Inelasticity in atmospheric $\nu$ experiments
Measurement and importance of hadron energy measurements

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Philosophy of this talk

- Measurement of hadron energy (inelasticity) event-by-event, and how it can improve detector performance in an atmospheric $\nu$ experiment.
Measurement of hadron energy (inelasticity) *event-by-event*, and how it can improve detector performance in an atmospheric $\nu$ experiment

INO-ICAL taken as a sample detector, but the principles and results should be applicable to other current and future atmospheric neutrino experiments (SK, HK, ORCA, PINGU, ...)
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- Shall point out some examples where the effect of hadron energy / inelasticity measurements can be clearly demonstrated.
- Quantifying information gain from hadron energy measurements would help in deciding priorities (bigger detector or closer active detector elements ?)
Inelasticity in atmospheric neutrino experiments

1. Inelasticity and hadron energy measurements

2. Inelasticity to improve detector performance
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Inelasticity in neutrino interactions

\[ y \equiv \frac{E_\nu - E_\mu}{E_\nu} = \frac{E_h - m_N}{E_\nu} = \frac{E'_h}{E_\nu} \]

The problem of unknown inelasticity

- \( E_\nu \) cannot be determined given only \( E_\mu \)
- All “clean” probability expressions involve \( E_\nu \)
- Statistical determination \( \Rightarrow \) dilutes results
QE, RS and DIS processes (CC interactions)

Cross sections of neutrinos and antineutrinos:

Note different scales

Events spectrum at ICAL in different channels: All INO-ICAL results with GEANT4-based detector simulations
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Events spectrum at ICAL in different channels:

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Differential cross sections of CC DIS events:

$$\frac{d\sigma^{CC}}{dy} = -[a + b(1 - y)^2] \times 10^{-38} \text{ cm}^2 \frac{E_\nu}{1 \text{ GeV}}$$

Neutrinos: $a \gtrsim b$, Antineutrinos: $a \lesssim b$
Differential cross sections of CC DIS events:

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Neutrinos: \( a \gtrsim b \), Antineutrinos: \( a \lesssim b \)

Normalized inelasticity distribution:

\[
p \equiv -\frac{1}{\sigma} \frac{d\sigma}{dy} = \frac{a + b(y - 1)^2}{a + b/3}
\]
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Normalized inelasticity distribution:

\[ \rho \equiv -\frac{1}{\sigma} \frac{d\sigma}{dy} = \frac{a + b(y - 1)^2}{a + b/3} \]

Distribution of inelasticity at ICAL:
IceCube will be able to access the high-energy limit, maybe use it for their energy calibration of starting events, etc.

(Talk by Mauricio Bustamante)
Hadron showers at INO-ICAL

INO White paper, Pramana 2017
1505.07380

- 5.6 cm thick iron plate
- 4 cm air gap for RPC detector

Diagram showing hadron shower with interaction vertex, muon track, and energy values:
- $E_x = 8.16$ GeV
- $E_p = 2.14$ GeV
- $E_{had} = 6.02$ GeV
Hadron hit distribution at ICAL

M. M. Devi et al, JInst 2013
Determination of hadron energy

Hadron energy resolution
M. M. Devi et al, JInst 2013

Comparison of simulations with beam tests
S. M. Lakshmi et al, JInst 2014
Fraction of hadrons for which direction may be reconstructed: 50-80% depending on $E'_h$ and $\theta'_h$

For $E'_h \gtrsim 4$ GeV, direction may be reconstructed to within $20^\circ - 40^\circ$. 

M. M. Devi et al, JInst 2018
Currently, rather simplistic procedure for hadron energy calibration, uses only the number of hits.

Information on the shape of hadron shower not used in hadron energy calibration (Desirable to employ machine-learning methods).

Hadron energy reconstructed to
\[ \sim 30 \text{ – } 50\% \text{ for } E'_h \gtrsim 4 \text{ GeV} \]

Hadron direction may be reconstructed to
\[ \sim 20^\circ \text{ – } 40^\circ \text{ for } E'_h \gtrsim 4 \text{ GeV} \] (though not for all events), but not used in further analyses in this talk.
Inelasticity in atmospheric neutrino experiments

1. Inelasticity and hadron energy measurements

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Statistical separation of $\nu$ and $\bar{\nu}$

- For each (small enough) $(E_\mu, \theta_\mu)$ bin, measure the $y$-distribution, $p(y)$.
- Fit for the $y$-distribution $p(y) = (1 - \alpha)p_\nu(y) + \alpha p_{\bar{\nu}}(y)$, where $\alpha$ is the fraction of $\bar{\nu}$ events.
Inelasticity for learning about events

Ribordy and Smirnov, PRD 2013

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Angle $\beta$ between muon and incoming neutrino

Kinematical smearing: $\langle \beta \rangle \approx 0.75 \sqrt{\frac{y}{1 - y}} \frac{1}{\sqrt{E_\nu/1 \text{ GeV}}}$
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Identification of background events

- $\nu_\tau$ events, with large $y$-values, may be tagged.
Sensitivity to mass ordering: $(E_\mu, \cos \theta)$ planes, $y$-bins

- ORCA 1 year
- $\sigma_E = \sqrt{0.35E}$
- $\sigma_\psi = 10^\circ \sqrt{\frac{m_N}{E_\mu}}$

Using $y$-information would increase the significance of MH identification by 20-50%

Ribordy and Smirnov, PRD 2013
“3D” framework in ICAL: \((E_\mu, \cos \theta_\mu, E'_h)\)

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\chi^2 = \min_{\xi_l} \sum_{i=1}^{N_{E_{\text{had}}}} \sum_{j=1}^{N_{E_\mu}} \sum_{k=1}^{N_{\cos \theta_\mu}} \left[ 2(N_{\text{theory}}_{ijk} - N_{\text{data}}_{ijk}) - 2N_{ijk} \ln \left( \frac{N_{\text{theory}}_{ijk}}{N_{\text{data}}_{ijk}} \right) \right] + \sum_{l=1}^{5} \xi_l^2 ,
\]

\[
N_{\text{theory}}_{ijk} = N_{ijk}^{0} \left( 1 + \sum_{l=1}^{5} \pi_{ijk}^{l} \xi_l \right).
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2D: A. Ghosh et al, JHEP 2013

3D: M. M. Devi et al, JHEP 2014

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Correlations between \(E_\mu\) and \(E'_h\)

3D binning crucial, not just adding \(E'_h\) to \(E_\mu\) reconstruct \(E_\nu\)
Impact of hadron energy information on MH sensitivity

Without $E'_h$ information (2D)  With 4 $E'_h$ bins (3D)

Top panels: $\mu^-$ (neutrinos),  bottom panels: $\mu^+$ (antineutrinos)
Detector performance improvement with $E_h'$

For mass ordering: $\sim 30 - 40\%$ improvement in $\Delta \chi^2$

M. M. Devi et al, JHEP 2014
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For precision measurements
For higher $\Delta m^2$, information is mainly in the number of events, so information about $E'_h$ not so useful

For lower $\Delta m^2$, oscillation information in the energy and angular spectra, so $E'_h$ crucial

S. P. Behera et al, EPJC 2017; T. Thakore et al, 1804.09613
Sterile neutrinos: mass ordering

Sterile mass ordering schemes

Addition of $E' h$ information improves sterile MH sensitivity by $\sim 40\%$ for $\Delta m^2_{41} \sim (0.5 - 5) \times 10^{-3}$ eV$^2$.

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Concluding remarks

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- For future detectors: Detector development / planning should also give due weightage for extraction of hadron information (closely spaced active detector elements ?)