Abstract

The largest tau neutrino dataset to date is IceCube's atmospheric tau neutrino appearance dataset containing >1,000 tau neutrino and antineutrino events as determined by a fit to a standard three-flavor oscillation framework. On an event-by-event basis, however, it is impossible to know that any given event is a tau neutrino as they are identical to either an electron neutrino charged-current event or a neutral-current interaction of any active flavor. Nonetheless, we conclusively show that, using only the cascade sample even without knowledge of the oscillation parameters and without assuming that the lepton mixing matrix is unitary, tau neutrino identification is still possible and there is no viable scenario in which all of the tau neutrino candidates are actually electron neutrinos. This is primarily due to the matter effect and the tau lepton production threshold, as well as the fact that tau neutrinos are systematically reconstructed at a lower energy than electron neutrinos due to one or more outgoing neutrinos. This conclusively shows that it is possible for an atmospheric neutrino oscillation experiment to confirm that $U_{\tau 1}$, $U_{\tau 2}$, and $U_{\tau 3}$ are not all zero even with limited particle identification.

Tau Neutrino Identification at IceCube for Unitary Violation Tests

Peter B. Denton

Snowmass BSM Workshop

February 11, 2022

2109.14576

Brookhaven National Laboratory

Brookhaven NDI
Neutrino Discovery Initiative

Tau Neutrino Whitepaper!

64 authors! 674 references! Lots of subsubsubsections!

Read only overleaf: overleaf.com/read/khpgmxpdccwv

Executive Summary 4

1 History and Motivation (Denton) 8
1.1 Tau Neutrino History . . . 9
1.1.1 Theory . . . 9
1.1.2 Experimental discoveries . . . 10
1.2 Tau Neutrino Motivations . . . 11

2 Theoretical and Phenomenological Interests (de Gouvea, Mocioiu, Gehrlein) 13
2.1 Tau neutrinos and the Standard Neutrino Paradigm . . . 13
2.1.1 Precision measurement of oscillation parameters . . . 13
2.1.2 Testing the Standard Neutrino Paradigm: Unitarity Violation . . . 14
2.2 Tau neutrinos and sterile neutrinos . . . 16
2.2.1 Light Sterile Neutrinos . . . 17
2.2.2 Heavy Sterile Neutrinos . . . 19
2.2.3 Dipole portal . . . 21
2.3 Tau neutrinos and other new physics scenarios . . . 24
2.3.1 Non-Standard Interactions . . . 25
2.3.2 Neutrino Decay . . . 25
2.3.3 Tau neutrinos and Dark Matter . . . 27
2.3.4 New physics in tau neutrino scattering . . . 30
2.4 Connections of tau neutrinos to other new physics phenomena . . . 31
2.4.1 Tau neutrinos and charged lepton anomalies . . . 31
2.5 Looking for new phenomena with HE and UHE tau neutrinos . . . 31
2.5.1 Astrophysical neutrinos . . . 31
2.5.2 Neutrino self-interactions . . . 34

3 Experimental Probes at the GeV Scale (Adam, Peter) 37
3.1 Short-baseline Accelerator . . . 37
3.1.1 NOMAD . . . 37
3.1.2 DUNE Near Detector . . . 37
3.2 Fixed Target Experiments . . . 37
3.2.1 The NA65 Experiment at CERN . . . 37
3.2.2 The SHiP fixed target experimental proposal at CERN . . . 39
3.3 Long-baseline Accelerator . . . 44
3.3.1 OPERA . . . 44
3.3.2 DUNE (Adam) . . . 44
3.4 Atmospheric . . . 44
3.4.1 Super-Kamiokande/Hyper-Kamiokande . . . 47
3.4.2 DeepCore (Jason Koskinen) . . . 47
3.4.3 KM3NeT/ORCA (Hallmann) . . . 47
3.4.4 DUNE Far Detector (Adam) . . . 48

4 Experimental Probes at Intermediate Energies (de Roeck) 48
4.1 FASERν . . . 50
4.2 SND@LHC . . . 53
4.3 The Forward Physics Facility project . . . 57
4.4 FASERν2 at the FPF . . . 60
4.5 AdvSND at the FPF . . . 61
4.6 FLArE at the FPF . . . 65

5 High Energy Astrophysical Experimental Probes (Wissel) 69
5.1 Detection techniques . . . 77
5.2 In-ice or Water Optical Experiments . . . 89
5.3 In-Air Optical or Fluorescence Experiments . . . 92
5.4 In-ice Radio Experiments . . . 95
5.5 In-air Radio Experiments . . . 97
5.6 Lunar Experiments . . . 102
5.7 Shower-based Experiments . . . 103

6 Tools 106
6.1 Production Simulation . . . 106
6.1.1 LBNF Neutrino Flux Simulation . . . 106
6.1.2 SHiP Neutrino Flux Simulation . . . 107
6.1.3 LHC Neutrino Flux Simulation . . . 108
6.1.4 Atmospheric Neutrino Simulations . . . 109
6.2 Neutrino Event Generators & Tau Neutrino Cross Section Code . . . 112
6.2.1 GiBUU . . . 113
6.2.2 GENIE . . . 113
6.2.3 NuWRO . . . 114
6.2.4 NEUT . . . 114
6.2.5 FLUKA . . . 114
6.2.6 TAUOLA . . . 114
6.3 Special Considerations for High-Energy Neutrino Event Generators . . . 114
6.4 Special Considerations for Tau Neutrino Cross Sections . . . 115
6.5 Reconstruction Techniques . . . 117
6.5.1 Emulsion detectors: τ-decay Identification . . . 117
6.5.2 Tracking calorimeters: Transverse kinematic reconstruction . . . 120
6.5.3 Water and Ice Cherenkov at Lower Energies . . . 123
6.5.4 Water and Ice Cherenkov at High Energies . . . 125
6.5.5 In-ice radio detection at UHE energies . . . 128
6.6 Ultra-High Energy Tau Neutrino and Tau Lepton Propagation Codes . . . 129
6.6.1 nuPyProp . . . 131
6.6.2 TauRunner . . . 131
6.6.3 NuPropEarth . . . 132
6.6.4 NuTauSim . . . 132
6.6.5 Danton . . . 133
6.6.6 νSpaceSim . . . 133
6.7 In-ice Radio Detection Simulation Codes . . . 134

7 Conclusions 135

Endorsers 136

References 137

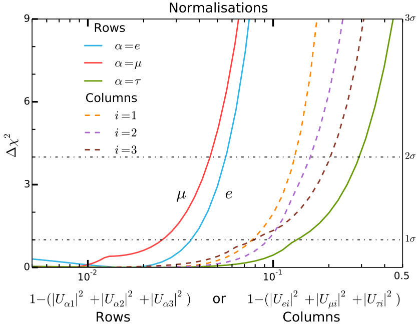
Unitarity Constraints on Tau Neutrinos

Past studies used:

1. $\nu_\mu \to \nu_\tau$ at OPERA
2. SNO NC and CC data

S. Ellis, K. Kelly, S. Li 2008.01088

Z. Hu, J. Ling, J. Tang, T. Wang 2008.09730



S. Parke M. Ross-Lonergan 1508.05095

More Tau Neutrinos!

The global tau neutrino data set:

Experiment	Source	~Events detected
DONuT	Production	7.5
OPERA	Long-baseline	8
SK	Atmospheric	291
IceCube	Atmospheric	1804[1]
IceCube	Astrophysical	2

[1] with ~ 10k en route soon, see J. Koskinen IceCube NuTau2021 talk

Dominant unitarity constraint comes from atmospheric ν_τ appearance

PBD, J. Gehrlein 2109.14575

More Tau Neutrinos!

The global tau neutrino data set:

Experiment	Source	∼Events detected
DONuT	Production	7.5
OPERA	Long-baseline	8
SK	Atmospheric	291
IceCube	Atmospheric	1804[1]
IceCube	Astrophysical	2

[1] with $\sim$ 10k en route soon, see J. Koskinen IceCube NuTau2021 talk

Dominant unitarity constraint comes from atmospheric ν_τ appearance

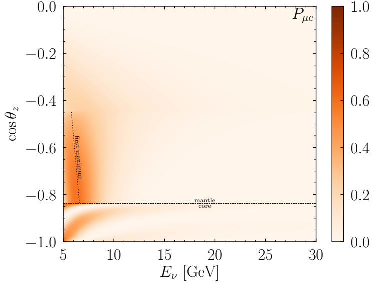
PBD, J. Gehrlein 2109.14575

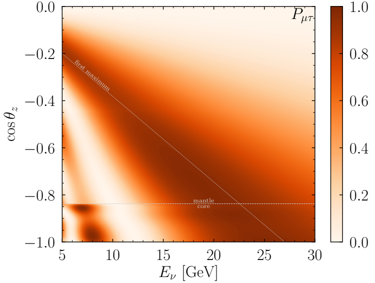
A word on solar neutrinos:

1. SK 1998: showed that ν_μ-ν_τ mixing is large
2. SNO 2001,2002: ES and NC measured a statistically significant non-ν_e flux
3. $\Rightarrow \nu_e \to \nu_\tau$ at SNO with input from SK

Atmospheric Tau Neutrino Appearance

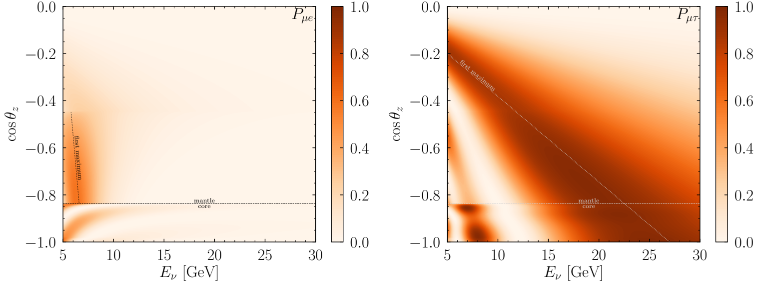
- Atmospheric neutrinos begin as ν_μ and mostly oscillate away to ν_τ

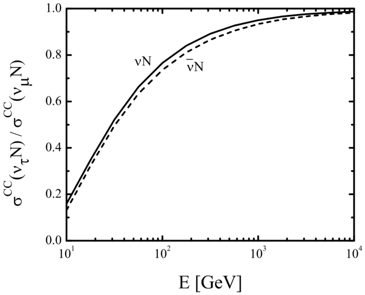




Atmospheric Tau Neutrino Appearance

- Atmospheric neutrinos begin as ν_μ and mostly oscillate away to ν_τ
- High tau lepton production threshold diminishes events

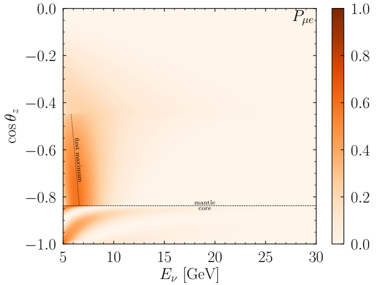


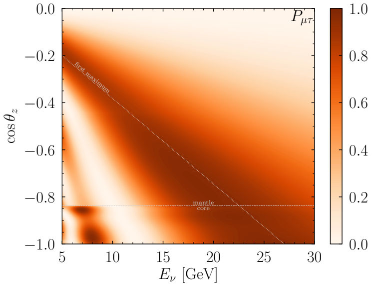


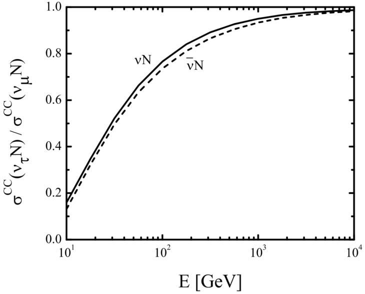
Y. Jeong, M. Reno 1007.1966

Atmospheric Tau Neutrino Appearance

- Atmospheric neutrinos begin as ν_μ and mostly oscillate away to ν_τ
- High tau lepton production threshold diminishes events
- Identifying tau lepton in large coarse detectors is hard







Y. Jeong, M. Reno 1007.1966

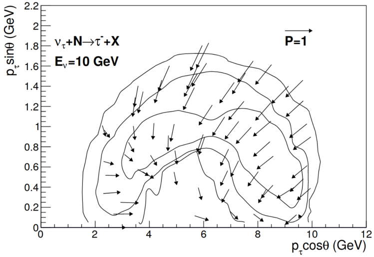
Tau Neutrino Appearance at SuperK

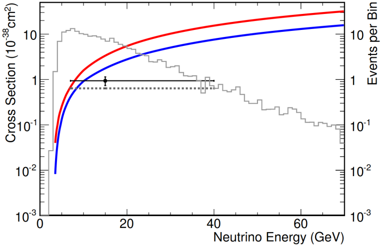
SuperK used:

1. Hadronic tau decay information
2. Tau polarization information
3. Neural net
4. *and standard oscillations*

Detected few hundred tau neutrino events, constrained the ν_τ "normalization"
e.g. weighted cross section: 1.47 ± 0.32 x SM

Super-KamiokaNDE 1711.09436





Tau Neutrino Appearance at IceCube

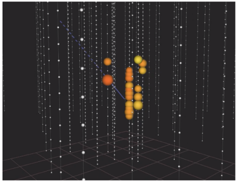
IceCube/DeepCore:

1. Much bigger than SuperK
2. 3D compared to SuperK's 2D
3. Much worse detector than SuperK
4. No ability to differentiate:
   - ν_τ CC that goes to a muon
   - ν_μ CC

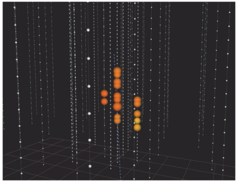
   or

   - ν_τ CC (that go to an electron or hadrons)
   - ν_e CC
   - ν NC

Track with energy of 26 GeV



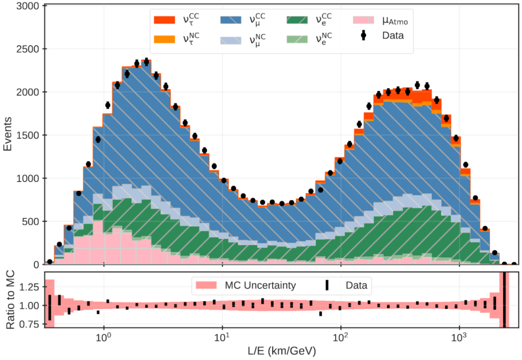
Cascade with energy of 30 GeV

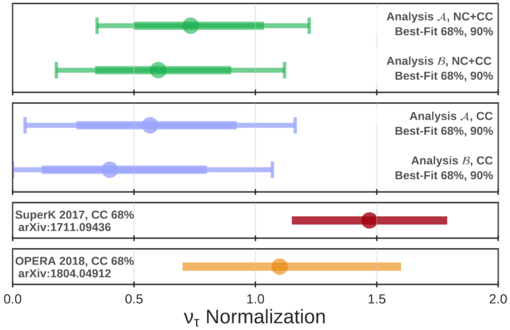


M. Rodriguez IceCube slides

IceCube Results

Using oscillation parameters IceCube finds:





IceCube 1901.05366

Past Work

Tau neutrino appearance in a large coarse detector is possible with:

1. Tau neutrino threshold
2. NC

T. Stanev astro-ph/9907018

Seeing extra low energy tau neutrinos could indicate astrophysical sources

H. Athar, F. Lee, G. Lin hep-ph/0407183

Both papers largely overlooked

My Motivation

- Tau neutrino identification is relevant for unitarity

  yet neither SuperK nor IceCube constrained unitarity with their data
- IceCube has the biggest data sets
- IceCube has extremely limited particle identification

  cascades vs. tracks
- It would seem like $\nu_\mu \to \nu_e$ could mimic $\nu_\mu \to \nu_\tau$

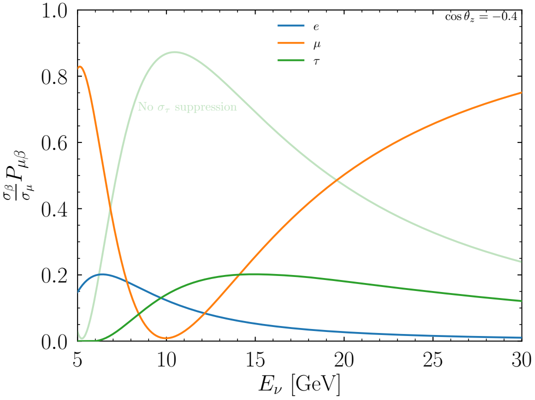
  For different oscillation parameters or with unitarity violation

What, if any, physical effects allows for the identification of tau neutrinos without particle identification and without assuming unitarity?

Mimicry Isn't Always Flattery

How to mimic $\nu_\mu \to \nu_\tau$ with $\nu_\mu \to \nu_e$ in the Earth:

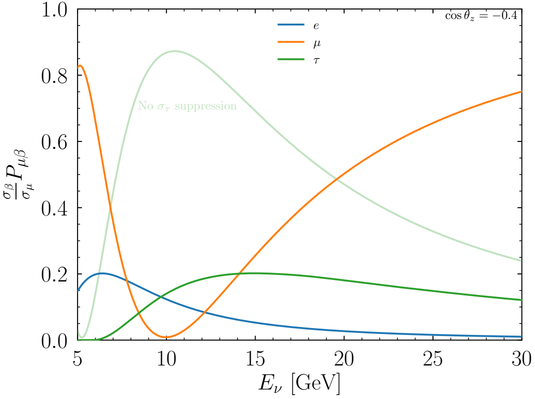
Through the mantle:



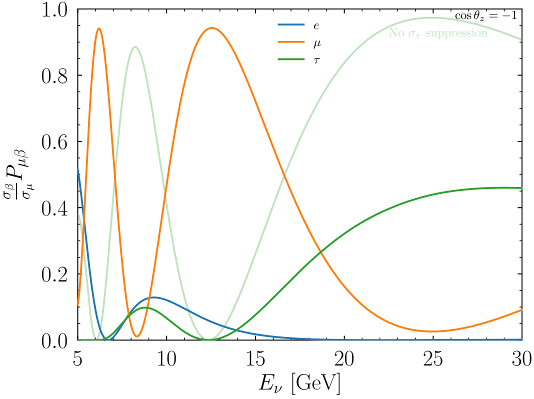
Mimicry Isn't Always Flattery

How to mimic $\nu_\mu \to \nu_\tau$ with $\nu_\mu \to \nu_e$ in the Earth:

Through the mantle:



Through the core:



Unitarity Violation Framework

- Suppose there are m total neutrinos and n kinematically accessible: (m, n)

  Accessible: [10 eV, 15 MeV]; inaccessible: $\gtrsim$ 40 MeV

  ν_τ is an exception to this that requires care
  - Standard: (3,3)
  - One accessible sterile: (4,4)
  - Two heavy steriles: (5,3)
- Include matter effect
  - Steriles don't experience it - relevant for $m = n$
  - It modifies the probability - relevant for $m > n$
- For $m = n$ oscillation probabilities can be calculated in the usual fashion
- For $m > n$ care is required:
  - Flux, cross sections, and weak interaction need to be rescaled
  - Oscillation probability needs to be rescaled and carefully calculated:

$$P^r_{\alpha\beta} = \left| \left[N^* W e^{-i\Lambda L} W^\dagger N^T \right]_{\alpha\beta} \right|^2$$

N: $m \times m$ submatrix

W, Λ eigenvectors/eigenvalues of Hamiltonian in mass basis with matter effect

Back to IceCube Observables

Define this cascade ratio:

$$\mathcal{R}_c(E_{\rm reco},\cos\theta_z)\equiv\frac{\frac{d^2N_c}{dE_{\rm reco}\,d\cos\theta_z}}{\Phi_i(E_{\rm reco})\sigma_{\rm tot}(E_{\rm reco})}$$

$$=f_{\rm CC}\left[P^r_{\mu e}(E_{\rm reco},\cos\theta_z)+\eta_{\nu_\tau}^{\gamma-1}R_{\tau\mu}(E_{\rm reco}/\eta_{\nu_\tau})(1-f_{\tau\mu})P^r_{\mu\tau}(E_{\rm reco}/\eta_{\nu_\tau},\cos\theta_z)\right]$$

$$+(1-f_{\rm CC})\eta_{\rm NC}^{\gamma-1}\sum_{\beta\in\{e,\mu,\tau\}}P^r_{\mu\beta}(E_{\rm reco}/\eta_{\rm NC},\cos\theta_z)$$

- ν_e CC appearance
- ν_τ CC appearance with $\tau\to\nu_\tau+(e,X)$
- τ production threshold
- Reconstructed energy shift from spectrum and cross section

  Different for $\tau\to\nu_\tau$ and NC
- NC

Results

Effects considered:

1. NC
2. Matter effect
3. η_{ν_τ}: Tau neutrino reconstruction
4. $R_{\tau\mu}$: Tau lepton production threshold
5. External Δm^2_{31} constraint
6. External ν_e row constraint

Conclusions:

1. **With all known effects tau neutrinos can be identified even without assuming unitarity**
2. With all effects off and no unitarity: ν_τ's cannot be identified.
   Dial up ν_e to match
3. Including NC doesn't matter much
4. Turning on $R_{\tau\mu}$, η_{ν_τ}, or the matter significantly enhances sensitivity
5. Certain combinations approximately cancel:
   Just $R_{\tau\mu}$ and η_{ν_τ} has almost no sensitivity

Atmospheric Appearance Unitarity Key Points

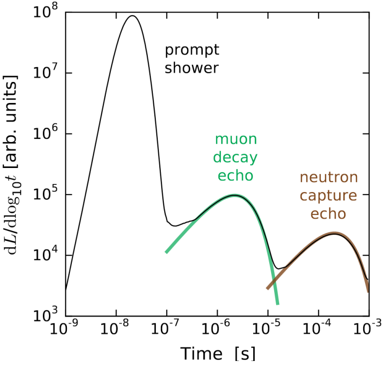
1. Conservatively didn't include down-going or tracks which add more information
2. Assume only oscillations, τ properties, and the matter effect
3. Numerous effects allow for model independent detection of ν_τ with no event-by-event identification
4. Some of the effects actually partially cancel
5. Experiments can confidently report unitarity constraints

Thanks!

Backups

Possible Means of Identifying Tau Neutrinos Event-By-Event

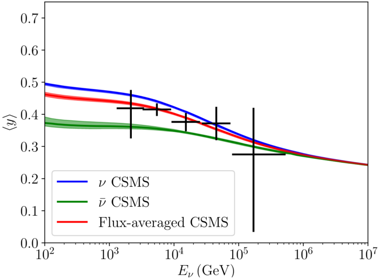
Hadronic showers contain far more muons and neutrons than electromagnetic showers



In practice, not possible

S. Li, M. Bustamante, J. Beacom 1606.06290

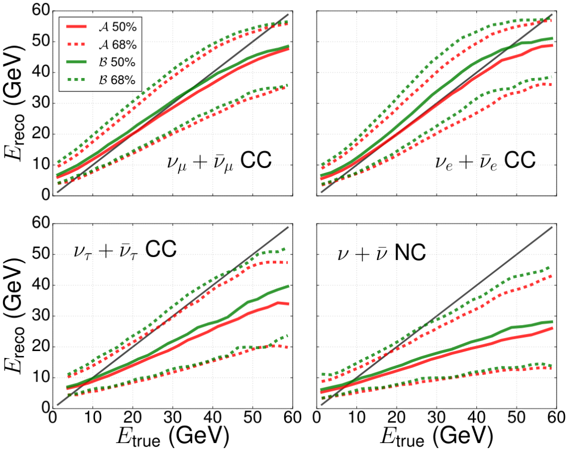
Inelasticity correlates with E_ν not E_{dep} and could be used



IceCube 1808.07629

Too hard to measure at low energies

Reconstructed vs. True Energy



τ's always decay to invisible energy ν_τ

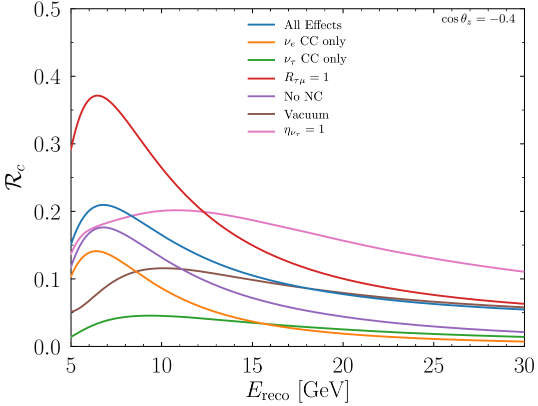
$$\eta_{\nu_\tau} = 0.625$$

NC always loses some energy

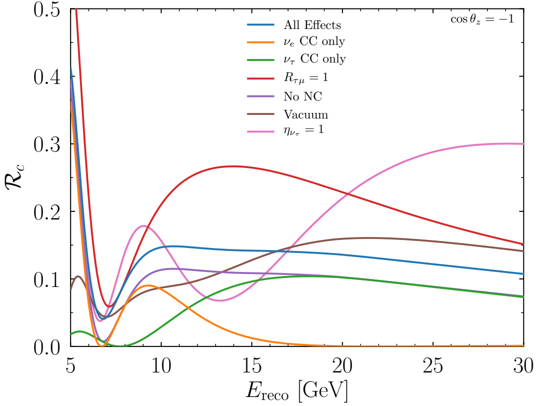
$$\eta_{\rm NC} \simeq \frac{1}{3}$$

Impact of Effects

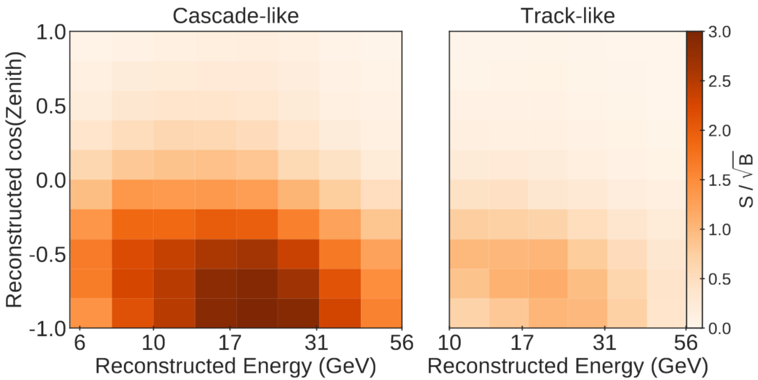
Through the mantle:



Through the core:



IceCube Detector Sensitivities



Contains all information on detector efficiencies, flux, and track/cascade misidentification