Inelasticity in atmospheric ν experiments

Measurement and importance of hadron energy measurements

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

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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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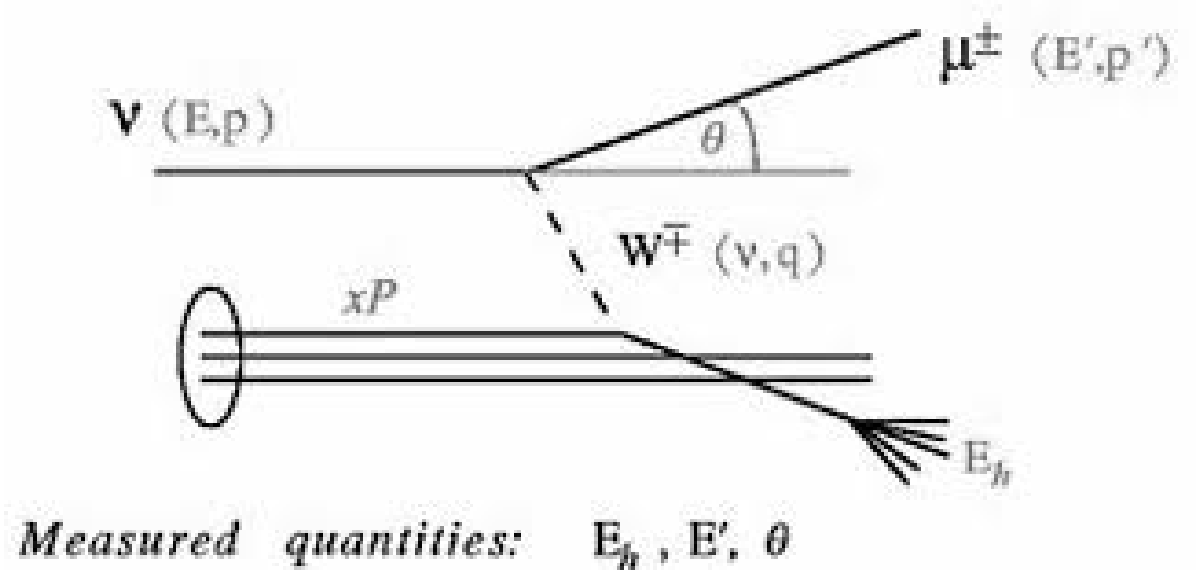
Inelasticity in neutrino interactions



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

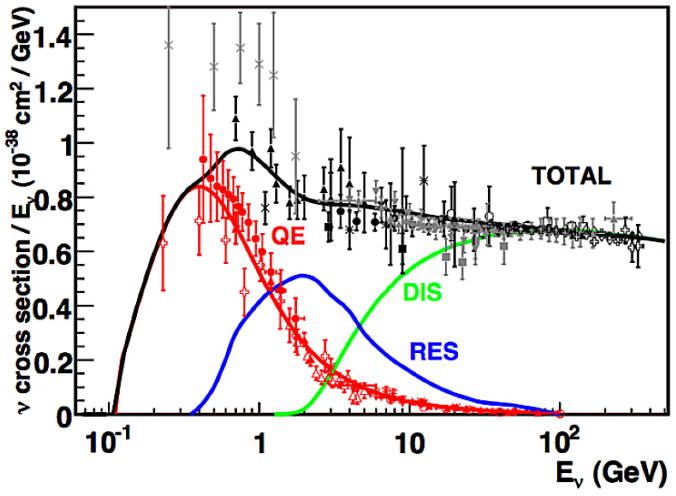
The problem of unknown inelasticity

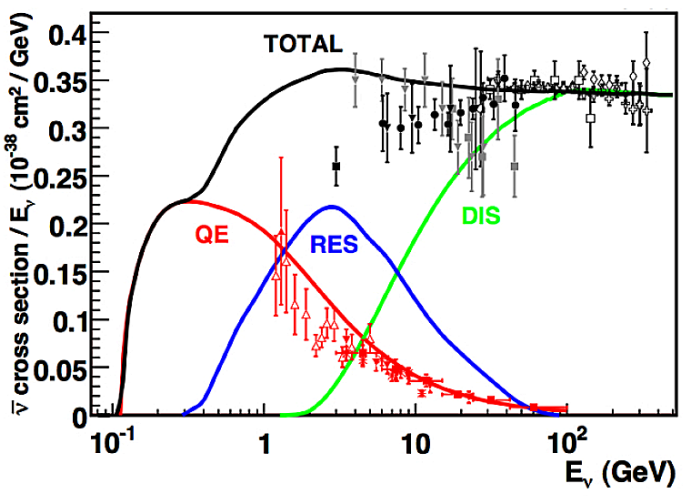
- E_ν cannot be determined given only E_μ
- All “clean” probability expressions involve E_ν
- Statistical determination $\Rightarrow$ dilutes results

QE, RS and DIS processes (CC interactions)

Cross sections of neutrinos and antineutrinos:

Note different scales





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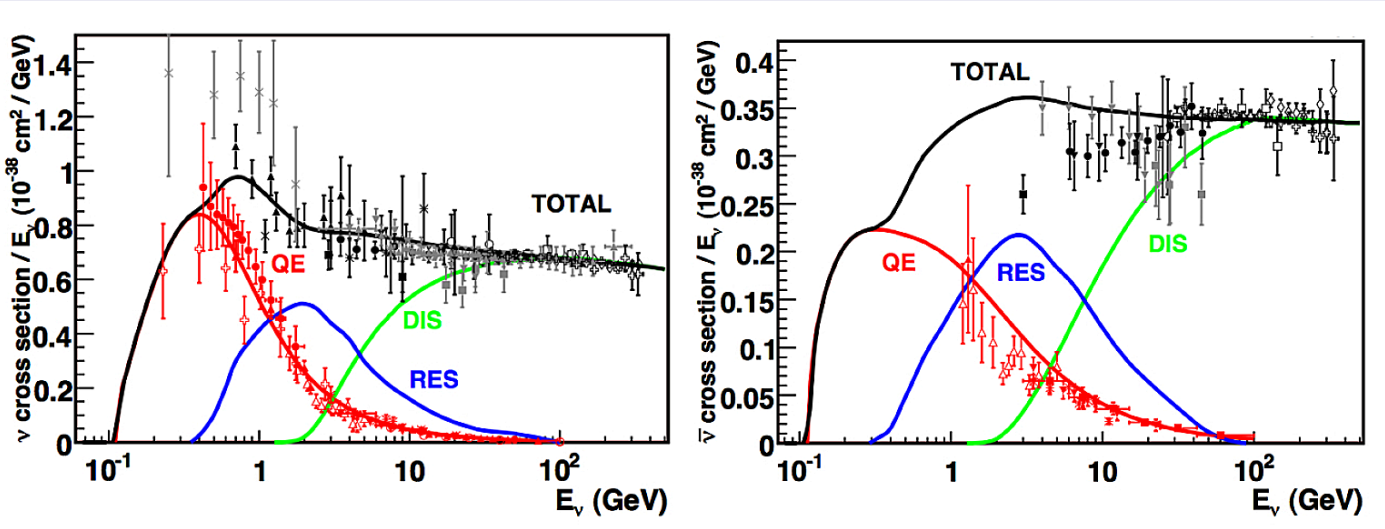
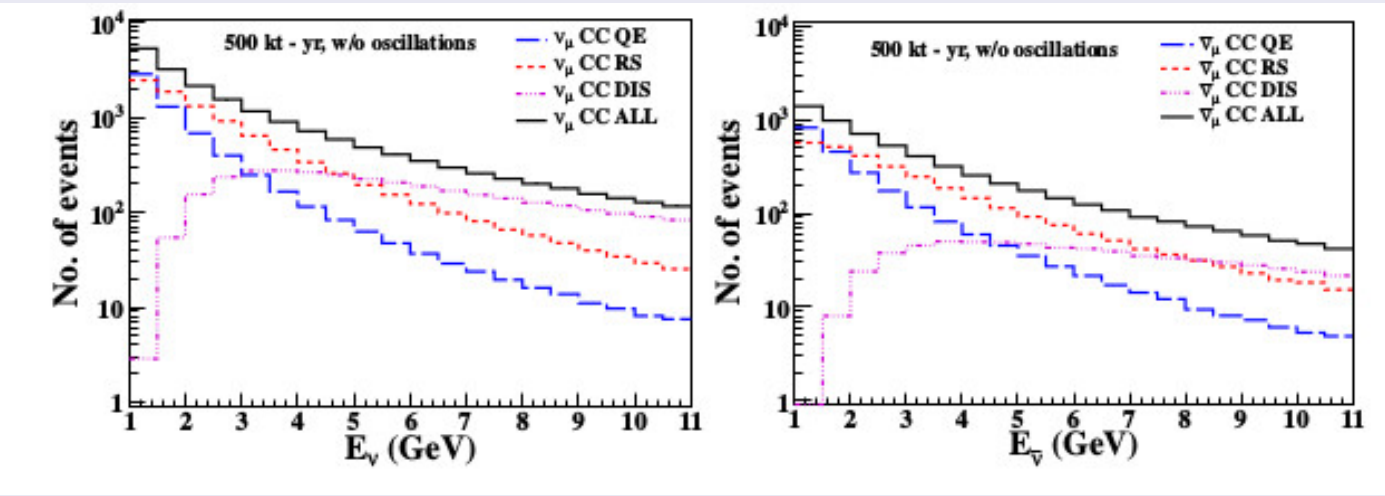


Events spectrum at ICAL in different channels:

All INO-ICAL results with GEANT4-based detector simulations



Differential cross sections of CC DIS events:

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

Neutrinos: $a \gtrsim b$, Antineutrinos: $a \lesssim b$

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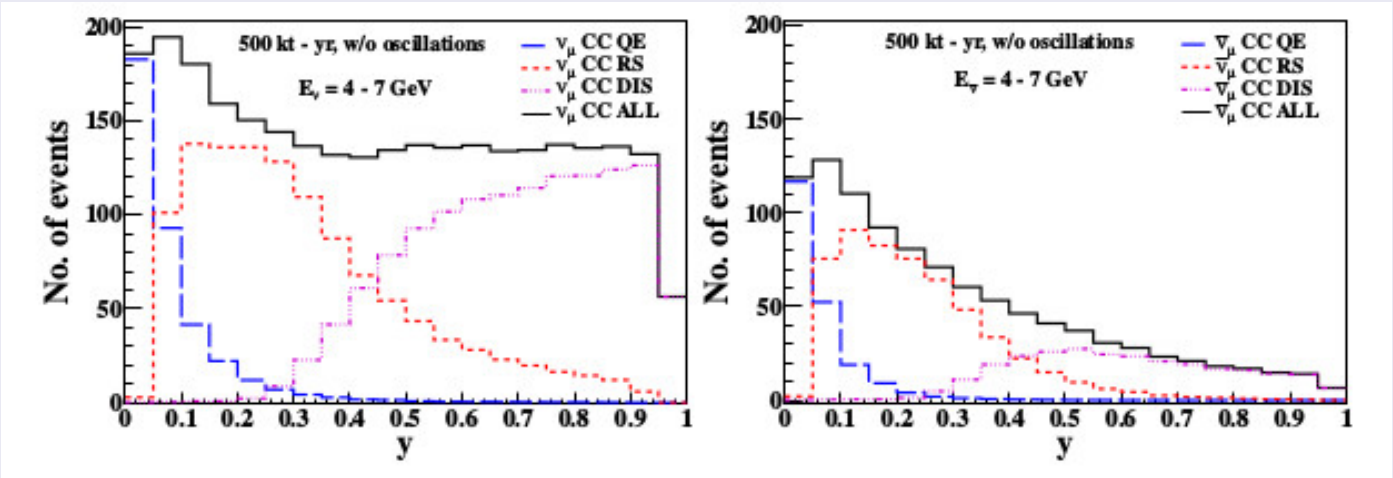
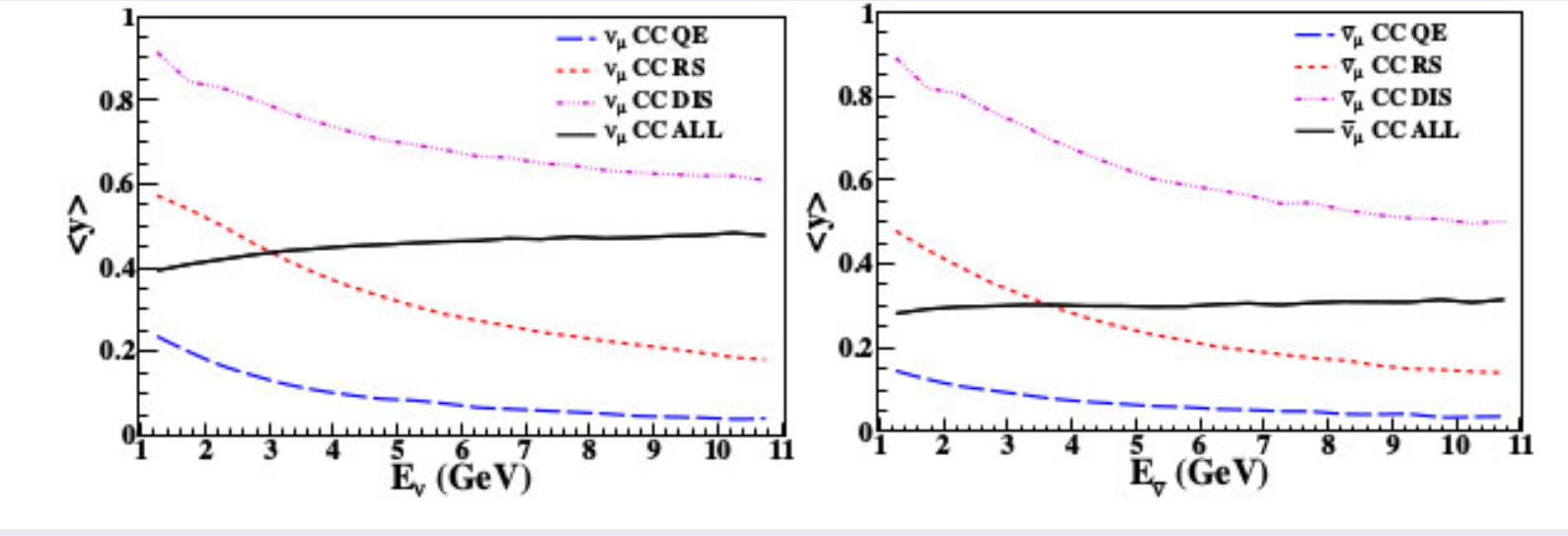
Distribution of inelasticity at ICAL :



The average inelasticity (CC)

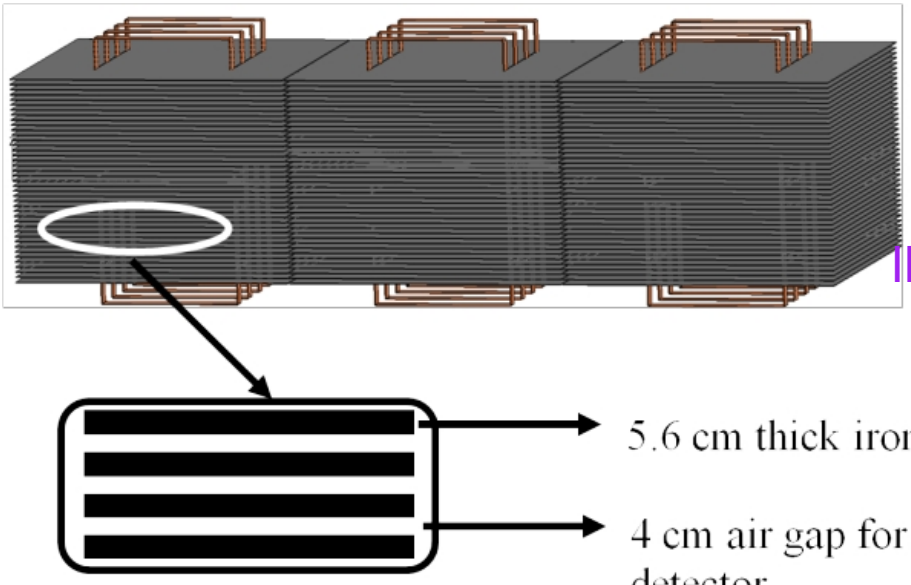
Average inelasticity *y* as a function of energy:



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

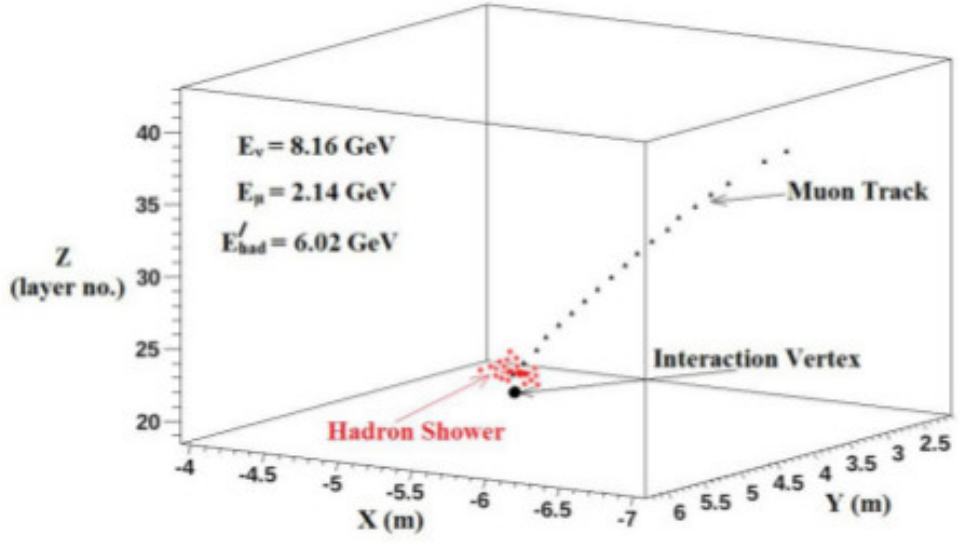
(Talk by Mauricio Bustamante)

Hadron showers at INO-ICAL

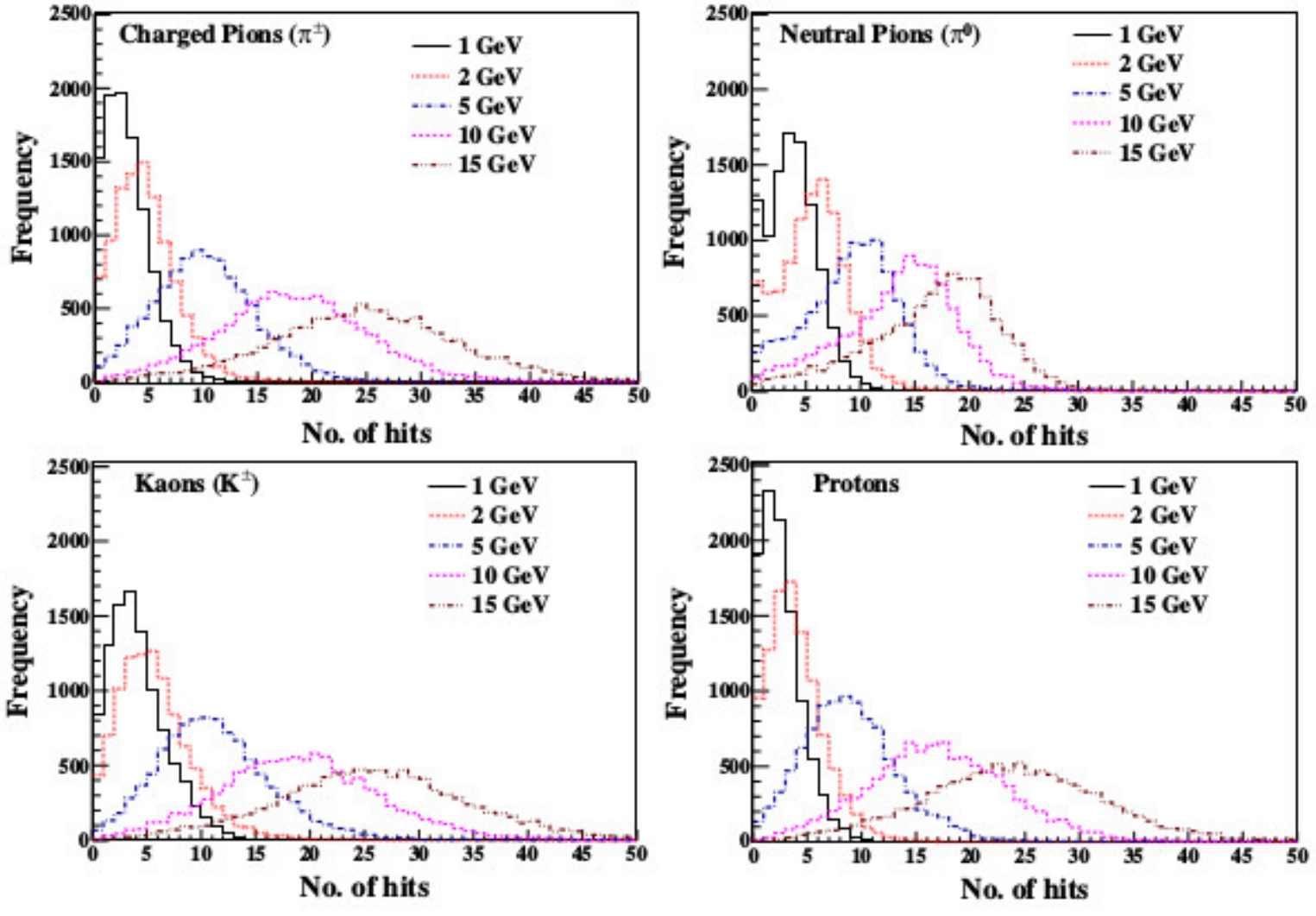


INO White paper, Pramana 2017

1505.07380

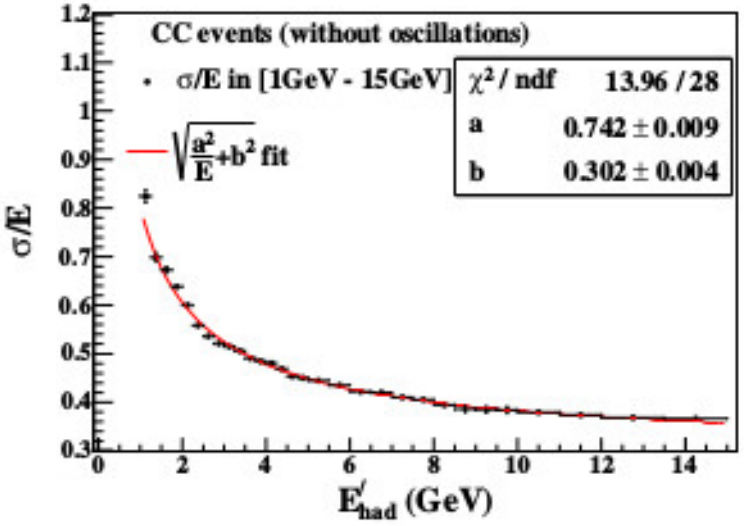


Hadron hit distribution at ICAL



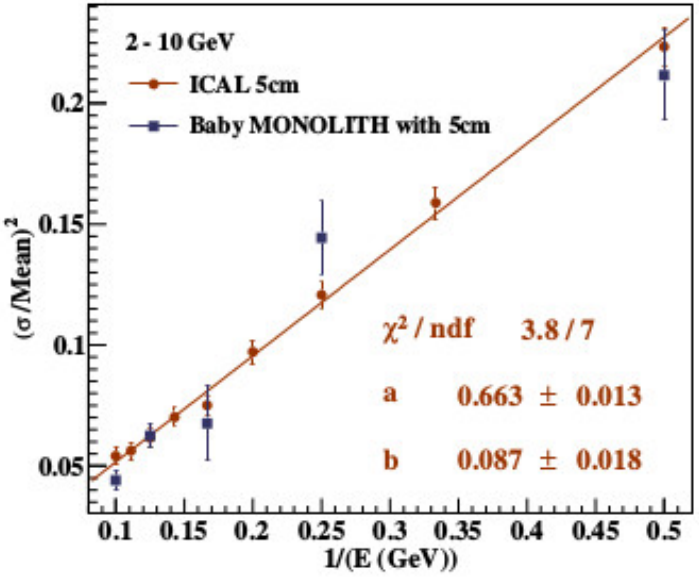
M. M. Devi et al, JInst 2013

Determination of hadron energy



Hadron energy resolution

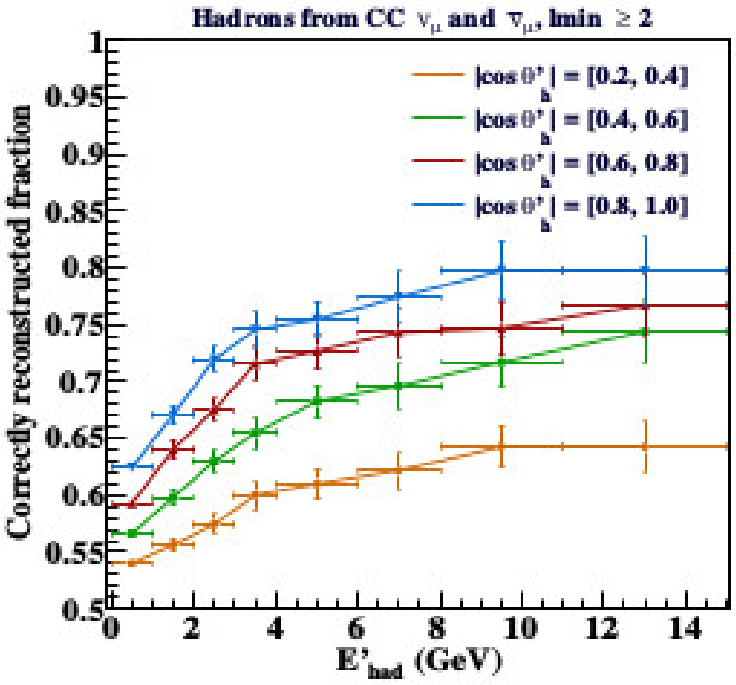
M. M. Devi et al, JInst 2013

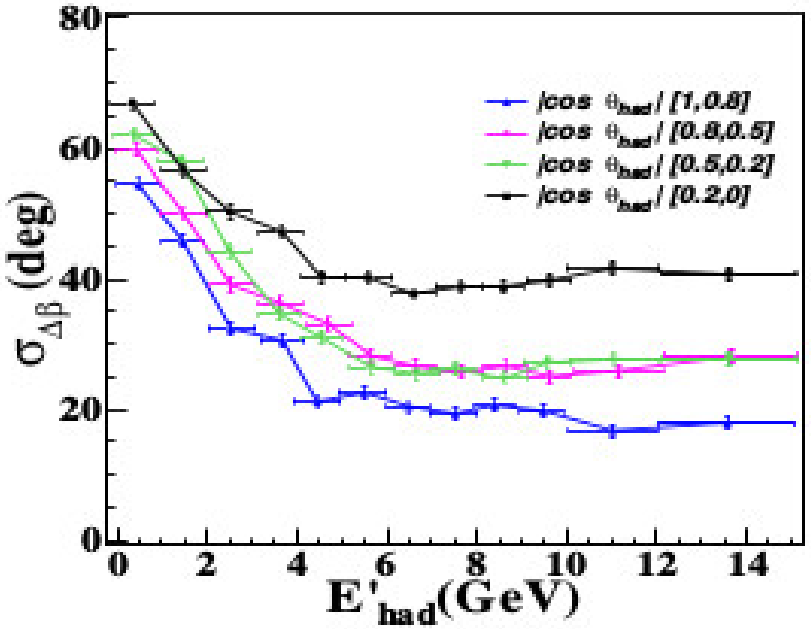


Comparison of simulations with beam tests

S. M. Lakshmi et al, JInst 2014

Hadron direction reconstruction





M. M. Devi et al, JInst 2018

- Fraction of hadrons for which direction may be reconstructed: 50-80% depending on E'_h and θ'_h
- For $E'_h \gtrsim 4$ GeV, direction may be reconstructed to within 20°–40°.

Comments on hadron energy measurement at ICAL

- 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 $\sim 30 - 50\%$ for $E'_h \gtrsim 4$ GeV
- Hadron direction may be reconstructed to $\sim 20^\circ - 40^\circ$ for $E'_h \gtrsim 4$ 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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Inelasticity for learning about events

Ribordy and Smirnov, PRD 2013

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

- For each (small enough) (E_μ, θ_μ) 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 α is the fraction of $\bar{\nu}$ events

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Angle β between muon and incoming neutrino

Kinematical smearing: $\langle\beta\rangle \approx 0.75\sqrt{\frac{y}{1-y}}\frac{1}{\sqrt{E_\nu/1\ \mathrm{GeV}}}$

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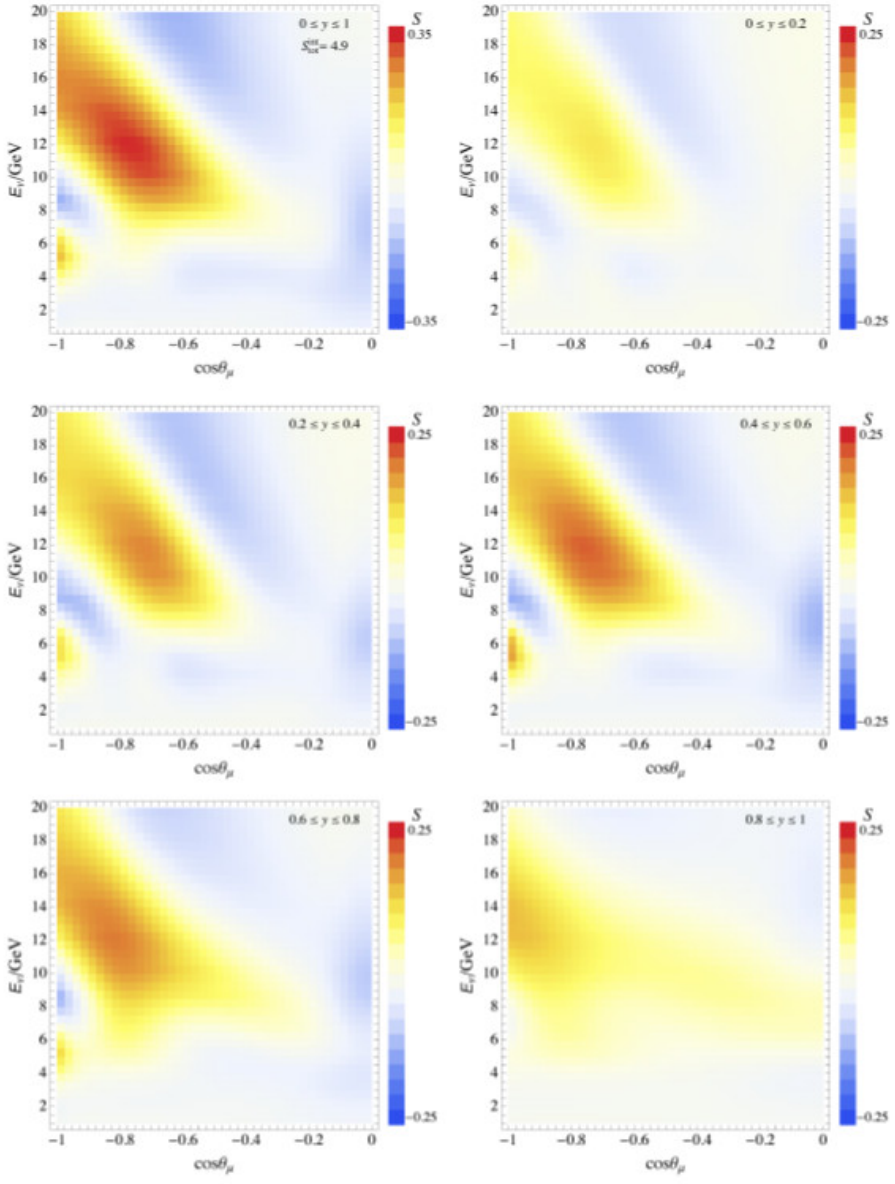
Identification of background events

- ν_τ 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 identifiation by 20-50%

Ribordy and Smirnov, PRD 2013

"3D" framework in ICAL: $(E_\mu, \cos\theta_\mu, E'_h)$

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

$$N_{ijk}^{\rm theory} = N_{ijk}^{0}\left(1 + \sum_{l=1}^{5} \pi_{ijk}^{l} \xi_l\right).$$

2D: A. Ghosh et al, JHEP 2013

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

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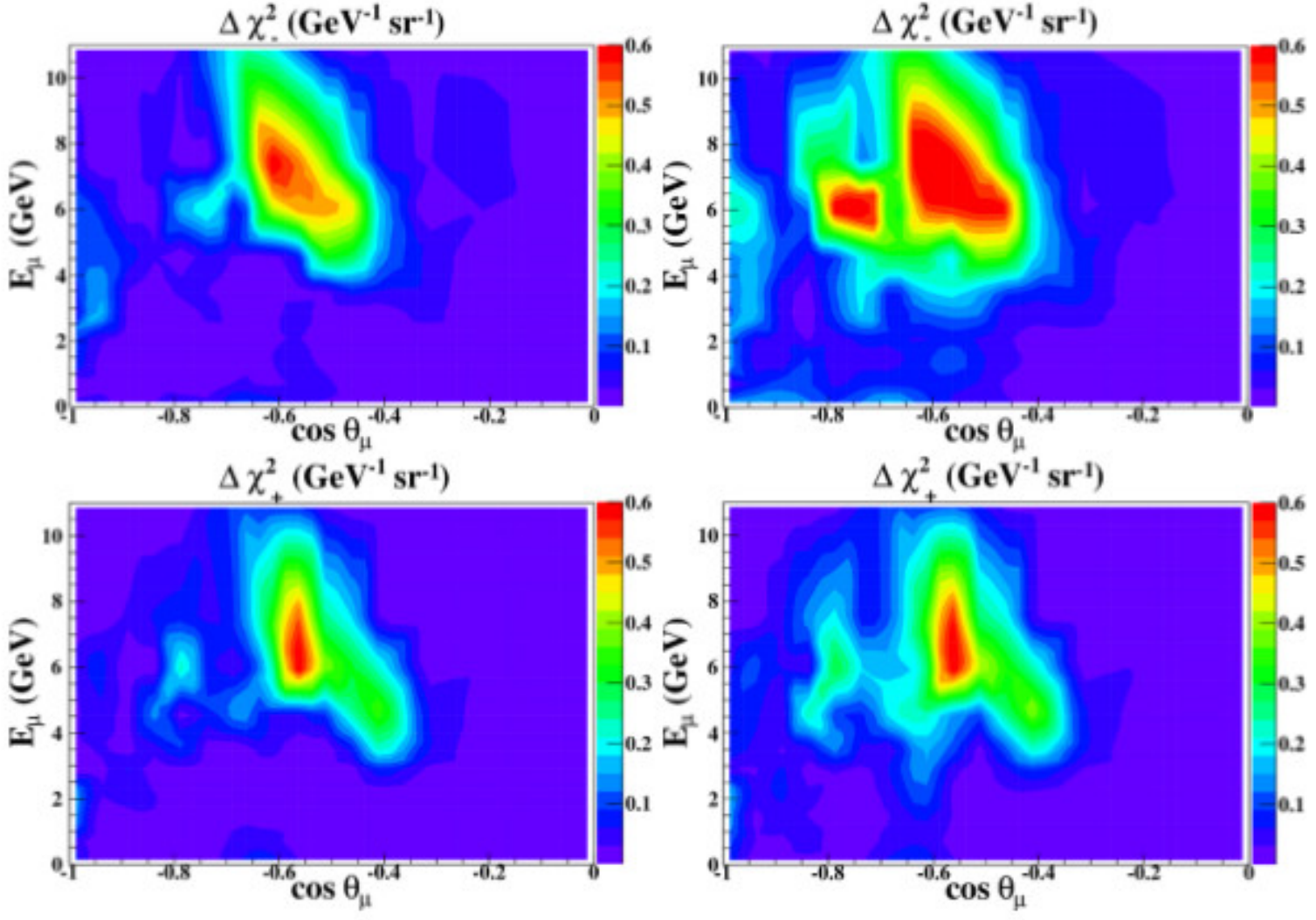
Correlations between E_μ and E'_h

3D binning crucial, not just adding E'_h to E_μ reconstruct E_ν

Impact of hadron energy information on MH sensitivity

Without E'_h information (2D)

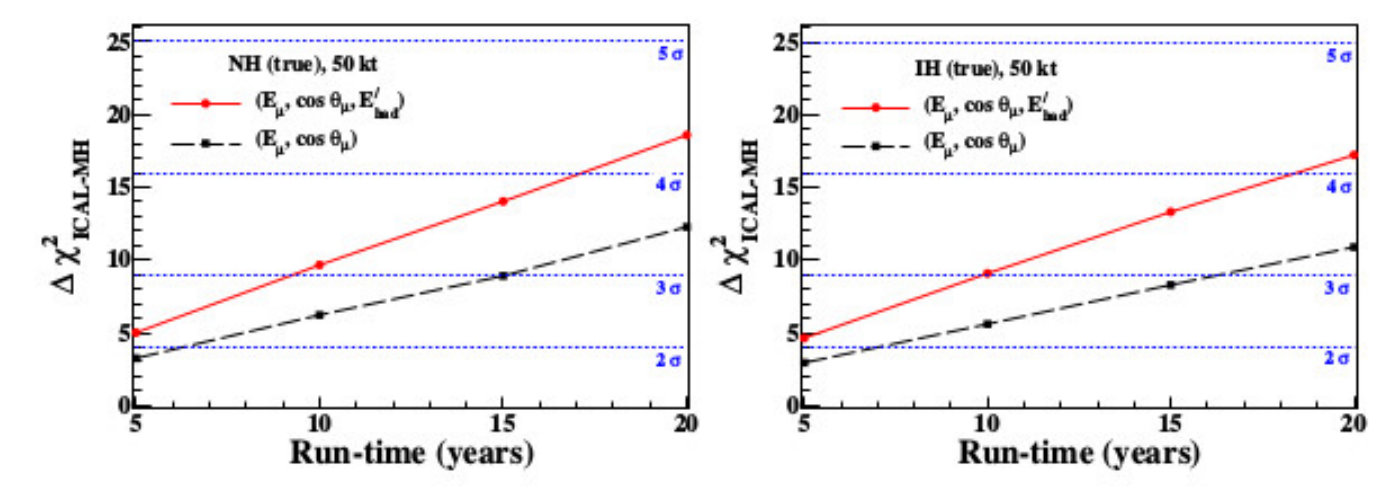
With 4 E'_h bins (3D)



Top panels: μ^- (neutrinos), bottom panels: μ^+ (antineutrinos)

Detector performance improvement with E'_h

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



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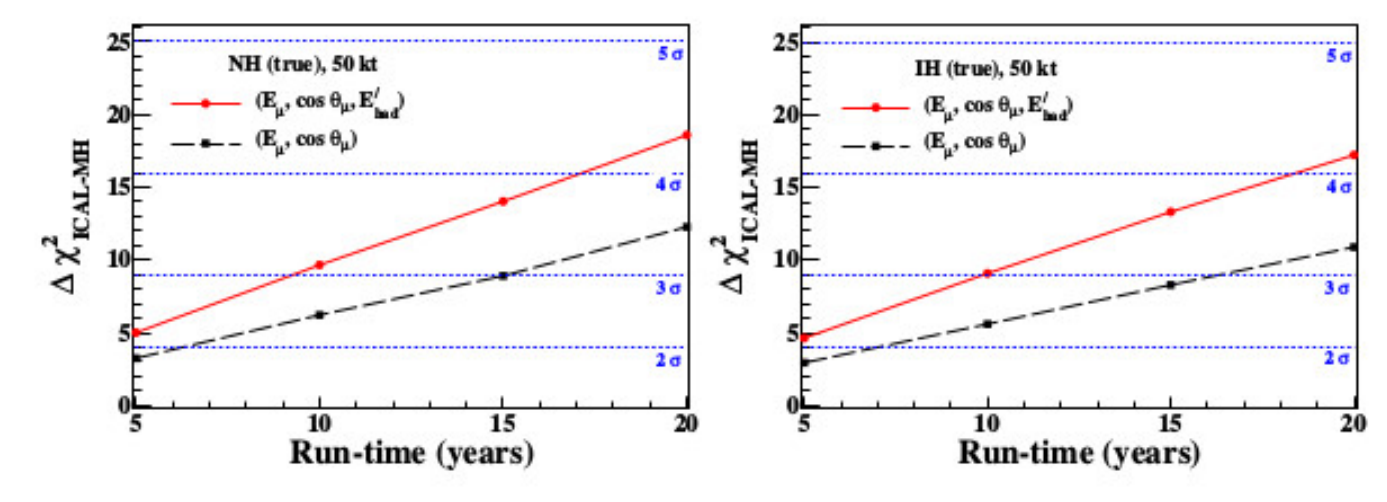
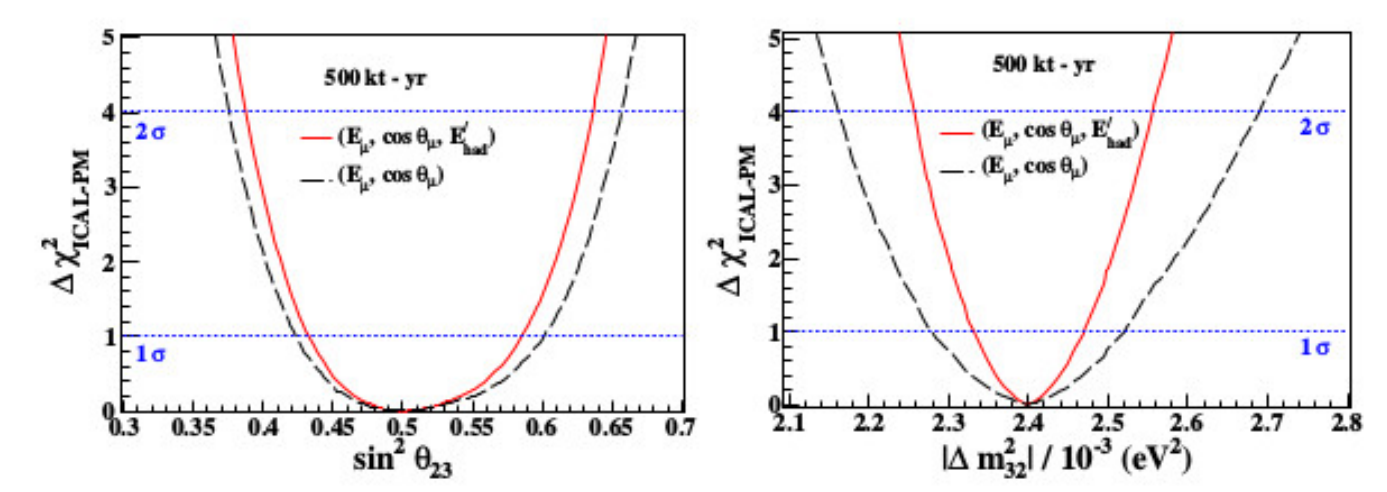
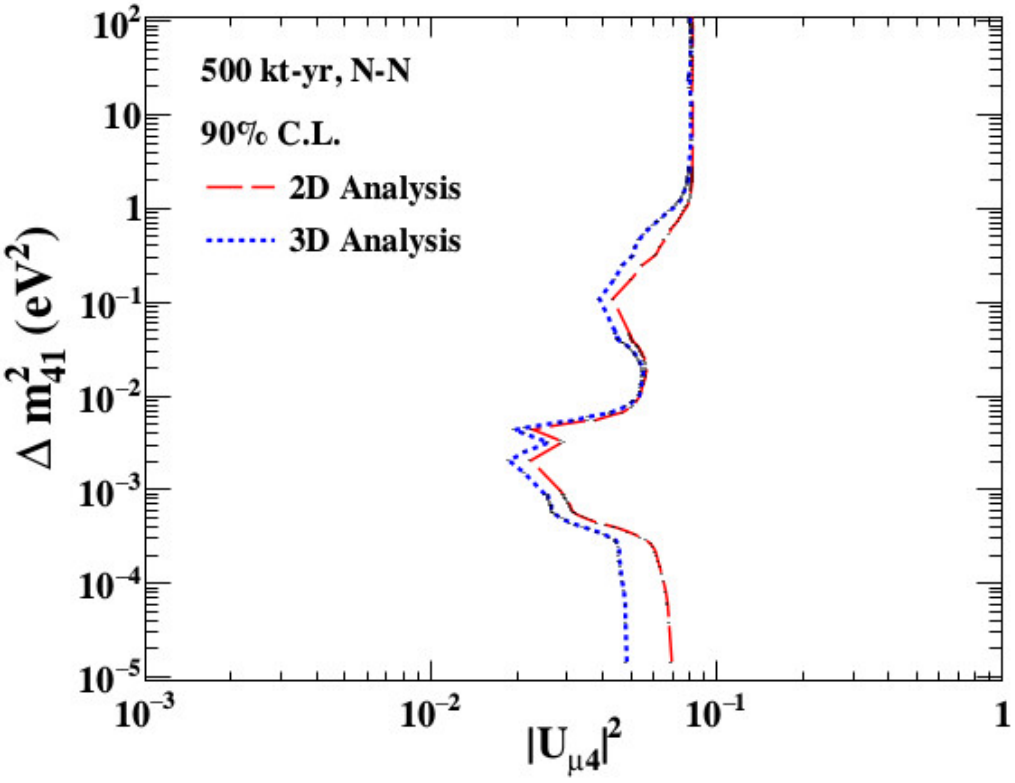


M. M. Devi et al, JHEP 2014

For precision measurements



Sterile neutrino sensitivity

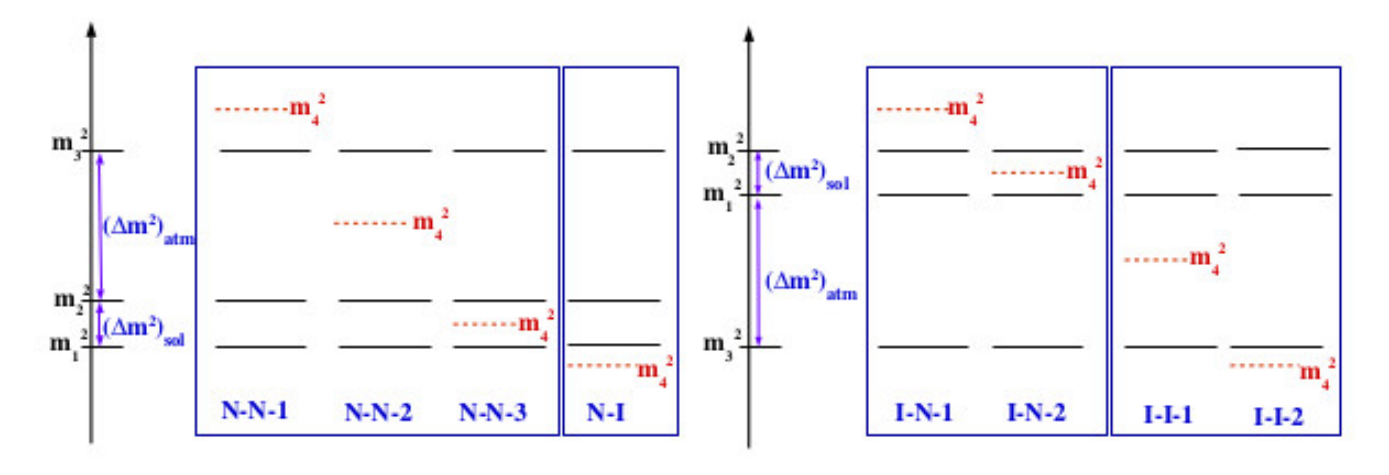


- For higher Δm^2, information is mainly in the number of events, so information about E'_h not so useful
- For lower Δm^2, oscillation information in the energy and angular spectra, so E'_h crucial

S. P. Behera et al, EPJC 2017; T. Thakore et al, 1804.09613

Sterile neutrinos: mass ordering

Sterile mass ordering schemes



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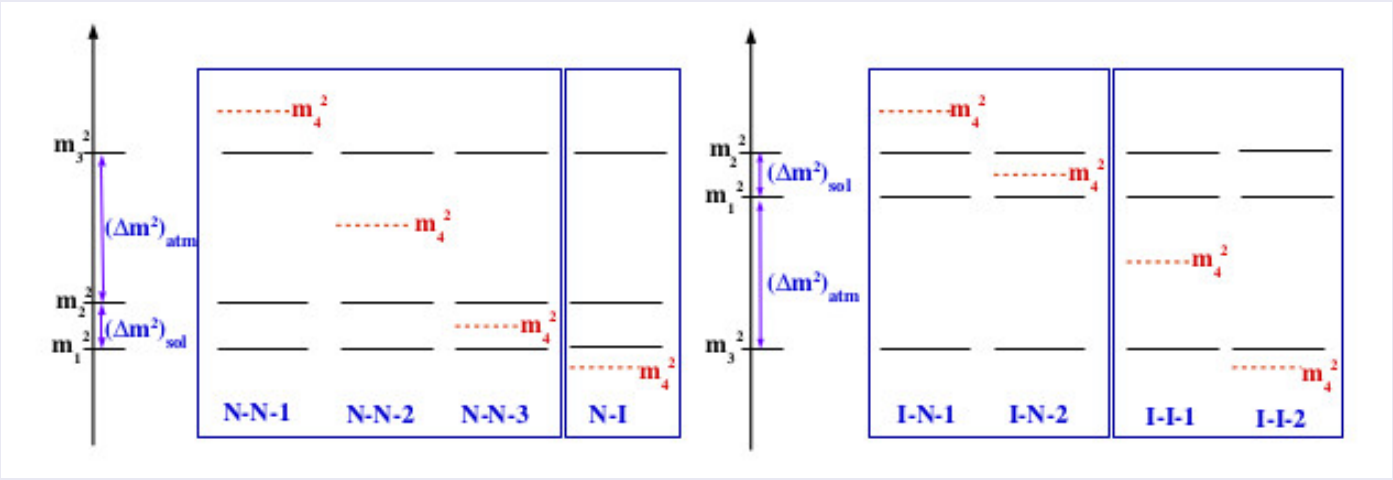

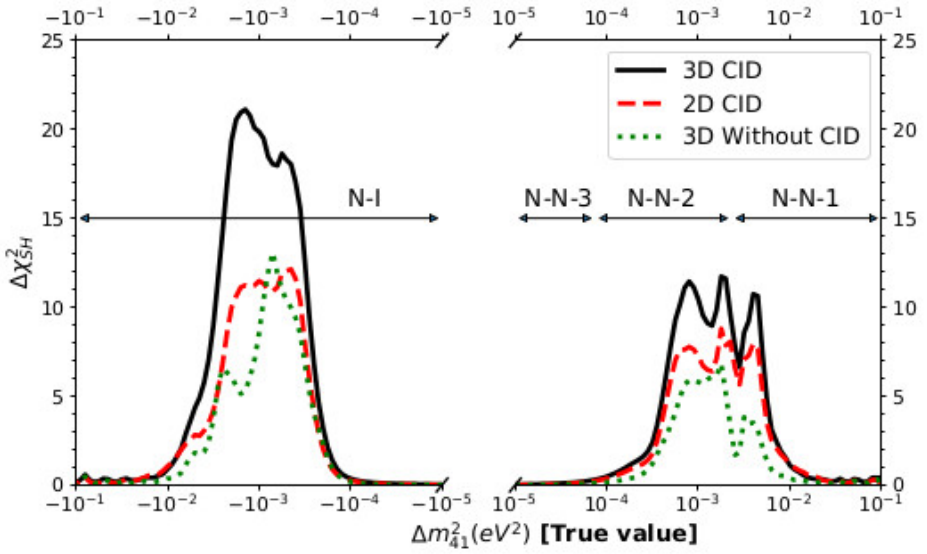

Addition of E'_h information improves sterile MH sensitivity by $\sim$ 40% for $\Delta m^2_{41} \sim (0.5 - 5) \times 10^{-3}$ eV^2

T. Thakore et al, 1804.09613

Concluding remarks

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- Improved algorithms to determine the hadron information, and to use it for extracting quantities of interest
- For future detectors: Detector development / planning should also give due weightage for extraction of hadron information (closely spaced active detector elements ?)