Prospects for Physics with ν_τ Appearance in DUNE

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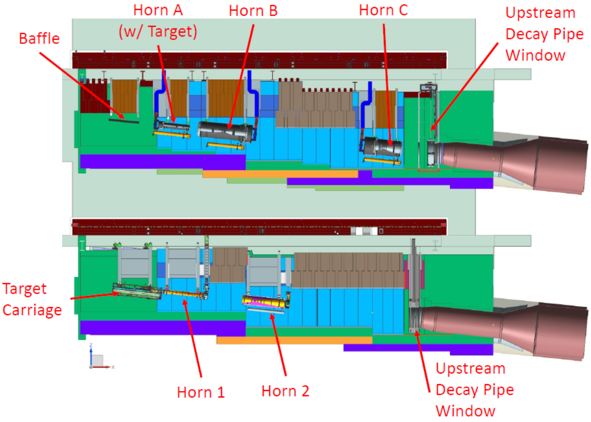
Probing unitarity with $\nu_\mu \rightarrow \nu_\tau$ in DUNE: beam oscillations

Different LBNF/DUNE ν Beam Designs

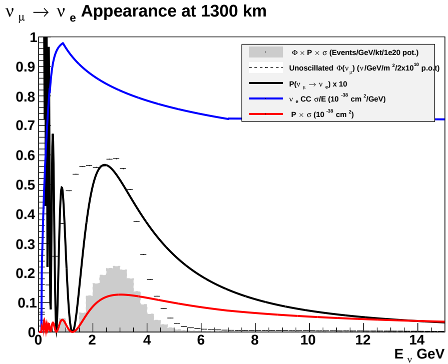
The current LBNF/DUNE reference design is a 3-horn design optimized using genetic algorithim to maximize sensitivity to CPV.

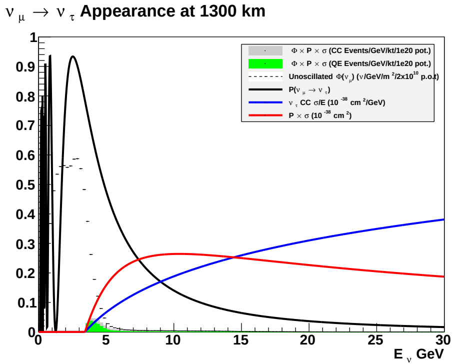
The original LBNF/DUNE design in the CDR was NuMI-like with 2 upgraded NuMI horns, a movable target upstream



Higher ν Energy Beam Tunes with DUNE (M. Bishai proposal)

CPV Optimized Design





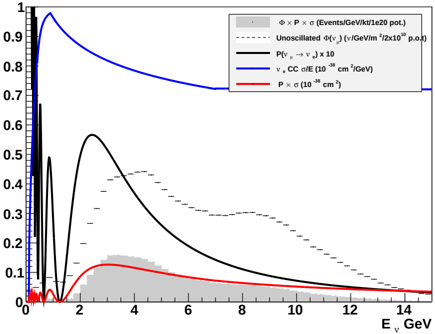
$\nu_\mu \rightarrow \nu_e$ 290 events $\qquad$ **ν_μ rightarrowν_τ 60 events**

in 40 ktons, 1 year at 1.2 MW

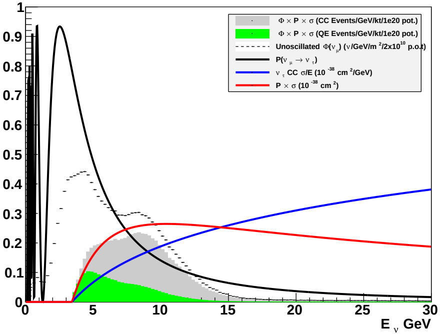
Higher ν Energy Beam Tunes with DUNE (M. Bishai proposal)

NuMI-like design target -2m from horn 1, horns 17m apart with 230kA

$\nu_\mu \rightarrow \nu_e$ Appearance at 1300 km



$\nu_\mu \rightarrow \nu_\tau$ Appearance at 1300 km



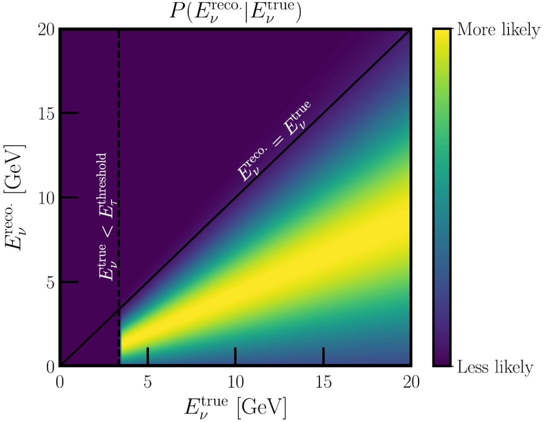
$\nu_\mu \rightarrow \nu_e$ 330 events **$\nu_\mu \rightarrow \nu_\tau$ 700 events**

in 40 ktons, 1 year at 1.2 MW

Increase ν_τ appearance 10x!!! Increase high energy ν_e appearance = NSI/Sterile searches

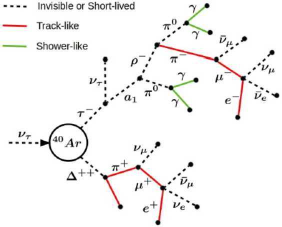
The Trouble with Taus

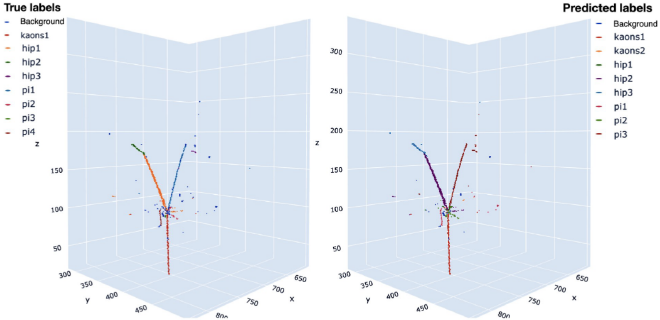
Using ν_τ appearance for precision oscillation measurements is difficult. For ν_τ CC interactions where the τ decays hadronically there is a lot of smearing:



Phys. Rev. D. 100, 016004 (2019)

ν_τ in LArTPC





ν_τ CC signature in a LArTPC is complex - machine learning techniques are still under development to fully take advantage of the level of detail available.

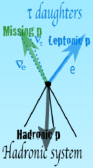
see talk by A. Aurisano at NuTau2021

Kinematic reconstruction of ν_τ using $\tau \to e\nu_e\bar{\nu}_\tau$ in DUNE

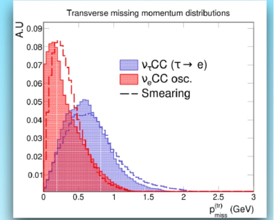
τ—>e analysis (I)

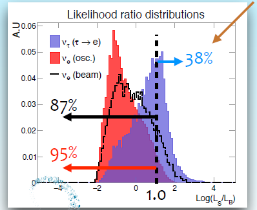
Signal = ν_τ (τ—>e) || Backgrounds = ν_e (osc. + beam)

ν_μ—>ν_e ν_e—>ν_e



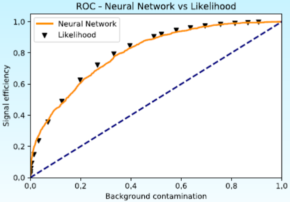
- Transverse missing momentum has **powerful separation power**. Use also hadronic and leptonic momenta and the 3 angles of the plane. 6 variables in total (see back-up).
- Irreducible missing momentum for νe due to final state interaction, Fermi momentum, neutrons ...
- Corresponding log-likelihood distributions. 38% signal efficiency for 95% oscillated νe rejection and 87% beam ν_e rejection (harder separation because they have higher energy).





- Analysis repeated also with **machine learning techniques.**
- Artificial Neural Network (Tensorflow keras) and BDT (TMVA toolkit) didn't improve the likelihood S/B separation results, even in the most favorable case without smearing applied.

Samples S&B size: 30000 events



from presentation by Thomas Kosc at NuTau2021

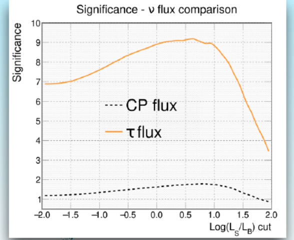
Kinematic reconstruction of ν_τ using $\tau \rightarrow e\nu_e\bar{\nu}_\tau$ in DUNE

τ—>e analysis (II)

Signal = ν_τ (τ—>e) || **Backgrounds** = ν_e **(osc. + beam)**

- Significant improvement using the τ **optimized flux:**
  - ν_e from oscillations ~ constant
  - ν_e from beam contamination x1.5
  - ν_τ **statistics x6 !**
- Initial S/B gets a factor of 4 !

	CP optimized flux	τ optimized flux
ν mode		
ν_e from osc.	1197	1199
$\bar{\nu}_e$ from osc.	18	11
ν_e from beam cont.	365	543
$\bar{\nu}_e$ from beam cont.	57	56
ν_μ	9660	37673
$\bar{\nu}_\mu$	741	683
ν_τ from oscillation (QEL/RES/DIS)	270 (124/62/70)	1658 (531/597/448)
$\bar{\nu}_\tau$ from oscillation	25	22
NC	8228	17564



- The likelihood was found to perform slighly less well with the alternative configuration beam. However the Asimov significance (plotted as a function of the log-likelihood cut value used), 3.5 years staged normalized is **boosted (from 2 to 9 at corresponding maxima).**
- Corresponding number of events for the τ optimized beam:

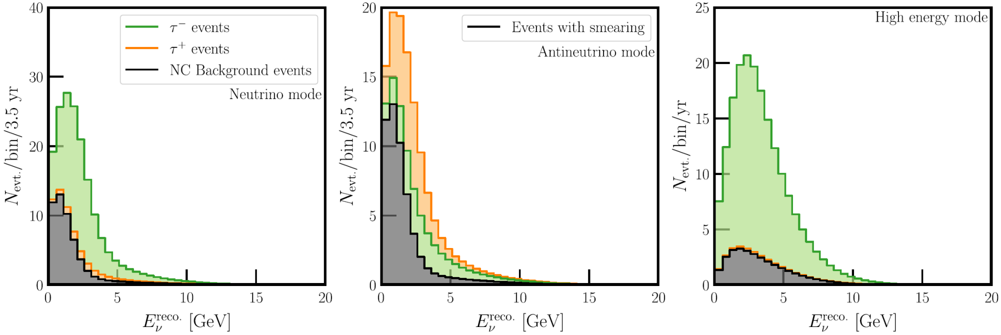
log-LH cut	0.6	1.0	1.6
ντ signal	151.6 ± 1.2	98.2 ± 1.0	23.8 ± 0.7
νe (osc.)	143.6 ± 0.5	60.0 ±0 .3	6.1 ± 0.1
νe (beam)	82.3 ± 2.0	38.1 ±1 .4	6.6 ± 0.6
νe (total)	225.9 ± 2.1	98.1 ± 1.4	12.7 ± 0.6

from presentation by Thomas Kosc at NuTau2021

ν_τ Appearance Measurements in DUNE

Using some optimistic assumptions about ν_τ CC events in DUNE with τ hadronic decays and simple smearing a possible signal in 3.5 yrs running in CPV optimized beam and 1 yr in HE beam:

Appearance spectra



Phys. Rev. D. 100, 016004 (2019)

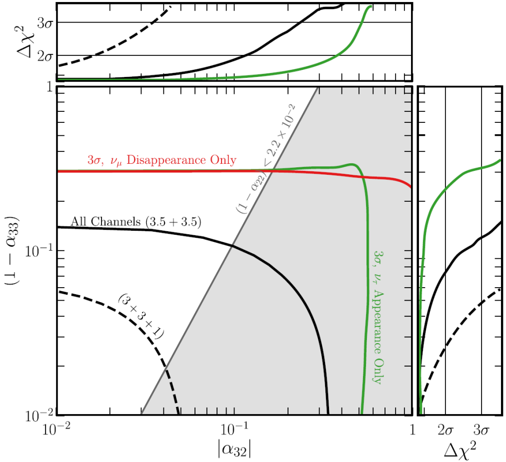
Simple Unitarity Tests with ν_τ Appearance in DUNE

Run in 3.5 (ν) +3.5 ($\bar{\nu}$) years with ν_μ disappearance, ν_e appearance and ν_τ appearance in the default CPV-optimized beam or combine all 3 modes with 3+3 years in LE + 1 year in ν_τ-optimized beam:

U: Unitary matrix, N: non-unitary matrix

$$U \rightarrow NU = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U$$

A small amount of running in the ν_τ beam can provide a powerful unitarity constraint

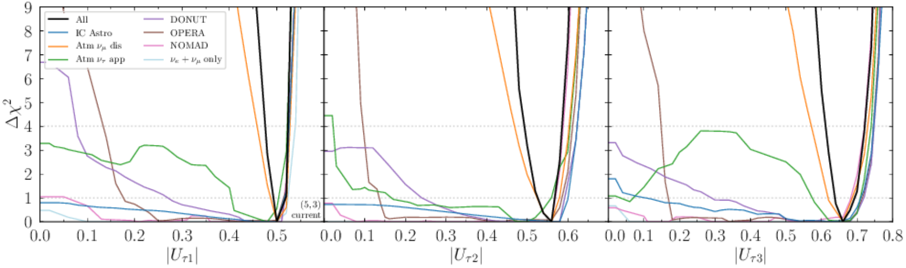


Phys. Rev. D. 100, 016004 (2019)

PMNS Matrix Elements: 3rd Row

The elements of the 3rd row of PMNS matrix elements are the least well measured. Experiments probing ν_τ physics are key to precision measurements of PMNS.

Precision from current experiments (arXiv:2109.14575v2 [hep-ph]):

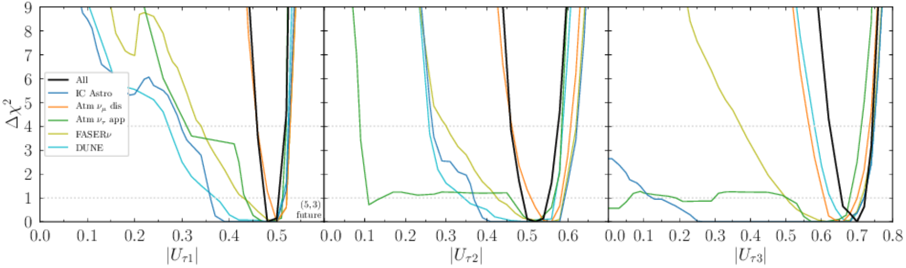


It takes a combination of many very different experiments to constrain the 3rd row of PMNS. The DUNE constraint is the most powerful from a single experiment and does not yet include the significant improvement that could be achieved with the ν_τ optimized beam.

PMNS Matrix Elements: 3rd Row

The elements of the 3rd row of PMNS matrix elements are the least well measured. Experiments probing ν_τ physics are key to precision measurements of PMNS.

Precision from future experiments (arXiv:2109.14575v2 [hep-ph]):

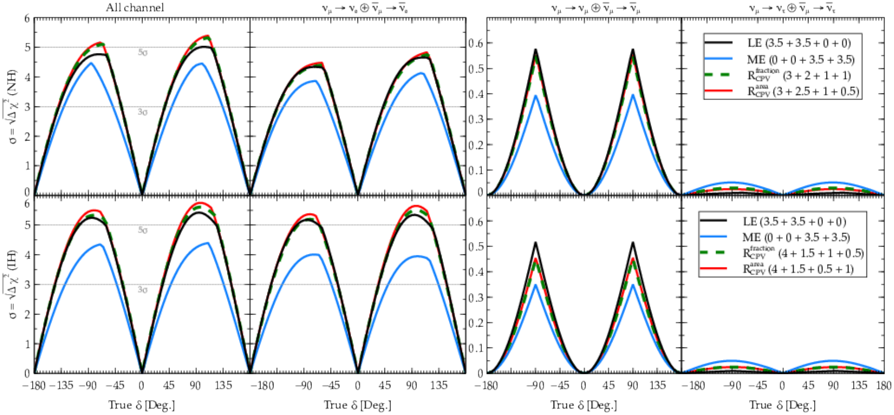


It takes a combination of many very different experiments to constrain the 3rd row of PMNS. The DUNE constraint is the most powerful from a single experiment and does not yet include the significant improvement that could be achieved with the ν_τ optimized beam.

Improved 3-flavor physics sensitivities with running in combined CPV+ν_τ optimized beams (ν CPV+$\bar{\nu}$ CPV+ν nutau + $\bar{\nu}$ nutau)

Running in CP-optimized beam (LE) **Running in ν_τ-optimized beam (ME)**

- - - - maximize fraction of δ_{cp} values with $> 3\sigma$ sensitvity **maximize CP sensitivity area**



Phys.Rev.D 102 (2020) 116018

Searches for anomalous ν_τ appearance in DUNE ND

See Miriama Rajaoalisoa talk at NuTau2021

ν_τ selection using kinematic variables in multiple channels

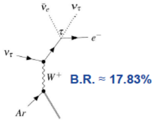
Signal and background separation

Transverse kinematic variables

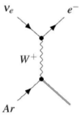
DUNE

τ decay channels

- Electron channel

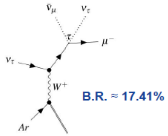


ν_τ CC ($\tau \to e^-$)

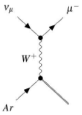


ν_e CC

- Muon channel

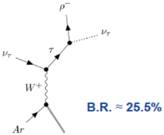


ν_τ CC ($\tau \to \mu^-$)

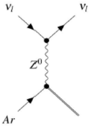


ν_μ CC

- Rho channel



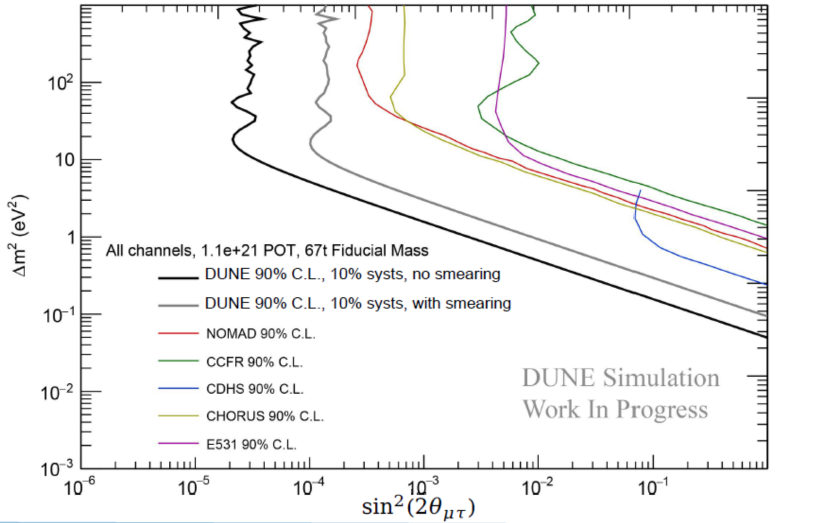
ν_τ CC ($\tau \to \rho^-$)



Neutral Current

- Select the ν_τ events from corresponding backgrounds based on their kinematic differences (similar to those used in NOMAD).
  - In ν_τ CC interactions, the τ will decay into some visible products and neutrinos.
  - The neutrinos take away some energy, use missing energy to differentiate.
  - ROOT TMVA : Machine Learning algorithm (Boosted Decision Tree Gradient - BDTG) to separate ν_τ CC from their backgrounds.

Combined sensitivity from $\tau \to \mu\nu\bar{\nu}$, $\tau \to e\nu\bar{\nu}$ and $\tau \to \rho^-\nu_\tau$, $\rho^- \to \pi^-\pi^0$, $\pi^0 \to \gamma\gamma$



Constraining the ν_τ neutrino transition magnetic moments in DUNE

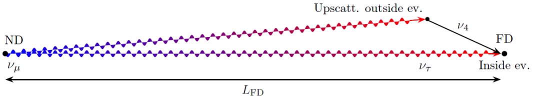
See Jing-yu Zhu talk at NuTau2021

DUNE Sensitivity to a Heavy Neutral Lepton (HNL)

The HNL interacts with the SM through a *transition magnetic moment to active neutrinos*. The HNL is produced through up-scattering of active neutrinos and subsequent decay inside the detector with a single photon signal.

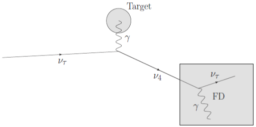
Methods at DUNE

We start with the tau neutrino flux generated by the neutrino oscillations and consider coherent scattering off nuclei and incoherent scattering off protons, neutrons and electrons.



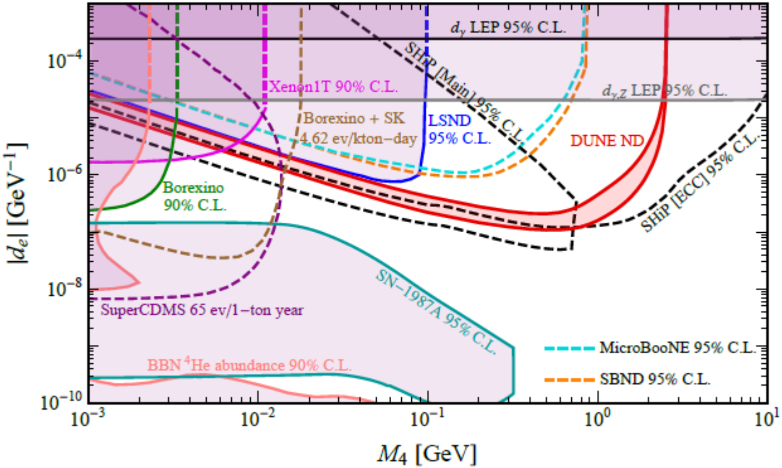
Assumptions:

- Dirac neutrinos
- The heavy neutrino flavor mixing with active neutrinos is negligible and the dipole interaction dominates.



JHEP 07 (2021) 200

DUNE limits on HNL



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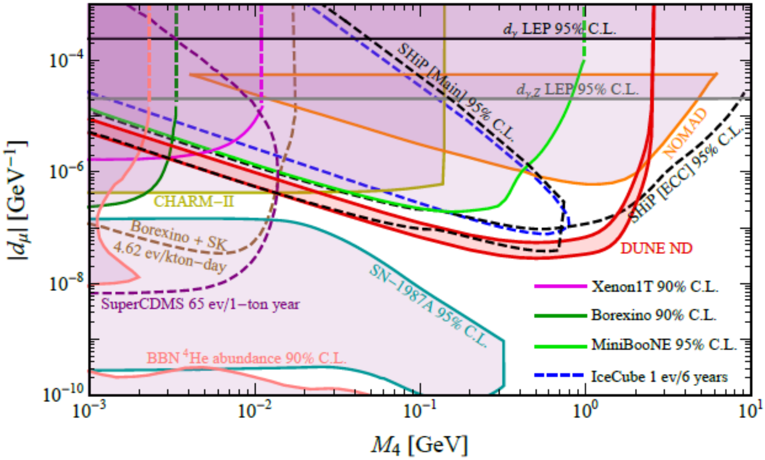

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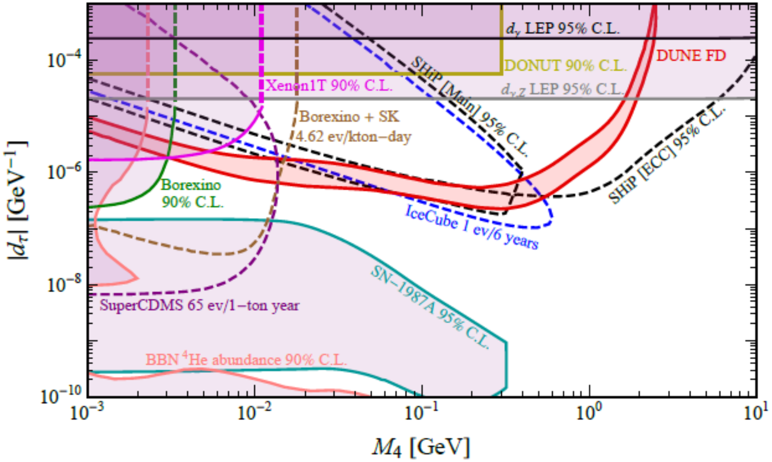
DUNE limits on HNL



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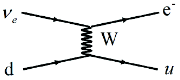
Probing new physics beyond 3-flavor oscillations with the higher energy beam tunes in DUNE

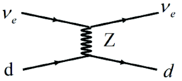
NSI in Long-Baseline Oscillations

Prospects for Physics with ν_τ Appearance in DUNE
Mary Bishai
ν_τ Appearance in DUNE FD
ν_τ in ND
ν_τ magnetic moment
Beyond νSM with HE beams
Summary

- 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

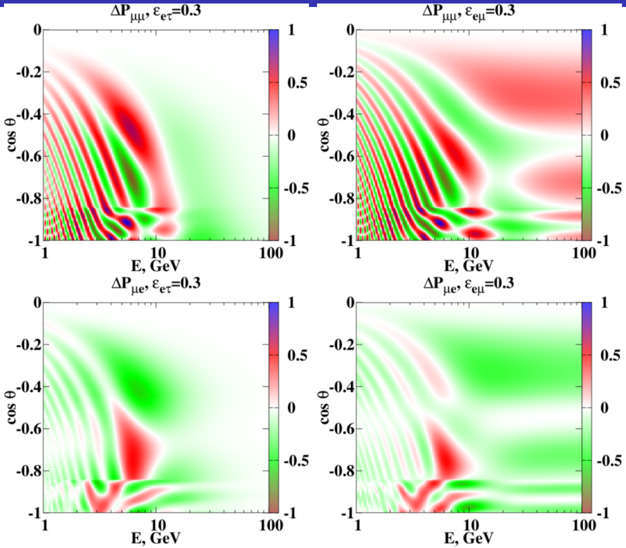
$$\mathcal{L}_{NC} = (\overline{\nu_\alpha}\gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P_{L,R} f')$$

NC NSI
propagation

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

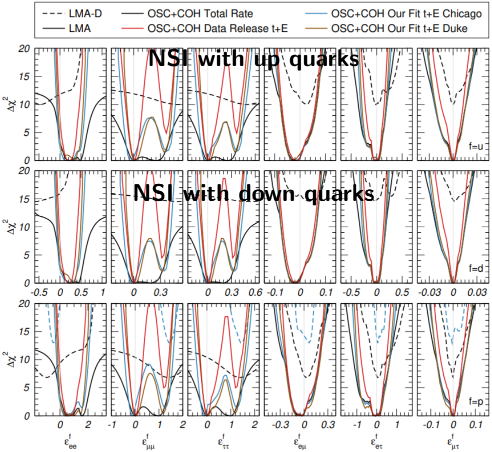
$$\tilde{V}_{\rm MSW} = \sqrt{2} G_F N_e \begin{pmatrix} 1+\epsilon^m_{ee} & \epsilon^m_{e\mu} & \epsilon^m_{e\tau} \\ \epsilon^{m*}_{e\mu} & \epsilon^m_{\mu\mu} & \epsilon^m_{\mu\tau} \\ \epsilon^{m*}_{e\tau} & \epsilon^{m*}_{\mu\tau} & \epsilon^m_{\tau\tau} \end{pmatrix}$$

NSI impact on Atmospheric Long Baseline



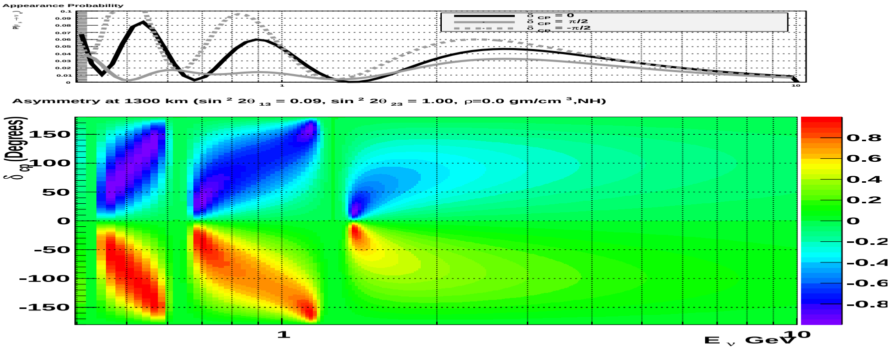
NSI limits from Current Experiments

P. Coloma *et. al.* **JHEP 02 (2020) 023:**



CP Asymmetry vs E_ν and δ_{cp}

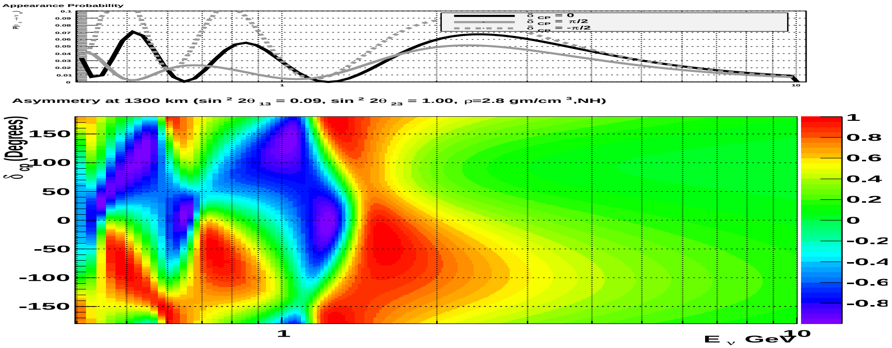
$$\mathcal{A} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)}$$



Asymmetries caused by CPV and matter are a complex phenomena

CP Asymmetry vs E_ν and δ_{cp}

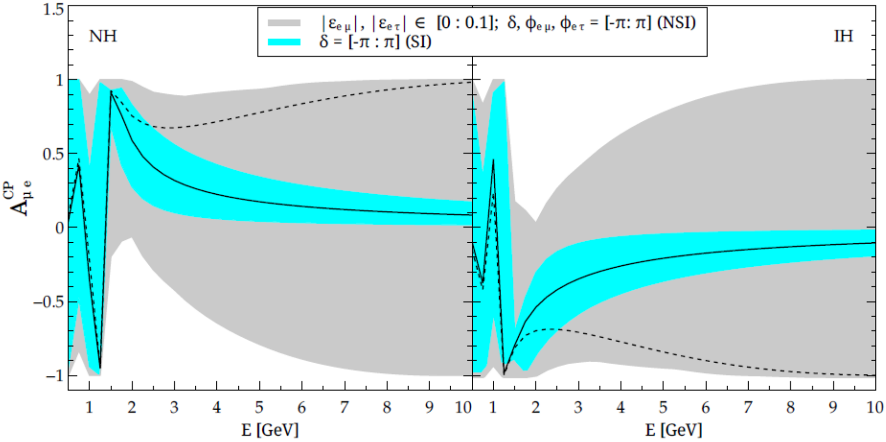
$$\mathcal{A} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)}$$



Asymmetries caused by CPV and matter are a complex phenomena

Extricating NSI from 3-flavor Oscillations

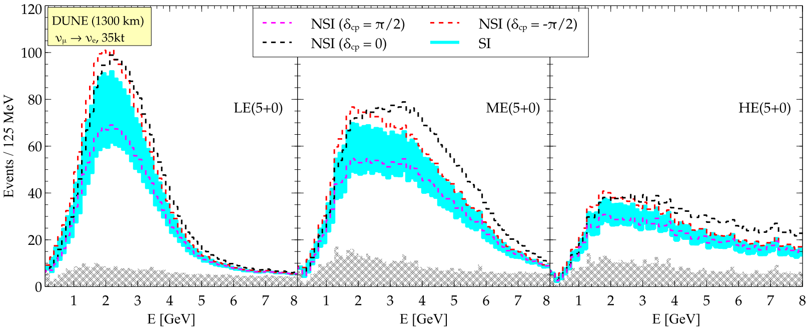
NSI could also impact interpretation of observed CP asymmetries in long-baseline:



J.Phys.G 43 (2016) 9, 095005

Extricating NSI from 3-flavor Oscillations

Study NSI sensitivity with GLoBeS using $\nu_\mu \to \nu_{\mu,e}$ and 3 sample LBNF-like beam tunes : LE, ME and HE*. NSI parameters used: $|\epsilon_{e\mu}| = 0.04$, $|\epsilon_{e\tau}| = 0.04$, $\epsilon_{ee} = 0.4$, $\phi_{e\mu}$=0, $\phi_{e\tau}$



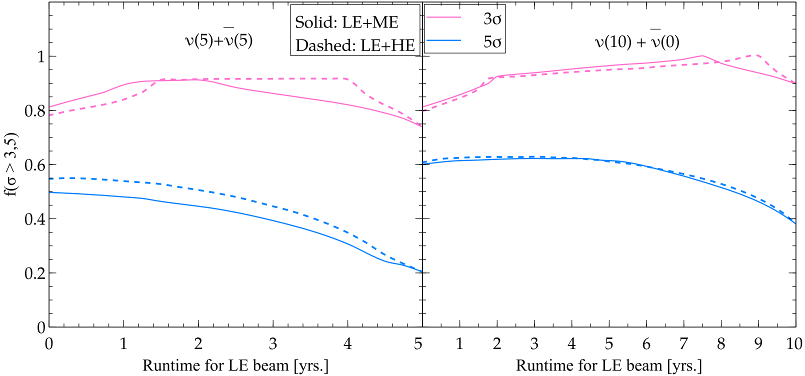
NSI effects in $\nu_\mu \to \nu_e$ are larger at higher energy

Sci. Rep. 9 (2019) no.1, 352

* **2 NuMI horns, 230kA, 6.6m apart and horns were not moved for higher energy beam tunes (non-optimal beams). Decay pipe was assumed to be 250m.**

Extricating NSI from 3-flavor Oscillations

Fraction of SI δ_{cp} for which SI/NSI can be separated at the $3/5\sigma$ level:

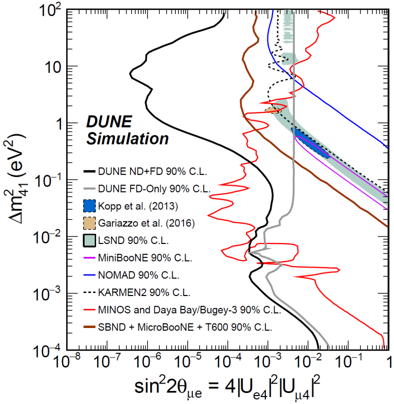


Can achieve 3σ separation for $> 80\%$ of true δ_{cp} **No beam optimization attempted yet!**

Sci. Rep. 9 (2019) no.1, 352

Other physics enabled by the higher energy beam

- **Extend the search for large compactified extra dimension from String Theory models that manifest through mixing between the Kaluza-Klein states and the three active neutrino states.**
- **Extend the search for $\nu_\mu \to \nu_s$ in both ND and FD to lower masses and smaller mixing angles.**
- **Precision measurements of θ_W in DUNE ND**



Summary and Conclusions

Summary

Prospects for Physics with ν_τ Appearance in DUNE

Mary Bishai

- **A strong and *incomparable* program of precsion measurements of the full 3-flavor oscillation model using $\nu_\mu \to \nu_\tau$ is possible at DUNE using proven MW neutrino beamline designs from NuMI that can be installed in the LBNF beamline**
- **Studies show that running in the ν_τ optimized beam for 15-20% of the time** *does not impact sensitivity to CPV and may even improve it!*
- **Preliminary simulation and reconstruction efforts demonstrate that DUNE can extract a clean ν_τ CC signature from other ν interaction backgrounds. Further work is needed to realize the full potential of DUNE LArTPCs (both ND and FD) to reconstruct ν_τ**
- **The higher energy wider-band beam optimized for ν_τ appearance also opens up a new frontier of using precision oscillation measurements to search for physics beyond the SM for example HNLs, new interactions in matter, compactified large extra dimensions, sterile neutrinos, precision EW measurements in ND..etc**

IMHO, incorporating a program of running in a higher-energy beam tune optimized for ν_τ appearance in DUNE Phase II is a NO-BRAINER. This can also set physics requirements for new LArTPC technologies for detectors 3 and 4 given the complexity of ν_τ CC topologies and the need for accurate reconstruction of kinematics.