Beyond Three-Flavor ν Oscillations with DUNE

Alexandre Sousa
University of Cincinnati, on behalf of the DUNE Collaboration

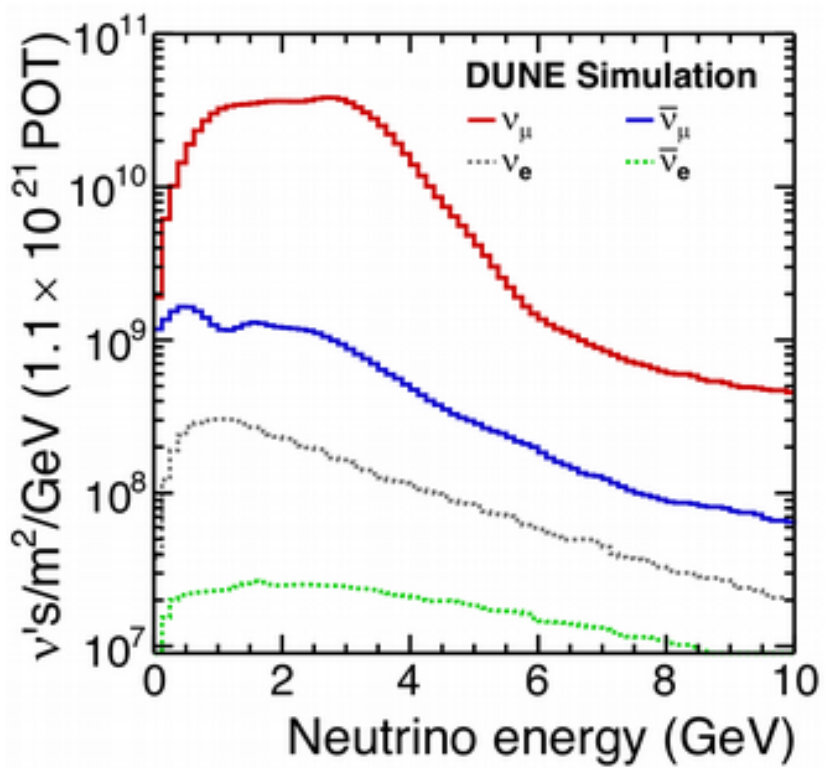
Snowmass 2021 Community Summer Study, Seattle
July 19, 2022

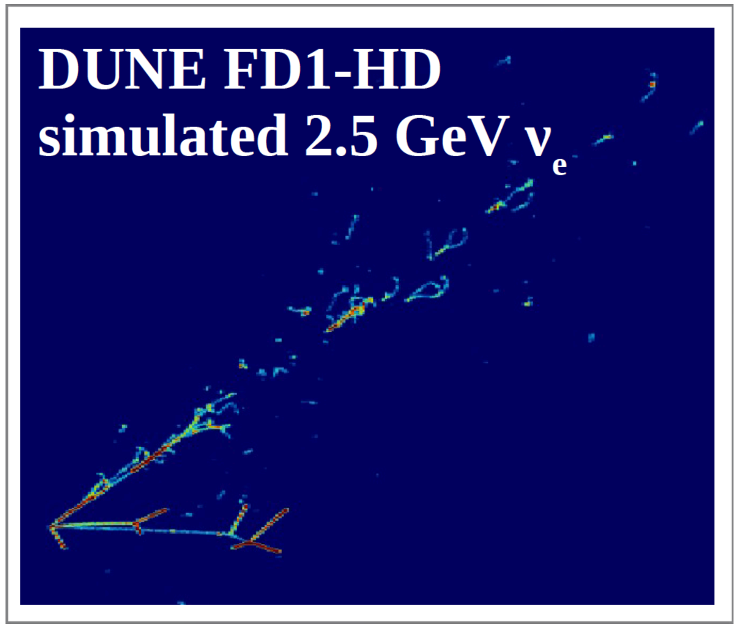
UNIVERSITY OF Cincinnati

DUNE

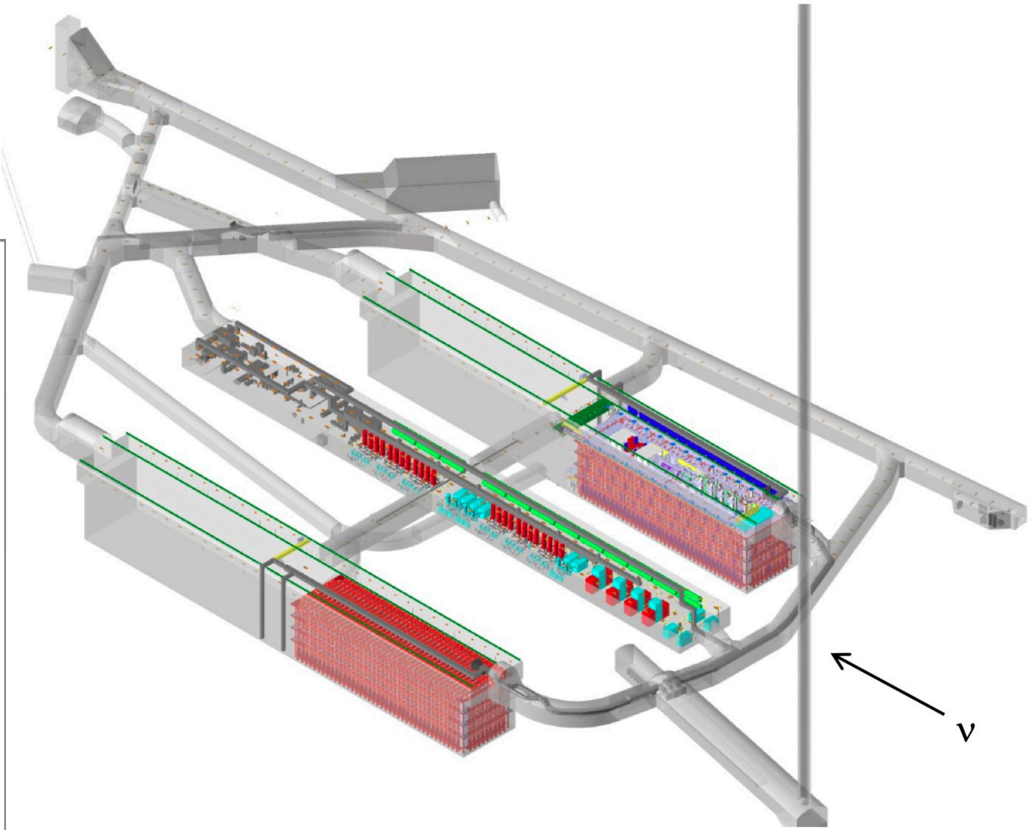
DUNE is a Machine for Discovery!

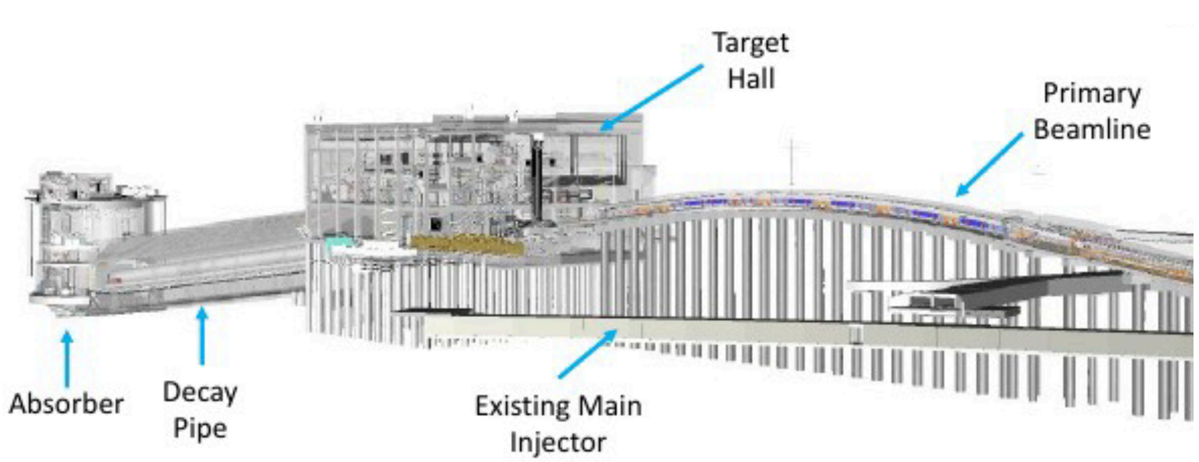
- High-intensity wide-band LBNF neutrino beam
  - 1.2 MW upgradeable to 2.4 MW



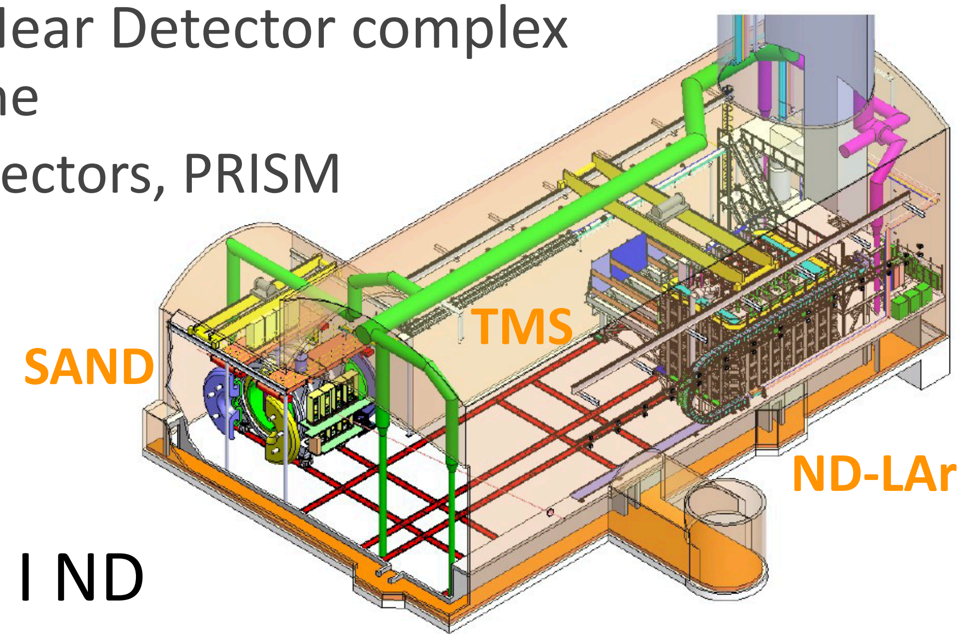


- Far Detector 1500m underground at SURF
  - 1300 km baseline
  - up to 4×17 kton modules, LArTPC technology





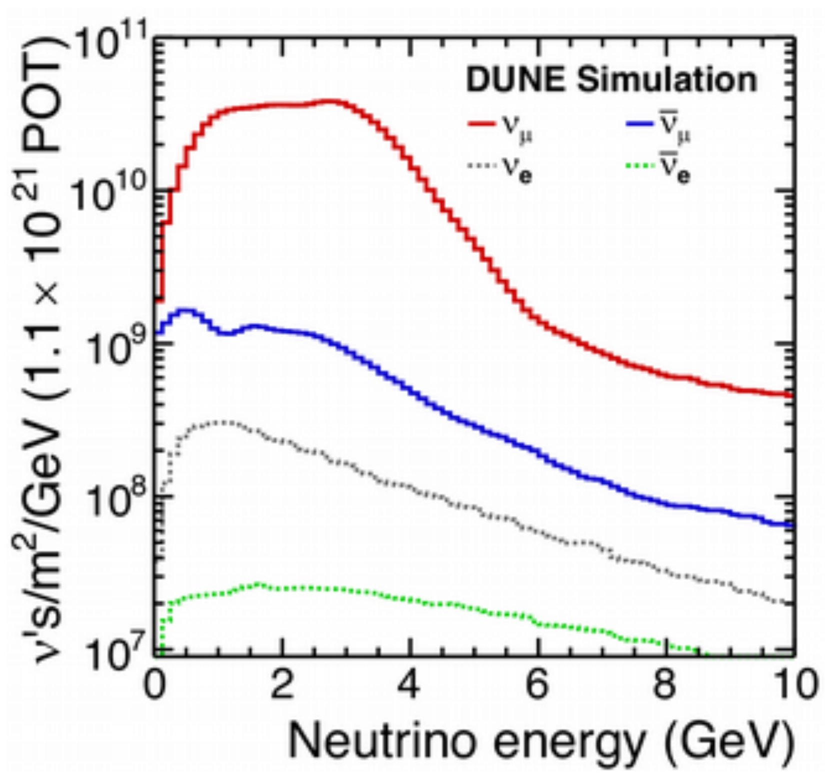
- Highly-capable Near Detector complex
  - 574 m baseline
  - High-Res. Detectors, PRISM

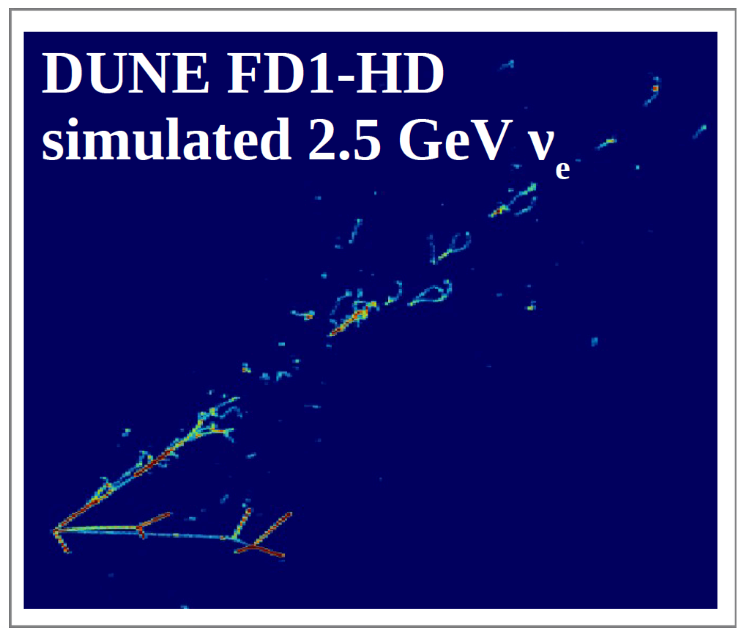


Phase I ND

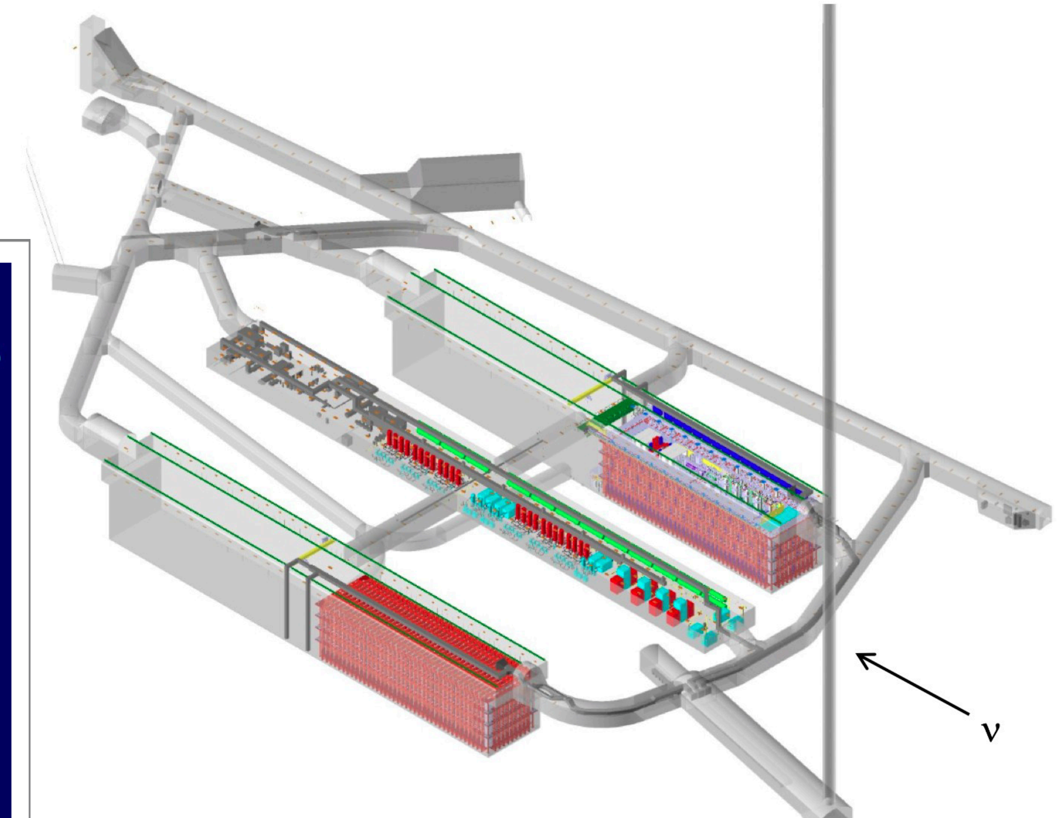
DUNE is a Machine for Discovery!

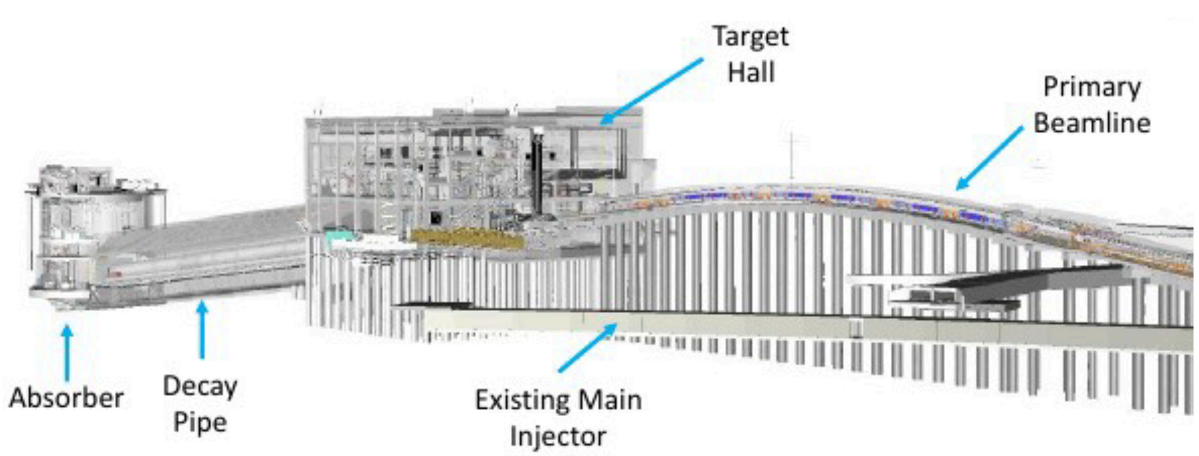
- High-intensity wide-band LBNF neutrino beam
  - 1.2 MW upgradeable to 2.4 MW



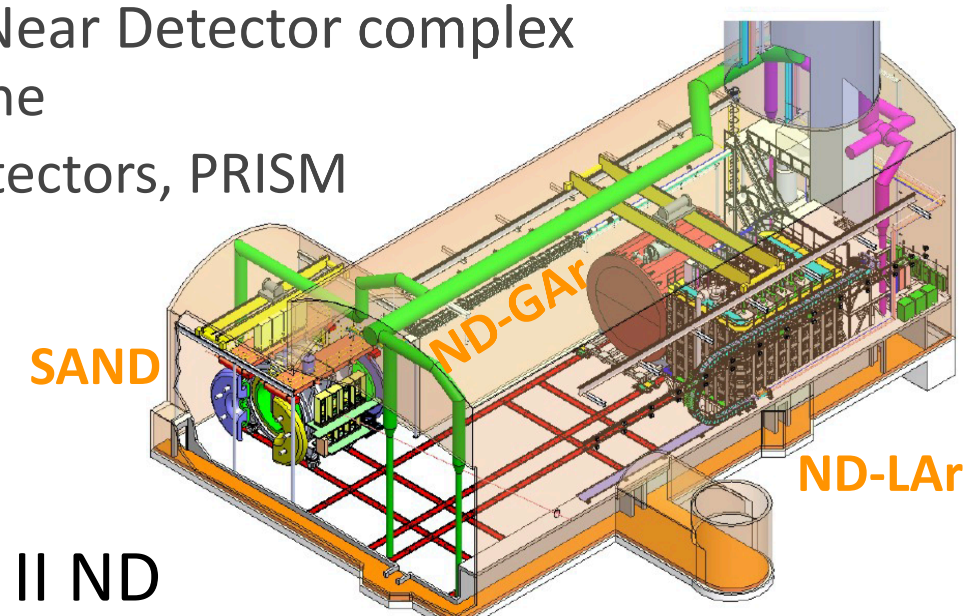


- Far Detector 1500m underground at SURF
  - 1300 km baseline
  - up to 4×17 kton modules, LArTPC technology





- Highly-capable Near Detector complex
  - 574 m baseline
  - High-Res. Detectors, PRISM



Phase II ND

DUNE is a Machine for Discovery!

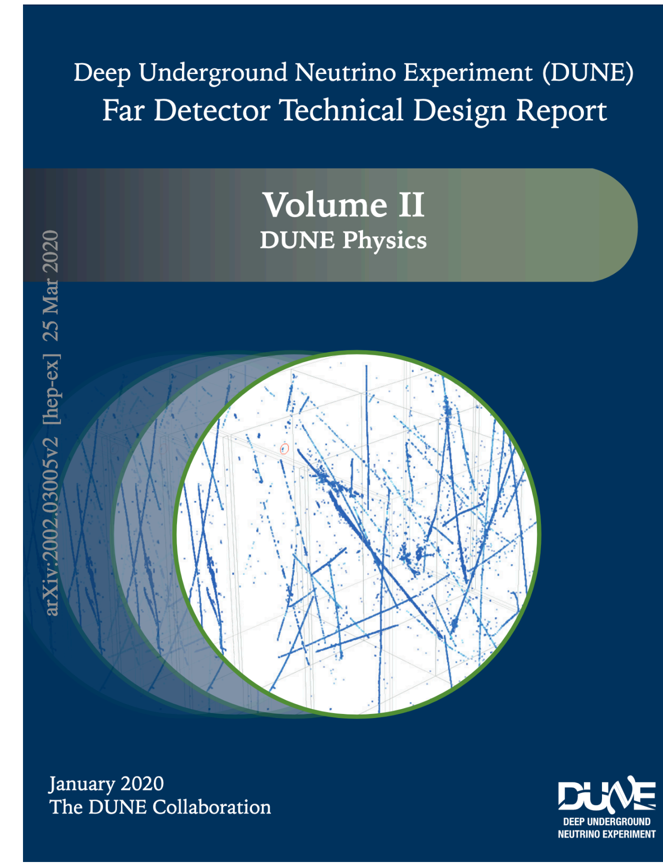
- **Non-standard short-baseline and long-baseline oscillation phenomena**
  - Mixing with light sterile neutrinos
  - Large extra-dimensions
  - Non-unitarity of the mixing matrix
  - Non-standard neutrino interactions
  - Violation of CPT Symmetry

In this talk!

- **Searches for new phenomena/particles at the ND**
  - Neutrino trident interactions
  - Heavy neutral leptons
  - Low-mass dark matter
  - Axion-like particles

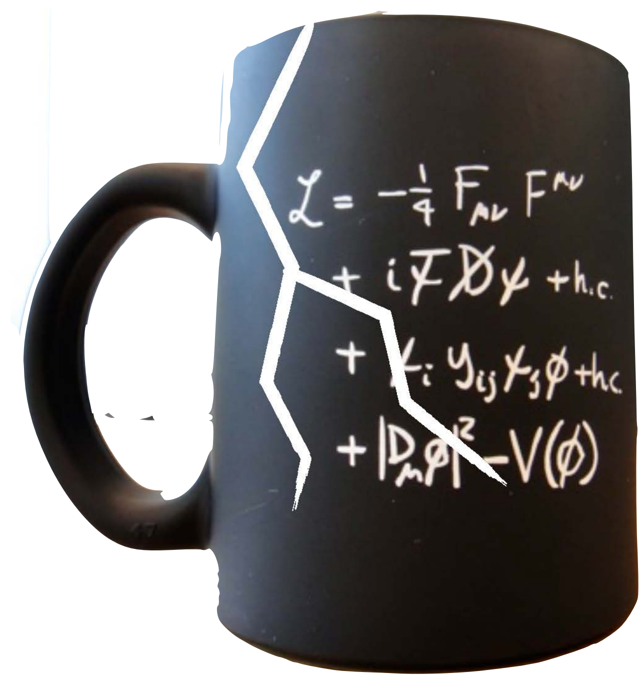
See next talk by Jae Yu!

- **Searches for new phenomena at the FD** benefitting from its large mass and high resolution
  - Inelastic boosted dark matter from the galactic core
  - Boosted dark matter from the Sun
  - Nucleon decay



Far Detector Technical Design Report

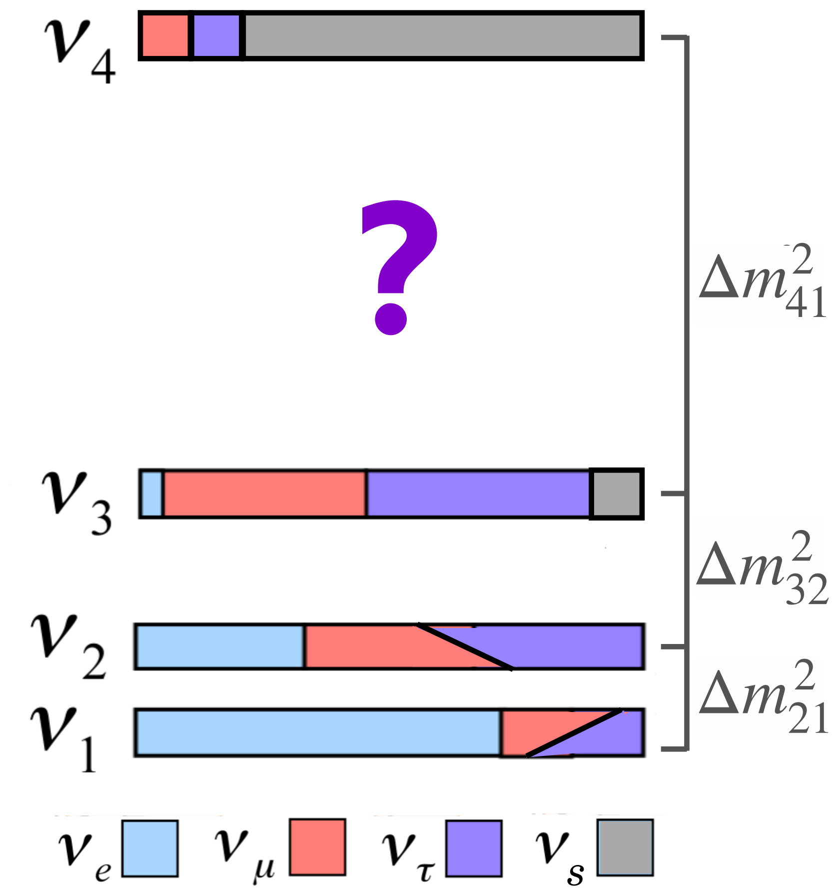
DUNE BSM Paper, Eur. Phys. J. C 81, 322 (2021)

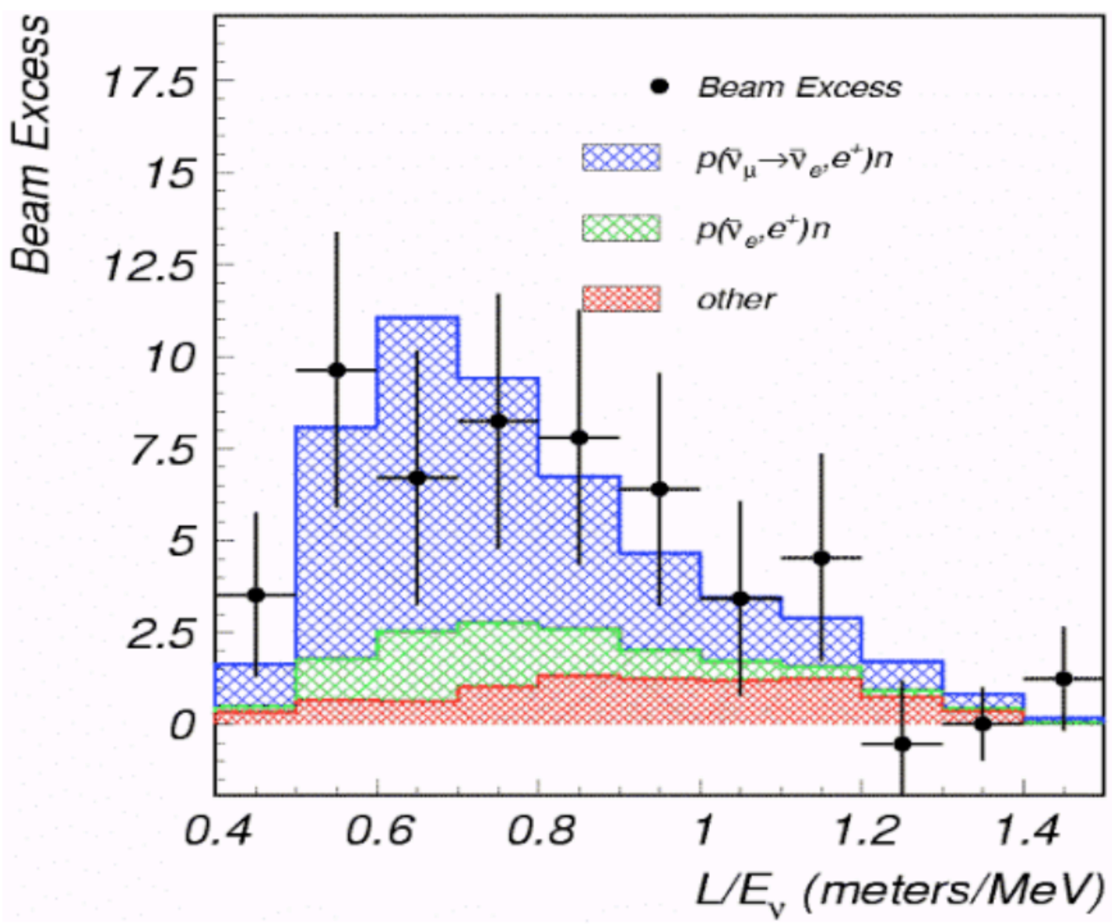


More than Three Neutrinos?

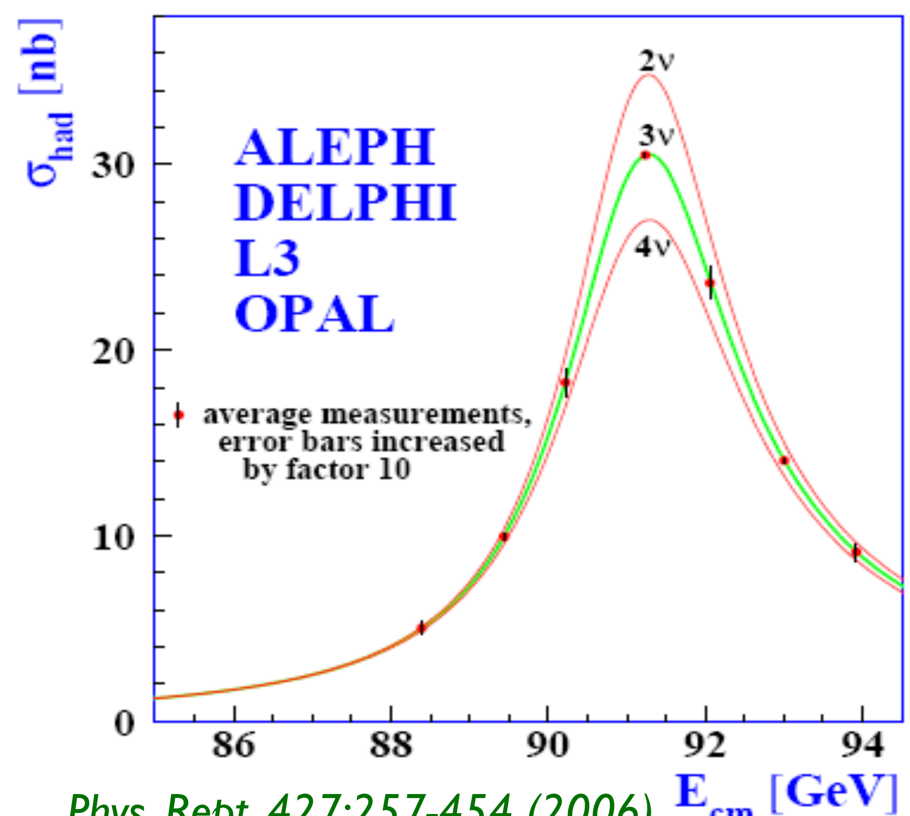
- The LSND experiment measured a 3.8σ excess of ν_e in a DAR ν_μ beam over a very short baseline (~30 m).
- Oscillation explanation requires 4th neutrino state with $\Delta m^2_{41} \sim 1\ \mathrm{eV}^2$
  - Z^0 width measured at LEP => only 3 light active neutrinos
  - 4th neutrino is very heavy or has no weak interactions

    => **Sterile neutrino (ν_s)**





LSND, Phys. Rev. D 64, 112007 (2001)

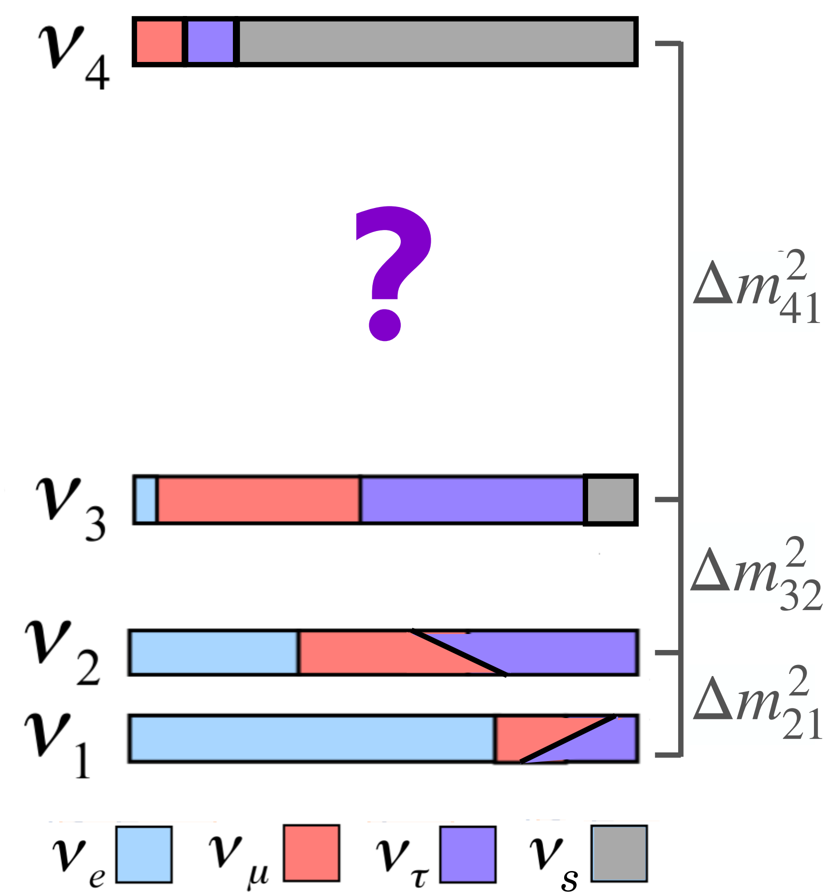


Phys. Rept. 427:257-454 (2006)

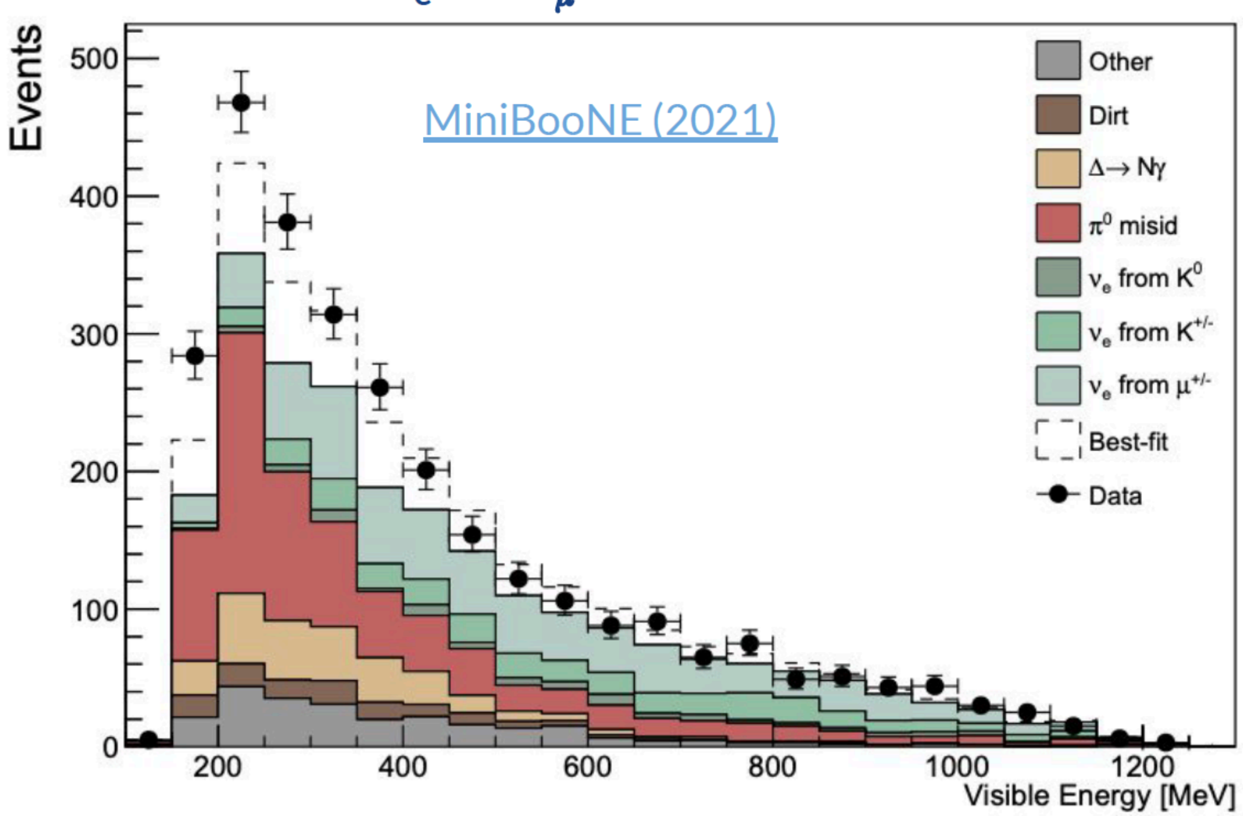
More than Three Neutrinos?

- The LSND experiment measured a 3.8σ excess of ν_e in a DAR ν_μ beam over a very short baseline (~30 m).
- Oscillation explanation requires 4th neutrino state with $\Delta m^2_{41} \sim 1\ \text{eV}^2$
  - Z^0 width measured at LEP => only 3 light active neutrinos
  - 4th neutrino is very heavy or has no weak interactions

    => **Sterile neutrino (ν_s)**



excess $\overset{(-)}{\nu}_e$ in a $\overset{(-)}{\nu}_\mu$ dominated beam, 4.8σ



- In a 3+1 model, have 1 new mass scale, Δm^2_{41}, 3 new mixing angles, θ_{14}, θ_{24}, θ_{34}, and 2 new CP phases δ_{14}, δ_{24}

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

- Further motivated by MiniBooNE, Reactor, Gallium anomalies

Looking for Light Sterile Neutrinos

- ν_e, $\bar{\nu}_e$ CC appearance (LSND, KARMEN, mBooNE, µBooNE, etc.): θ_{14}, θ_{24}

$$P_{\mu e} \approx 2\sin^2 2\theta_{14} \sin^2\theta_{24} \times \sin^2\frac{\Delta m^2_{41} L}{E} \qquad 4|U_{e4}|^2|U_{\mu 4}|^2$$

- $\bar{\nu}_e$ CC disappearance (Reactor experiments): θ_{14}

$$P_{ee} \approx 1 - 2\sin^2 2\theta_{14} \times \sin^2\frac{\Delta m^2_{41} L}{E} \qquad |U_{e4}|^2$$

- ν_μ, $\bar{\nu}_\mu$ CC disappearance (mBooNE, MINOS(+), NOvA, T2K, IceCube, etc.): θ_{24}

$$P_{\mu\mu} \approx 1 - 2\sin^2 2\theta_{24} \times \sin^2\frac{\Delta m^2_{41} L}{E} \qquad |U_{\mu 4}|^2$$

- NC disappearance (MINOS(+), NOvA, T2K, etc.): θ_{24}, θ_{34}

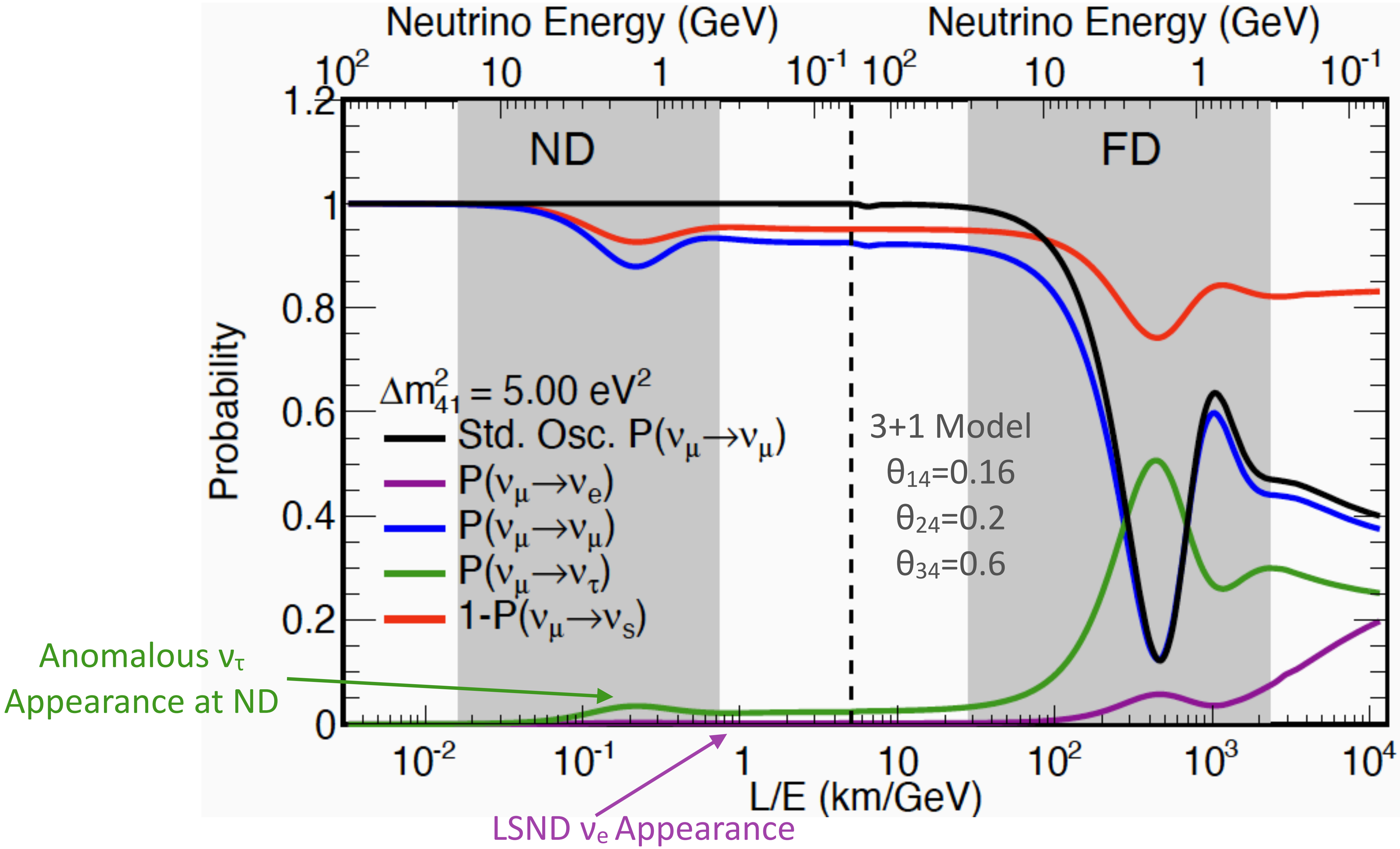
$$1 - P_{\mu s} \approx 1 - \underbrace{\sin^2 2\theta_{24} \sin^2\frac{\Delta m^2_{41} L}{E}}_{\text{SBL}} - \sin^2\theta_{34}\sin^2 2\theta_{23}\sin^2\frac{\Delta m^2_{31} L}{E} \qquad |U_{\mu 4}|^2,\ |U_{\tau 4}|^2$$

SBL

LBL

- Thanks to the intense LBNF neutrino beam and exquisite detector spatial resolution of its detectors, DUNE is sensitive to all of these channels in a single experiment!
  - Also sensitive to atmospheric measurements due to large FD, 1500 m deep at SURF

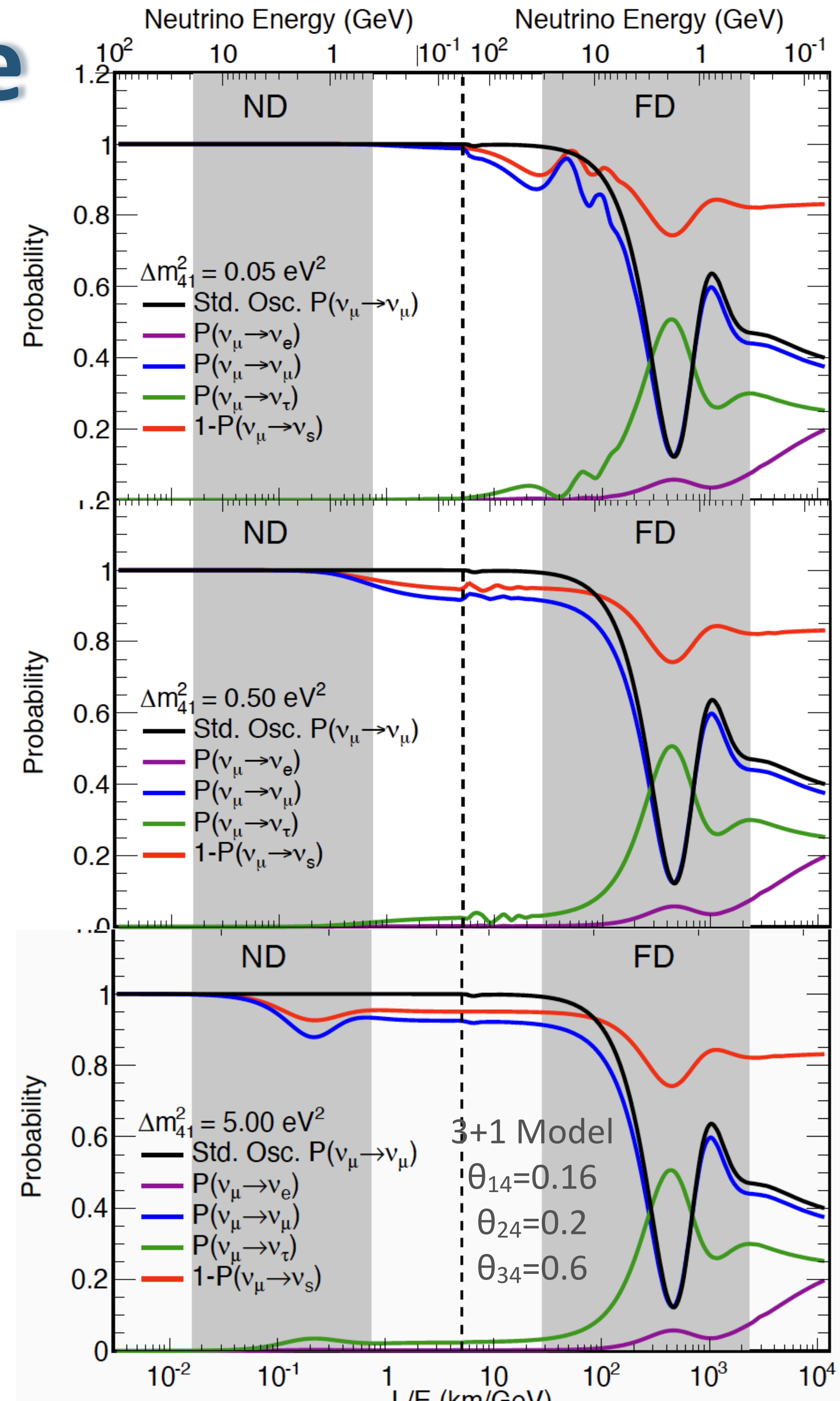
Looking for Light Sterile Neutrinos



- **Active-sterile mixing would distort standard oscillation probabilities**
  - DUNE will be sensitive to this effect through both the Near and Far detectors
  - Wide-band LBNF beam enables probes over large regions of parameter space
  - Plot shows distortion of standard oscillation probabilities for L/E or ν energies at ND and FD

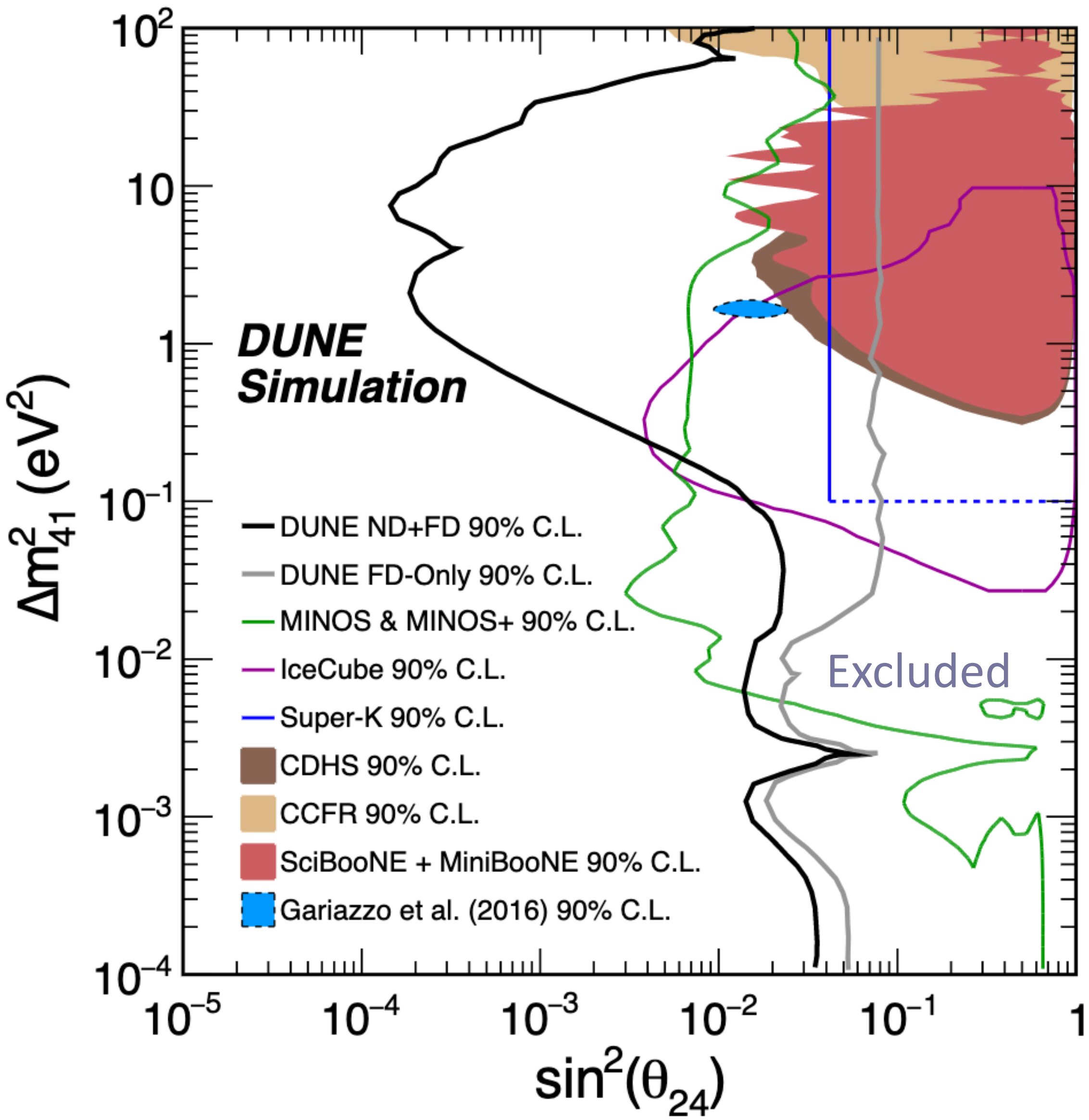
Looking for Light Sterile Neutrinos

- Distortions of standard oscillation probabilities change for different values of Δm^2_{41}
  - **Small Δm^2_{41}**: slow oscillations visible at FD only (FD-dominated region)
  - **Intermediate Δm^2_{41}**: rapid oscillations average out at FD but still not visible at ND (Counting experiment)
  - **Large Δm^2_{41}**: oscillations average out at FD and distortions are visible at the ND (ND-dominated region)

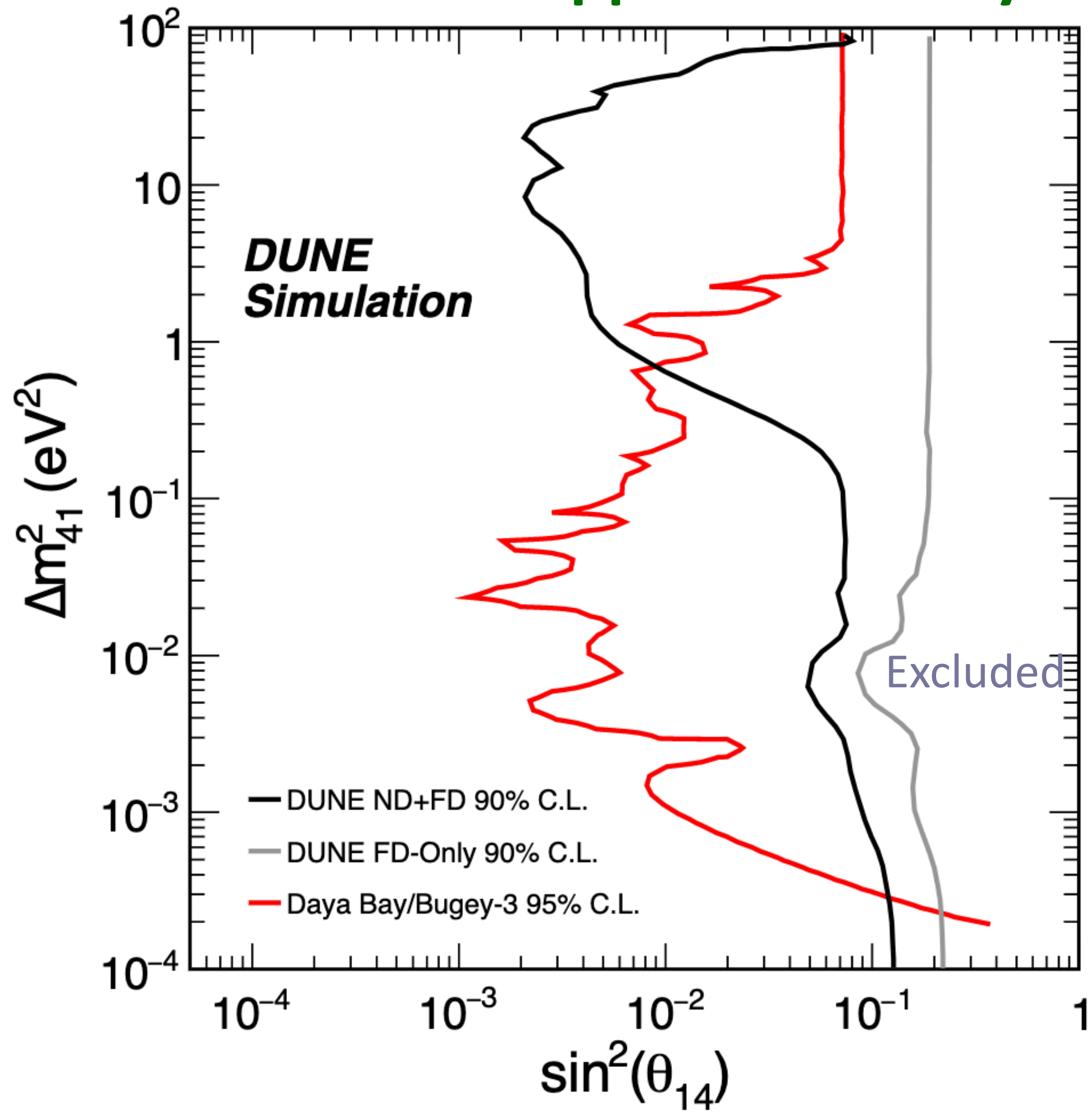


DUNE Sensitivities to Sterile Mixing

ν_μ CC + NC Disappearance



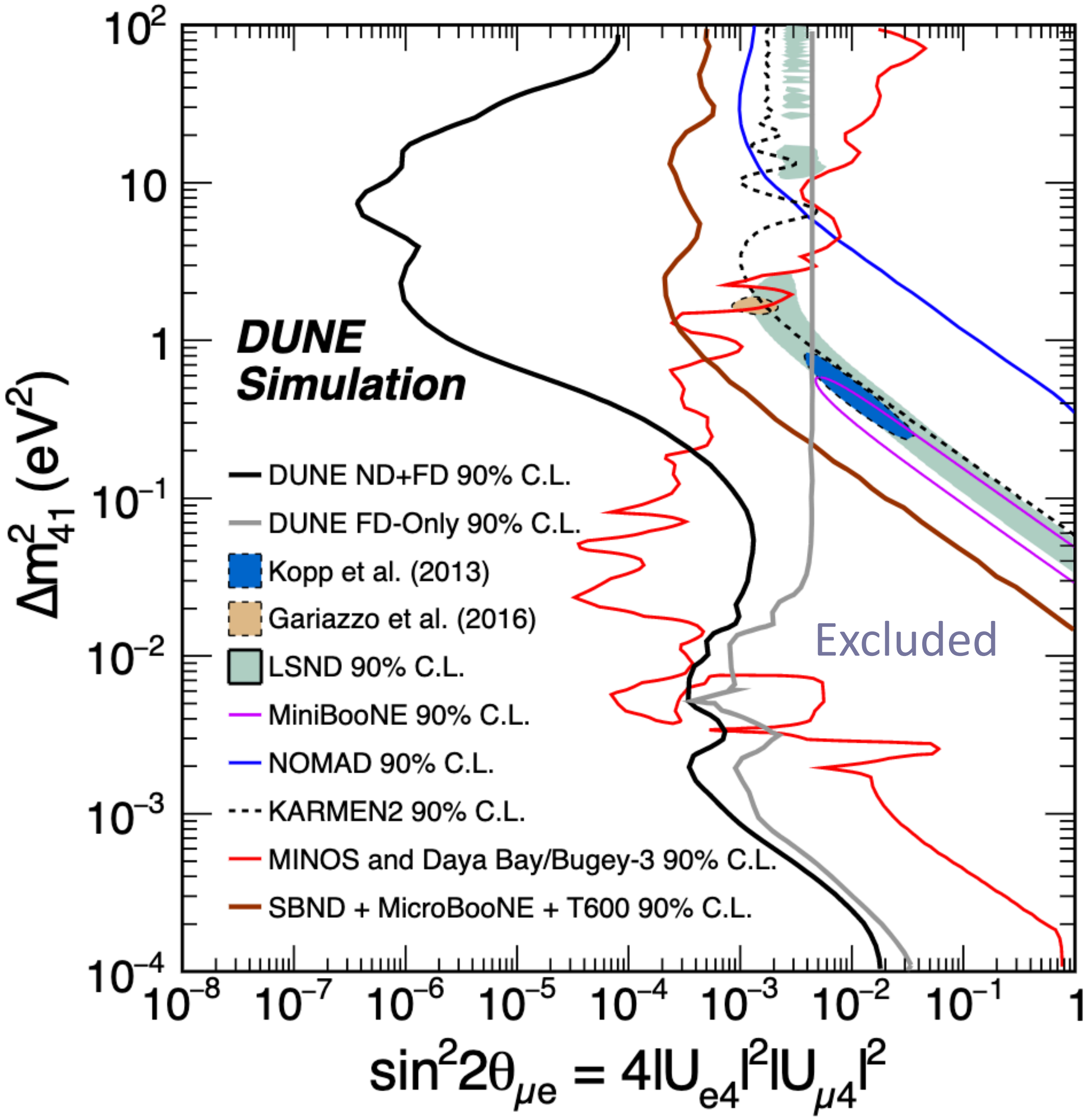
ν_e CC Disappearance Only



- Assuming 300 kton.MW.year exposure (Phase I ND) for 3+1 model with simultaneous fit to oscillations at ND and FD
  - GLoBES sensitivities include normalization-only systematics, so the two DUNE lines represent best (black) and worst (gray) scenarios
  - On its own, DUNE can potentially probe the sterile mixing parameter space at same level or better than present and future experiments, depending on Δm^2_{41}

DUNE Sensitivities to Sterile Mixing

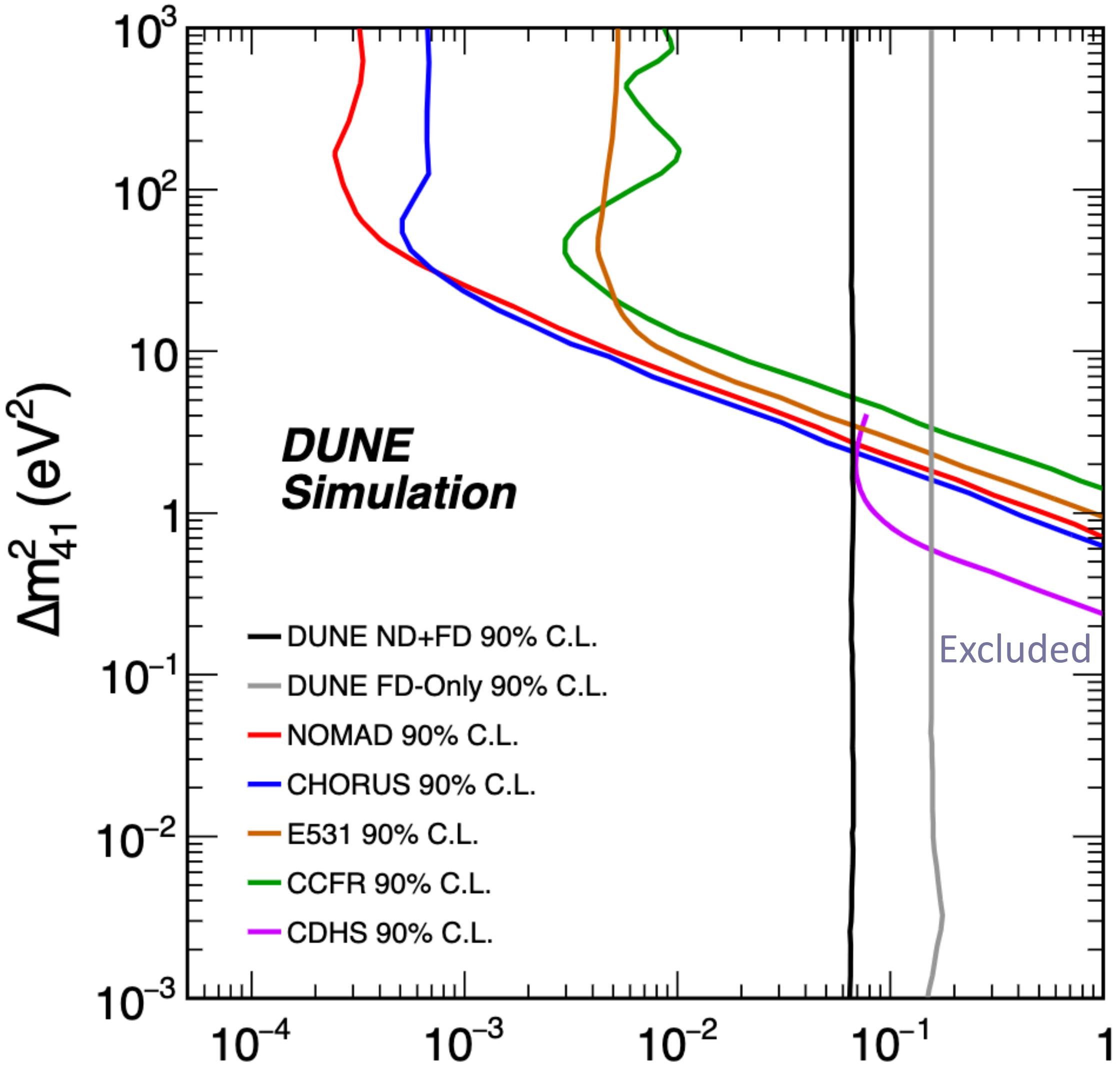
ν_e CC Appearance



- Assuming 300 kton.MW.year exposure (Phase I ND) for 3+1 model with simultaneous fit to oscillations at ND and FD
  - PRISM and Phase II ND will help control systematics in ND-dominated region, $\Delta m^2_{41} \gtrsim 0.5$ eV^2
  - Strong complementarity with SBN program, thanks to ND measurement, while extending probes to lower values of Δm^2_{41} via the FD measurement

DUNE Sensitivities to Sterile Mixing

ν_μ CC + NC Disappearance



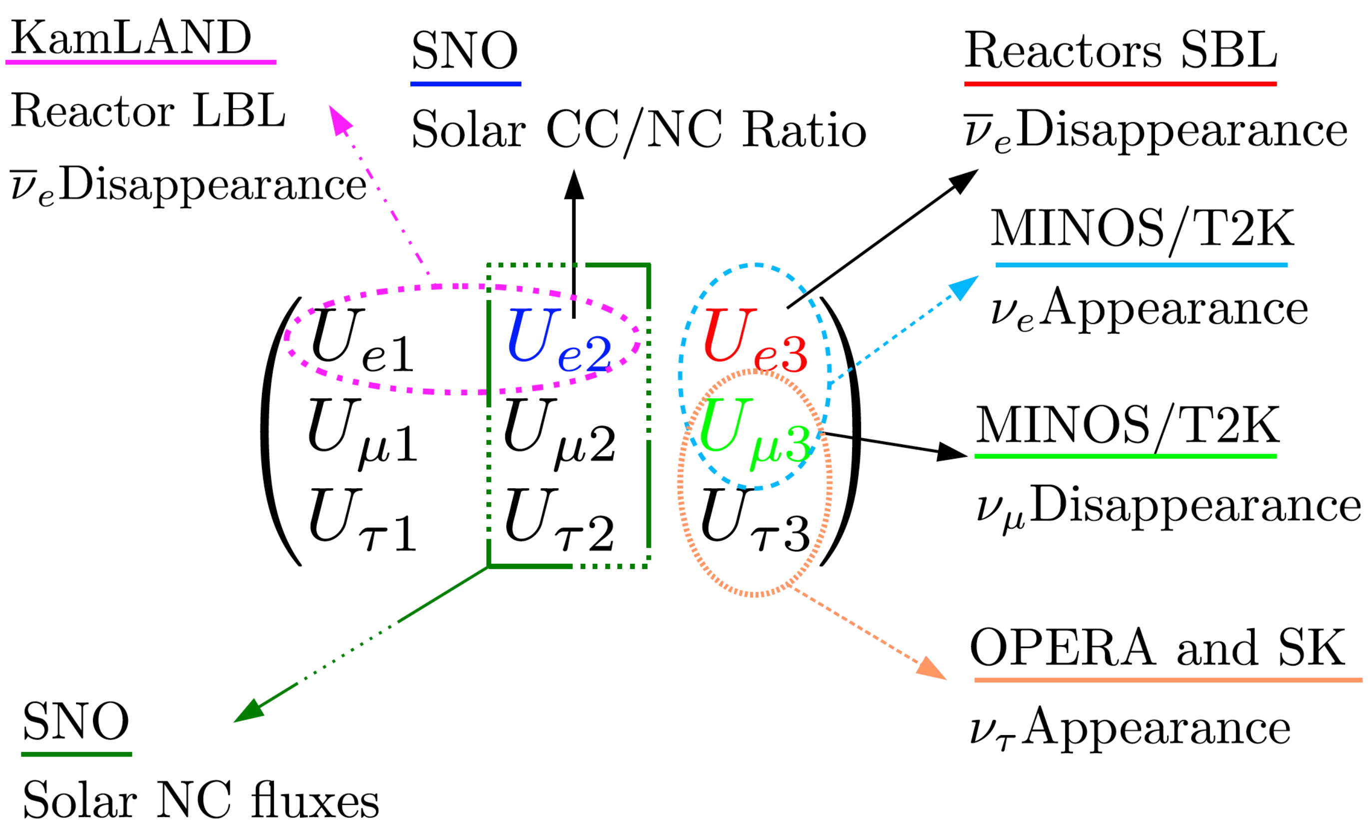
$\sin^2(2\theta_{\mu\tau}) \equiv 4|U_{\mu4}|^2|U_{\tau4}|^2 = \cos^4\theta_{14}\sin^2 2\theta_{24}\sin^2\theta_{34}$

3+1 limits at $\Delta m^2_{41} = 0.5$ eV^2

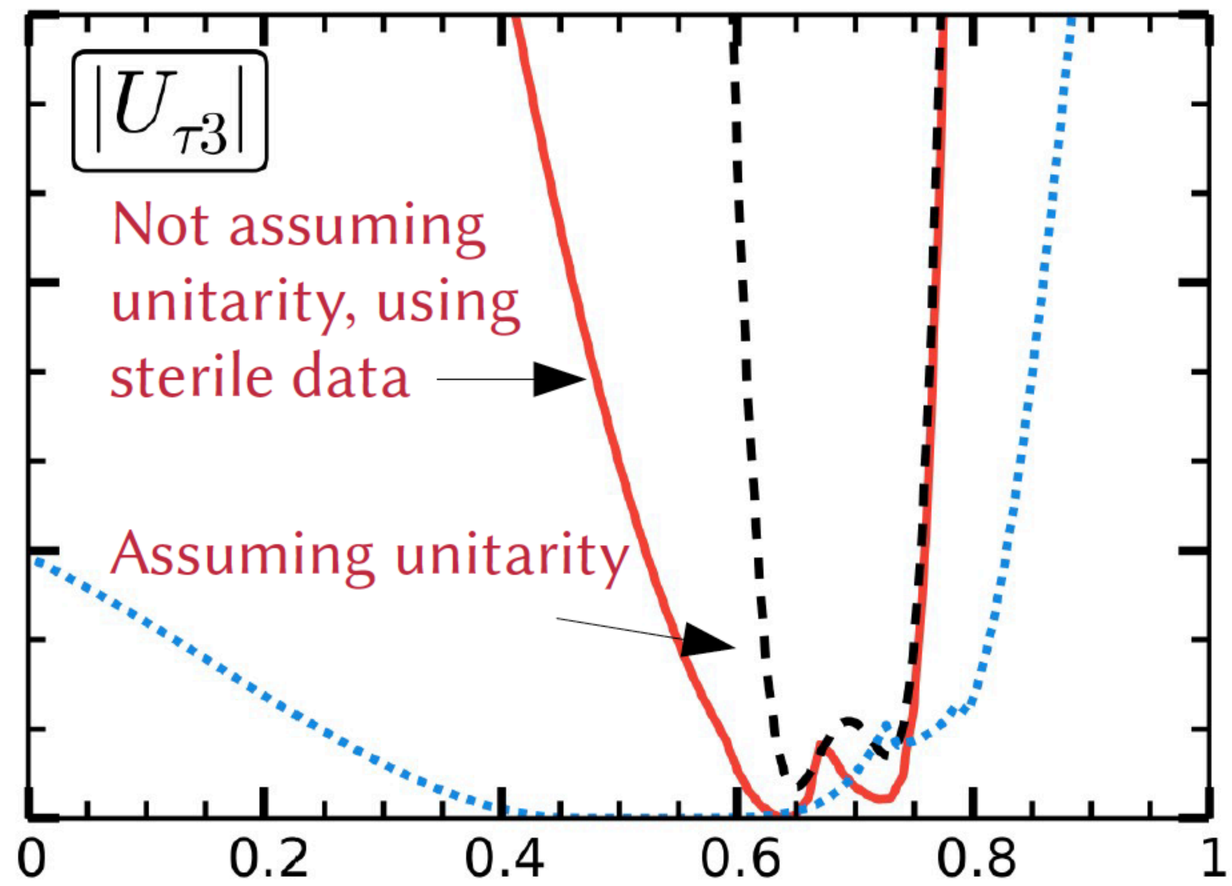
	θ_{24}	θ_{34}	$\lvert U_{\mu4}\rvert^2$	$\lvert U_{\tau4}\rvert^2$
DUNE Best-Case	1.8°	15.0°	0.001	0.067
DUNE Worst-Case	15.1°	25.5°	0.068	0.186
NOvA	20.8°	31.2°	0.126	0.268
MINOS/MINOS+	4.4°	23.6°	0.006	0.16
Super–Kamiokande	11.7°	25.1°	0.041	0.18
IceCube	4.1°	-	0.005	-
IceCube-DeepCore	19.4°	22.8°	0.11	0.15

- Assuming 300 kton.MW.year exposure (Phase I ND) for 3+1 model with simultaneous fit to oscillations at ND and FD
  - DUNE can extend probes of ν_τ-sterile mixing to lower values of Δm^2_{41} and improve the limits on θ_{34}, the least constrained sterile mixing angle
  - Can be further improved by combining beam + atmospheric measurements

DUNE and ν_τ Probes



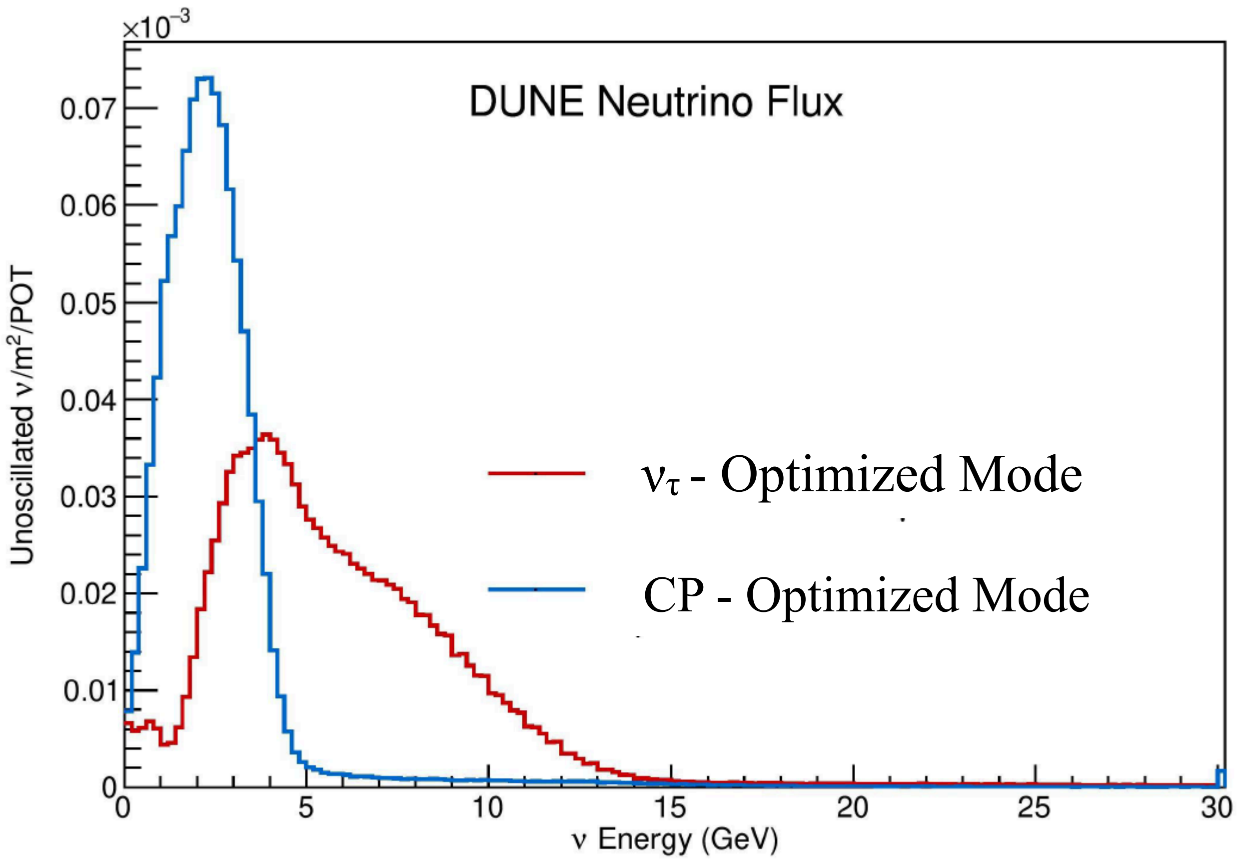
Parke, Ross-Lonergan, Phys. Rev. D 93, 113009 (2016)



- Most of our knowledge of ν_τ sector results from assuming unitarity of PMNS matrix and lepton universality for cross sections
  - ν_τ CC production threshold, $E_\nu > 3.5$ GeV, is very challenging for signal accumulation

- DUNE is in a unique position to probe the ν_τ sector using:
  - High-energy tail of CP-optimized beam during Phases I and II (130 ν_τ CC, 30 $\bar{\nu}_\tau$ CC/year in FD)
  - **Dedicated ν_τ - optimized beam run during Phase II (800 ν_τ CC/year in FD)**
  - Also atmospheric neutrino measurements with FD, like SuperK and IceCube

Anomalous ν_τ Appearance at DUNE ND

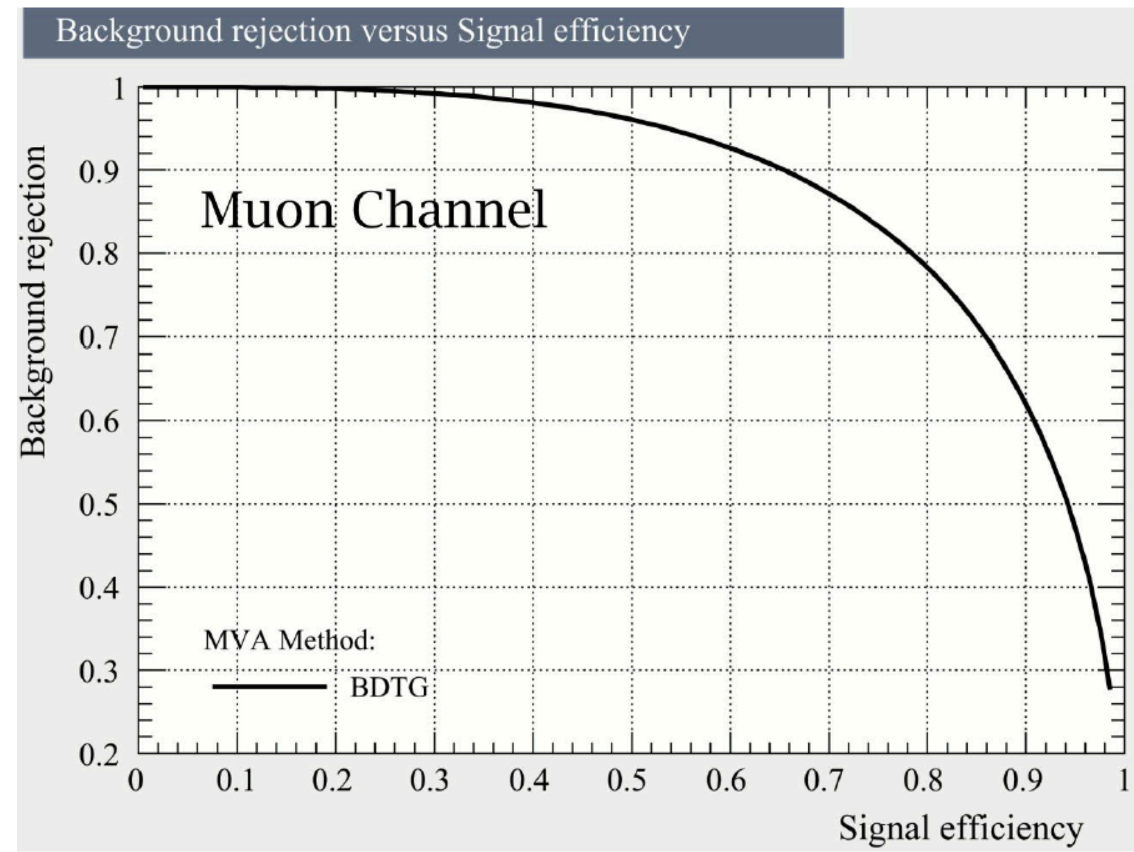


$$P_{\mu\tau} \approx \sin^2 2\theta_{\mu\tau} \sin^2 \frac{\Delta m^2_{41} L}{E}$$

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

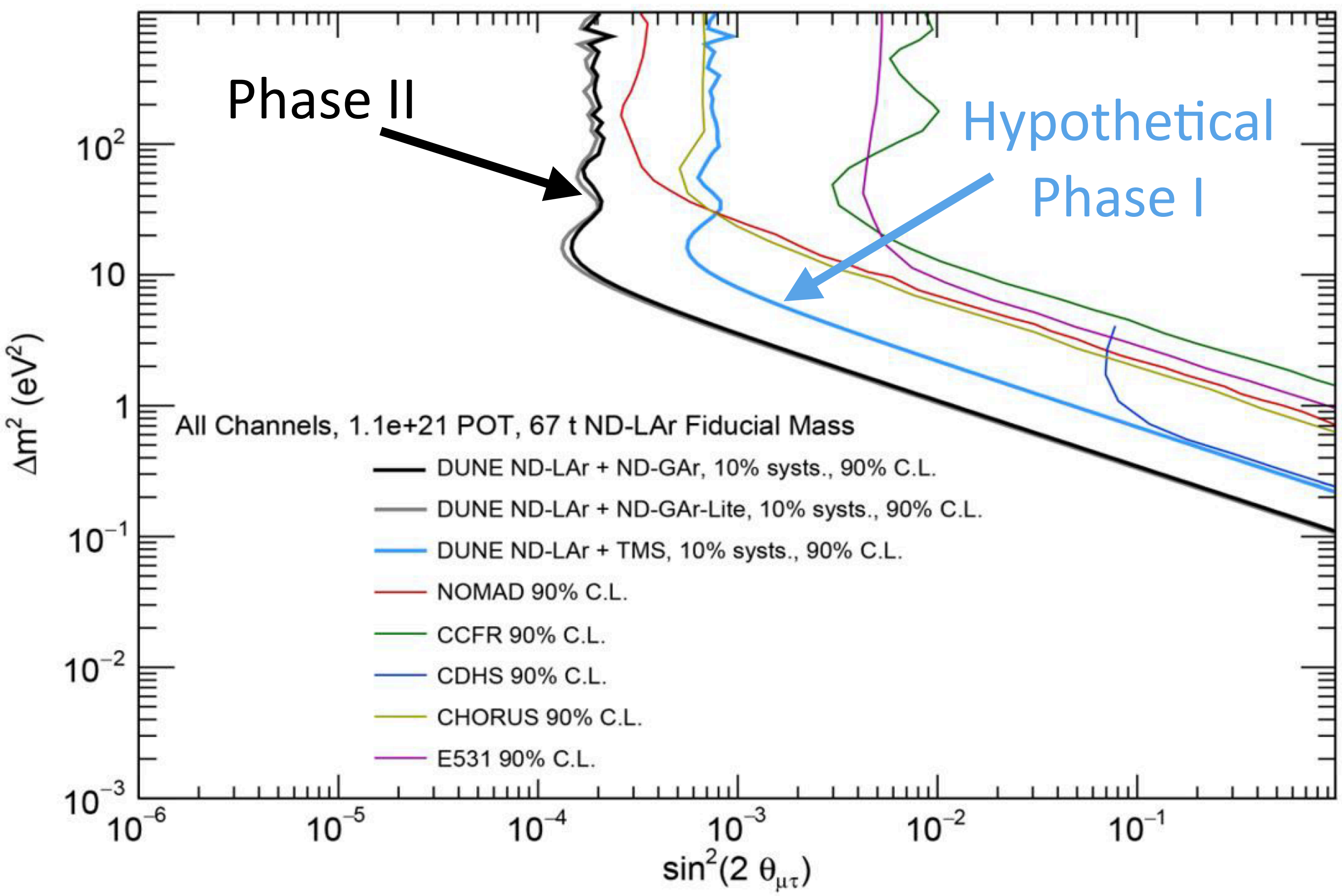
τ decay modes

Decay mode	Branching ratio (%)
$\pi^- \; \pi^0 \; \nu_\tau$	25.49
$e^- \; \bar{\nu}_e \; \nu_\tau$	17.82
$\mu^- \; \bar{\nu}_\mu \; \nu_\tau$	17.39
$\pi^- \; \nu_\tau$	10.82
$\pi^- \; 2\pi^0 \; \nu_\tau$	9.26



- Higher energy of ν_τ - optimized beam, BDT based on kinematic variables, and measurements of a wide range of muon momenta from curvature in DUNE ND Phase II's ND-GAr, enable good statistics in selection of ν_τ CC sample from ν_μ CC backgrounds.

Anomalous ν_τ Appearance at DUNE ND



- Sensitivities for 1 year of running with ν_τ - optimized beam (not expected during Phase I)
  - Including an overall 10% syst. uncertainty; smearing according to each detector's resolution
- Potential leading sensitivity in difficult to probe parameter space during DUNE Phase II
  - Further improvements possible by using the SAND detector in the ND complex
  - Complementary to ν_τ-sterile mixing probes with FASERnu and FPF@LHC *Bai et al., arXiv:2002.0301*

See H. Razafinime's talk, Saturday NF EC parallel

DUNE and the Experimental ν Anomalies

Source	**Flavor Conversion:** 3+N Oscillations	**Flavor Conversion:** Anomalous Matter Effects	**Flavor Conversion:** Lepton Flavor Violation	**Dark Sector:** Decays in Flight	**Dark Sector:** Neutrino-induced Up-scattering	**Dark Sector:** Dark-particle-induced Up-scattering
Reactor	DANSS Upgrade, JUNO-TAO, NEOS-II, Neutrino-4 Upgrade, PROSPECT-II					
Radioactive Source	BEST-2, IsoDAR, THEIA, Jinping					
Atmospheric	IceCube Upgrade, KM3NET ORCA and ARCA, DUNE, Hyper-Kamiokande, THEIA				IceCube Upgrade, KM3NET, ORCA and ARCA, DUNE, Hyper-Kamiokande, THEIA	
Pion/Kaon Decay-At-Rest	JSNS^2, COHERENT, Coherent-Captain-Mills, KPIPE		JSNS^2, COHERENT, Coherent-Captain-Mills, KPIPE, PIP2-BD			COHERENT, Coherent-Captain-Mills, KPIPE, PIP2-BD, SBN-BD
Beam Short Baseline	SBN			SBN, FASERν, SND@LHC, FLArE		
Beam Long Baseline	DUNE, Hyper-Kamiokande, ESSnuSB			DUNE, Hyper-Kamiokande, ESSnuSB		
Muon Decay-In-Flight	nuSTORM				nuSTORM	
Beta Decay and Electron Capture	KATRIN/TRISTAN, Project-8, HUNTER, BeEST, DUNE (^{39}Ar), PTOLEMY, $2\nu\beta\beta$					

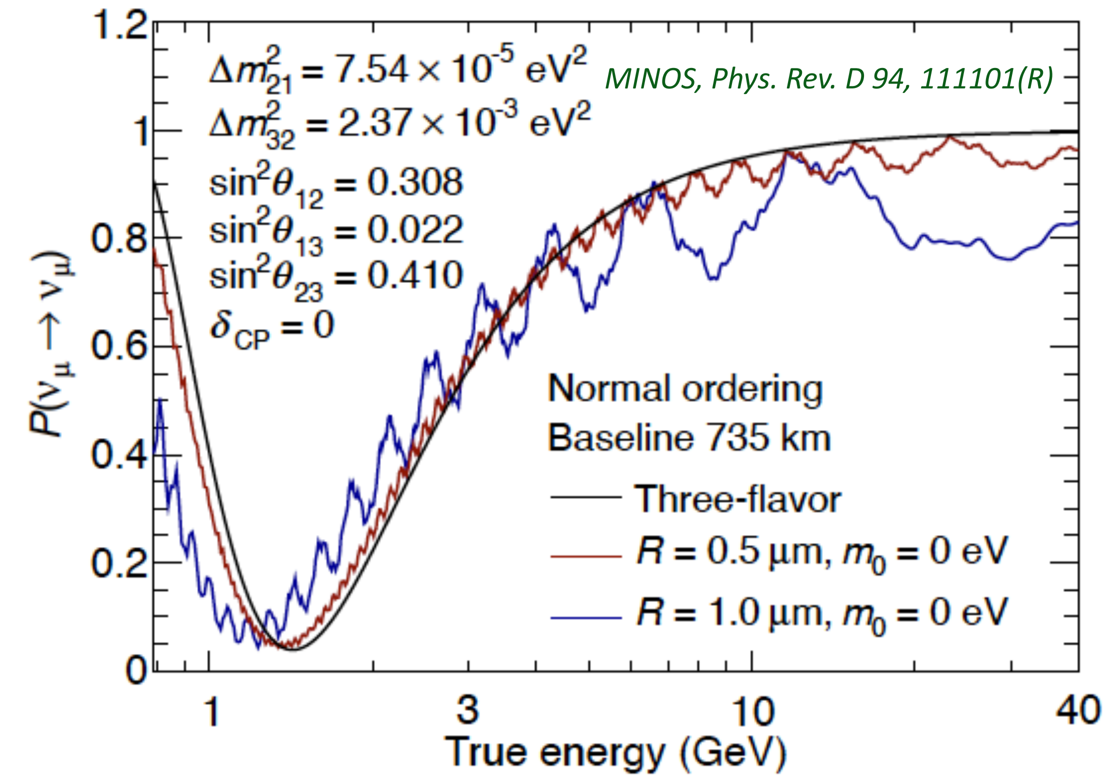
NF02 White Paper, hep-ex/2203.07323

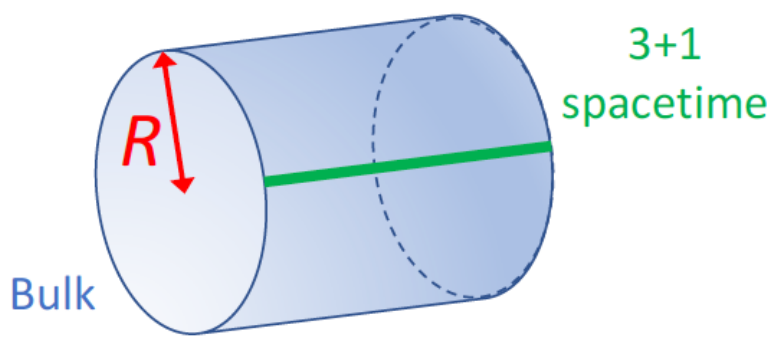
NF02 Session on Expt. ν Anomalies, Thurs, 10 am

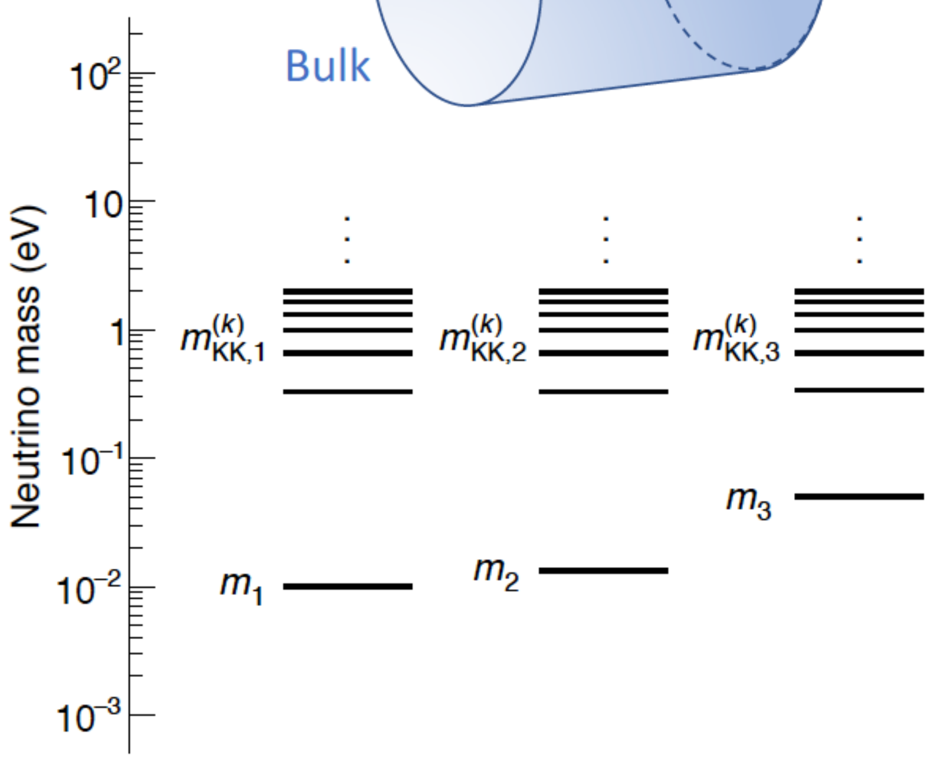
- Pure 3+N sterile mixing disfavored as explanation for global neutrino data due to tension between appearance signals and null disappearance results
- With its strong multi-channel sensitivity and wide-band beam, DUNE will test more exotic scenarios

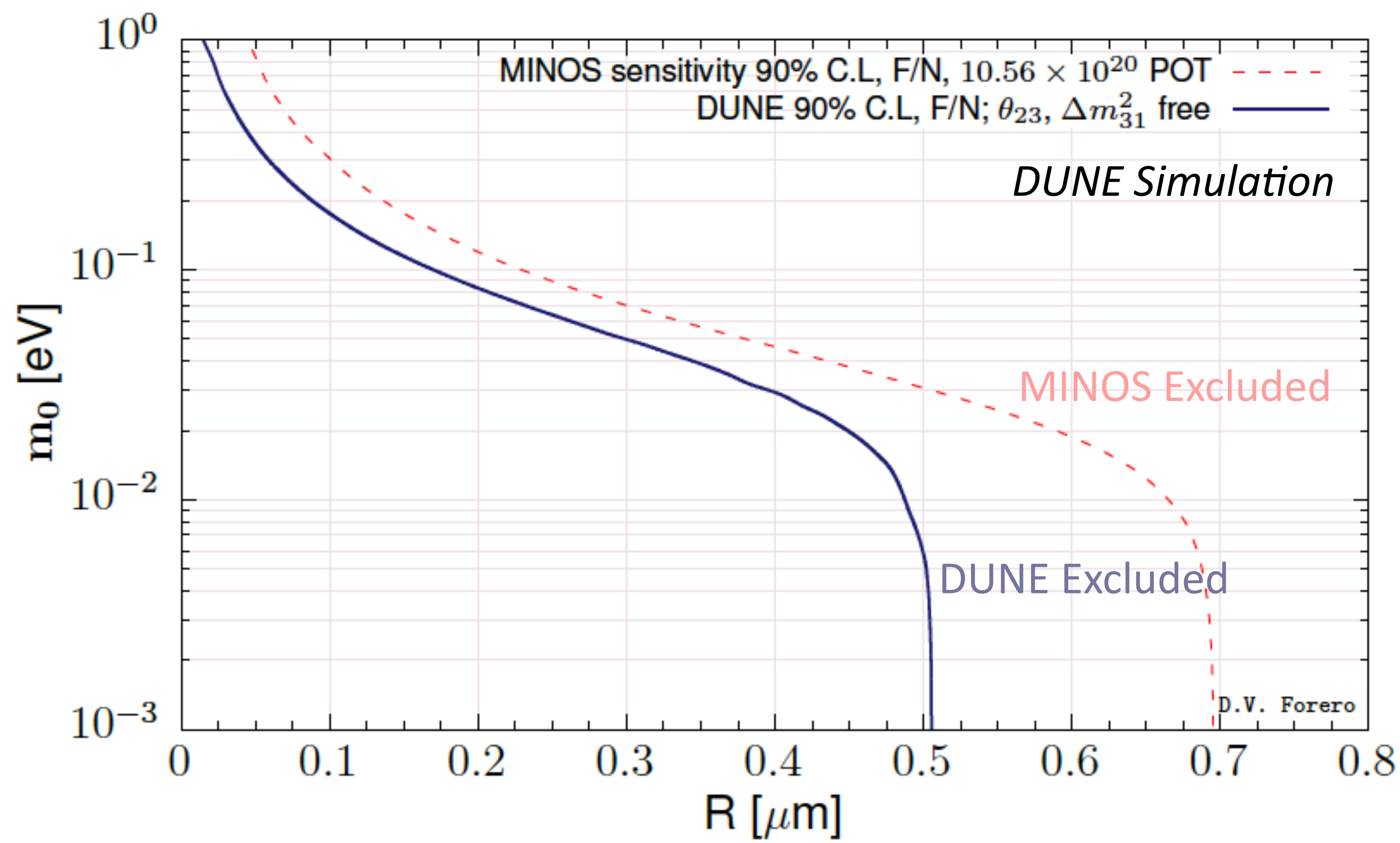
Large Extra-Dimensions

- Large Extra-Dimensions would cause distortions of 3-flavor oscillations from mixing of neutrinos with Kaluza-Klein (KK) modes
  - For LED model, *Davoudiasl et al., PRD **65**, 105015 (2002),* assuming one LED in the bulk, KK modes in 3+1 spacetime brane behave like sterile neutrinos
  - Showing DUNE sensitivity for 300 kton.MW.year (Phase I) compared to MINOS published results







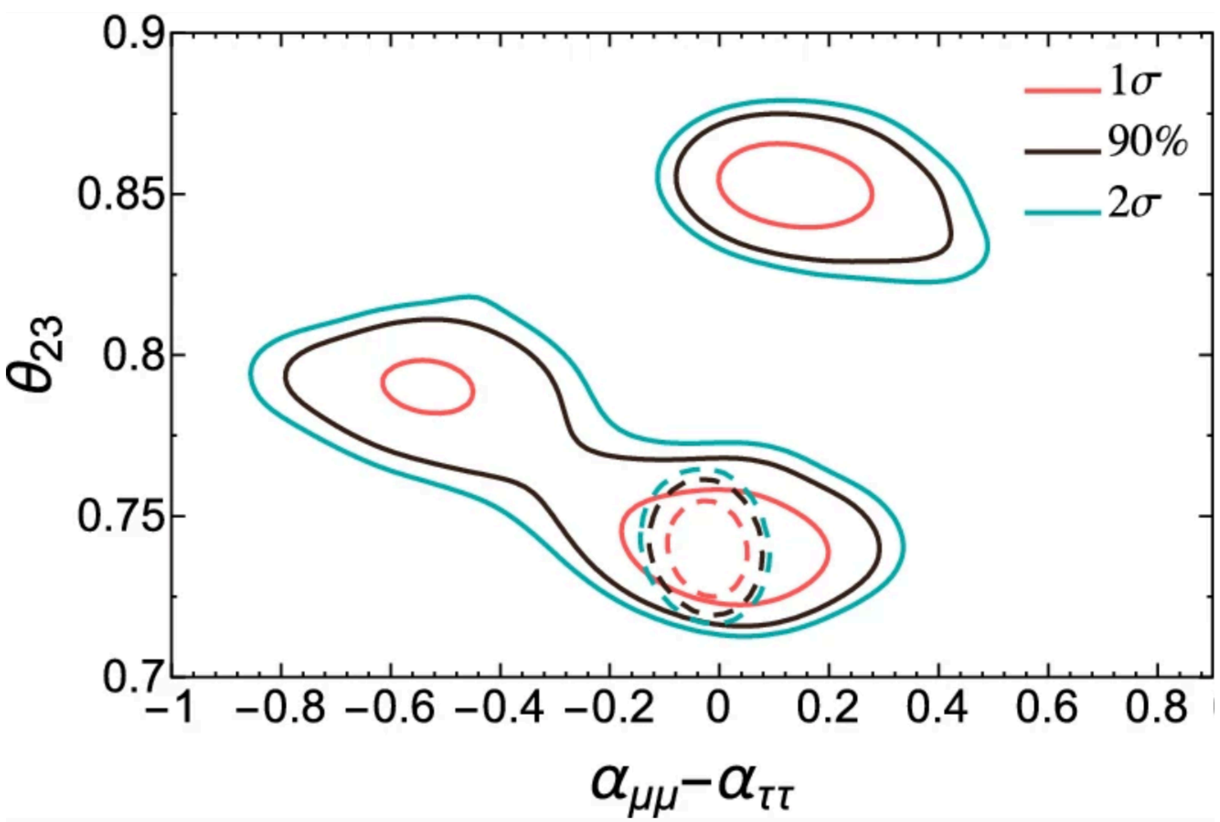


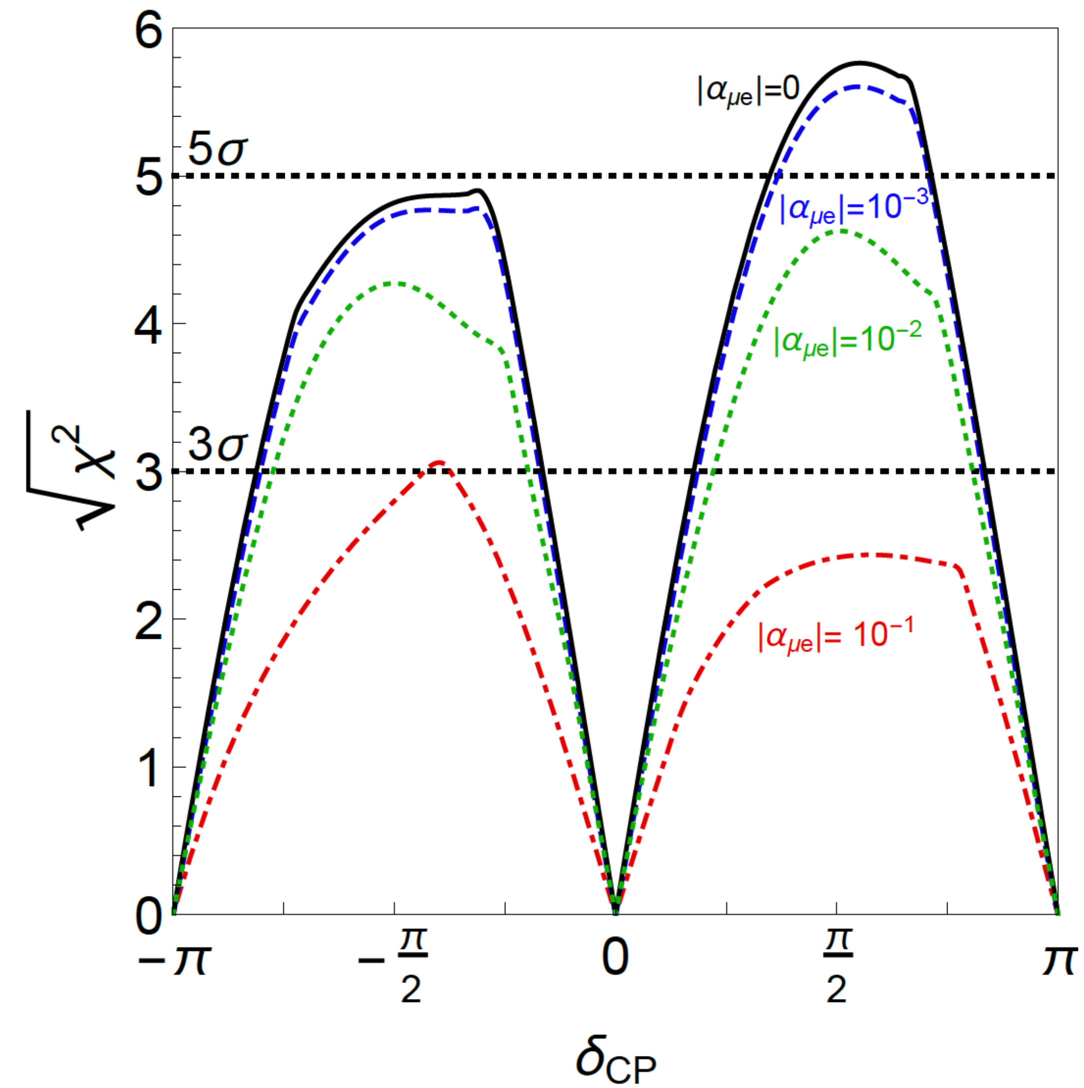
See D. V. Forero's talk, Saturday NF EC parallel

Non-Unitary Mixing

- If new heavy states mix with active neutrinos (*e.g.* if neutrinos acquire mass through a type I seesaw mechanism), the mixing matrix need not be unitary

$$N = \begin{pmatrix} 1-\alpha_{ee} & 0 & 0 \\ \alpha_{\mu e} & 1-\alpha_{\mu\mu} & 0 \\ \alpha_{\tau e} & \alpha_{\tau\mu} & 1-\alpha_{\tau\tau} \end{pmatrix} U^{3\times 3}$$



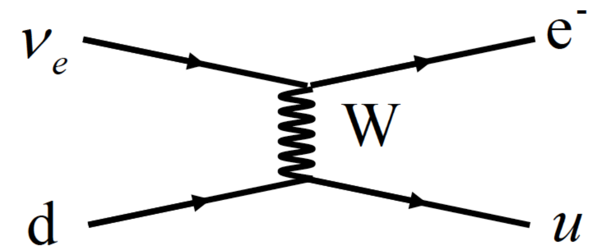


- Allowed regions at the 1σ, 90%, and 2σ CL for non-unitary mixing parameters for DUNE-only (solid), and DUNE + existing constraints (dashed)
  - Assuming 300 kton.MW.year (Phase I ND)
- Potential impact of non-unitarity on the DUNE CP violation discovery potential

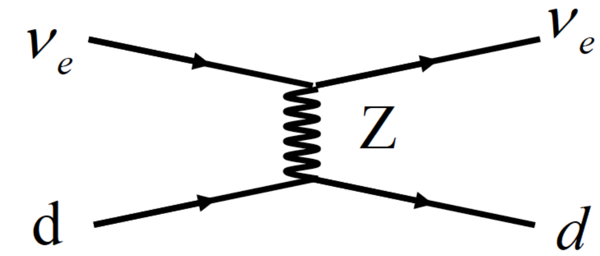
Non-Standard Neutrino Interactions (NSI)

- New neutral-current-like interactions during neutrino propagation between the Near and Far detectors can be described as new contributions to the neutrino matter effect (MSW)
  - These contributions are encoded by the new coefficients ε_{ij}

- In the Standard Model,



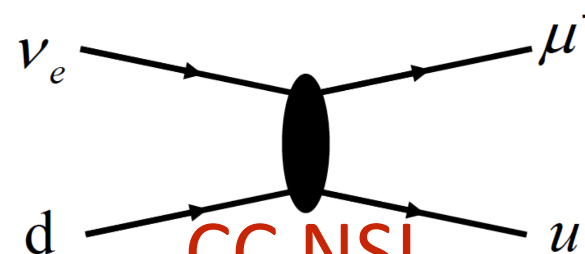
$$\mathcal{L}_{CC} = (\overline{\ell_\alpha} \gamma^\mu P_L \nu_\alpha)(\bar{f} \gamma_\mu P_L f')$$



$$\mathcal{L}_{NC} = (\overline{\nu_\alpha} \gamma^\mu P_L \nu_\alpha)(\bar{f} \gamma_\mu P_L f')$$

- With new physics, we could have

$$\mathcal{L}_{CC} = (\overline{\ell_\alpha} \gamma^\mu P_L \nu_\beta)(\bar{f} \gamma_\mu P_{L,R} f')$$



CC NSI

production, detection

$$\mathcal{L}_{NC} = (\overline{\nu_\alpha} \gamma^\mu P_L \nu_\beta)(\bar{f} \gamma_\mu P_{L,R} f')$$

NC NSI

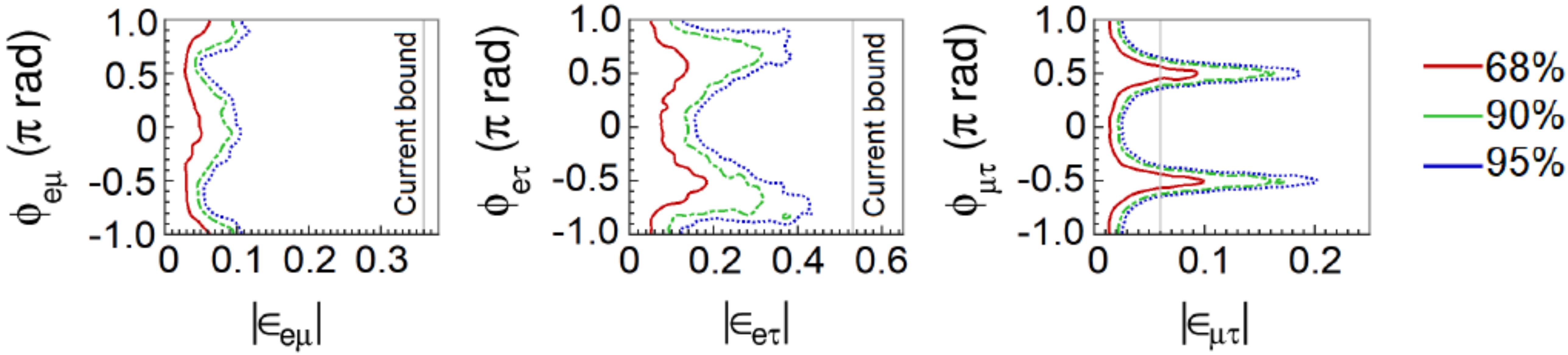
propagation

$$H = U \begin{pmatrix} 0 & & \\ & \Delta m_{21}^2/2E & \\ & & \Delta m_{31}^2/2E \end{pmatrix} U^\dagger + \tilde{V}_{\mathrm{MSW}}$$

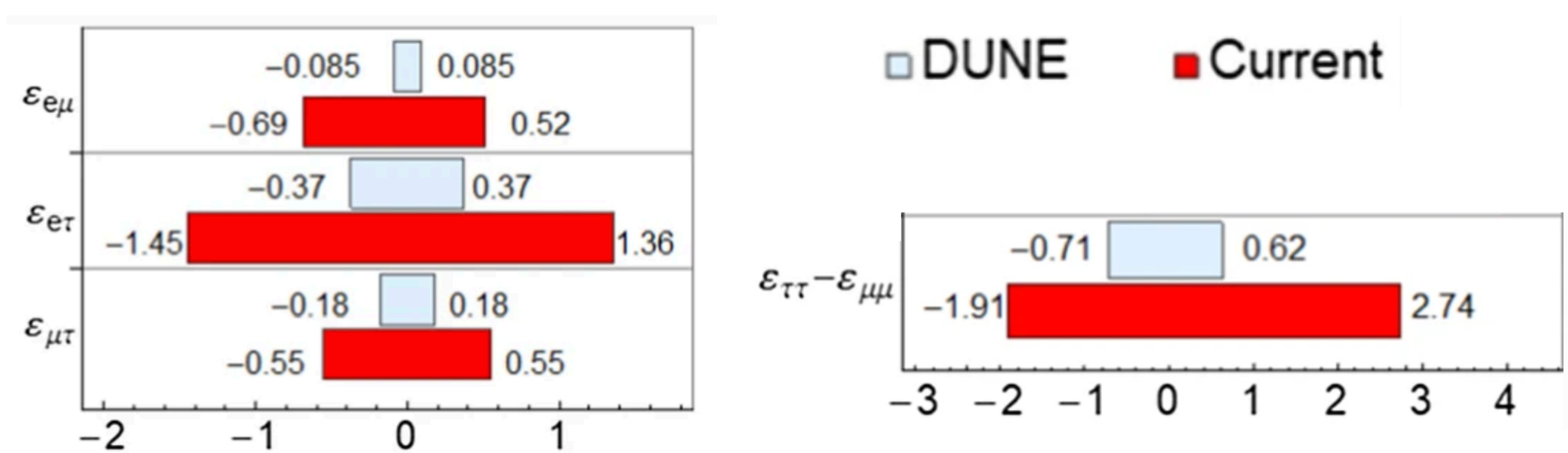
$$\tilde{V}_{\mathrm{MSW}} = \sqrt{2} G_F N_e \begin{pmatrix} 1 + \epsilon_{ee}^m & \epsilon_{e\mu}^m & \epsilon_{e\tau}^m \\ \epsilon_{e\mu}^{m*} & \epsilon_{\mu\mu}^m & \epsilon_{\mu\tau}^m \\ \epsilon_{e\tau}^{m*} & \epsilon_{\mu\tau}^{m*} & \epsilon_{\tau\tau}^m \end{pmatrix}$$

Non-Standard Neutrino Interactions (NSI)

- DUNE can improve current constraints on $|\epsilon_{e\mu}|$ and $|\epsilon_{e\tau}|$ by a factor of ~2



- Allowed regions for an exposure of 300kt.MW.year. Current bounds from *Gonzalez-Garcia, Maltoni, arXiv:1307.3092*



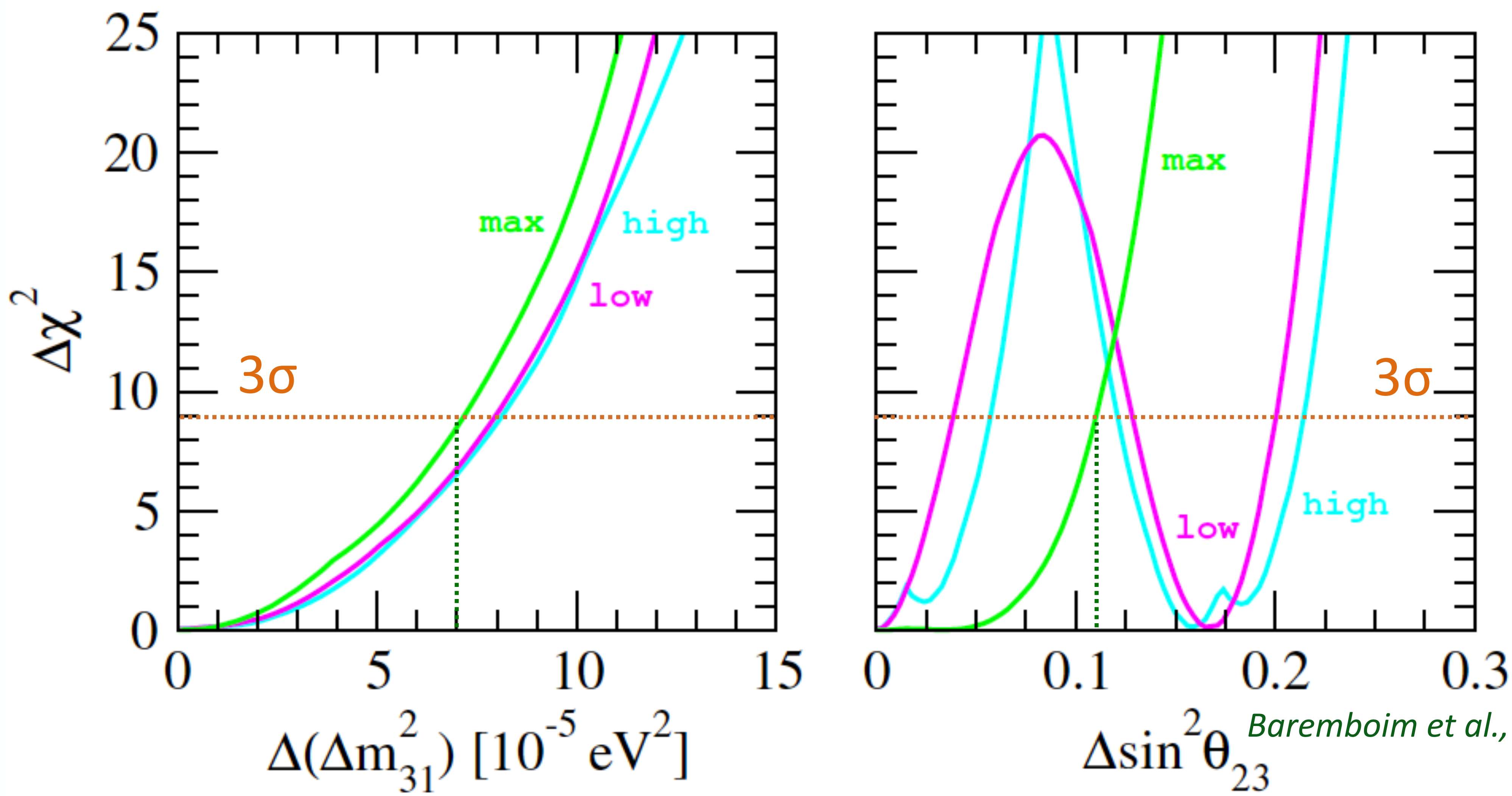
- 90% C.L. 1-dim. DUNE constraints compared with bounds from *Gonzalez-Garcia, Maltoni, arXiv:1307.3092*

Violation of CPT symmetry

- DUNE can search for CPT violation by comparing ν_μ and $\bar{\nu}_\mu$ disappearance between ND and FD

$$P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e) \Rightarrow \text{CP violation}$$

$$P(\nu_\mu \to \nu_\mu) \neq P(\bar{\nu}_\mu \to \bar{\nu}_\mu) \Rightarrow \text{CPT violation}$$



Baremboim et al., Phys. Lett. B ***780****, 631 (2018)*

- With 300 kton.MW.year running, DUNE can improve limits on $\Delta(\Delta m^2_{31})$ by over a factor of 5 and, depending on the octant of θ_{23} (low, high, maximal), the limits on $\Delta(\sin^2\theta_{23})$

Present limits

$$\Delta(\Delta m^2_{31}) \equiv \left|\Delta m^2_{31} - \Delta\bar{m}^2_{31}\right| < 3.7 \times 10^{-4}\ \text{eV}^2$$

$$\Delta(\sin^2\theta_{23}) \equiv \left|\sin^2\theta_{23} - \sin^2\bar{\theta}_{23}\right| < 0.32$$

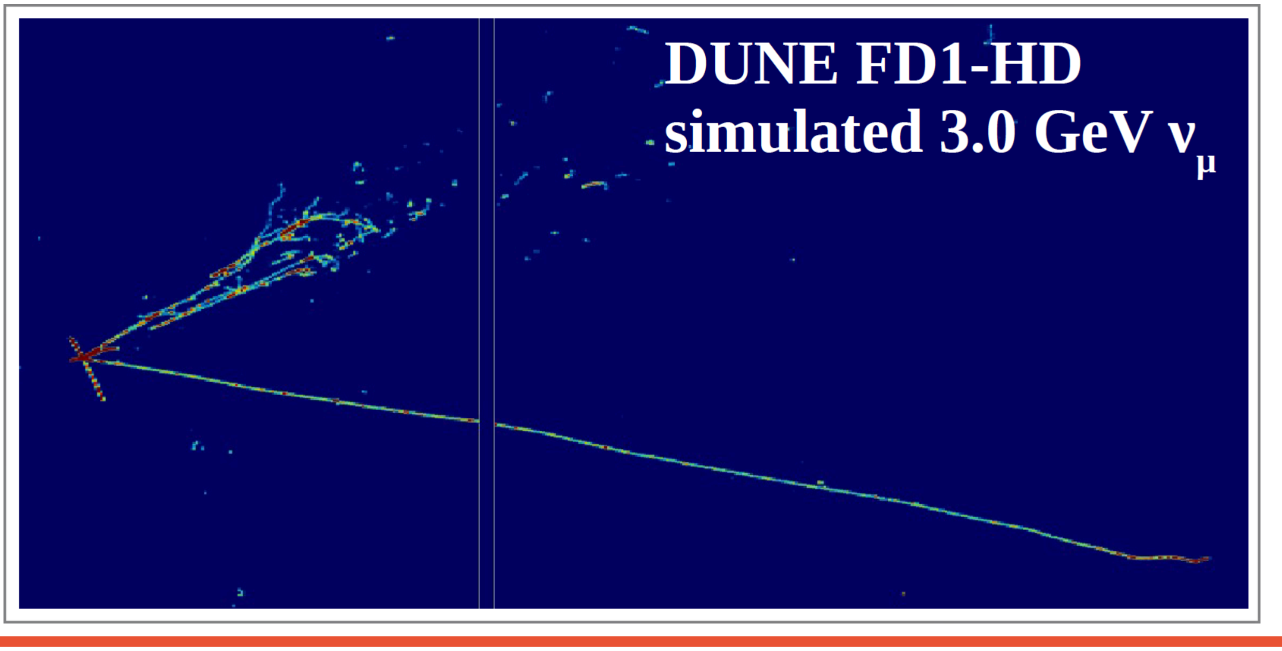
Summary and Outlook

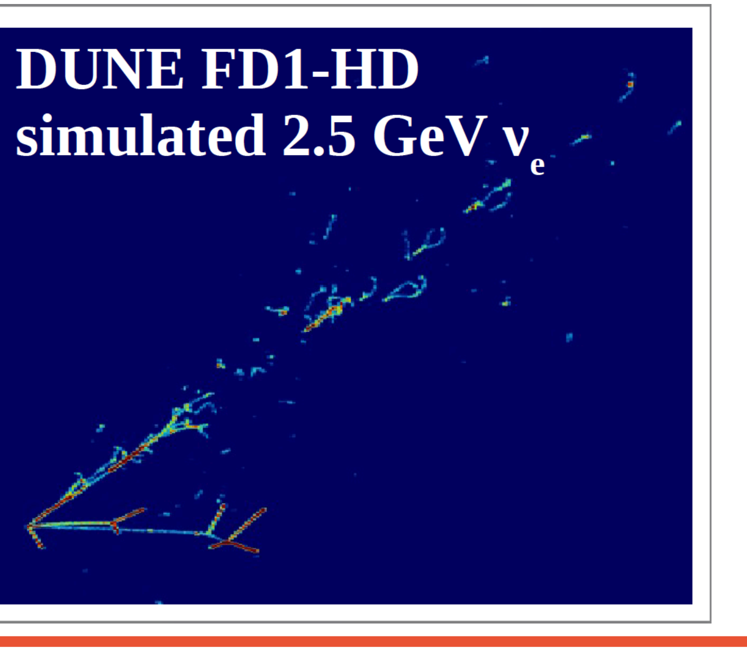
- The highly-capable DUNE detectors and the powerful LBNF beam will enable a very rich and diverse program for New Physics probes in the next decades

- DUNE has powerful physics reach for a broad range of beyond three-flavor neutrino mixing models
  - Can probe most flavor transition channels over wide energy spectrum within single expt.
  - Deployment of Phase II essential for DUNE to achieve its full BSM physics potential
  - Highly complementary to other efforts, ongoing or projected for the next decade

- As a machine for discovery, DUNE will provide leading guidance to experimental and theoretical efforts involving neutrinos and/or new particles/interactions

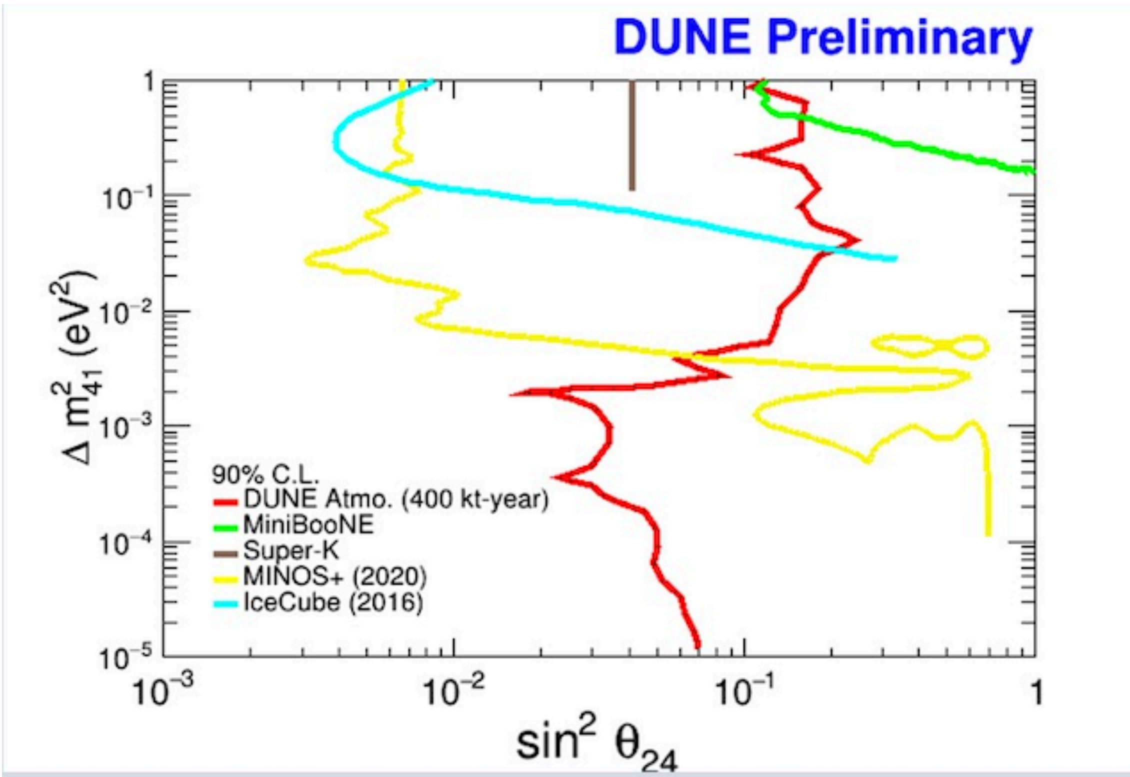
- Stay tuned for the next talk on further exciting DUNE BSM Physics opportunities!

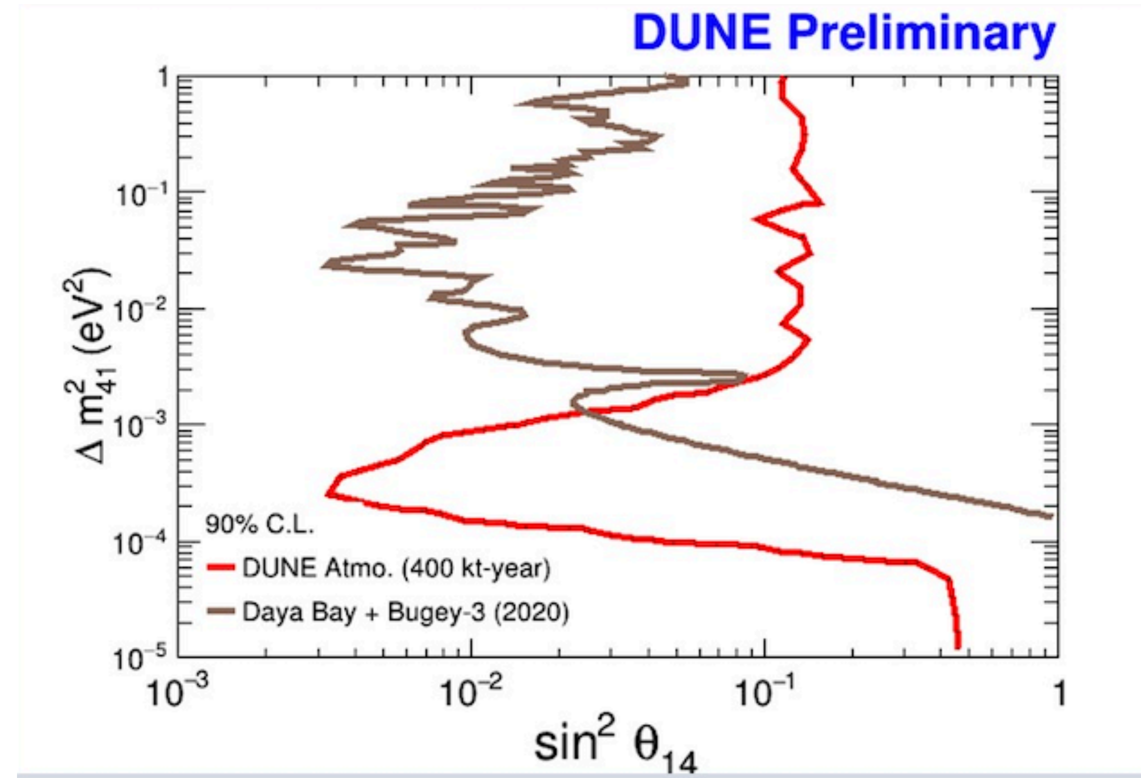


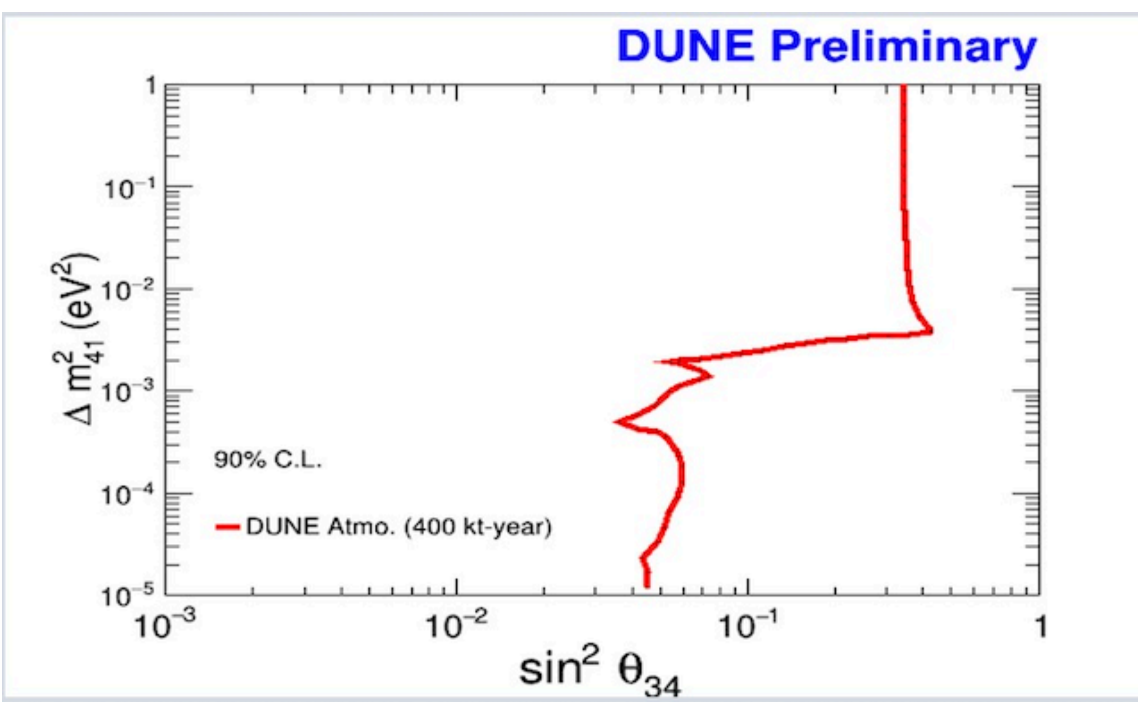


Supplements

Preliminary Atmos. Sterile Sensitivities







- Assuming 400 kton.years exposure

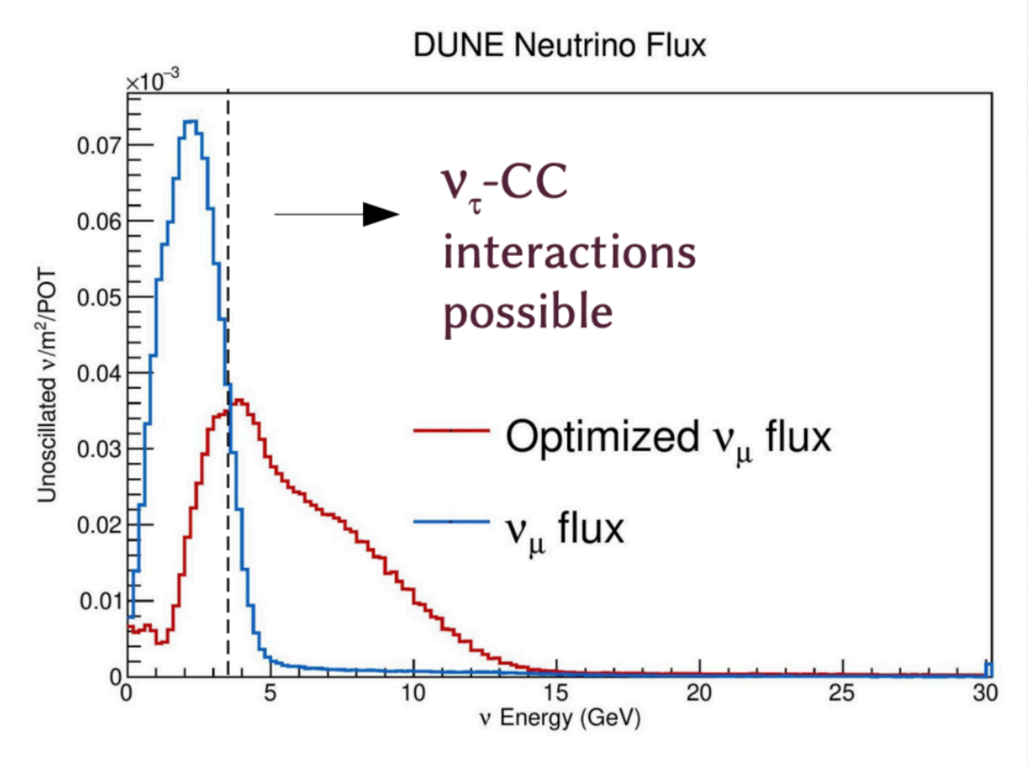
	Track-like events	Shower-like events
Reconstruction efficiency (CC)	80%	80%
Reconstruction efficiency (NC)		0.5%
Neutrino energy resolution	18%	13%
Neutrino direction resolution	10 degrees	10 degrees

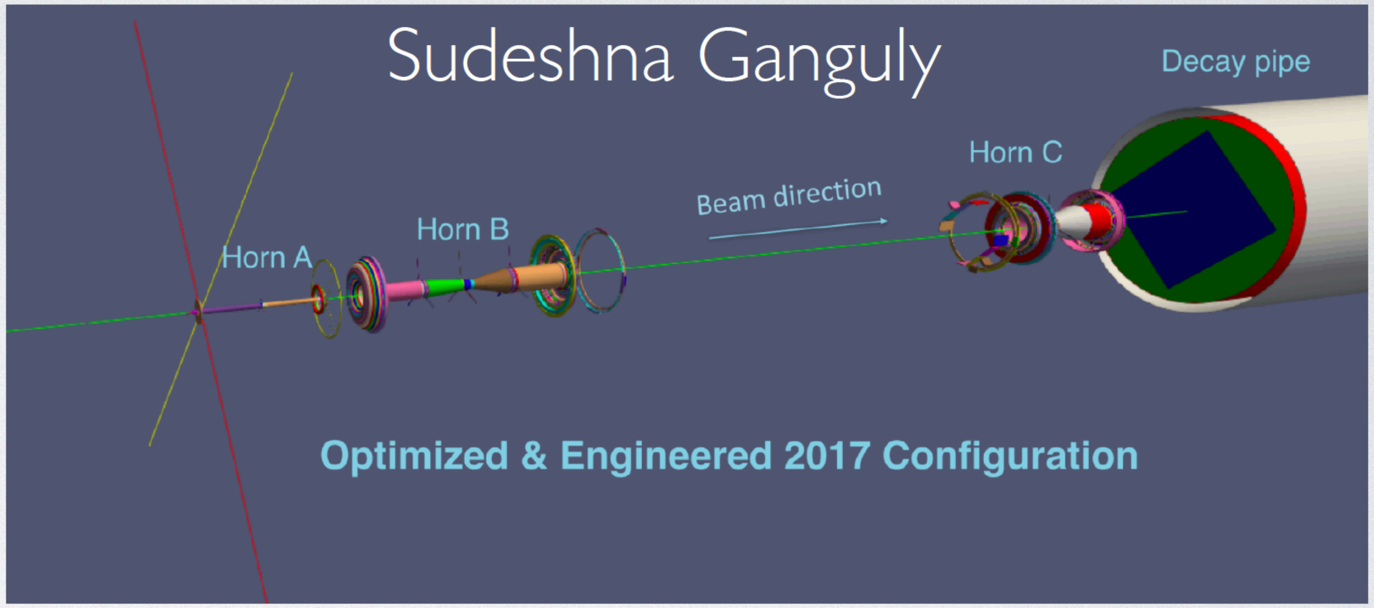
T. Thakore, Neutrino '22

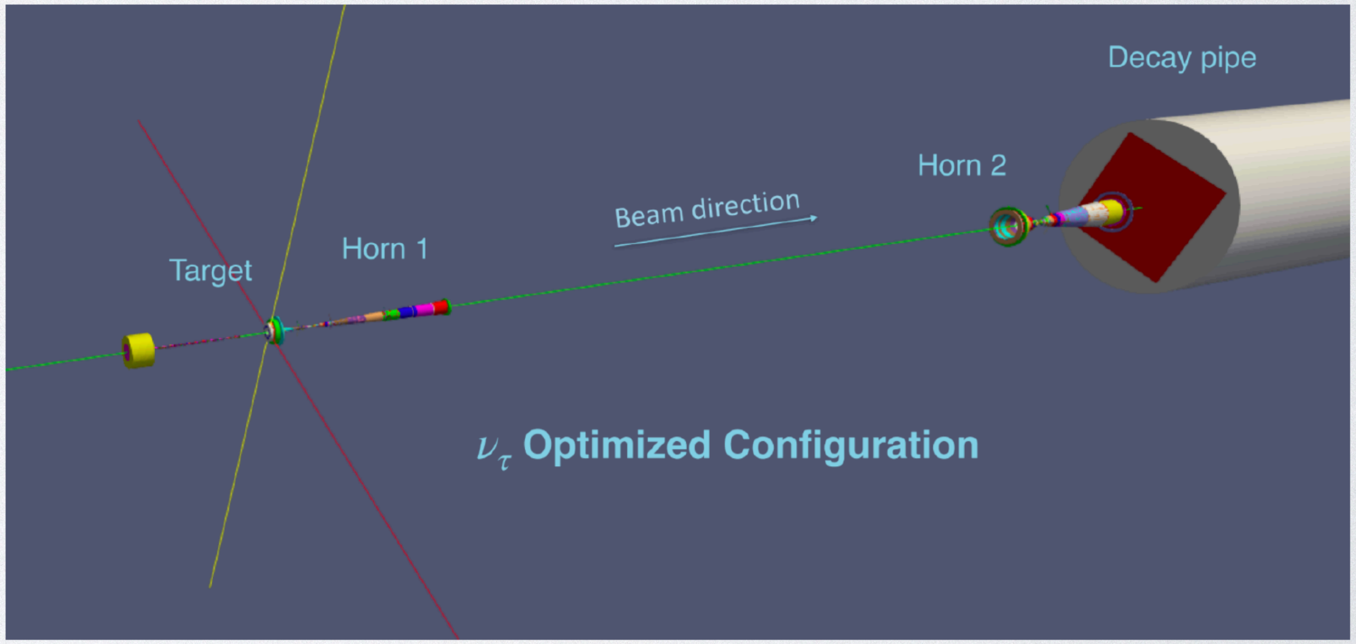
ν_τ-Optimized Beam

Laura Fields, NuTau 2021

FUTURE: DUNE



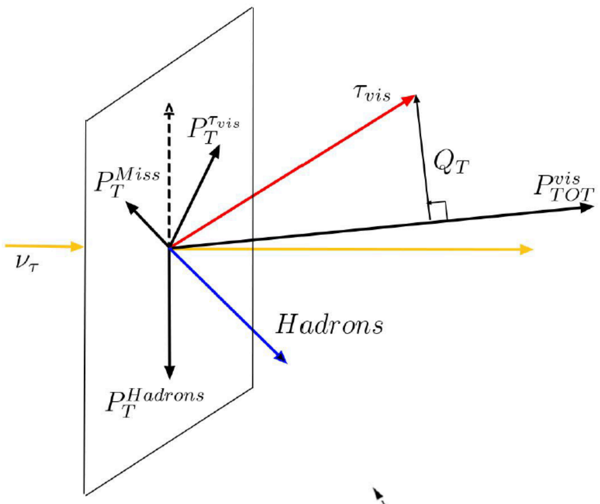


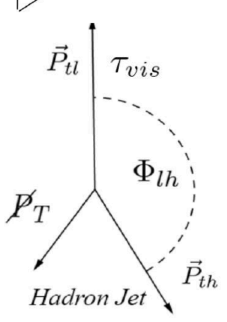


- Beamline **can be tuned to higher energy** by using two NuMI horns and increasing horn separation
- Fairly **simple optimization**; can probably be improved on, but not dramatically

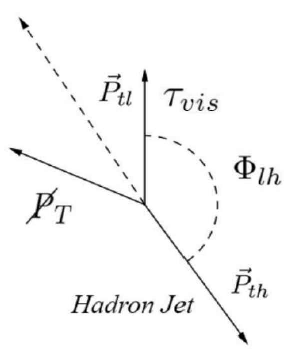
ν_τ CC Selection Variables

- The signal and background separation is based on kinematic differences. Used a total of 18 variables.





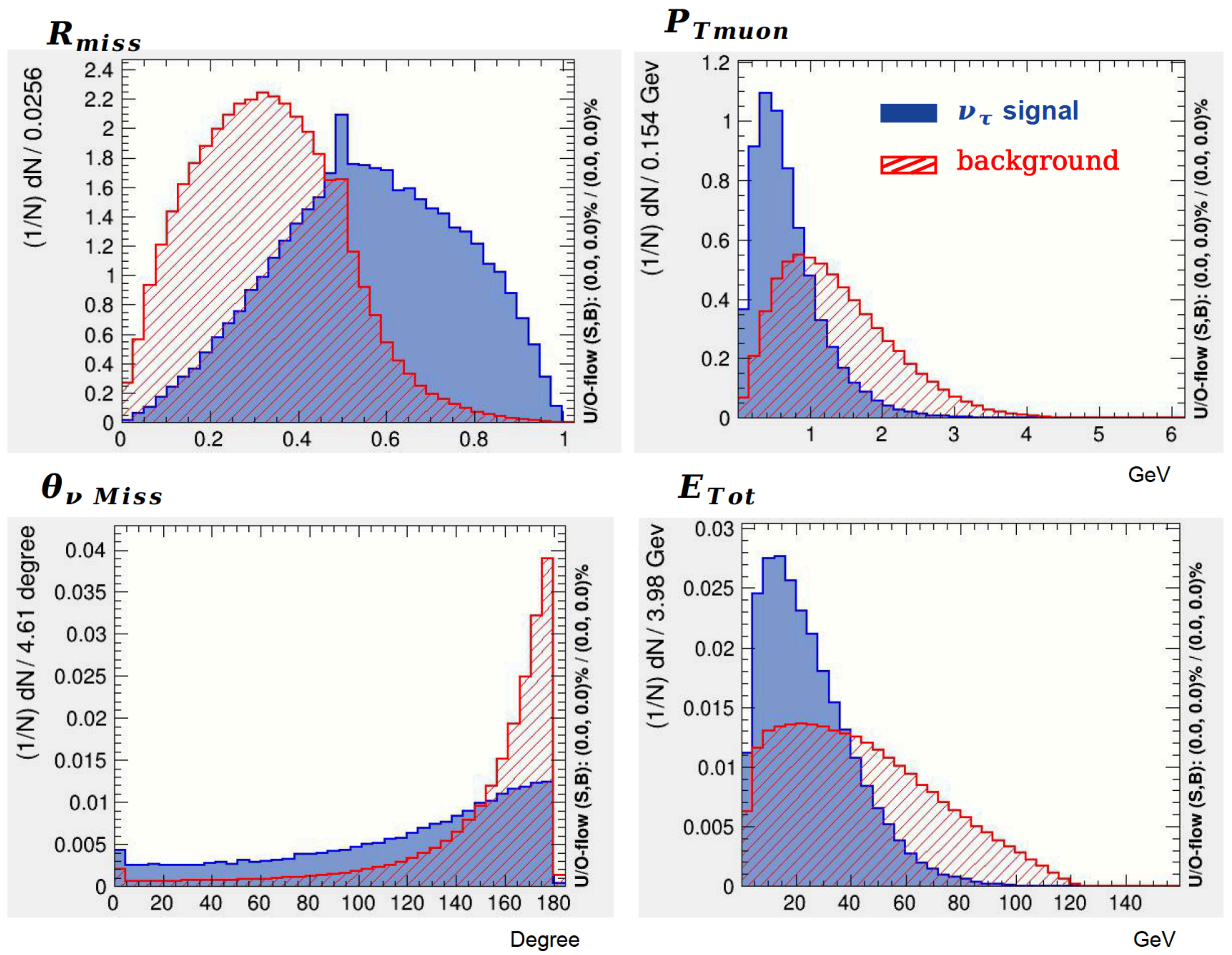
Background interaction products in the transverse plane



ν_τ CC interaction products in the transverse plane

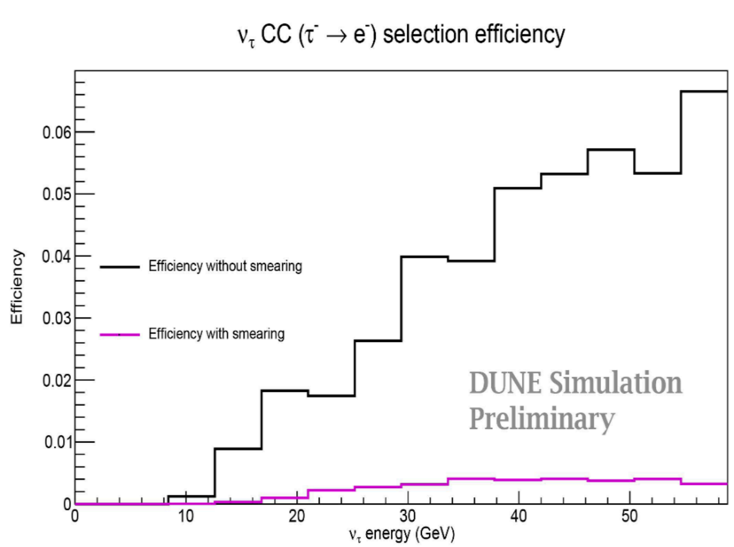
Table shows 6 variables providing highest signal/bg separation

Ranking	Kinematic varialbles
1	$R_{miss} = \frac{P_{TMiss}}{P_{TMiss} + P_{Tmuon}}$
2	P_{Tmuon}: transverse lepton momentum
3	$\theta_{\nu\ Miss}$: angle between beam direction and missing transverse momentum
4	E_{Tot}: total visible energy
5	$\Phi_{muon\ hadron}$: angle between transverse muon and hadron momentum
6	P_{Tot}: total transverse momentum

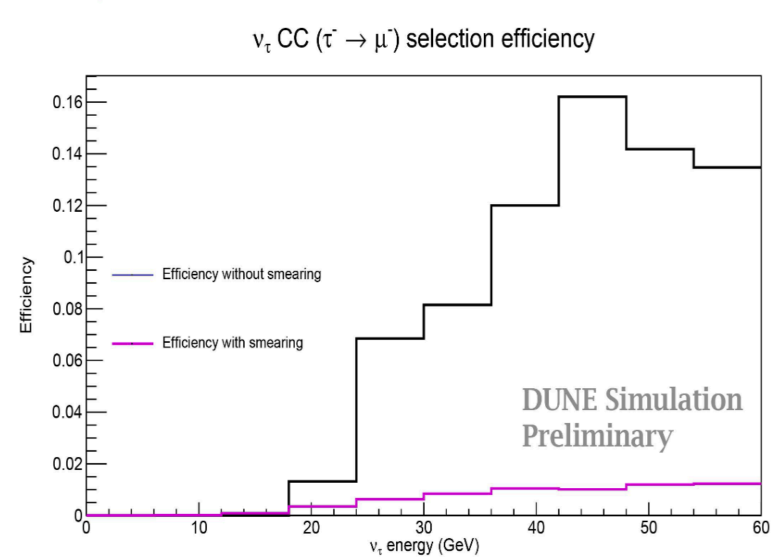


Examples of ν_τ signal (blue) and background (red) kinematic variables distribution.

- Electron channel



- Muon channel

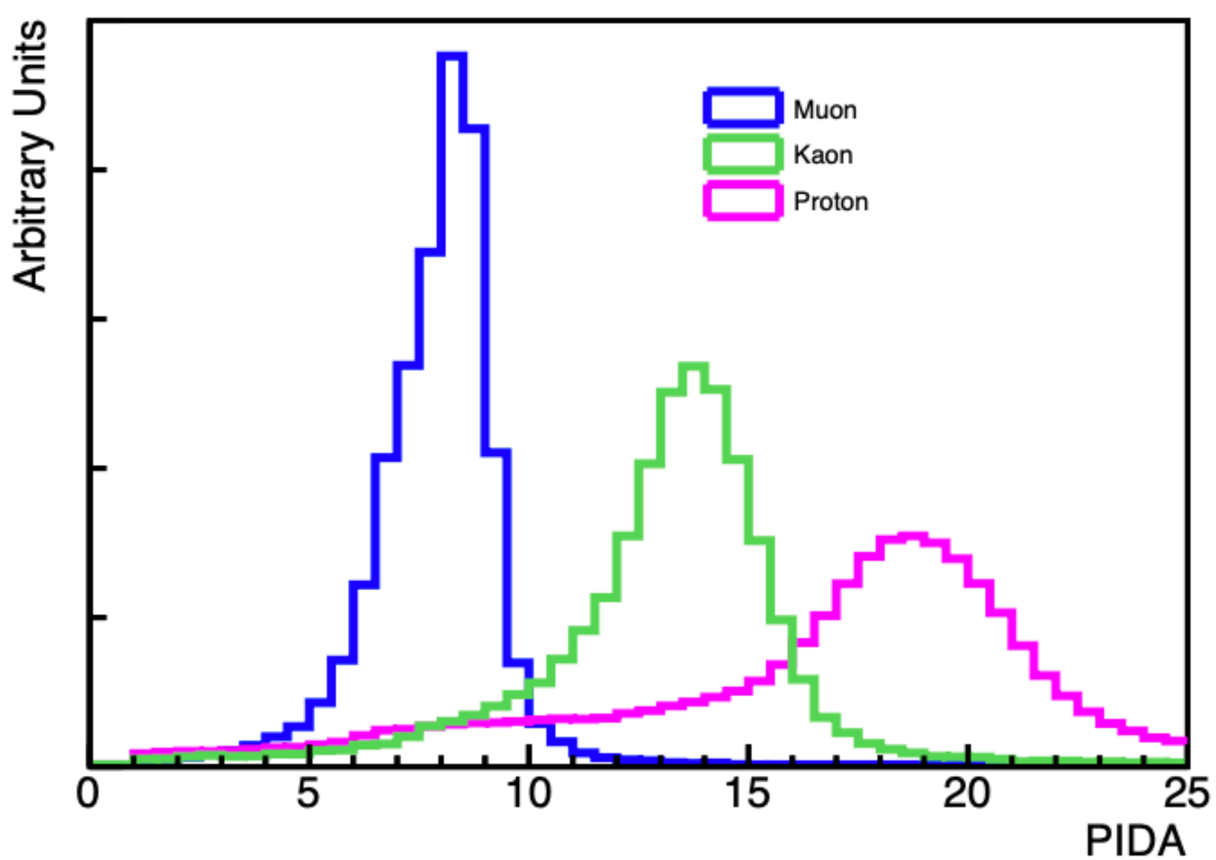


H. Razafinime, Neutrino '22

M. Rajaolisoa, APS '21

Proton Decay

- Proton decay expected to occur in Grand Unified Theories with a lifetime of ~10^{34} - 10^{36} years
- DUNE is most sensitive to proton decay in the $p \rightarrow K^+ + \bar{\nu}$ channel
  - Excellent calorimetric capabilities of LArTPCs enable good kaon identification, as well as high kaon/muon tracking efficiency
  - A lower limit on the proton lifetime of 1.3×10^{34} yrs@90%CL is expected if no signal is observed in 10 years



- World's Best Limits from SuperK:

$$\tau\left(p \rightarrow e^+\pi^0\right) > 2.4 \times 10^{34}\ \text{years}$$

$$\tau\left(p \rightarrow K^+\bar{\nu}\right) > 8.2 \times 10^{33}\ \text{years}$$