Hadron Energy Estimation in Atmospheric Neutrino Events

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Introduction

- Initial studies on the oscillation parameter measurement were done using the information of $E_\mu$ and $\cos \theta_\mu$ only (T. Thakore et al, JHEP 1305 (2013) 058, arXiv: 1303.2434).

- They showed that $|\Delta m^2_{31}|$ can be measured to a precision of 5% and $\sin^2 \theta_{23}$ to a precision of 17% with ten years of exposure.

- A later analysis studied the improvement in the precision of these measurements by considering a third kinematical variable $E_{\text{had}}$. (M. M. Devi et al, JHEP 1410 (2014) 189, arXiv:1406.3689).

- For the same ten years of exposure, it was found that the precision in $|\Delta m^2_{31}|$ improves to 3% and that in $\sin^2 \theta_{23}$ improves to 12%.

- Therefore, we have done a systematic study of hadron energy calibration in ICAL.
The muon (minimum ionising particle) produced in the ICAL leaves a track, which gives the charge, the energy and the direction of the muon with good precision.

An atmospheric neutrino interaction also produces a set of hadrons (mesons and baryons).

Most of the time, the hits due to the hadrons can not be reconstructed into tracks because (a) the energy of a typical hadron is much smaller than the energy of the muon and (b) the hadrons can be absorbed by the detector nuclei.

The first estimate of the hadron energy of atmospheric neutrino events in ICAL was done by M M Devi et al.

In S.Set al. and Lakshmi S. Mohan et al., charged pions of different energies and different directions with respect to the zenith were injected into Geant4 simulator.

A correlation between the pion energy and the number of hits was established and the resolution in pion energy was estimated. These correlations and the resolutions were assumed to hold for all hadrons produced in atmospheric neutrino interactions.
In this work (DOI:10.1007/s12043-020-01986-x), we found that a significant number of baryons are produced in a large fraction of these events.

Therefore, the hit pattern produced by an isolated, single charged pion does not represent the hit pattern produced by the hadrons in an atmospheric neutrino event properly.

We generated 100 years of unoscillated atmospheric neutrino events through the GENIE and NUANCE event generators and did a full Geant4 simulation of all the $\nu_\mu$-CC and $\bar{\nu}_\mu$-CC events.

We isolated the hits produced by the hadrons by eliminating the track hits from the total number of hits.

We used this hadron hit information to estimate the hadron energy and the energy resolution.

We avoid the problem of "Ghost hits" by taking the number of hits in an RPC to be the maximum of (number of X strips with a signal, number of Y strips with a signal).
Figure: $E_{\text{baryon}}/E_{\text{had}}$ vs frequency for GENIE
Baryons in atmospheric neutrino events

Figure: $E_{\text{baryon}}/E_{\text{had}}$ vs frequency for NUANCE
Baryons in atmospheric neutrino events

\[ E_{\text{had}} = E_\nu - E_\mu \]
\[ E_{\text{baryons}} = E_\nu - E_\mu - E_{\text{mesons}} \]

- Baryons carry almost all of the hadron energy for a vast majority of events when \( 0 \leq E_{\text{had}} \leq 5 \) GeV.
- For larger values of hadron energy, the energy fraction carried by the baryons becomes smaller until it becomes negligibly small for \( E_{\text{had}} > 20 \) GeV.
\begin{equation*}
E_{\text{baryon-mean}} = (\gamma - 1 - \ln P_0 - P_1)P_3 + P_2, \\
\sigma_{E_b} = \sqrt{\frac{(2 - P_1)}{2P_0} P_3^2},
\end{equation*}

where \( \gamma \) is the Euler’s constant and \( P_i \) are the parameters of the Vavilov fit.

| baryon_hits | \( E_{\text{baryon-mean}} \) | \( \sigma_{E_b} \) | \( E_{\text{baryon-mean}} \) | \( \sigma_{E_b} \) |
|-------------|-------------------------------|-----------------|-----------------------------|-----------------|
| 0-1         | GENIE 0.98                    | GENIE 0.73      | GENIE 1.0                   | GENIE 0.6       |
| 2-3         | GENIE 1.03                    | GENIE 0.85      | GENIE 1.3                   | GENIE 0.8       |
| 4-5         | GENIE 1.14                    | GENIE 0.97      | GENIE 2.0                   | GENIE 1.1       |
| 6-7         | GENIE 1.29                    | GENIE 1.12      | GENIE 2.6                   | GENIE 1.2       |
| 8-9         | GENIE 1.35                    | GENIE 1.11      | GENIE 3.2                   | GENIE 1.4       |
| 10-11       | GENIE 1.43                    | GENIE 1.16      | GENIE 3.7                   | GENIE 1.5       |
| 12-13       | GENIE 1.67                    | GENIE 1.47      | GENIE 4.3                   | GENIE 1.6       |
| 14-15       | GENIE 1.65                    | GENIE 1.35      | GENIE 4.8                   | GENIE 1.8       |
| 16-17       | GENIE 1.82                    | GENIE 1.51      | GENIE 5.6                   | GENIE 2.2       |
| 18-21       | GENIE 1.94                    | GENIE 1.63      | GENIE 6.6                   | GENIE 2.9       |
| \( \geq 22 \) | GENIE 2.62                    | GENIE 2.27      | GENIE 13.6                  | GENIE 10.1      |

\textbf{Table:} baryon_hits and \( E_{\text{baryon-mean}} \) table from GENIE and NUANCE.
\( E_{\text{baryon-mean}} = 0.29 \, (\text{baryon\_hits}) + 0.70 \)

\( E_{\text{pion}} = 0.64 \, (\text{Mean\_no\_\_hits}) - 1.57 \)
Hadron hit analysis

hadron_hits(4,5)

- Entries: 86668
- Mean: 0.5071
- RMS: 0.419
- $\chi^2$/ndf: 1237 / 15
- p0: 0.1 ± 0.0
- p1: 0.1871 ± 0.0363
- p2: 0.2319 ± 0.0026
- p3: 0.1567 ± 0.0019
- p4: 8583 ± 36.4

hadron_hits(10,11)

- Entries: 23628
- Mean: 1.406
- RMS: 1.111
- $\chi^2$/ndf: 190.6 / 15
- p0: 0.1 ± 0.0
- p1: 0.1 ± 0.0
- p2: 0.6911 ± 0.0070
- p3: 0.4117 ± 0.0042
- p4: 5795 ± 42.9

hadron_hits(70,79)

- Entries: 5906
- Mean: 4.999
- RMS: 3.788
- $\chi^2$/ndf: 53.86 / 25
- p0: 0.1 ± 0.0
- p1: 0.1 ± 0.0
- p2: 2.643 ± 0.040
- p3: 1.384 ± 0.024
- p4: 3473 ± 48.6

hadron_hits(70,79)

- Entries: 793
- Mean: 28.37
- RMS: 17.86
- $\chi^2$/ndf: 73.03 / 80
- p0: 0.1 ± 0.1
- p1: 0.2788 ± 0.0761
- p2: 18.13 ± 1.71
- p3: 6.858 ± 0.904
- p4: 736.7 ± 27.7
| hadron_hits | $E_{\text{had}-\text{mean}}$ | $\sigma_{E_h}$ | $E_{\text{had}-\text{mean}}$ | $\sigma_{E_h}$ |
|------------|----------------------------|---------------|----------------------------|---------------|
|            | GENIE                      |               | NUANCE                     |               |
| 2-3        | 0.4                        | 0.5           | 0.4                        | 0.4           |
| 4-5        | 0.6                        | 0.8           | 0.5                        | 0.5           |
| 6-7        | 1.1                        | 1.3           | 0.9                        | 1.1           |
| 8-9        | 1.8                        | 1.8           | 1.2                        | 1.3           |
| 10-11      | 2.4                        | 1.9           | 1.4                        | 1.3           |
| 12-13      | 3.3                        | 2.6           | 1.9                        | 1.7           |
| 14-15      | 4.1                        | 3.1           | 2.3                        | 2.0           |
| 16-17      | 5.0                        | 3.6           | 2.9                        | 2.4           |
| 18-19      | 6.3                        | 4.4           | 3.7                        | 3.1           |
| 20-21      | 6.8                        | 4.4           | 4.1                        | 3.4           |
| 22-24      | 8.2                        | 5.4           | 5.1                        | 4.3           |
| 25-29      | 9.9                        | 6.3           | 6.6                        | 5.4           |
| 30-34      | 12.5                       | 7.6           | 8.4                        | 6.8           |
| 35-39      | 15.1                       | 9.1           | 11.4                       | 9.1           |
| 40-44      | 17.8                       | 10.2          | 13.3                       | 10.1          |
| 45-49      | 19.8                       | 11.0          | 15.3                       | 10.9          |
| 50-54      | 22.9                       | 12.0          | 16.7                       | 11.6          |
| 55-59      | 26.1                       | 13.8          | 20.2                       | 14.2          |
| 60-69      | 28.6                       | 15.8          | 24.5                       | 16.9          |
| 70-79      | 34.7                       | 18.7          | 29.1                       | 20.2          |
| 80-99      | 37.4                       | 19.2          | 32.4                       | 21.1          |
| $\geq$ 100| 49.2                       | 23.7          | 44.4                       | 24.7          |

Table: hadron_hits and $E_{\text{had}-\text{mean}}$ table from GENIE and NUANCE.
(GENIE) \(E_{\text{had-mean}} \simeq 0.19x + 0.005x^2\)

(NUANCE) \(E_{\text{had-mean}} \simeq 0.11x + 0.004x^2\)

Parametrized as \(\sigma(E)/E = \sqrt{a^2/E + b^2}\)

\[a = 1.18 \pm 0.06 \text{ and } b = 0.51 \pm 0.01.\]

Parametrized as \(\sigma(E)/E = \sqrt{a^2/E + b^2}\)

\[a = 1.44 \pm 0.15 \text{ and } b = 0.62 \pm 0.02.\]
In a previous work, the authors of M. M. Devi et. al. also have used the hadron hit information from the Geant4 simulation of NUANCE generated atmospheric neutrino events. There are a number of differences in the procedure they used and in the procedure used in this work.

- Their data set consists of 1000 years of atmospheric neutrino events, whereas our set consists of 100 years of data.

- They obtained hadron hit information by doing the Geant4 simulation of an event with the muon turned off at the input level. In our case, we did the full Geant4 simulation of all the charged particles in the event and subtracted the hits which went into the track reconstruction. This is the procedure which will be utilized in the case of actual data.

- The avalanche produced in an RPC by one charged particle can, quite often, produce hits in two adjacent strips. Thus, the number of hadron hits in an RPC is likely to be larger than the number of charged particles passing through it. This feature is built into Geant4 through the option `multiplicity`. The authors of M. M. Devi et. al. kept this option `off` and hence obtained a smaller number of hits for a given hadron energy. In our case, we kept the multiplicity option `on` and obtained about 30 to 40% larger number of hits for the same hadron energy. This is a more realistic simulation of the detector.

![Figure: Strip multiplicity as a function of position in a strip (Gobinda Majumder, PoS (ICHEP2018)357)](attachment://strip_multiplicity.png)
In this work, we attempted to obtain an estimate of the energy of hadrons produced in a charged current interaction of an atmospheric muon neutrino/anti-neutrino in ICAL at INO. This was done by doing a full Geant4 simulation of atmospheric neutrino events generated by the neutrino event generators NUANCE and GENIE. We have used the un-oscillated data simulated for a period of 100 years. The events generated by both the generators show the following features:

- For $E_{had} < 5 \text{ GeV}$, almost all of the hadron energy is carried by the baryons.

- The relation between the number of hits and the energy of hadrons is very different for the two cases when the hadrons are mesons and when the hadrons are baryons.

- When the events are classified into bins with different number of hadron hits, the resulting spectra are reasonably well described by Vavilov distributions.

- There is a good correlation between the number of hits and the mean value of $E_{Ehad}$ of the Vavilov distributions.

- The width ($\sigma$) of the Vavilov distributions is related to the mean energy ($E_{had-mean} = E$) through the expected relation $\sigma(E)/E = \sqrt{(a^2/E + b^2)}$. Values of $\sigma$ and $E$ from GENIE fit the above form much better than those from NUANCE.
References

1. Shakeel Ahmad et al, Physics Potential of the ICAL detector at the India-based Neutrino Observatory (INO), Pramana 88 (2017) 79.
2. Ali Ajmi et al., Improving the hierarchy sensitivity of ICAL using neural net- work, arxiv:1510.02350 [physics.ins-det].
3. Tarak Thakore et al., The Reach of INO for Atmospheric Neutrino Oscillation Parameters, JHEP 05 (2013) 058.
4. Anushree Ghosh et al., Determining the Neutrino Mass Hierarchy with INO, T2K, NOvA and Reactor Experiments, JHEP 04 (2013) 009.
5. M M Devi et al., Hadron energy response of the Iron Calorimeter detector at the India-based Neutrino Observatory, JINST 08 (2013) P11003.
6. S. Seth et al., Update of INO-ICAL reconstruction algorithm, JINST 13 (2018) P09015.
7. Lakshmi S. Mohan et al., Simulation studies of hadron energy resolution as a function of iron plate thickness at INO-ICAL, JINST 9.09 (2014) T09003.
8. M M Devi et al., Enhancing sensitivity to neutrino parameters at INO combining muon and hadron information, JHEP 2014 (2014) 189.
9. Tarak Thakore., Physics Potential of the India-based Neutrino Observatory (INO), PhD thesis. TIFR, Mumbai, DHEP (2014).
10. D. Casper, The nuance neutrino physics simulation, and the future, Nuclear Physics B -Proceedings Supplements 112 (2002) 161.
11. P. V. Vavilov, Ionization losses of high-energy heavy particles, Sov. Phys. JETP 5 (1957) 749.