Charmed-Meson-Induced Double Cascades in Neutrino Telescopes

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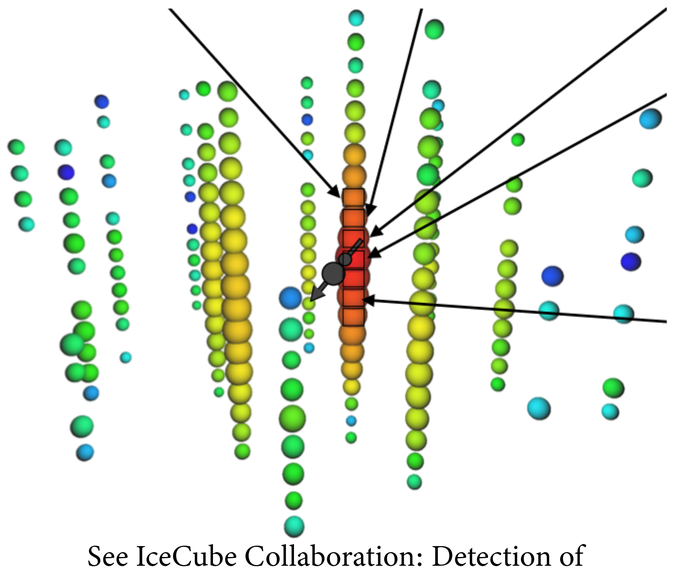
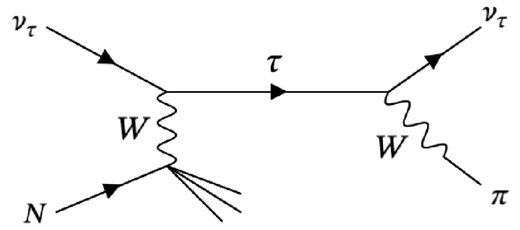
Double Cascades and Why They Are Important

Water/Ice-Cherenkov Neutrino telescopes see high energy astrophysical tau neutrinos, who exhibit double-cascade-like signatures in the detector region. Identifying and studying these tau neutrinos may provide us with impormation regarding astrophysical neutrino sources and their flavor compositions.



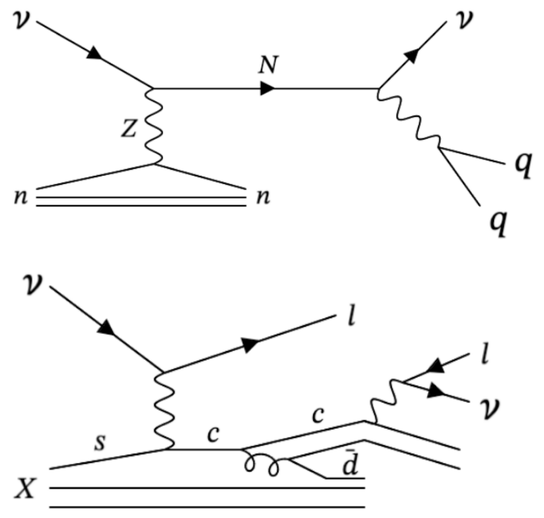
See IceCube Collaboration: Detection of astrophysical tau neutrino candidates in IceCube



Taus, Heavy Neural Leptons, and ... Charmed Mesons!

Tau Neutrinos are not the only particles that leave a double-cascade signature. In fact, any scattering followed by a decay counts! This includes not only HNL's as an interesting signal, but also D-Mesons as a very similar background signature since

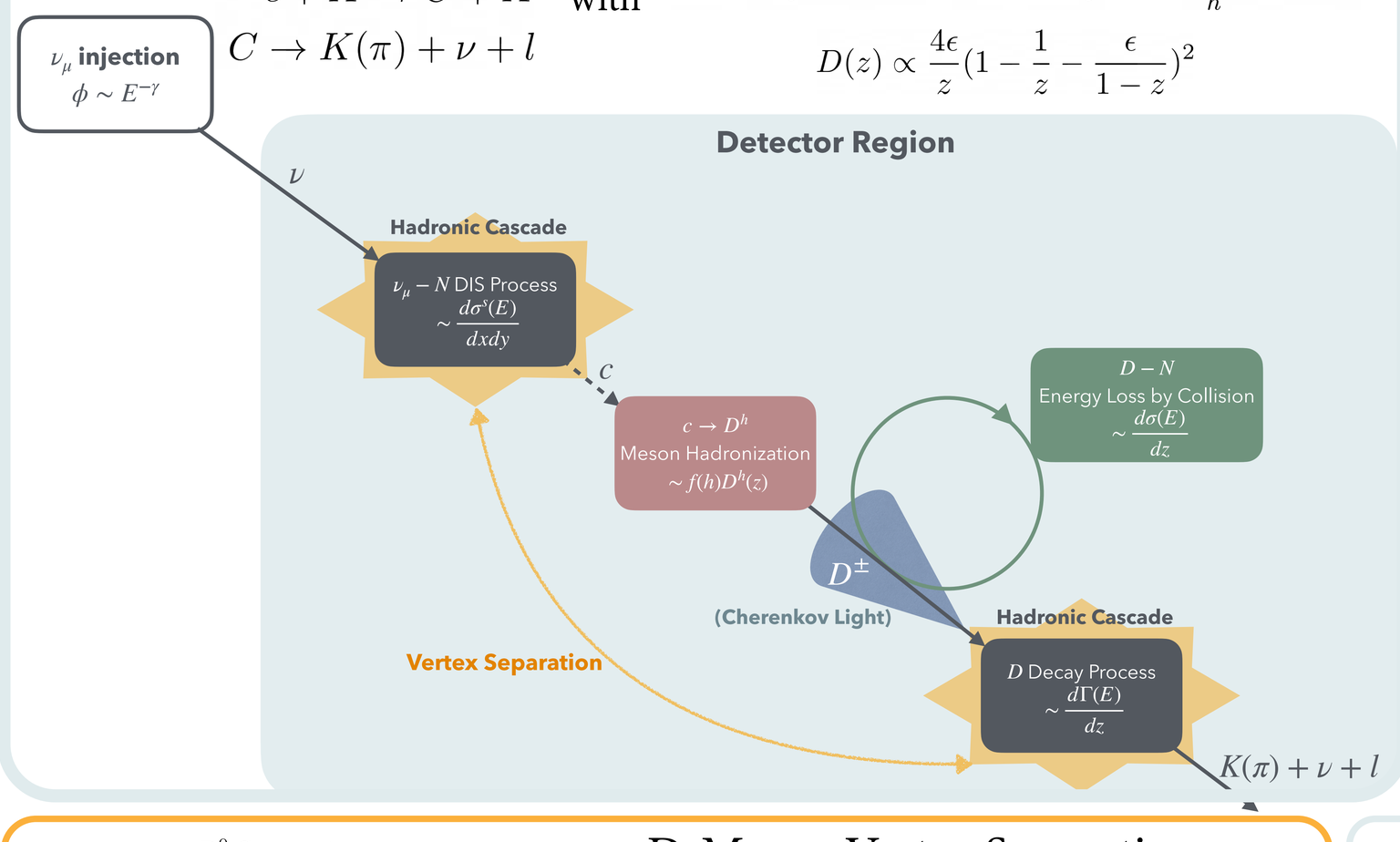
$$(410 \pm 7) \times 10^{-15}\text{s} = \tau_{D^0} \approx \tau_{\tau\ \text{lepton}} = (290.3 \pm 0.5) \times 10^{-15}\text{s}$$



Simulation

We base our simulation upon the open-source simulation package SIREN. A set of new interactions are implemented to sample from the procedures:

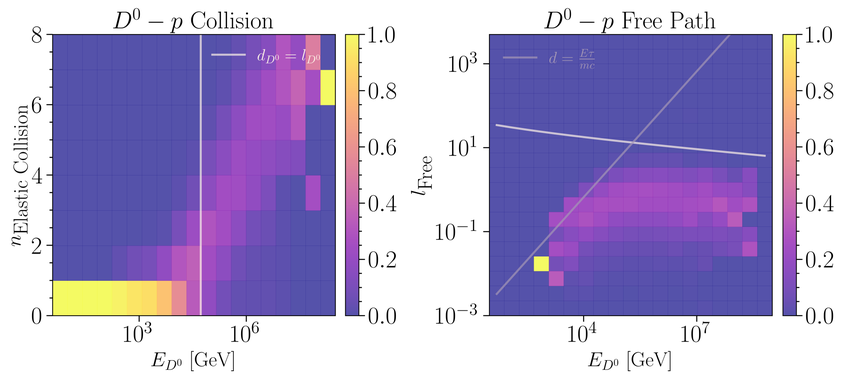
$$\nu + N \to l + c + X$$
$$c + X \to C + X \quad \text{with} \quad \frac{d\sigma(\nu N \to lCX)}{dxdydz} \approx \frac{d\sigma^{\nu c}(\nu N \to lX)}{dxdy} \sum_h f_h D_c^h(z)$$
$$C \to K(\pi) + \nu + l \qquad D(z) \propto \frac{4\epsilon}{z}(1 - \frac{1}{z} - \frac{\epsilon}{1-z})^2$$



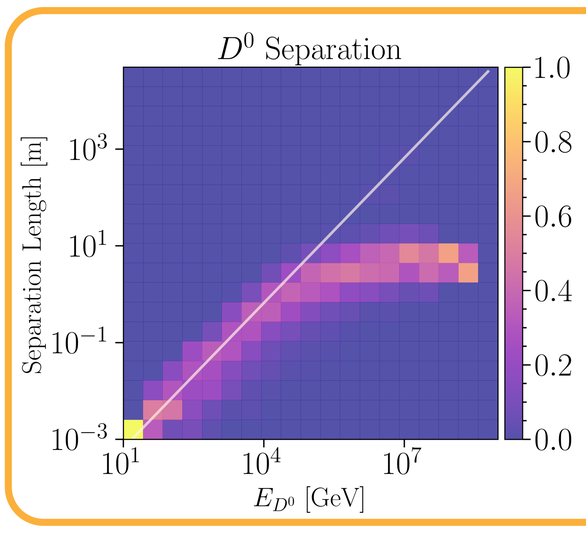
D-mesons: DECAY and COLLISION

Upon Hadronization, D-mesons travel through the detector region, elastically scattering off neucleons before eventually decaying.
The length of its free path is regulated by both the decay length and the interaction length, with the critical length at $d_{\text{DECAY}} = l_{\text{COLLISION}}$

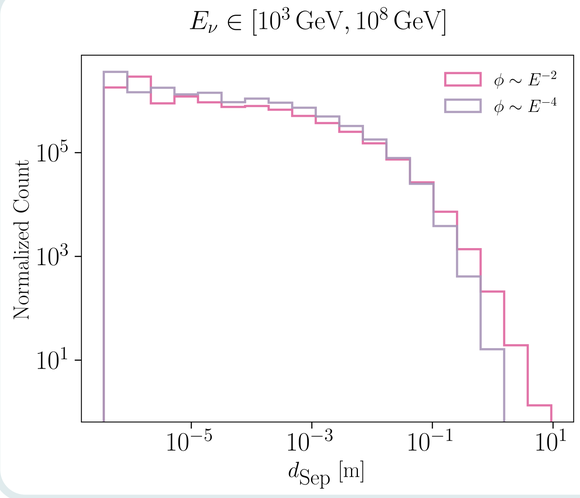
$$d_{\text{DECAY}} = \frac{E\tau}{mc}$$
$$l_{\text{COLLISION}} = \frac{m_{\text{ice}}}{\rho N_A \sigma E}$$



D-Meson Vertex Separation



As shown on the right, D-meson vertex separation plateaus at higher energies. This is due to elastic collisions with nucleon, shown on the upper-right. This resuls in a boost in number of D-meson-induced events with separation distance of order 1 ~ 10 meters, comparable to separation of tau neutrinos identifiable by double-pulse analysis in IceCube.



BONUS: Vertex separation distances distributions vary for astrophysical/ atmospheric neutrino fluxes.

TAKE HOME MESSAGE: NEED TO STUDY + CLASSIFY CHARMED-MESON-INDUCED DC'S

Whether in search for astrophysical tau neutrinos or physics beyond the Standard Model (e.g. HNL), charmed-mesons-induced double cascades exist as a major double-cascade morphology background. Especially, due to collisions with nucloen, there is a boost in the number of events with o(10) meters vertex separation, further aggrevating confusion with tau-neutrino-induced double cascades.

References and Acknowledgement
1. Schneider, Austin, Nicholas W. Kamp, and Alex Y. Wen. "SIREN: An Open Source Neutrino Injection Toolkit." arXiv preprint arXiv:2406.01745 (2024).
2. Lazar, Jeffrey, et al. "Prometheus: An Open-Source Neutrino Telescope Simulation." arXiv preprint arXiv:2304.14526 (2023).
3. IceCube Collaboration https://icecube. wisc. edu/analysis@ icecube. wisc. edu, et al. "Detection of astrophysical tau neutrino candidates in IceCube." The European Physical Journal C 82.11 (2022): 1031.

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