NuFACT 2023

KOREA INSTITUTE FOR ADVANCED STUDY

Non-Standard Neutrino Interactions Mediated by Light Scalars

Sumit Ghosh
Korea Institute for Advanced Study
ghosh@kias.re.kr

https://neutrino.syr.edu/research/neutrino-oscillations/

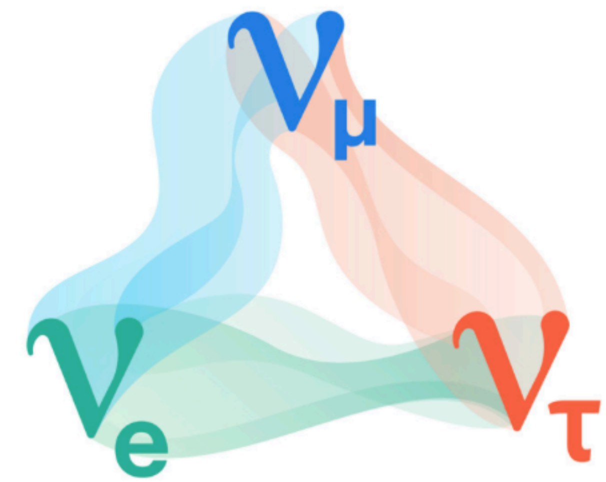
based on: arXiv 2309.XXXXX (appears soon)

On behalf of the collaboration with:
Bhaskar Dutta,
Tianjun Li,
Kevin Kelly,
Adrian Thompson,
and Ankur Verma.

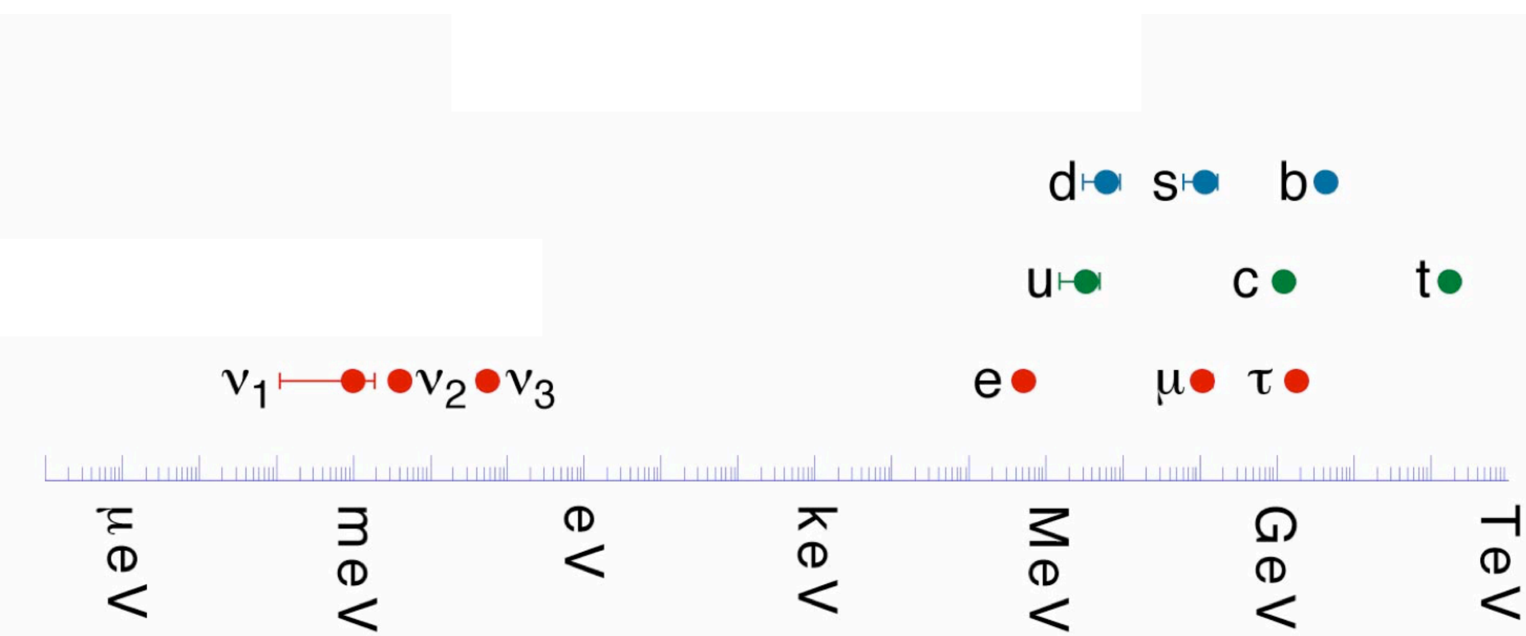
SM is not complete

- Neutrino mass and oscillations is a well known phenomenon. However, the neutrino mass generation mechanism remains unknown.

- New physics in neutrino sector can give rise to non-standard interactions of neutrinos.



https://neutrino.physics.iastate.edu/project/dune



Ferruccio Feruglio

- So far, no experimental evidence for NSI of neutrinos, but if exist, directly indicate new physics beyond SM- well motivated from a phenomenological point of view.

WHAT DO WE DO

- We consider light scalar mediated NSI and want to study it's effects on neutrino oscillation specifically on CP measurements at neutrino oscillation experiment such as DUNE.

- We want to find sensitivity on NSI parameters, considering all at the same time, for CP measurements at DUNE.

- Finally we want to translate the NSI parameters into sensitivity on the parameter space for light scalar models and compare with existing constraints.

SCALAR NSI

- Consider interactions between neutrinos and fermions present inside matter mediated by a light scalar.

$$\mathscr{L}_{\phi'} = \bar{\nu}(i\gamma^\mu \partial_\mu - m_\nu)\nu - y_\nu \bar{\nu}\nu\phi' - y_f \bar{f} f \phi' - \frac{1}{2}(\partial_\mu \phi')^2 - \frac{1}{2} m_{\phi'}^2 \phi'^2$$

- The effect of ϕ' on neutrino propagation is equivalent to changing the neutrino mass. Calculating e.o.m. of neutrino,

$$m_\nu \rightarrow m'_\nu = m_\nu + \delta m_\nu; \qquad \delta m_\nu = y_\nu \phi$$

- This correction to neutrino mass modifies the neutrino oscillation Hamiltonian.

$$H_s \simeq E_\nu + \frac{m_\nu^2}{2E_\nu} + V_{SI} + \frac{m_\nu}{E_\nu}\delta m_\nu$$

PARAMETRIZATION

- The ϕ' is induced by fermion matter density. Calculating e.o.m. of ϕ', we estimate mass correction.

$$\delta m_\nu \simeq \frac{y_\nu y_f n_f}{m_{\phi'}^2}; \qquad \text{for } q^2 \ll m_{\phi'}^2$$

- We parametrize in terms of dimensionless quantities $\eta_{\alpha\beta}$

$$\delta m_\nu \equiv \sqrt{|\Delta m_{31}^2|} \begin{pmatrix} \eta_{ee} & \eta_{e\mu} e^{i\phi_{e\mu}} & \eta_{e\tau} e^{i\phi_{e\tau}} \\ \eta_{e\mu} e^{-i\phi_{e\mu}} & \eta_{\mu\mu} & \eta_{\mu\tau} e^{i\phi_{\mu\tau}} \\ \eta_{e\tau} e^{-i\phi_{e\tau}} & \eta_{\mu\tau} e^{-i\phi_{\mu\tau}} & \eta_{\tau\tau} \end{pmatrix}$$

- The model parameters are related to the $\eta_{\alpha\beta}$'s

$$\sqrt{|y_f y_{\alpha\beta}|} = \left(2.17 \cdot 10^{-4} \times |\eta_{\alpha\beta}| \left(\frac{|\Delta m_{31}^2|}{\text{eV}^2}\right)^{-1/2} \times \left(\frac{m_\phi}{\text{keV}}\right)^2 \times \left(\frac{\text{g/cm}^3}{\rho}\right)\right)^{1/2}$$

Properties of scalar NSI

- In the presence of scalar NSI, the oscillation probabilities are sensitive to absolute mass scale of neutrinos.

— look at the propagation of $\psi_{\alpha,\beta}(t) = < \nu_\beta | \nu_\alpha(t) >$ for SI

$$i\frac{d}{dx}\psi_{\alpha\beta}(x) = \left(E_\nu + V_{NC}\right)\psi_{\alpha\beta}(x) + \sum_\eta \left(\sum_k U_{\beta k}\frac{m_k^2}{2E_\nu}U^*_{\eta k} + \delta_{\beta\eta}\delta_{\beta e}V_{CC}\right)\psi_{\alpha\eta}(x)$$

— we can subtract an identity matrix proportional to the lightest neutrino mass and write in terms of mass square quantities Δm_{k1}^2 .

— in presence of scalar NSI, even after subtraction we have terms of the form $m\delta m$.

$$i\frac{d}{dx}\psi_{\alpha\beta}(x) = \left(E_\nu + \frac{m_1^2}{2E_\nu}V_{NC}\right)\psi_{\alpha\beta}(x) + \sum_\eta \left(\sum_k U_{\beta k}\left(\frac{\Delta m_k^2}{2E_\nu} + \frac{m_k\delta m_k}{E_\nu}\right)U^*_{\eta k} + \delta_{\beta\eta}\delta_{\beta e}V_{CC}\right)\psi_{\alpha\eta}(x)$$

Properties of Scalar NSI

- The scalar NSI can have unphysical phases that have physical consequences on the neutrino oscillations.
  - — neutrino mass matrix can be diagonalized using $V = P_l^\dagger U_{PMNS} P_\nu$, which is coming from the leptonic charged current weak interaction current .

$$\mathscr{L}_{cc} = -\frac{g}{\sqrt{2}} \bar{l}_L \gamma^\mu V \nu_L W_\mu^- + h.c.$$

  - — here P_l and P_ν are unphysical diagonal rephrasing matrices which can be rotated away.
  - — in presence of scalar NSI δm_ν , we can not rotate away the unphysical matrix P_l.
  - — these unphysical phases contribute to the phases of NSI parameters and can affect the measurements of CP phase at oscillation experiments.

AN EXAMPLE MODEL

- Light scalar mediator model: we propose one.

— by extending the SM scalar sector by:

$$H_1 \sim (2,1/2), \quad H_2 \sim (2,1/2), \quad \phi \sim (1,0), \quad \Delta \sim (3,1) \ .$$

— we consider $< H_1 > = v_1/\sqrt{2}, \ < H_2 > = 0, \ < \phi > = v_\phi/\sqrt{2}, \ < \Delta > = v_\Delta/\sqrt{2}$.

— mixing in the scalar sector give rise to one light scalar, ϕ', with mass ≤ 1keV.

— Yukawa term $\bar{l}'^{c}_{L_i}(y')_{ij} i\sigma_2 \Delta l'_{L_j}$ and scalar mixing give NSI of neutrinos with the light scalar.

— fermions interactions with H_2 give rise to FCNC at tree level and scalar mixing then gives fermions interactions with the light scalar .

— thus all possible NSI terms with SM fermions mediated by the light scalar arise from:

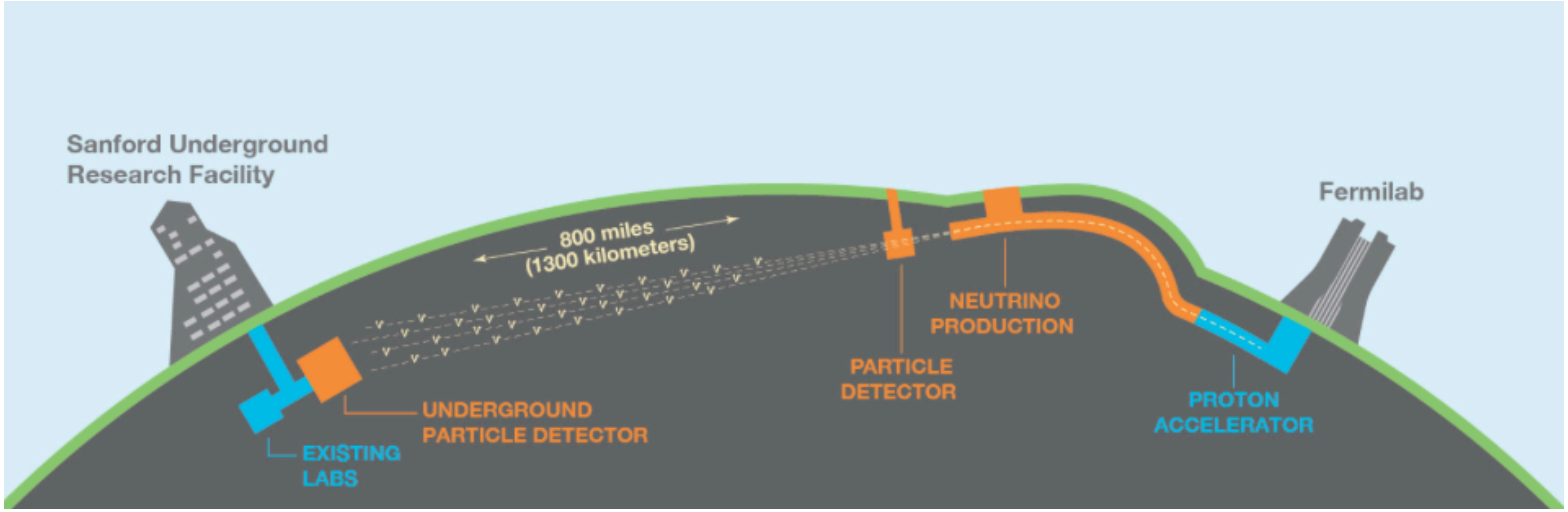
$$-\mathscr{L}_{Yukawa} \subset \bar{\nu}^c_i (y_\nu)_{ij} \nu_j \phi' + \bar{f}_i (y_f)_{ij} f_j \phi'$$

DUNE EXPERIMENT

- Scalar mediated NSI can impact the CP violation measurement at DUNE.
  — we measure the effect and find the sensitivity of DUNE on NSI parameters.

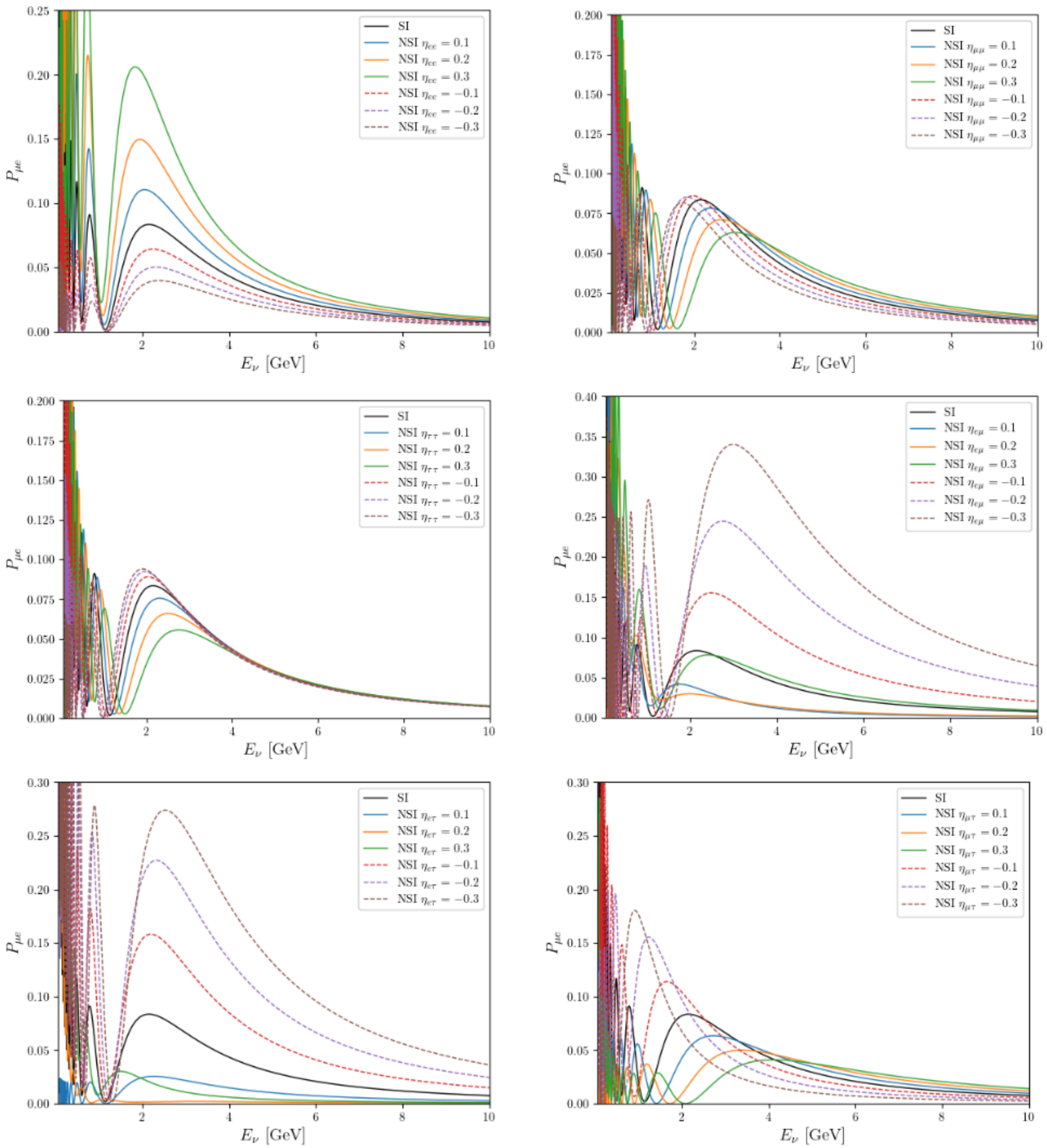
  — we take the baseline length 1300 kms.

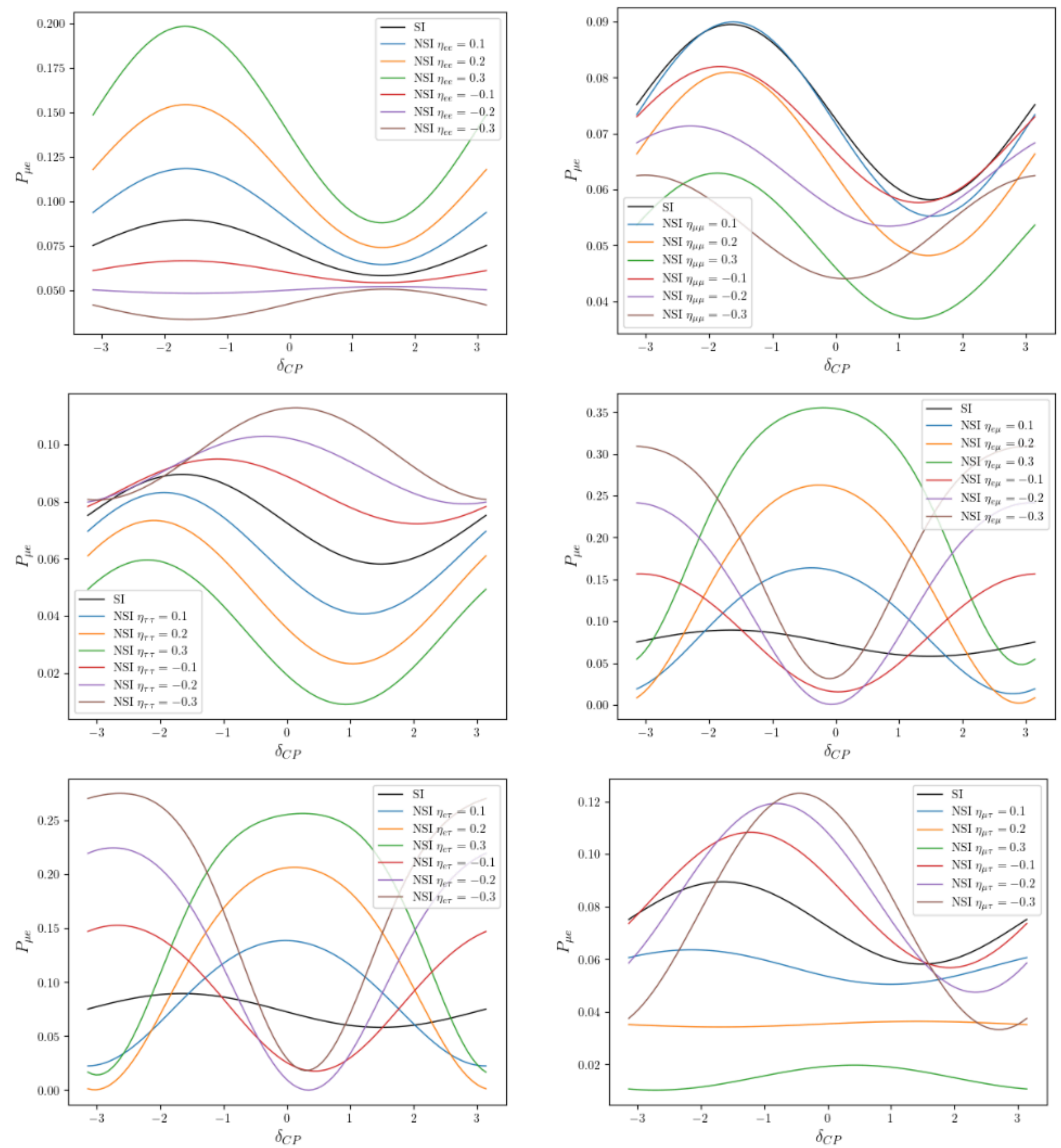
  — we consider an exposure of 7 years in equal neutrino and antineutrino mode.



https://neutrino.physics.iastate.edu/project/dune

OSCILLATION PROBABILITY

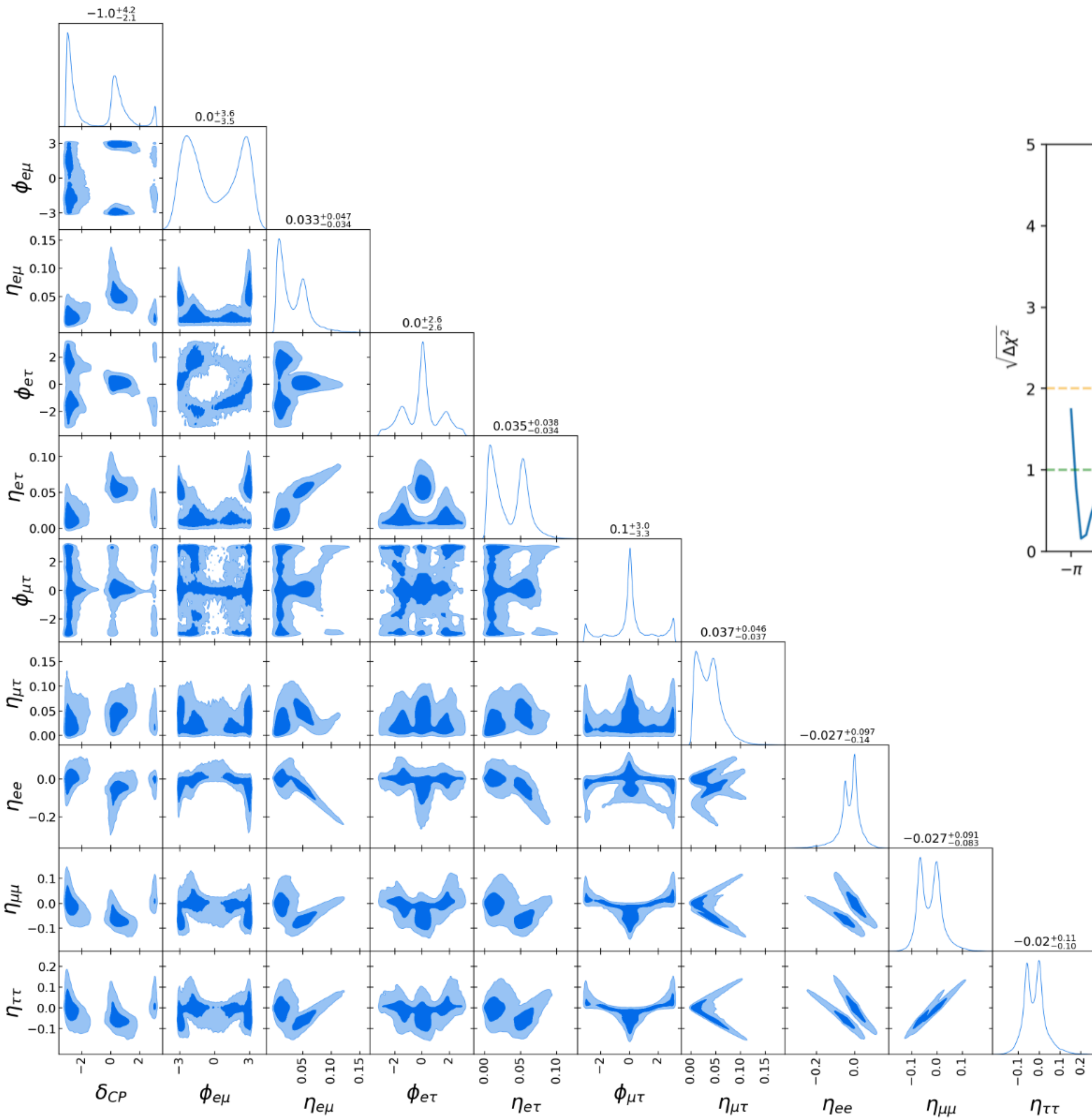


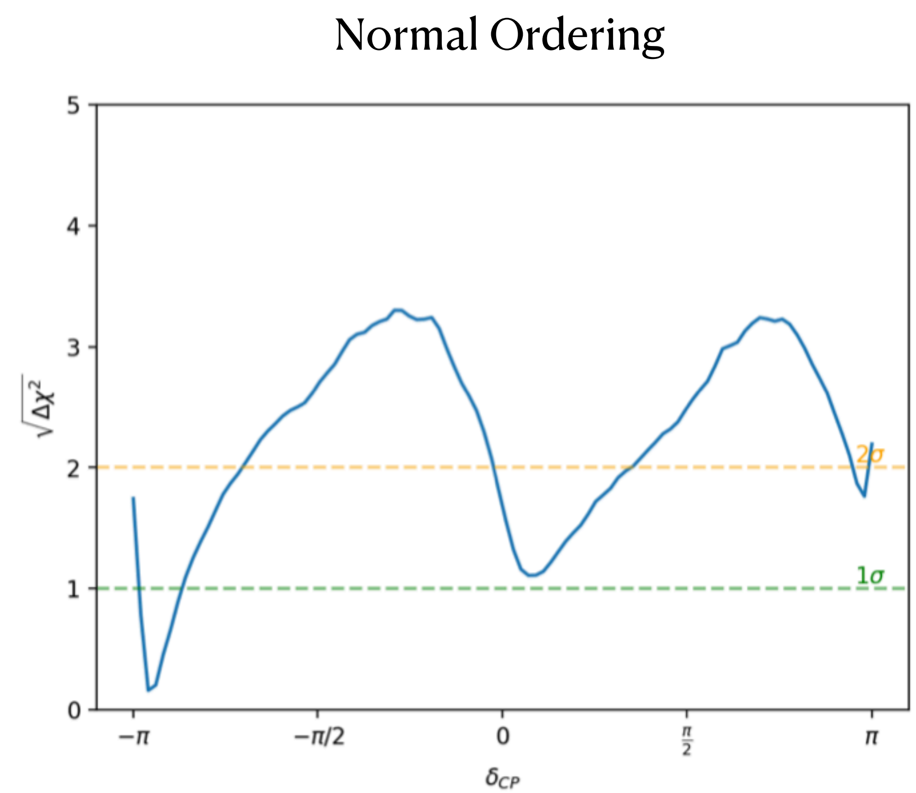


Normal Ordering, $L = 1300$ km, $\rho = 2.84$ g cm^{-3}, $m_1 = 0$

Normal Ordering, $E_\nu = 2.5$ GeV

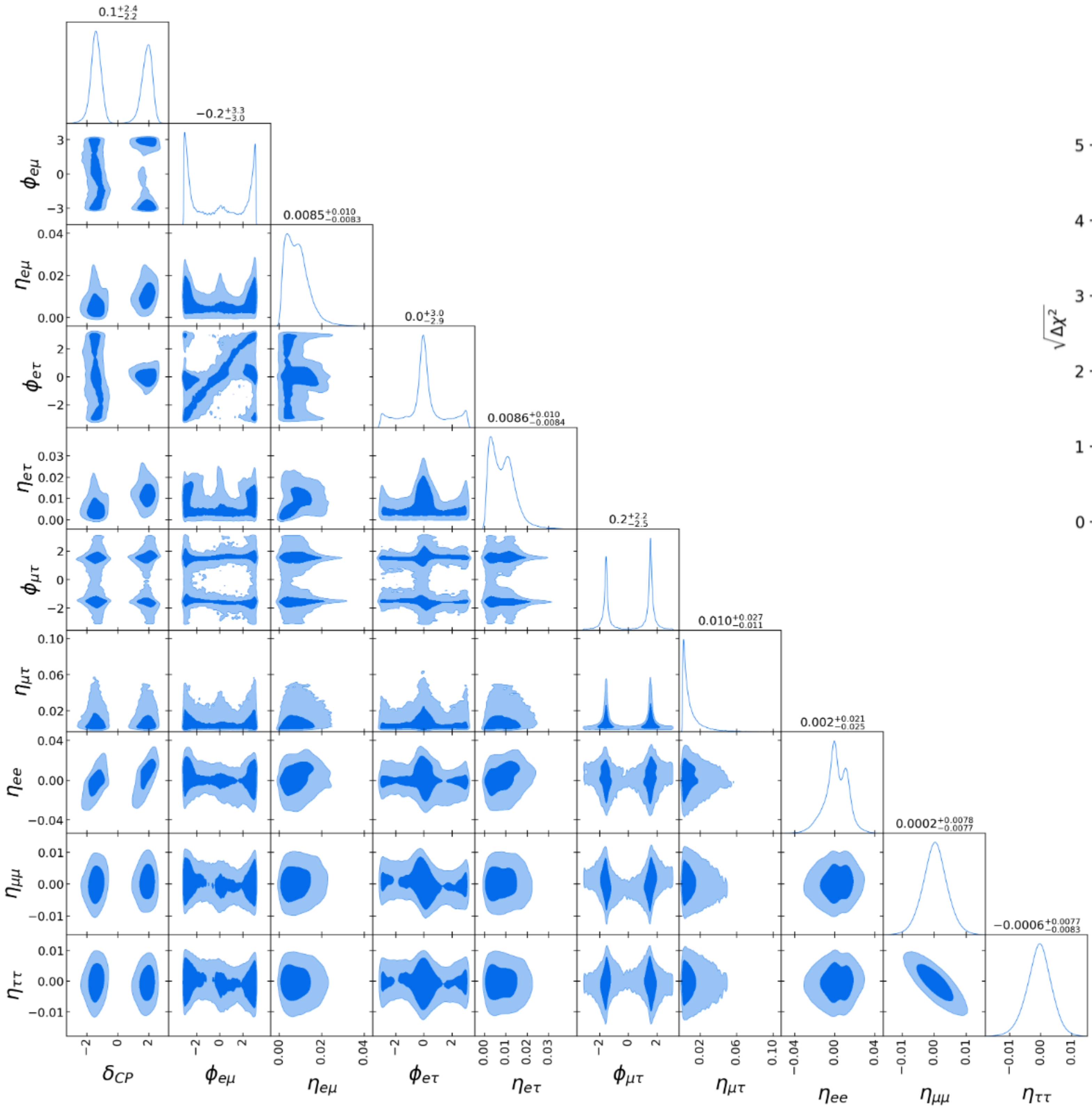
DUNE Sensitivity: NO

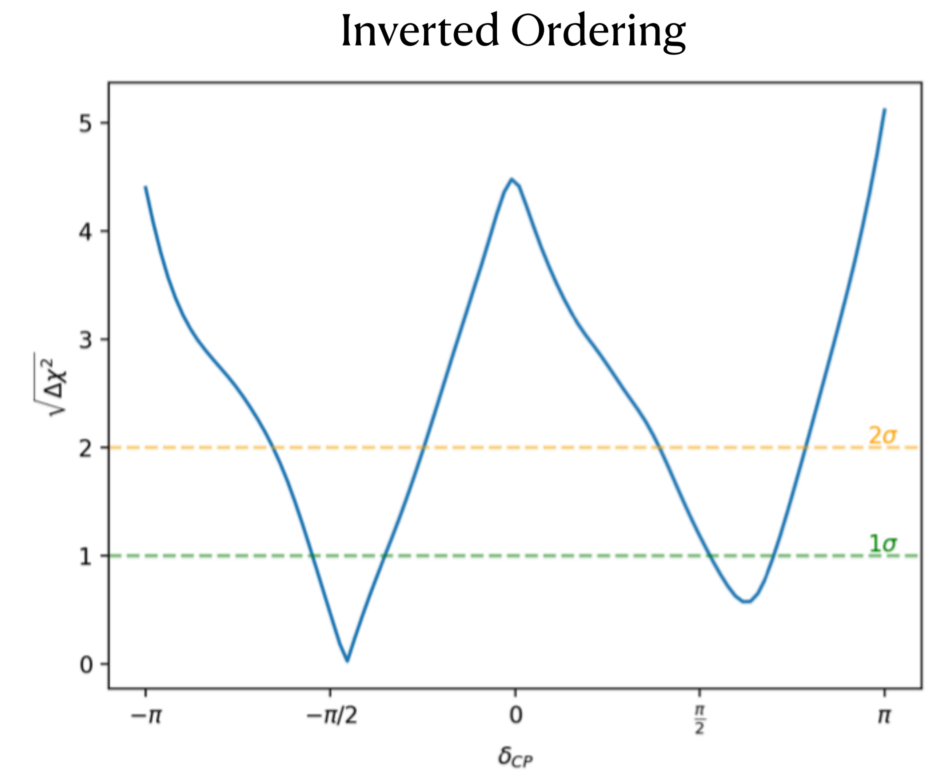




Preliminary

DUNE Sensitivity: IO

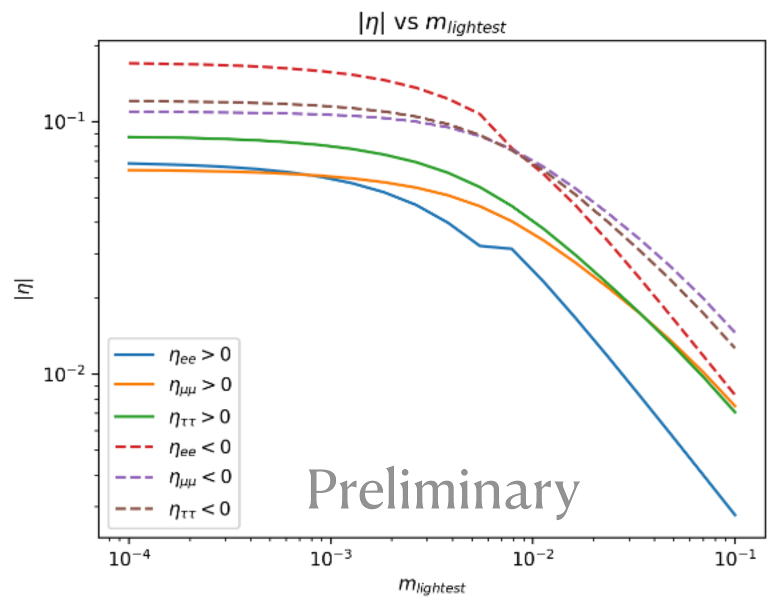


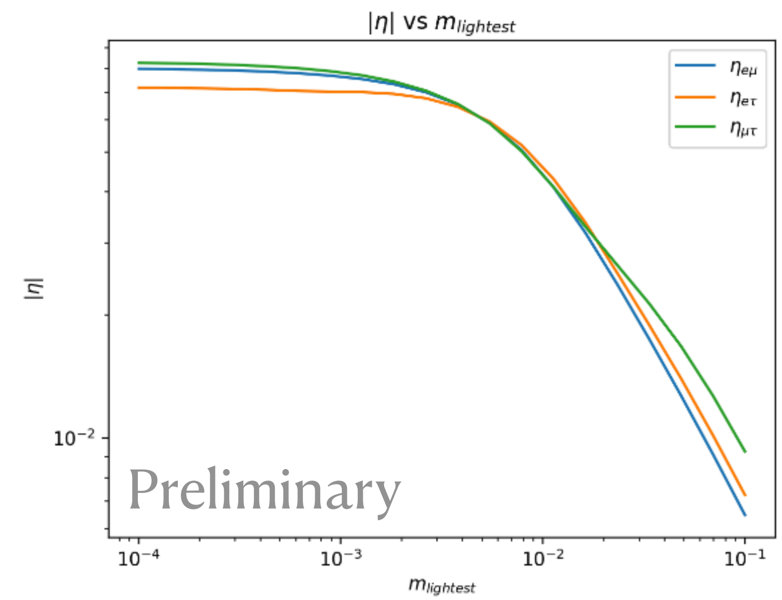


Preliminary

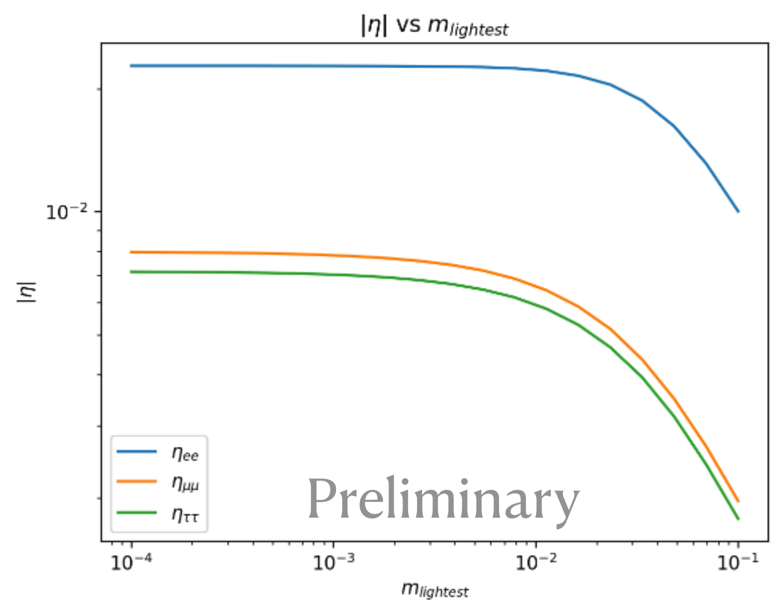
DEPENDENCE ON LIGHTEST m_ν

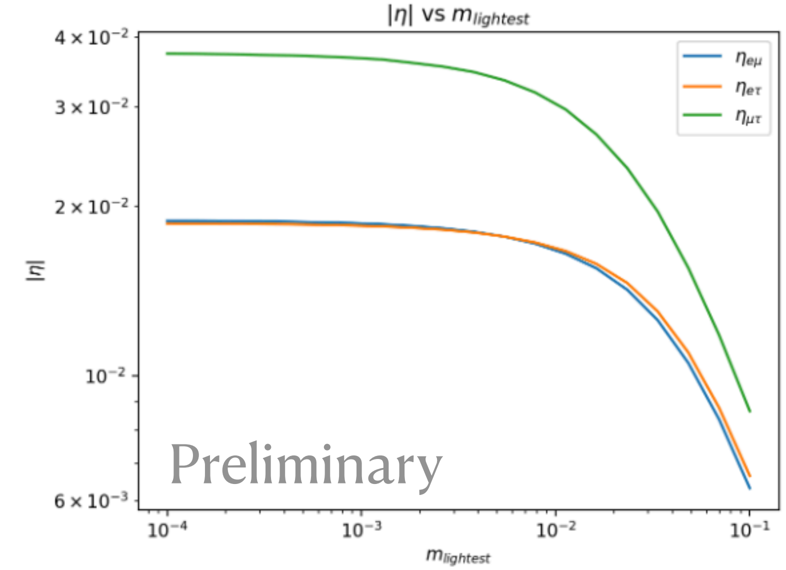
Normal Ordering





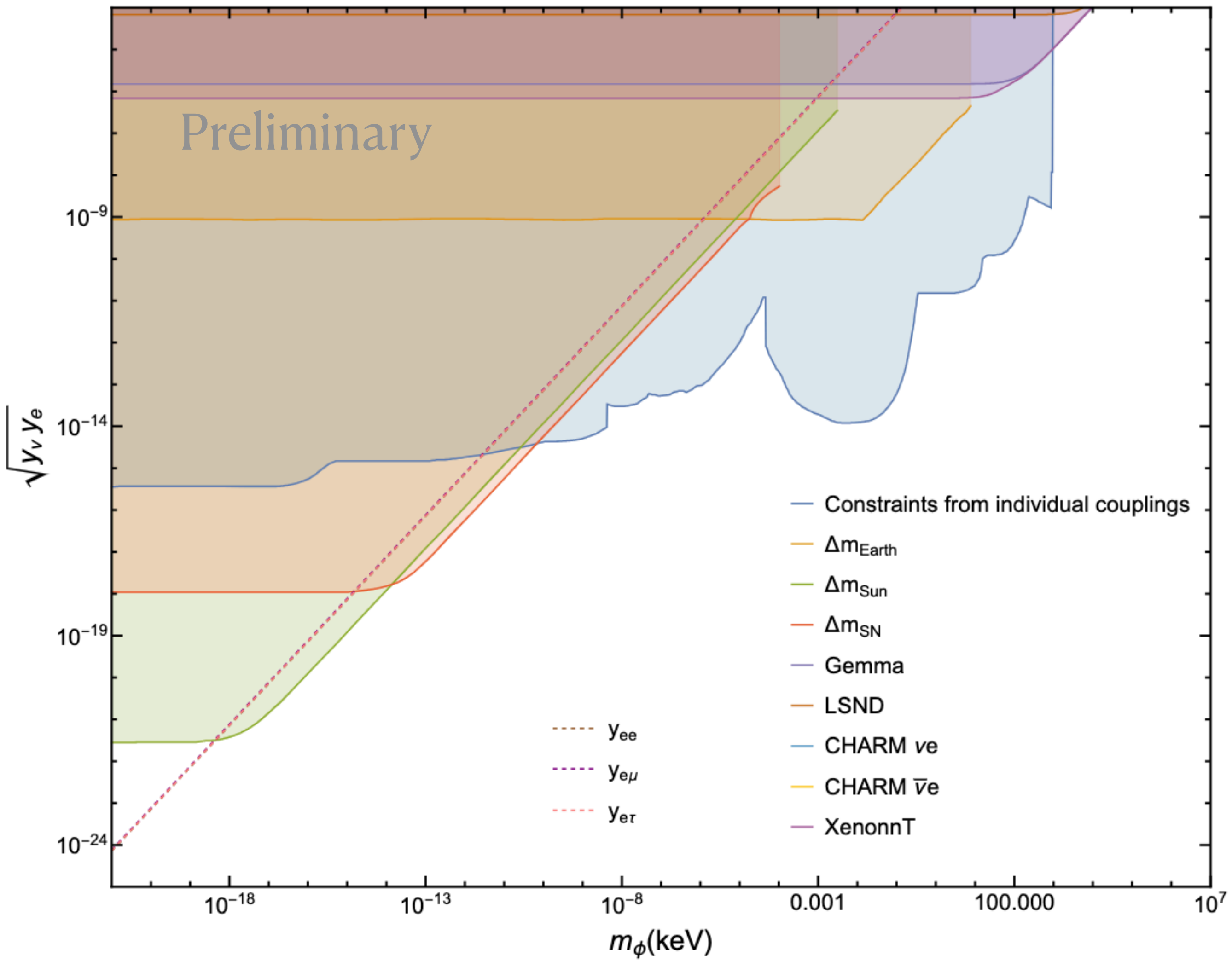
Inverted Ordering



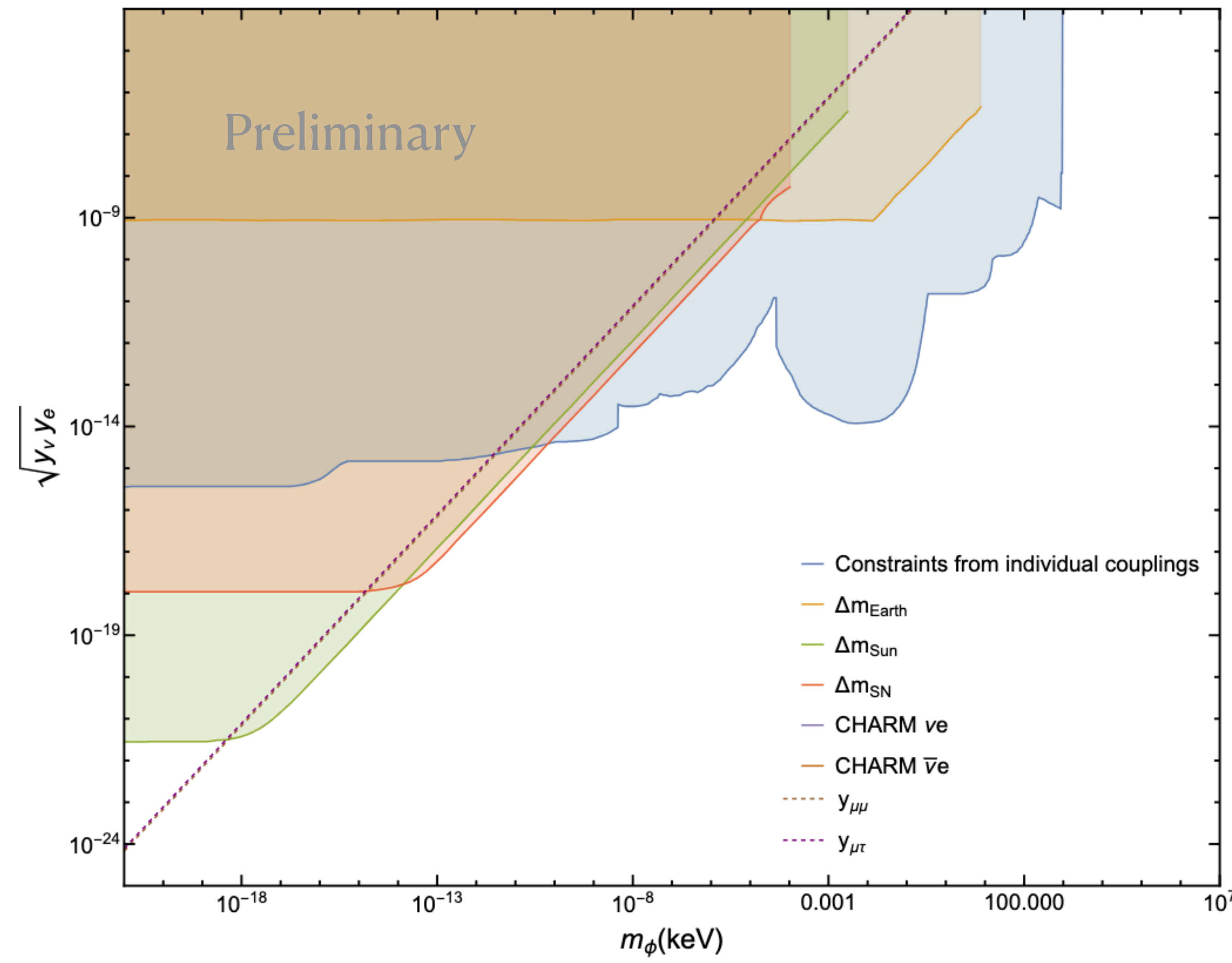


Bounds on parameter space

Normal Ordering

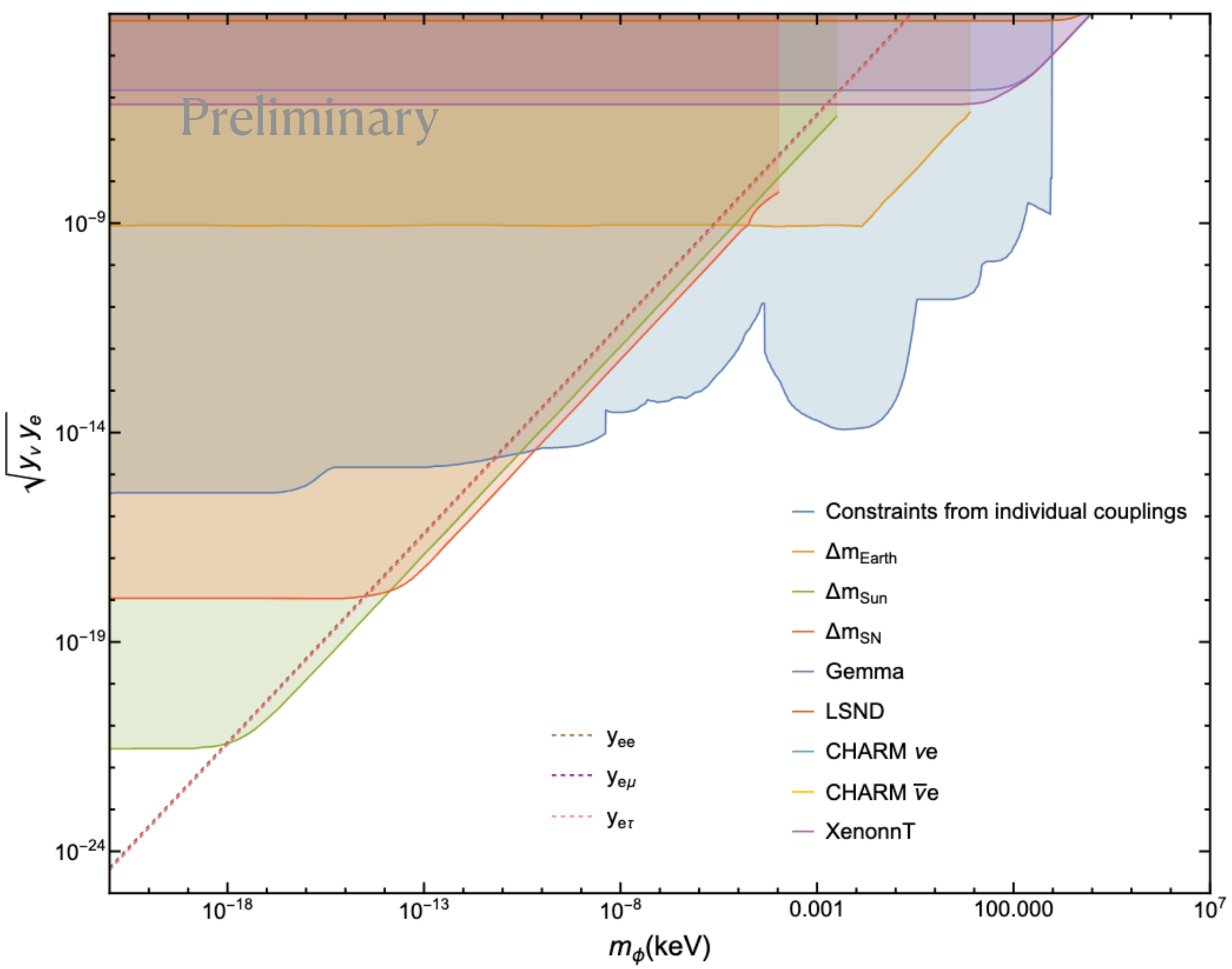


Normal Ordering

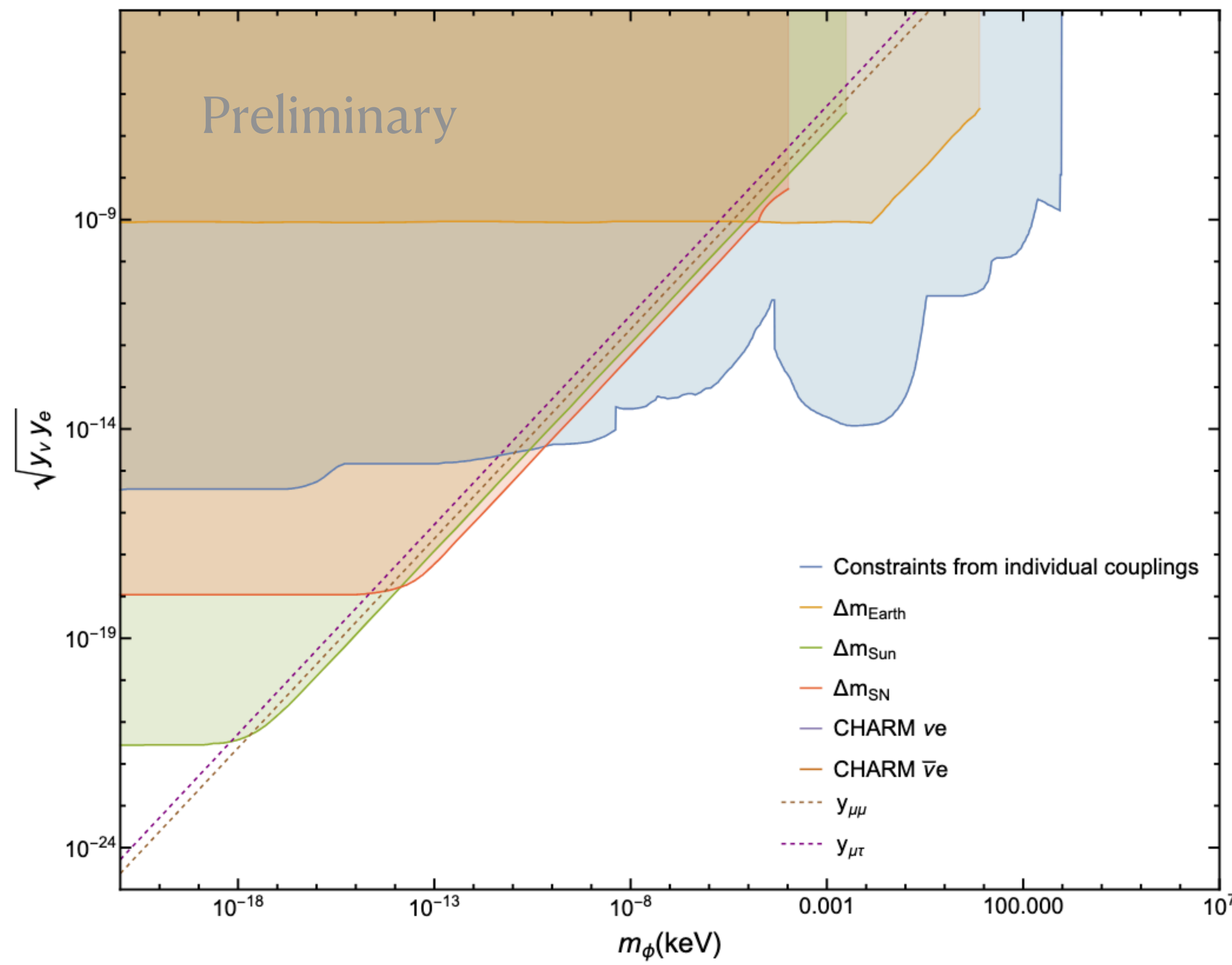


Bounds on Parameter Space

Inverted Ordering



Inverted Ordering



NO

OUR WORK IN A NUTSHELL

- Light Scalar-Mediated NSI appears as a correction to the neutrino mass term.
- Unphysical phases have physical consequences on neutrino oscillations.
- CP measurements at Neutrino oscillations experiments such as DUNE can be impacted by the presence of light scalar mediated NSI.
- We measure the DUNE sensitivity on NSI parameters considering all the parameters at the same time.
- NSI parameters can be translated into sensitivity on the parameter space for light scalars model and compared with existing constraints.

EXTRA PAGE

True Values

MO	Parameters	True Values
NO	$sin^2(\theta_{12})$	0.318
	$sin^2(\theta_{13})$	0.022
	$sin^2(\theta_{23})$	0.574
	δ_{CP}	1.08π
	Δm_{21}^2	$7.506 \times 10^{-5}\mathrm{eV}^2$
	Δm_{31}^2	$2.55 \times 10^{-3}\mathrm{eV}^2$
IO	$sin^2(\theta_{12})$	0.304
	$sin^2(\theta_{13})$	0.022
	$sin^2(\theta_{23})$	0.578
	δ_{CP}	1.58π
	Δm_{21}^2	$7.506 \times 10^{-5}\mathrm{eV}^2$
	Δm_{31}^2	$2.45 \times 10^{-3}\mathrm{eV}^2$

Table 1: Oscillation parameters used for DUNE analysis

SUMMARY

$m_{\text{lightest}} = 0\text{eV}$

MO	NSI	$\eta_{\alpha\beta}$
NO	η_{ee}	$[-0.167, 0.07]$
	$\eta_{\mu\mu}$	$[-0.11, 0.064]$
	$\eta_{\tau\tau}$	$[-0.12, 0.09]$
	$\eta_{e\mu}$	0.08
	$\eta_{e\tau}$	0.073
	$\eta_{\mu\tau}$	0.083
IO	η_{ee}	$[-0.023, 0.023]$
	$\eta_{\mu\mu}$	$[-0.0075, 0.008]$
	$\eta_{\tau\tau}$	$[-0.0089, 0.0071]$
	$\eta_{e\mu}$	0.018
	$\eta_{e\tau}$	0.018
	$\eta_{\mu\tau}$	0.037

$m_{\text{lightest}} = 0.05\text{eV}$

MO	NSI	$\eta_{\alpha\beta}$
NO	η_{ee}	$[-0.016, 0.005]$
	$\eta_{\mu\mu}$	$[-0.026, 0.013]$
	$\eta_{\tau\tau}$	$[-0.023, 0.013]$
	$\eta_{e\mu}$	0.012
	$\eta_{e\tau}$	0.013
	$\eta_{\mu\tau}$	0.016
IO	η_{ee}	$[-0.017, 0.016]$
	$\eta_{\mu\mu}$	$[-0.003, 0.003]$
	$\eta_{\tau\tau}$	$[-0.0042, 0.0031]$
	$\eta_{e\mu}$	0.01
	$\eta_{e\tau}$	0.01
	$\eta_{\mu\tau}$	0.015

$m_{\text{lightest}} = 0.1\text{eV}$

MO	NSI	$\eta_{\alpha\beta}$
NO	η_{ee}	$[-0.0083, 0.0027]$
	$\eta_{\mu\mu}$	$[-0.015, 0.008]$
	$\eta_{\tau\tau}$	$[-.0127, 0.0068]$
	$\eta_{e\mu}$	0.006
	$\eta_{e\tau}$	0.007
	$\eta_{\mu\tau}$	0.009
IO	η_{ee}	$[-0.01, 0.01]$
	$\eta_{\mu\mu}$	$[-0.0018, 0.002]$
	$\eta_{\tau\tau}$	$[-0.0024, 0.0018]$
	$\eta_{e\mu}$	0.0064
	$\eta_{e\tau}$	0.0067
	$\eta_{\mu\tau}$	0.0087

Table 2: Summary of Expected Sensitivities of DUNE to scalar NSI parameters $\eta_{\alpha\beta}$