Hadron energy resolution as a function of iron plate thickness and hadron direction resolution at INO ICAL

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Motivation : 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

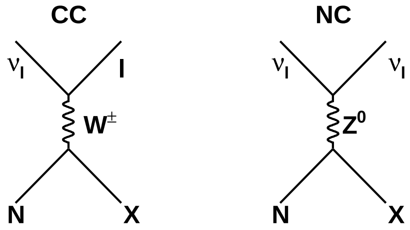
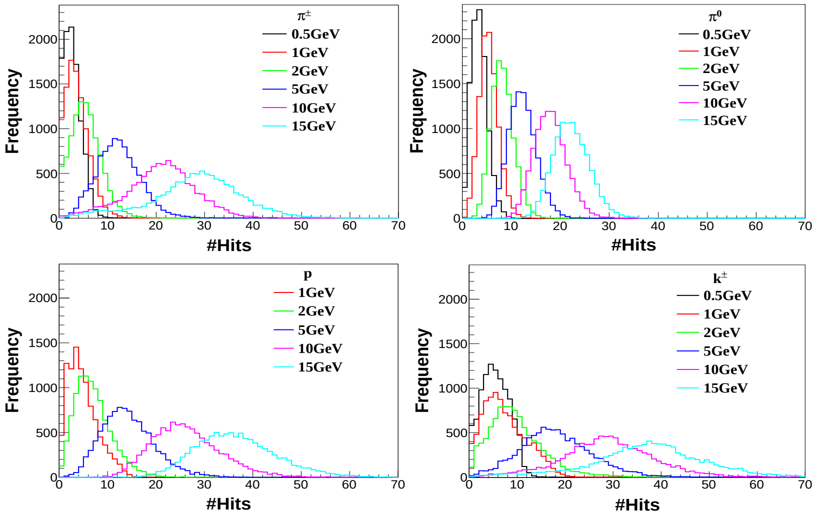


Figure 1: Charged current and neutral current interactions of neutrino with nucleons.

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



- Majority : pions $\rightarrow$ Study for single pions.
- No:of hadron hits depends on plate thickness & hadron energy.
- 11 different thicknesses from 1.5cm,...,8cm.
- Gaussian fit over estimates the width of the distribution at low energies and higher thickness.

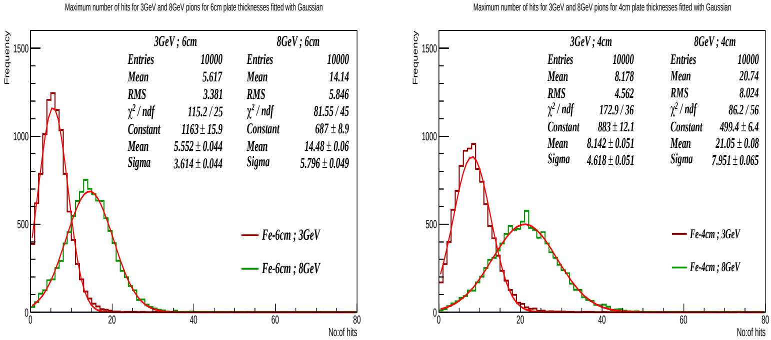


Figure 2: Hit distributions for 3 GeV and 8 GeV pions in (left) 6 cm and (right) 4cm iron, fitted with gaussian.

- $\bar{n}(E) = n_0 \left[1 - exp\left(-\frac{E}{E_0}\right)\right]$, 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 distribtution.
- 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. Ideal case : $b = 0$.
- $(\sigma/E)^2 = a^2/E + b^2$: easier to analyze since linear in $1/E$.
- Analysis in [2 GeV - 5GeV) ; [5GeV - 15GeV] ; [2GeV - 15GeV]
- 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

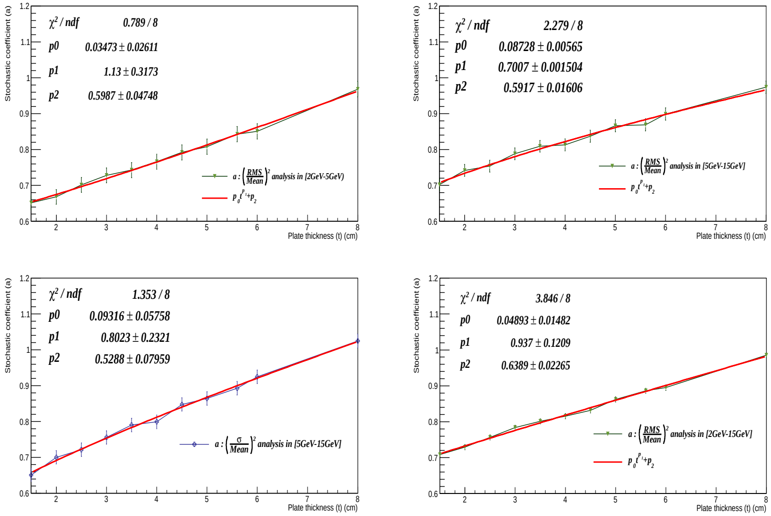


Figure 3: a as a function of t (cm) in various energy ranges. p_0 = constant, p_1 = exponent which gives the thickness dependence, p_2 = residual resolution

- The exponent p_1 in the range [5GeV - 15GeV] = 0.701±0.002=$p_0 t^{p_1} + p_2$=$\alpha + p_2$
- Constant term p_2 in this range = 0.592±0.016 → dominant residual resolution.
- Optimisation : a improves with decreasing thickness, but very slightly. $\alpha_{5.6cm} = 0.276$

t (cm)	α_t	$\Delta\alpha = \alpha_{5.6cm} - \alpha_t$
4	0.221	0.055
2.5	0.162	0.114
1.5	0.167	0.167

- 5.6cm → say 2.5cm : increase in no:of layers, and hence no:of RPCs and other components.
- Thickness ↓ , cost ↑ and not much gain in resolution from hadron point of view.
- Hence 4cm to 5.6cm are optimum thicknesses.

Hadron angle resolution

- For 5.6cm Fe only.
- Single, double pions at different θs with ϕ smeared fully; fixed θ - fixed ϕ, hadrons from neutrino events.
- Direction reconstruction using hit information :
  1. Centroid technique
  2. Orientation matrix method
  3. Raw hit method with timing
- **Centroid method** : for each simulated event, the vertex position and the positions of hits forming the shower are taken and the centroid of the shower is found by summing over the position vectors (w.r.to the vertex) of each hit in that event $\rightarrow$ reconstructed shower direction.
- **Orientation matrix method** : Orientation matrix T for a collection of unit vectors (x_i, y_i, z_i), i=1,...,n

Orientation matrix method...

$$T = \begin{pmatrix} \Sigma x_i^2 & \Sigma x_i y_i & \Sigma x_i z_i \\ \Sigma x_i y_i & \Sigma y_i^2 & \Sigma y_i z_i \\ \Sigma x_i z_i & \Sigma y_i z_i & \Sigma z_i^2 \end{pmatrix}$$

Eigen analysis of this symmetric matrix $\rightarrow$ idea of the shape of the underlying distribution. If a unit mass is placed at each point, moment of inertia of the n points about an arbitrary axis (x_0, y_0, z_0) is,

$$n - \begin{pmatrix} x_0 & y_0 & z_0 \end{pmatrix} T \begin{pmatrix} x_0 \\ y_0 \\ z_0 \end{pmatrix}$$

The variation of moment of inertia gives information about the scatter of the points as the choice of axis varies. The axis about which the moment is least $\rightarrow$ principal axis $\rightarrow$ shower direction. Distributions of the sine of the error angles $(\sin \Delta\theta)$ fitted with the function : $\Delta\theta = A\Delta\theta \exp(-B\Delta\theta)$, where, A and B parameters.

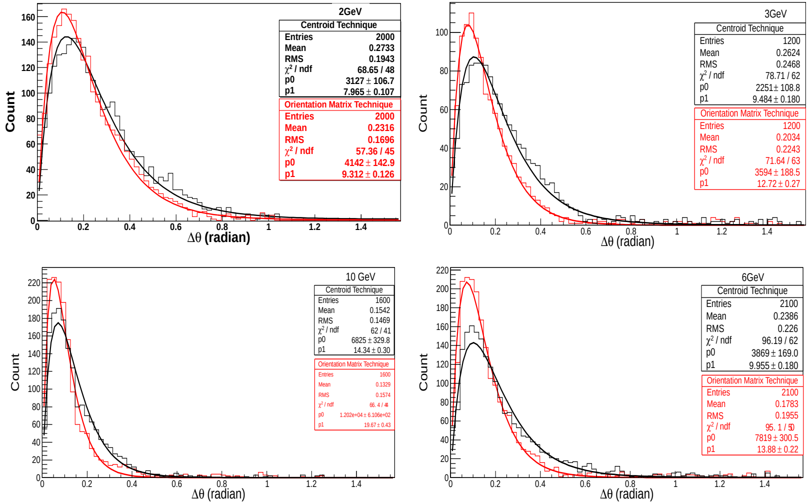


Figure 4: $\Delta\theta$ distribution obtained using the two techniques at 2GeV, 3Gev, 6GeV and 10GeV (clockwise from top-left).

Raw hits and timing method

- No vertex position is needed. Only hit information in X-Z and Y-Z plane separately. Time window of $\leq$50 ns.
- Average x and y positions in the i^{th} layer of an event are found separately.
- 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.
- 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.

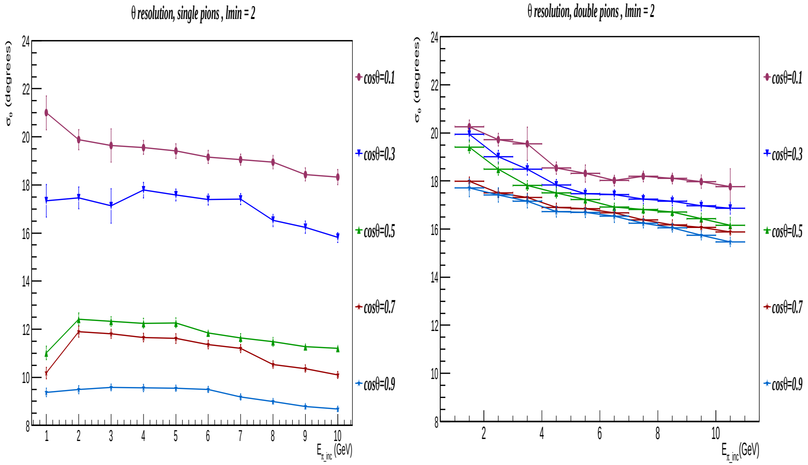


Figure 5: θ resolution in degrees for (a) single pions and (b) double pions with lmin = 2 cut

Single and double pions in a fixed direction (fixed θ - fixed ϕ) :

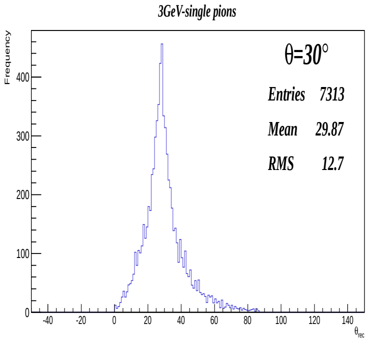


Figure 6: Comparison of θ resolution at 30° for (left) single pions and (right) double pions propagated in the fixed direction $\theta = 30^\circ$ and $\phi = 30^\circ$ with lmin = 2 cut.

- Hadrons are reconstructed as showers in the detector since they don't leave clean tracks like muons to which ICAL is most sensitive.
- Even then it is possible to extract their direction information from hit pattern.
- Resolution worsens in the realistic case of several hadrons in the final state since multiple hadrons may travel in different drections thus giving hits in a larger region (larger spread).

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