



# Workshop on Tau Neutrinos from GeV to EeV (NuTau2021) Summary Sep 28<sup>th</sup> – Oct 1<sup>st</sup> 2021 (virtual)

Mary Bishai (BNL, Chair), Julia Gehrlein (BNL, Co-chair), Adam Aurisano (U. Cincinnati), Peter Denton (BNL), Andre de Gouvea (Northwestern), Irina Mocioiu (Penn State), Stephanie Wissel (Penn State)

Friday December 17<sup>th</sup>, 2021

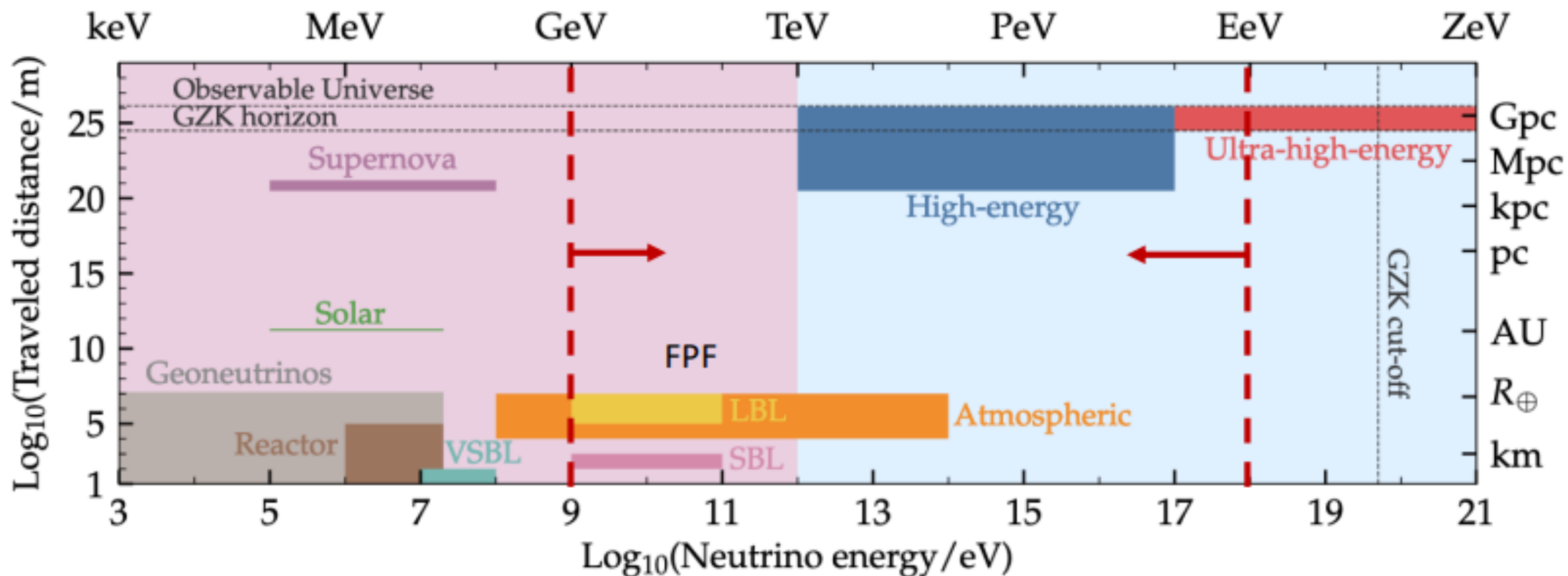
    @BrookhavenLab

# Workshop Goals

In the next generation of planned and proposed experiments and observatories there will be unique opportunities to extend our knowledge of the tau neutrino and its interactions from GeV to EeV scales. The goals of NuTau2021 were as follows:

- Summarize the state of knowledge of tau neutrinos
- Examine the theory opportunities provided by current and future studies of tau neutrinos
- Explore the capabilities of future experiments to advance our knowledge of tau neutrinos and explore the complementarity between them
- Explore the connections of tau neutrinos to astrophysics and cosmology
- Understand the impact of advancements in the understanding of the tau neutrino on its use as a cosmological probe
- *Launch the effort to prepare a comprehensive Snowmass 2021 Whitepaper on tau neutrinos.*

# From GeV – EeV



M. Ackerman et al., Astro2020 Science White Paper, arXiv:1903.04333

# Workshop Participation

- 171 registered participants
- 23 invited plenary speakers
- 16 contributed talks (approx 19 abstracts submitted)
- Attendance: Sep 28 (125), Sep 29 (113), Sep 30 (96), Oct 1 (107). Steady attendance by around 50 participants.
- BNL intellectual interests: M. Bishai (DUNE nutau appearance for unitarity and BSM physics searches), P. Denton (UHE nutau radio neutrinos, PMNS matrix and unitarity constraints), J. Gehrlein (PMNS matrix and unitarity constraints), M. Diwan (Nutau detection with LHC Far Forward Physics Facility)

# Workshop Agenda - AM

Sep 28, 2021		Sep 29, 2021		Sep 30, 2021		Oct 1, 2021	
9:30 AM	Introduction - <a href="#">Mary Bishai (Brookhaven National Laboratory)</a> (This workshop will be held as a virtual event) <a href="#">nutau2021_intro_bishai.pdf</a>	9:30 AM	Experimental techniques (GeV energies) - <a href="#">Jeremy Hewes (University of Cincinnati)</a> (until 11:10 AM) (This workshop will be held as a virtual event) <a href="#">nutau21_sep29_morning_saved_chat.txt</a>	9:30 AM	Tau neutrino cross sections - <a href="#">Milind Diwan (Brookhaven National Lab)</a> <a href="#">Austin Cummings (Penn State)</a> (until 10:45 AM) (This workshop will be held as a virtual event) <a href="#">nutau2021_thurs_30sep_saved_chat.txt</a>	9:00 AM	Tau neutrinos and BSM - <a href="#">Roshan Mammen Abraham (Oklahoma State University)</a> <a href="#">Ahmed Ismail (Oklahoma State)</a> (until 10:15 AM) (This workshop will be held as a virtual event)
9:45 AM	Overview - <a href="#">Peter Denton (Brookhaven National Lab)</a> <a href="#">Andre De Gouvea (Northwestern)</a> (until 11:30 AM) (This workshop will be held as a virtual event) <a href="#">sep28_meeting_saved_chat.txt</a>	9:30 AM	Production and detection of tau neutrinos from accelerator sources in DUNE - <a href="#">Pedro Machado (Fermilab)</a> (This workshop will be held as a virtual event) <a href="#">Machado-NuTau-2021-Production and detection of tau neutrinos at DUNE.pdf</a>	9:30 AM	Cross Section Measurement of Tau Neutrinos from GeV to TeV in Ar <sub>40</sub> - <a href="#">Barbara Yaeggy (Cincinnati)</a> (This workshop will be held as a virtual event) <a href="#">NuTau2021_XSecAr40_BarbaraYaeggy (003).pdf</a>	9:00 AM	Tau neutrinos and BSM - <a href="#">Carlos Argüelles (Harvard)</a> (This workshop will be held as a virtual event) <a href="#">nuTau2021_carguelles.pdf</a>
9:45 AM	Theory overview: New Physics in Neutrino Oscillations and role of tau neutrinos - <a href="#">Jacobo Lopez-Pavon (Valencia U, IFIC)</a> (This workshop will be held as a virtual event) <a href="#">NuTau2021_JLP.pdf</a>	9:50 AM	Experimental Detection and Studies of Atmospheric Tau Neutrinos in DUNE - <a href="#">Adam Aurisano (University of Cincinnati)</a> (This workshop will be held as a virtual event) <a href="#">aurisanoNuTau2021DUNEAtmos.pdf</a>	9:50 AM	Cross sections across all energies-theory - <a href="#">Hallsie Reno (U Iowa)</a> (This workshop will be held as a virtual event) <a href="#">NuTau2021-Reno.pdf</a>	9:20 AM	Physics with Atmospheric Tau Neutrino at ICAL-INO - <a href="#">Sanjib Agarwalla (Institute of Physics, Bhubaneswar)</a> (This workshop will be held as a virtual event) <a href="#">Sanjib-NuTau-2021.pdf</a>
10:15 AM	Experimental overview: artificial sources - <a href="#">Laura Fields (Fermilab)</a> (This workshop will be held as a virtual event) <a href="#">NuTau_Fields_2021_ExperimentalOverview.pdf</a>	10:10 AM	Experimental techniques: Tau Neutrino Searches at Super-Kamiokande and Hyper-Kamiokande - <a href="#">Roger Wendell (Kyoto University)</a> (This workshop will be held as a virtual event) <a href="#">wendell_nutau_20210929_up.pdf</a>	10:10 AM	Neutrino cross-sections from GeV to ZeV energies - experiment - <a href="#">Spencer Klein (LBNL)</a> (This workshop will be held as a virtual event) <a href="#">Neutrinocross-sections-experiment.pdf</a>	9:40 AM	High-energy and ultra-high-energy tau neutrinos and BSM - <a href="#">Mauricio Bustamante (Niels Bohr Institute)</a> (This workshop will be held as a virtual event) <a href="#">2021-10-01-Bustamante-NuTau_no_backup.pdf</a>
10:45 AM	Experimental overview: natural sources - <a href="#">Tyce DeYoung (Michigan State University)</a> (This workshop will be held as a virtual event) <a href="#">Tyce_DeYoung_NuTau2021.pdf</a>	10:30 AM	Experimental techniques: IceCube atmospheric - <a href="#">Jason Koskinen (NBIA)</a> (This workshop will be held as a virtual event) <a href="#">Koskinen_NuTau2021_IceCubeOscillation.pdf</a>	10:30 AM	Discussion (This workshop will be held as a virtual event)	10:00 AM	Discussion (This workshop will be held as a virtual event)
11:15 AM	Discussion (This workshop will be held as a virtual event)	10:50 AM	Discussion (This workshop will be held as a virtual event)	10:45 AM	UHE experimental techniques - <a href="#">Stella Oh (U Cincinnati)</a> <a href="#">Carlos Argüelles (Harvard)</a> (until 12:40 PM) (This workshop will be held as a virtual event)	10:15 AM	Tau neutrinos in astrophysics - <a href="#">Ivan Martinez-Soler (Fermilab and Northwestern University)</a> <a href="#">Barbara Yaeggy (Cincinnati)</a> (until 10:50 AM) (This workshop will be held as a virtual event)
11:30 AM	--- Lunch break ---	11:10 AM	High energy tau neutrinos at CERN - <a href="#">Alexandre Sousa (Cincinnati)</a> (until 12:20 PM) (This workshop will be held as a virtual event)	10:45 AM	High Energy Tau Neutrino Detection - <a href="#">Dawn Williams (University of Alabama)</a> (This workshop will be held as a virtual event) <a href="#">nutau2021_williams_opticaluhetau.pdf</a>	10:15 AM	Prompt atmospheric tau neutrino flux - <a href="#">Yu Seon Jeong (CERN)</a> (This workshop will be held as a virtual event) <a href="#">NuTau2021_YSeong.pdf</a>
		11:10 AM	Looking forward to Tau Neutrinos at the LHC - Ideas and Physics Potential - <a href="#">Felix Kling (SLAC)</a> (This workshop will be held as a virtual event) <a href="#">FPF@NuTau-09_21.pdf</a>	11:30 AM	The radio technique and UHE tau neutrino searches - <a href="#">Enrique Zas (Santiago de Compostela U.)</a> (This workshop will be held as a virtual event) <a href="#">EnriqueZas.pdf (2).pdf</a>	10:35 AM	Discussion (This workshop will be held as a virtual event)
		11:30 AM	Looking Forward to Tau Neutrinos at CERN - Experiments - <a href="#">Albert De Roeck (CERN)</a> (This workshop will be held as a virtual event) <a href="#">deroeck_NuTau_2021_v4.pdf</a>			10:50 AM	Contributed talks II - <a href="#">Barbara Yaeggy (Cincinnati)</a> <a href="#">Oleksandr Tomalak (Los Alamos National Laboratory)</a> (until 11:20 AM) (This workshop will be held as a virtual event)
		11:50 AM	Discussion (This workshop will be held as a virtual event)	12:15 PM	Discussion (This workshop will be held as a virtual event)	10:50 AM	nutau-nucleon/nucleus deep inelastic scattering in the multi-GeV energy region - <a href="#">VANIYA ANSARI (ALIGARH MUSLIM UNIVERSITY)</a> (This workshop will be held as a virtual event) <a href="#">NuTau2021VaniyaAnsari.pdf</a>
						11:05 AM	On the Tau flavor of the cosmic neutrino flux - <a href="#">Yasaman Farzan (IPM)</a> (This workshop will be held as a virtual event) <a href="#">NUTau.pdf</a>
						11:20 AM	--- Lunch ---



# Workshop Agenda - PM

PM	12:30 PM	Tau neutrinos and SM - Xin Qian (BNL) Nitish Nayak (BNL) (until 2:30 PM) (This workshop will be held as a virtual event)	12:20 PM	--- Lunch break ---		12:40 PM	--- Lunch break ---		12:20 PM	Contributed talks II - Yuchieh Ku (Penn State) Nepomuk Otte (Georgia Institute of Technology) Tom Stuttard (Niels Bohr Institute) Mahdi Bagheri (Georgia Institute of Technology) (until 2:30 PM) (This workshop will be held as a virtual event)
	12:30 PM	Tau neutrinos and 3-flavor model - Stephen Parke (Fermilab) (This workshop will be held as a virtual event)	1:20 PM	Contributed talks I - Stella Oh (University of Cincinnati) Pedro Machado (Fermilab) Thomas Kuttler (LSU) Jeremy Hewes (University of Cincinnati) (until 3:30 PM) (This workshop will be held as a virtual event)		1:40 PM	Tau neutrino reconstruction techniques - Barbara Yaeggy (Cincinnati) Hanyu Wei (Brookhaven National Laboratory) (until 3:30 PM) (This workshop will be held as a virtual event)		12:20 PM	KM3NeT/ORCA sensitivity to atmospheric tau-neutrino appearance - Steffen Hallmann (DESY) (This workshop will be held as a virtual event)
		parke_nutau2021.pdf	1:20 PM	On the reliability of present predictions for tau neutrino fluxes - Maria Vittoria Garzelli (University of Hamburg) (This workshop will be held as a virtual event)		1:40 PM	Reconstruction of multi-GeV tau neutrinos in tracking detectors - Dario Autiero (Lyon, IPN) (This workshop will be held as a virtual event)			nutau2021_tau_appearance_km3net_compressed.pdf
	1:15 PM	Discussion (This workshop will be held as a virtual event)	1:35 PM	Appearance of tau neutrinos in the near detectors due to the oscillations involving sterile neutrinos - Katarzyna Grzelak (University of Warsaw) (This workshop will be held as a virtual event)		2:10 PM	Reconstruction, Flavor Identification and Future Prospects at High Energies - Juliana Stachurska (MIT) (This workshop will be held as a virtual event)		12:35 PM	The Giant Radio Array for Neutrino Detection - the experimental status and plans - Lech W Piotrowski (University of Warsaw) (This workshop will be held as a virtual event)
	1:30 PM	Tau neutrinos and lepton flavor at colliders-experiment - Vladimir Gligorov (CNRS France) (This workshop will be held as a virtual event)		Constraining tau neutrino transition magnetic moments at DUNE - Jingyu Zhu (Karlsruhe Institute of Technology) (This workshop will be held as a virtual event)			Discussion (This workshop will be held as a virtual event)			lwp_grand_nutau2021.pdf
		NuTau2021_LFAtColliders_092021.pdf	1:50 PM	Kinematic Tau neutrino search at DUNE far detectors - Thomas Kosc (Institut de Physique des 1 Infinis (Lyon, France)) (This workshop will be held as a virtual event)		2:30 PM	White paper writing session (until 5:30 PM) (This workshop will be held as a virtual event)		12:50 PM	Prospects for EeV tau-neutrino physics with in-ice radio detectors - Christian Glaser (Uppsala University, Sweden) (This workshop will be held as a virtual event)
	1:50 PM	Tau neutrinos and lepton flavor at colliders-theory - Yuval Grossman (Cornell) (This workshop will be held as a virtual event)	2:05 PM	Break (This workshop will be held as a virtual event)						glaser_inice_radio_tau.pdf
		nuTau2021.pdf	2:20 PM	Learning from Tau Neutrino Appearance at Long Baselines - Kevin J Kelly (Fermilab) (This workshop will be held as a virtual event)					1:05 PM	POEMMA: Probe Of Extreme Multi-Messenger Astrophysics - John F Krizmanic (UMBC/CRESST/NASA/GSFC) (This workshop will be held as a virtual event)
	2:10 PM	Discussion (This workshop will be held as a virtual event)	2:30 PM	Prospects for anomalous tau neutrino appearance searches at the DUNE Near Detector - Miriama Rajaoalisoa (University of Cincinnati) (This workshop will be held as a virtual event)						POEMMA-nuTau2021-Krizmanic.pdf
				New tau neutrino oscillation constraints on unitary violation - Julia Gehrlein (Brookhaven National Laboratory) (This workshop will be held as a virtual event)					1:20 PM	Break (This workshop will be held as a virtual event)
	2:30 PM	White paper discussion - Peter Denton (Brookhaven National Lab) (until 3:00 PM) (This workshop will be held as a virtual event)	2:45 PM	Constraining neutrino magnetic moments at the LHC - Roshan Mammen Abraham (Oklahoma State University) (This workshop will be held as a virtual event)						Tomalak_talk_Tau2021.pdf
		NuTau21_Whitepaper_Overview.pdf	3:00 PM	White paper writing session (until 5:30 PM) (This workshop will be held as a virtual event)					1:30 PM	Axial and pseudoscalar form factor with tau neutrinos - Oleksandr Tomalak (Los Alamos National Laboratory) (This workshop will be held as a virtual event)
	3:00 PM	White paper writing session (until 5:30 PM) (This workshop will be held as a virtual event)	3:15 PM							Tomalak_talk_Tau2021.pdf
									1:45 PM	Looking for HNLs via Double Bang signals - Ivan Martinez-Soler (Fermilab and Northwestern University) (This workshop will be held as a virtual event)
										Talk_IMS.pdf
									2:00 PM	Tau neutrino propagation with NuPropEarth - Alfonso Garcia (Harvard University) (This workshop will be held as a virtual event)
										nutau.pdf
									2:15 PM	Probing Secret Interactions of Tau Neutrinos in the High-Statistics Era - Ivan Esteban (CCAPP, Ohio State University) (This workshop will be held as a virtual event)
										Talk.pdf
									2:30 PM	Summary/Discussion - Julia Gehrlein (until 3:00 PM) (This workshop will be held as a virtual event)
										closing_nutau_2021.pdf
									3:00 PM	White paper writing session (until 5:00 PM) (This workshop will be held as a virtual event)
									5:00 PM	Fermilab W&C from MicroBooNE (This workshop will be held as a virtual event)

# Snowmass Frontiers

- ▶ NF01: neutrino oscillations
- ▶ NF03: neutrino BSM
- ▶ NF04: neutrinos from natural sources
- ▶ NF06: neutrino interaction cross sections
- ▶ NF08/TF11: theory of neutrino physics
- ▶ NF09: artificial neutrino sources
- ▶ NF10: neutrino detectors
- ▶ EF03: EW Physics: Heavy flavor and top quark physics
- ▶ EF09: BSM: More general explorations
- ▶ CF7: Cosmic Probes of Fundamental Physics
- ▶ UF01: Underground Facilities for Neutrinos
- ▶ IF: Instrumentation Frontier

# Overall Themes to Emerge from Wkshp

- ▶ More tau neutrino experiments are coming online  
→ push towards a common goal of **high precision measurements of the PMNS matrix elements**. What will be the ultimate precision on the matrix elements we can achieve, what are the (experimental) requirements to achieve this goal?
- ▶ Use of **multiple experiments and combination** to approach the challenge of tau neutrinos: BSM scenarios, unitarity, NSI, . . . , alleviate common systematic uncertainties? Driven by theorists or experimentalists?



# Overall Themes to Emerge from Wkshp

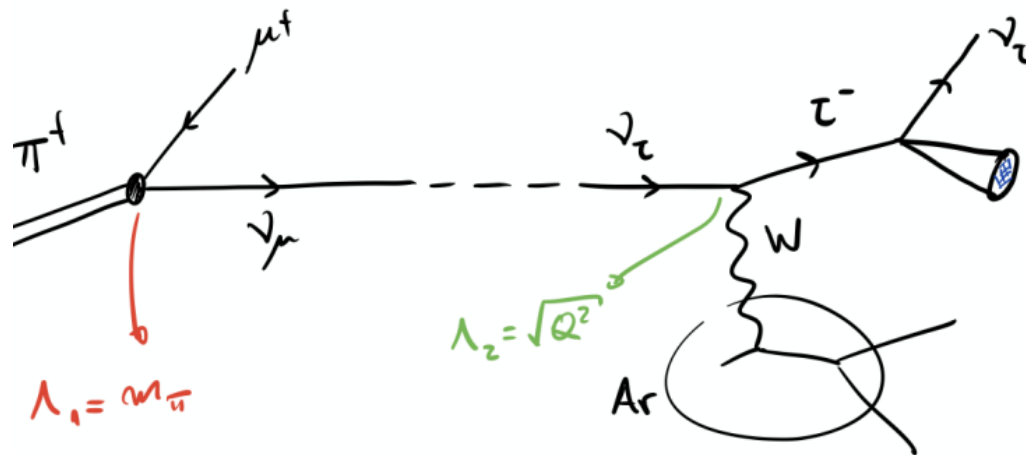
- ▶ **Connections** of tau neutrinos at the LHC with VHE atmospheric measurements in water/ice detectors needs further exploring:  
How will we address the low x region needed as input for the atmospheric oscillation experiments?  
  
→ Bring these communities together to develop the measurement programs needed
- ▶ **Lepton universality** is another big physics theme that we can explore in the neutral lepton sector of which  $\nu_\tau$  is the least understood.  
  
→ What do we need to improve the experimental data and theoretical calculations needed to do these tests?

# Some new topics/ideas to explore

## What can we learn with tau neutrinos?

Energy dependent neutrino mixing parameters

Babu et al 2108.11961



Standard case

$$A(\nu_\mu \rightarrow \nu_\tau) = \langle \nu_\tau | \exp(-iHL) | \nu_\mu \rangle \\ = \sum_i U_{\tau i} U_{\mu i}^* \exp\left(-\frac{im_i^2 L}{2E}\right)$$

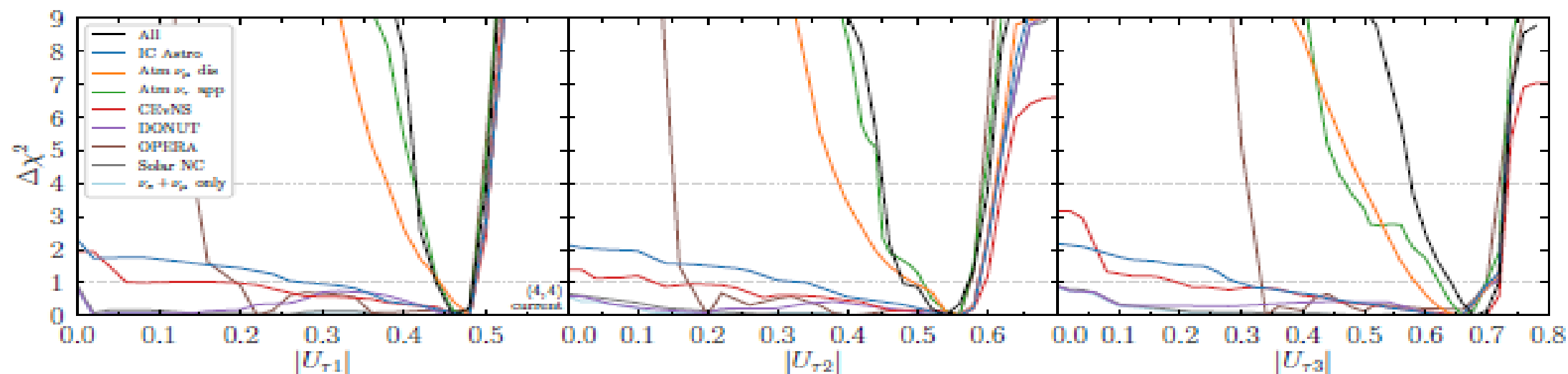
With E dependent effects

$$A(\nu_\mu \rightarrow \nu_\tau) = \langle \nu_\tau, Q_2^2 | \exp(-iHL) | \nu_\mu, Q_1^2 \rangle \\ = \sum_i U_{\tau i}(Q_2^2) U_{\mu i}^*(Q_1^2) \exp\left(-\frac{im_i^2 L}{2E}\right)$$

This effect induces zero baseline  $\nu_\mu$  to  $\nu_\tau$  appearance, particularly at high energies

# Precision estimation of PMNS tau matrix elements with combination of many datasets

**most** impactful constraints: atmospheric  $\nu_\mu$  disappearance, atmospheric  $\nu_\tau$  appearance, long baseline  $\nu_\tau$  appearance data



[Denton, Gehrlein '21]

# UHE Tau Neutrinos and Earth Skimming

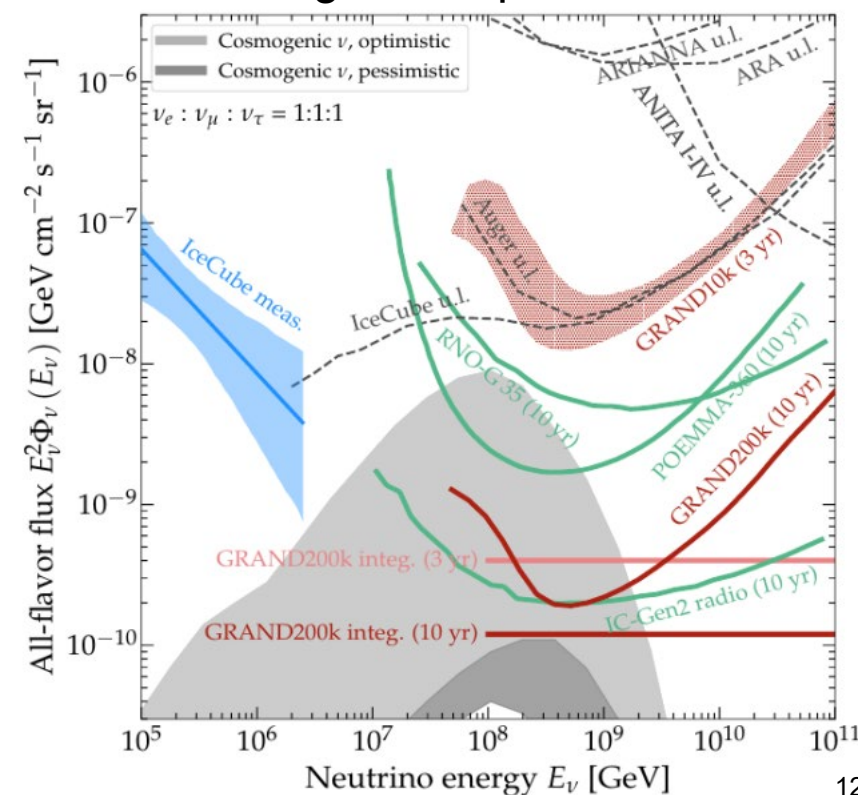
## Earth skimming channel for detection



### Complex three stage process

- Attenuation through Earth with regeneration: NC  
CC +  $\tau$  CC  
CC +  $\tau$  decay
- CC interaction and  $\tau$  energy loss → rate strongly depends on loss range up to 40 km!
- Exit and  $\tau$  decay in air, decay length 50 km EeV → escapes > 10 EeV

Several new very large array radio experiments proposed to detect UHE nutau using earth skimming techniques:

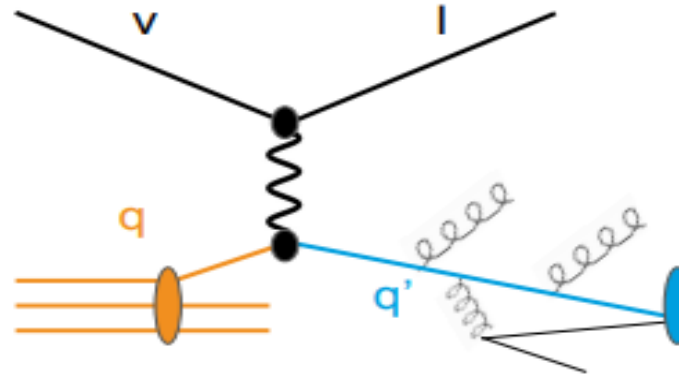


# Physics with Nutaus at LHC

## Physics with tau Neutrinos: Interactions.

From  
Felix Kling:

The FPF is essentially a Neutrino-Ion collider with  $\sqrt{s} \sim 50 \text{ GeV}$



### Initial State

nuclear PDFs via  
measurements on  
different targets

strange quark PDFs  
via  $\nu s \rightarrow l c$

### Final State

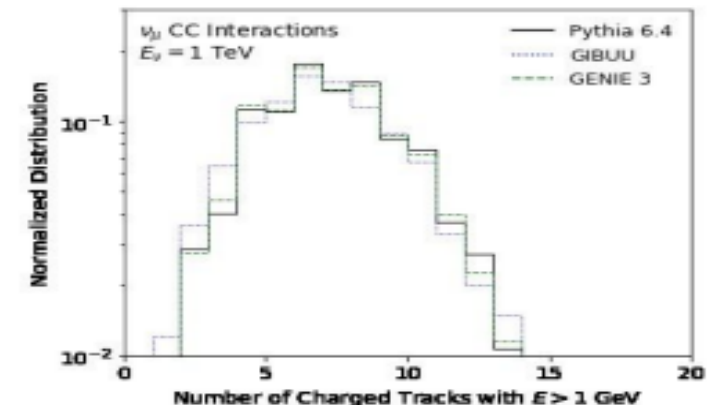
response of cold nuclear matter to  
fast moving quarks

medium-induced energy losses

fragmentation functions

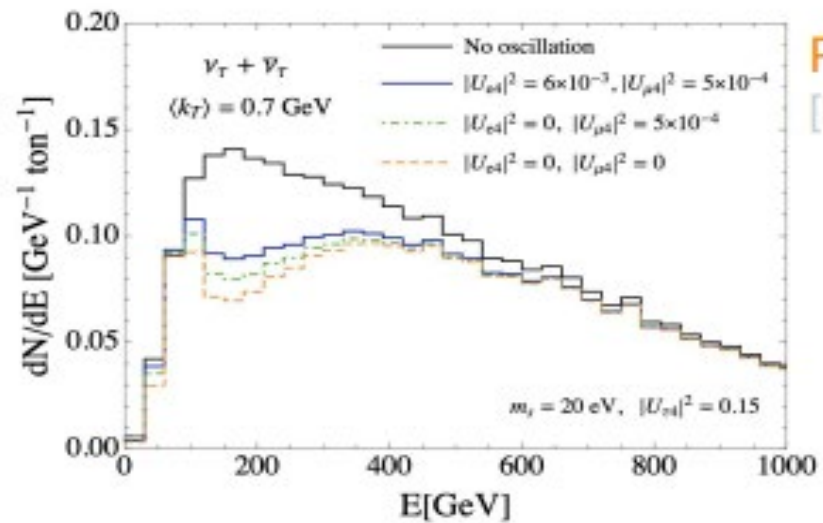
final state interactions

(see M. Diwan  
Talk for more  
detail)



# Physics with tau Neutrinos: BSM.

Use tau neutrinos as probe of new physics.

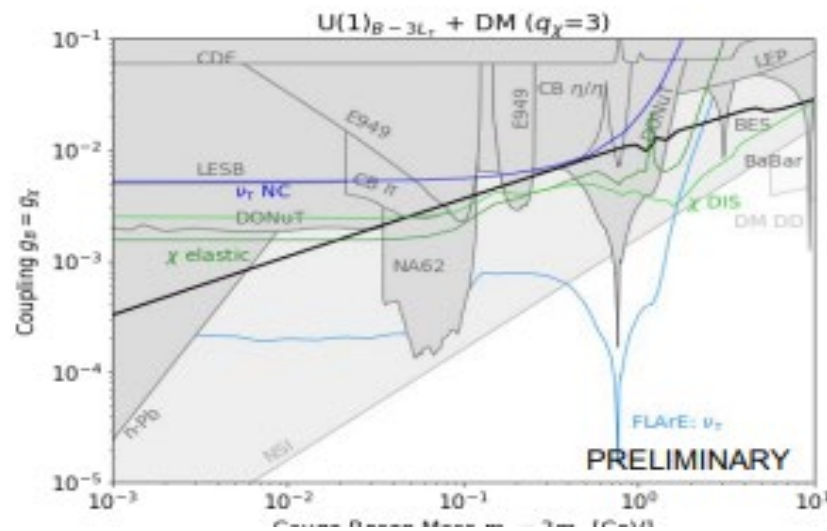
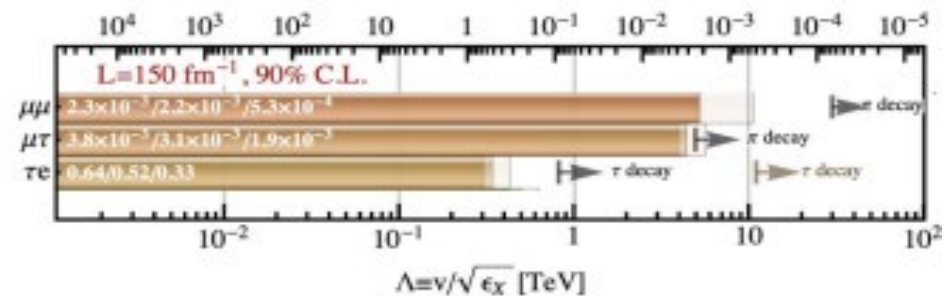


## Probing Sterile Neutrino Oscillations

[Bai et al, 2002.03012]

## Probing EFTs

[Falkowski et al, 2002.03012]



## Probing Light Tau-Neutrinophilic Mediators

[Kling, 2005.03594, Batell et al, in progress]

also see talk by  
Roshan Mammen Abraham on  
Tau Neutrino MDMs



# Snowmass NuTau Whitepaper (P. Denton leads)

The read only version of the Whitepaper is available [here](#)

- ▶ Title: **Tau Neutrinos in the Next Decade: from GeV to EeV**  
**A Snowmass Whitepaper**

Scope: physics where it matters that it's a tau neutrino

- ▶ Sections:
  1. History and motivation (Denton)
  2. Experimental probes (Bishai, de Roeck(?), & Wissel)
  3. Tools (Aurisano)
  4. Theoretical interests (de Gouvêa & Mocioiu)
  5. Conclusions

Organizers will take charge with the abstract, history, and conclusions with input from all authors

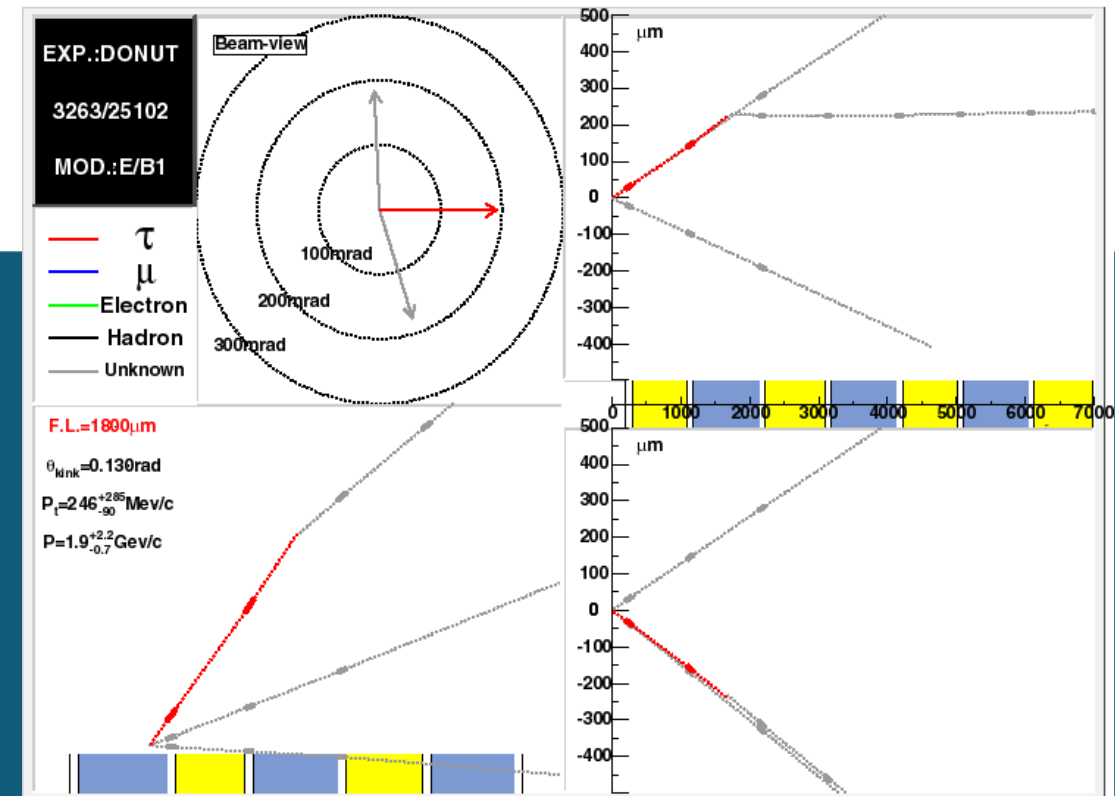
- ▶ This is about the future: Snowmass & P5

How are we going to spend resources on tau neutrinos in the next decade+?

- ▶ Don't (extensively) reproduce existing work

A brief introductory section on tau neutrino history exists

# Nutaus are here!



BNL scientists are emerging as leaders of a very diverse community focused on opening up new opportunities and searches using the least understood and studied particle of the Standard Model.