Atmospheric Neutrino Oscillations with the IceCube Neutrino Observatory

DESY Summer Student Session 2021

Mohamed Saad
Vaibhavi Gawas

Outline

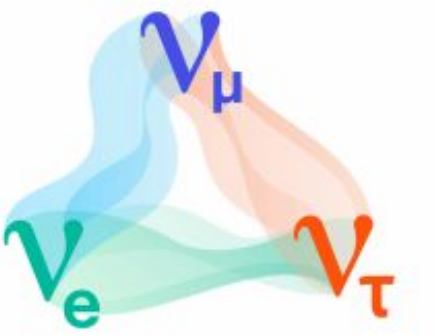
Theory of neutrino oscillations

Neutrino detection at IceCube

Neutrino Oscillations

- Important discovery in 1998: neutrino oscillations, which is the quantum mechanical phenomenon whereby a neutrino created with a specific lepton flavour (electron, muon, or tau) can later interact and be measured to have a different flavour.

- The probability of measuring a particular flavour for a neutrino varies between 3 known states as it propagates through space



$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta_{CP}} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta_{CP}} & c_{13}c_{23} \end{pmatrix}$$

$c_{ij} \equiv \cos\theta_{ij},\ s_{ij} \equiv \sin\theta_{ij}$

Can be re-parameterized by: θ_{12},θ_{13},θ_{23} and δ_{CP}

Neutrinos oscillations in vacuum

Let's assume that at *t = 0* a alpha neutrino is produced:

$$|\nu, t=0\rangle = |\nu_\alpha\rangle = \sum U_{\alpha i} |\nu_i\rangle$$

The time-evolution is given by the solution of the Schrodinger equation with free Hamiltonian *(V=0)*:

$$|\nu, t\rangle = \sum_i U_{\alpha i} e^{-iE_i t} |\nu_i\rangle$$

The probability of oscillation:

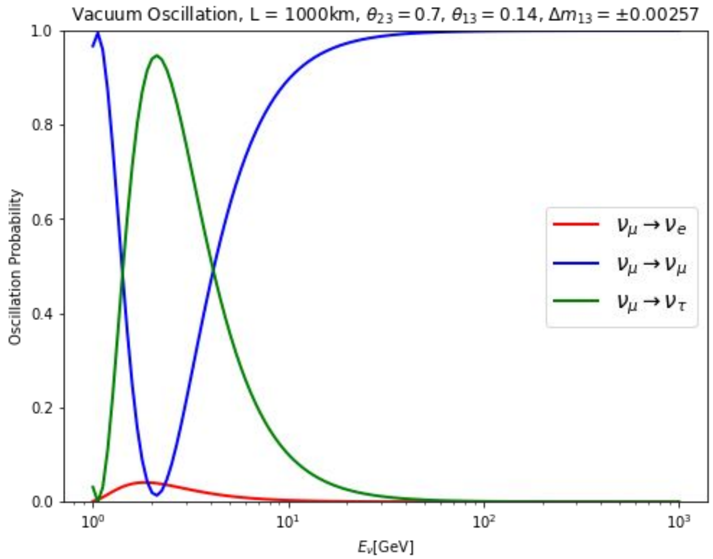
$$P\left(\nu_\alpha \rightarrow \nu_\beta\right) = |\langle \nu_\beta \mid \nu, t\rangle|^2$$

Neutrinos oscillations in vacuum

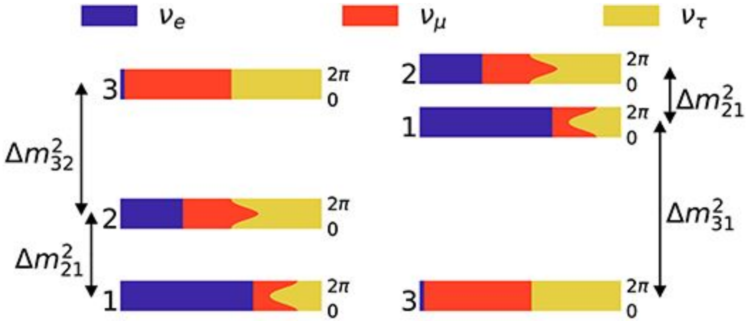
If we considered muon neutrino oscillations:

$$P(\nu_\mu \to \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right)$$

$$\Delta m_{ij}^2 \equiv m_i^2 - m_j^2 \text{ and } L \simeq ct$$



Mass Hierarchy:



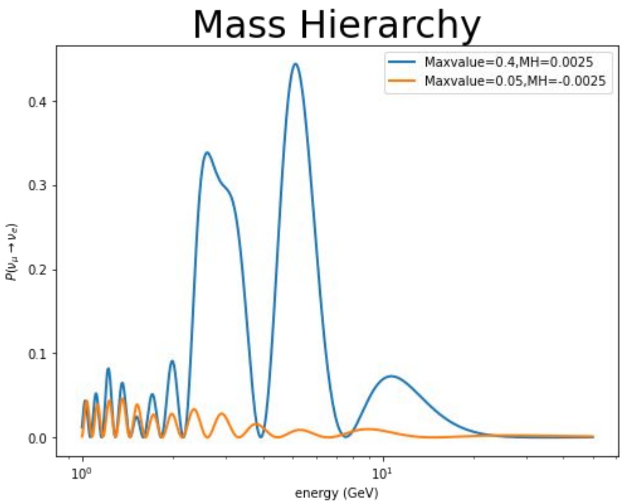
$m_1 < m_2 < m_3$ $m_3 < m_1 < m_2$

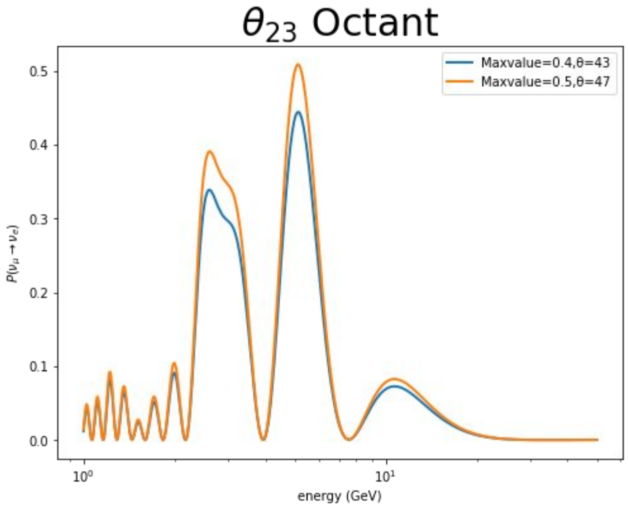
θ23 octant:

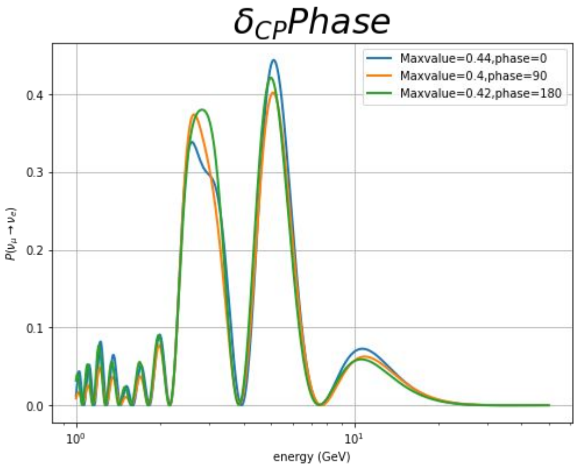
Measured values of θ23 are close to 45, but the data are so far inconclusive as to whether θ23 is less than or greater than 45.

Neutrinos oscillations Through Earth

The oscillation probability gets more complicated due to matter interactions. It will carry more additional terms that depend on the electron composition of the traversed matter.

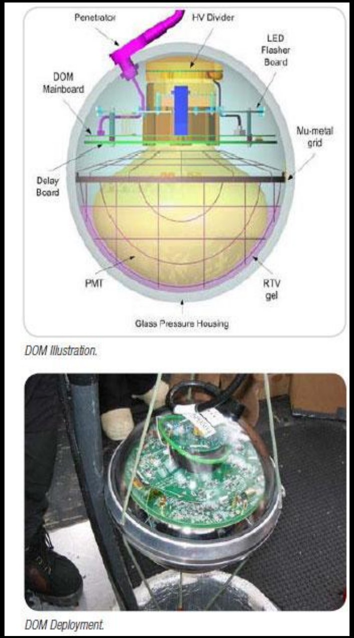




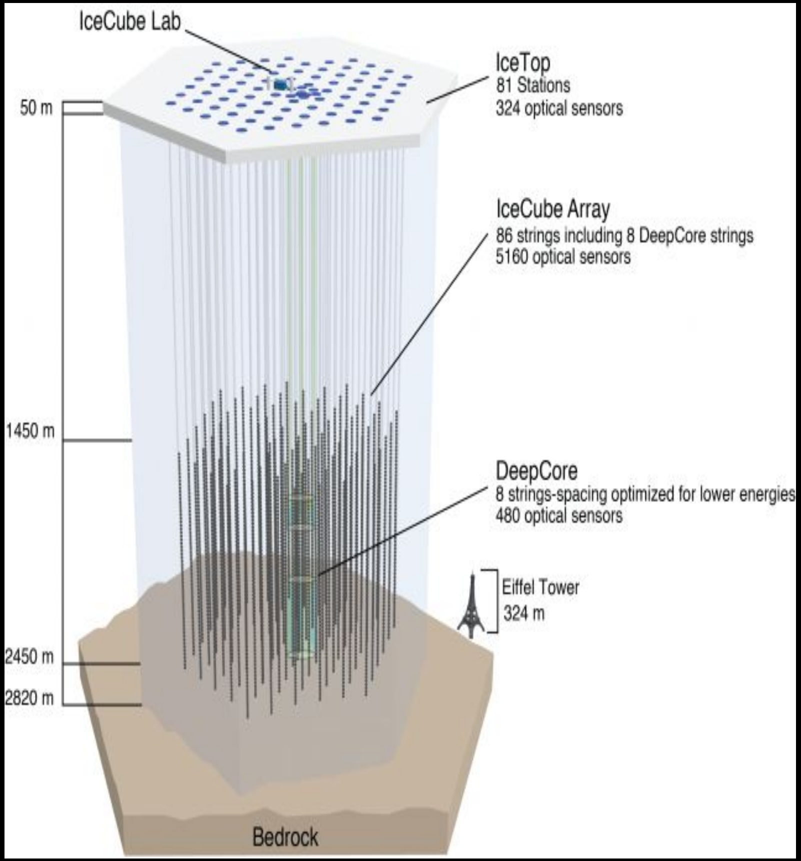


Icecube Detector

ICECUBE ARRAY

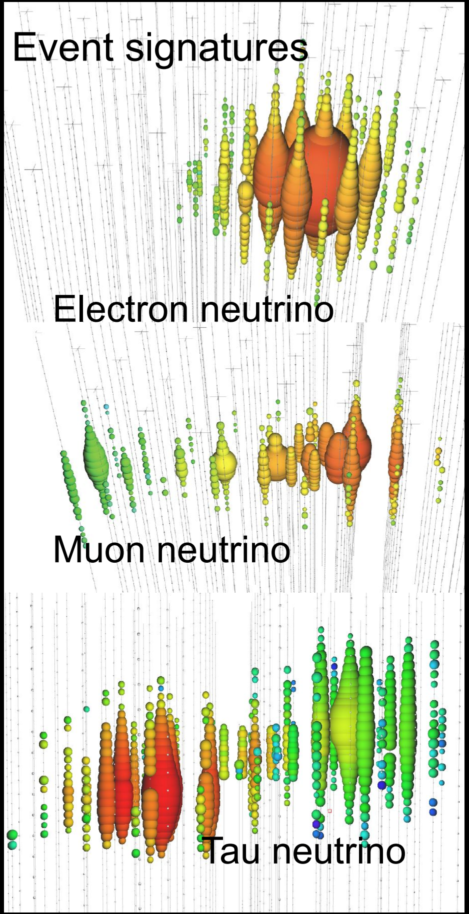


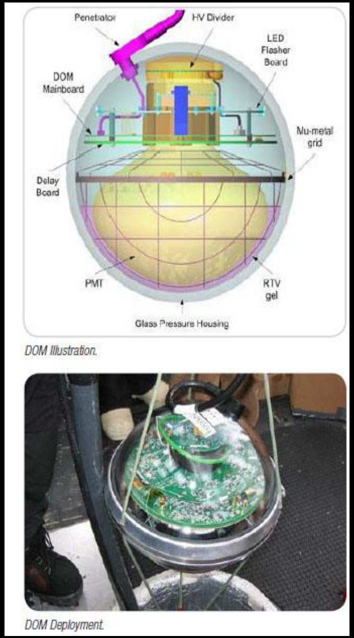
Digital Optical Modules (DOMS) for detecting the Cherenkov photons, are attached to the strings.



- LOWER ENERGY THRESHOLD
- ICECUBE : > 100 GeV
- DEEPCORE: > 5 GeV

Icecube Detector





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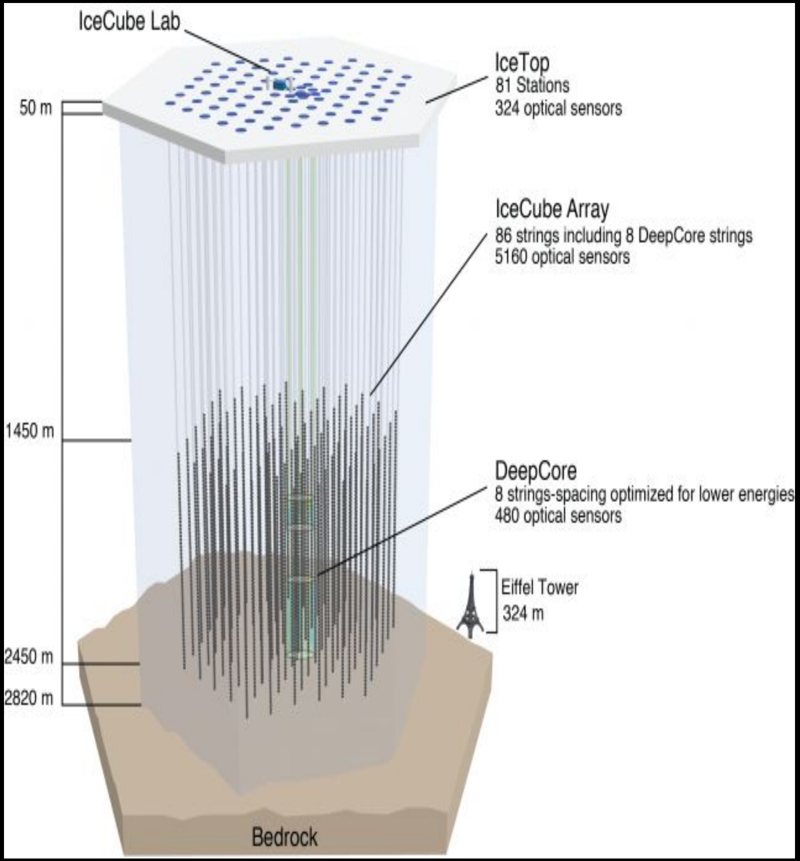

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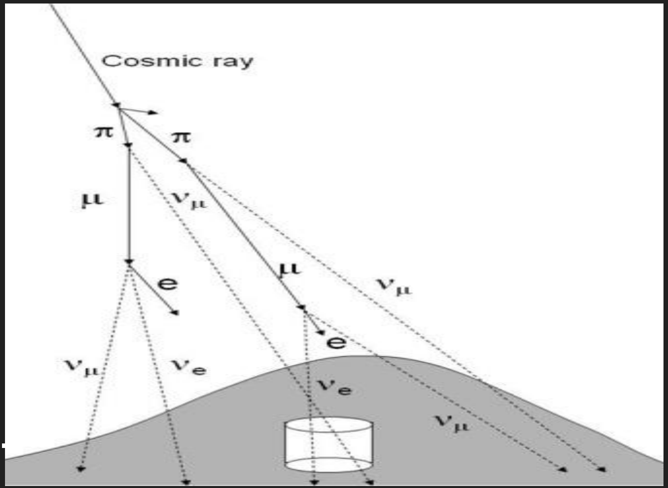
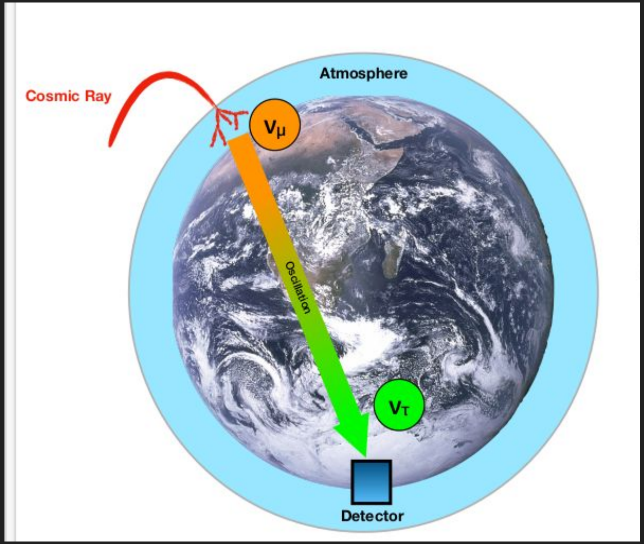
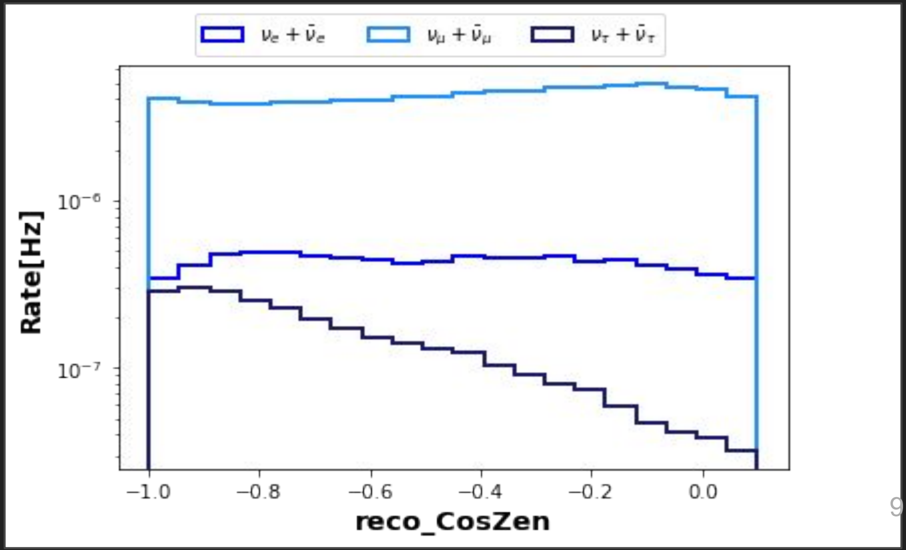
Atmospheric Neutrinos

- The cosmic rays interacting with atmospheric molecules produce cascade of unstable particles.
- These particles (mostly Pions) are short-lived and decay into muons, and muon neutrinos.
- Muons further decay into electron, electron neutrino and muon neutrino.
- The atmospheric flux has negligible amount of tau neutrinos.



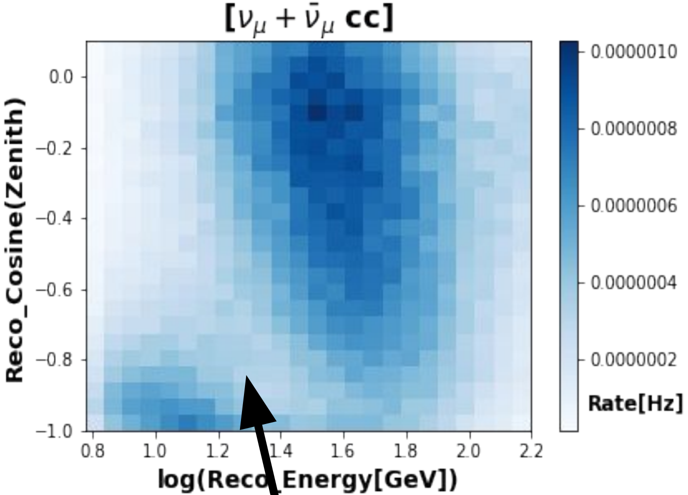




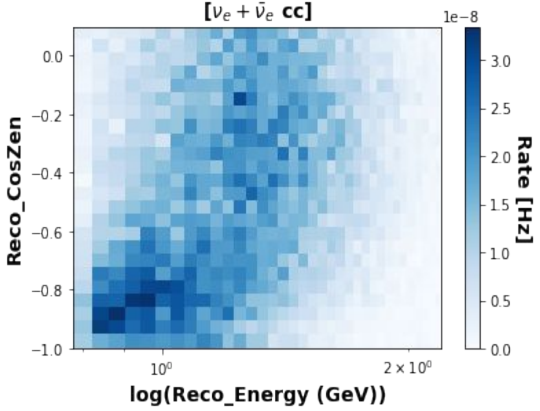
Some Results: MC Simulated Data

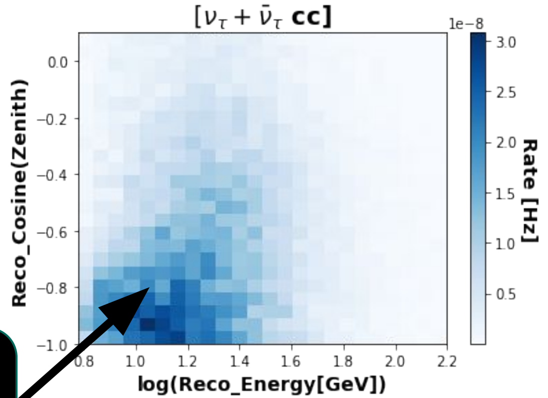
- The reconstructed energy and zenith are computed by applying several predefined selection criteria

- The distributions use oscillated weights calculated through known atmospheric mixing parameters



Muon + Antimuon neutrino disappearance



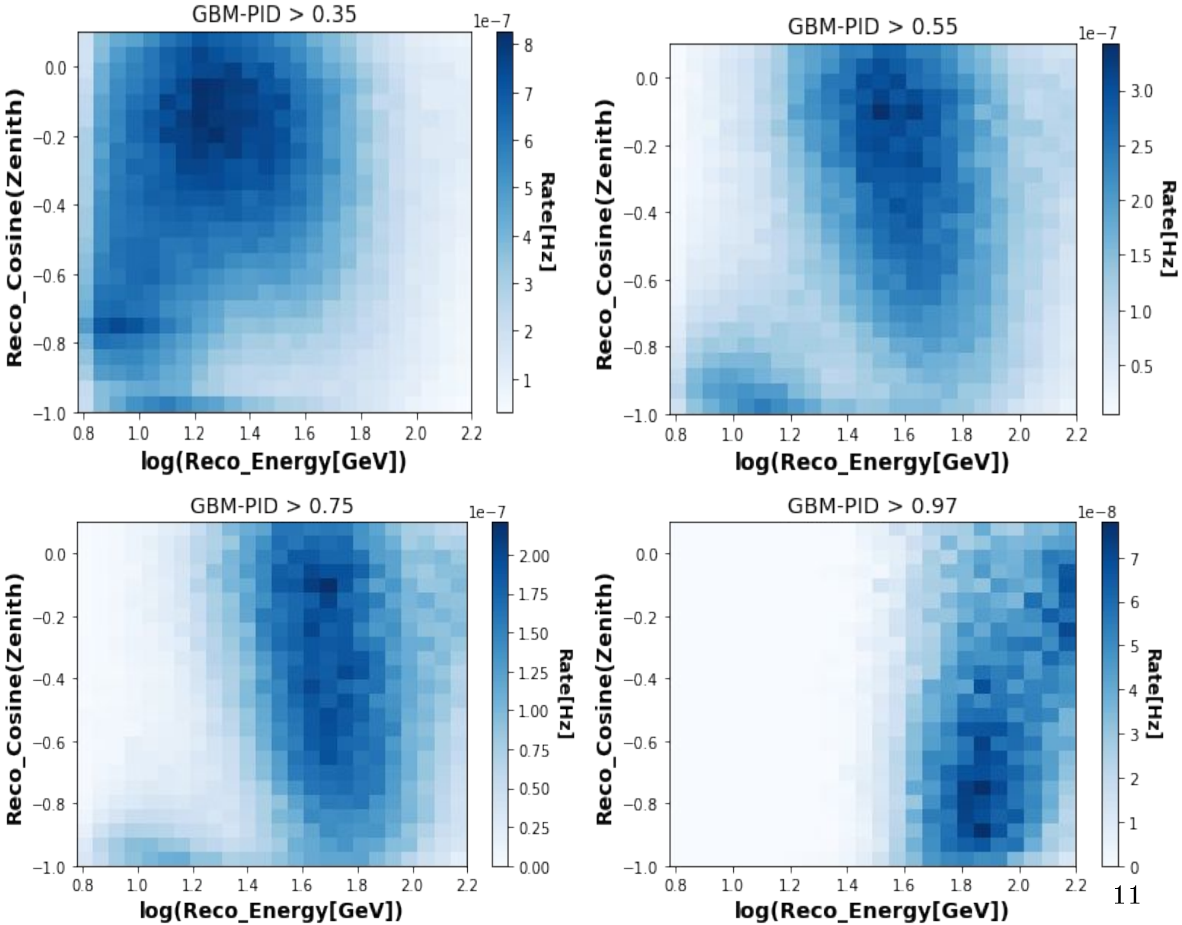


Tau + Antitau neutrino appearance

Some Results: MC Simulated Data

PID Selection:

- PID characterize the track like nature of an event.
- PID value equal to 0 is not at all track like event, while value equal to 1 is most track-like.
- Default criteria of PID > 0.55 is used for all analyses, where the oscillation effects and the available statistics are optimum.



Summary and Outlook

- The effects of mass hierarchy, octant angle and cp phase on the muon to electron neutrino oscillation probability have been investigated
- If the neutrino/antineutrino flux contribution is known the mass hierarchy and octant position might be measured with IceCube
- BUT: Since IceCube is not sensitive to the neutrino/antineutrino composition this is not possible
- The standard atmospheric neutrino oscillation analysis is done by binning the measured events in energy and cosine(zenith)
- The effects of the neutrino oscillation parameters on the 2-dimensional distributions can be seen and the effect of applying a cut on a reconstructed track classification variable shows the expected results
- The simulated event sample that we looked at will be used to compare to data and to extract the newest neutrino oscillation parameter results from 10 years of icecube data

References

- https://neutrinos.fnal.gov/sources/atmospheric-neutrinos/
- 10.1103/PhysRevD.91.072004
- 10.1103/PhysRevD.99.032007
- *J. Phys.: Conf. Ser.* **1468** 012169
- 0.1016/j.ppnp.2017.10.001.
- 0.1103/PhysRevD.97.035023

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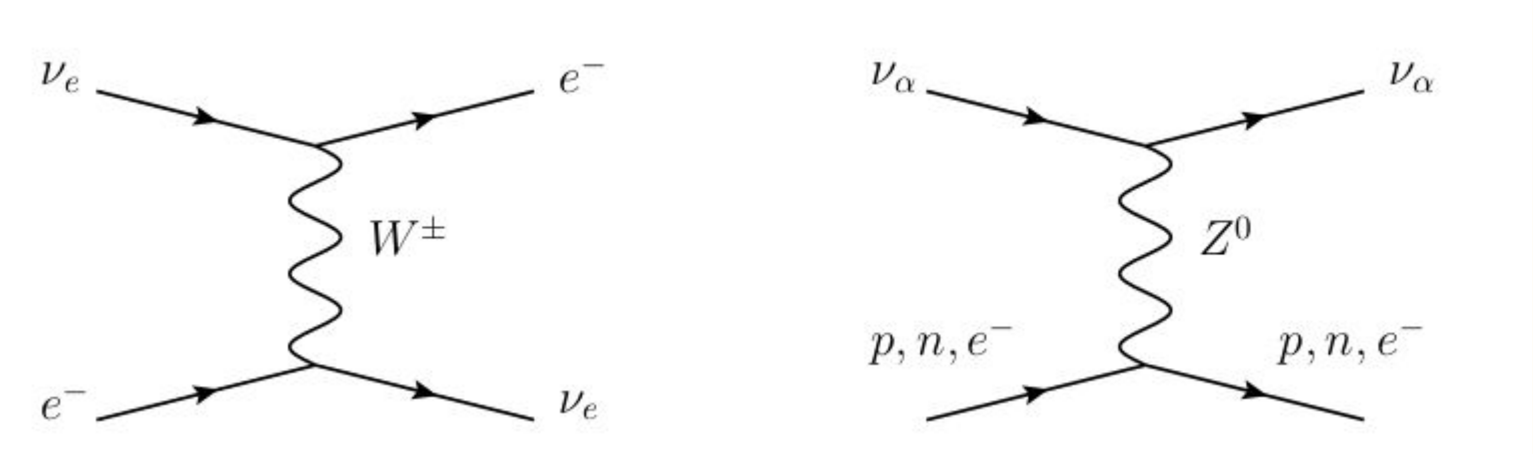
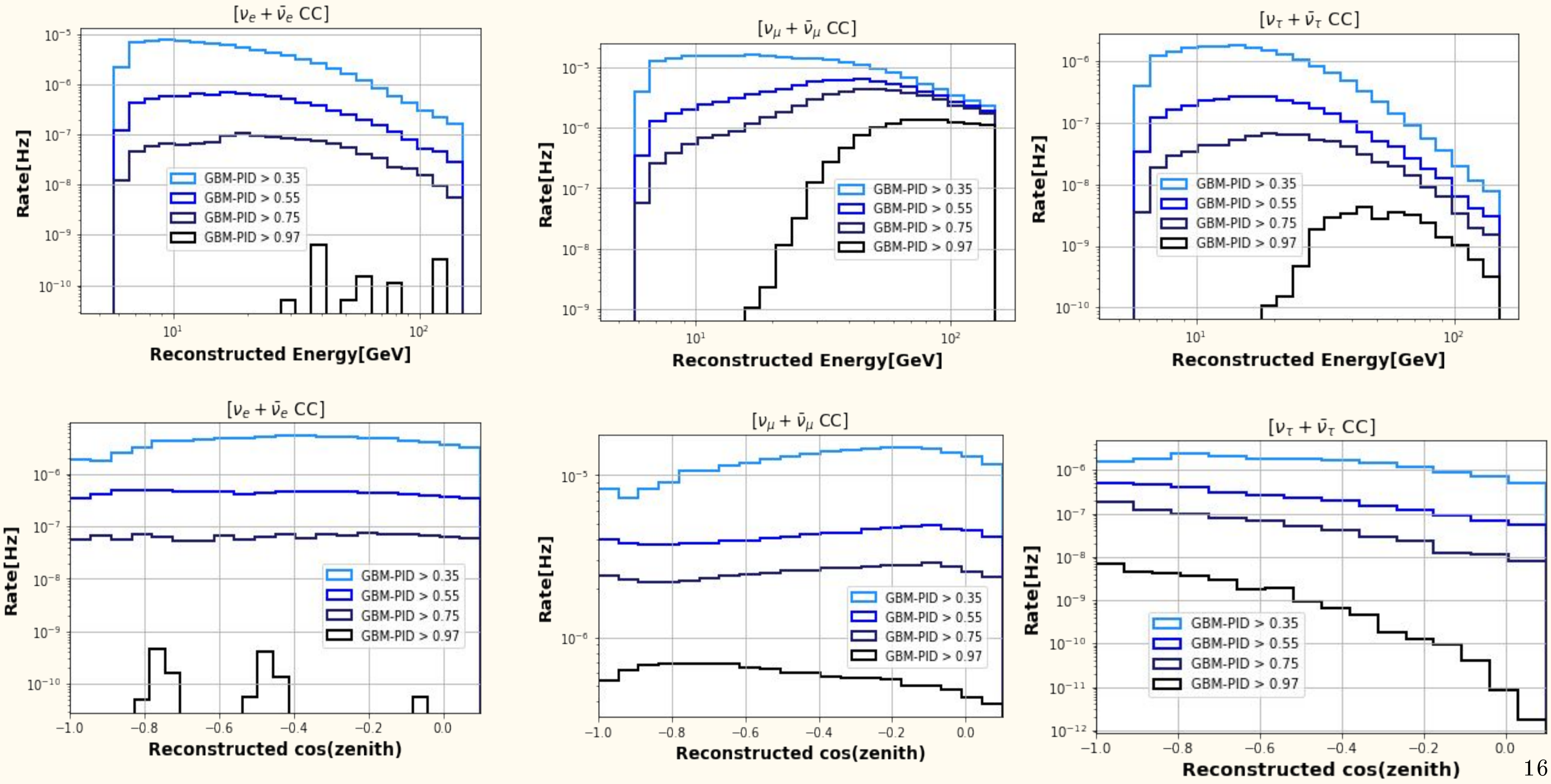
THANK YOU

BACK-UP- Charge and neutral current interaction

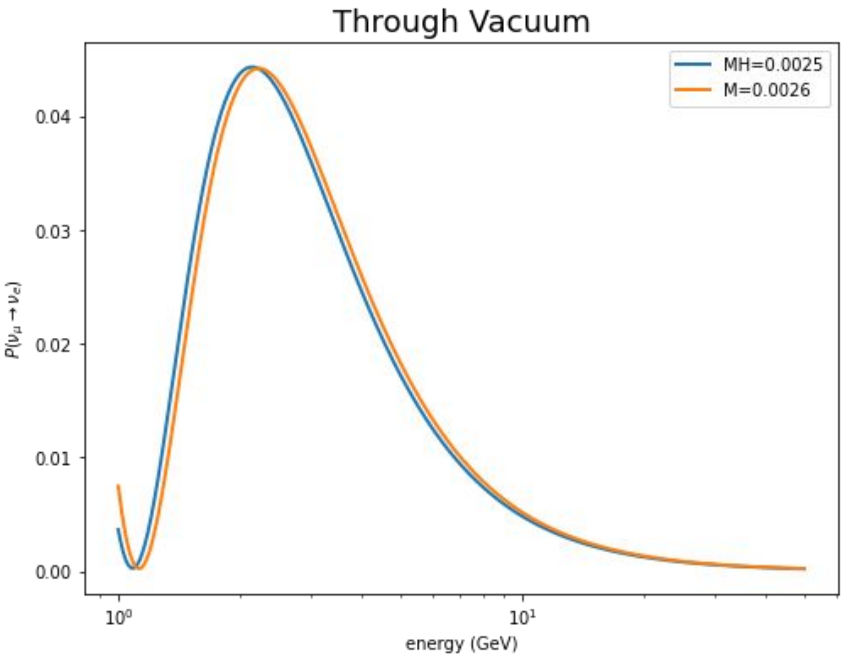


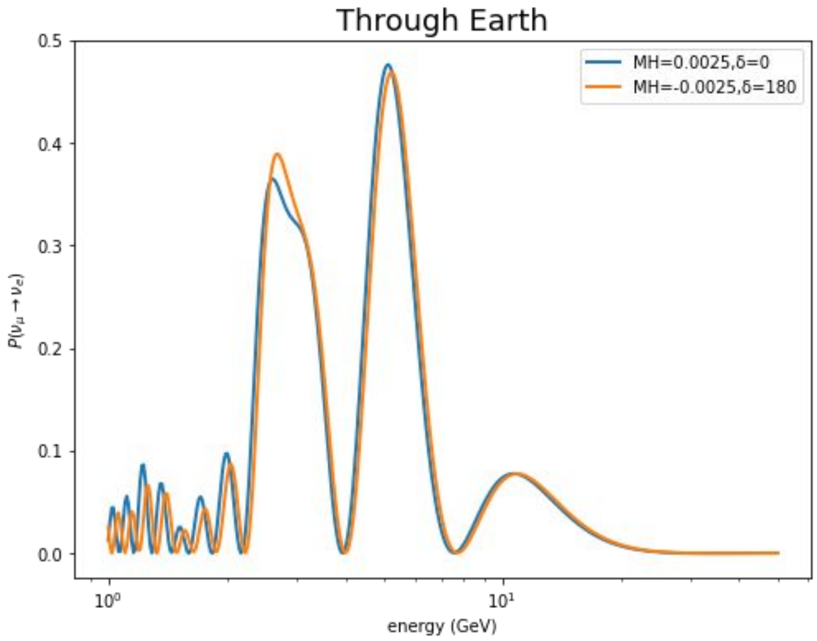
The figure in the left panel shows the neutrino-lepton interaction via exchange if the W boson, also known as charged current interaction. It is possible to identify the neutrino flavor by detecting its corresponding lepton in this type of interaction. The right panel shows the neutral current interaction of a neutrino. In this the neutrino scatter away from the matter particles such as protons, neutrons or leptons via exchange of the Z boson.

BACK-UP- GBM-PID distributions



Are Neutrinos and Antineutrinos the same





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