Energy and direction resolution of hadrons in INO ICAL detector

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December 12, 2013

Contents

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1. *To measure the properties of atmospheric neutrinos of energies in the few GeV energy range.*
2. *To study the physics of neutrino oscillation and do precision measurements on oscillation parameters.*
3. *Measurement of the magnitude of Δm^2_{32} and θ_{23}.*
4. *To measure matter effects and hence obtain information about the sign of Δm^2_{32} (normal vs inverted hierarchy) and the deviation of θ_{23} from maximum.*
5. *Needs information about the behaviour of neutrino and anti-neutrino separately.*
6. *Source of neutrinos : secondary cosmic rays.*
7. *Sensitive mainly to (anti-)muons produced in the charged current interactions of muon-(anti-)neutrinos with Fe.*

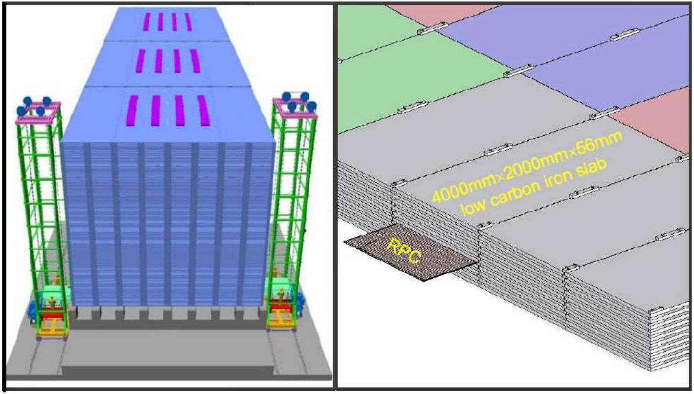


Figure 1: Schematic of INO ICAL detector with its three magnetised modules (left) and a zoom in of a section of ICAL with an RPC taken out (right).

Some basics about the INO ICAL detector

- **50 kton** magnetised iron detector of dimension 48 m × 16 m × 14.45 m.
- Inhomogeneous magnetic field; central value of ≈ 1.5 T.
- 151 layers of 5.6 cm thick iron plates interleaved with 150 layers of Resistive Plate Chambers (RPC).
- About 30k RPCs, each of dimension 2 m × 2 m × 8 mm, with 64 channels in X and Y directions resp.
- Position resolution of 2.8 cm (strip width).
- **Fe** : *target* material with which the (anti-)neutrinos interact and produce final state particles.
- **RPC** : *active detector*; detects charged particles.
- For muons : very good charge identification (cid) and very good energy and direction resolutions.
- For hadrons : poorer resolutions, still can improve the physics reach.

Important points to remember.

- **Neutrino detection is always indirect.**
- **Why large detector?**

  $\mathbf{N_{det}} = \mathbf{\Phi} \times \sigma \times \mathbf{N_{target}} \times \mathbf{t_{exp}}$, where

  N_{det} is the number of neutrino events detected

  Φ is the flux of neutrinos

  σ is the interaction cross section

  N_{target} is the number of target particles available for interaction

  t_{exp} is the exposure time
- **Why go underground?**

  To reduce background, mainly the cosmic ray muons. The deeper you go into the earth the lesser the cosmic ray muon background will be. Uniform cover of

Why determine hadron energy and direction?

As inputs for the determination of the energy and direction of atmospheric neutrinos interacting with iron nuclei in the ICAL detector via charged current (CC) and neutral current (NC) channels.

- `CC interactions :`
  $\nu_l + N \rightarrow l^- + X$
  $\overline{\nu_l} + N \rightarrow l^+ + X$

- `NC interactions :`
  $\nu_l + N \rightarrow \nu_l + X$
  $\overline{\nu}_l + N \rightarrow \overline{\nu}_l + X$

  $l = e, \mu, \tau$
  v_l = neutrino of flavour l
  N = target nucleon
  X = hadronic final state

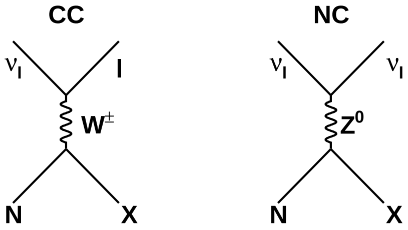


Figure 2: `Charged current and neutral current interactions of neutrino with nucleons.`

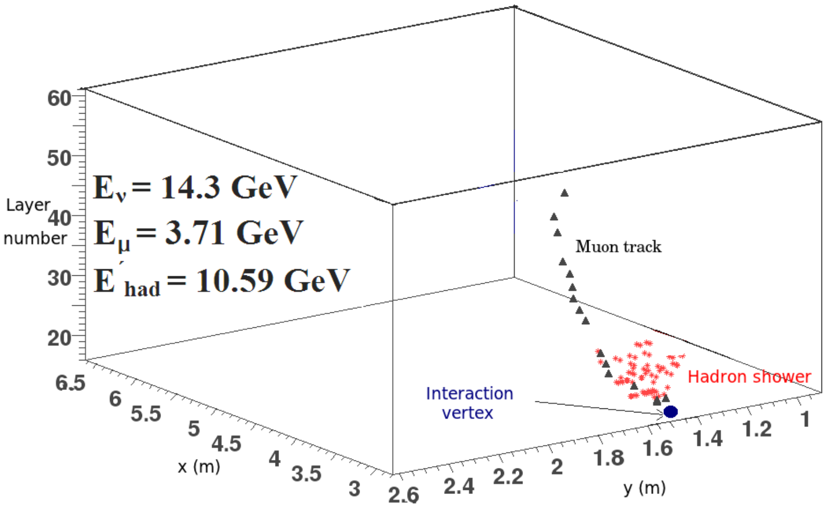
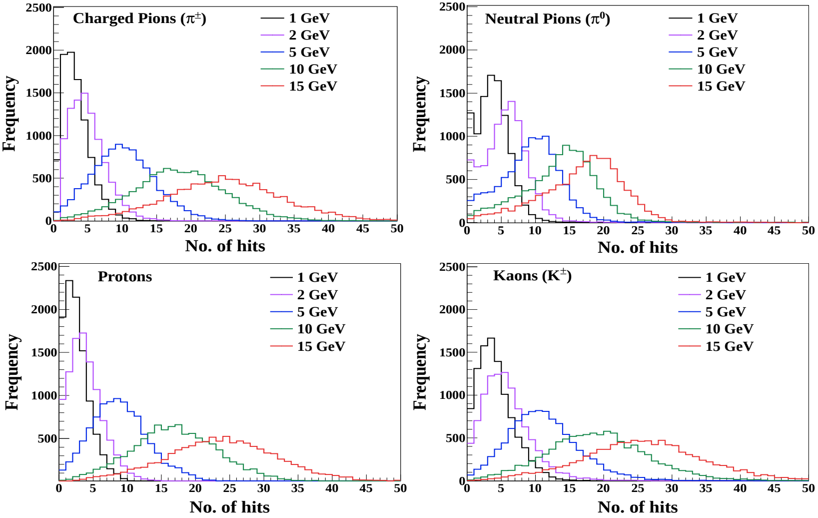


Figure 3: For a charged current muon neutrino interaction in INO ICAL. Net hadron energy $E'_{had} = E_\nu - E_\mu$, where E_ν is the energy of the incident neutrino, E_μ is the energy of outgoing muon.

ICAL can't distinguish individual hadrons. Only a bunch of hits.



- Majority : pions $\rightarrow$ study for single pions in the region 2–15 GeV.
- In the range $E < 5~GeV$ $\rightarrow$ contribution from quasi elastic (nucleon recoil), resonance and deep inelastic scattering (DIS).
- For $E > 5~GeV$ DIS dominates.
- Hence analysis in different sub ranges.
- 11 different thicknesses from 1.5cm,...,8cm.

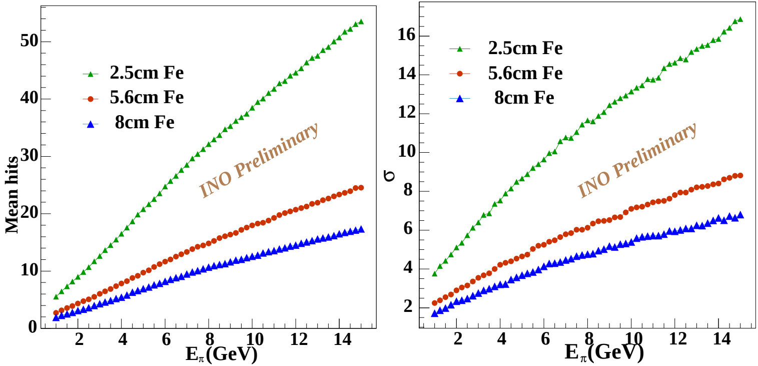


Figure 4: Mean hits (left) and σ (right) as functions of pion energy for some sample thicknesses.

Energy resolution vs plate thickness t (cm)

- $\bar{n}(E) = n_0 \left[1 - exp\left(-\frac{E}{E_0}\right)\right]$, where, n_0 and E_0 are constants.
- $E_0 \gg E$ in the range of energies of interest, $E \leq 15GeV$. Hence linearised by expanding the exponential: $\bar{n}(E)/n_0 \simeq E/E_0$
- $\Delta n(E)/\bar{n}(E) = \sigma/E$, where, Δn = width of the distribution , $\bar{n}(E)$ = mean number of hits obtained from the distribution.
- Parametrize $\sigma(E)/E = \sqrt{a^2/E + b^2}$, where, a = stochastic coefficient (dependent on absorber thickness ; has dimensions of $\sqrt{E}$), b = a dimensionless constant.
- $(\sigma/E)^2 = a^2/E + b^2$: easier to analyze since linear in $1/E$.
- Thickness dependence : $a(t) = p_0 t^{p_1} + p_2$, where
  p_0 = a constant ,
  p_1 = power giving the thickness dependence ,
  p_2 = residual resolution

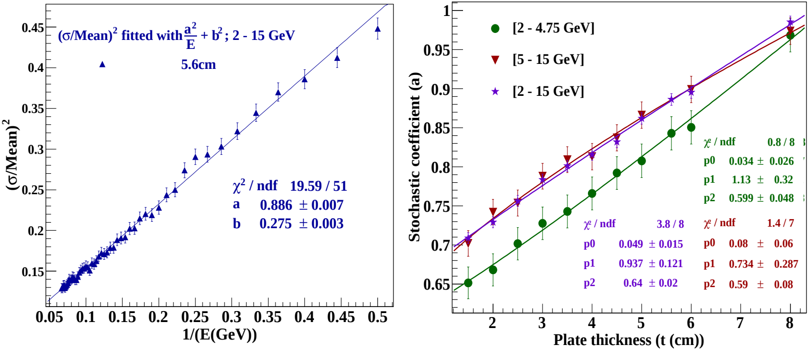


Figure 5: Hadron energy resolution in the range 2–15 GeV for the default thickness of ICAL (left). Stochastic coefficient a as a function of t (cm) in various energy ranges (right). p_0 = constant, p_1 = exponent which gives the thickness dependence, p_2 = residual resolution

Hadron direction resolution

- For 5.6cm Fe only.
- Single, pions at different θs with ϕ smeared fully; fixed θ - fixed ϕ, hadrons from neutrino events.
- Direction reconstruction using hit information of hadrons.
- Raw hit method : uses hit timing information also for direction reconstruction.
- No vertex position is needed. Only hit information in X-Z and Y-Z plane separately.
- Hence can be used both in charged current (CC) and neutral current (NC) events.
- Average x and y positions in the i^{th} layer of an event are found separately.
- Hits within a time window of $\leq$50 ns within a layer are averaged.
- Fitted with straight lines $x = m'_x z + c_1$ and $y = m'_y z + c_2$ separately in the X-Z and Y-Z planes. Inverses of slopes m'_x and $m'_y \rightarrow$ reconstruct the direction. m_x and m_y.

Raw hits and timing method (Continued$\cdots$)

- Using polar co-ordinates, θ and ϕ can be reconstructed as : $tan\phi = tan\omega / tan\lambda$ & $tan\theta = 1/cot\theta$, where , ω = angle made by a line with the X axis, in the XZ plane and λ = angle made by a line with the Y axis in the YZ plane.
- Timing information $\rightarrow$ to break the quadrant degeneracy of m_x and m_y.
  - All events UP in time $\rightarrow$ θ in 1^{st} quadrant.
  - All events DOWN in time $\rightarrow$ θ in 2^{nd} quadrant.
- Minimum 2 layers required to reconstruct the direction.
- Direction resolutions for single pions and hadrons from neutrino interactions are calculated.

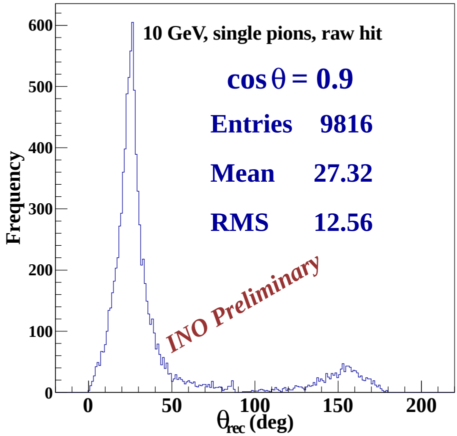


Figure 6: Distribution of reconstructed θ (θ_{rec} in degrees for a 10 GeV single pion incident in the $\cos\theta = 0.9$ direction. The small peak shows the number of events in the wrong quadrant. A cut of lmin = 2 is required for the reconstruction.

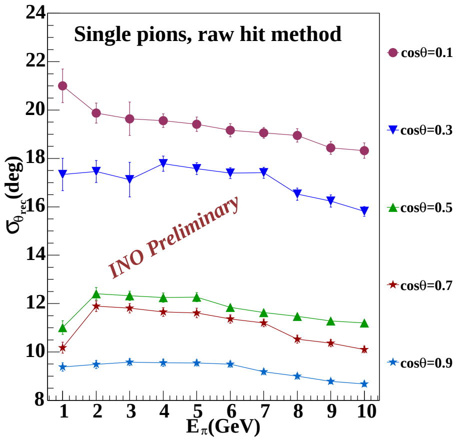


Figure 7: Resolution of reconstructed θ ($\sigma_{\theta_{rec}}$) in degrees as a function of incident pion energy for single pions; with lmin = 2 cut.

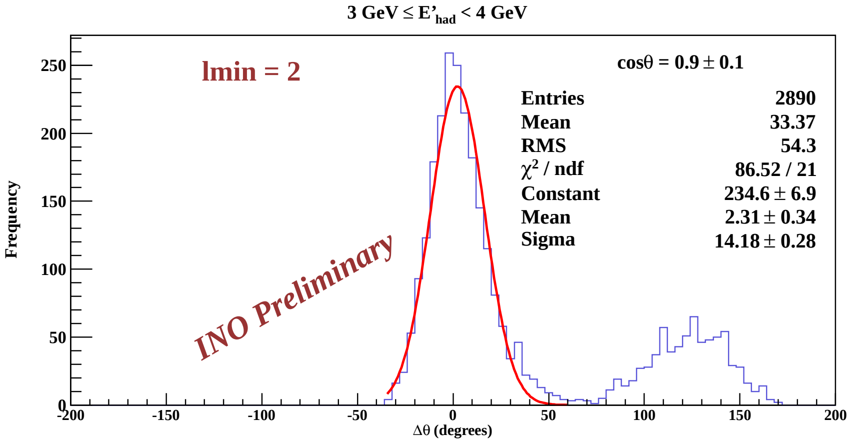


Figure 8: Distribution of the difference $\Delta\theta = \theta_{rec} - \theta_{in}$ in degrees for hadrons from neutrino interactions in the energy bin $E'_{had} = E_\nu - E_\mu$ = 3-4 GeV and direction bin $\cos\theta = 0.9 \pm 0.1$.

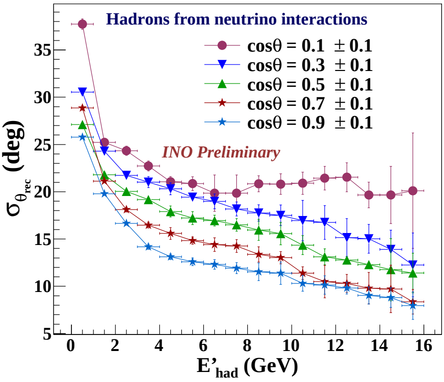


Figure 9: Resolution of reconstructed θ ($\sigma_{\Delta\theta_{rec}}$) in degrees as a function of E'_{had} in GeV for hadrons from neutrino interactions; with lmin = 2 cut.

References

1. Athar M S *et.al India-based Neutrino Observatory: Project Report Volume I*, 2006
2. Devi M M *et.al Hadron energy response of the Iron Calorimeter detector at the India-based Neutrino Observatory* JINST 8 P11003, 2013
3. Dan Green, *Physics of Particle Detectors* (Cambridge: Cambridge Monographs on Particle Physics, Nuclear Physics and Cosmology, Cambridge University Press) p 266–8, 2000
4. Dan Green, *Hadron Calorimeter Performance with a* $PbWO_4$ *EM Compartment*, January, 1996
5. C.W.Fabjan, *Calorimetry in high energy physics* CERN, Geneva, Switzerland
6. K. Kleinknecht, *Particle Detectors*, Institut für Physik der Universität Dortmund, Dortmund, Germany

Acknowledgements

Heartfelt thanks to Prof. D. Indumathi, IMSc, Chennai. Also to Prof.M.V.N.Murthy, IMSc, Chennai, Prof.N. K. Mondal, TIFR, Mumbai, Prof. Gobinda Majumdar , TIFR, Mumbai and Asmita Redij. Thanks to all my collaborators in the hadron group. Also, thanks to the organisers of SERC EHEP 2013, IITM for providing the opportunity to present these works.

THANK YOU