India-based Neutrino Observatory

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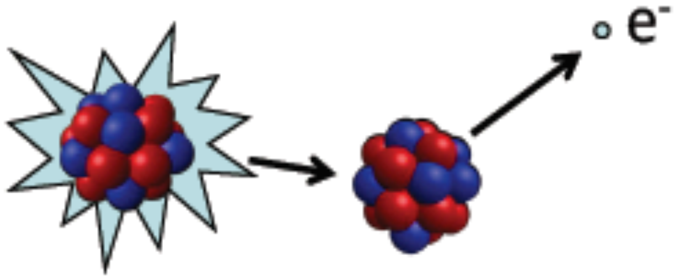
(On behalf of the INO collaboration)

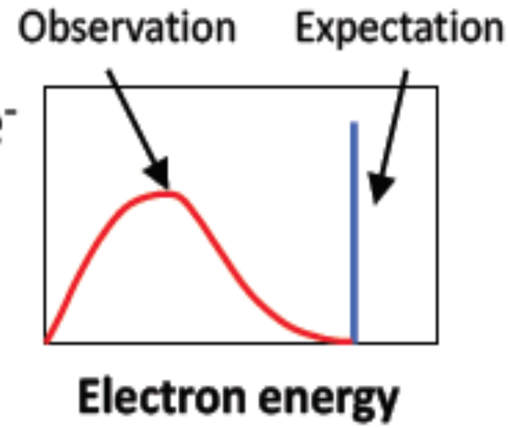
http://www.ino.tifr.res.in/ino/

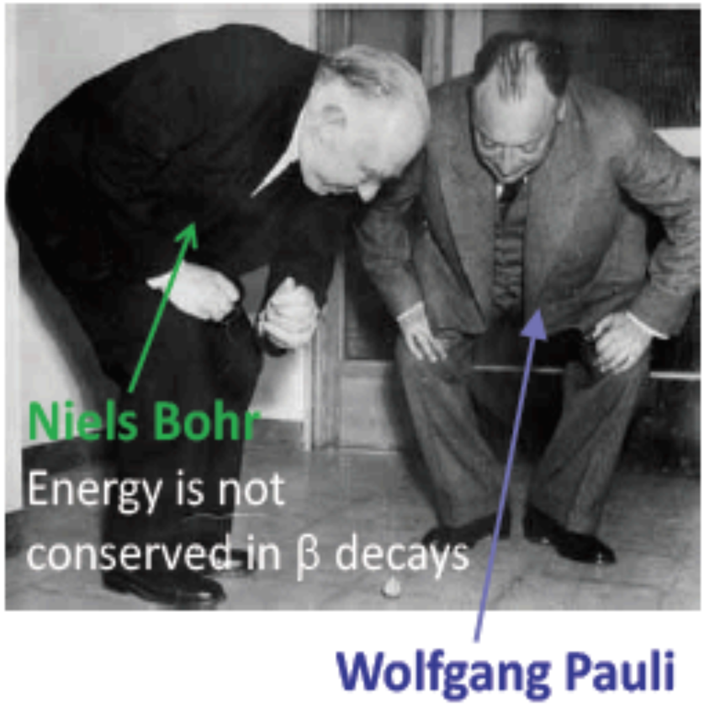
Mission Impossible: Detect Neutrinos !

The problem (1914)

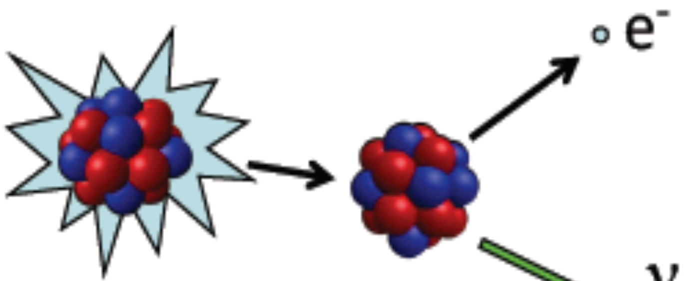


$n \rightarrow p + e^-$





The desperate remedy (1930)



$n \rightarrow p + e^- + \nu$

There is a neutral particle able to cross all detectors without leaving any trace and carrying all the missing energy

«I have done a terrible thing. I have postulated a particle that cannot be detected.» (1930)

Fortunately Pauli was wrong and neutrinos have been detected successfully

Neutrinos are everywhere

Detected (1950s)

✓ Nuclear Reactors

Detected (1960s)

Sun ✓

Created & Detected (1960s)

✓ Particle Accelerators

Detected (1980s)

Supernovae
(Stellar Collapse)
SN 1987A ✓

Detected (1960s)

✓ Earth Atmosphere
(Cosmic Rays)

Recently, IceCube reports the detection of 28 extremely HE neutrinos

Astrophysical Accelerators Soon ?

Detected (2000s)

✓ Earth Crust
(Natural Radioactivity)

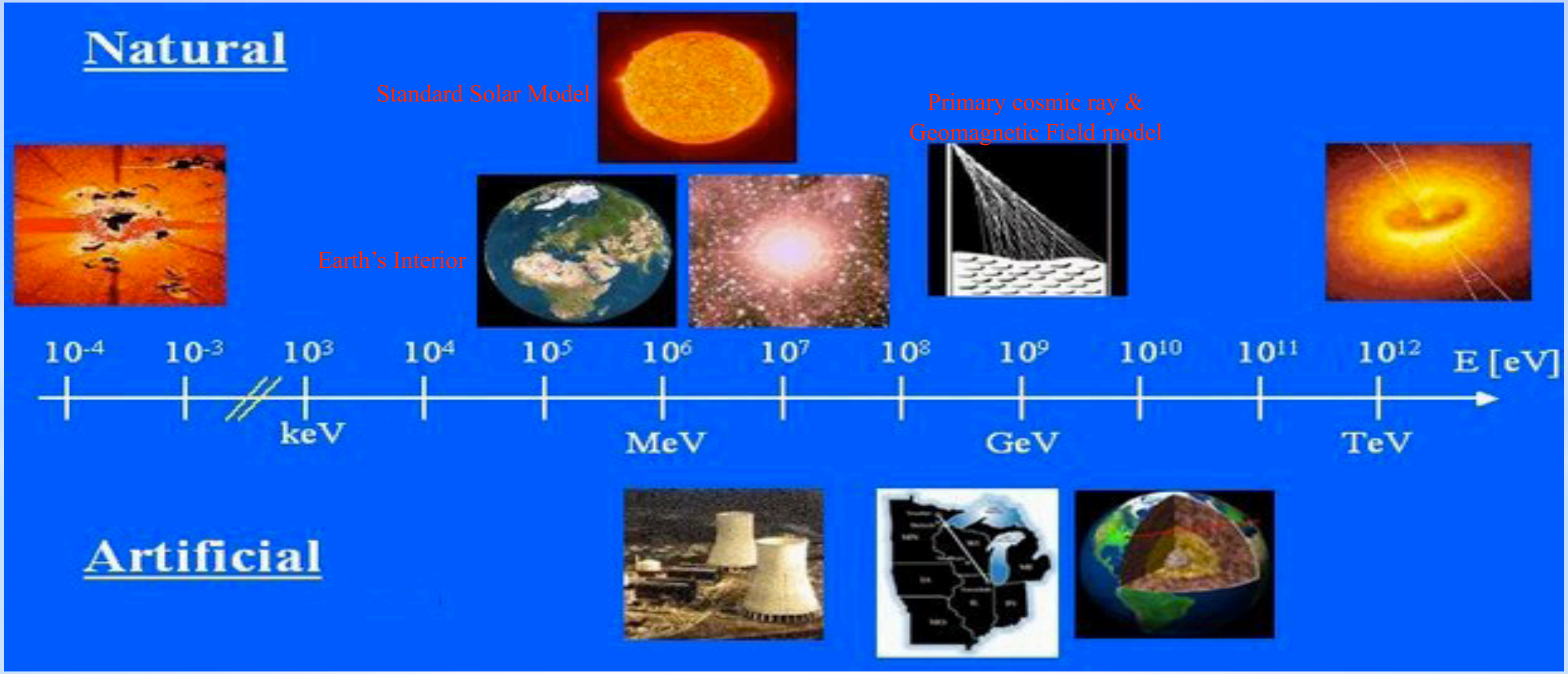
Not even close

Cosmic Big Bang
(Today 330 ν/cm^3)
Indirect Evidence

Extremely rich and diverse neutrino physics program!

Neutrinos: Exceptional Probe for Environments

Neutrino Observation: Go Beyond optical and radio observation



Detect neutrinos from the Sun, Supernovae, AGN, GRBs: Era of Neutrino Astronomy

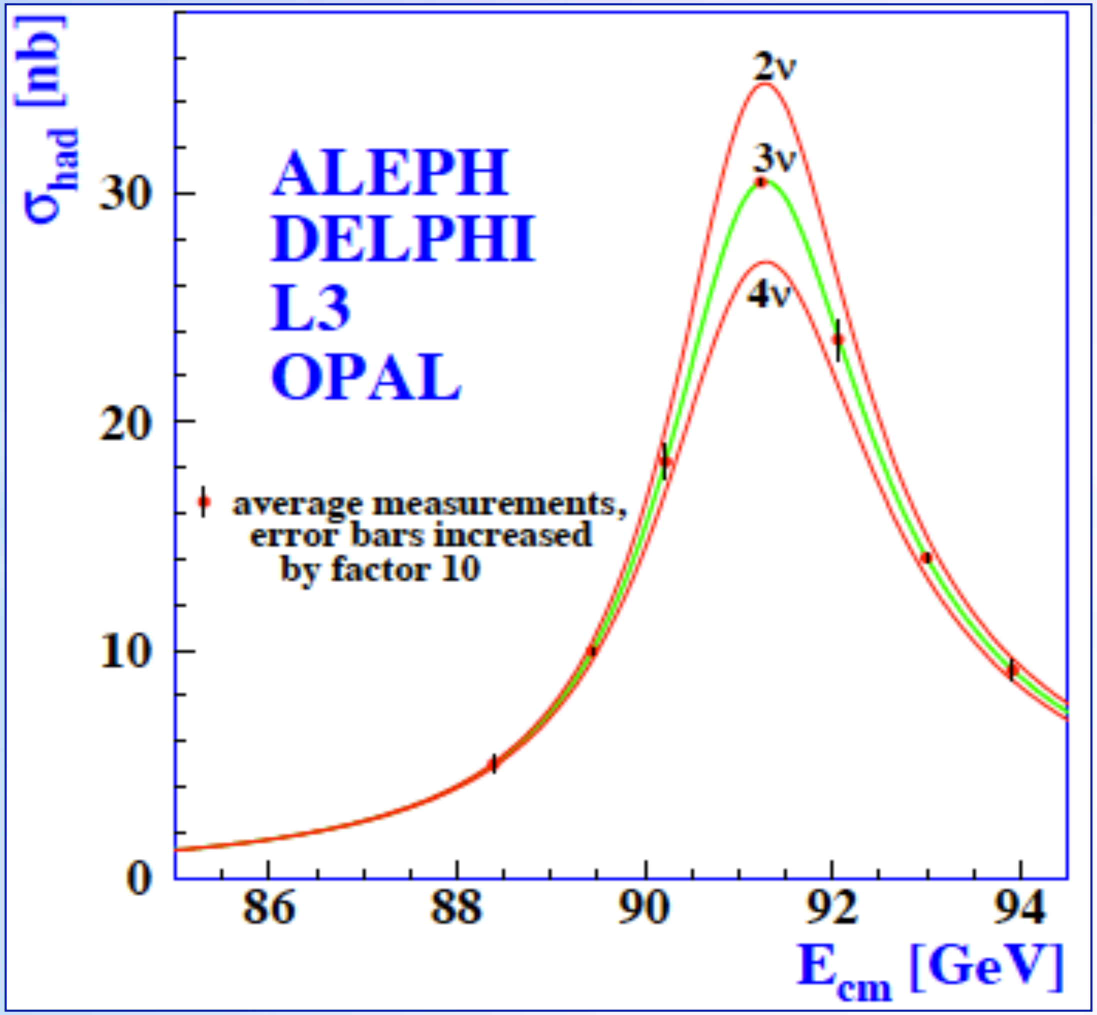
- ***detection involves several methods on surface, underground, under the sea, or in the ice***
- ***detector masses range from few kgs to megatons, with volumes from few m^3 to km^3***

Neutrinos in Hollywood!

Dr. Satnam Tsurutani in India has discovered that neutrinos from a massive solar flare from the Sun are causing the temperature of the Earth's core to increase rapidly!

Legal warnings! Considering Hollywood movies seriously may be harmful to sanity

Three Light Active Neutrinos



Precision data of the Z-decay width at the e^+e^- collider at LEP

$$e^+e^- \to Z \xrightarrow{\text{invisible}} \sum_{a=\text{active}} \nu_a \bar{\nu}_a$$

$$N_{\nu_{\text{active}}} = 2.9840 \pm 0.0082$$

[LEP, Phys. Rept. 427 (2006) 257, hep-ex/0509008]

3 light active flavor neutrinos

$\nu_e \;\; \nu_\mu \;\; \nu_\tau$

The Standard Model: Massless Neutrinos

The Standard Model is a gauge theory & it unifies strong, weak & electromagnetic forces!

$SU(3)_C \times SU(2)_L \times U(1)_Y \Rightarrow SU(3)_C \times U(1)_{EM}$

$(1,2)_{-\frac{1}{2}}$	$(3,2)_{\frac{1}{6}}$	$(1,1)_{-1}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{1}{3}}$
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} u^i \\ d^i \end{pmatrix}_L$	e_R	u^i_R	d^i_R
$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} c^i \\ s^i \end{pmatrix}_L$	μ_R	c^i_R	s^i_R
$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	$\begin{pmatrix} t^i \\ b^i \end{pmatrix}_L$	τ_R	t^i_R	b^i_R

3-fold repetition of the same representation!

- 3 *active* neutrinos: ν_e , ν_μ , ν_τ
- Neutral elementary particles of Spin ½
- Only couple to *weak force* (& gravity)
- Only *left handed* neutrinos
- There are no right-handed neutrinos
- *No* Dirac Mass term: $m(\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L)$

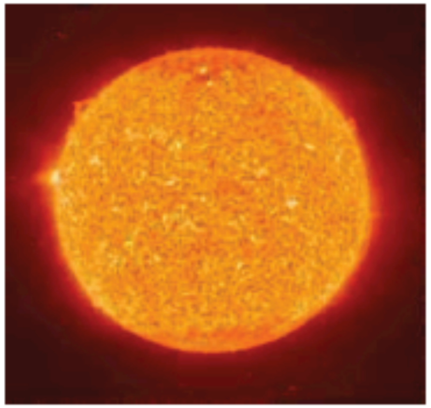
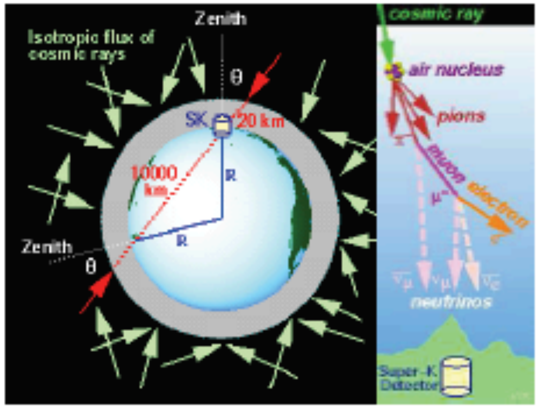
Neutrinos are massless in the Basic SM!

- ❑ Over the past decade, marvelous data from world class neutrino experiments firmly established that they change flavor after propagating a finite distance!
- ❑ Neutrino flavor change (oscillation) demands non-zero mass and mixing!

Non-zero ν mass: first experimental proof for physics beyond the Standard Model!

!! An extension of the Standard Model is necessary !!

Golden Age of Neutrino Physics (1998 – 2012 & Beyond)

sun	reactors	atmosphere	accelerators
			
Homestake, SAGE, GALLEX SuperK, SNO, Borexino	KamLAND, CHOOZ Double Chooz, Daya Bay, RENO	SuperKamiokande IceCube	K2K, MINOS, T2K

Over the last fourteen years or so, marvellous data from world-class experiments

- Solar neutrinos (ν_e)
- Atmospheric neutrinos ($\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$)
- Reactor anti-neutrinos ($\bar{\nu}_e$)
- Accelerator neutrinos ($\nu_\mu, \bar{\nu}_\mu$)

Data driven field – new data are coming

→ ***Data from various neutrino sources and vastly different energy and distance scales***

We have just started our journey in the mysterious world of neutrinos!

Neutrino Physics: An Exercise in Patience

The three most fundamental questions were formulated in the past century…

1. How tiny is the neutrino mass? (Pauli, Fermi, '30s)

Recent Planck satellite data set an upper limit of 0.23 eV for the sum of neutrino masses!

Planck Collaboration, arXiv:1303.5076 [astro-ph.CO]

2. Can a neutrino turn into its own antiparticle? (Majorana, '30s)

Hunt for ν-less Double-β decay (Z,A → Z+2, A) is still on, demands lepton number violation!

Nice Review by Avignone, Elliott, Engel, Rev.Mod.Phys. 80 (2008) 481-516

3. Do different ν flavors 'oscillate' into one another? (Pontecorvo, Maki-Nakagawa-Sakata, '60s)

B. Pontecorvo, Sov. Phys. JETP 26, 984 (1968) [Zh. Eksp. Teor. Fiz. 53, 1717 (1967)]

The last question has been positively answered only in recent years. It is now an established fact that **neutrinos are massive** and leptonic flavors are not **symmetries of Nature**!

With the recent measurement of the **last unknown mixing angle θ_{13}**, a clear first order picture of the 3-flavor lepton mixing matrix has emerged, signifies a major breakthrough in ν physics!

The year 2013 marks the **100th anniversary** of the birth of Pontecorvo, a great tribute to him!

Neutrino Oscillations in 3 Flavors

ν oscillation is a quantum mechanical phenomenon like electrons in the double slit experiment!
It happens because flavor (weak) eigenstates do not coincide with mass eigenstates

Flavor States: ν_e, ν_μ, ν_τ (produced in weak interactions)
Mass States: ν_1, ν_2, ν_3 (propagate from source to detector)

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i} |\nu_i\rangle \quad (\alpha = e, \mu, \tau)$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atmospheric sector — connection between solar and atmospheric — solar sector

$c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$

U is a 3×3 unitary matrix containing θ_{23}, θ_{13}, θ_{12} and one CP violating (Dirac) phase δ_{CP}

3 mixing angles simply related to flavor components of 3 mass eigenstates

$$\tan^2\theta_{12} \equiv \frac{|U_{e2}|^2}{|U_{e1}|^2}; \quad \tan^2\theta_{23} \equiv \frac{|U_{\mu 3}|^2}{|U_{\tau 3}|^2}; \quad U_{e3} \equiv \sin\theta_{13} e^{-i\delta}$$

Over a distance L, changes in the relative phases of the mass states may induce flavor change!

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}[U^*_{\alpha i} U_{\alpha j} U_{\beta i} U^*_{\beta j}] \sin^2\Delta_{ij} - 2\sum_{i>j} \mathrm{Im}[U^*_{\alpha i} U_{\alpha j} U_{\beta i} U^*_{\beta j}] \sin 2\Delta_{ij}$$

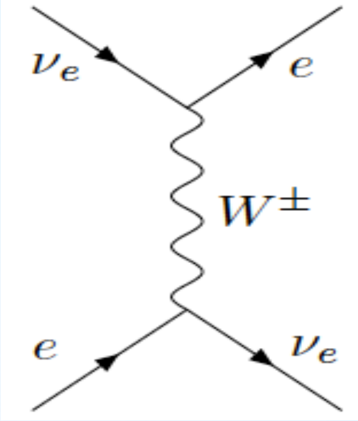
$$\Delta_{ij} = \Delta m^2_{ij} L / 4E_\nu$$

$$\Delta m^2_{ij} = m^2_i - m^2_j$$

2 independent mass splittings Δm^2_{21} and Δm^2_{32}, for anti-neutrinos replace U by U^*

Neutrino Oscillations in Matter

Neutrino propagation through matter can modify the oscillations significantly!



There is coherent forward elastic scattering of neutrinos with matter particles!

Can be compared with the visible light travelling through glass!

Charged current interaction of ν_e with electrons creates an extra potential for ν_e!

Wolfenstein matter term: $A = \pm 2\sqrt{2} G_F N_e E$ or $A(\mathrm{eV}^2) = 0.76 \times 10^{-4} \rho \ (\mathrm{g/cc}) E(\mathrm{GeV})$

N_e = electron number density , + (-) for neutrinos (anti-neutrinos) , ρ = matter density in Earth

Matter term changes sign when we switch from neutrino mode to anti-neutrino mode!

$P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \neq 0$ → ***even if $\delta_{CP} = 0$, causes fake CP asymmetry!***

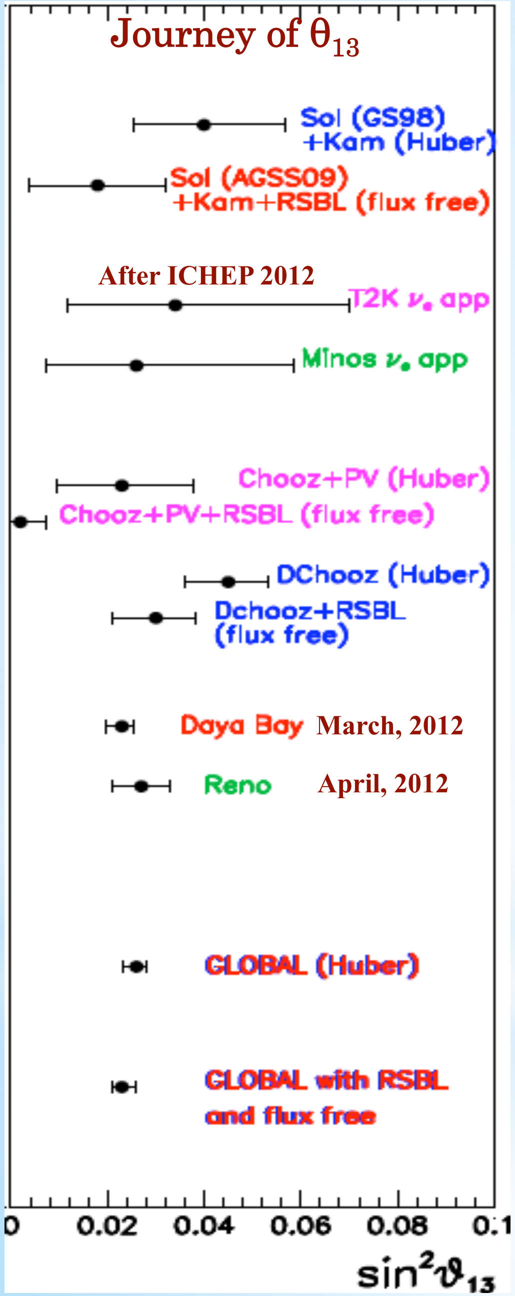
Matter term modifies oscillation probability differently depending on the sign of Δm^2

$\Delta m^2 \simeq A \quad \Leftrightarrow \quad E_{\mathrm{res}}^{\mathrm{Earth}} = 6 - 8\,\mathrm{GeV}$ → ***Resonant conversion – the MSW effect***

	ν	$\bar{\nu}$
$\Delta m^2 > 0$	MSW	-
$\Delta m^2 < 0$	-	MSW

→ ***Resonance occurs for neutrinos (anti-neutrinos) if Δm^2 is positive (negative)***

θ_{13} Revolution and Present Status of Neutrino Parameters



	bfp $\pm 1\sigma$	3σ range	Relative 1σ Precision
$\sin^2\theta_{12}$	0.30 ± 0.013	$0.27 \to 0.34$	(3.9%)
$\theta_{12}/^\circ$	33.3 ± 0.8	$31 \to 36$	
$\sin^2\theta_{23}$	$0.41^{+0.037}_{-0.025} \oplus 0.59^{+0.021}_{-0.022}$	$0.34 \to 0.67$	(11%)
$\theta_{23}/^\circ$	$40.0^{+2.1}_{-1.5} \oplus 50.4^{+1.2}_{-1.3}$	$36 \to 55$	
$\sin^2\theta_{13}$	0.023 ± 0.0023	$0.016 \to 0.030$	(10%)
$\theta_{13}/^\circ$	$8.6^{+0.44}_{-0.46}$	$7.2 \to 9.5$	
$\delta_{CP}/^\circ$	300^{+66}_{-138}	$0 \to 360$	(Not Known)
$\dfrac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	7.50 ± 0.185	$7.00 \to 8.09$	(2.4%)
$\dfrac{\Delta m^2_{31}}{10^{-3}\ \text{eV}^2}$ (N)	$2.47^{+0.069}_{-0.067}$	$2.27 \to 2.69$	(2.8%)
$\dfrac{\Delta m^2_{32}}{10^{-3}\ \text{eV}^2}$ (I)	$-2.43^{+0.042}_{-0.065}$	$-2.65 \to -2.24$	

Gonzalez-Garcia, Maltoni, Salvado, Schwetz, JHEP 1212 (2012) 123

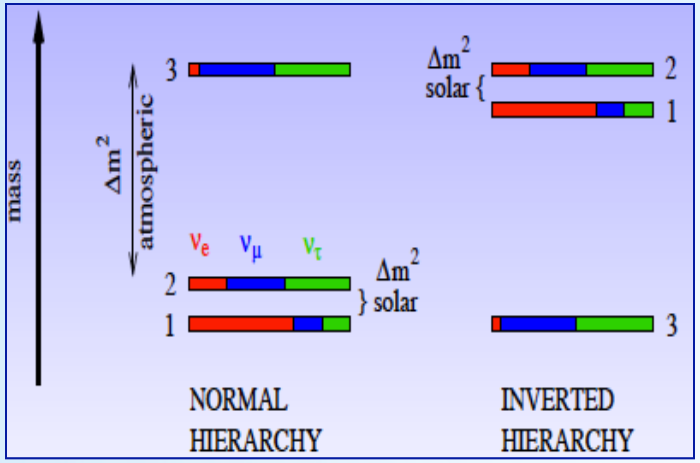
θ_{13} has been determined to be reasonably large, not too far from its previous upper bound!

More than 10σ confirmation of non-zero θ_{13}! Relative 1σ precision of 10% achieved!

Indication of non-maximal 2-3 mixing angle (~ 2σ) by the MINOS accelerator experiment!

Fundamental Unknowns in Neutrino Sector

1. What is the hierarchy of the neutrino mass spectrum, normal or inverted?



- *The sign of* $\Delta m^2_{31} = m^2_3 - m^2_1$ *is not known!*
- *Currently do not know which neutrino is the heaviest?*
- *Only have a lower bound on the mass of the heaviest ν!*

$$\sqrt{2.5 \cdot 10^{-3} \mathrm{eV}^2} \sim 0.05 \ \mathrm{eV}$$

2. What is the octant of the 2-3 mixing angle, lower ($\theta_{23} < 45°$) or higher ($\theta_{23} > 45°$)?

If $\sin^2 2\theta_{23}$ differs from 1 as indicated by the recent neutrino data, we get two solutions for θ_{23}: one < 45°, termed as lower octant (LO) and the other > 45°, known as higher octant (HO)

2. Is there CP violation in the leptonic sector, as in the quark sector?

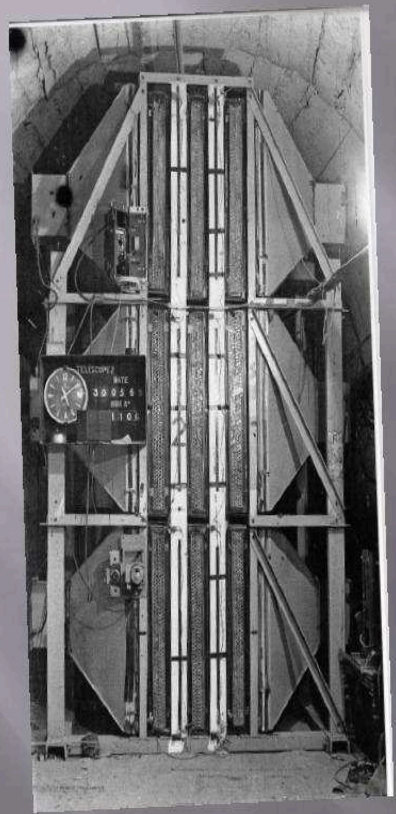
Mixing can cause CP violation in the leptonic sector (if δ_{CP} differs from 0° and 180°)!
Need to measure the CP-odd asymmetries: $\Delta P_{\alpha\beta} \equiv P(\nu_\alpha \to \nu_\beta; L) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta; L)$ $(\alpha \neq \beta)$

With our current knowledge of θ_{13}, resolving these fundamental unknowns fall within our reach!
Sub-leading 3 flavor effects are extremely crucial in current and future oscillation experiments!

An Old Saga of Underground Laboratory in India

- *KGF: Deepest underground lab in world till 1992 > 6500 MWE*
- *In 1965, at KGF at a depth of 2.3km, first atmospheric neutrino was observed by the TIFR-Osaka-Durham group*
- *During early 80s dedicated detectors were setup at KGF by TIFR-Osaka collaboration to look for proton decay*

Atmospheric neutrino detection in 1965



Atmospheric neutrino detector at Kolar Gold Field -1965

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 Aug 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 Aug. 1965

India Based Neutrino Observatory

- *A multi-institutional attempt to build a world-class underground facility to study fundamental issues in science with special emphasis being on neutrinos*
- *With ~1 km all-round rock cover accessed through a 2 km long tunnel. A large and several smaller caverns to pursue many experimental programs*
- *Complementary to ongoing efforts worldwide to explore neutrino properties*
- *A mega-science project (~250 M$) in India, jointly funded (50:50) by the Department of Atomic Energy and the Department of Science and Technology*
- *One of the largest basic science projects in India, involving nearly 100 scientists from 25 research institutes and Universities all over India*
- *INO facility is available for international community for setting up experiments like Neutrino-less Double Beta Decay, Dark Matter searches*

INO Collaboration

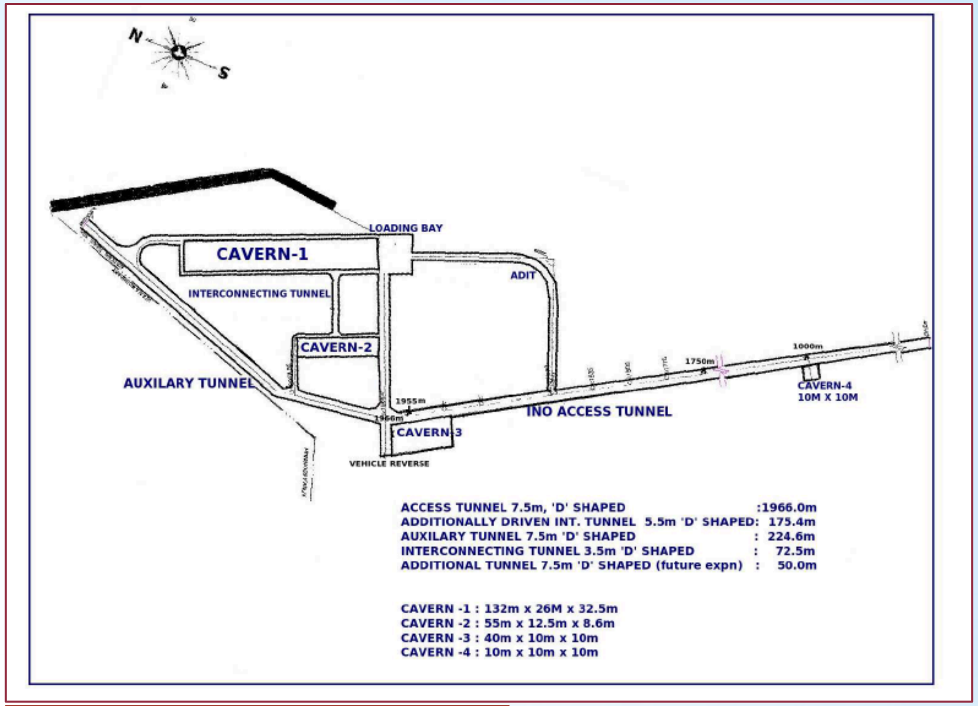
Ahmadabad: Physical Research Lab.
Aligarh: Aligarh Muslim University
Allahabad: HRI
Bhubaneswar: Institute of Physics
Calicut: University of Calicut
Chandigarh: Panjab University
Chennai: IIT, Madras IMSc
Delhi: University of Delhi
Guwahati: IIT, Guwahati
Hawaii (USA): University of Hawaii
Indore: IIT, Indore
Jammu: University of Jammu
Kalpakkam: IGCAR
Kolkata: Ramakrishna Mission Vivekananda University,
SINP, VECC, University of Calcutta
Lucknow: Lucknow University
Madurai: American College
Mumbai: BARC, IIT, Bombay TIFR
Mysore: University of Mysore
Sambalpur: Sambalpur University
Srinagar: University of Kashmir
Varanasi: Banaras Hindu University

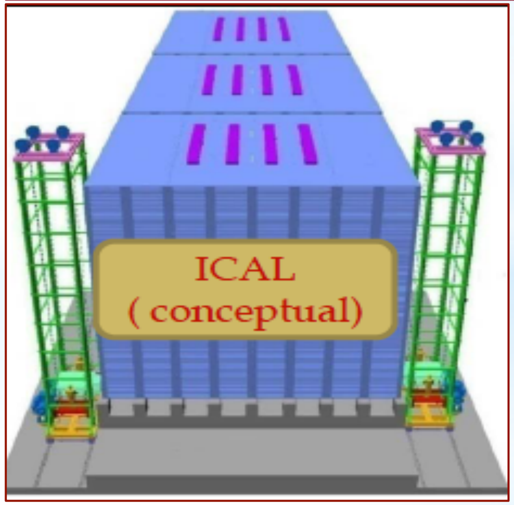
Recent Updates on the Site Front

- *INO project approved by DAE and DST*
- *Environmental and Forest clearance for the site obtained*
- *26 hectars of land provided free by Tamil Nadu state government*
- *Site preparation works are being tendered*
- *Funds have already been transferred to the Tamil Nadu government from the INO budget for construction of approach roads and water connection to the INO site*
- *Construction of an INO Centre:*
  The National Centre for High Energy Physics (NCHEP)
  planned at Madurai, land has been acquired
- *The fencing of both, Pottipuram and Madurai lands, will start soon*

Approved projects under INO

- *To come up with an underground lab and surface facilities near Pottipuram village in Theni district of Tamil Nadu.*
- *To build massive 50 kt magnetized Iron calorimeter (ICAL) detector to study properties of neutrinos.*
- *Construction of the INO centre:*
  The NCHEP at Madurai
- *Human Resource Development*
  (INO Graduate Training Program)
- *Completely in-house Detector R&D with substantial INO-Industry interface*
  Projected Time Frame (2012-2018)

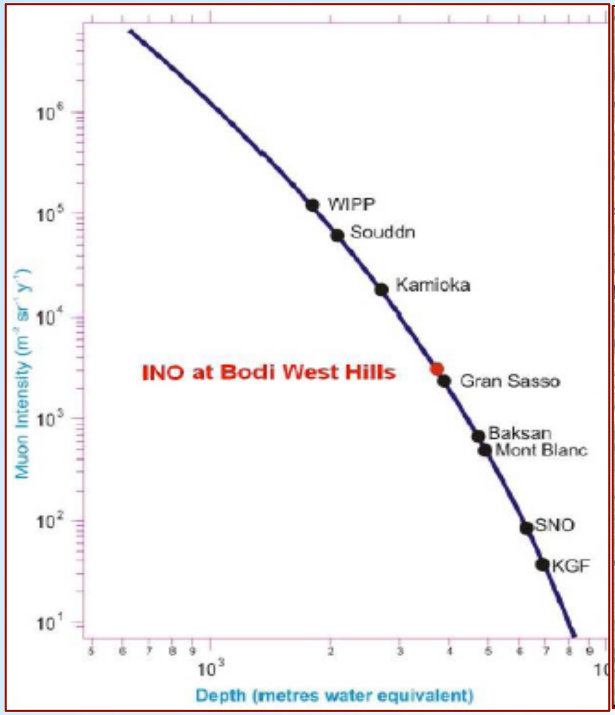


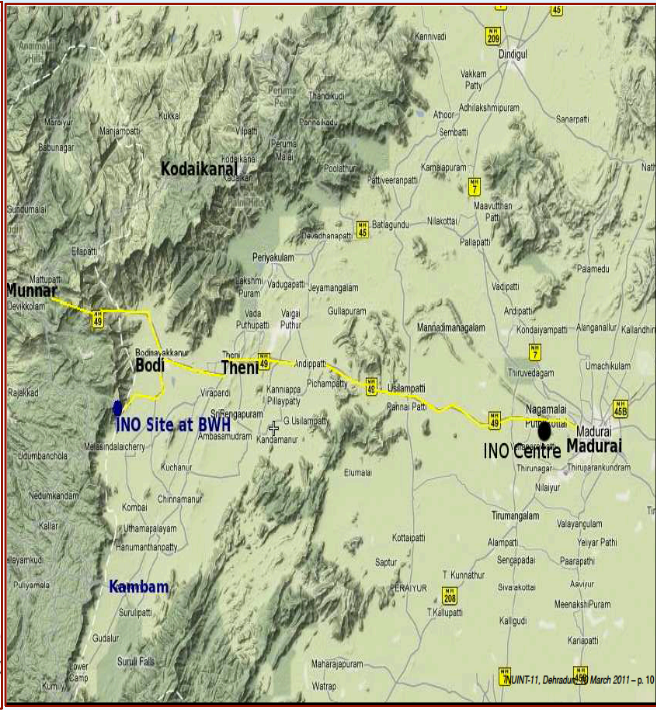


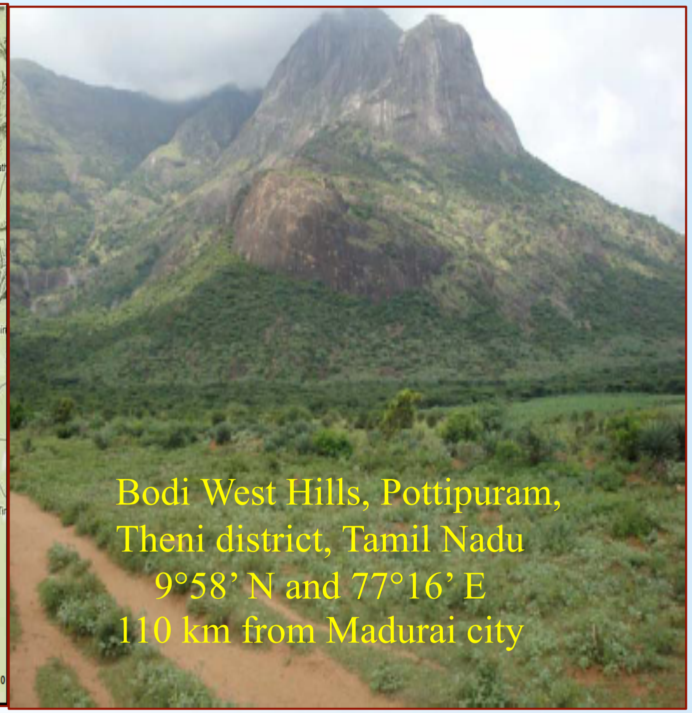
Spokesperson:
N.K. Mondal

Host Institute:
TIFR

Location of INO & Unique Features







- ***Transport:*** *Flat terrain with good access from major roads*
- ***Geotechnical Issues:*** *Good rock quality, Cavern set in massive Charnockite rock under the 1589 m peak, Vertical cover approx. 1289 m, Tunnel length 1.91 km*
- ***Environmental Issues:*** *Portal set outside the reserve forest boundary, no disturbance to forest Surface facilities not on Forest Land. No clearing of forest*
- ***Weather:*** *Warm, low rainfall area, low humidity throughout the year*

INO Phase 1

Study Atmospheric neutrinos with a wide range of L/E

What do we want to achieve?

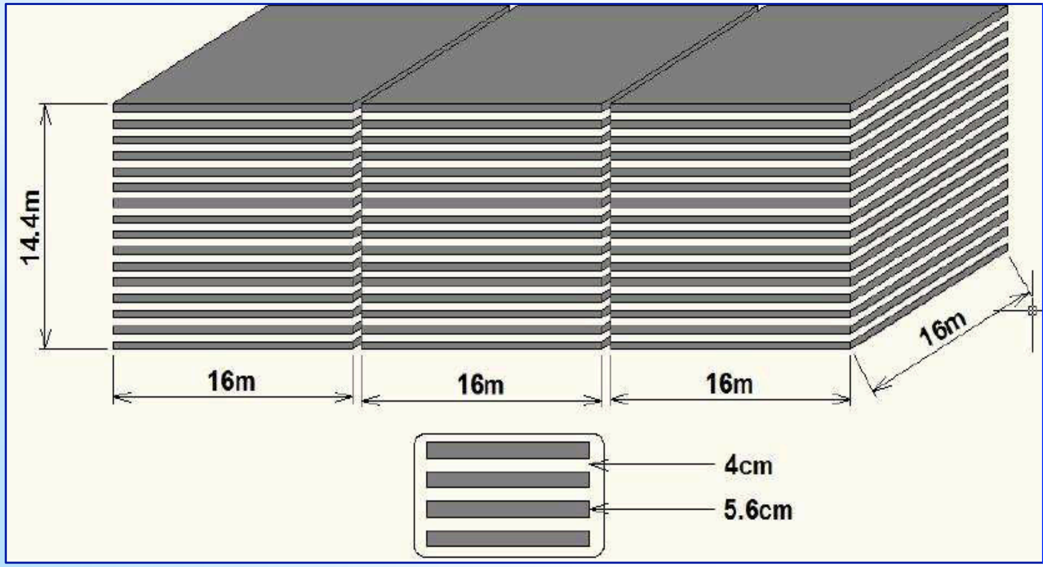
- ***Reconfirm neutrino oscillations using neutrinos and anti-neutrinos separately***
- ***Improved precision of oscillation parameters (*** $|\Delta m^2_{31}|$, $\sin^2 2\theta_{23}$ ***)***
- ***Determine the sign of*** Δm^2_{31} ***using matter effects via charge discrimination***
- ***Measure the deviation of*** θ_{23} ***from its maximal value and its octant***
- ***Test bed for various new physics like NSI, CPT violation, long range forces***
- ***Detect Ultra high energy Neutrinos and cosmic muons***

What kind of Detector do we need?

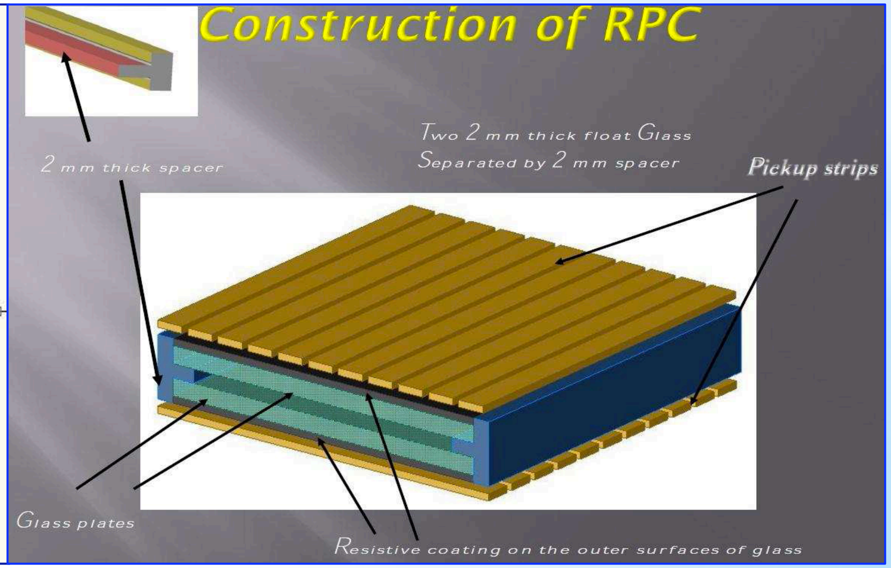
- *Should have large target mass (50 – 100 kton)*
- *Good tracking and Energy resolution (tracking calorimeter)*
- *Good directionality for up/down discrimination (nano-second time resolution)*
- *Charge identification (need to have uniform, homogeneous magnetic field)*
- *Ease of construction & Modularity*
- *Complementary to the other existing and proposed detectors*

What is the ideal choice?

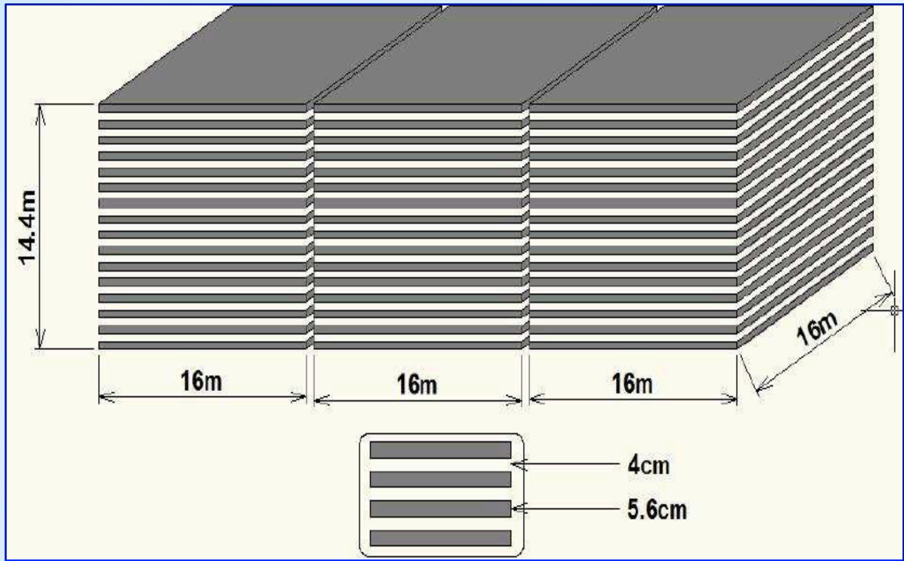
Magnetized iron (target mass): ICAL



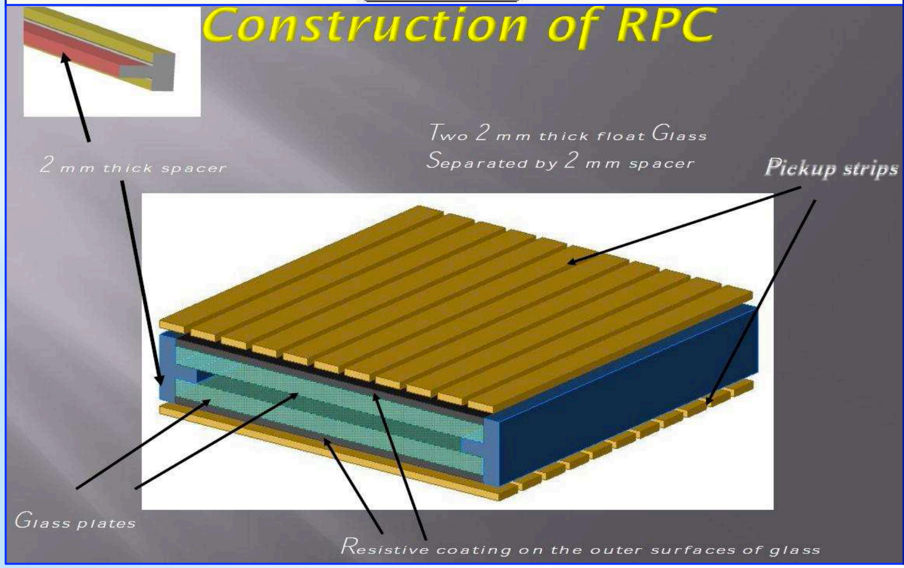
RPC (active detector element)



Specifications of the ICAL Detector

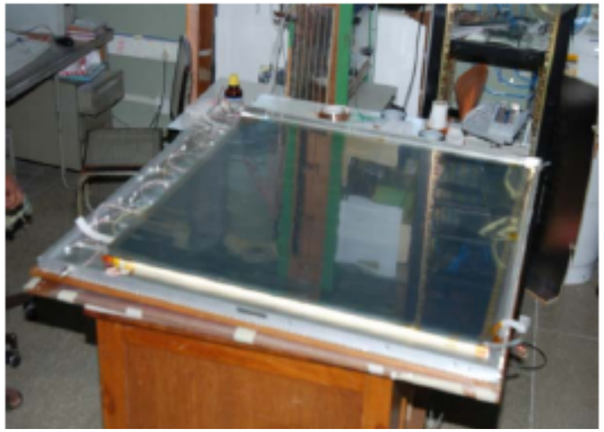


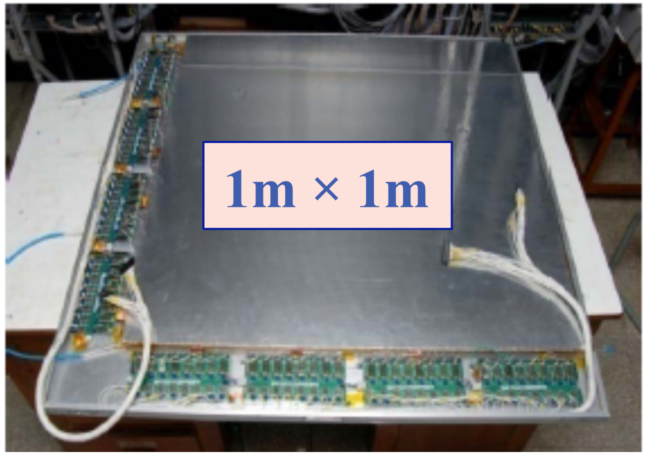
ICAL	
No. of modules	3
Module dimension	16 m × 16 m × 14.4 m
Detector dimension	48 m × 16 m × 14.4 m
No. of layers	150
Iron plate thickness	∼ 5.6 cm
Gap for RPC trays	4.0 cm
Magnetic field	1.3 Tesla

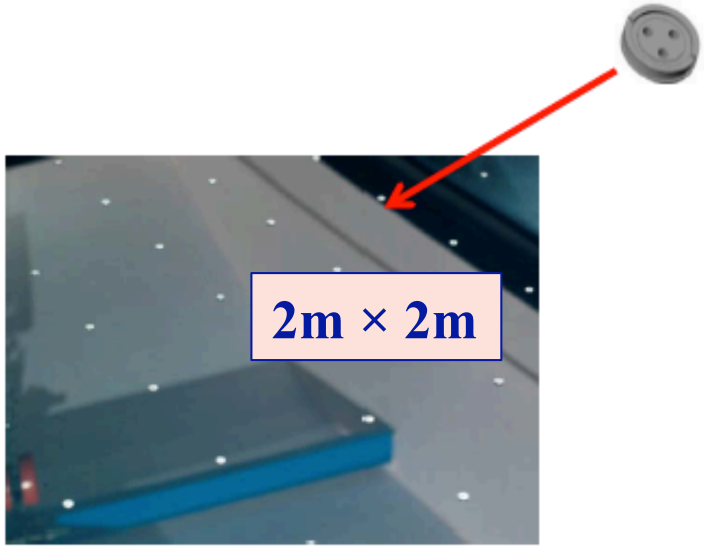


RPC	
RPC unit dimension	1.84 m × 1.84 m× 24mm
Readout strip width	3 cm
No. of RPC units/Road/Layer	8
No. of Roads/Layer/Module	8
No. of RPC units/Layer	192
Total no. of RPC units	∼ 28800
No. of electronic readout channels	3.6864×10^6

Making of Glass RPCs at TIFR

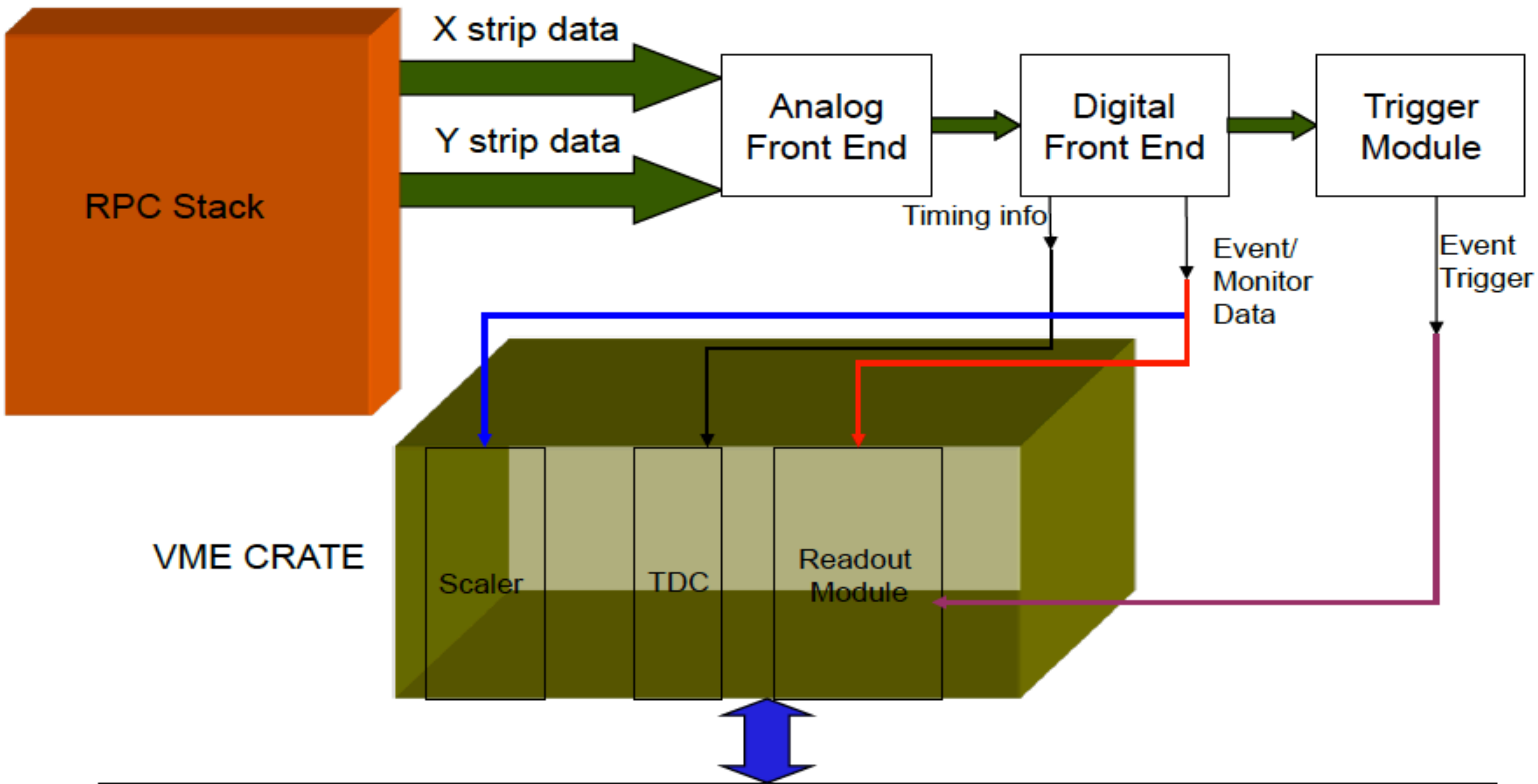






- ***12 glass RPCs of 1m × 1m developed, tested for long in avalanche mode***
- ***Recently 5 glass RPCs of 2m × 2m successfully assembled and tested***

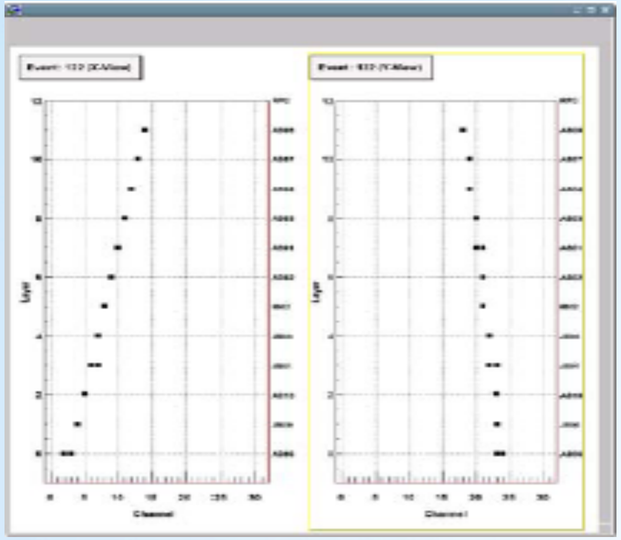
VME Based DAQ Setup



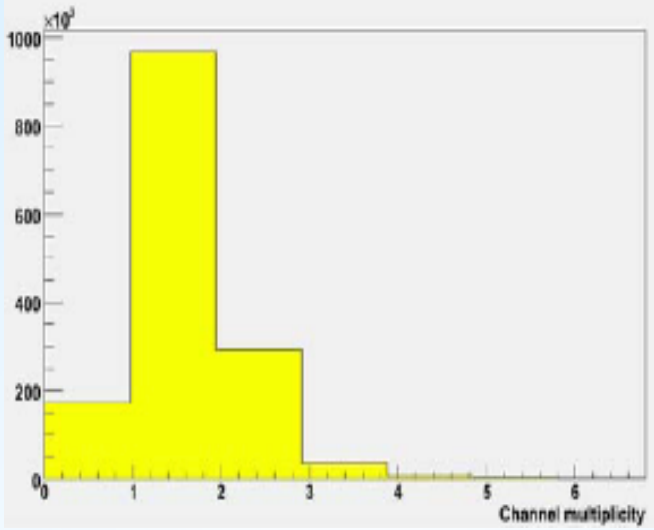
Linux based DAQ software (C++, Qt, ROOT)

- ✓Interrupt Based
- ✓Multi-Threaded
- ✓Graphical User Interface
- ✓Online 2D/3D Event Display
- ✓RPC Strip Monitoring
- ✓Online Error Reporting

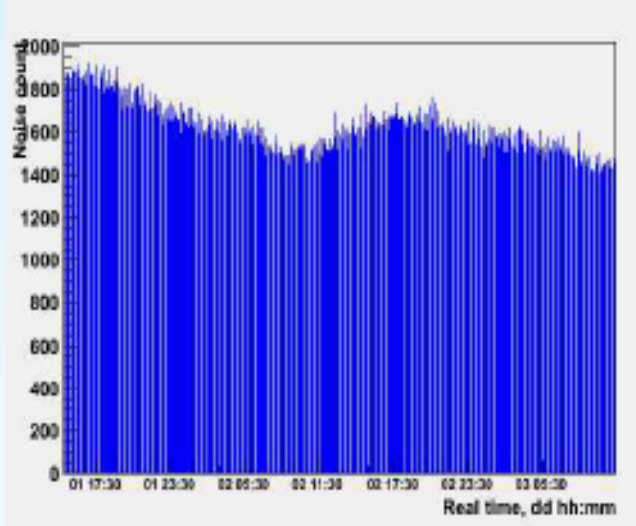
Performance of RPC using Cosmic Muons



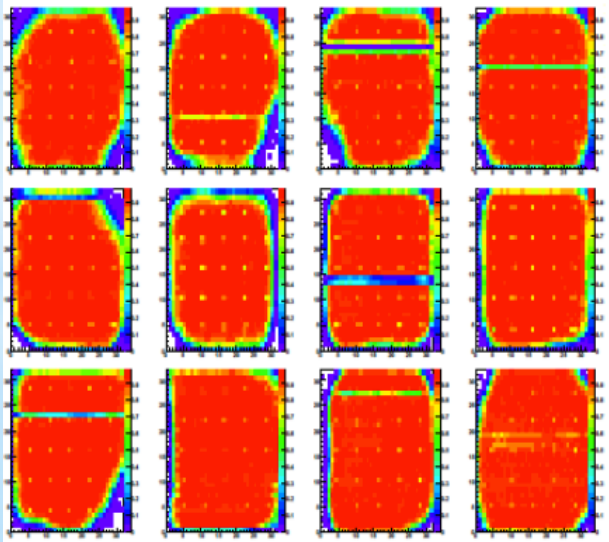
Cosmic Ray Tracks



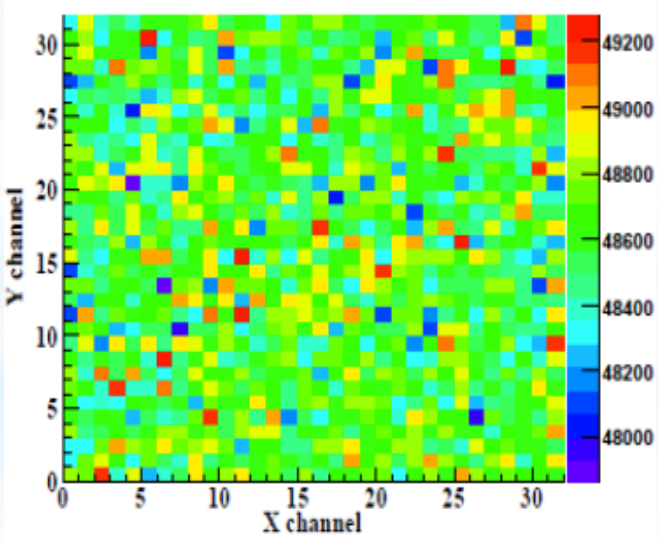
Strip multiplicity due to crossing muons



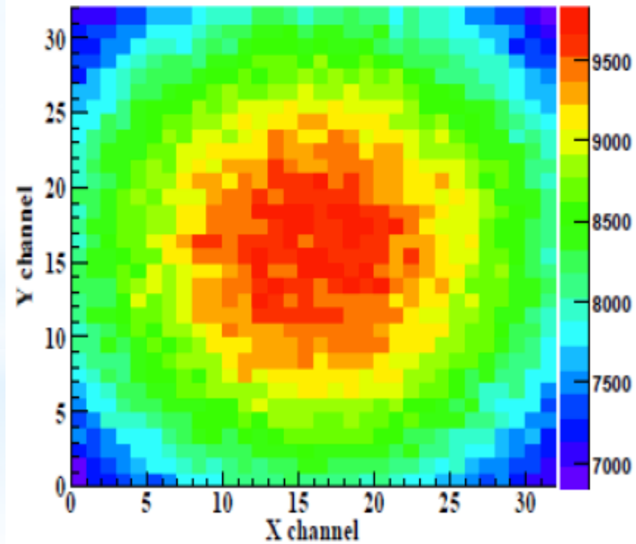
Strip noise rate .vs. time



Cosmic muon imaging



Hit distribution in top RPCs



Hit distribution in bottom RPCs

Efforts at VECC & SINP (Kolkata)

- ***Bakelite RPCs being developed, operating in streamer mode, inner surface coated with PDMS (silicone) for smooth surface, efficiency plateau over 96% with reduced noise rate and long term stability***

- ***ICAL@INO being modular in size, can use both glass as well as Bakelite RPC***

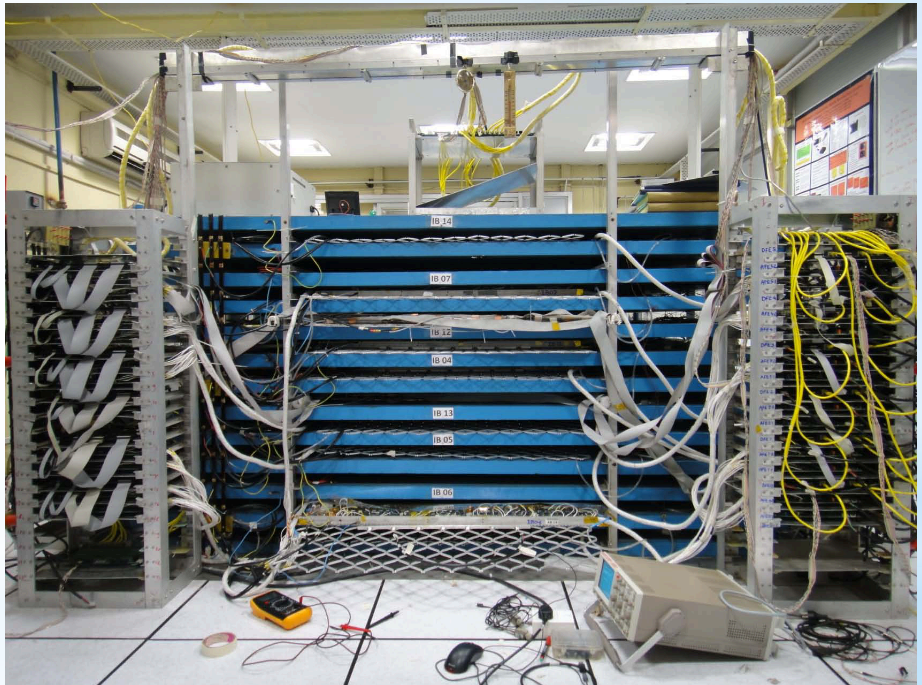
13 layers of soft iron
Each Iron Plate: 2.48m x 2.17m x 0.05m

12 layers of 1m × 1m RPCs
8 glass RPCs and 4 Bakelite RPCs

Total of 4 coils, each having 5 turns
perpendicular to the plane of the Fe (1.6 Tesla)

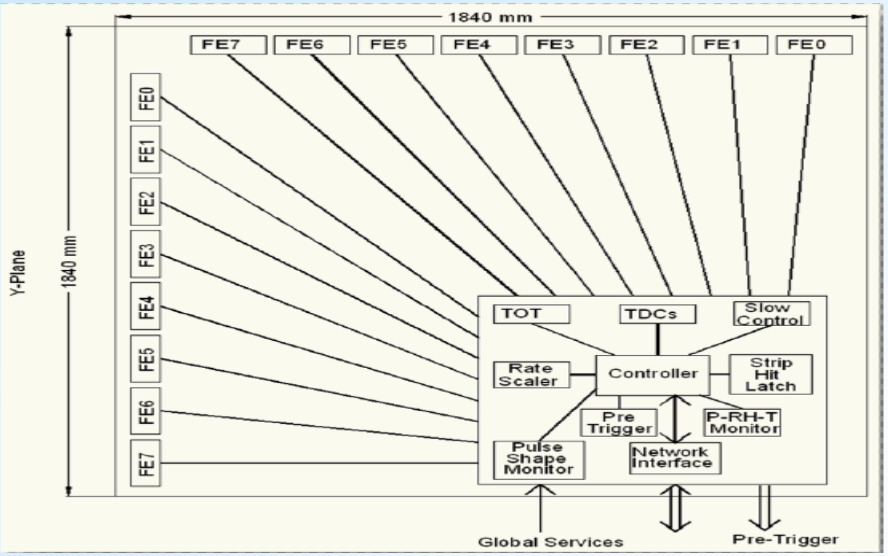
512 channels of preamp for 8 glass RPCs
timing discriminators for avalanche RPCs

Designed to study the working behavior of RPCs together with the front end electronics in presence of magnetic field

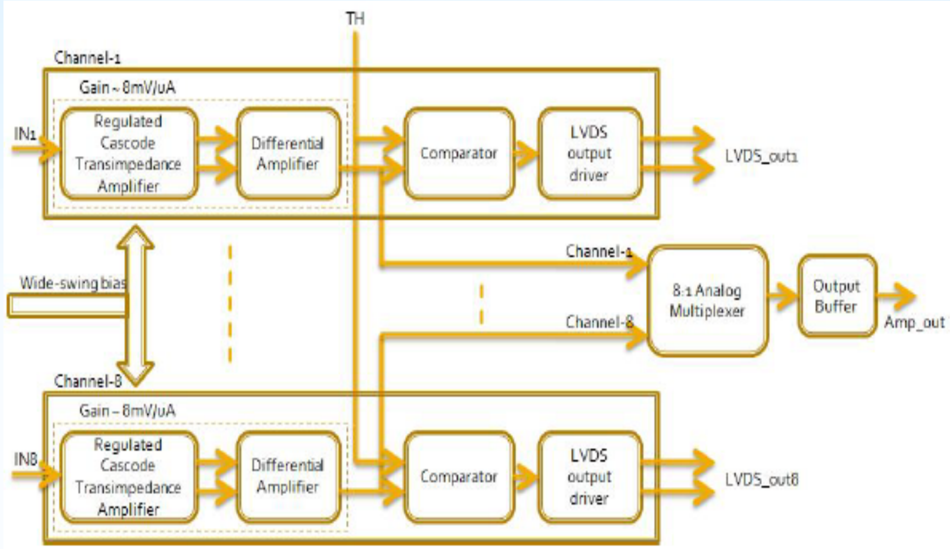


ICAL@INO Prototype Detector ~ 50 tons
Total Height 1.302 m

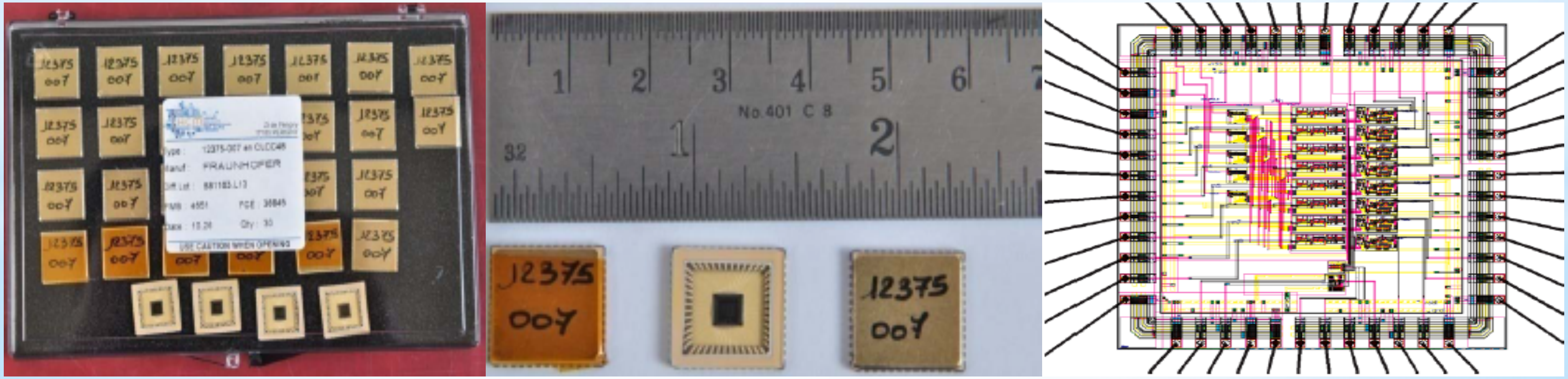
ICAL Front End Electronics



The Scheme



Layout of the Electronics Chip



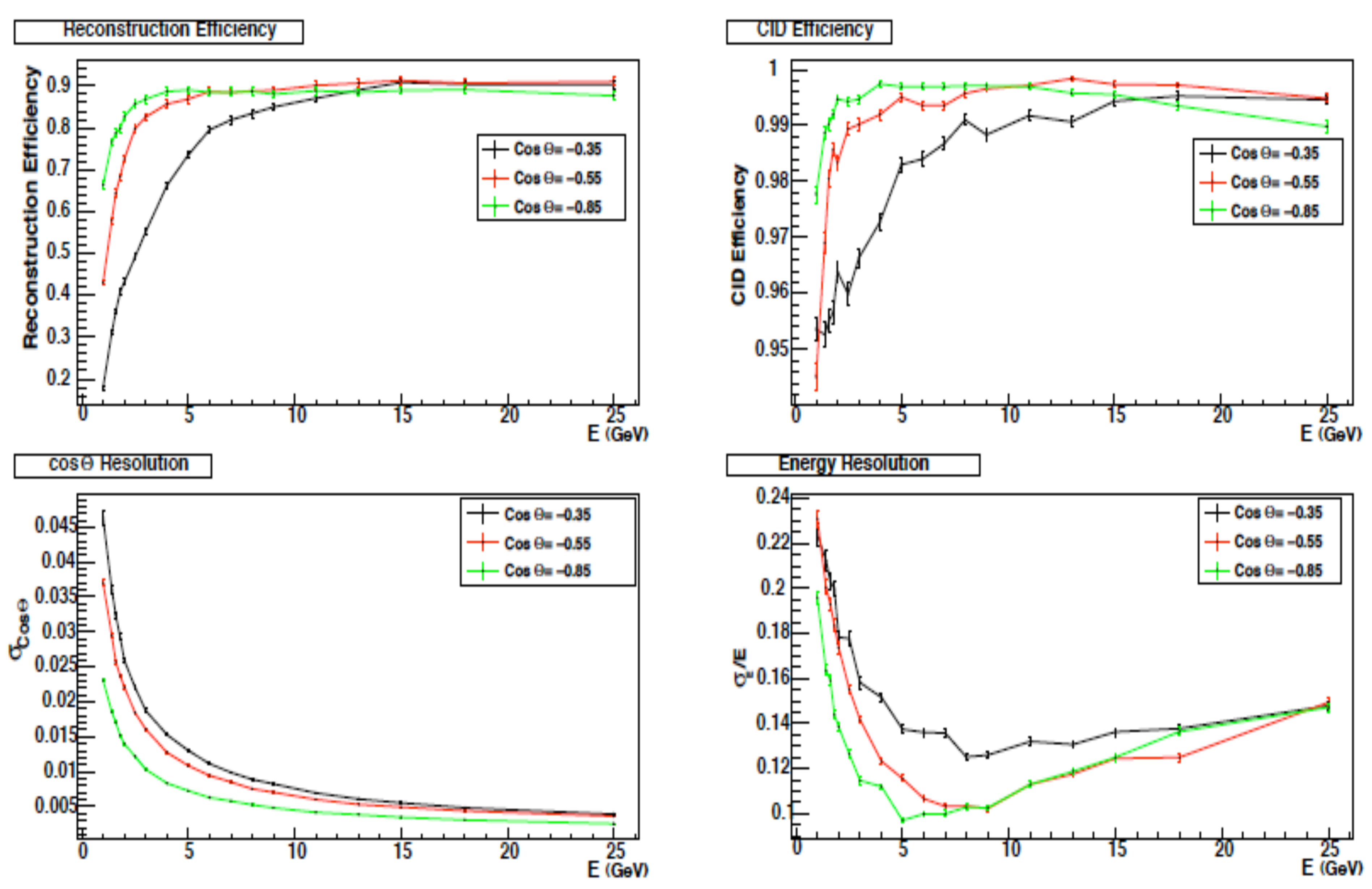
Electronics Chip developed at BARC Electronics division

Detector Simulation Strategy

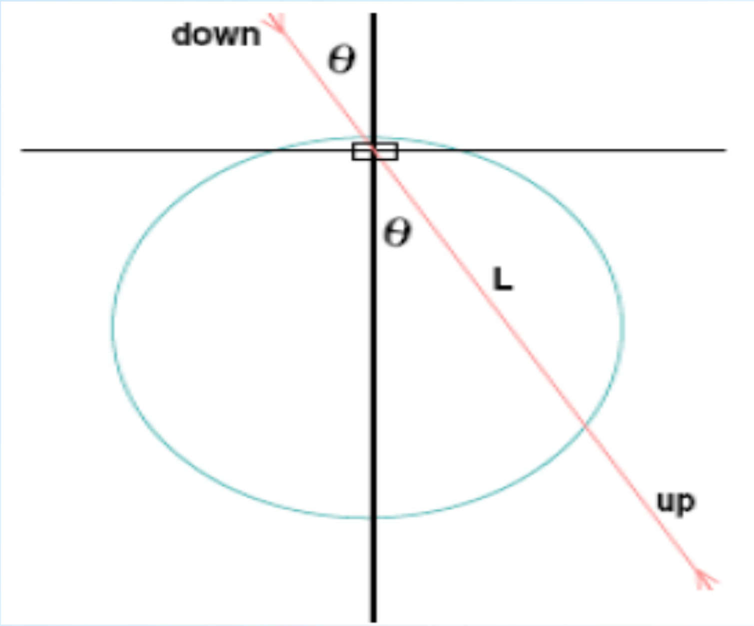
NUANCE	**Neutrino Event Generation** $\nu_a + X \rightarrow A + B + \ldots$ Generates particles that result from a random interaction of a neutrino with matter using theoretical models .	**Output:** i) Reaction Channel ii) Vertex Information Iii) Energy & Momentum of all Particles
GEANT	**Event Simulation** A + B + ... through RPCs + Mag.Field Simulate propagation of particles through the detector (RPCs + Magnetic Field)	**Output:** i) x,y,z,t of the particles at their interaction point in detector ii) Energy deposited iii) Momentum information
	Event Digitisation (x,y,z,t) of A + B + ... + noise + detector efficiency Add detector efficiency and noise to the hits	**Output:** i) Digitised output of the previous stage (simulation)
	Event Reconstruction (E,p) of ν + X = (E,p) of A + B + ... Fit the tracks of A + B + ... to get their energy and momentum.	**Output:** i) Energy & Momentum of the initial neutrino

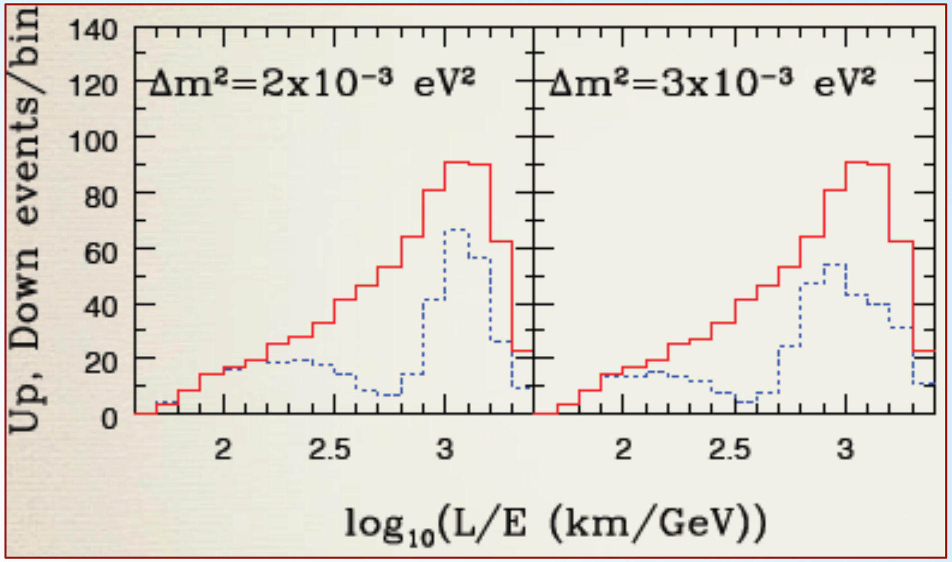
Simulation work is under progress

Muon efficiencies and resolutions



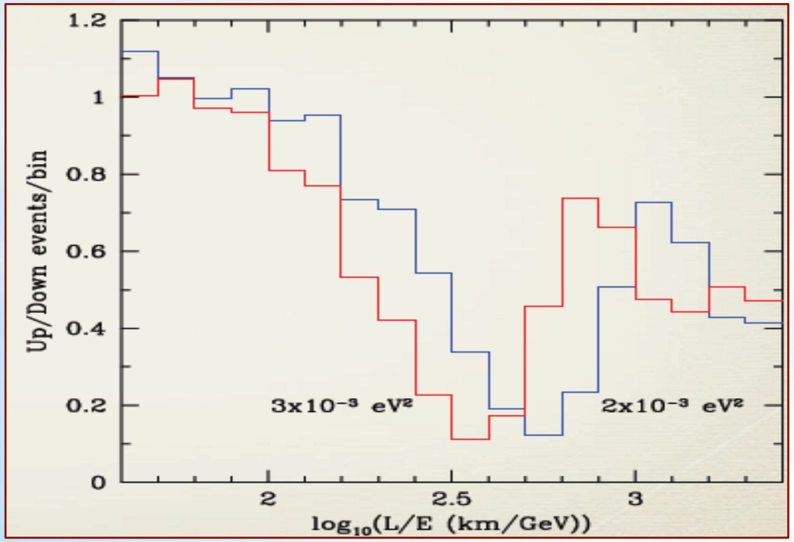
Reconfirmation of L/E Dip





Red: Downward μ **Blue: Upward μ**

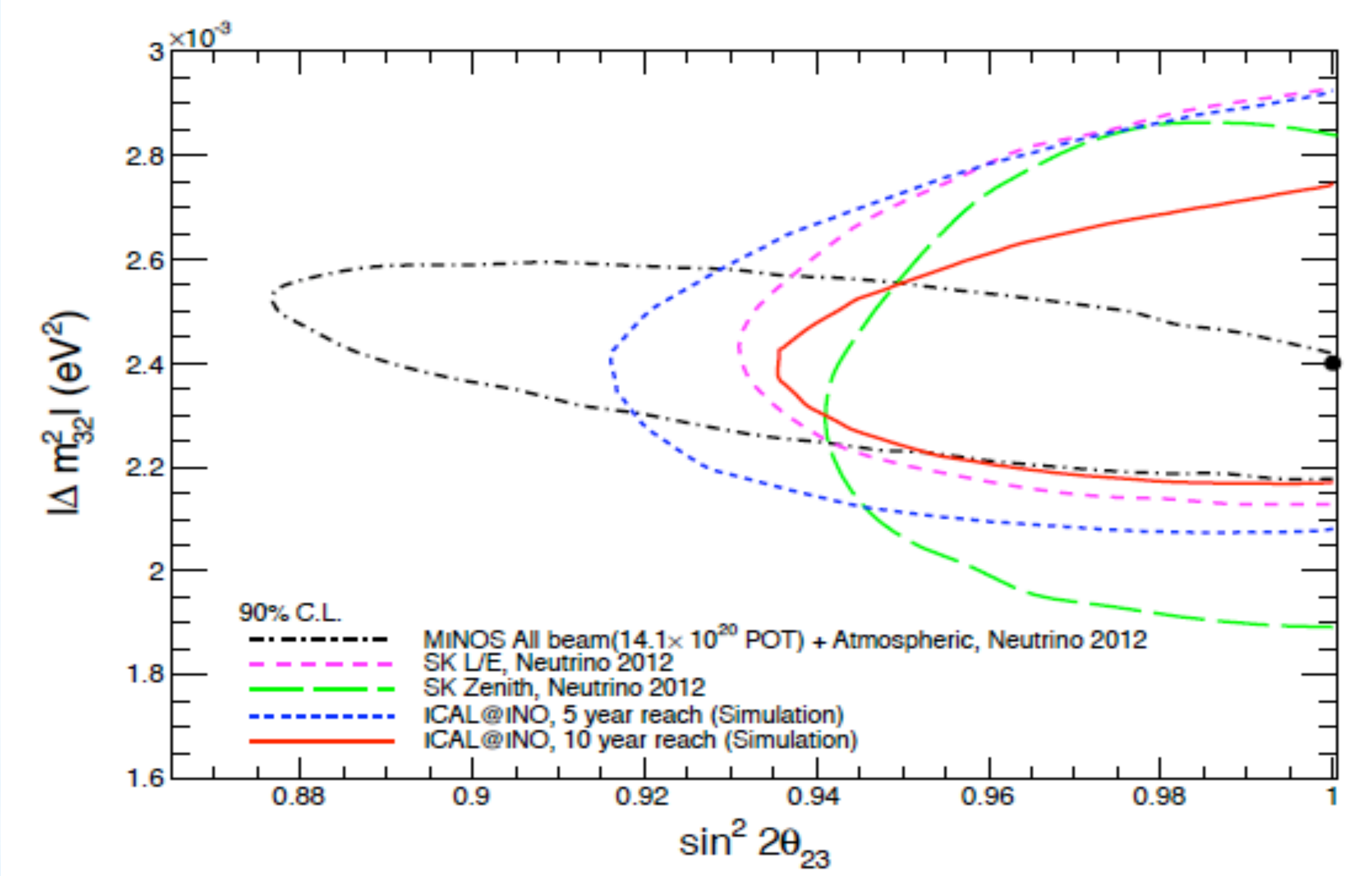
250 kt.yr exposure



Observing fall and rise of up/down ν_μ

Crucial for Precision of $|\Delta m^2_{31}|$

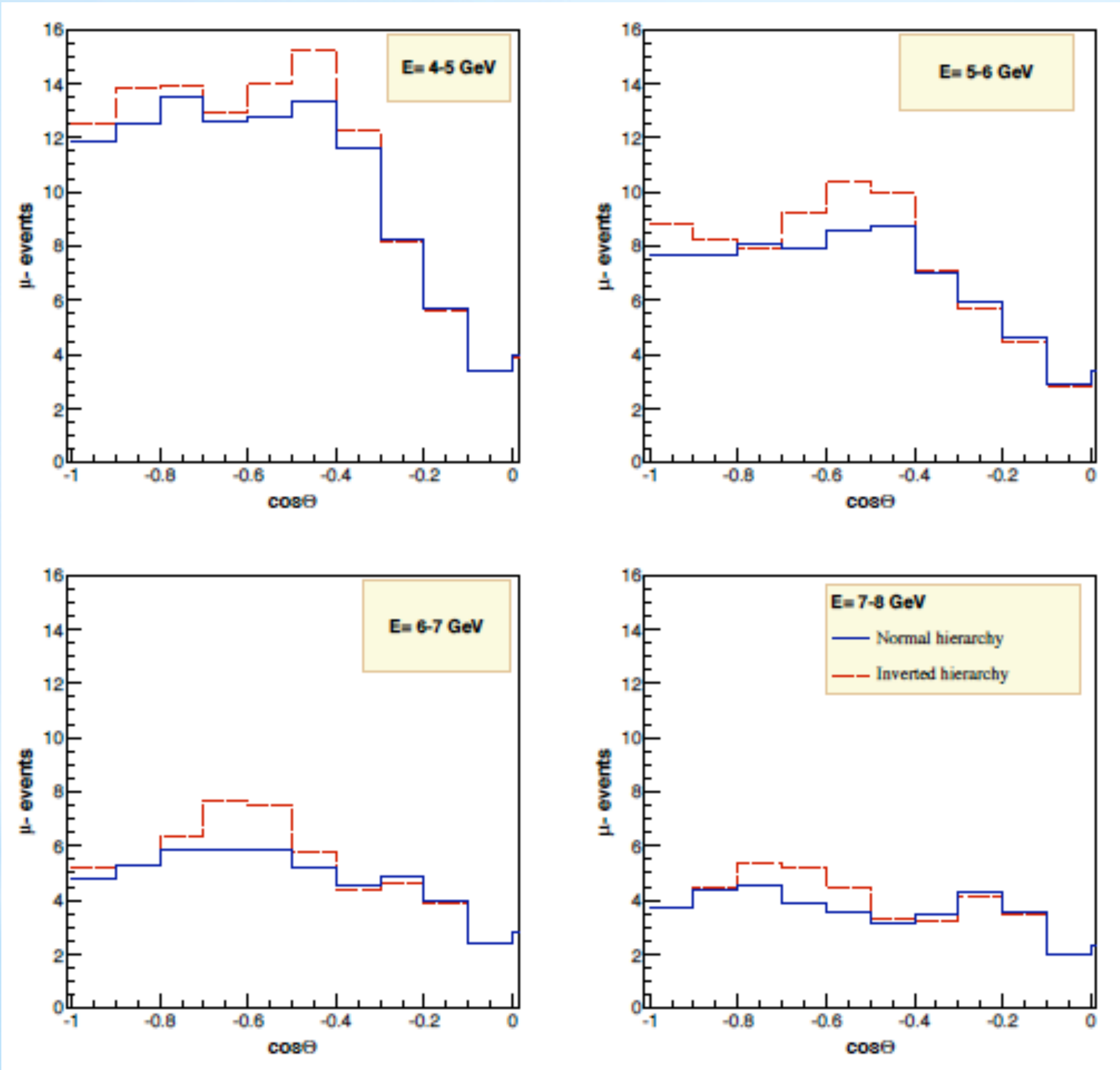
Precision of atmospheric oscillation parameters



Thakore, Ghosh, Choubey, Dighe, arXiv:1303.2534

Precision complementary to Long-baseline experiments

Event spectrum at ICAL@INO

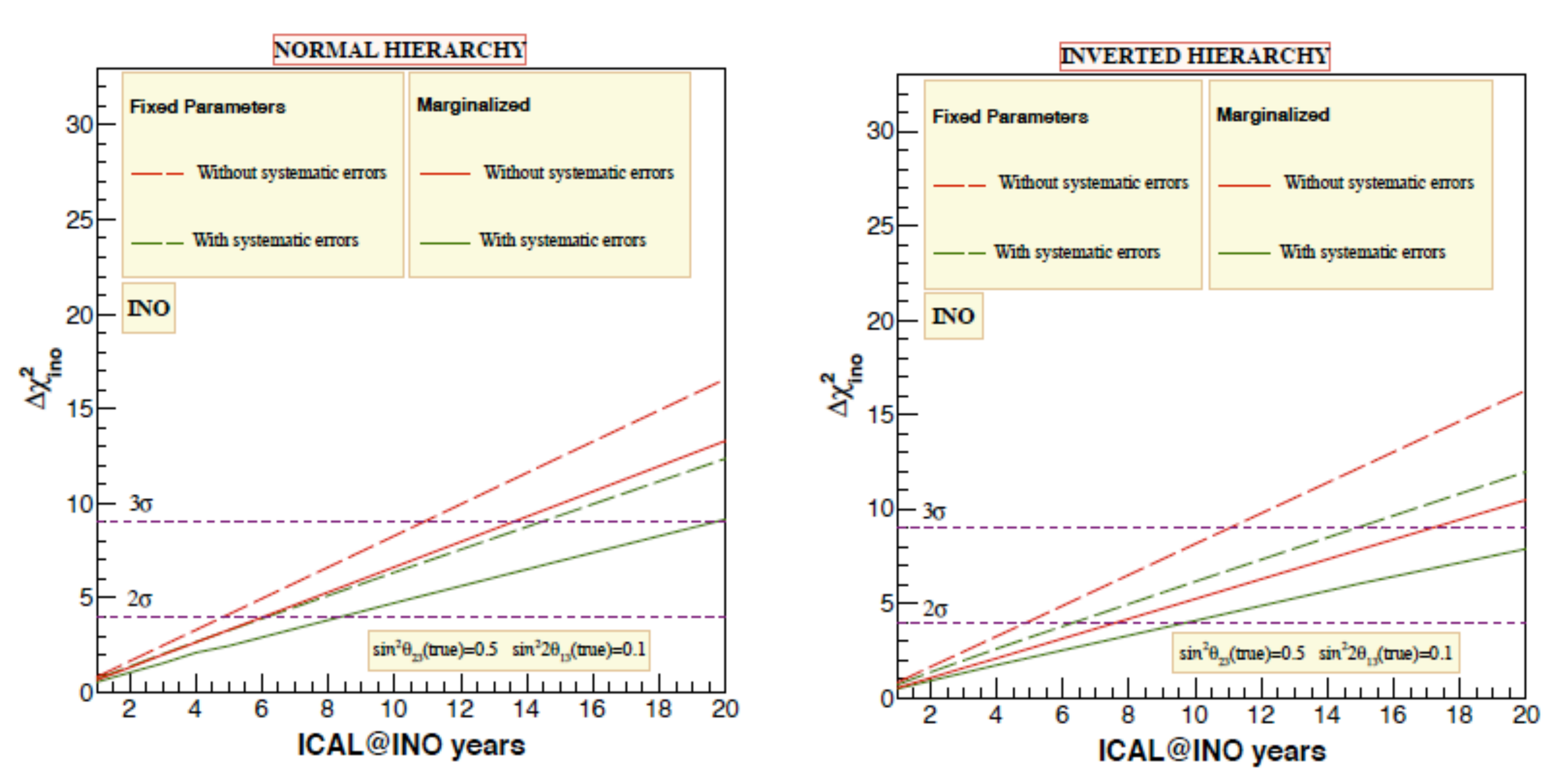


μ^- event spectrum for 10 years exposure

Comparison between Normal and Inverted Hierarchy!

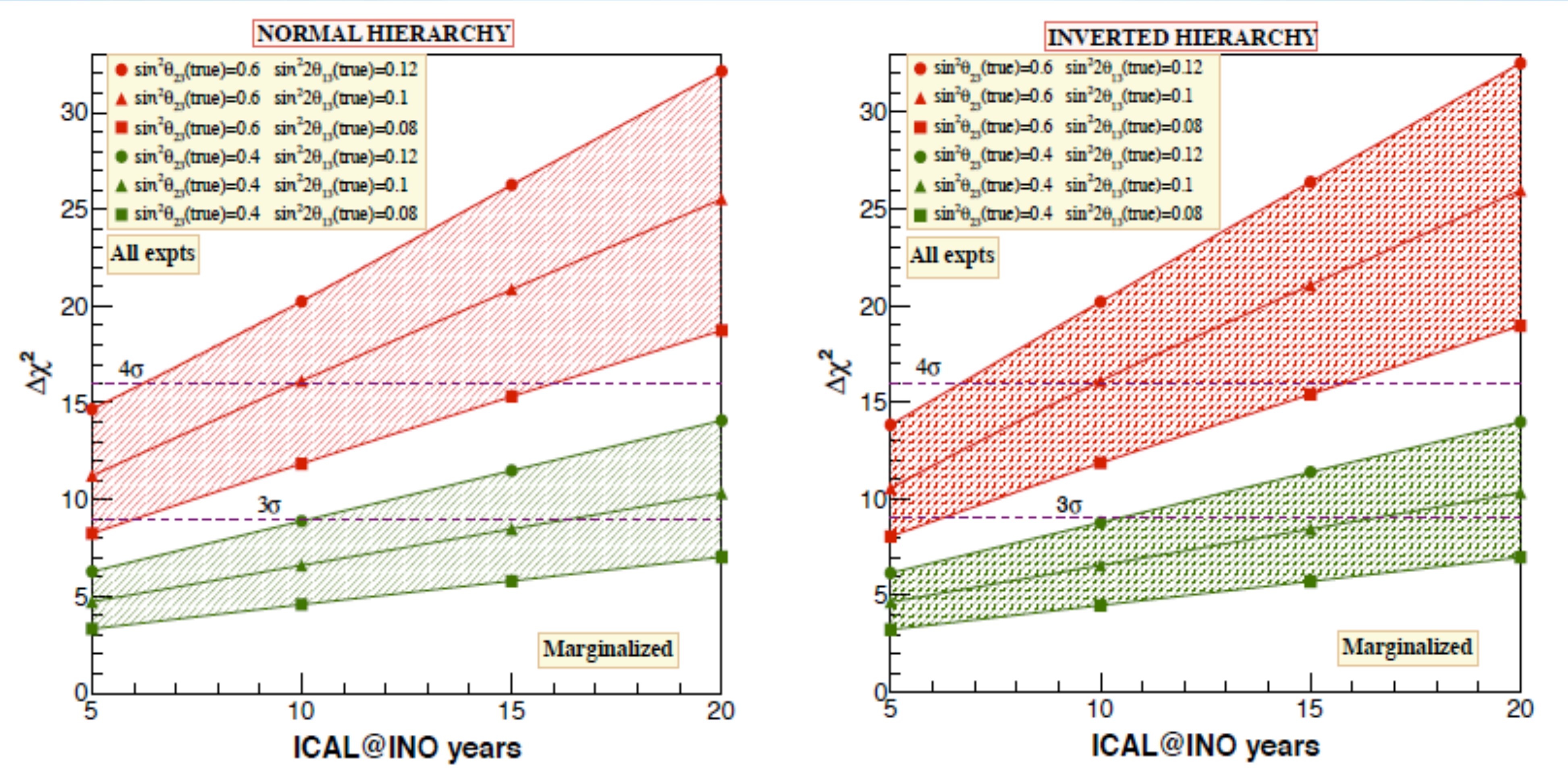
Thakore, Ghosh, Choubey, arXiv:1212.1305

Mass Hierarchy with ICAL@INO



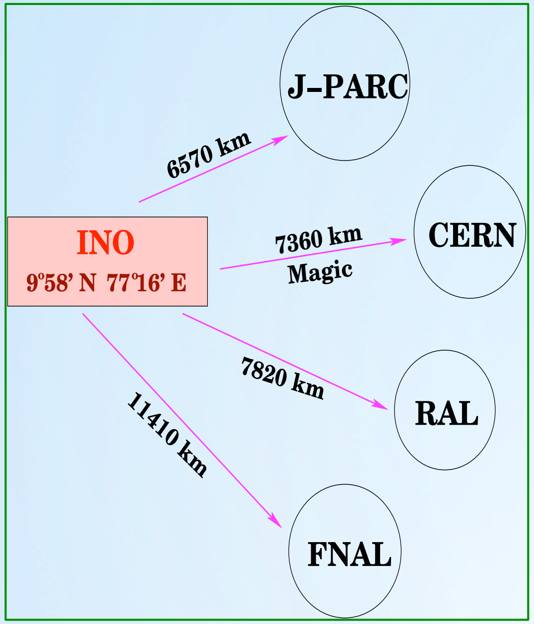
Thakore, Ghosh, Choubey, arXiv:1212.1305

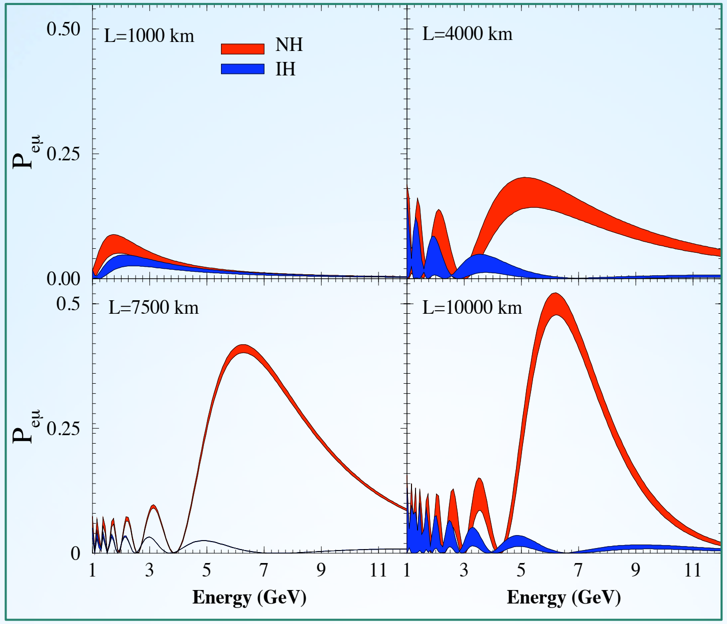
Mass Hierarchy with ICAL@INO+Reactors+T2K+NOvA

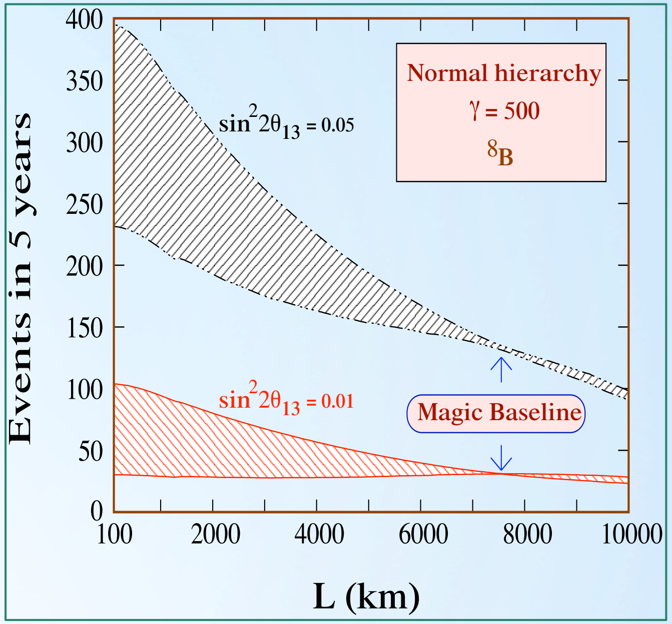


Thakore, Ghosh, Choubey, arXiv:1212.1305

Physics with Beams (INO Phase 2)



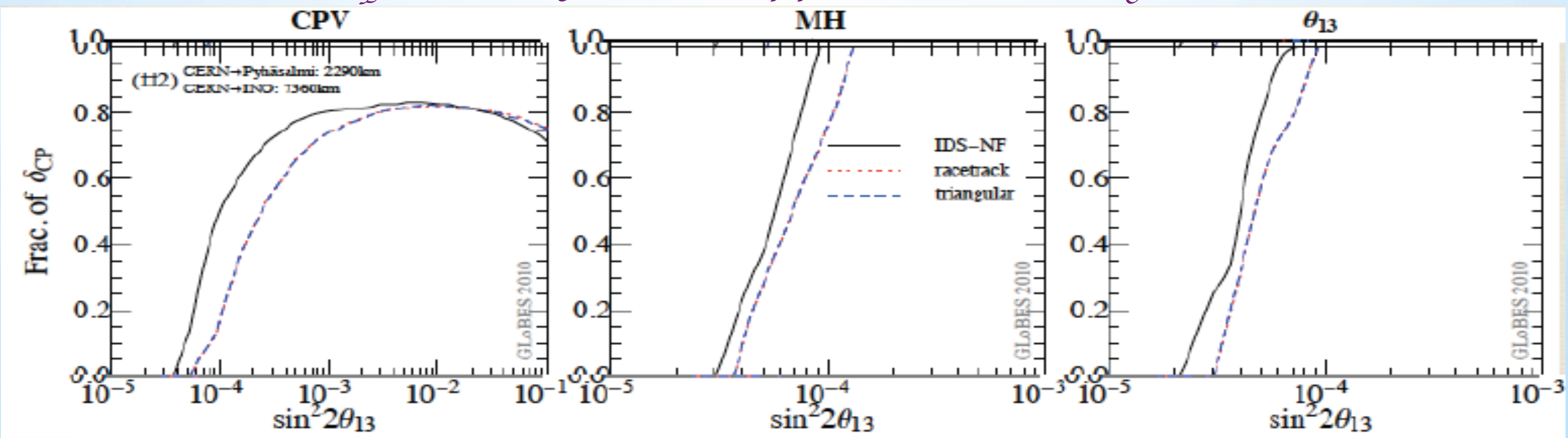




Near Resonant Matter Effect

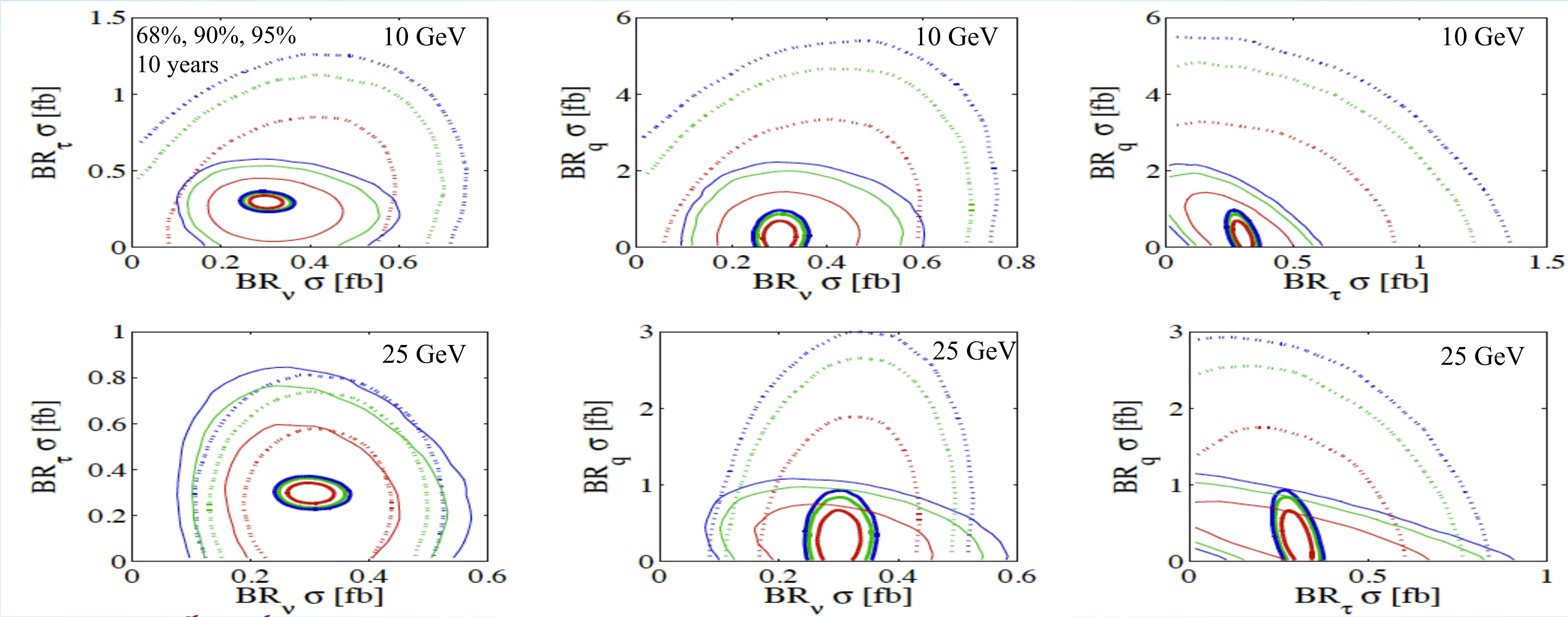
Agarwalla etal., hep-ph/0610333

Agarwalla etal., arXiv:0711.1459



Agarwalla etal., arXiv:1012.1872

Indirect detection of Dark Matter with ICAL



Agarwalla etal., arXiv:1105.4077

Dotted line: 100 kt ICAL Thin line: 34 kt LAr Thick line: 100 kt LAr

Experiment	DM mass	$BR_\tau\sigma$ [fb]	$BR_\nu\sigma$ [fb]	$BR_q\sigma$ [fb]
MIND (100 kt)	10 GeV	0.70	0.35	3.4
	25 GeV	0.34	0.15	1.7
LArTPC (34 kt)	10 GeV	0.15	0.11	0.73
	25 GeV	0.16	0.10	0.21
GLACIER (100 kt)	10 GeV	$1.5 \cdot 10^{-2}$	$6.4 \cdot 10^{-3}$	0.25
	25 GeV	$1.0 \cdot 10^{-2}$	$5.2 \cdot 10^{-3}$	0.19
Super-K data [5]	10 GeV	0.65	0.12	10
	25 GeV	0.45	0.19	5.0

Sensitivity to branching ratio × capture cross section at 90% C.L., 10 years data

DM particles gravitationally trapped inside the Sun may annihilate into SM particles, producing a flux of neutrinos

Energy & Angular resolution, crucial to suppress atmospheric background

More Physics Motivations with ICAL@INO

Testing CPT violation ➔ hep-ph/0312027, arXiv:0802.0121, arXiv:1005.4851

Constraining Sterile Neutrinos ➔ arXiv:0709.0383, arXiv:1108.4360

Probing NSI ➔ hep-ph/0608034, arXiv:1105.5936

Impact of long range forces ➔ hep-ph/0310210, arXiv:1001.5344

Very High Energy Muons ➔ hep-ph/0512179

Intra-nuclear neutron-anti-neutron transformations inside an Fe nucleus. Signature will be the GeV energy pions. Existing SK limits can be improved using ICAL

work under progress....

Profile of the atm. ν flux at INO is very different from existing facility due to geomagnetic field, critical test for the calculation of the atmospheric neutrino flux

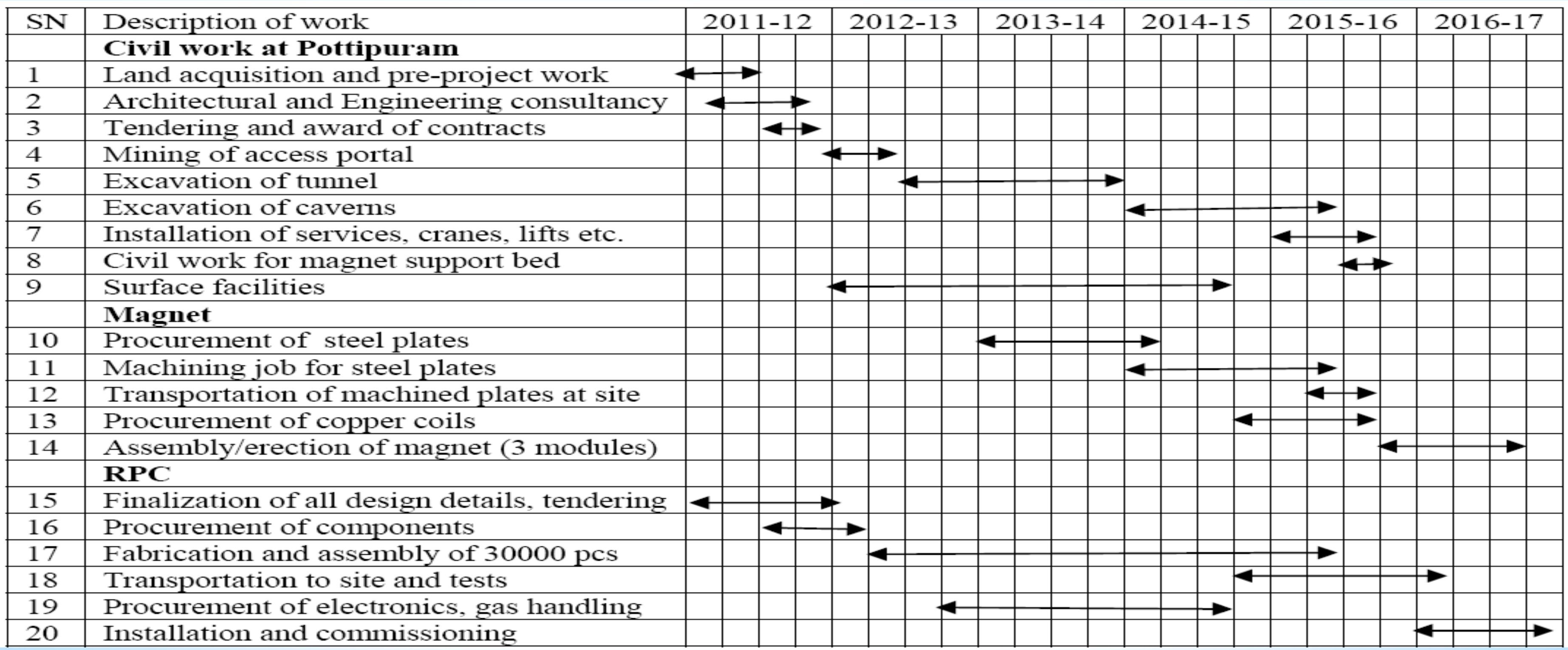
M. Honda, NUINT 2011, work under progress....

ICAL can study the cosmic ray muon asymmetry reported by IceCube, since this detector can see the galactic center as well

work under progres....

Short term goals and Future Roadmap

- *Prepare the Physics White paper with detailed Detector Simulation*
- *Build a large 8m X 8m -20 layer detector with final specifications*
- *Magnet & coil design & fabrication, Industrial production of RPCs*
- *Final Electronics and DAQ, Pre-project activities at site*



Collaborators are most welcome!

!! Stay Tuned for Exciting Discoveries at INO !!

Thank You