The Generalized Neutrino Self-Veto for Neutrino Telescopes

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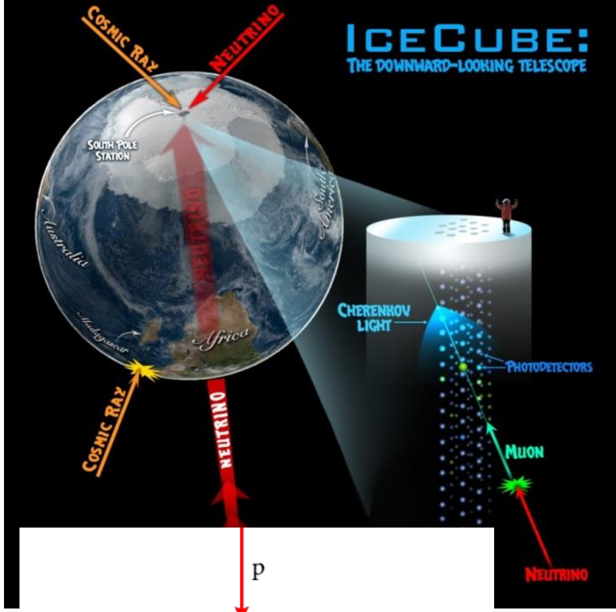
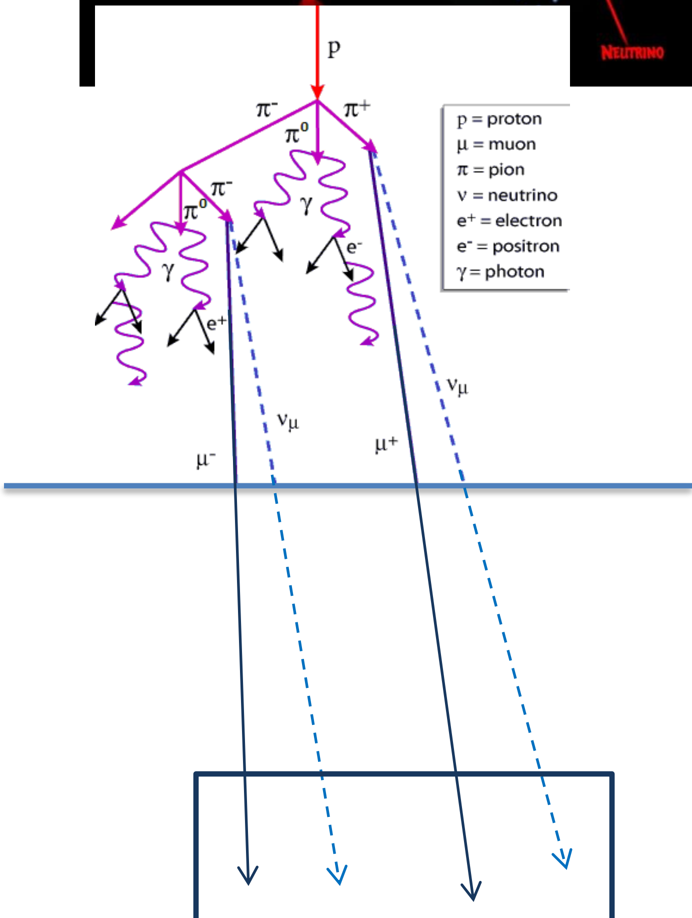
Background

- Traditional astrophysical neutrino detection rely on using the Earth as a shield for cosmic ray muons that allows for the detection of a surplus of neutrinos above expected atmospheric rates
- However, the same muons that are shielded in up-going searches can provide an air shower and atmospheric neutrino veto
  - For most cases a probability of an accompanying muon
    - Vetoing atmospheric neutrinos in a high energy neutrino telescope by Schönert et al.

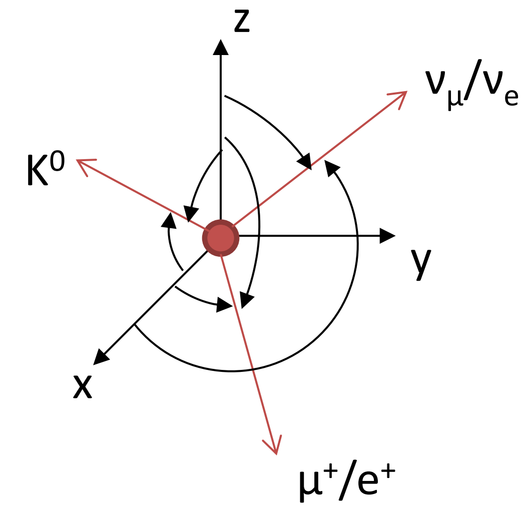




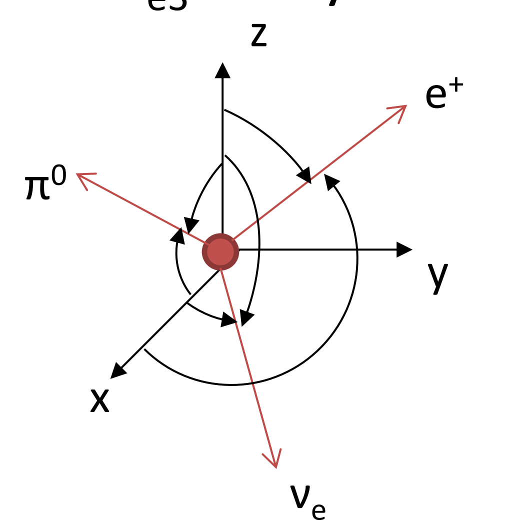
Motivation

- Is there also a veto for ν's other then ν_μ from conventional decays?
  - For ν_μ from prompt decay there is a sibling μ
    - The decay is 3-bodied, so relation between muon and neutrino energy is loosely constrained
  - For ν_e from conventional and prompt decays there is no sibling μ
- Air showers contain many muons, so you don't need to have the particles be siblings
  - Is this sufficient to give veto power?

Decay of a D^+



K^+_{e3} decay



A Generalized Self-Veto

- Use complimentary methods to obtain results
  - Determine analytic description
    - Needs to be verified by data or simulation
  - Determine from simulation
    - Dependent on hadronic model used
    - Natural rates of high energy neutrinos from air showers requires a large amount of statistics
      - Modify simulation to give more you what you want faster
      - Get good statistics at lower energies and extrapolate with a model

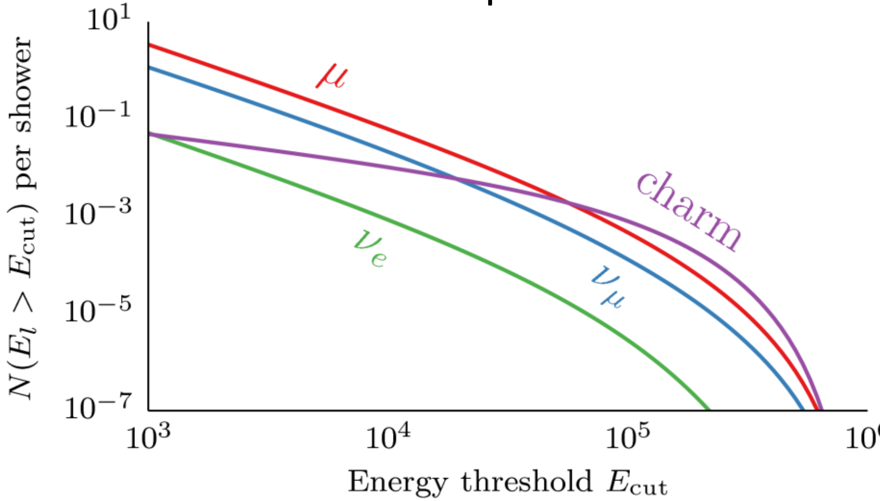
Analytic Model

From Monte Carlo calculations to veto Passing Rates

Lepton Yields

- Correlated muon and neutrino in a shower content requires considering the entire shower structure
- Use the Elbert formula to obtain yields of neutrinos and muons

1 PeV vertical proton showers



Conv.
ν's μ's

$$N_l(>, E_l, A, E, \theta) = K_l \frac{A}{E_l cos^* \theta} x^{-p_1}(1 - x^{p_3})^{p_2}$$

$$x = \frac{AE_l}{E}$$

Prompt.
ν's

$$N_l(>, E_l, A, E, \theta) = K_l A\, x^{-p_1}(1 - x^{p_3})^{p_2}$$

$cos^*\theta$ is $cos\,\theta$ evaluated at the average altitude of the first interaction

Yields to Passing Rate

- The response for a given lepton, l, is the multiplication of the flux of a primary times the differential form of the Elbert formula

$$R_l(A, E, E_l, \theta) = \varphi_N(A, E) \times \frac{dN_l(> E_l, A, E, \theta)}{dE_l}$$

- Integrating this over this and summing over the primary types gives the flux of neutrinos

$$\varphi_l(E_l, \theta) = \sum_A \int dE\ R_l(A, E, E_l, \theta)$$

- The passing rate is then the given by the flux of unaccompanied neutrinos divided by the total flux of neutrinos

$$P_\nu(E_\nu, \theta) = \frac{\sum_A \int dE\ R_\nu P(N_\mu = 0)}{\sum_A \int dE\ R_\nu}$$

Muon "Propagation"

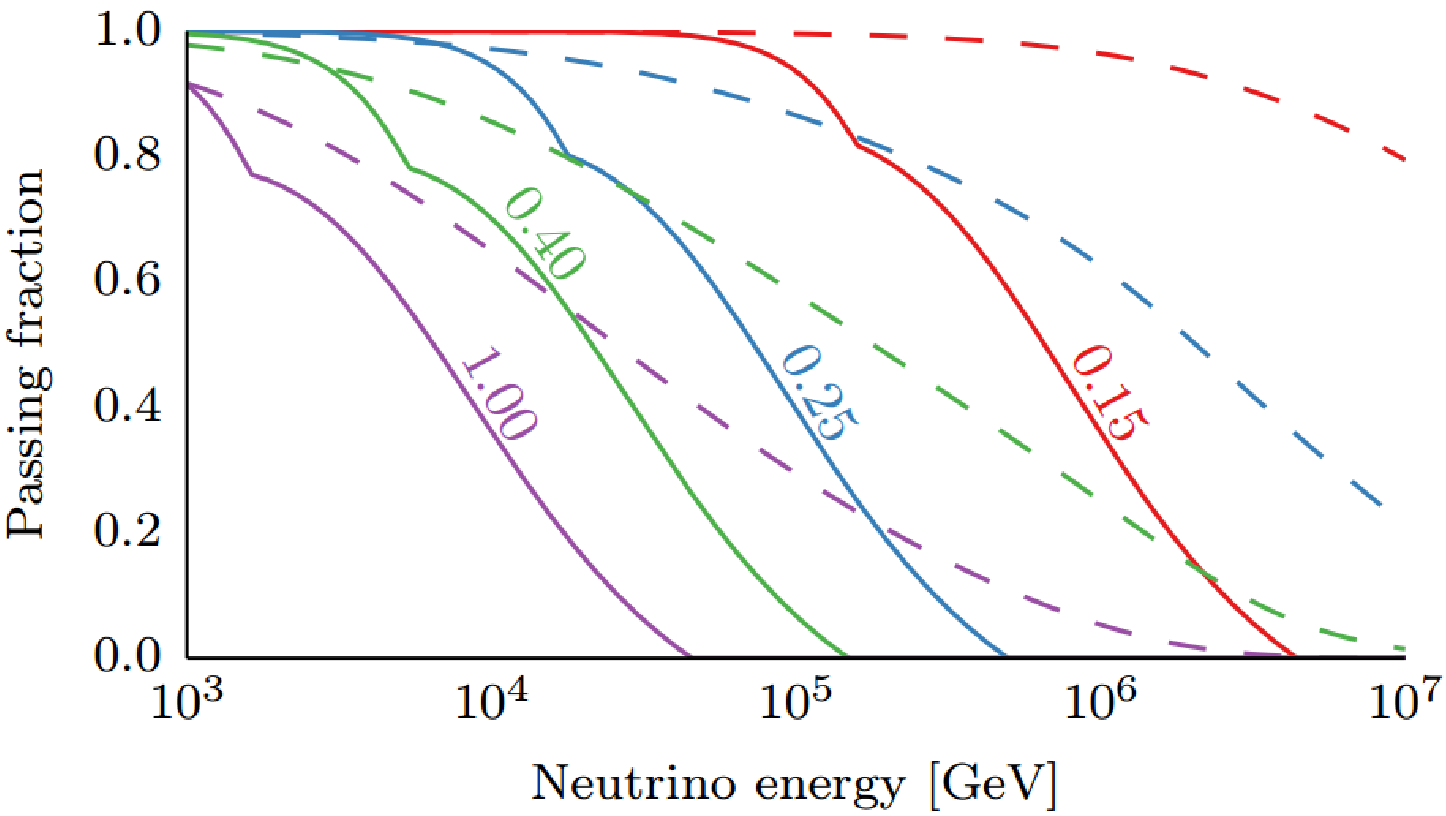
- Interested in the probability of muon content from shower dropping below the detector threshold before reaching the detector
  - Approximate this as a Poisson probability

$$P\left(N_\mu = 0 \middle| E, E_{\mu,min}, \theta\right) = e^{-N_\mu(A,E,\bar{E}_{\mu,min}(\theta),\theta)}$$

  - $\bar{E}_{\mu,min}(\theta)$ is the required surface energy required to reach the detector with the detector threshold 50% of the time

$$P_\nu(E_\nu, \theta) = \frac{\sum_A \int dE\ R_\nu P(N_\mu = 0)}{\sum_A \int dE\ R_\nu}$$

Analytic Results



- Colored numbers indicate the cosine of the zenith angle
- Solid is the result from the paper by Schönert et al. for paired muon and muon neutrinos
- Dashed is the result found by the analytic method for uncorrelated muons

Simulation

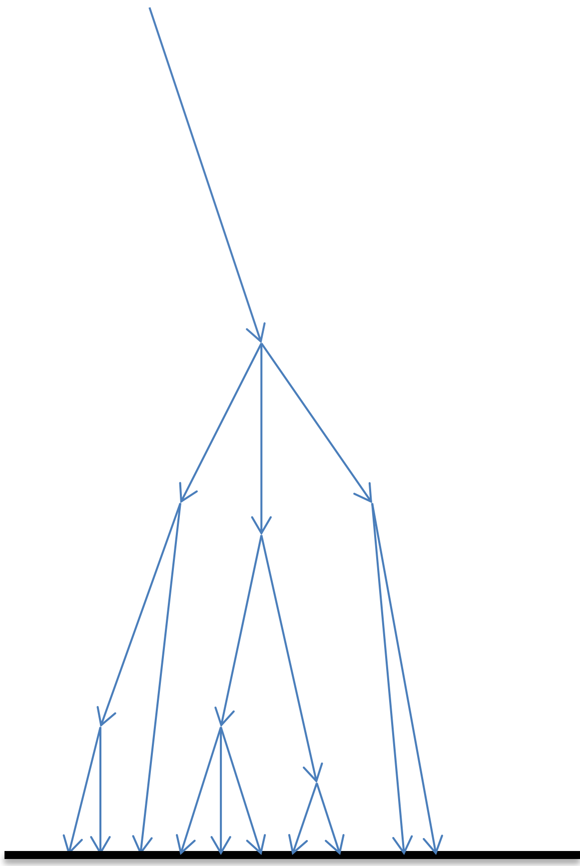
Underground Neutrino Detector CORSIKA

Idealistic Modifications to CORSIKA

- There is a minimum energy of neutrinos in which you are interested
- If you can stop simulating a shower when it is no longer able to produce a neutrino of that energy you can get to showers that are interesting faster
- The higher the neutrino energy with respect to the primary energy you are interested in the sooner you will be able to stop showers

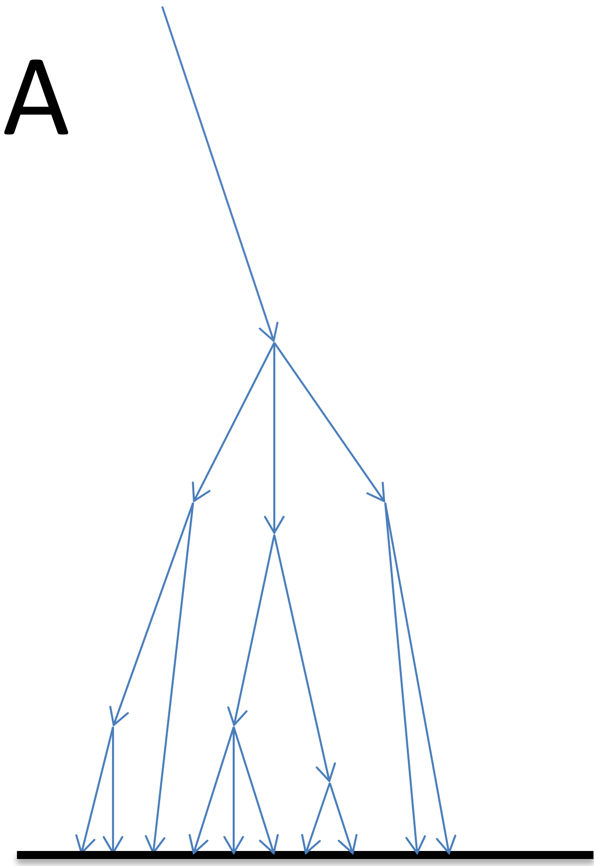
Reality of CORSIKA

- Developed in 1985 to properly handle cosmic ray primaries of all energies
  - The total number of particles is too large to hold in RAM
  - Two options to keep enough information to propagate the shower fully
    - Breadth first, keep all the particles at roughly the same interaction number
    - Depth first, propagate the most recently created particle first
  - The second is what is done because it requires less memory to operate
- Options exist to remove particles of a certain type once they are below a threshold energy, but not stop the entire shower if certain particles are below a certain energy



Modified CORSIKA

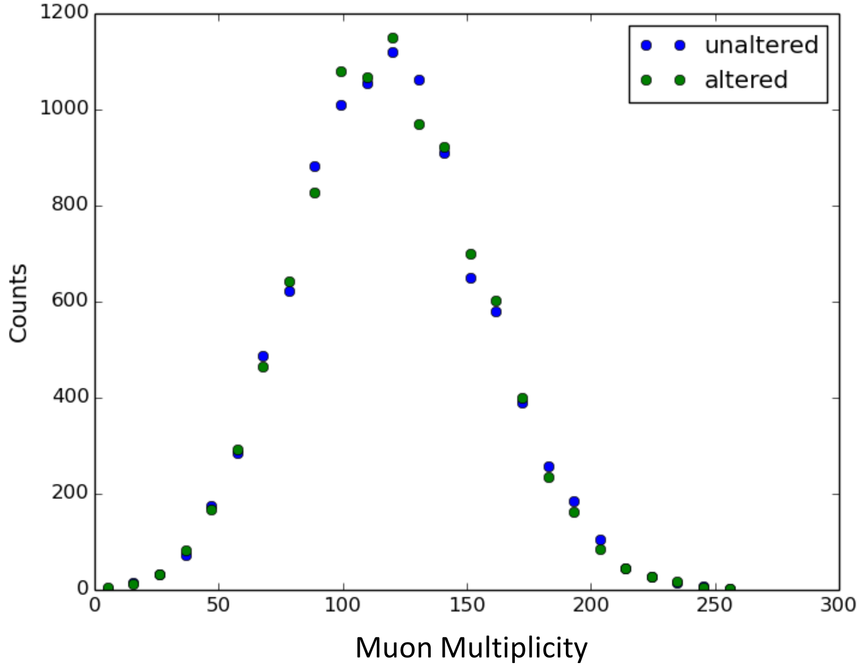
- Modern computing systems have enough memory to handle breadth first propagation
  - Changed particle stack from queue to a FIFO ring buffer
- Keep track of things as they go into and out of the stack and note how many interesting things are currently alive
  - If the number of interesting things drops to zero, nothing interesting can be created the shower can be safely killed
  - We are also only interested in showers that have a neutrino above a minimum energy so stop showers that don't meet this criterion

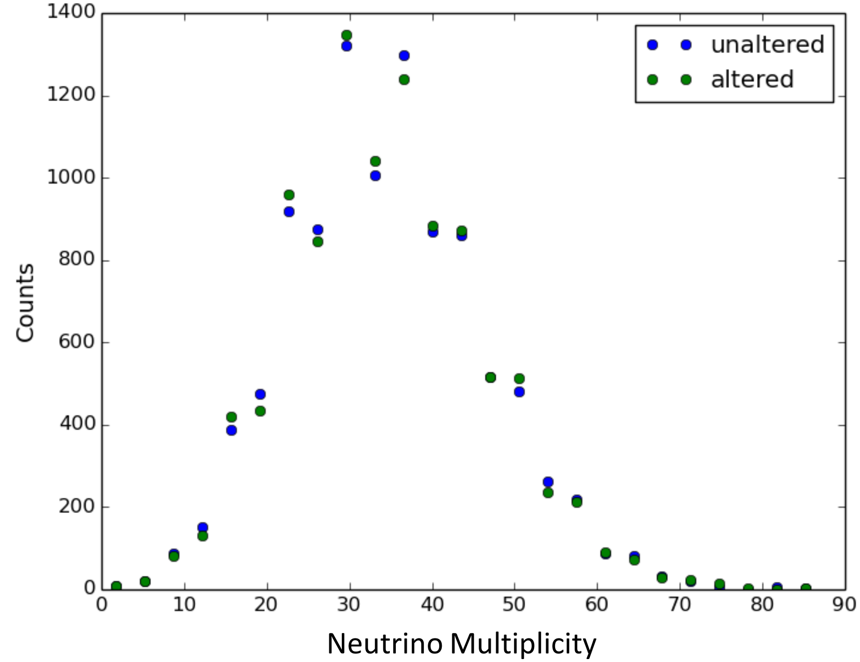


Sanity Checks

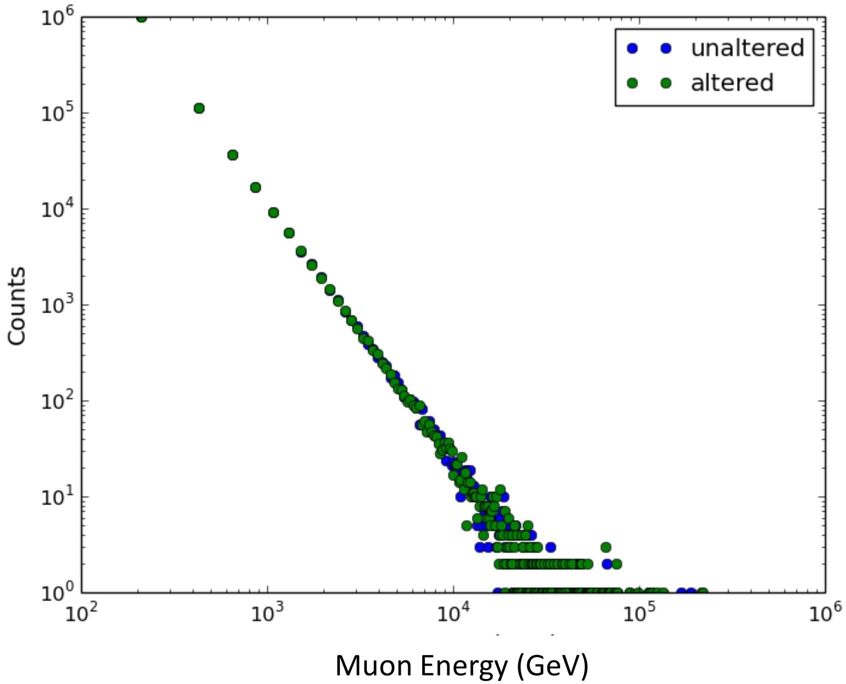
- Showers should posses exactly the same energy and multiplicity distributions for muons and neutrinos **if** the shower killing cut is below muon and hadron removal energy
- With the shower killing energy above the hadron and muon killing energy, the neutrino energy distribution should match normal CORSIKA above the shower killing energy.

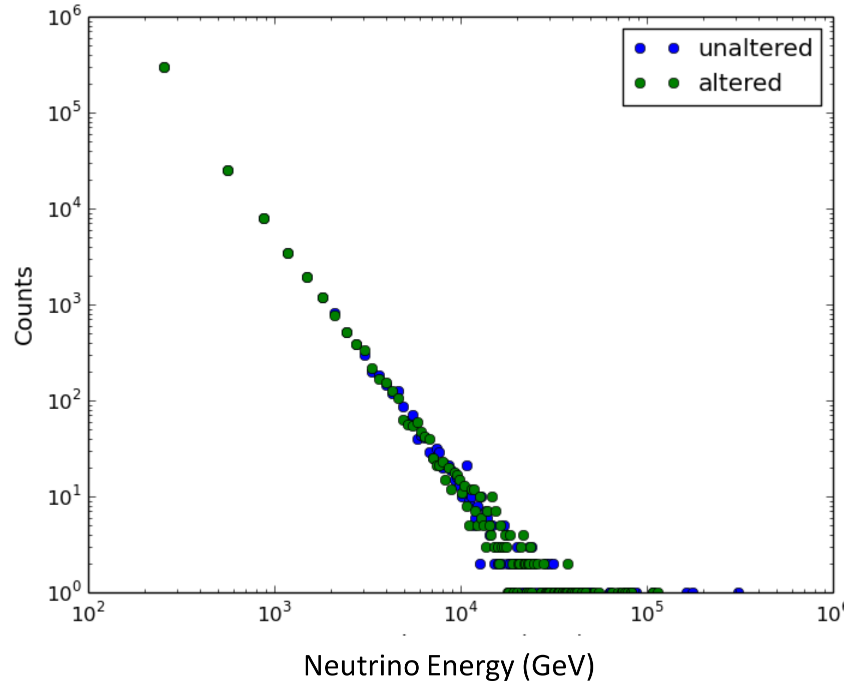
Shower killing energy at muon and hadron killing energy





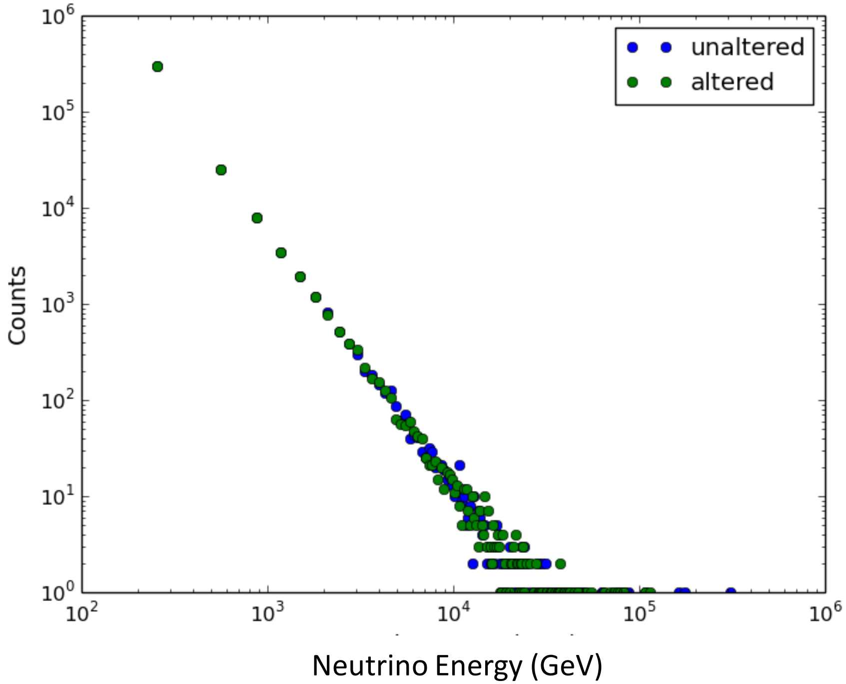
Shower killing energy at muon and hadron killing energy



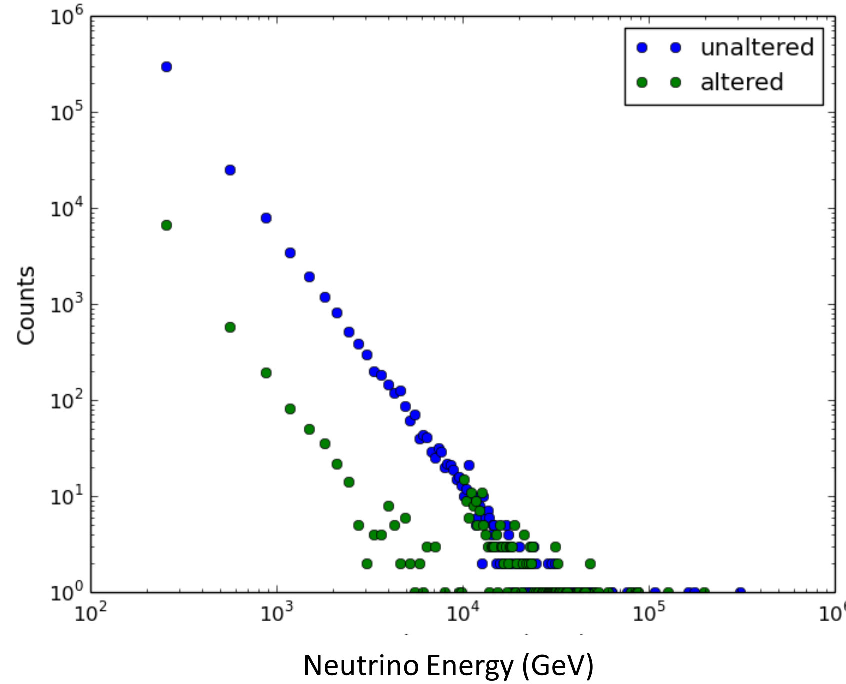


Neutrino energy with shower killing threshold at 10 TeV compared to shower killing energy at muon/hadron killing energy

Shower Kill Energy=Muon/Hadron Kill Energy



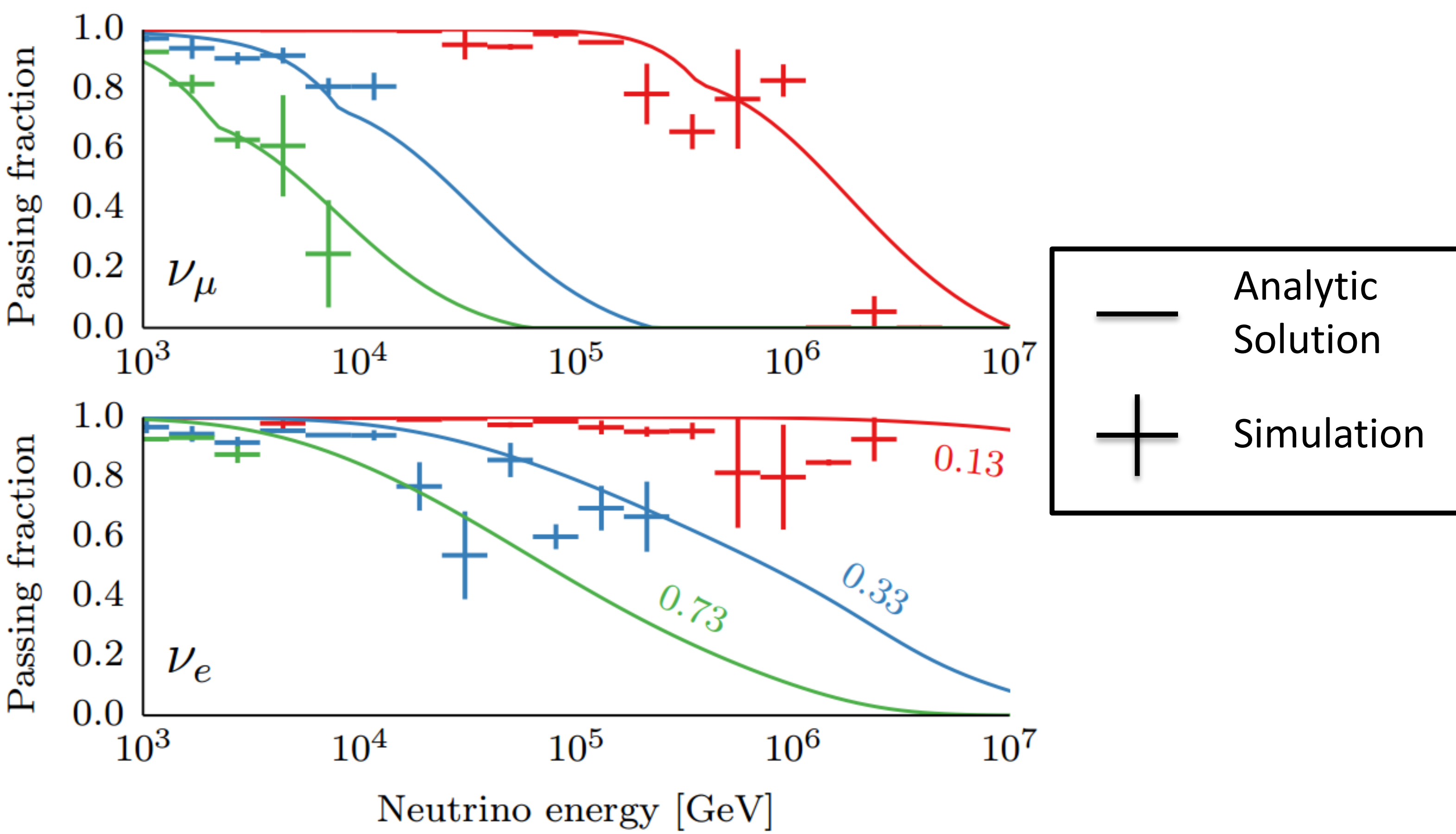
Shower Kill Energy>Muon/Hadron Kill Energy



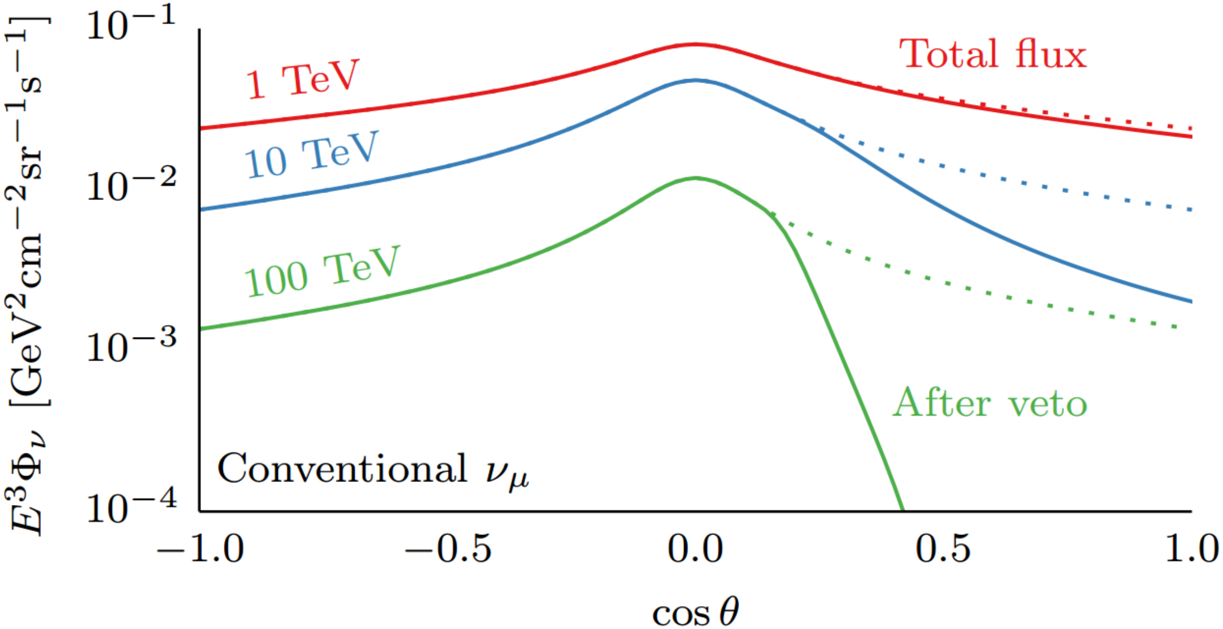
Muon Propagation

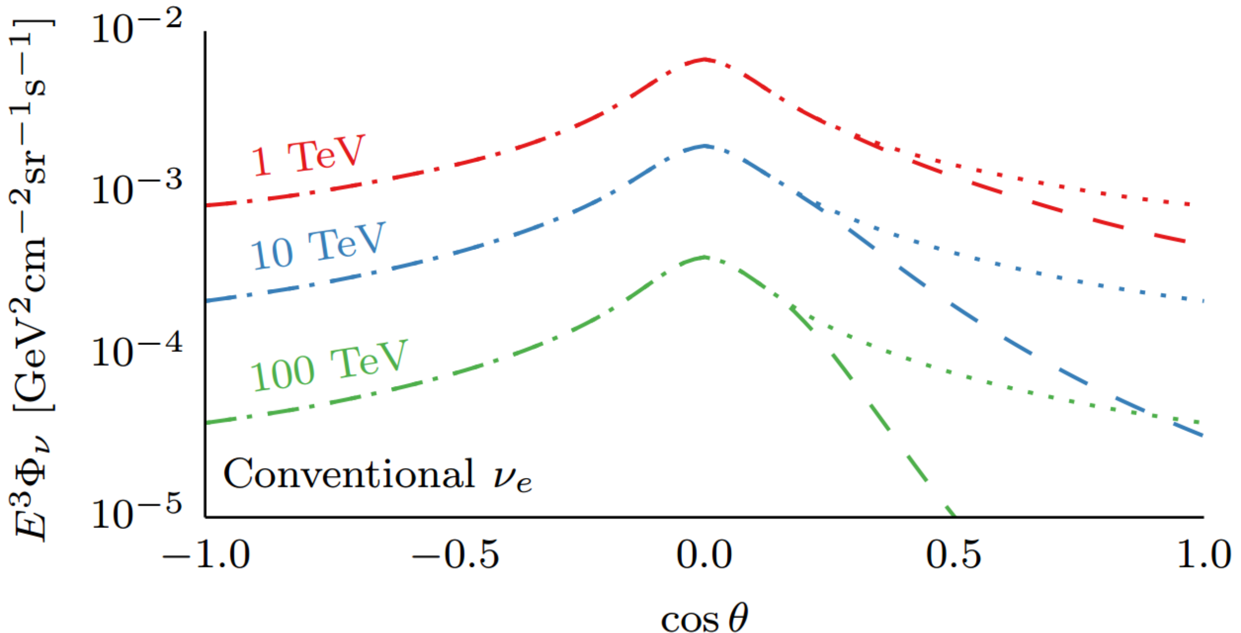
- Muons are propagated from the surface of the ice to the middle of the detector
- Muon bundles with a cumulative energy of 1 TeV are counted as triggering the detector
- No detector simulation is run

Combining the Results

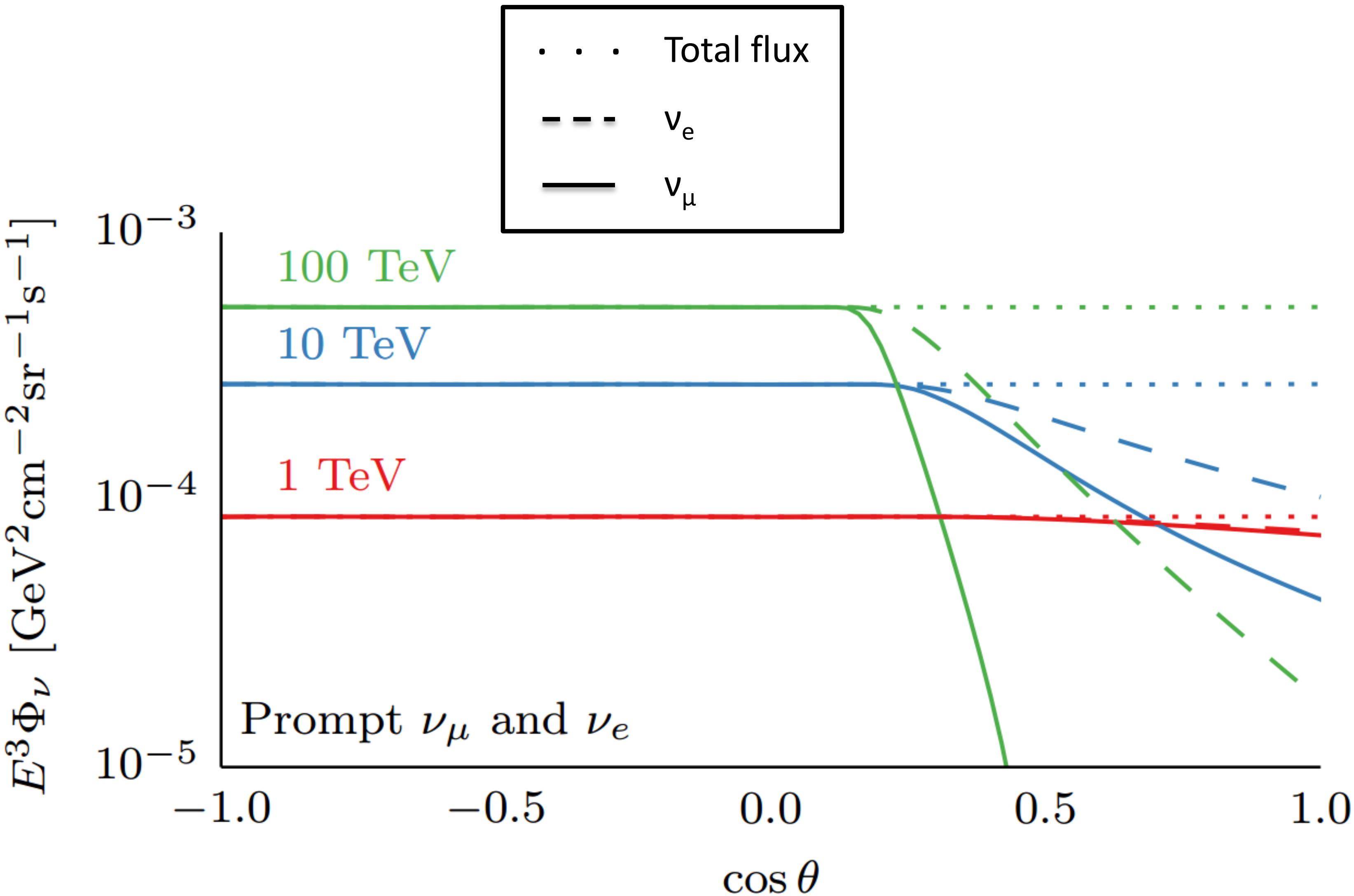


Affect on conventional neutrinos





Affect on prompt neutrinos



Consequences

- Addition of veto for ν_e and prompt neutrinos boosts significance of results like the high energy starting events search
- Gives cascade events intrinsic probability of astrophysical origin
- Provides additional endorsement for future IceCube extensions

Slide credit to Ramesh Koirala

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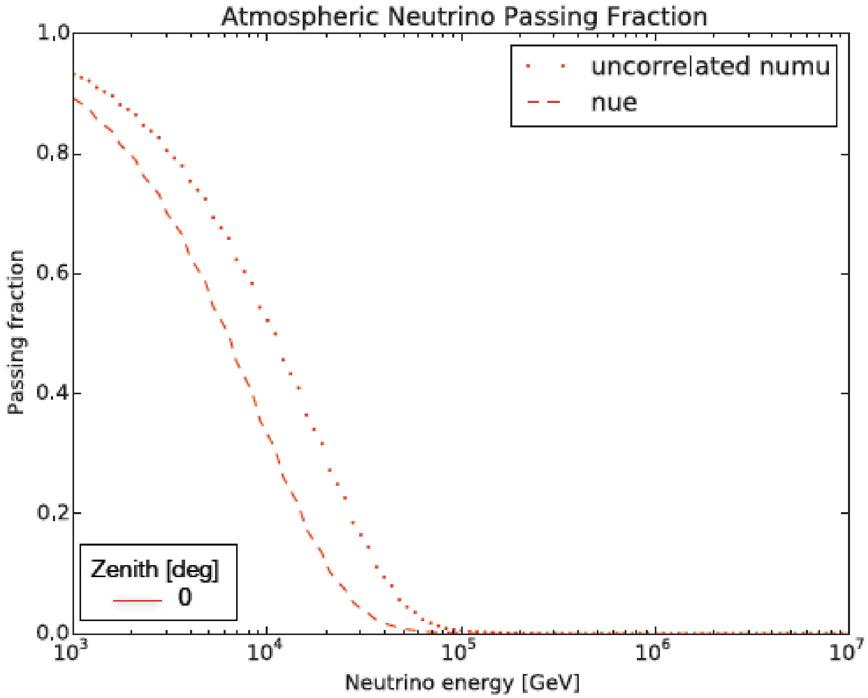
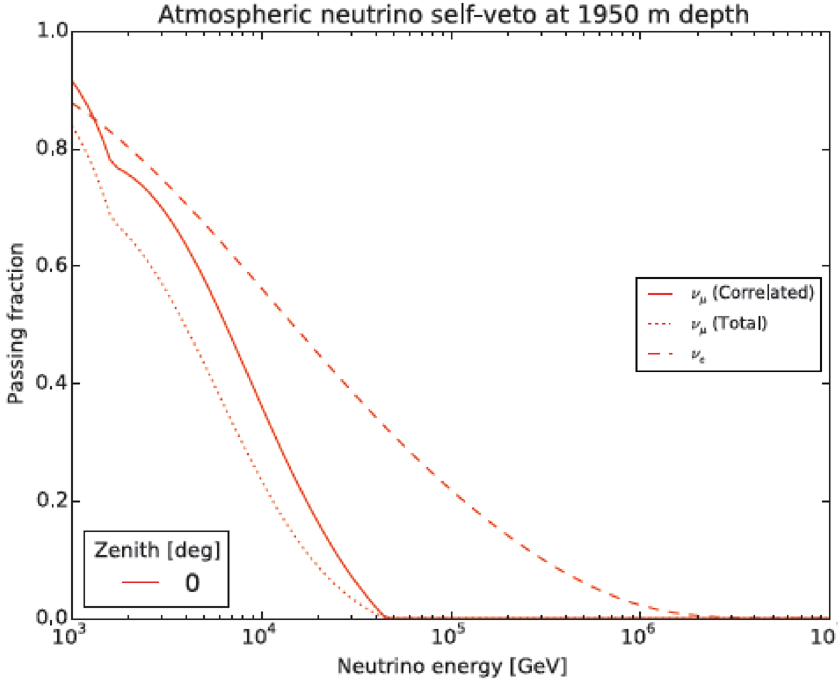
Surface Veto and Self Veto



Surface Veto



Self Veto