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





Tau Neutrino Whitepaper!

64 authors! 674 references! Lots of subsubsubsections! Read only overleaf: overleaf.com/read/khpgmxpdccwv

E	cecu	tive Summary	4
1	His	tory 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	The	coretical and Phenomenological Interests (de Gouvea, Mocioiu.	
	Gel	arlein)	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	Evi	perimental 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 KMSN-T/ORGA (Rishimum)				
4 Experimental Probes at Intermediate Energies (de Resek) 4				
41 PASHER 50 42 SNDBIR 53 43 The Foresard Physics Reality project 53 43 The Foresard Physics Reality project 53 44 TASHER 54 PK 57 45 PASHER 54 PK 56 46 PASHER 54 PK 56 47 DASHER 54 PK 56 48 PASHER 54 PK 56 49 PASHER 54 PK 56 40 PASHER 54 PK 56 PK 56 PK 40 PASHER 54 PK 56 PK 56 PK 40 PASHER 56 PK 56 PK 56 PK 41 PASHER 56 PK 56 PK 56 PK 42 PK 56 PK 56 PK 56 PK 43 PK 56 PK 56 PK 56 PK 44 PK 56 PK 56 PK 56 PK 45 PK 56 PK 56 PK 56 PK 45 PK 56 PK 56 PK 56 PK 46 PK 56 PK 56 PK 56 PK 56 PK 46 PK 56 PK 56 PK 56 PK 56 PK 46 PK 56 PK 56 PK 56 PK 56 PK 56 PK 56 PK 46 PK 56 PK			3.4.4 DUNE Far Detector (Adam)	48
41 PASHER 50 42 SNDBIR 53 43 The Foresard Physics Reality project 53 43 The Foresard Physics Reality project 53 44 TASHER 54 PK 57 45 PASHER 54 PK 56 46 PASHER 54 PK 56 47 DASHER 54 PK 56 48 PASHER 54 PK 56 49 PASHER 54 PK 56 40 PASHER 54 PK 56 PK 56 PK 40 PASHER 54 PK 56 PK 56 PK 40 PASHER 56 PK 56 PK 56 PK 41 PASHER 56 PK 56 PK 56 PK 42 PK 56 PK 56 PK 56 PK 43 PK 56 PK 56 PK 56 PK 44 PK 56 PK 56 PK 56 PK 45 PK 56 PK 56 PK 56 PK 45 PK 56 PK 56 PK 56 PK 46 PK 56 PK 56 PK 56 PK 56 PK 46 PK 56 PK 56 PK 56 PK 56 PK 46 PK 56 PK 56 PK 56 PK 56 PK 56 PK 56 PK 46 PK 56 PK	4	Evr	perimental Probes at Intermediate Energies (de Roeck)	18
42 NOBALIC				
43 The Forum Physics Pacility project 17				
44 PASTRIC at the FPF 66 45 AdvSND at the FPF 66 45 PALAE at the FPF 66 55 Digit Energy at the PASTRIC ASSTRAIN STATE ASSTRAIN ASSTRAIN STATE ASSTRAIN ASSTRAIN STATE ASSTRAIN STATE ASSTRAIN STATE ASSTRAIN STATE ASSTRAIN STATE ASSTRAIN				
45 AbriSND at the FFF 61 45 FLAGE atte FFF 65 51 High Energy Astrophysical Experimental Probes (Wissel) 60 51 High Energy Astrophysical Experiments 77 52 Indice on Water Optical Experiments 79 53 Indice on Water Optical Experiments 79 54 Indice on Water Optical Experiments 79 55 Indice Indice Experiments 79 55 Indice Indice Experiments 79 56 Inner Experiments 70 57 Shower-based Experiments 70 58 Indice Indice Experiments 70 59 Indice Indice Experiments 70 50 Indice Indice Experiments 70 50 Indice Indice Experiments 70 50 Indice Indice Experiments 70 51 Indice Indice Experiments 70 52 Indice Indice Experiments 70 53 Indice Indice Experiments 70 54 Indice Indice Experiments 70 55 Indice Experiments 70 56 Indice Indice Experiments 70 57 Indice Indice Experiments 70 58 Indice Indice Experiments 70 59 Indice Experiments 70 50 Indice Ex		4.4		60
40 FLAE at the FFF				
5.1 Detection techniques				
5.1 Detection techniques				
5.2 Incise or Water Optical Experiments 9.9 5.3 Incise of Incise or Froncescence Experiments 9.2 5.4 Incise Rudio Experiments 9.5 5.5 Incise Rudio Experiments 9.5 5.6 Incise Rudio Experiments 9.7 5.6 Lime Experiments 10.2 5.7 Shower Scand Experiments 10.2 6.7 Shower Scand Experiments 10.6 6.1 Pordon Experiments 10.6 6.1 Experiments 10.6 6.2 Experiments 10.6 6.2 Experiments 10.6 6.3 Experiments 10.6 6.4 Experiments 10.6 6.5 Experiments 10.6	5			
5.3 Lock Optical or Theoremical Superiments 92 5.1 Inside Radio Experiments 59 5.2 Inside Radio Experiments 97 5.3 Inside Radio Experiments 192 5.5 Lama Experiments 193 6.7 Tools 100 6.1 Patrice Theorem Simulation 100 6.1. La LIVE Secretics Play Simulation 100 6.1.2 RIVE Number Flay Simulation 100 6.1.3 LIC Neutrino Flay Simulation 100 6.1.4 Autospiers Neutron Simulation 100 6.1.3 Autospiers Neutron Simulation 100 6.2 Neutrino Fenet Generators & Tan Neutrino Cross Section Code 112 6.2.2 Section 113 6.2.3 NAWIGO 114 6.2.4 FLUX 114 6.2.5 FLUX 114 6.2.6 FLUX 114 6.2.6 Section Considerations for Tan Neutrino Cross Sections 115 6.5 Reconstruction Techniques 117 6.5.1 Example and Contractors relacely Contribution reconstruction 120 6.5.1 Neutrino Techniques 122 6.5.3 Water and bet Chromabova in High Exercise 125 <tr< td=""><td></td><td></td><td></td><td></td></tr<>				
5.1 Incirc Radio Experiments 95 5.5 Incirc Radio Experiments 97 5.5 Incirc Radio Experiments 102 5.7 Shower-Board Experiments 102 6.7 Shower-Board Experiments 103 6.8 Todale 106 6.1 Porduction Simulation 106 6.1 Porduction Simulation 106 6.1 Early Neutrino Plan Simulation 106 6.1 Sulfa Neutrino Plan Simulation 106 6.1 Sulfa Neutrino Plan Simulation 108 6.1 Sulfa Neutrino Plan Simulation 108 6.2 Sulfa Neutrino Plan Simulation 108 6.2 Sulfa Neutrino Plan Simulation 108 6.2 Sulfa Consult Generators & Tan Neutrino Cone Section Code 112 6.2 GRUU 113 6.2.5 Sulfa Consult Generators & Tan Neutrino Cone Section Code 112 6.2.6 TalVOIA 114 6.3 Special Consideration for High-Energy Neutrino Event Generators 114 6.5 Special Considerations for Tan Neutrino Cone Sections 117 6.5.1 Emislous decetors r-docay Destination 117 6.5.2 Talvoin Geleinterette Tannevore kinematic reconstruction 117 6.5.3 Water and fee Cherwidez at High Energies 125 6.5.5 Indicate and decetors at Ultim Energies 125 6.5.5 Indicate and decetors at Ultim Energies 125 6.5.5 Indicate and Section 118 12 6.5.5 Indicate and decetors at Ultim Energies 125 6.5.5 Indicate and Section 118 12 6.5.5 Indicate and Section 118 12 6.5.6 Indicate and Section 118 12 6.5.7 Indicate and Section 118 12 6.5.8 Indicate and Section 118 12 6				
5.5 Louis Fladio Esperiments 97				
50 Loan Experiment 192 57 Shower-board Experiment 193 61 Tolin 195 61 Probaction Simulation 196 61 Probaction Simulation 196 61 Probaction Simulation 196 61 Probaction Simulation 196 61 State St				
5.7 Shower-bosed Experiments 103				
6 Tools 6.1 Tools 6.1 Tools 6.2 Tools 6.3 Tools 6.4 Start Sta				
6.1 Production Simulation		5.7	Shower-based Experiments	03
6.1 Production Simulation	6	Ton	de 1	200
6.1.2 SHIP Neutrino Plac Simulation 107				
6.1.2 SHIP Neutrino Plac Simulation 107			6.1.1 LRNF Neutrino Flux Simulation 1	06
6.1.3 LIC Nontrino Paus Simulation 108				
6.1.4 Atmospheris Nortition Simulations . 100 6.2 Neutrino Foundation & Tran Nontition Cone Section Code . 112 6.2.1 GBRU . 113 6.2.2 GBRU . 113 6.2.3 NeWNO . 114 6.2.5 PELVER . 114 6.2.5 PELVER . 114 6.2.6 PELVER . 114 6.2.6 PELVER . 114 6.2.6 PELVER . 114 6.3 Special Considerations for High-Energy Neutrino Event Generators . 114 6.5 Special Considerations for High-Energy Neutrino Event Generators . 114 6.6 Reconstruction Techniques . 117 6.3.1 Emission devictors relaxed positions . 117 6.3.1 Emission devictors relaxed positions . 117 6.3.5 Water and to Chemiston at Lower Energies . 128 6.5.5 Index and de Chemiston at High Energies . 128 6.5.5 Index and des Chemiston at High Energies . 128 6.5.5 Index and des Chemiston at High Energies . 128				
6.2.1 GBUU				
6.22 CUENIF		6.2	Neutrino Event Generators & Tau Neutrino Cross Section Code 1	12
6.2.8 NWHO			6.2.1 GiBUU	13
6.24 NRIT			6.2.2 GENIE	13
62.5 FUKA			6.2.3 NuWRO	14
6.2.6 TAUGIA 6.3 Special Considerations for High-Energy Neutrino Event Generators 1.14 6.1 Special Considerations for The Neutrino Cross Sections 1.15 6.2 Reconstruction Techniques 1.17 6.3.1 Emission devictors re-deep Redefication 1.17 6.3.1 Emission devictors re-deep Redefication 1.17 6.3.1 Water and the Chemistruction 1.10 Performance of the Redefication 1.17 6.3.1 Water and for Chemistruction 1.10 Performance 1.10 Pe			6.2.4 NEUT	14
6.3 Special Considerations for High-Energy Neutrino Fourd Generators			6.2.5 FLUKA	14
6.4 Special Considerations for Tan Neutrino Cross Sections			6.2.6 TAUOLA	14
6.5 Reconstruction Techniques 117 6.5.1 Emission detectors r-deery Identification 117 6.5.2 Tracking calcularaters Transverse kinematic reconstruction 120 6.5.3 Water and Ice Cherenkow at Hope Energies 128 6.5.4 Water and Ice Cherenkow at High Energies 125 6.5.5 Insice radio detection at UIE energies 128		6.3	Special Considerations for High-Energy Neutrino Event Generators 1	14
6.5.1 Emulsion detectors: r-decay Identification 117 6.5.2 Tracking calorimeters: Transverse kinematic reconstruction 120 6.5.3 Water and Ice Cherenkow at Lower Baregies 123 6.5.4 Water and Ice Cherenkow at High Energies 125 6.5.5 In-lace radio detection at UHE energies 128		6.4	Special Considerations for Tau Neutrino Cross Sections	15
6.5.2 Tracking calorimeters: Transverse kinematic reconstruction 120 6.5.3 Water and Ice Cherenkow at Lower Energies 123 6.5.4 Water and Ice Cherenkow at High Energies 125 6.5.5 In-ice radio detection at UHE energies 128		6.5		
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			6.5.1 Emulsion detectors: τ -decay Identification	17
6.5.4 Water and Ice Cherenkov at High Energies 125 6.5.5 In-ice radio detection at UHE energies 128			6.5.2 Tracking calorimeters: Transverse kinematic reconstruction 1	20
6.5.5 In-ice radio detection at UHE energies			6.5.3 Water and Ice Cherenkov at Lower Energies	23
6.6 Ultra-High Energy Tau Neutrino and Tau Lepton Propagation Codes 129				
		6.6	Ultra-High Energy Tau Neutrino and Tau Lepton Propagation Codes 1	29

adon	sers																							136
	iclusio	ms																						135
6.7	In-ice	Radio	Dete	cti	OI.	1.5	Sin	m	ılı	ti	on	C	ю	le	8									134
	6.6.6	<i>ν</i> Spa ₀	1081	٠.																				133
	6.6.5	Dante																						
	6.6.4	NuTax																						
	6.6.3	NuPro																						
	6.6.2	TauRu																						

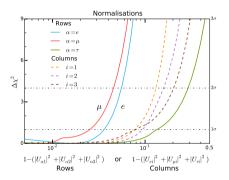
Unitarity Constraints on Tau Neutrinos

Past studies used:

- 1. $\nu_{\mu} \rightarrow \nu_{\tau}$ 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 $\sim 10 k$ 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	\sim Events detected
DONuT	Production	7.5
OPERA	Long-baseline	8
SK	Atmospheric	291
IceCube	Atmospheric	1804^{1}
IceCube	Astrophysical	2

 $^{^{1}}$ with ~ 10 k en route soon, see J. Koskinen IceCube NuTau2021 talk

Dominant unitarity constraint comes from atmospheric ν_{τ} appearance

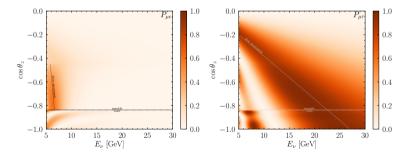
PBD, J. Gehrlein 2109.14575

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. $\Rightarrow \nu_e \rightarrow \nu_\tau$ at SNO with input from SK

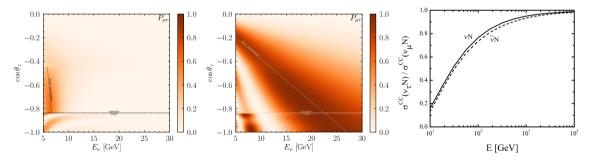
Atmospheric Tau Neutrino Appearance

 \triangleright Atmospheric neutrinos begin as ν_{μ} and mostly oscillate away to ν_{τ}



Atmospheric Tau Neutrino Appearance

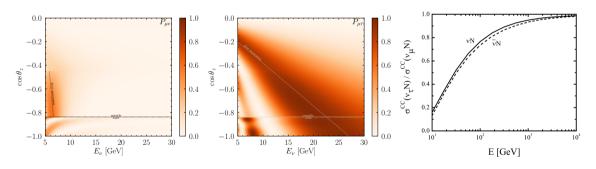
- \triangleright Atmospheric neutrinos begin as ν_{μ} and mostly oscillate away to ν_{τ}
- ▶ High tau lepton production threshold diminishes events



Y. Jeong, M. Reno 1007.1966

Atmospheric Tau Neutrino Appearance

- \triangleright 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



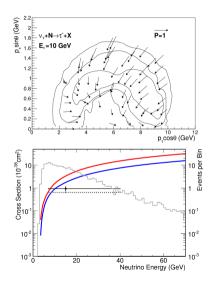
Y. Jeong, M. Reno 1007.1966

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: $1.47 \pm 0.32 \text{ x SM}$ Super-KamiokaNDE 1711.09436



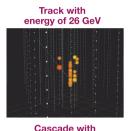
Tau Neutrino Appearance at IceCube

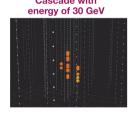
IceCube/DeepCore:

- 1. Much bigger than SuperK
- 2. 3D compared to SuperK's 2D
- 3. Much worse detector than SuperK
- 4. No ability to differentiate:
 - $\triangleright \nu_{\tau}$ CC that goes to a muon
 - $\triangleright \nu_{\mu} \text{ CC}$

or

- ν_{τ} CC (that go to an electron or hadrons)
- $\triangleright \nu_e$ CC
- $\triangleright \nu NC$

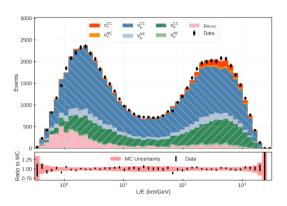


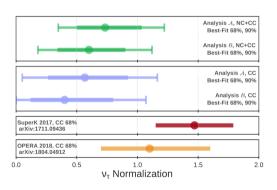


M. Rodriguez IceCube slides

IceCube Results

Using oscillation parameters IceCube finds:





 ${\it IceCube~1901.05366}$

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 $\nu_{\mu} \rightarrow \nu_{e}$ could mimic $\nu_{\mu} \rightarrow \nu_{\tau}$

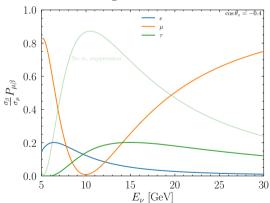
For different oscillation parameters or with unitarity violation

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

Mimicry Isn't Always Flattery

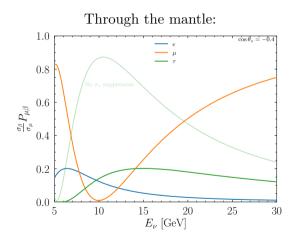
How to mimic $\nu_{\mu} \rightarrow \nu_{\tau}$ with $\nu_{\mu} \rightarrow \nu_{e}$ in the Earth:

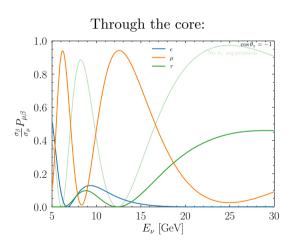
Through the mantle:



Mimicry Isn't Always Flattery

How to mimic $\nu_{\mu} \rightarrow \nu_{\tau}$ with $\nu_{\mu} \rightarrow \nu_{e}$ in the Earth:





Unitarity Violation Framework

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

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

 ν_{τ} is an exception to this that requires care

- ► Standard: (3,3)
- ▶ One accessible sterile: (4.4)
- ightharpoonup Two heavy steriles: (5,3)
- ► Include matter effect
 - \triangleright Steriles don't experience it relevant for m=n
 - ▶ It modifies the probability relevant for m > n
- ightharpoonup 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:

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

 $N: m \times m \text{ submatrix}$

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

Back to IceCube Observables

Define this cascade ratio:

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

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

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

- $\triangleright \nu_e$ CC appearance
- ν_{τ} CC appearance with $\tau \to \nu_{\tau} + (e, X)$
- $\triangleright \tau$ 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. $\eta_{\nu_{\tau}}$: Tau neutrino reconstruction
- 4. $R_{\tau\mu}$: Tau lepton production threshold
- 5. External Δm_{31}^2 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 $R_{\tau\mu}$, $\eta_{\nu_{\tau}}$, or the matter significantly enhances sensitivity
- 5. Certain combinations approximately cancel:

 Just $R_{\tau\mu}$ and $\eta_{\nu\tau}$ has almost no sensitivity

Atmospheric Appearance Unitarity Key Points

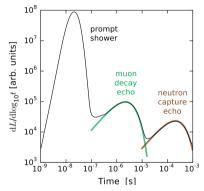
- 1. Conservatively didn't include down-going or tracks which add more information
- 2. Assume only oscillations, τ properties, and the matter effect
- 3. Numerous effects allow for model independent detection of ν_{τ} with no event-by-event identification
- 4. Some of the effects actually partially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

Thanks!

Backups

Possible Means of Identifying Tau Neutrinos Event-By-Event

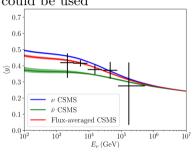
Hadronic showers contain far more muons and neutrons than electromagnetic showers



In practice, not possible

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

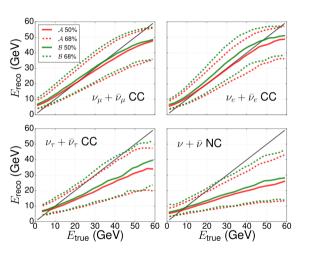
Inelasticity correlates with E_{ν} not $E_{\rm dep}$ and could be used



IceCube 1808.07629

Too hard to measure at low energies

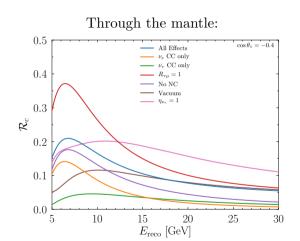
Reconstructed vs. True Energy



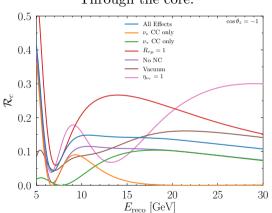
 τ 's always decay to invisible energy ν_{τ} $\eta_{\nu_{\tau}} = 0.625$

NC always loses some energy $\eta_{\rm NC} \simeq \frac{1}{3}$

Impact of Effects

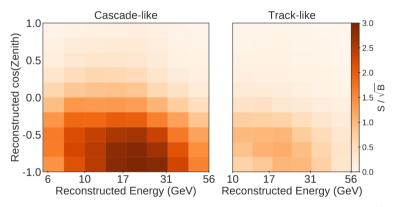


Through the core:



2109.14576

IceCube Detector Sensitivities



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