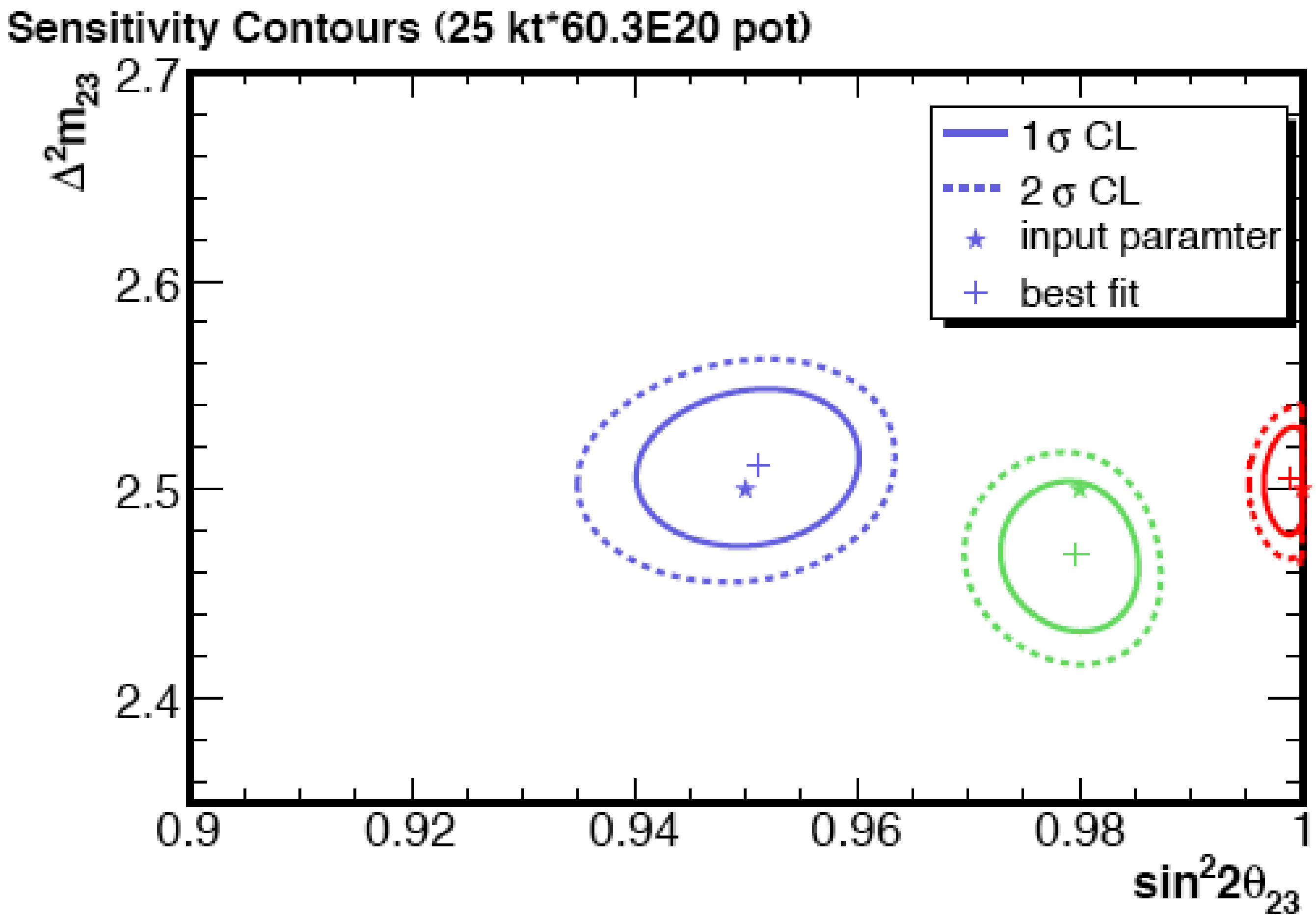
Excellent Energy Resolution

Essentially no Neutral Current Background

Allows for Clean Measurement of $Sin^2 2\theta_{23}$

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

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



For maximal mixing that is $Sin^2 2\theta_{23}$ = 1, $\delta(Sin^2 2\theta_{23})$ = 0.004, otherwise $\delta(Sin^2 2\theta_{23})$ = 0.01.

NOνA TIMELINE, COST & SENSITIVITY FOR θ_{13}

- ✓ 4/2006 – CD1 review – Unanimous recommendation
- ✓ 10/2006 – CD2 review
- ● 10/2008 – First Module factory ready – Begin FD construction
- ● 06/2009 – Occupancy of the Far Detector enclosure
- ● 11/2010 – First 5Kton of FD complete, start taking data
- ● 11/2011 – Far detector completed

- ❑ COST - $226M in FY2006 dollars, including $57M in contingency. In actual year dollar this is $247M

- ➢ Estimated timeline to establish a 3σ sensitivity to $\theta_{13} \neq 0$ for normal mass ordering with $\Delta m^2_{23} = 2.5 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23} = 1.0$, and $\delta = 0$
  - ✓ Jan. 2012, if $\sin^2 2\theta_{13} = 0.05$
  - ✓ Nov. 2012, if $\sin^2 2\theta_{13} = 0.02$
  - ✓ Aug. 2014, if $\sin^2 2\theta_{13} = 0.01$

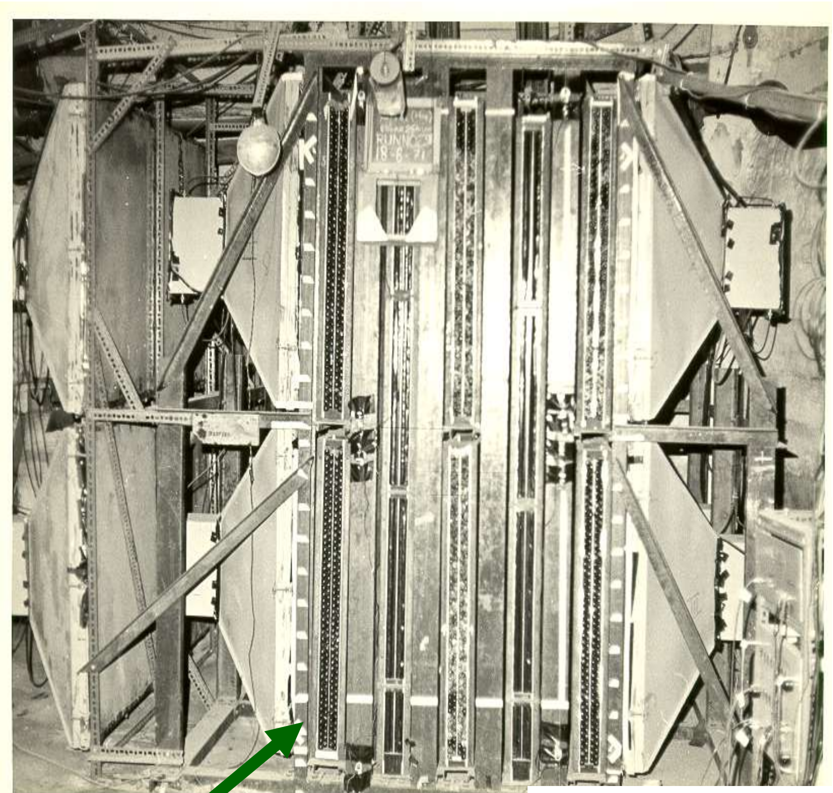
NOνA SUMMARY & CONCLUSIONS

1. **NOνA is a major Fermilab and US DOE HEP effort.**
2. **NOνA has CD1 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.**

HISTORY OF ATMOSPHERIC NEUTRINO IN INDIA

- **The KGF group from TIFR, India, Osaka University, Japan, & Durham University, UK were the first to report observation of 3 atmospheric neutrino induced events in:**
  - **Physics Letters 18, (1965) 196, dated 15th Aug 1965 .**
  - **Events were recorded on 30th March, 27th April, and 25th May, 1965.**
- Reines et al. reported observation of 7 events in:
  - PRL 15, (1965), 429, dated 30th Aug. 1965.
  - The first ever neutrino event was recorded on 23rd Feb. 1965.
- KGF collaboration contributed immensely to the cosmic ray and related physics. Glorious period of **"Cosmic Ray Physics in India".** The KGF mine was closed in early 90's for financial reasons . **What a shame!**
- India-based Neutrino Observatory is an attempt not to just have an underground laboratory in India but to revive the culture of doing most fundamental physical sciences in India at a large scale with international collaboration.
- ***<u>It has both excellent scientific and social value.</u>***

HISTORY OF ATMOSPHERIC NEUTRINO IN INDIA



Atmospheric Neutrino Detector at Kolar Gold Field – 1965. Depth ~ 7600 ft or ~7500 mwe.

50 days of operation ~ 2140 m^2 days steradian

DETECTION OF MUONS PRODUCED BY COSMIC RAY NEUTRINO DEEP UNDERGROUND

C. V. ACHAR, M. G. K. MENON, V. S. NARASIMHAM, P. V. RAMANA MURTHY and B. V. SREEKANTAN,
Tata Institute of Fundamental Research, Colaba, Bombay

K. HINOTANI and S. MIYAKE,
Osaka City University, Osaka, Japan

D. R. CREED, J. L. OSBORNE, J. B. M. PATTISON and A. W. WOLFENDALE
University of Durham, Durham, U.K.

Received 12 July 1965

Physics Letters 18, (1965) 196, dated 15th August 1965

EVIDENCE FOR HIGH-ENERGY COSMIC-RAY NEUTRINO INTERACTIONS*

F. Reines, M. F. Crouch, T. L. Jenkins, W. R. Kropp, H. S. Gurr, and G. R. Smith

Case Institute of Technology, Cleveland, Ohio

and

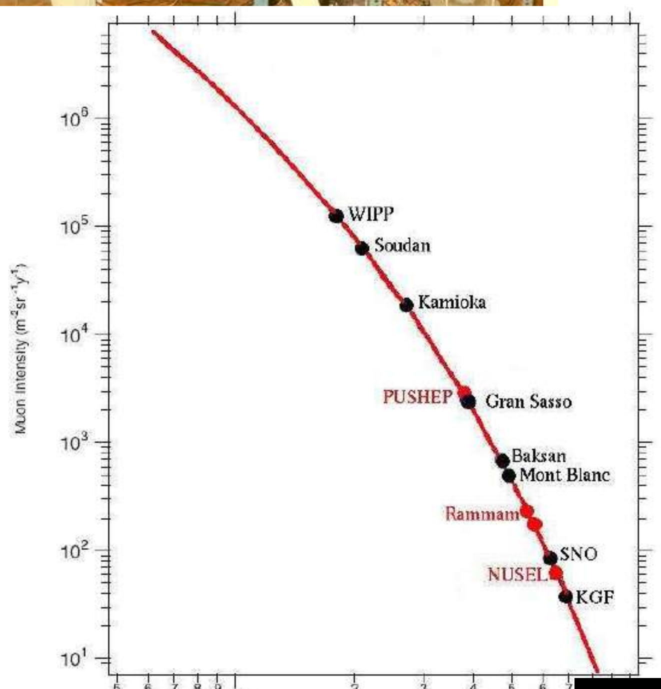
J. P. F. Sellschop and B. Meyer

University of the Witwatersrand, Johannesburg, Republic of South Africa
(Received 26 July 1965)

PRL 15, (1965), 429, dated 30th August 1965

AND KOLAR GOLD FIELD CONTINUED

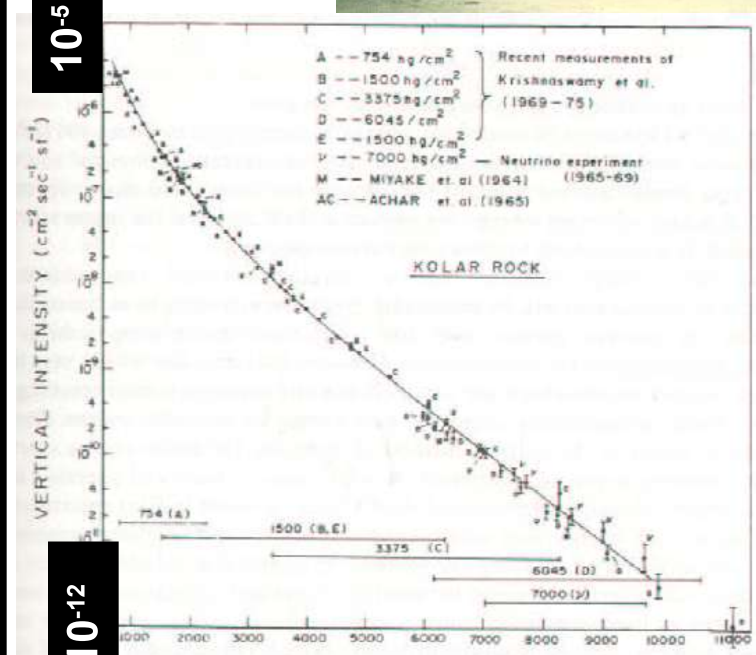
KGF collaboration contributed immensely to the Cosmic Ray and Particle Physics. The KGF mine was closed in early 90's.



10^3 mwe 10^4

Vertical Intensity (cm^{-2} Sec^{-1} sr^{-1})

10^{-5}



10^{-12}

1K 2K 3K 4K 5K 6K 7K 8K 9K 10K 11K
DEPTH (hg/cm^2) - For all cosmic ray experiments conducted until 1970

INO INITIATIVE

- ✓ **Multi Institutional Collaborative Approach from beginning - MOU signed by Directors of 7 Research Institutes under Department of Atomic Energy (DAE) in a meeting attended by Chairman, AEC on August 30th 2002. Universities joined later.**
- ✓ **At present 16 Institutions mostly from India on collaboration**
- ✓ **Two Phases Approach:**

R&D and Construction	Detector Operation
Phase I	**Phase I**
Detector R&D Physics Studies Site Survey Human Resource Development	Physics with Atmospheric ν 2012-2020
Phase II	**Phase II**
Construction of the Detector	Physics with Neutrino Beam from a Factory Sometimes in Future

INO DETECTOR

- **Detector choice based on:**
  - ✓Technological capabilities available within the country
  - ✓Existing/Planned other neutrino detectors around the world
  - ✓Modularity and the possibility of phasing
  - ✓Compactness and ease of construction
- **Detector should have:**
  - ✓Large target mass (50-100 KTon)
  - ✓Good tracking and energy resolution (tracking calorimeter)
  - ✓Good directionality or time resolution ~ 1nsec
- **The proposed detector is:**
  - ✓Phase I – A 50 KTon magnetized iron-RPC based modular detector
  - ✓Phase II – Expect to increase target mass to 100KTon

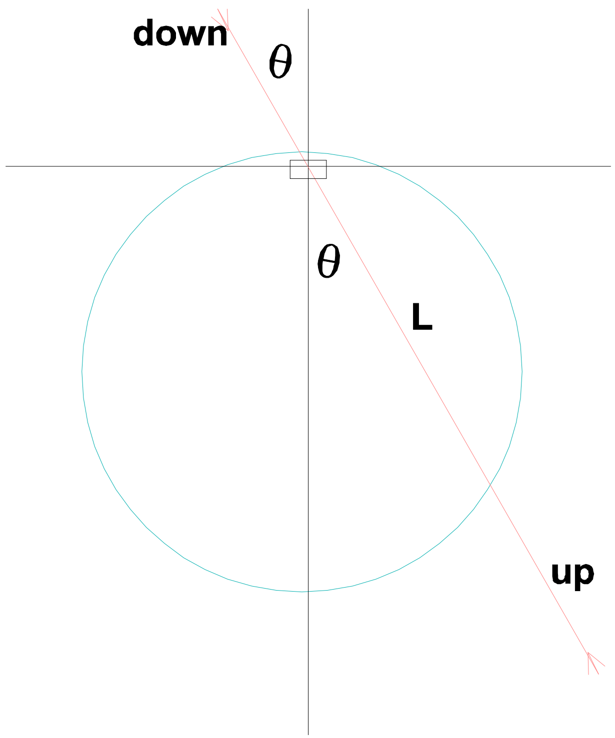
Magnetized Fe-RPC calorimeter, a la MONOLITH.

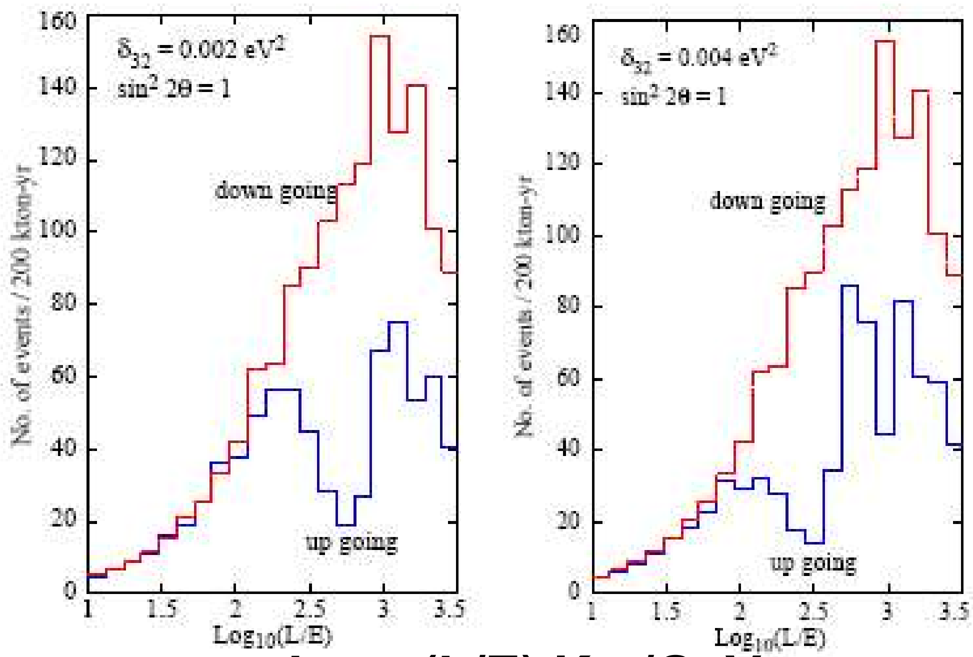
WHAT PHYSICS ONE CAN DO WIT SUCH A DETECTOR?

- **Phase I – Atmospheric neutrino**
  - ✓ Explicit observation of first oscillation swing as a function of L/E
  - ✓ Improved measurement of Δm^2_{23} and $Sin^2 2\theta_{23}$
  - ✓ Search for potential matter effect and sign of Δm^2_{23} from μ^+ & μ^- events
  - ✓ Discrimination between $\nu_\mu \to \nu_\tau$ vs. $\nu_\mu \to \nu_s$
  - ✓ CPT violation
- **Phase II – Beam neutrino (Neutrino Factory)**
  - ✓ Determination of θ_{13} from $\nu_e \to \nu_\mu$ oscillations
  - ✓ Sign of Δm^2_{23} from $\nu_e \to \nu_\mu$ oscillations
  - ✓ CP violation
  - ✓ Search for potential matter effects in $\nu_\mu \to \nu_\tau$ and sign of Δm^2_{23}
- **Other Physics Possibilities**
  - ✓ Ultra high energy neutrinos and muons

EXPLICIT MEASUREMENT OF L/E

Measure the disappearance probability with a single detector and two equal sources – down-going and up-going muons produced by neutrino interactions



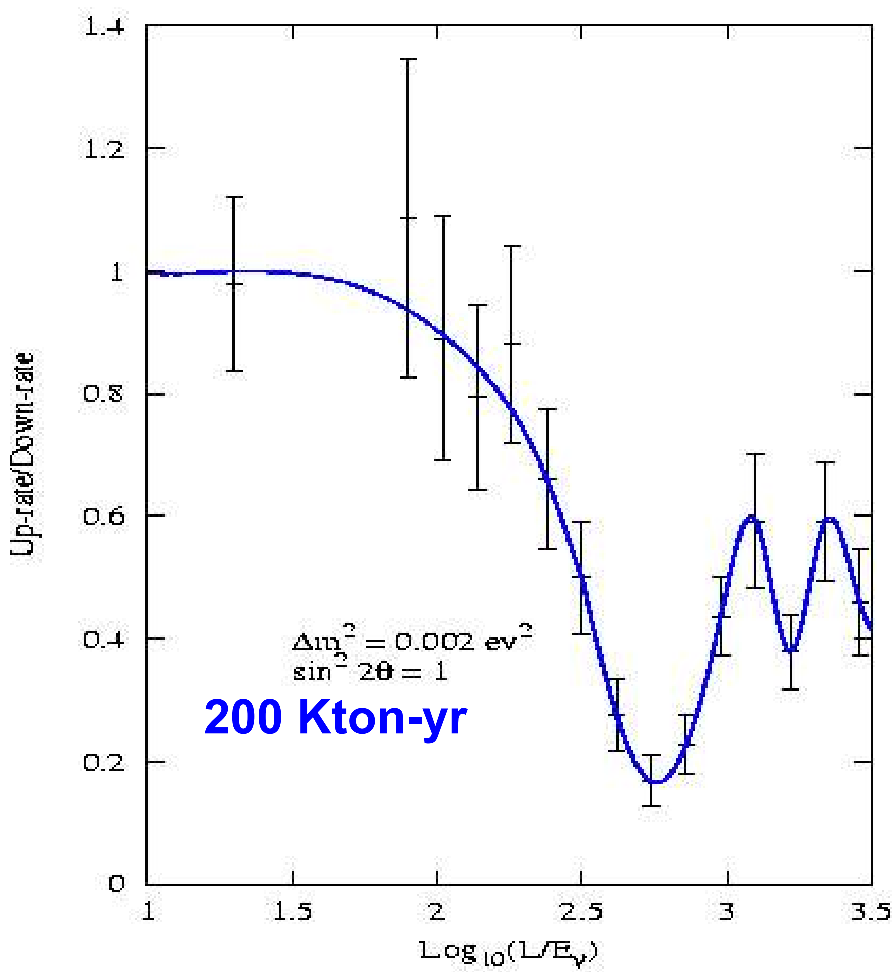


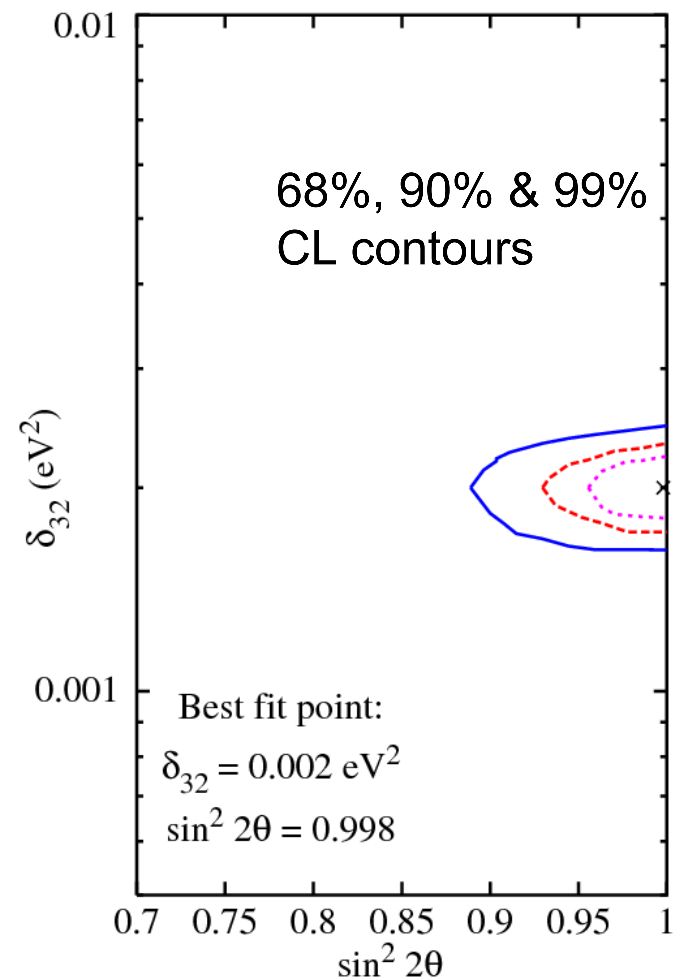
Log_{10}(L/E) Km/GeV

Expect to measure Δm^2_{23} to ~10% and $Sin^2\theta_{23}$ to ~30% precision at 3σ (total spread around central value)

EXPLICIT MEASUREMENT OF L/E

$N^{\uparrow}_{\mu}(L/E)/N_{\downarrow}^{\mu}(L/E) = P(\nu_\mu \rightarrow \nu_\mu\ ;\ L/E) = 1 - \mathrm{Sin}^2(2\theta_{23})\ \mathrm{Sin}^2(1.27\Delta m^2_{23} L/E)$





CPT VIOLATION

CPT violation can be studied by different survival probabilities of ν_μ and $\bar{\nu}_\mu$ atmospheric neutrino generated muons in a magnetized iron detector.

Consider the effective C and CPT-odd interactions terms $\bar{\nu}^{\alpha}_{L} b^{\mu}_{\alpha\beta} \gamma_\mu \nu^{\beta}_{L}$, where α and β are flavor indices. In presence of this CPTV terms, the neutrino energy acquires an additional term which comes from the matrix $b^o{}_{\alpha\beta}$. For anti-neutrinos this term has opposite sign.

$$P_{\mu\mu}(L) = 1 - \sin^2 2\theta \sin^2\left[\left(\frac{\delta_{32}}{4E} + \frac{\delta b}{2}\right)L\right]$$

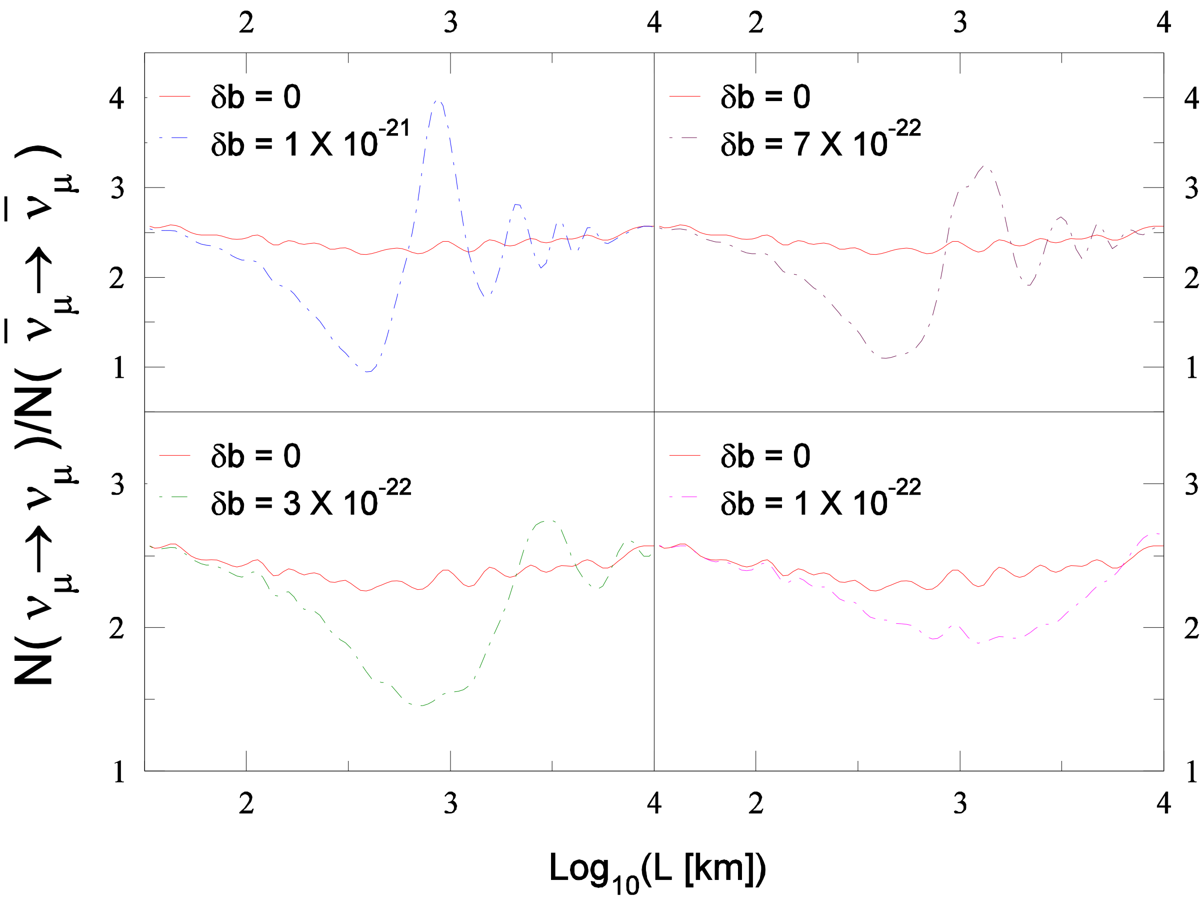
R. Gandhi et al., PLB597, 356 (2004)

$$\Delta P^{CPT}_{\mu\mu} = P_{\mu\mu} - P_{\bar{\mu}\bar{\mu}} = -\sin^2 2\theta \sin\left(\frac{\delta_{32} L}{2E}\right) \sin(\delta b L)$$

where δ_{32} and δb are the differences between the eigenvalues of the matrices m^2 and b, respectively, and α corresponds to μ or τ flavor. Equal mass has been assumed for neutrino and anti-neutrino. Mixing angle that diagonalize the matrix are $\theta_m = \theta_b = 0$. Additional phase arising due to two different unitary matrices needed to diagonalize the δ_{32} and δb is set to zero.

Observable CPTV in 2-flavor case is a consequence of interference of CPT-even and CPT-odd terms.

CPT VIOLATION



Ratio of total (up+down) muon to anti-muon.

Plots for values
Δm^2_{23} = 0.002 eV^2
$Sin^2 2\theta_{23}$ = 1.0
$Sin^2 2\theta_{13}$ < 0.1
Matter-Effect neglected.

An exposure of 400KTon years would be sufficient for statistically significant signals to emerge.

MATTER EFFECT

R. Gandhi et al PRL 94, 051801, 2005

Total no. of ν_μ charge current events:

$$N_\mu = N_n \times M_Y \int dE \int d\cos\theta_z \left[\frac{d^2\phi_\mu}{dEd\cos\theta_z} P_{\mu\mu}(E,L) + \frac{d^2\phi_e}{dEd\cos\theta_z} P_{e\mu}(E,L) \right] \sigma_\mu(E)$$

Neglecting Δ_{21} and for constant density approximation:

$$P^{vac}(\nu_\mu \to \nu_e) = \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2(1.27\Delta_{31} L/E)$$

$$P^{mat}(\nu_\mu \to \nu_e) = \sin^2\theta_{23} \sin^2 2\theta^m{}_{13} \sin^2(1.27\Delta^m{}_{31} L/E)$$

Where

$$\sin 2\theta^m{}_{13} = \sin 2\theta_{13}\Delta_{31} / \Delta^m{}_{31}$$

$$\Delta^m{}_{31} = \sqrt{(\Delta_{31}\cos 2\theta_{13} - A)^2 + (\Delta_{31}\sin 2\theta_{13})^2}$$

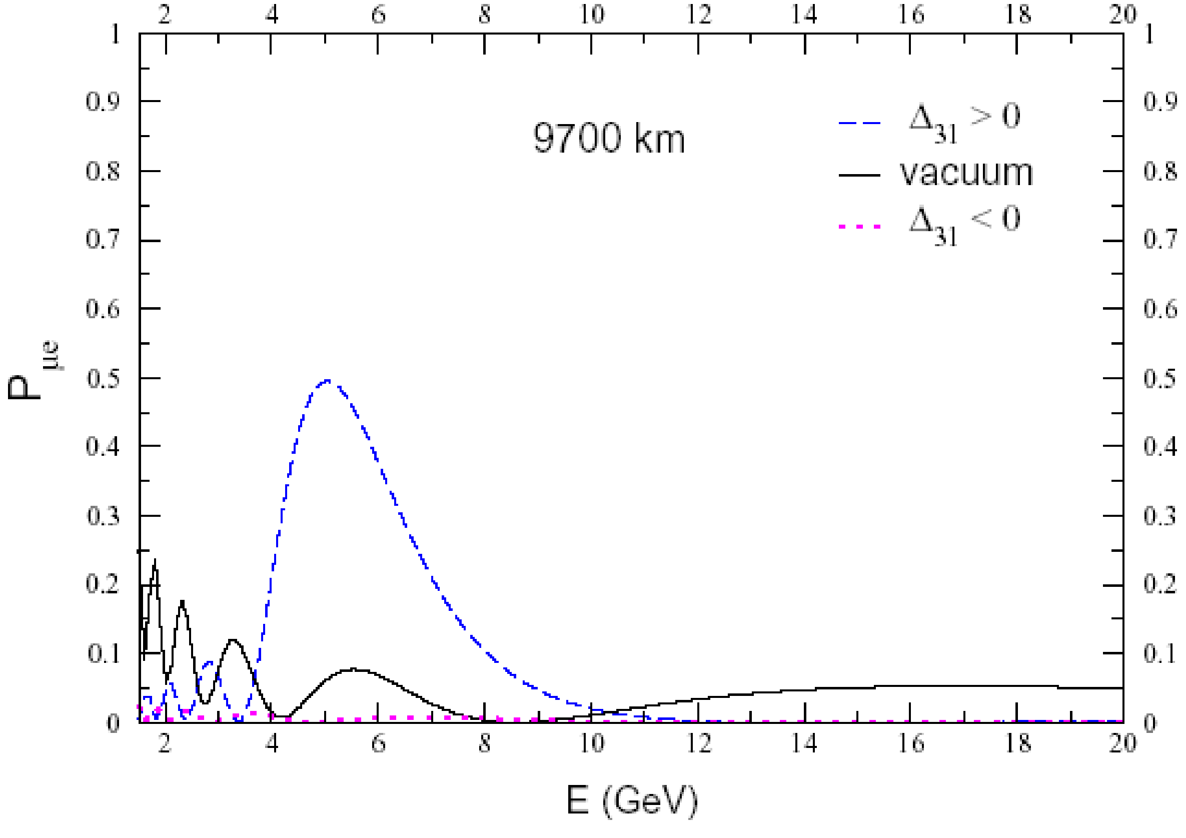
$$A = 0.76\times 10^{-4} \rho(gm/cc) E(GeV)$$

For positive Δ_{31} resonance occurs
When ρ and E are such that
$A=\Delta_{31}\cos 2\theta_{13}$ **condition is satisfied**

$$\rho L^{max}{}_{\mu e} = \frac{\pi\, 5.18\times 10^3}{\tan 2\theta_{13}}$$

$P_{\mu e}$

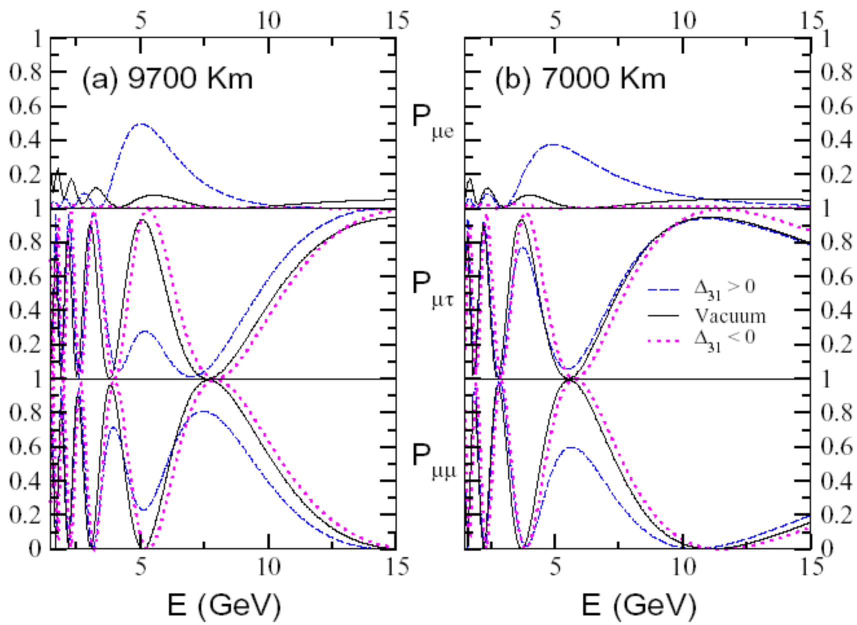
R. Gandhi et al PRL 94, 051801, 2005



For negative Δ_{31} no resonence occurs for neutrinos, but it occurs for anti-neutrinos

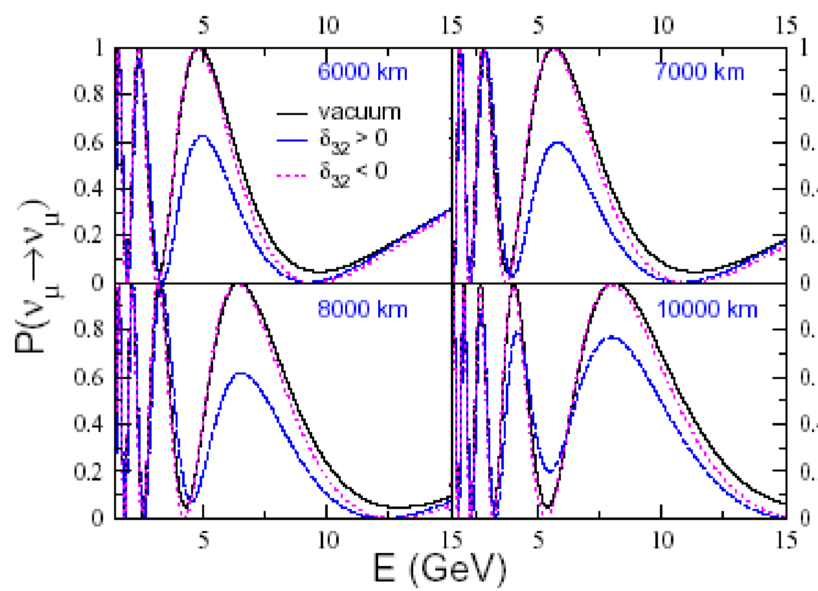
MATTER EFFECT CONTINUED

R. Gandhi *et al.*, Phys. Rev. Lett. **94**, 051801 (2005); hep-ph/0411252

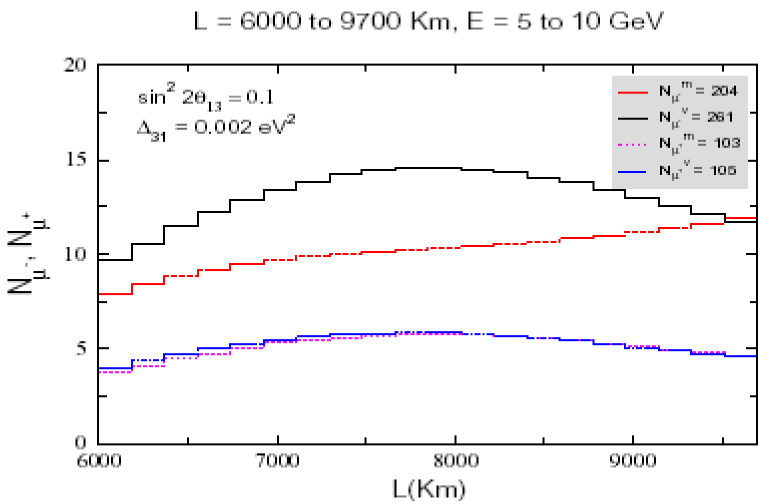


The $\nu_\mu \to \nu_\tau$ oscillation probability can also undergo significant change, a reduction as high as ~70% or an increase of ~15% compared to vacuum values over a broad range of energy and baseline.

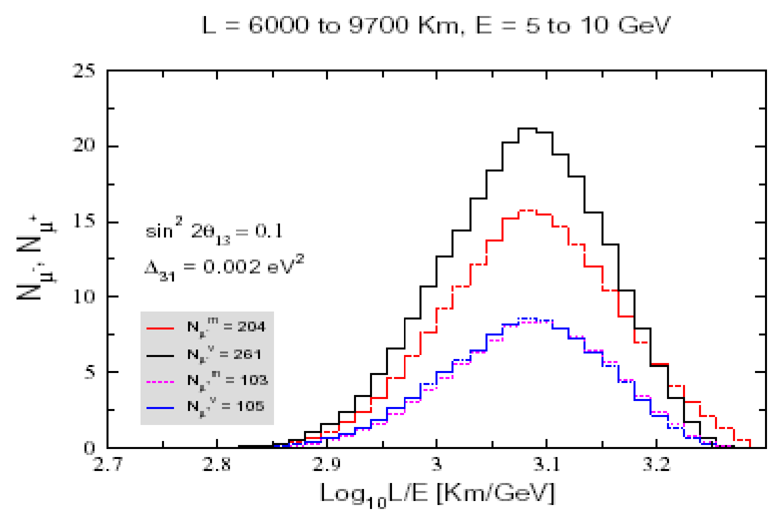
$P_{\mu\mu} = 1 - P_{\mu e} - P_{\mu\tau}$



MATTER EFFECT FROM EVENT RATE



R. Gandhi *et al.*, hep-ph/0411252

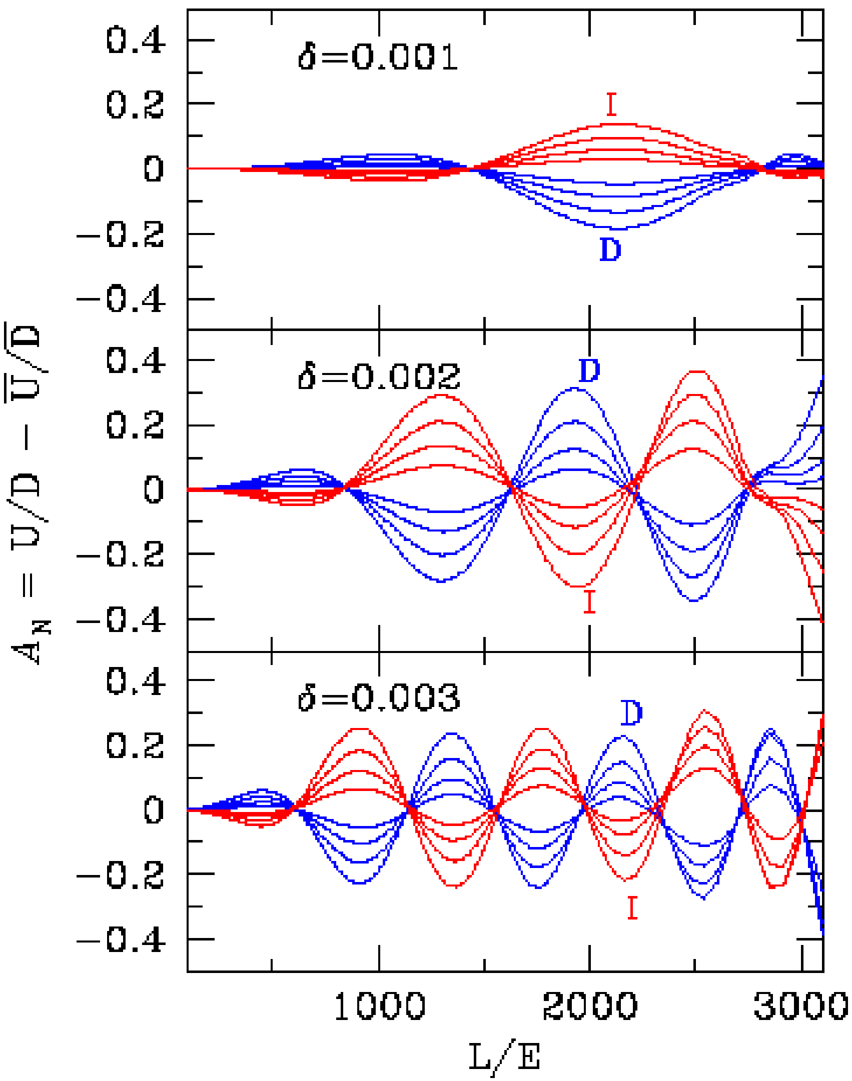


For 1000 Kton-Yr 4σ effect at $Sin^2 2\theta_{13}$ = 0.1

At $Sin^2 2\theta_{13}$ =0.05 - 2.5σ effect.

SIGN OF ΔM^2_{32} FROM MATTER INDUCED ASYMMETRY

D. Indumathi *et al.*, Phys. Rev. D71, 013001 (2005)



The neutrino and anti-neutrino up/down event ratios are different from each other as well as different with direct and inverted mass hierarchies.

E > 4 GeV

δ= 1,2,3 X 10^{-3} eV^2

θ_{13} = 5, 7, 9, 11 degrees

Exposure ~ 500 KTonYr

Baseline 4Km – 10Km

INO COLLABORATION

- At present INO collaboration consists of

  ~90 Physicists and Engineers from

  - 15 Indian institutions, and
  - 1 US Institution

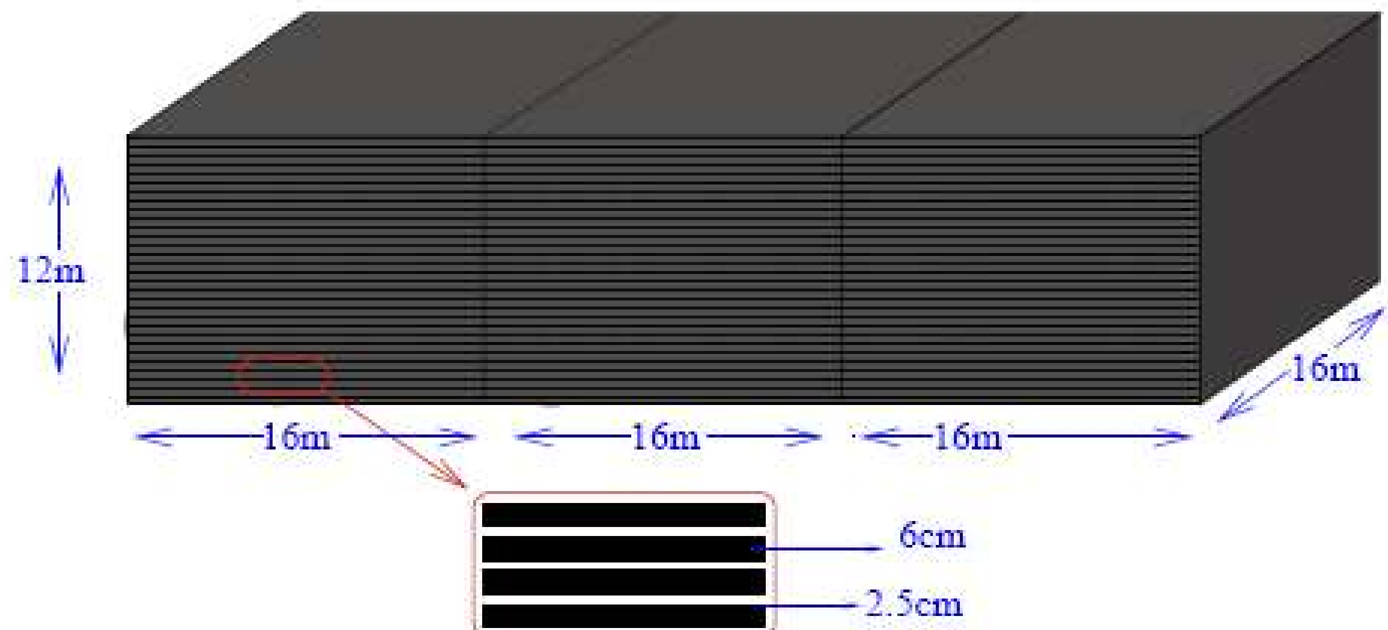
- <u>Spokesperson – Prof. Naba Mondal – TIFR, Mumbai</u>

- Planned to be an international facility-
  - Begin with a Fe-RPC magnetized ν detector 50-100Kton
  - Later use the facility possibly for:
    - Low energy Neutrinos (solar ν, reactor ν, supernova ν, β decay, $0\nu\beta\beta$ decay, global radioactivity in earth, nucleon decay etc. etc.)
    - Neutrino Astronomy (cosmic ray composition, UHE ν astronomy)
    - Low Energy Accelerator for nuclear astrophysics

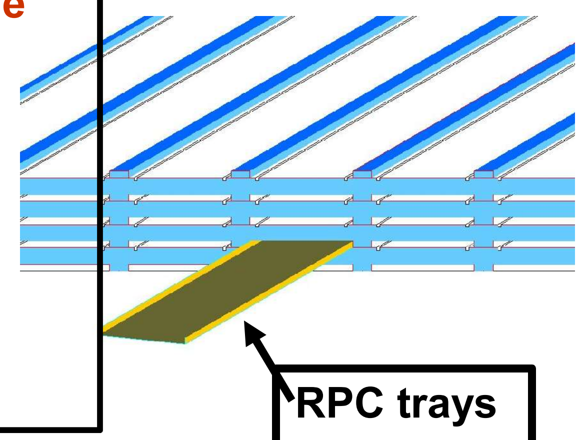
<u>International community is most welcome and we invite them to join the effort in this program – INO needs more experimentalists.</u>

INO DETECTOR – INITIAL DESIGN CONCEPT

Magnetized Fe with RPCs (50 KTon with ~1.3T magnetic Field)

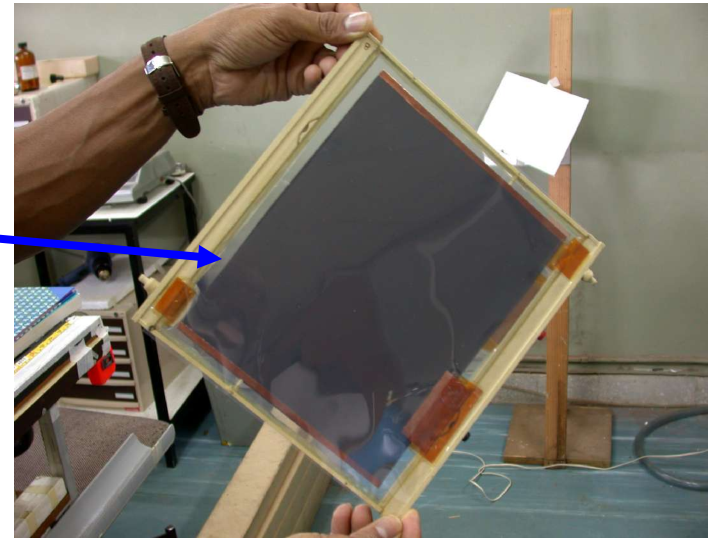


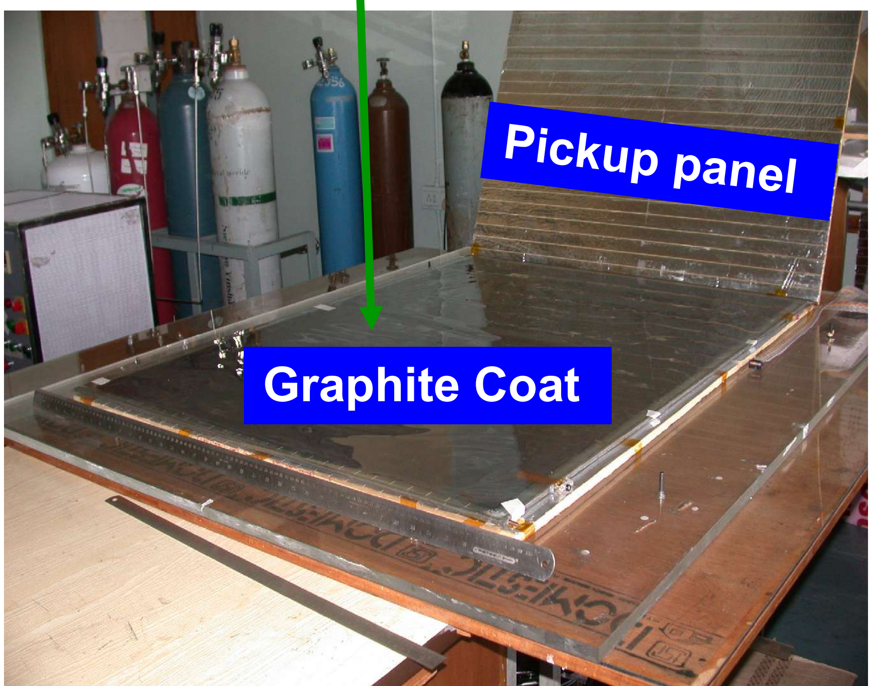
- ✓3 Modules of 16m X 16m X 12m each – 140 Layers/module
- ✓Each layer - 6cm thick Fe + RPC in 2.5cm Gap
- ✓Each RPC of size 2m X 2m – 27000 RPC's needed
- ✓Readout Strip Width – 3cm
- ✓Active Detector Area ~ 108,000 m^2
- ✓Number of Electronic Channel – 3.6 X 10^6

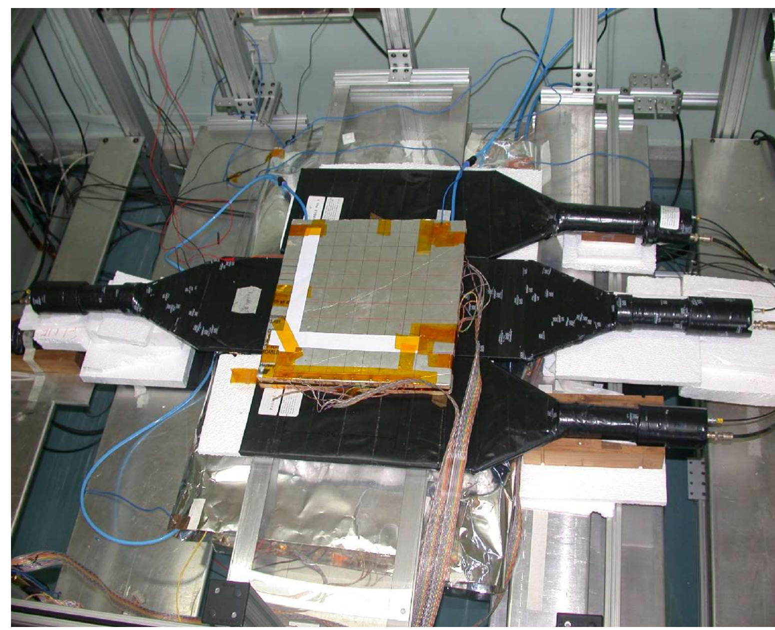


RPC R&D AT TIFR, MUMBAI & SINP, KOLKATTA

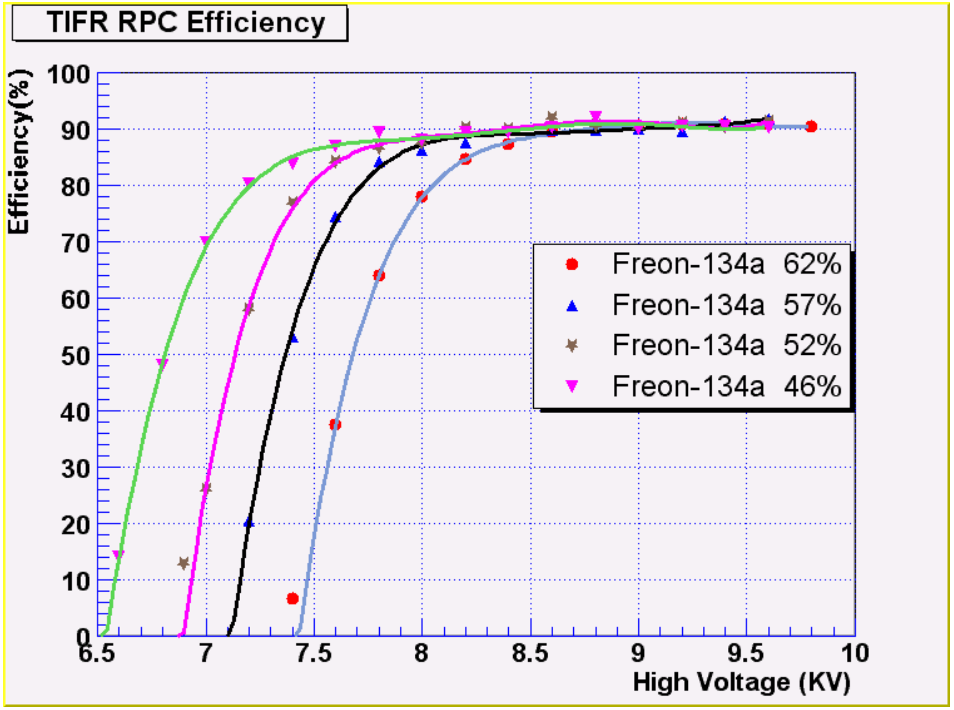
- **Build GlassRPC's of different sizes**
  - **30 cm X 30 cm**
  - **120 cm X 90 cm**





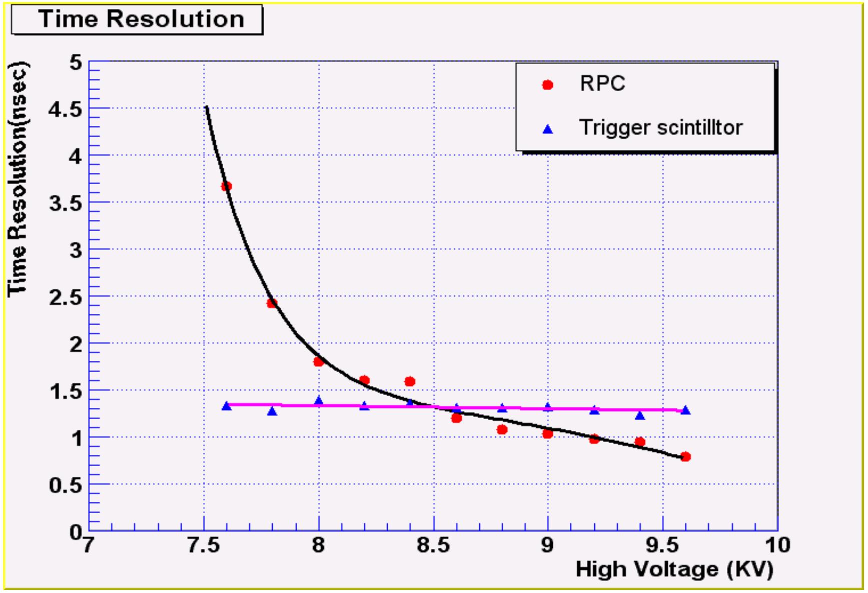


RPC EFFICIENCY AND TIMING RESOLUTION



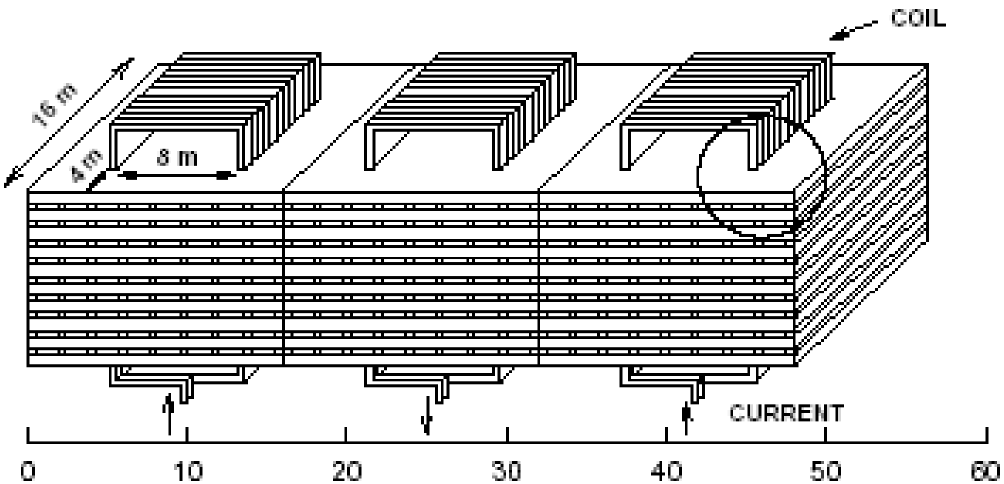
RPC Working in the Streamer Mode

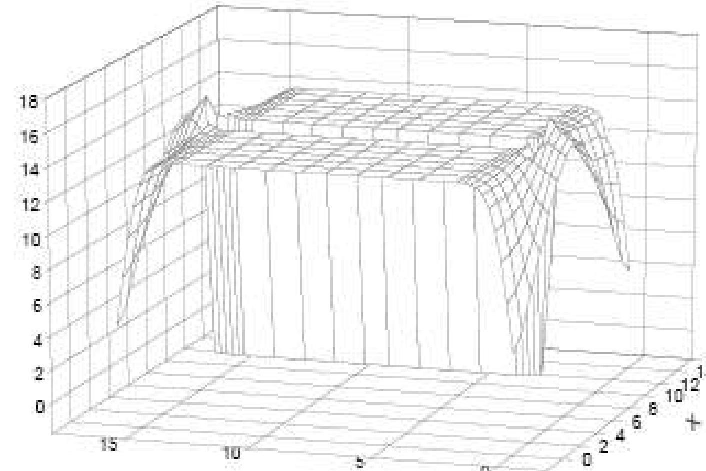
Typical timing resolution (σ) as a function of applied voltage



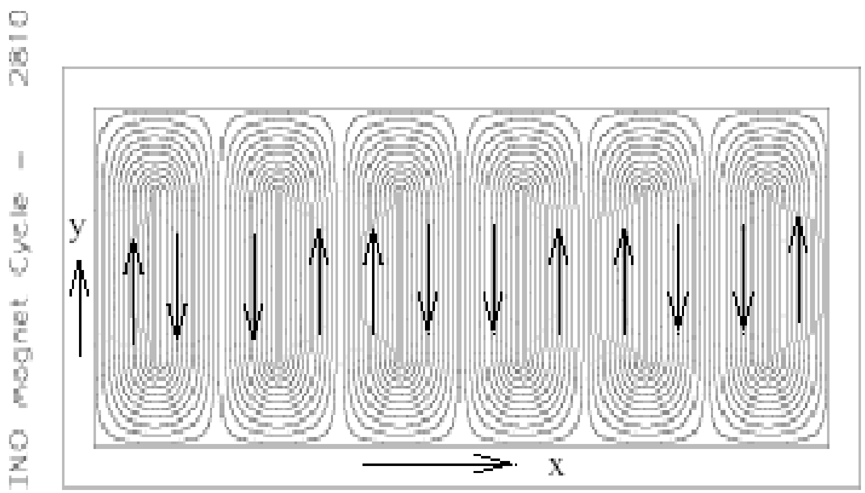
Efficiency ≥ 90% for HV ≥ 8.5 kV for all possible gas mixtures

INO DETECTOR – THE MAGNET





Uniform magnetic field in a horizontal plane inside a Fe plate

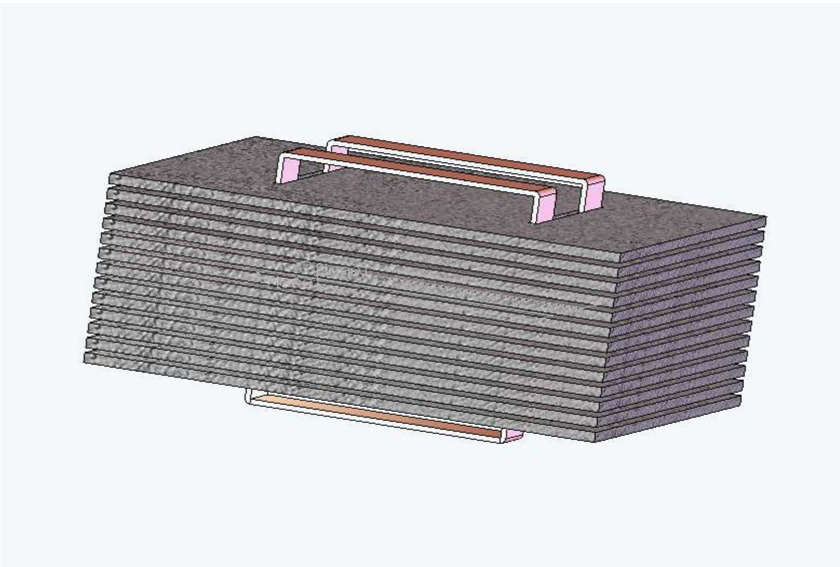


Field lines in a Horizontal Plane. Arrow shows the field direction.

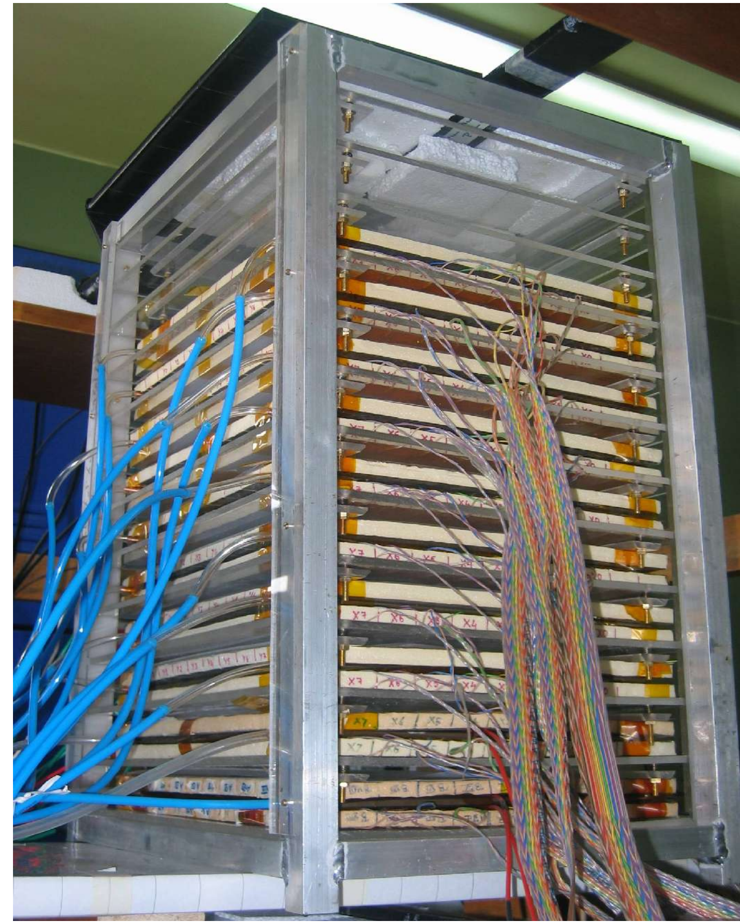
Two independent Studies:

- ✓ Using Poisson Code at VECC with toroidal coil a la MINOS.
- ✓ Using 3D commercial code MagNet 6.0 at BARC/ TIFR with Helmholtz coil for prototype.

INO PROTOTYPE DETECTOR – COSMIC MUON TEST

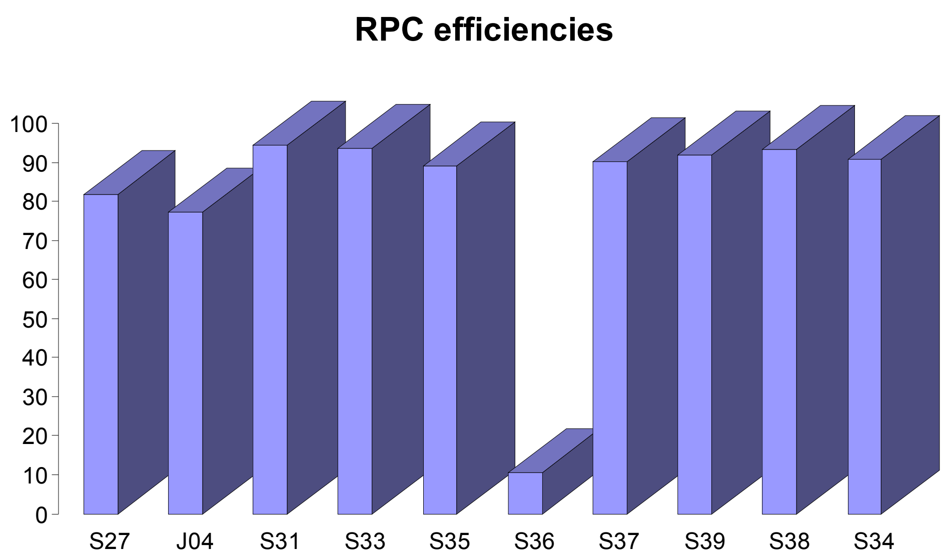


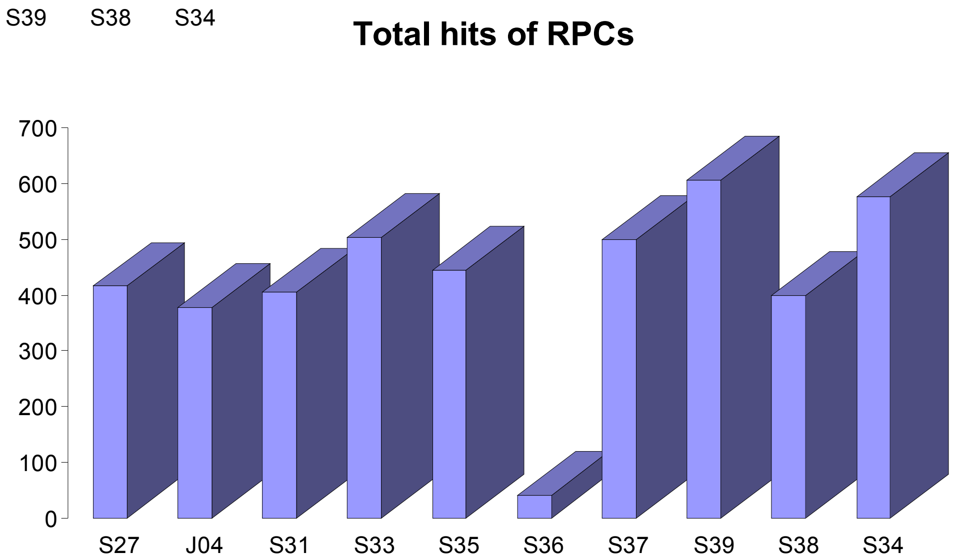
- ✓ 12, 1m² RPC layers
- ✓ 6cm thick mag. Fe plates
- ✓ ~1000 readout channels
- ✓ RPC & scintillation paddle triggers
- ✓ Hit and timing information, noise rates
- ✓ Streamer mode (R134a=62%, Argon=30% and the rest Iso-Butane)



Stack of 10 RPCs

SOME EXTRACTED PARAMETERS



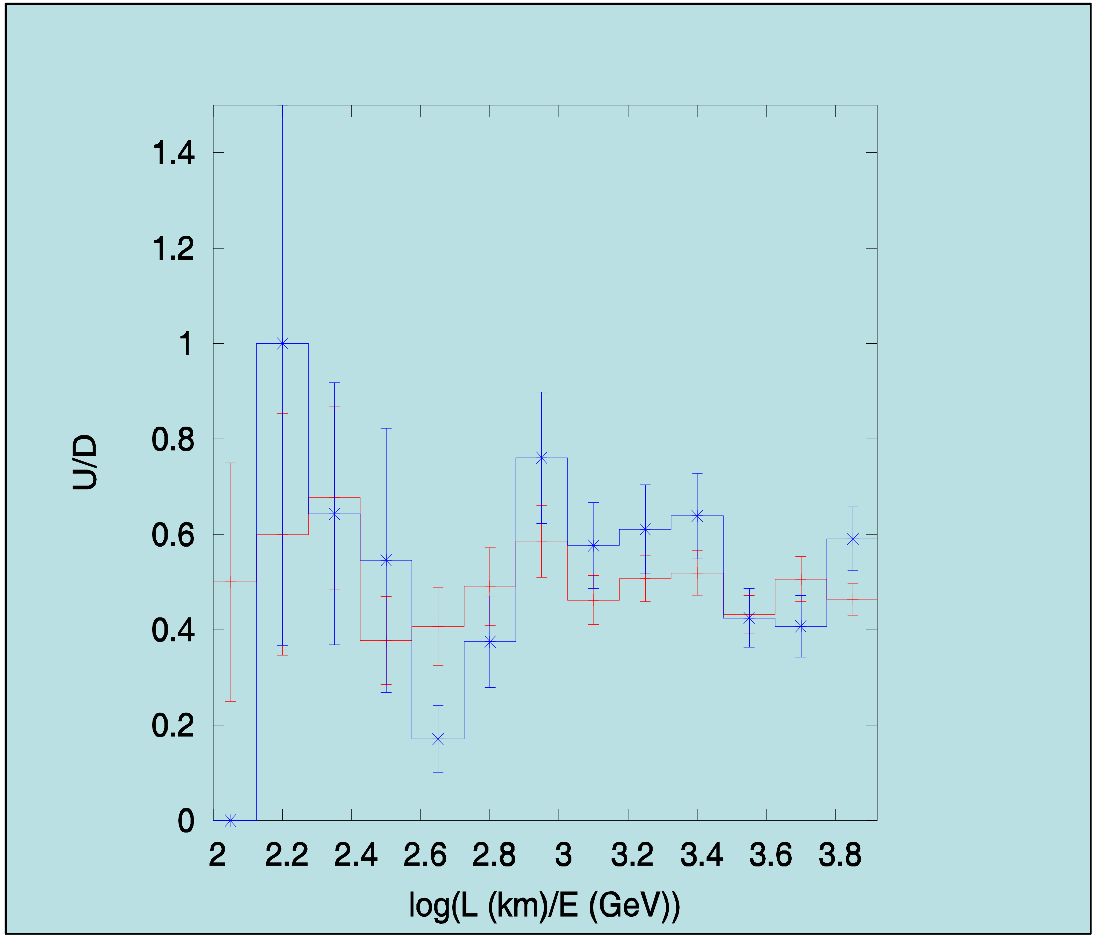


DETECTOR AND PHYSICS SIMULATION

- Nuance Neutrino Event Generator
  - ✓ Generate atmospheric neutrino events inside the INO detector
- Used Atmospheric Neutrino Flux of Honda et. al
- GEANT3 Detector Simulation Package
  - ✓ Simulate the detector response for the neutrino events
- Generate 5 years equivalent of simulated data
- Analyse Oscillation data at two levels for Physics performance of the baseline INO detector –
  - ✓ Using NUANCE output and kinematic resolution function
  - ✓ With full detector simulation
- Preliminary results available. Detailed simulation underway.

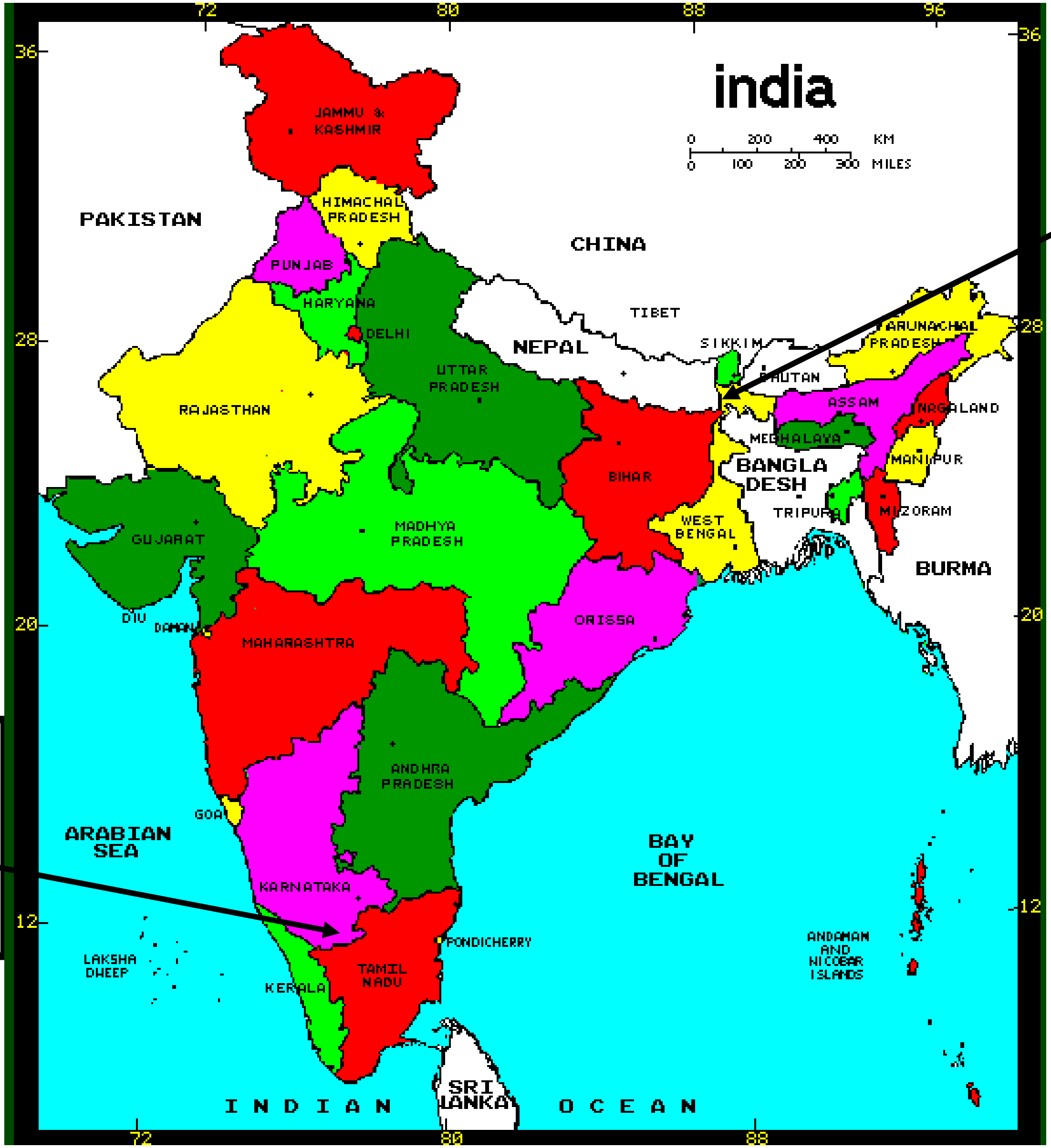
MATTER EFFECTS: SIGN OF Δ_{32}

Preliminary –
500 KTon-Yr Exposure



$$\frac{U}{D} - \frac{\overline{U}}{\overline{D}} = 0.64 \pm 0.35$$

POSSIBLE SITES FOR INO



Rammam

Lat. N 27.4^0
Long. E 88.1^0

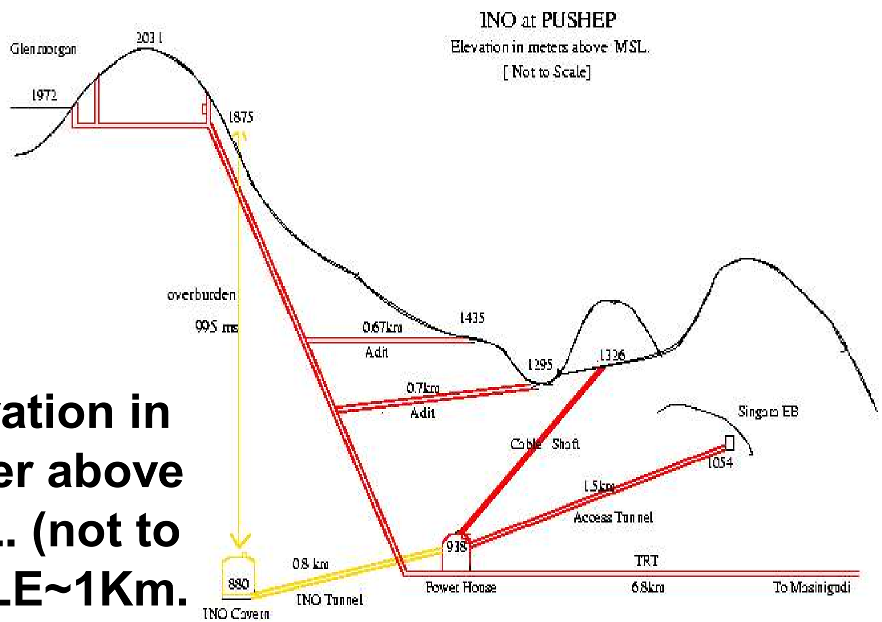
Studies were performed on two potential sites

PUSHEP

Lat. N 11.5^0
Long. E 76.6^0

PUSHEP – LOCATION OF THE UNDERGROUND LAB

PUSHEP (Pykara Ultimate Stage Hydro Electric Project) in South India, near Bangalore. Site Selection Committee have recommended PUSHEP as the preferred site for the underground lab.

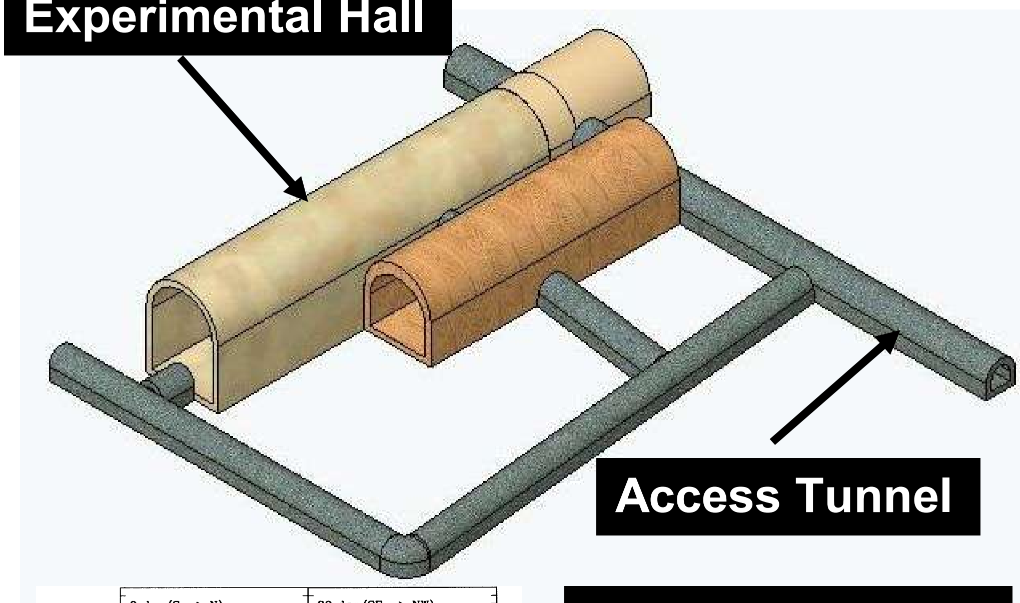


Elevation in meter above MSL. (not to scaLE~1Km.

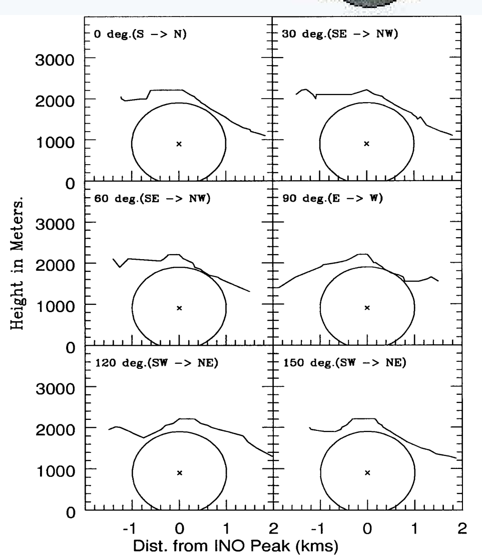
4 possible alignment of INO tunnel at PUSHEP

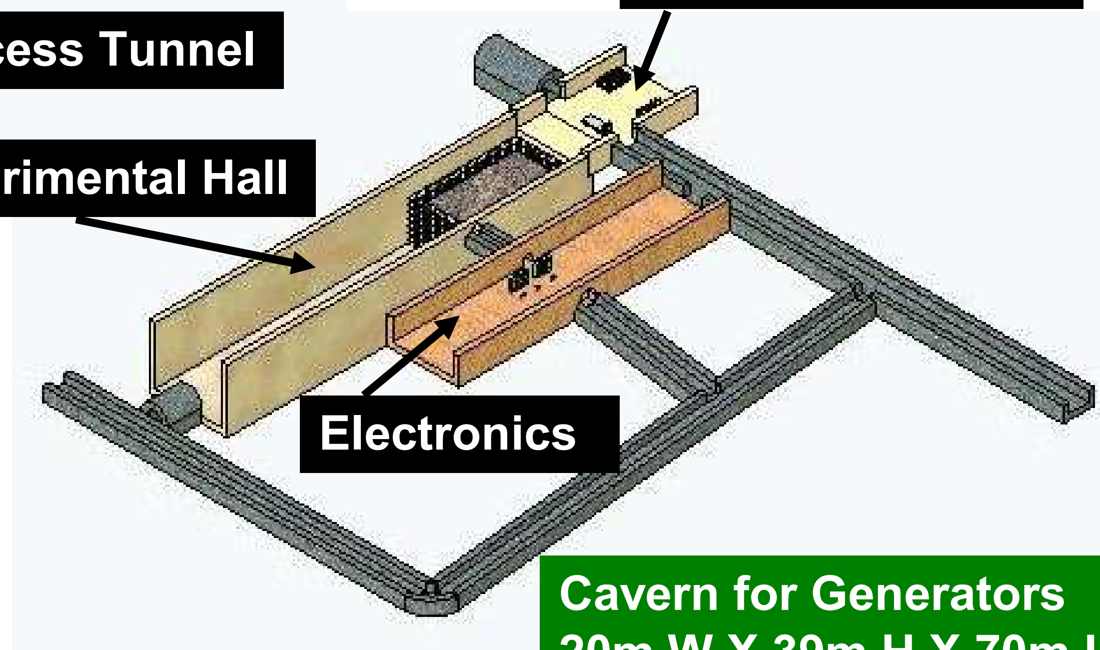
About 13Km of tunnel has already been constructed for this project.

UNDERGROUND CAVERN



Size of the Experimental Hall
150 m L X 22 m H X 30 m W
50 KTon Detector Dimension – 48 m X 16m X 12 m
Enough space for a 100KTon Detector





Cavern for Generators
20m W X 39m H X 70m L

COST ESTIMATION FOR LAB. CONSTRUCTION

ITEM	Cost at PUSHEP in millions of USD	Cost at Rammam in millions of USD
Tunnel and cavern excavation	8	19.3
Civil work surface and underground[1]	8	8
Facilities in the cavern[2]	4.5	4.5
TOTAL	**~$21M**	**~$32M**

1. **Includes access tunnel, the cavern, surface laboratory, housing/accommodation**
2. **Includes overhead crane, air-circulation in tunnel, air-conditioning in laboratory, electrical work**

Estimate given by L & T Limited. – FY2004 PRICE.

DETECTOR COST (IN MILLIONS of USD)

ITEM	Cost for 50KTon Detector	Cost for 100 KTon Detector
IRON (at $0.90/Kg)	45.5	91.0
Magnetization	4.6	9.2
Active Detector	27.3	54.6
Electronics and DAQ	5.7	11.4
Contingencies	9.1	18.2
TOTAL excluding IRON	46.7	93.4
TOTAL including IRON	~$92M	~$184M

TOTAL COST FOR A 50KTon DETECTOR + LAB = $115-125M

FY 2004 COST

TIME SCALE

a. Phase I - 12 to 18 months (to end ~ March-June 2007)

1. Draw up detailed design reports for tunnel and cavern complex.
2. Detector R&D will be over. Detailed design report on detector structure, RPC's, pick-up electrodes, FE electronics, power supply to be ready.

b. Phase II – 22 to 40 months. (to end ~ June 2010)

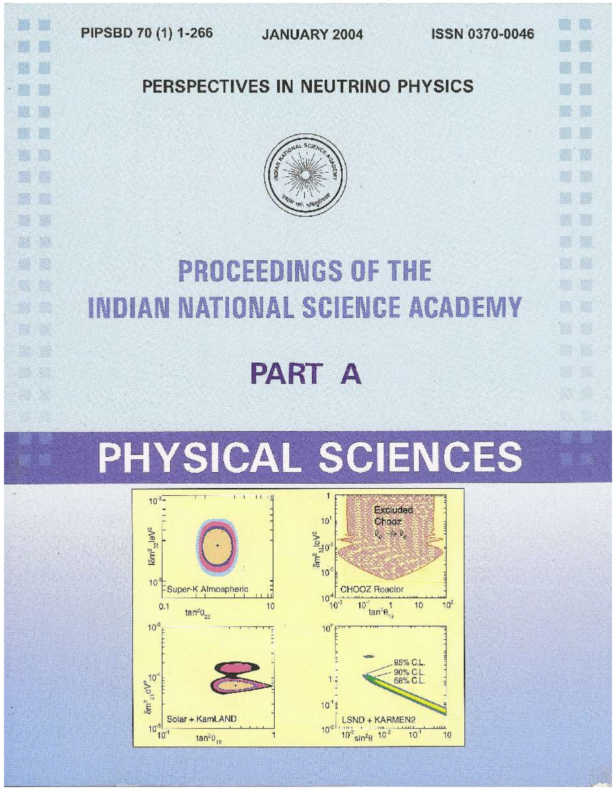
1. Tunnel and cavern excavation and related support measure.
2. Basic detector design frozen.
3. Tenders for supply of Fe, magnet coils, cables etc. to be issued.
4. Large scale RPC construction to begin.

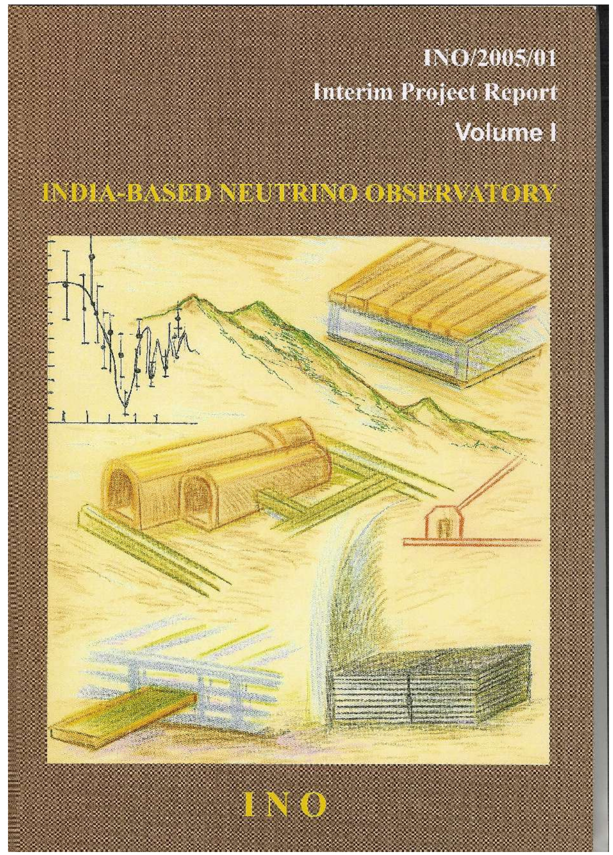
c. Phase III – 12 to 18 months (~ June to Dec 2011)

1. Laboratory outfitting, transport of detector components and assembly.
2. The first module may be completed early and the data taking may begin

ONE CAN EXPECT TO COLLECT DATA WITH ATMOSPHERIC NEUTRINOS BY 2011

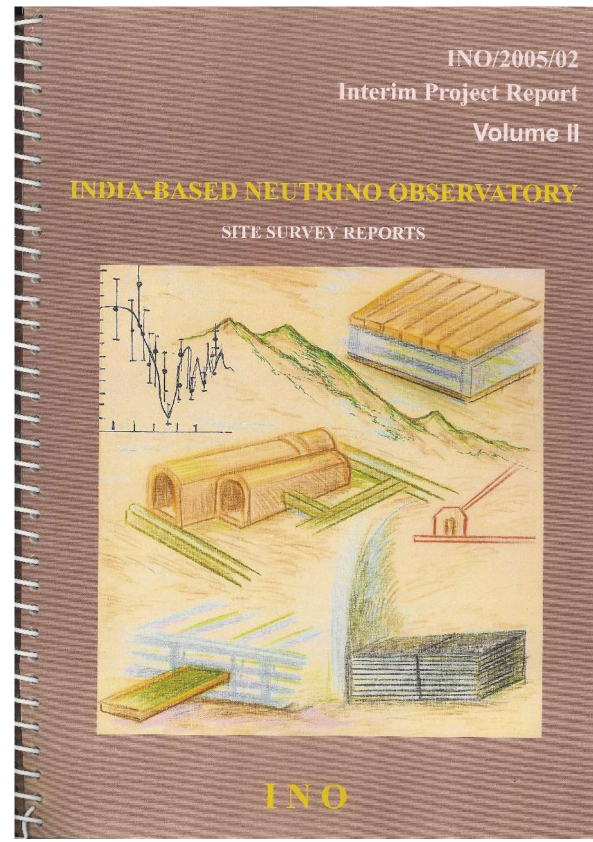
DOCUMENTATION PRODUCED SO FAR





Submitted to the funding agency on 1st May 2005.

Internal to collaboration only. Not for public release.



STATUS OF THE PROJECT & INNO INFORMATION

- ✓ **Presentation to the funding agencies – 5/2005**
- ✓ **Presentation to Science Advisory Council of Prime Minister –10/2005**
- ✓ **Site Selection Complete**
- ✓ **Task Force for Detailed Project Report on site – Constituted**
- ✓ **A committee setup jointly by DAE & DST to discuss the future projects of HEP in India - to meet soon**

- ➢ **INO Website: Home of the India-based Neutrino Observatory**
  - ✓ **http://www.imsc.res.in/~ino/**
  - ✓ **E-Mail: ino@imsc.res.in**
- ➢ **First INO School**
  - ➢ **Theoretical Courses – April 10th to 25th @ HRI, Allahabad**
  - ➢ **Experimental Courses – May 1st to 13th – SINP/VECC, Kolkatta**

INO SUMMARY & CONCLUSIONS

1. A large magnetized detector of 50-100 Kton can achieve some of the very interesting physics goals using neutrinos, especially:
   a. CPT violation
   b. Matter effect and sign of Δm^2_{23}
2. Magnetized Fe calorimeter will complement planned Water Cherenkov, Scintillator, and LAr Detectors
3. Will compliment present long baseline and reactor experiments
4. Can be used as FAR detector during neutrino factory era
5. R&D on all fronts progressing well
6. INO is looking for participation from larger international neutrino community.

CONCLUSIONS

- θ_{13} should be measured with good precision by ~2015 if $\sin^2 2\theta_{13} > 0.01$.
- The type of hierarchy is crucial in our understanding of neutrino physics.
- Matter effects are sensitive to the type of hierarchy.
- In future we can address this by:
  - ✓ LBL experiment NOνA – 810 km baseline
  - ✓ Atmospheric Neutrino Experiment – INO
- Measurement of CP violation in the lepton sector will most likely need a several MW power proton source and a second off-axis detector either in USA or Japan.