Tau neutrinos. What do we know ? What can we learn from them ?

Katarzyna Grzelak

High Energy Physics Seminar
University of Warsaw

2.06.2023

Outline

Tau neutrinos

- physics motivation
- detection techniques
- experiments that observed ν_τ's
- oscillations involving tau neutrinos
- new ideas and experiments

Physics motivation

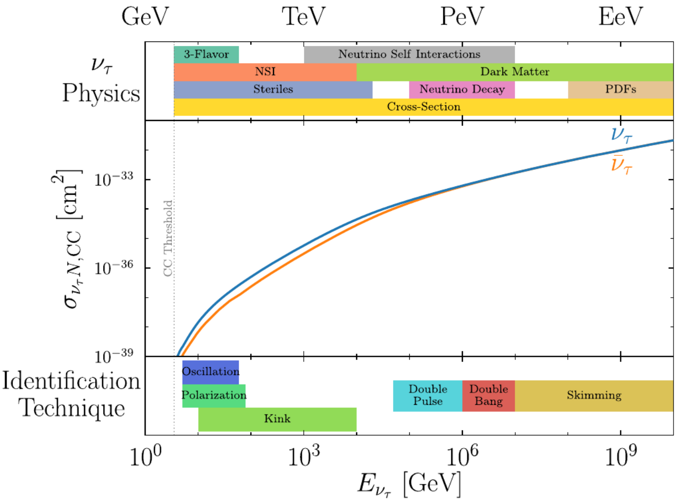
Why study tau neutrinos ?

- To improve knowledge of cross-sections and oscillations parameters, – BSM physics can be hidden here !
- To test the three neutrino flavour picture – is oscillation matrix unitary, are there sterile neutrinos ?
- To fully probe lepton flavour universality precision knowledge of all generations is needed
- Ultra High Energy Neutrinos: sources, flavour composition
- Anomalous ANITA events

NuTau White Paper: Tau neutrinos in the next decade: from GeV to EeV

R.Abraham et al.(K.Grzelak) 2022, J.Phys.G:Nucl.Part.Phys.49, 110501

Physics motivation



ν_τ cross-sections, various physics topics,detection techniques, and relevant energy scale.

NuTau White Paper

Tau lepton - reminder

Identification of $\nu_\tau \equiv$ identification of τ lepton

$$c\tau \simeq 87\mu m$$

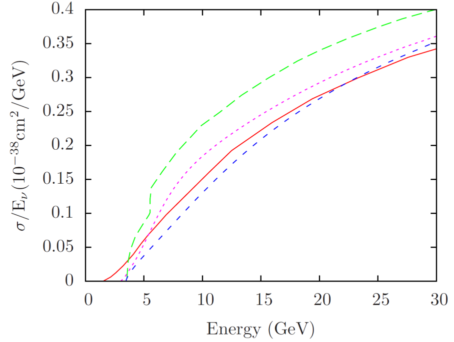
E_τ	$\gamma c\tau$
20 GeV	$\simeq$ 1 mm
1 PeV $= 10^6$ GeV	$\simeq$ 50 m
1 EeV $= 10^9$ GeV	$\simeq$ 50 km

Main τ decay modes:

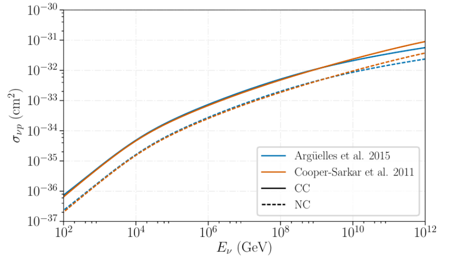
τ^- decay modes	Fraction (Γ_i/Γ)
$\mu^-\overline{\nu}_\mu\nu_\tau$	(17.41 ± 0.04) %
$e^-\overline{\nu}_e\nu_\tau$	(17.83 ± 0.04) %
$\pi^-\nu_\tau$	(10.83 ± 0.06) %
$\pi^-\pi^\circ\nu_\tau$	(25.52 ± 0.09) %
$\pi^-2\pi^\circ\nu_\tau$	(9.52 ± 0.11) %
$\pi^-\pi^+\pi^-\nu_\tau$	(9.31 ± 0.06) %
$\pi^-\pi^+\pi^-\pi^\circ\nu_\tau$	(4.62 ± 0.06) %

Theoretical ν_τ cross-sections

Energy threshold for charged-current ν_τ-nucleon interactions
$E_{th} \simeq 3.5$ GeV

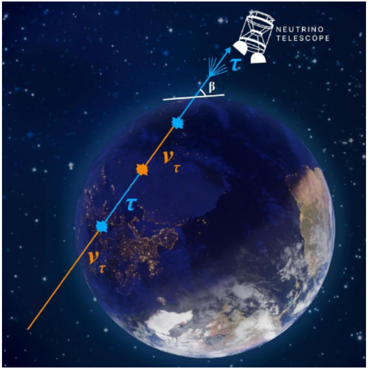


ν_τ cross-sections for high energies



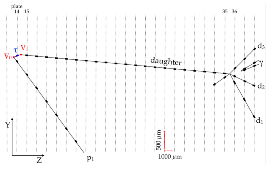
High energy

The neutrino interaction length for energies greater than tens of TeV becomes comparable to the size of the Earth.
Unique for $\nu_\tau' s$: regenerated tau neutrino flux $\nu_\tau \to \tau \to \nu_\tau$



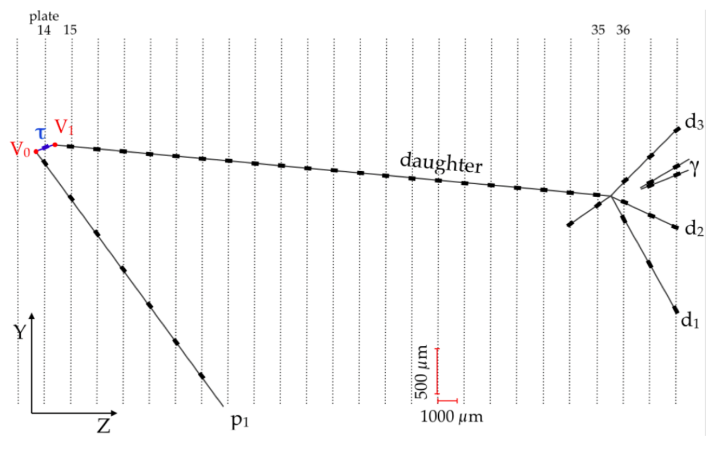
ν_τ detection techniques

- Direct observation of τ decay point (kink)



- Kinematic-based, statistical analysis
- Higher energies – observation of two correlated cascades
- Ultra high energies – Earth skimming events

Direct observation of τ decay point



Event display of one of the OPERA ν_τ candidates.

OPERA, Phys.Rev.Lett.115,121802 (2015)

Direct observation of τ decay point

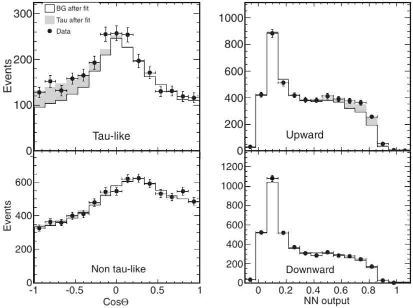
Experiments that found ν_τ candidates

- DONuT – Fermilab, beamdump experiment, ν_τ's from leptonic decays of D_s mesons
- OPERA – CERN-Gran Sasso, long-baseline experiment, first ν_τ's from oscillations

Steel (DONuT) or lead (OPERA) layers interleaved with nuclear emulsion sheets.

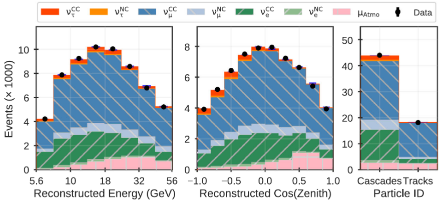
Kinematic based, statistical analyses

Studies of atmospheric neutrinos



SuperK

2018 Phys.Rev.D98 052006



IceCube DeepCore

2019 Phys.Rev.D99 032007

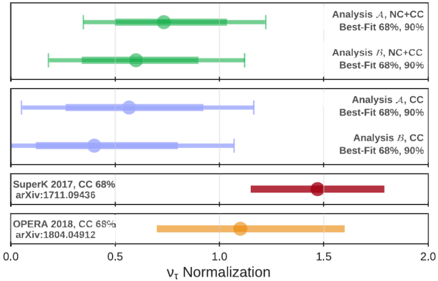
Statistical separation from not-ν_τ atmospheric neutrino backgrounds.

Kinematic based, statistical analyses

Experiments that found ν_τ candidates

- SuperK – Kamioka mine, atmospheric ν_τ's, 15 years of data taking
- IceCube DeepCore – South Pole, atmospheric ν_τ's, 3 years of data taking

Cherenkov optical radiation in water (SuperK) or ice (IceCube DeepCore)



Blue and green points: results from IceCube DeepCore analyses.

Analysis A: atmospheric muon simulation used

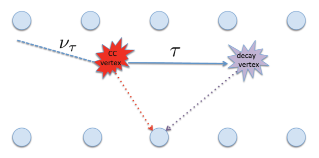
Analysis B: data-driven approach to estimate background

Aartsen et al (IceCube) 2019 Phys.Rev.D99 032007

τ normalization N

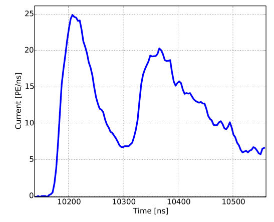
N = 0 $\rightarrow$ no ν_τ-appearance
N = 1 $\rightarrow$ standard 3-flavour oscillations
N > 1 $\rightarrow$ BSM physics

Higher energies – observation of two correlated cascades



Blue circles → photon sensors (in ice)

IceCube, Phys.Rev.D 93,022001 (2016)



IceCube

Simulated E_ν = 2.4 PeV.

Higher energies – observation of two correlated cascades

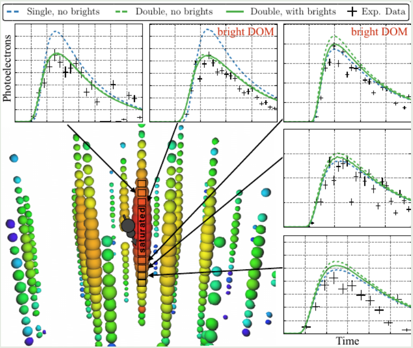
Experiment that found ν_τ candidates

Ice Cube - South Pole, astrophysical ν_τ's, 7.5 years of data taking, 2 ν_τ candidates

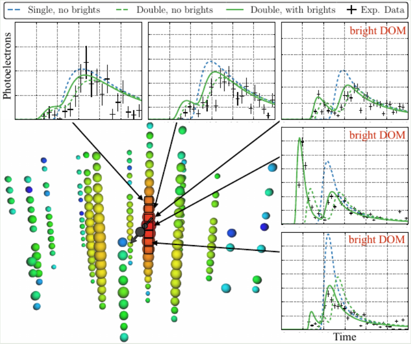
Cherenkov optical radiation in ice, spatially separated energy depositions (double pulse)

Higher energies – observation of two correlated cascades

Two IceCube astrophysical ν_τ candidates

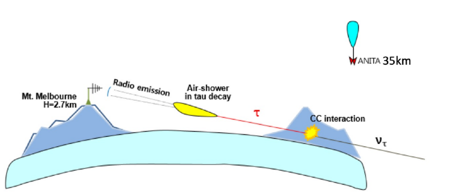


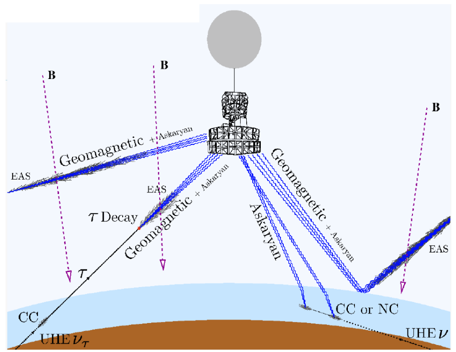
Energy > 1.5 PeV



Energy > 65 PeV

Earth skimming ν_τ events





EAS = Extensive Air Shower

UHE = Ultra High Energy

Sources of radio-frequency and microwave emission from high energy showers

EAS = Extensive Air Shower

Askaryan radiation, G.Askaryan (1962)

- EAS develop a charge asymmetry ($\sim$ 20 % electron excess) from Compton scattering and positron annihilation
- electron excess moves in a dielectric medium as a compact bunch
- $\Rightarrow$ coherent radio/microwave Cherenkov radiation

Geomagnetic radiation

- geomagnetic separation of charges
- $\Rightarrow$ synchrotron radiation

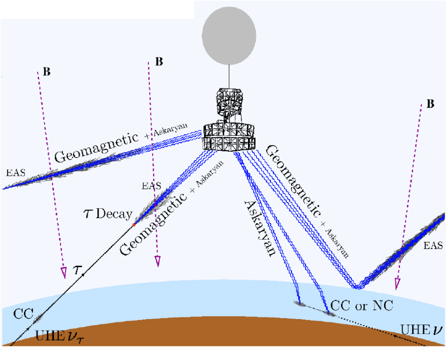
Earth skimming ν_τ events

Experiment that found (?) ν_τ candidates

ANITA - stratospheric baloon flying over Antarctic ice, astrophysical ν_τ's, 4 flights, 4(?) anomalous events

Radio/microwave Cherenkov radiation in ice.

Sources of radio-frequency and microwave emission from high energy showers



Four flights of ANITA over Antarctic ice:

- ANITA-I and ANITA-II – two anomalous upward-going events, suggesting cross-section for ν_τ interactions is smaller than in SM
- ANITA-IV – 4 events observed at angles close to the horizon, consistent with ν_τ hypothesis, but in tension with Auger's ν_τ limits

All ν_τ events detected to date

Experiment	Source	Nb of detected evts
DONuT	Production	9(1.48)
OPERA	Long-baseline	10(2.4)
SuperK	Atmospheric	291
IceCube	Atmospheric	2360/1379
IceCube	Astrophysical	2
ANITA	Astrophysical	4 ?

OPERA – ν_τ appearance with 6.1σ significance

SuperK – hypothesis of no-tau appearance excluded at 4.6σ

For DONuT and OPERA number of background events shown in brackets

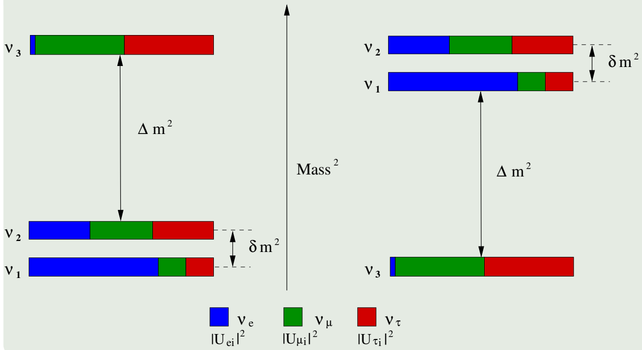
Three-flavour neutrino oscillations

Three-flavour neutrino oscillation matrix:

$$\mathrm{U} = \begin{pmatrix} U_{\mathrm{e}1} & U_{\mathrm{e}2} & U_{\mathrm{e}3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}.$$

- $|U_{\alpha j}|^2$, describe the neutrino flavour-α fraction of ν_j
- Unitarity of the oscillation matrix, e.q.:
  $|U_{e3}|^2 + |U_{\mu 3}|^2 + |U_{\tau 3}|^2 = 1$

Neutrino oscillation matrix



Neutrino mass states as the combination of known flavour states.

- Most of current knowledge about neutrino mixing matrix is from ν_e and ν_μ
- In global fits unitarity of the matrix is assumed
- From experiments: $|U_{e3}|^2 + |U_{\mu 3}|^2 \simeq 0.5$
  Tau row allows for significant deviations from unitarity.

Sterile neutrinos

Sterile neutrino:

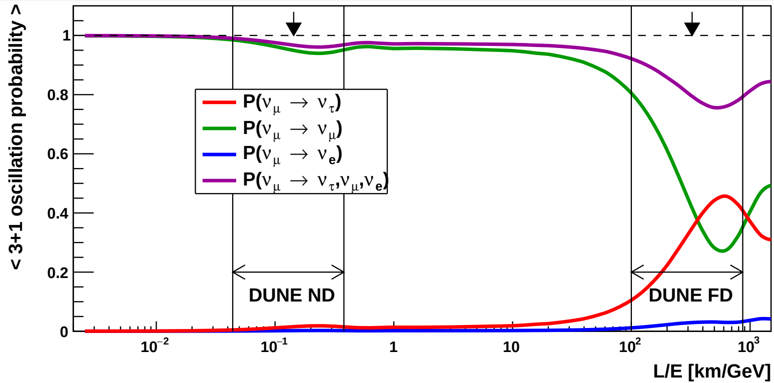
- neutral lepton that does not take part in the weak interactions
- theoretically well motivated (ν mass generation mechanism)
- can take part in neutrino oscillations

Extended oscillation matrix:

$$\mathrm{U} = \begin{pmatrix} U_{\mathrm{e}1} & U_{\mathrm{e}2} & U_{\mathrm{e}3} & U_{\mathrm{e}4} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \cdots \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \cdots \\ U_{\mathrm{s}1} & U_{\mathrm{s}2} & U_{\mathrm{s}3} & U_{\mathrm{s}4} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix} .$$

Model with one sterile neutrino

- Mixing matrix – 4 $\times$ 4 unitary matrix with 9 parameters
- One new mass-squared difference Δm^2_{41} (or Δm^2_{42} or Δm^2_{43})
- Possible effects: smaller observed flux, possibly energy-dependent or anomalous appearance of neutrinos



Example: 3+1 oscillation probabilities in the accelerator neutrino experiments

ν_τ interactions in the near detectors

τ appearance in the near detectors

- "Near detector"= detector located $\sim$ 500m - 1 km from the source of accelerator neutrinos
- Appearance of τ neutrinos in the near detectors = interesting signature of sterile neutrinos ...
- ... for $\Delta m^2_{41} \gtrsim 1\ \mathrm{eV}^2$

ν_τ interactions in the near detectors

In the near detectors:

$$\mathrm{P}_{\nu_\mu\to\nu_\tau}(L,E) \simeq 4|U_{\mu 4}|^2|U_{\tau 4}|^2 \sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right)$$
$$= \cos^4\theta_{14}\sin^2 2\theta_{24}\sin^2\theta_{34}\sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right).$$

$\rightarrow$ access to θ_{34} depends on θ_{24}

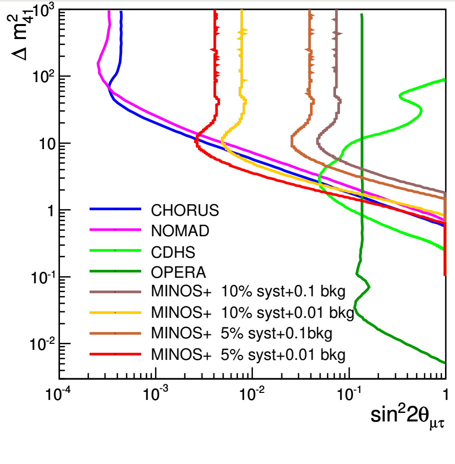
Sensitivity to ν_τ appearance in the near detectors

$$P_{\nu_\mu \to \nu_\tau}(L, E) = \sin^2 2\theta_{\mu\tau} \sin^2 \left(\frac{\Delta m^2_{41} L}{4E} \right)$$

where

$$\sin^2 2\theta_{\mu\tau} \equiv \cos^4 \theta_{14} \sin^2 2\theta_{24} \sin^2 \theta_{34}$$

Sensitivity to ν_τ appearance in the near detectors



Compilation of limits and sensitivities on the parameters of tau-sterile mixing.

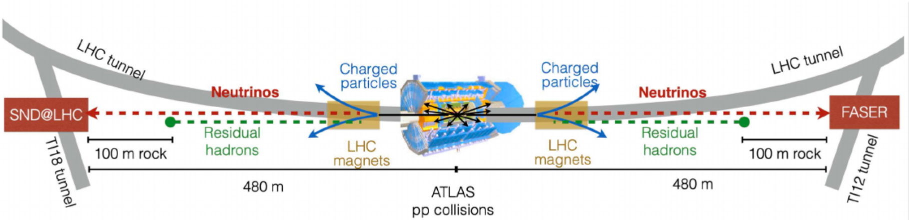
Future directions (in random order)

Neutrino sources

- Neutrinos from the LHC collider
- Ultra-high energy neutrinos ($\rightarrow$ L. Piotrowski seminar)
- Atmospheric neutrinos ($\rightarrow$ M.Posiadała-Zezula seminar)
- Accelerator neutrinos
- Neutrinos from D_s decays

FASERν et al. Detection of neutrinos from the LHC

- Flux of TeV-energy neutrinos from the collision of the LHC proton beams
- Location near the ATLAS interaction point
- Far forward direction, neutrinos of all flavours, ν_τ from decays of charm D mesons
- FASERν - emulsion films interleaved with tungsten plates

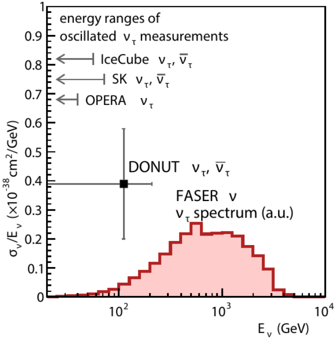


FASERν et al. Detection of neutrinos from LHC

	Detector			Number of CC interactions		
Name	Mass	Coverage	Luminosity	$\nu_e+\bar{\nu}_e$	$\nu_\mu+\bar{\nu}_\mu$	$\nu_\tau+\bar{\nu}_\tau$
FASERν	1 ton	$\eta \gtrsim 8.5$	150 fb^{-1}	901/3.4k	4.7k/7.1k	15/97
SND@LHC	800kg	$7 < \eta < 8.5$	150 fb^{-1}	137/395	790/1.0k	7.6/18.6
FASERν2	20 tons	$\eta \gtrsim 8$	3 ab^{-1}	178k/668k	943k/1.4M	2.3k/20k
FLArE	10 tons	$\eta \gtrsim 7.5$	3 ab^{-1}	36k/113k	203k/268k	1.5k/4k
AdvSND	2 tons	$7.2 \lesssim \eta \lesssim 9.2$	3 ab^{-1}	6.5k/20k	41k/53k	190/754

NuTau White Paper

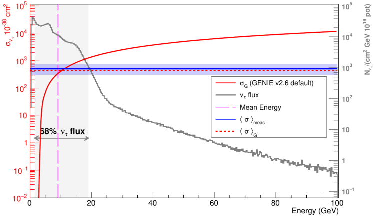
ν_τ cross sections



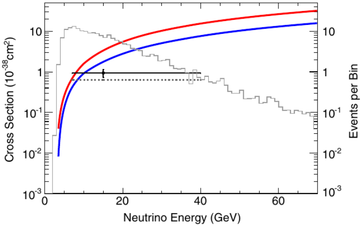
Abreu et al (FASER)

Eur.Phys.J.C 80 C1

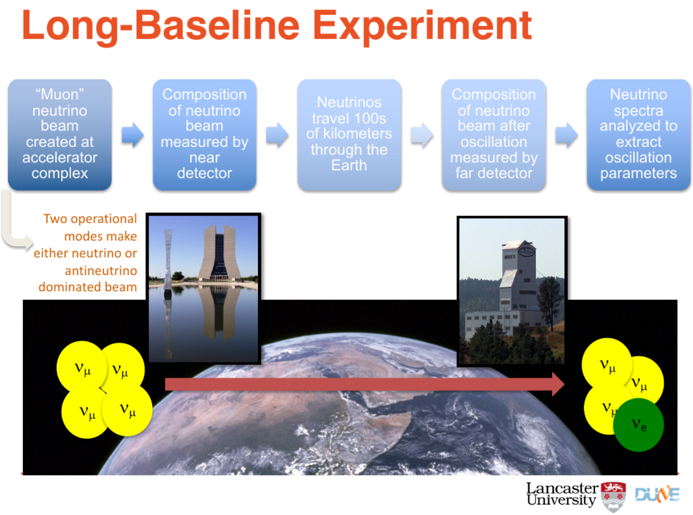
Flux-averaged charged-current ν_τ cross-sections.



OPERA

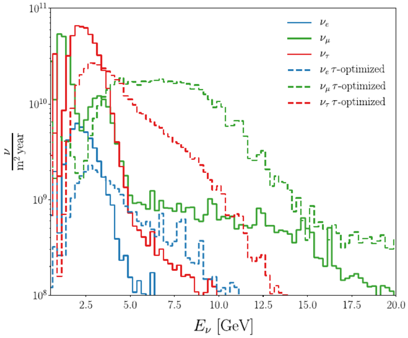


SuperK



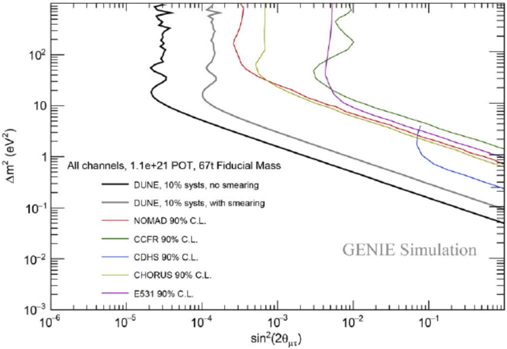
J.Nowak HEP Seminar in Warsaw

DUNE flux



- LAr technology: excellent event topology reconstruction capabilities
- High intensity beam (1.2 MW $\rightarrow$ 2.4MW)
- Part of the flux above τ production threshold
- Possible option of τ-optimized beam

Sensitivity to ν_τ appearance in the near detectors



NuTau White Paper

Initial approach to sensitivities on tau-sterile mixing in DUNE.

Instead of summary

Experiments designed to/interested in study ν_τ-related neutrino physics (present and future):

Neutrino sources

- Neutrinos from the LHC collider (FASERν,SNDLHC,AdvSND,FASERν2, FLArE)
- Ultra-high energy neutrinos (ANITA,ARA,GRAND,ARIANNA . . .)
- Atmospheric neutrinos (SuperK,IceCube/DeepCore,HyperK,KM3NeT/ORCA . . .)
- Accelerator neutrinos (DUNE)
- Neutrinos from D_s decays(NA65/DsTau)