Neutrino Physics: Tomorrow's directions

Amitava Raychaudhuri

University of Calcutta

For the INO Collaboration

Plan

Experimental Results

Neutrino Oscillations

India-based Neutrino Observatory (INO)

1. Genesis
2. The ICAL Detector design
3. Detector simulation
4. Physics issues
5. Site, Cost, . . .

Conclusions

Experimental Results

Experimental results

Past decade: New experimental results on neutrinos do not agree with theoretical predictions!

- Solar neutrinos ($\nu_{\mathbf{e}}$)
- Atmospheric neutrinos ($\nu_\mu, \quad \bar{\nu}_\mu, \quad \nu_{\mathbf{e}}, \quad \bar{\nu}_{\mathbf{e}}$)
- Reactor neutrinos ($\bar{\nu}_{\mathbf{e}}$)
- Accelerator neutrinos ($\nu_\mu, \quad \bar{\nu}_\mu$)

Neutrino mass $\Rightarrow$ oscillations + Standard Theory gives good agreement!

Solar Neutrino Problem

Observed ν_e less than Standard Solar Model prediction

Experiment	Homestake	Ga	Super-K	SNO ES	SNO CC
$\left(\frac{\mathrm{Observed}}{\mathrm{Predicted}}\right)$	0.34 ± 0.03	0.58 ± 0.04	0.46 ± 0.02	0.47 ± 0.07	0.35 ± 0.03
E_{th} (MeV)	0.8	0.233	5.0	5.0	6.75

$E_{th} \equiv$ threshold energy for detection

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Radiochemical $\Rightarrow$ Homestake (Chlorine), GNO, Gallex and SAGE (Gallium) (sensitive to ν_e only)
Čerenkov $\Rightarrow$ SNO CC (sensitive to ν_e only)

Čerenkov $\Rightarrow$ Super-Kamiokande (Water) and SNO ES ($\mathbf{D_2O}$) (less sensitive $\sim \frac{1}{6}$ to ν_μ, ν_τ)

Solar Neutrino Problem (contd.)

Solution consensus:

- ν_e oscillates to ν_μ or ν_τ in transit
- Detectors insensitive (or less sensitve) to ν_μ, ν_τ
- Observed number less than expected

Requirement: Neutrinos are massive

Solar Neutrino Problem (contd.)

Solution consensus:

- ν_e oscillates to ν_μ or ν_τ in transit
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- Observed number less than expected

Requirement: Neutrinos are massive

Confirmation: SNO Neutral Current (NC) detection mode

Equally sensitive to ν_e, ν_μ, ν_τ

$$\frac{\text{Observed rate}}{\text{Predicted rate}} = \mathbf{1.008 \pm 0.123}$$

Atmospheric Neutrinos

$$R = \frac{[(\nu_\mu + \overline{\nu}_\mu)/(\nu_e + \overline{\nu}_e)]_{\rm obsvd}}{[(\nu_\mu + \overline{\nu}_\mu)/(\nu_e + \overline{\nu}_e)]_{\rm MC}}$$

R = 1 $\Leftarrow$ consistency between Theory and Observation

Super-K: $R = 0.61 \pm 0.03 \pm 0.05$ (for sub-GeV neutrinos)

$R = 0.66 \pm 0.06 \pm 0.08$ (for multi-GeV neutrinos)

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Zenith angle dependence for ν_μ: $\frac{up}{down} = 0.52^{+0.07}_{-0.06} \pm 0.01$

No such up-down asymmetry seen for ν_e events

Accelerator and Reactor ν

Accelerator expts $\Rightarrow \nu_\mu, \bar{\nu}_\mu$ beams

K2K: (Beam from KEK $\longrightarrow$ SuperKamiokande) L $\sim$ 250 km, look for ν_μ disappearance; First results favour oscillations consistent with atmospheric neutrino data.

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Reactor experiments use $\bar{\nu}_e$ produced in fission reactions

CHOOZ: L $\sim$ 1.0 km, disappearance search; $\sin^2 2\theta < 0.10$ if Δm^2 is in atmospheric range

KAMLAND: Source (nuclear reactors in Japan) $<$L$>\sim$ 100 km, Consistent with solar MSW LMA solution

Experiment (Summary)

- Solar neutrinos $\Rightarrow \Delta m^2 = 8.3 \times 10^{-5}$ eV^2 and $\sin^2\theta = 0.27$ (MSW LMA)
- Atmospheric neutrinos $\Rightarrow |\Delta_{32}| = 2.2 \times 10^{-3}$ eV^2 with $\sin^2\theta_{23} = 0.5$
- Reactor neutrinos ($\bar{\nu}_{\mathbf{e}}$): KamLAND agrees with solar, CHOOZ constrains $\nu_e - \nu_\tau$ mixing
- Accelerator neutrinos ($\nu_\mu, \;\; \bar{\nu}_\mu$): K2K confirms atmospheric results

Neutrino mass + oscillations give good agreement!

Neutrino Oscillations

Neutrino Oscillations

Neutrino states change type (e.g., $\nu_e \leftrightarrow \nu_\mu$) during propagation: $P_{\nu_e \to \nu_e} \equiv$ survival prob. is an oscillatory function

- At any stage, $P_{\nu_e \to \nu_e} \leq 1$
- Also $P_{\nu_e \to \nu_\mu} \leq 1$
- $P_{\nu_e \to \nu_e} + P_{\nu_e \to \nu_\mu} = 1$ at every stage

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- $P_{\nu_e \to \nu_e} + P_{\nu_e \to \nu_\mu} = 1$ at every stage
- Explains the observed solar and atmospheric neutrino anomalies
- Consistent with all other experiments
- Consequence of quantum mechanics

Neutrino Oscillations

Quantum mechanical time evolution:

Stationary state $|\psi_k\rangle$, $E_k \equiv$ energy eigenvalue:

$$|\psi_k(t)\rangle = |\psi_k\rangle \;\; \exp\left(-i \; E_k t\right),$$

Arbitrary, *i.e.,* non-stationary, state:

$$|\psi(0)\rangle = \sum_k \; a_k \; |\psi_k\rangle, \quad |\psi(t)\rangle = \sum_k \; a_k \; |\psi_k\rangle \; \exp\left(-iE_k t\right).$$

where a_k are constants.

ν_e and ν_μ are not the stationary states ν_1 and ν_2, but their superpositions $\Rightarrow$ neutrino oscillations

Neutrino Oscillations

$$|\nu_e\rangle = |\nu_1\rangle\ c\ +\ |\nu_2\rangle\ s; \qquad |\nu_\mu\rangle = -|\nu_1\rangle\ s\ +\ |\nu_2\rangle\ c,$$

$c = \cos\theta, \quad s = \sin\theta, \qquad \theta \equiv$ mixing angle

ν_e at $t = 0 \quad \Rightarrow |\psi(0)\rangle \equiv |\psi_{\nu_e}\rangle = c|\psi_1\rangle + s|\psi_2\rangle$

If $|\psi_1\rangle$ and $|\psi_2\rangle$ correspond to energies E_1 and E_2

$$|\psi(t)\rangle = c|\psi_1\rangle\ \exp(-iE_1 t)\ +\ s|\psi_2\rangle\ \exp(-iE_2 t)$$

$$P_{\nu_e\to\nu_\mu}(t) = |\langle\psi_{\nu_\mu}|\psi(t)\rangle|^2 = c^2 s^2 |-\exp(-iE_1 t)\ +\ \exp(-iE_2 t)\ |^2$$

Neutrino Oscillations

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Neutrinos are ultra-relativistic ($p \gg m_i$). Hence $E_i \simeq p + \frac{m_i^2}{2p}$

$$\boxed{P_{\nu_e \to \nu_\mu}(t) = 4c^2 s^2 \sin^2 \left(\frac{\Delta m^2}{4p} t \right) = \sin^2 2\theta \sin^2 \left(\frac{\pi L}{\lambda} \right) ,}$$

where $\Delta m^2 = m_2^2 - m_1^2$ and

$$\lambda = 2.47 \mathrm{m} \left(\frac{E}{\mathrm{MeV}} \right) \left(\frac{\mathrm{eV}^2}{\Delta m^2} \right) \Rightarrow \text{oscillation length}$$

$$\boxed{P_{\nu_e \to \nu_e}(t) = 1 - P_{\nu_e \to \nu_\mu}(t) = 1 - \sin^2 2\theta \sin^2 \left(\frac{\pi L}{\lambda} \right) .}$$

Neutrino Oscillations

For oscillation

1. The neutrinos must be massive and *non*-degenerate.
2. The mass eigenstates of the neutrinos – $\nu_1,\ \nu_2$ – must be different from the flavour eigenstates – $\nu_e,\ \nu_\mu$.

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MSW mechanism is a matter induced effect
$\Rightarrow$ Interactions affect inertia ($\equiv$ mass) of neutrino
$\Rightarrow$ In matter m_ν different from in vacuo.

- MSW mechanism affects neutrinos and antineutrinos differently.
- MSW effect determines the sign of $\Delta_{ij} = m_i^2 - m_j^2$

Neutrino Oscillations

Three flavours (2 independent Δm^2, 3 mixing angles, 1 phase)

$$U^\dagger M_\nu U = \mathrm{diag}(m_1, m_2, m_3)$$

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

$$P_{\nu_\alpha \nu_\beta} = \delta_{\alpha\beta} - 4 \sum_{j>i} U_{\alpha i} U_{\beta i} U_{\alpha j} U_{\beta j} \sin^2\left(\frac{\pi L}{\lambda_{ij}}\right)$$

Neutrino parameters

- Solar neutrinos MSW (best fit) $\Rightarrow \Delta_{21} = 8.3 \times 10^{-5}$ eV^2 and $\sin^2\theta_{12} = 0.27$ (agrees with KamLAND reactor expt.)
- Atmospheric neutrinos (best fit) $\Rightarrow |\Delta_{32}| = 2.2 \times 10^{-3}$ eV^2 with $\sin^2\theta_{23} = 0.5$ (supported by K2K accelerator expt.)
- CHOOZ $\Rightarrow \sin^2 2\theta_{13} < 0.10$
- Δ_{21} is positive, the sign of Δ_{32} is **not** known

Open issues: Confirm oscillation dip and rise
Determine θ_{13}
sign of Δ_{32} $\Leftarrow ICAL@INO$
CP-phase δ
New physics?

India-based Neutrino Observatory (INO)

Running experiments

Experiment	Country	Type of detector	Major goals	Time schedule
Super-Kamiokande	Japan	Water Cerenkov	Solar, Supernova, Atmospheric, Long baseline (K2K)	1996-
SNO	Canada	D_2O Cerenkov	Solar, Supernova	1999-
GNO	Italy	Gallium	Solar	1998-
KamLAND	Japan	Scintillator	Reactor	2001-
MiniBooNE	USA	Scintillator	Short baseline from Fermilab booster	2003-

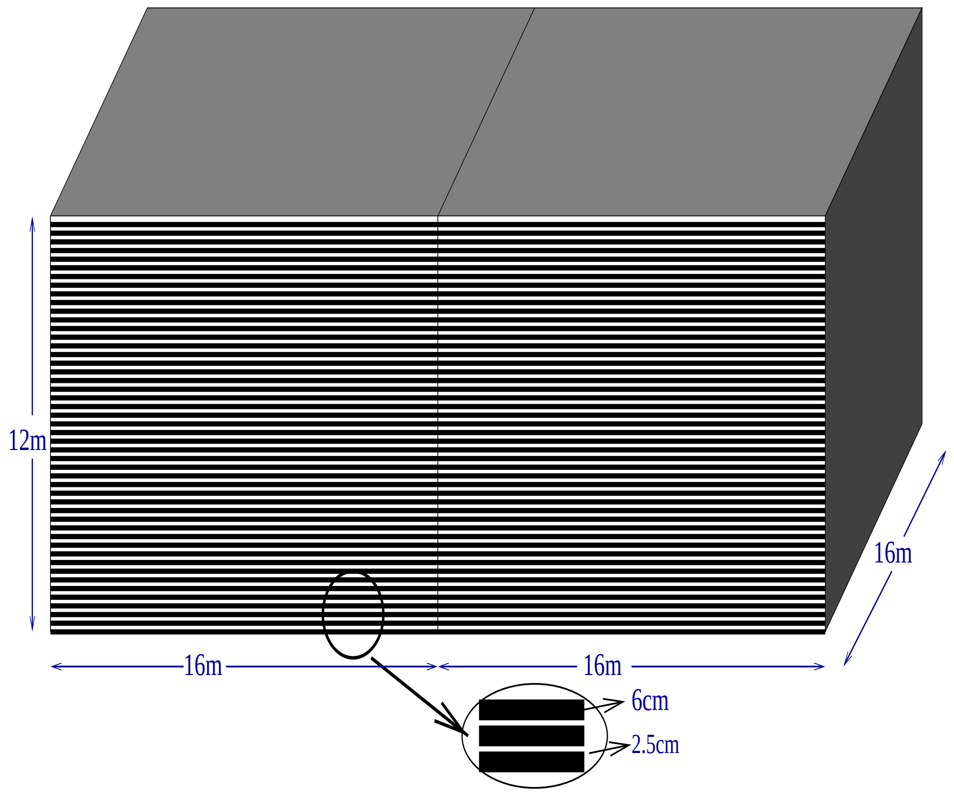
Planned experiments

Experiment	Country	Type of detector	Major goals	Time schedule
ICARUS	Italy	Liquid Argon	Atmospheric, Proton Decay, Long baseline	200?
MINOS	USA	Iron Calorimeter	Long baseline from Fermilab injector	2005
Opera	Italy	Iron/Emulsion	Tau appearance	2005
MONOLITH	?	Iron Calorimeter	Atmospheric, Long baseline	?

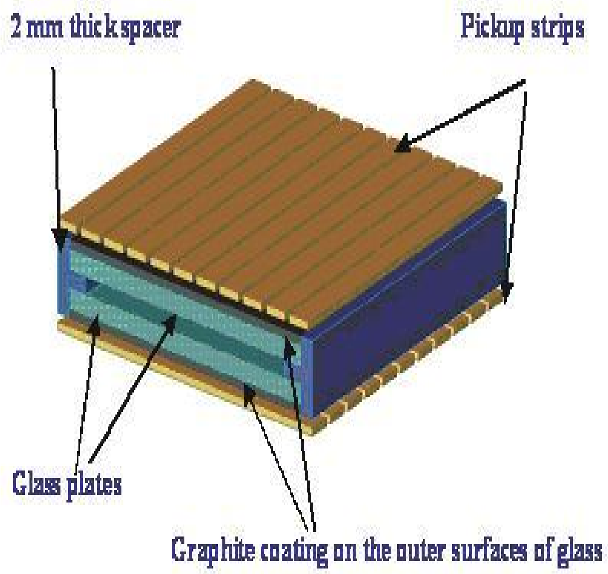
Genesis of ICAL

- Early Indian track record of neutrino experiments at Kolar
- Preliminary discussions started more than five years ago
  Iron calorimeter, Water Cerenkov, ...
- MOU between BARC, VECC, TIFR, SINP, IMSc, HRI, IOP; DAE support for initiating R&D
- Iron Calorimeter (ICAL) the preferred design
- Time schedule: Target to start detector running in 6 years (2011) in a modular manner going upto 100 tonnes in the first instance.

ICAL Design

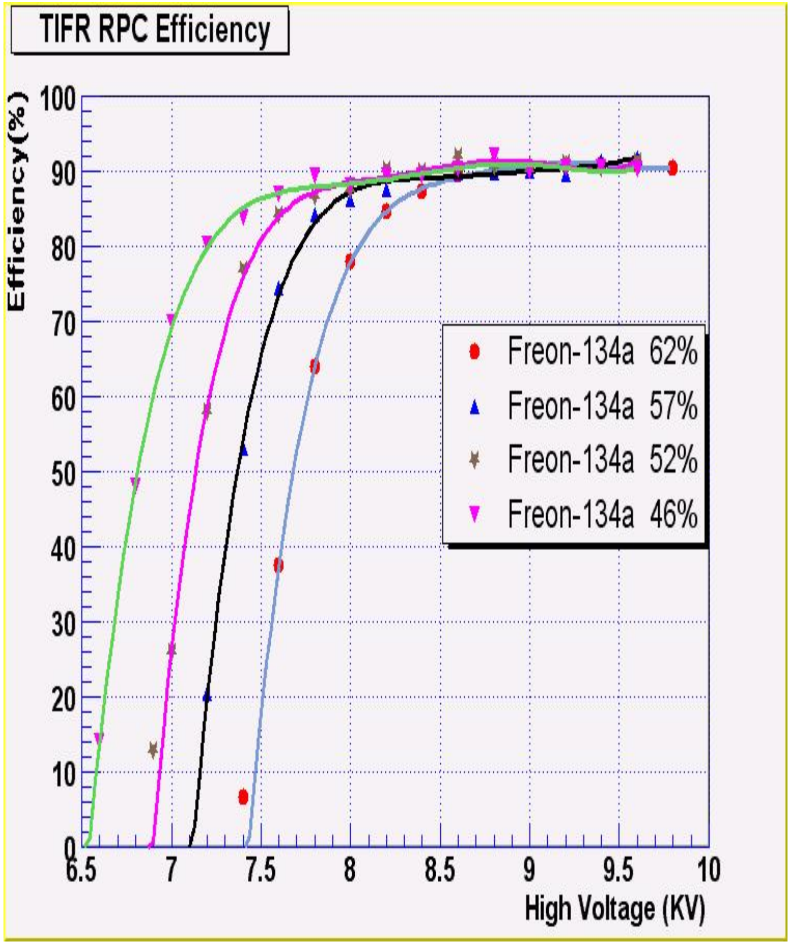


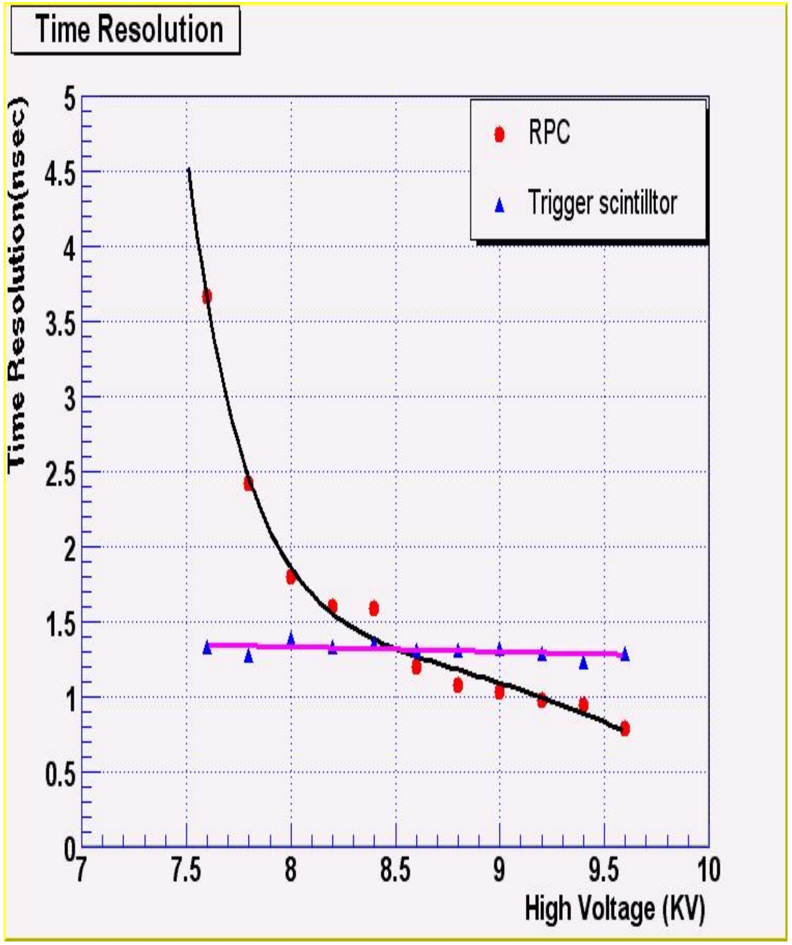
The ICAL Detecteor



A Glass RPC

RPC efficiency





RPC Efficiency

Time resolution

Magnetic field, Gas Mixing, DAQ

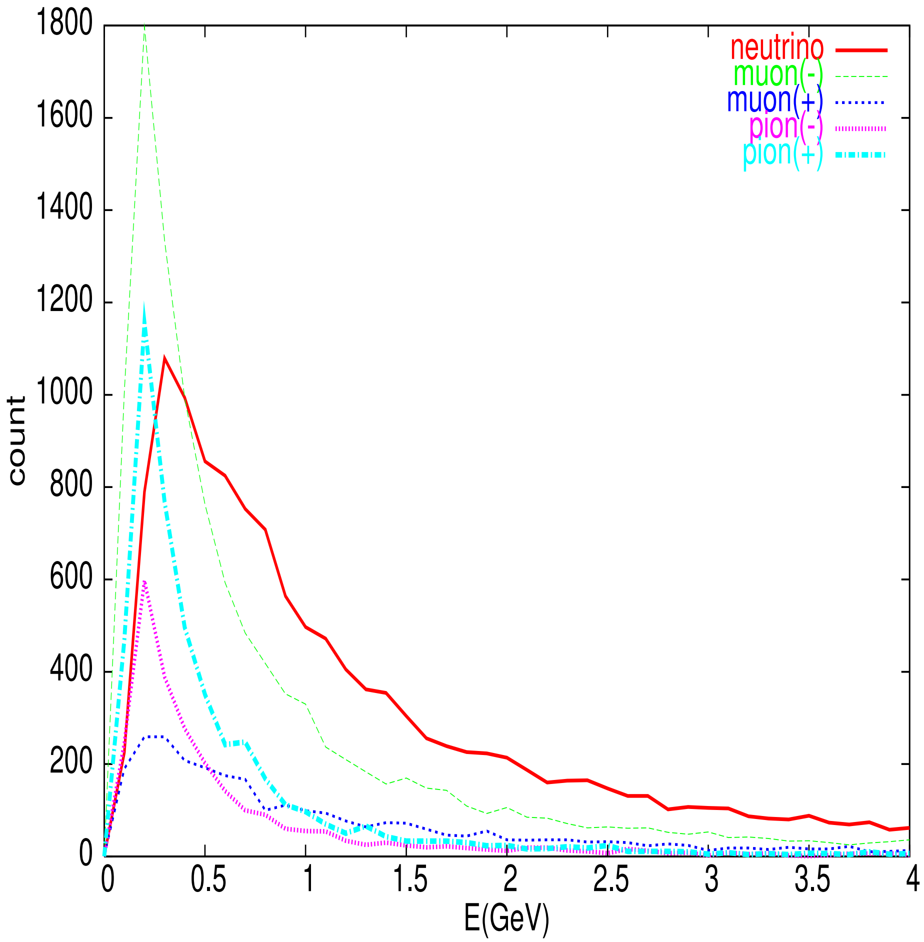
- Magnetic field essential for charge identification
  1. 1 Tesla field along z-direction
  2. Detailed magnet design in progress at BARC, VECC
- RPC Gas
  1. Appropriate mixture of Argon, Freon and Iso-butane
  2. Gas mixing unit designed and fabricated at SINP
- DAQ: Work in progress at TIFR

ICAL configurations

Geant3-based simulation study for three configurations:

- ICAL-H: 32kT detector
  140 horizontal iron layers (6cm thick) with interspersed Glass RPC (2.5cm)
  Dimension 16m$\times$16m$\times$12m
- ICAL-V: Iron layers arranged vertically – otherwise as in ICAL-H
- ICAL100: Three 32kT ICAL-H modules arranged lengthwise next to each other

Atmospheric ν spectrum



Energy spectrum of ν, μ, π

Particles produced in νN reactions (5yr sample using NUANCE)

Most product particles have energy $\sim$ GeV

ICAL threshold $\sim$ 800 MeV

ICAL calibration

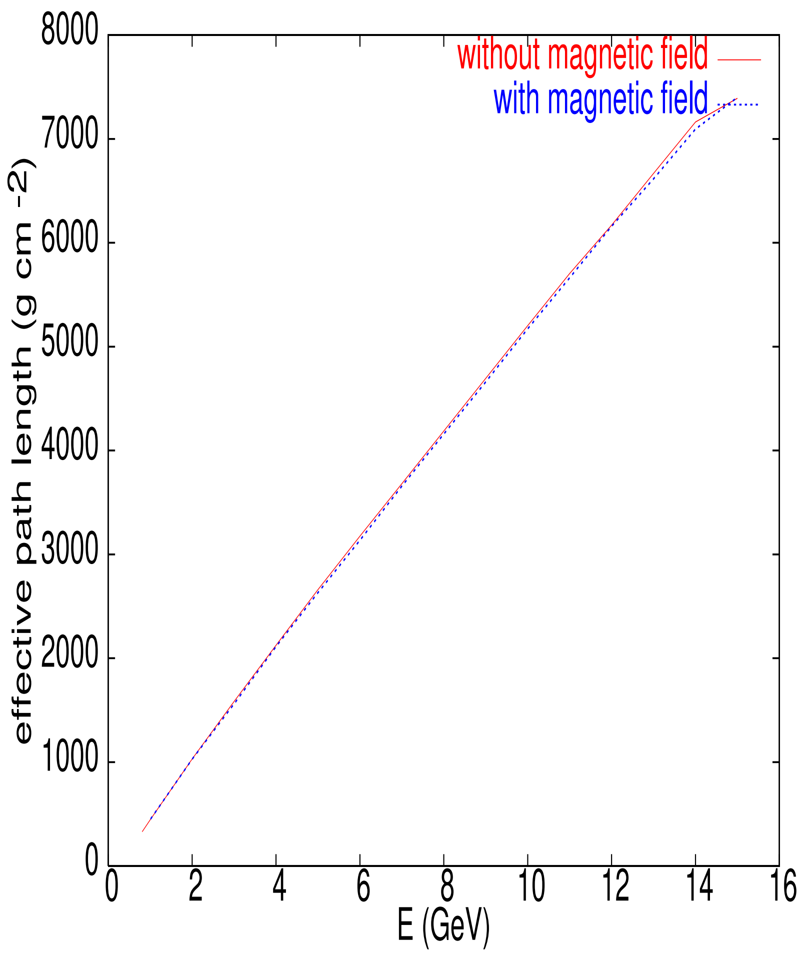
- Charge identification from direction of track curvature in magnetic field
- Energy determination
  1. From track length (FC events)
  2. From track curvature in a magnetic field (FC + PC events)
- Direction of parent neutrino from detected particle momenta

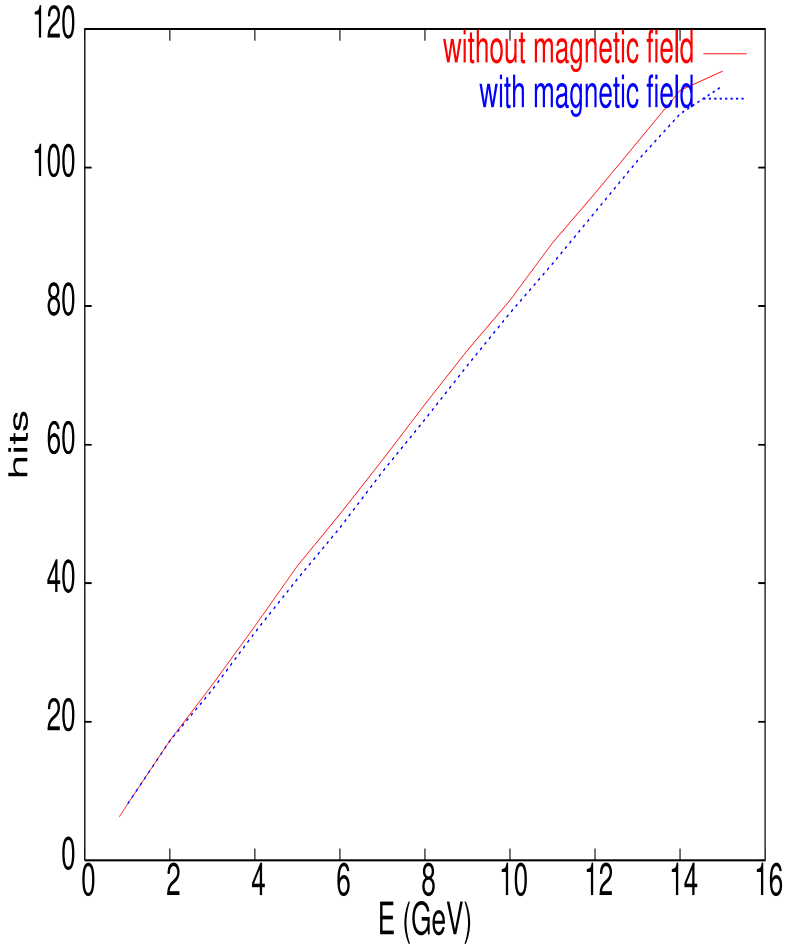
Charge identification

No. of years	FC			FC + PC		
	No. of selected events	No. with correct charge identification	Charge identification efficiency (%)	No. of selected events	No. with correct charge identification	Charge identification efficiency (%)
5	2613	2451	93.8	3169	2967	93.6
25	13314	12420	93.3	16136	15027	93.1

$\boxed{\text{Discrimination between } \mu^+ \text{ and } \mu^- \Rightarrow \text{important physics}}$

ICAL Energy calibration





Track length vs. Energy

No. of Hits vs. Energy

Atmospheric ν in ICAL

Type of event	Total Number	Fully Contained	No. of events with not less than n hits with $n =$			
			4	5	6	7
μ^+	2690	2042	1310	1156	1045	922
μ^-	7596	6209	3323	2815	2419	2109

5-year simulated atmospheric neutrino data (ICAL-H)

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5-year simulated atmospheric neutrino data (ICAL-H)

Oscillation prob. depends on neutrino L/E

$$L = (R-d)\cos\theta + \left[R^2 - (R-d)^2 \sin^2\theta\right]^{\frac{1}{2}}$$

$\theta \equiv \nu$ zenith angle, $R \equiv$ radius of the earth, $d \equiv$ depth of detector

Atmospheric ν oscillations

Without oscillations, no. of ν from zenith angle θ and $\pi - \theta$ same $\Rightarrow$ up-down symmetry

Down-going neutrinos: Small L, negligible oscillations
Up-going neutrinos: L upto 12000km, significant depletion due to oscillations

Atmospheric ν oscillations

Without oscillations, no. of ν from zenith angle θ and $\pi - \theta$ same $\Rightarrow$ up-down symmetry

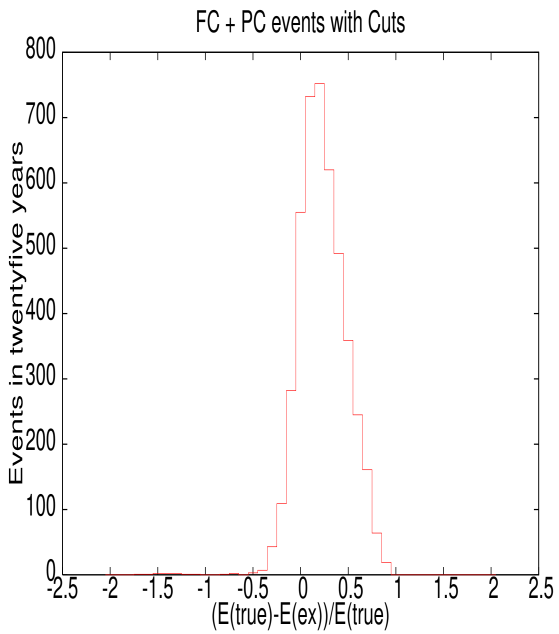
Down-going neutrinos: Small L, negligible oscillations
Up-going neutrinos: L upto 12000km, significant depletion due to oscillations

For any zenith angle θ, down-going neutrinos give no oscillation calibration for the upgoing neutrinos with zenith angle $\pi - \theta$

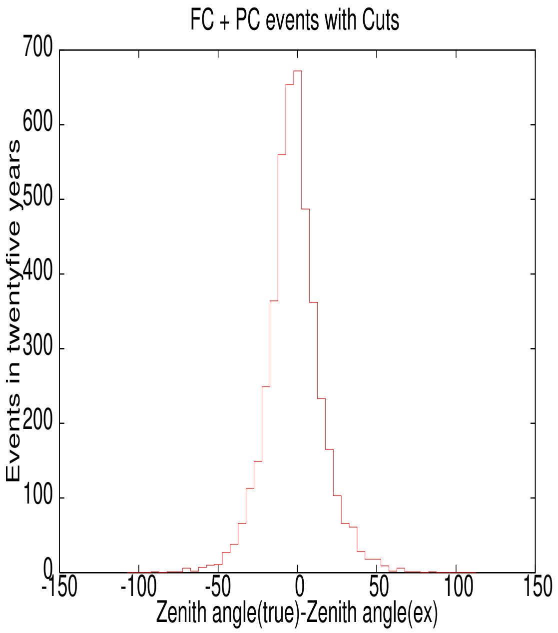
ν survival probability is a function of (L/E), L determined by zenith angle θ

(# of Up events)/(# of Down events) as a function of (L/E) captures oscillatory behaviour

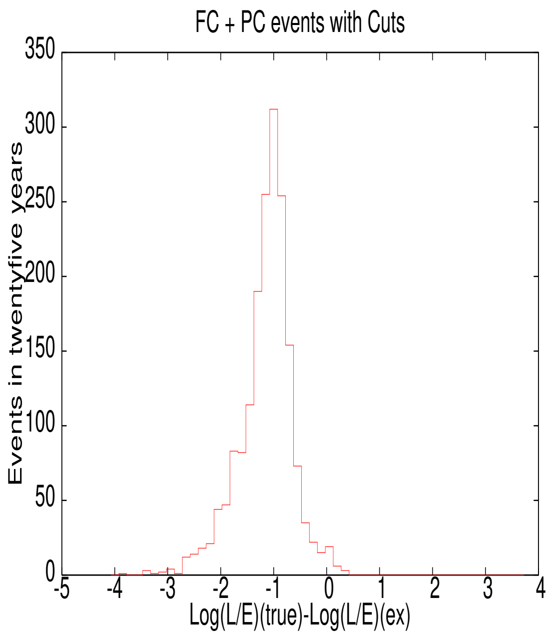
Detector resolutions



Energy



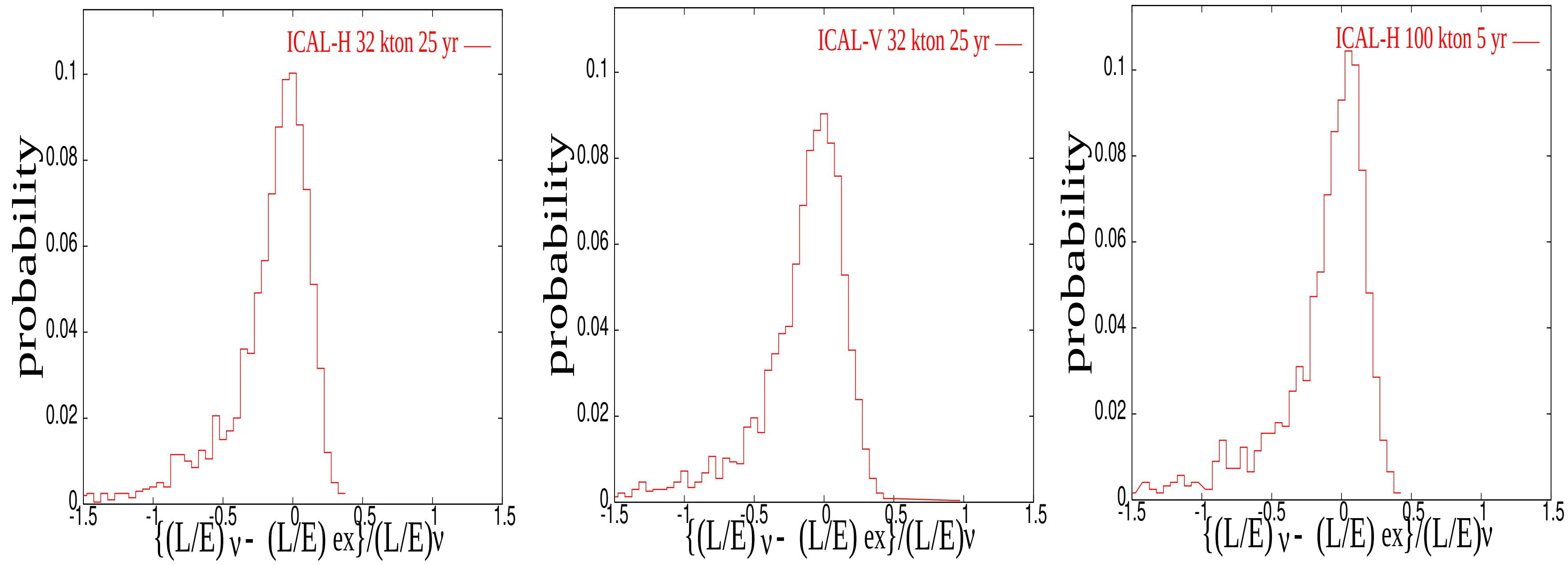
Zenith angle



L/E

FC + PC events

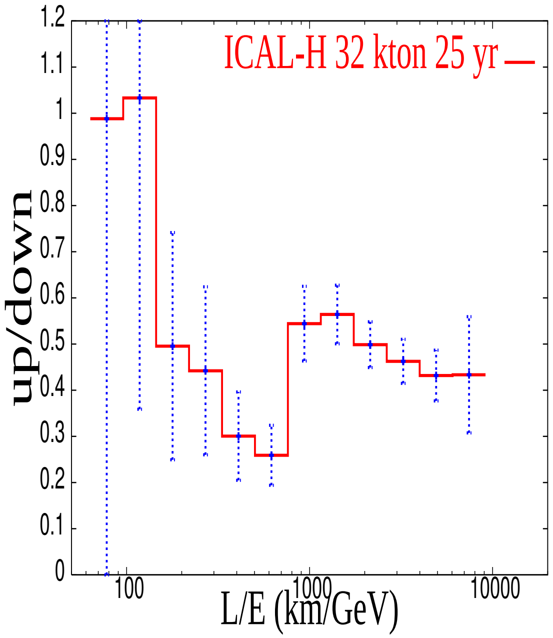
Detector resolutions

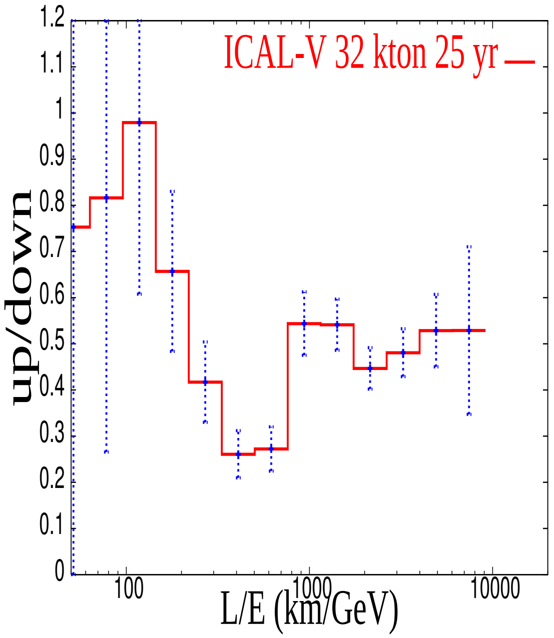


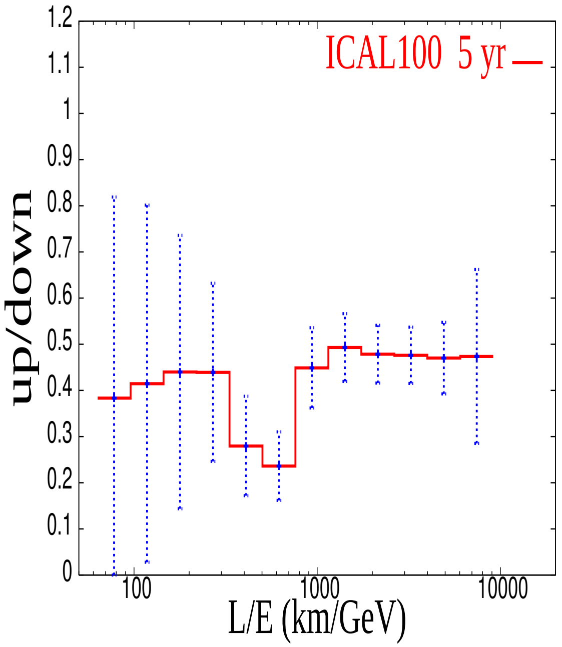
ICAL-H ICAL-V ICAL100

(L/E) resolutions for FC events

Atmos. ν-osc. at ICAL



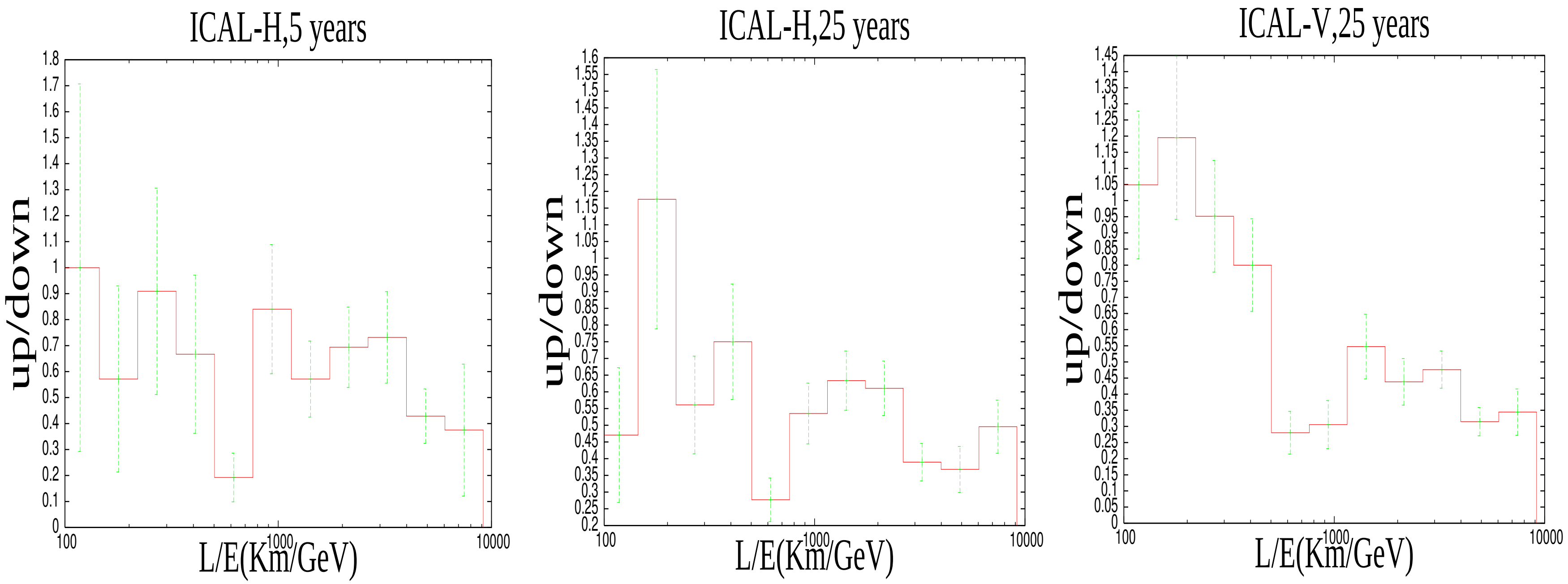




ICAL-H ICAL-V ICAL100

(up/dpwn) vs. (L/E) for FC events

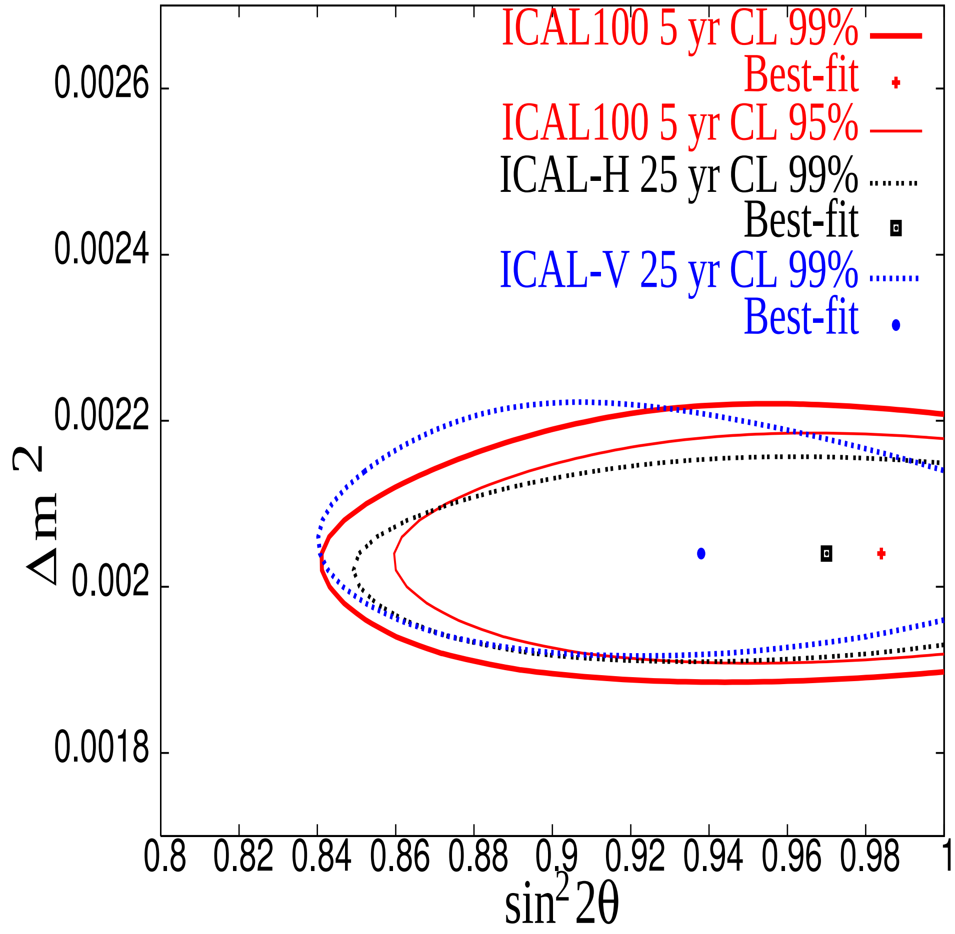
Atmos. ν-osc. at ICAL



ICAL-H 5yrs ICAL-H 25yrs ICAL-V 25yrs

(up/dpwn) vs. (L/E) for FC+PC events

Extraction of ν parameters



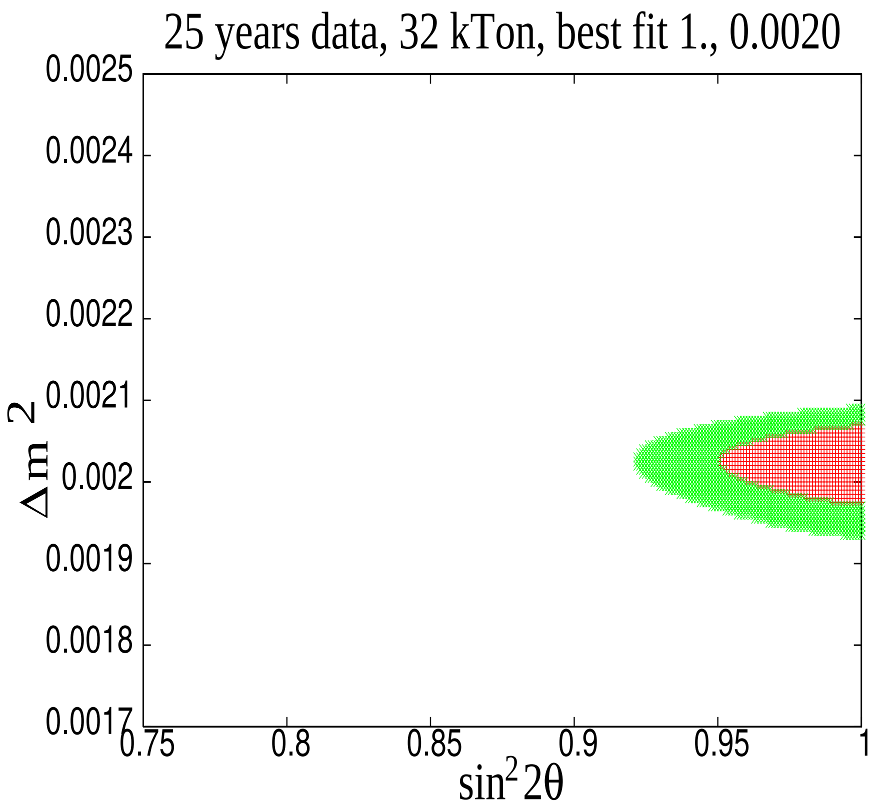
ICAL: FC events only

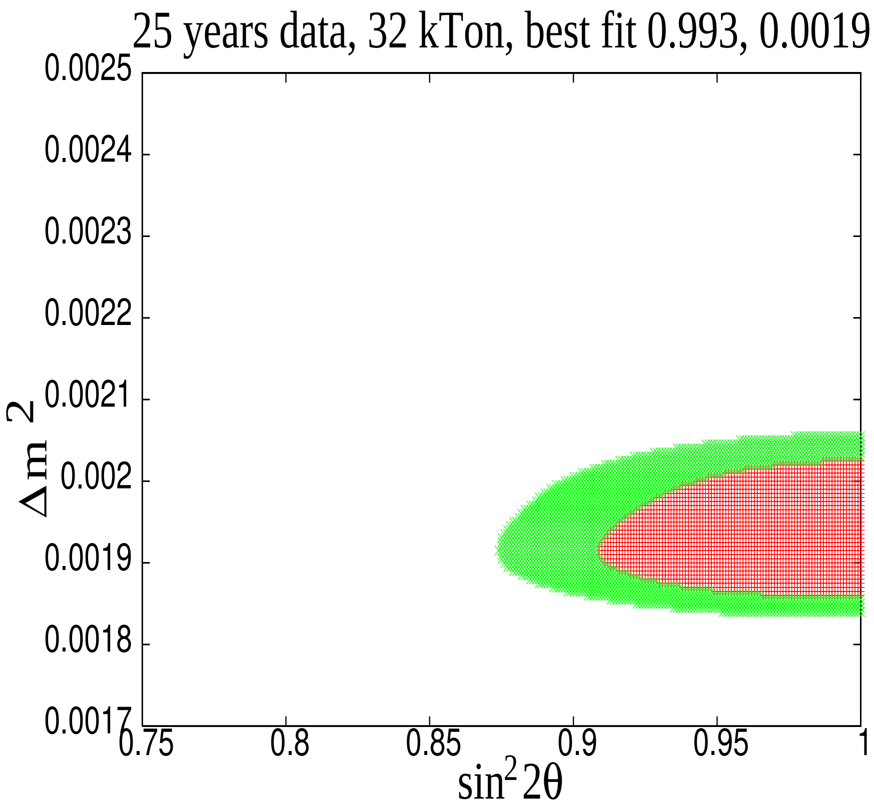
INPUT: Simulated data with $\Delta m^2 = 2 \times 10^{-3}eV^2, sin^2 2\theta$ = 1

99% CL contours, best-fits

ICAL-H (800 kT-yrs),
ICAL-V (800 kT-yrs),
ICAL100 (500 kT-yrs)

Extraction of ν parameters



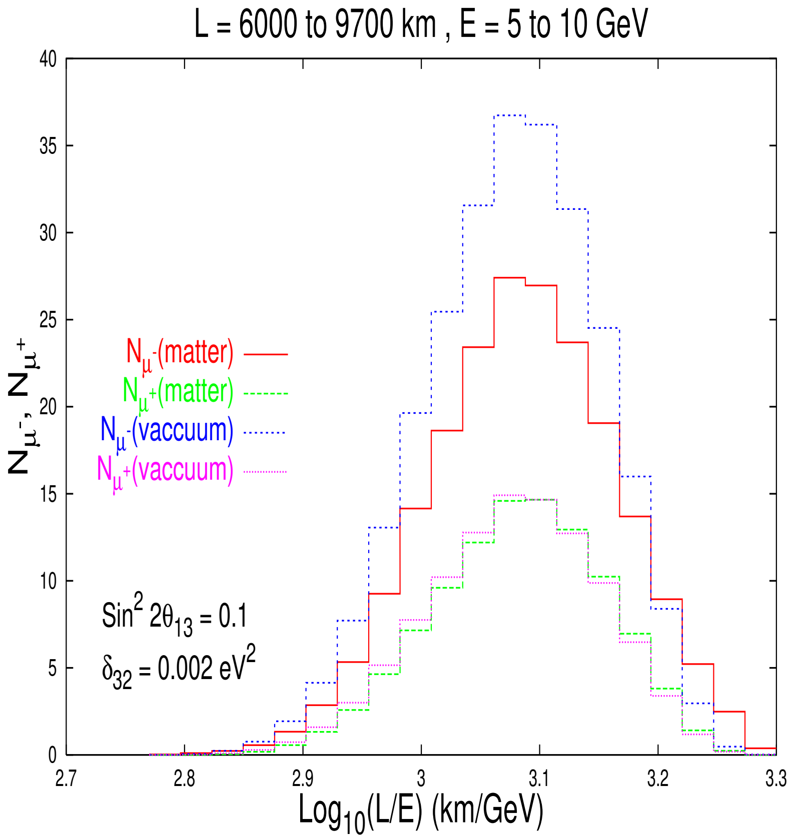


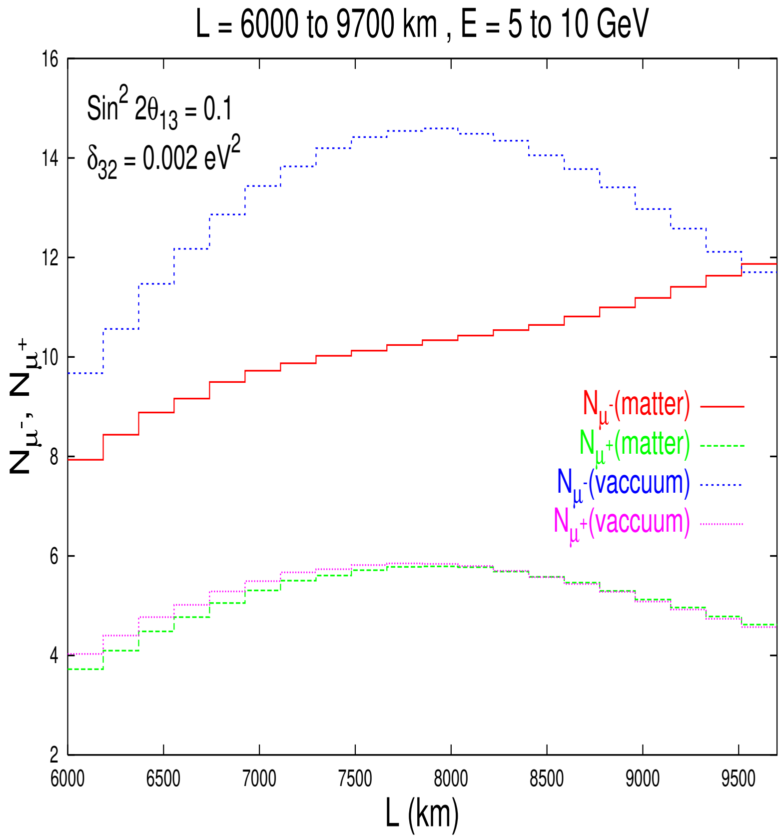
ICAL-H 25 years

ICAL-V 25 years

FC+PC events

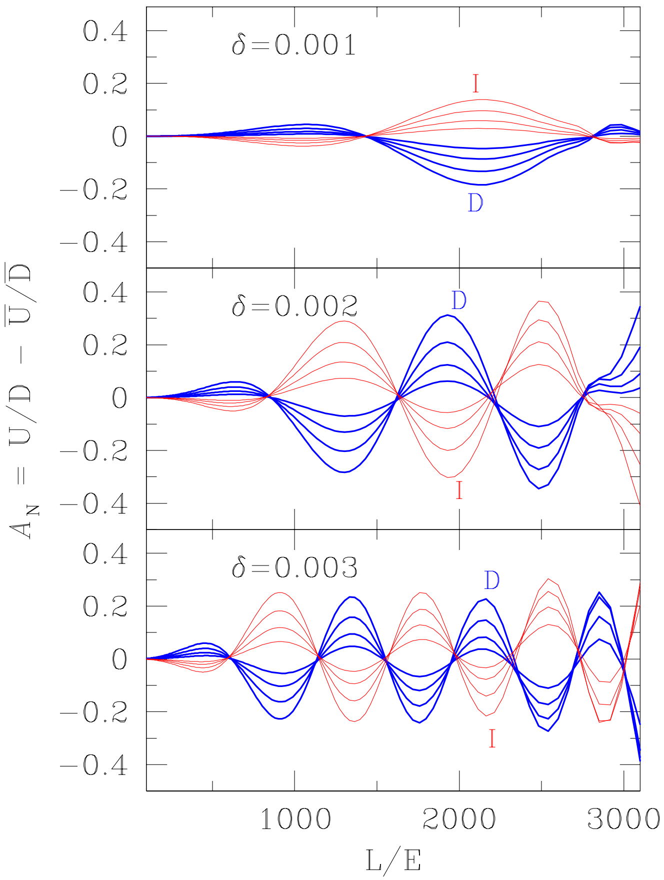
Extraction of matter effects



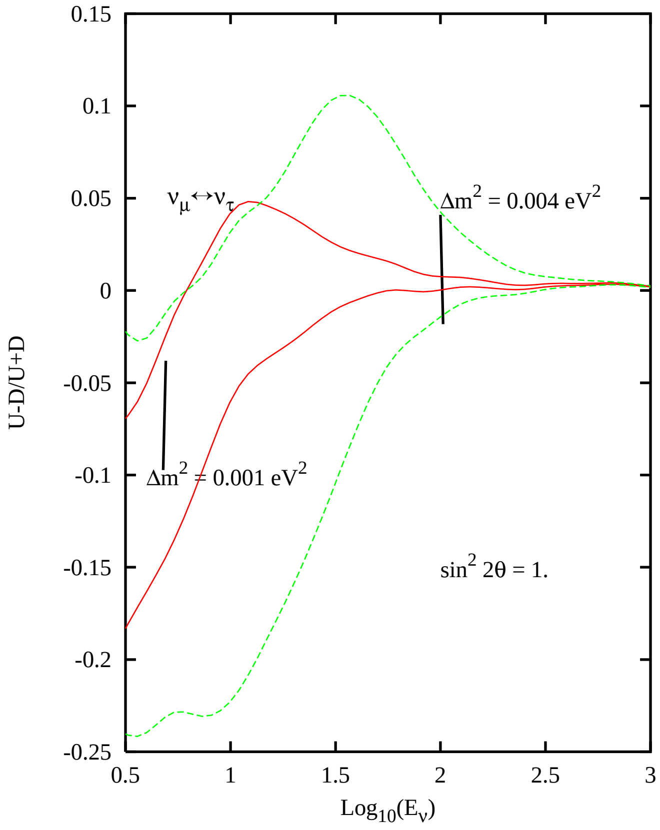


Matter interactions different for ν and $\bar{\nu}$
Relevant for upgoing events, negligible for down-going
Examine $\frac{U}{D} - \frac{\bar{U}}{\bar{D}}$

Matter effect; $\nu_\mu \leftrightarrow \nu_\tau$ vs. $\nu_\mu \leftrightarrow \nu_s$



Matter effect search



$\nu_\mu \leftrightarrow \nu_\tau$ vs. $\nu_\mu \leftrightarrow \nu_s$

U-D asymm. in *muonless* events

Competing experiments

Planned experiments in next 10 years:

Accelerator: MINOS, ICARUS, OPERA (L $\sim$ 730 km) $\Leftarrow$ Improve $\sin^2\theta_{13}$ by a factor of 2

Accelerator superbeam: JPARC-SK, NOvA $\Leftarrow$ Improve $\sin^2\theta_{13}$ by a factor of 4

Reactor: D-CHOOZ $\Leftarrow$ Improve $\sin^2\theta_{13}$ by a factor of 6

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Will refine Δm^2_{23}, $\sin^2\theta_{13}$

None will see matter effects. Cannot determine sign of Δm^2_{23}

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None will see matter effects. Cannot determine sign of Δm^2_{23}

Hyper-Water Cerenkov: HyperK, UNO $\Leftarrow$ Sign of Δm^2_{23}, improve $\sin^2\theta_{13}$. 12 years (?)

INO: possible accomplishments

Strongly substantiate SK oscillation dip (300 kT-yr)

Improved precision: Δm^2_{23} to within 10% (400 kt-yr)

$\sin^2\theta_{13}$ uncertainty (currently $\sim$ 35%) reduction by a factor 2 (400 kt-yr)

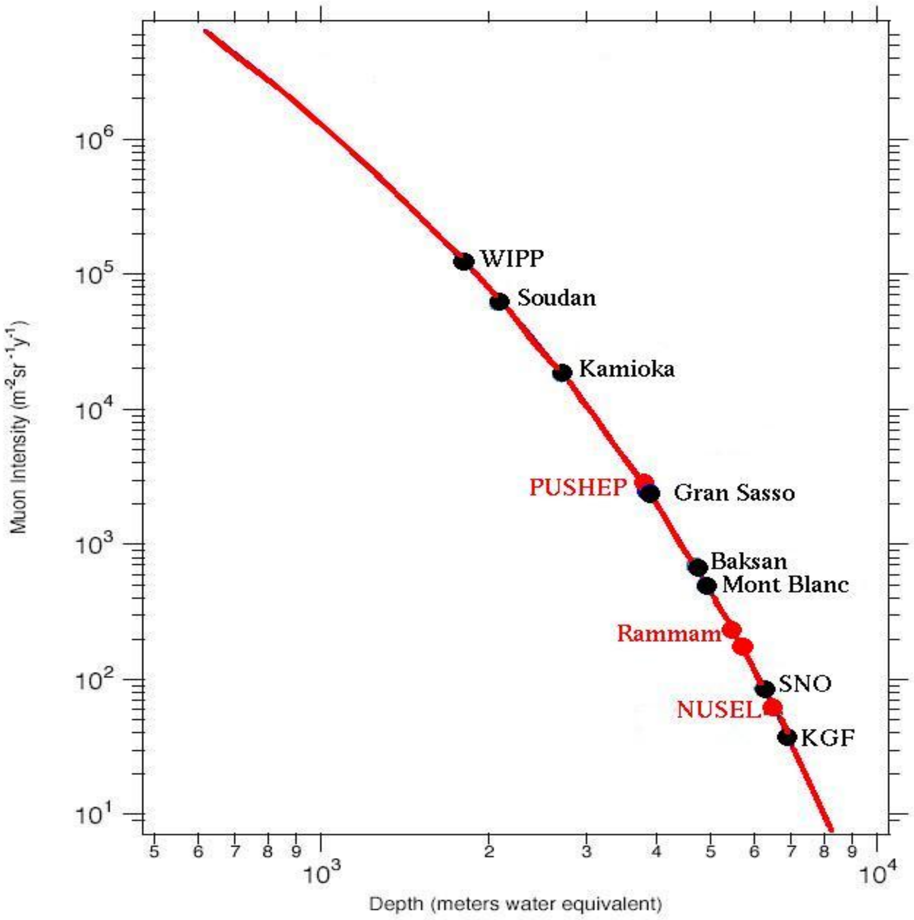
sign of Δm^2_{23} (1000 kT-yr)

End detector for beta beam/neutrino factory

ICAL/INO other physics

- θ_{13} with atmospheric neutrinos
- End detector for very long baseline experiment with neutrino factory source – presision measurements
  1. Sign of Δ_{23}
  2. Measure θ_{13}
  3. Leptonic CP-violation, CPT-violation, etc.
- Low background experiments
  1. Neutrinoless double beta decay
  2. Dark matter search
- Geophysical studies, Pollution free life sciences laboratory

INO: Possible Sites



Muon background vs. Depth

Reduction of muon background is crucial

Two possible INO sites: Rammam (Darjeeling) & PUSHEP (Ooty) surveyed

Note the advantage of INO

INO: Rough cost estimate

Item	Amount (in Rs. crores)
Tunneling and Cavern construction	30 - 80
Related civil work	50
Iron (for 32 kT)	140
Detector, Magnet, etc.	150
Total	370 - 420

1 crore = 10 million, Current equivalence: Rs 50 $\simeq$ 1 Euro

INO Status

Glass RPCs fabricated at TIFR & SINP

Gas mixing unit designed and built at SINP

Magnet design in progress at BARC and VECC

DAQ: Work in progress at TIFR, ...

Simulation: Atmospheric ν detailed study, Long baseline prospects examined at IMSc, SINP, HRI

Site: Survey completed for RAMMAM, PUSHEP. Comparative assessment in progress

Interim report will be completed in early 2005

Web site: http://www.imsc.res.in/$\sim$ino

Summary/Conclusions

Important results in neutrino physics expected soon

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THANK YOU!