Core-passing atmospheric neutrinos: a unique probe to discriminate between Lorentz violation and non-standard interactions

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Core-passing atmospheric neutrinos: a unique probe to discriminate between Lorentz violation and non-standard interactions

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Lorentz violation and non-standard interactions are two of the most popular scenarios beyond the Standard Model of particle physics. Both of these can affect neutrino oscillations significantly. However, their effects can mimic each other, and it would be difficult to distinguish between them in any fixed-baseline neutrino experiment. We show that atmospheric neutrinos, having access to a wide range of baselines, can break this degeneracy. Observations of core-passing atmospheric neutrinos and antineutrinos would be a potent tool to discriminate between these two new-physics scenarios.

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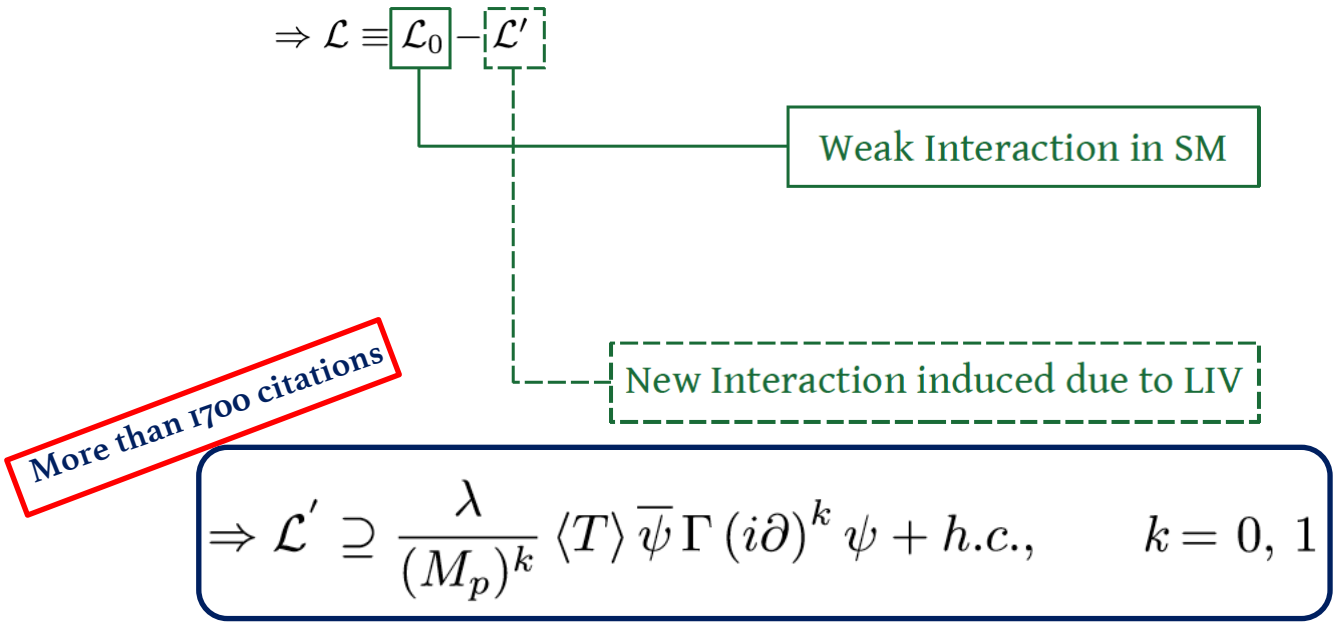
Brief discussion on Lorentz Violation (LV)

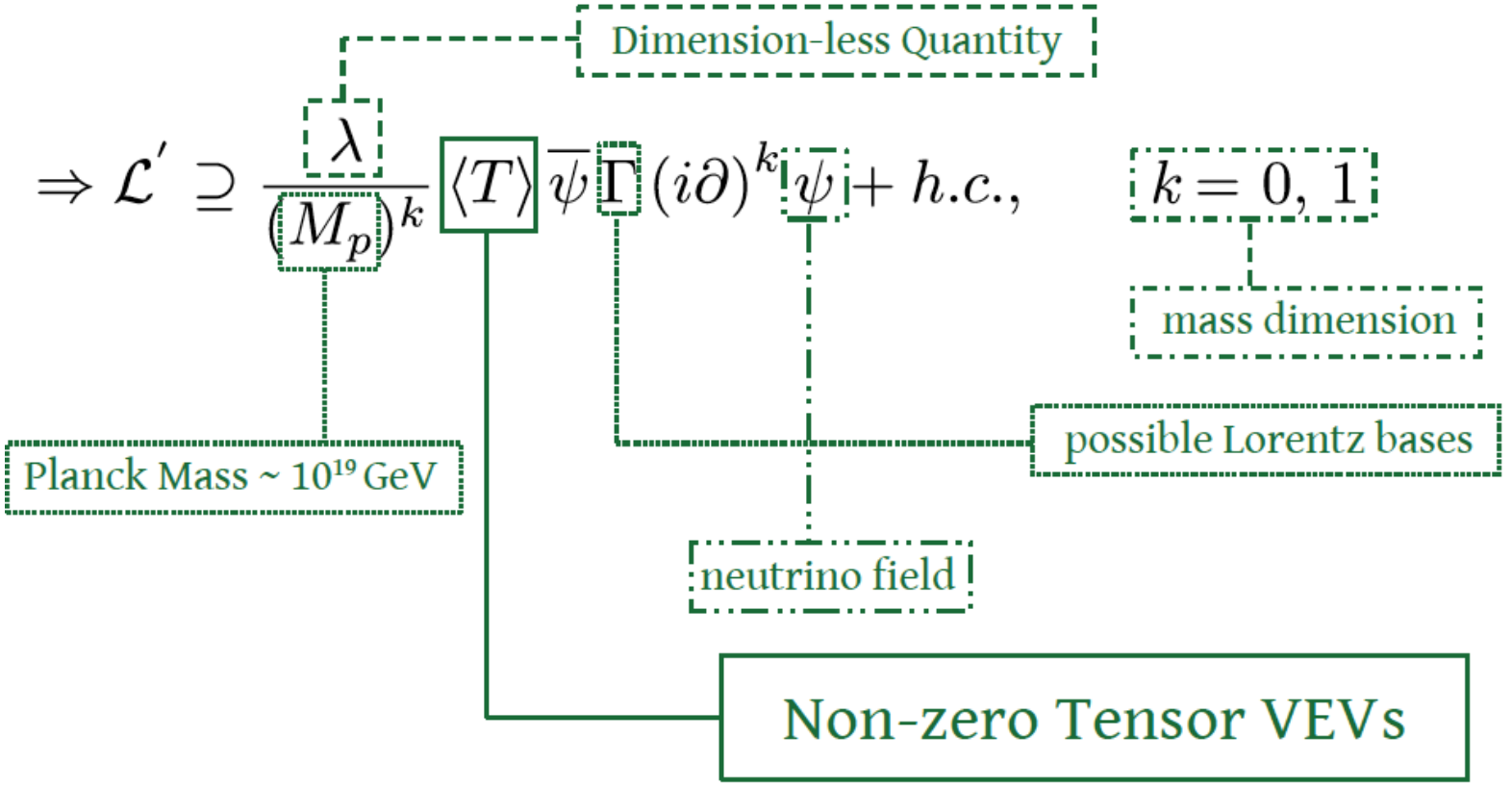
Spontaneous Lorentz Symmetry Breaking

- **Lorentz symmetry - A key ingredient of the Standard Model (SM) & local Quantum field theories**
- **However, there are a few proposed models in string theory and loop quantum gravity – which allow for Lorentz Invariance Violation (LIV)**
- **Direct observation of LIV at low energies would provide access to the Planck-scale *(Mp)* physics**



CPT violation and the Standard Model, Colladay, Kostelecky, PRD 55 (1997) 6760 - 6774

Spontaneous Lorentz Symmetry Breaking



CPT violation and the Standard Model, Colladay, Kostelecky, PRD 55 (1997) 6760 - 6774

Spontaneous Lorentz Symmetry Breaking

$$\Rightarrow \mathcal{L}^{'} \supseteq \frac{\lambda}{(M_p)^k} \langle T \rangle \overline{\psi} \Gamma (i\partial)^k \psi + h.c.,$$

$$\text{For} \quad k = 0$$

$$\mathcal{L}^{'} = \frac{1}{2} \left[a_\mu \overline{\psi} \gamma^\mu \psi + b_\mu \overline{\psi} \gamma_5 \gamma^\mu \psi \right] + h.c.$$

Lorentz violation (LV) arises from the interaction of neutrinos with the spacetime itself. The LV can manifest itself in vacuum as well as in matter.

Spontaneous Lorentz Symmetry Breaking

$$\mathcal{L}' = \frac{1}{2}\left[a_\mu \overline{\psi}\gamma^\mu\psi + b_\mu \overline{\psi}\gamma_5\gamma^\mu\psi\right] + h.c.$$

Can't Measure Individually

$$a_L = a + b$$

$$a_R = a - b$$

$$a_R = -a_L$$

Interference Effect

JHEP 03 (2022) 050

Note that the LIV parameters $(a^\mu)_L$ or $(a^\mu)_R$ break the CPT symmetry, since the elements of $(a^\mu)_L$ or $(a^\mu)_R$ change sign under the CPT transformation. Therefore, the LIV parameters $(a^\mu)_L$ or $(a^\mu)_R$ are known as CPT-violating LIV parameters.

Hamiltonian in Standard Model Extension

$$H_\nu = \frac{1}{2E} U M^2 U^\dagger + \sqrt{2} G_F N_e \tilde{I} + \mathring{A}$$

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$$U = \begin{pmatrix} u_{e1} & u_{e2} & u_{e3} \\ u_{\mu 1} & u_{\mu 2} & u_{\mu 3} \\ u_{\tau 1} & u_{\tau 2} & u_{\tau 3} \end{pmatrix}, \qquad M^2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix},$$

$$\tilde{I} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \qquad \mathring{A} = \begin{pmatrix} \mathrm{a}_{ee} & \mathrm{a}_{e\mu} & \mathrm{a}_{e\tau} \\ \mathrm{a}^*_{e\mu} & \mathrm{a}_{\mu\mu} & \mathrm{a}_{\mu\tau} \\ \mathrm{a}^*_{e\tau} & \mathrm{a}^*_{\mu\tau} & \mathrm{a}_{\tau\tau} \end{pmatrix}$$

hermiticity of interactions imposes $\mathrm{a}^\lambda_{\beta\alpha} = (\mathrm{a}^\lambda_{\alpha\beta})^*$

time-like component

$$\sqrt{2} G_F N_e \approx 7.6 \times 10^{-23} \cdot Y_e \cdot \rho \left(g/cm^3 \right) \mathrm{GeV}$$

Hamiltonian in Standard Model Extension

$$H_{\bar{\nu}} = \frac{1}{2E} U^* M^2 U^T - \sqrt{2} G_F N_e \, \tilde{I} - \mathring{A}^*$$

$$U = \begin{pmatrix} u_{e1} & u_{e2} & u_{e3} \\ u_{\mu 1} & u_{\mu 2} & u_{\mu 3} \\ u_{\tau 1} & u_{\tau 2} & u_{\tau 3} \end{pmatrix}, \qquad M^2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix},$$

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Oscillation Parameters

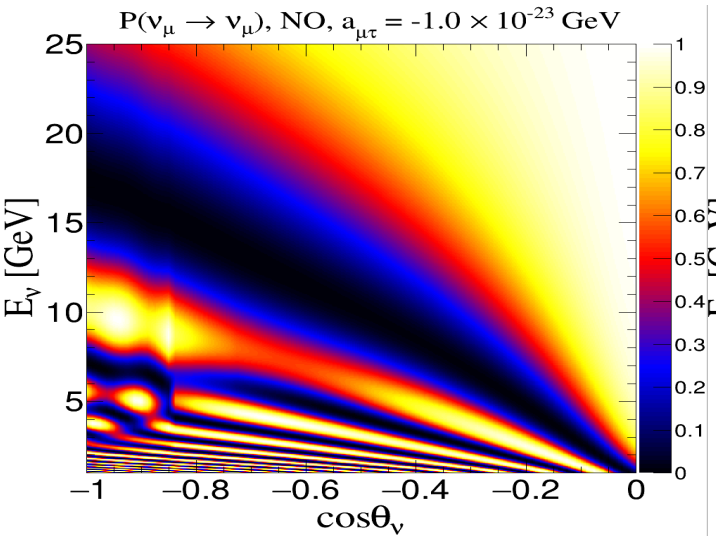
$\sin^2 2\theta_{12}$	$\sin^2 \theta_{23}$	$\sin^2 2\theta_{13}$	$\delta_{\rm CP}$	Δm^2_{21} (eV^2)	Δm^2_{32} (eV^2)	Mass Ordering
0.855	0.5	0.0875	0	7.4×10^{-5}	2.46×10^{-3}	Normal (NO)

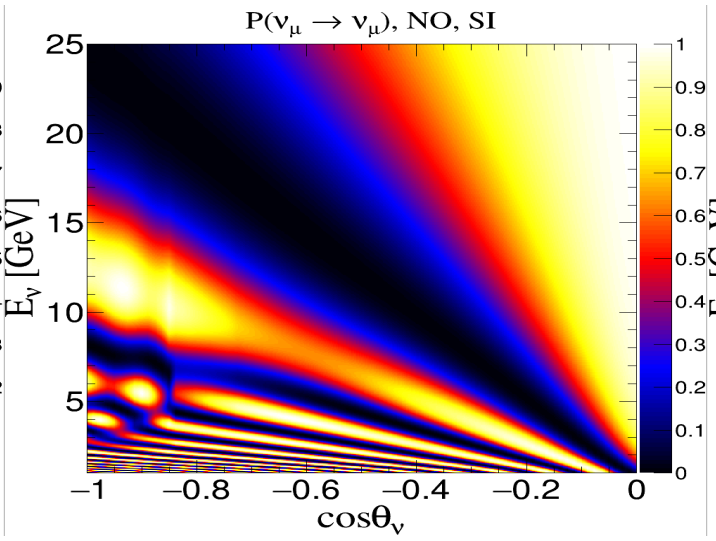
Current Constraints on LIV Parameters from Atmospheric Neutrino Experiments

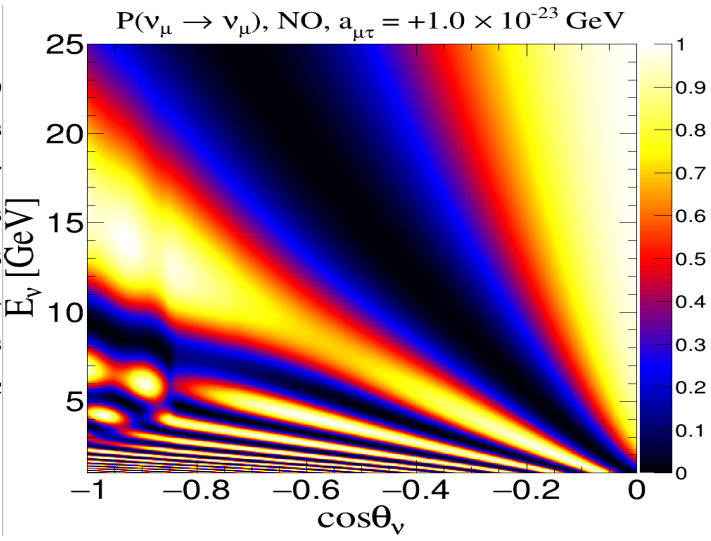
Current Experimental Constraints on CPT-violating LV parameters ($a_{\mu\tau}$)	
Super-K [1410.4267] $H = U \cdot (\Delta M^2/2E) \cdot U^\dagger + \sqrt{2} G_F N_e + a^0_{\alpha\beta}$	$\mathrm{Re}\,(a_{\mu\tau}) < 6.5 \times 10^{-24}$ GeV (95% C.L) $\mathrm{Im}\,(a_{\mu\tau}) < 5.1 \times 10^{-24}$ GeV (95% C.L)
IceCube [1709.03434] $H = U \cdot (\Delta M^2/2E) \cdot U^\dagger + a^0_{\alpha\beta}$	$\mathrm{Re}(a^{(3)}_{\mu\tau}) < 2.9 \times 10^{-24}$ GeV (99% C.L) $\mathrm{Im}(a^{(3)}_{\mu\tau}) < 2.0 \times 10^{-24}$ GeV (90% C.L)

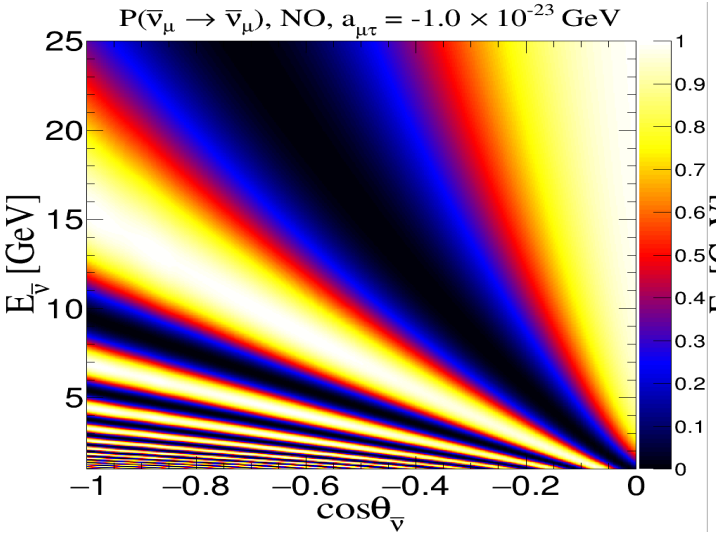
In case of atmospheric neutrinos, μ - τ channel is dominant, hence,
we consider only $a_{\mu\tau}$ in our analysis (both positive and negative real values)

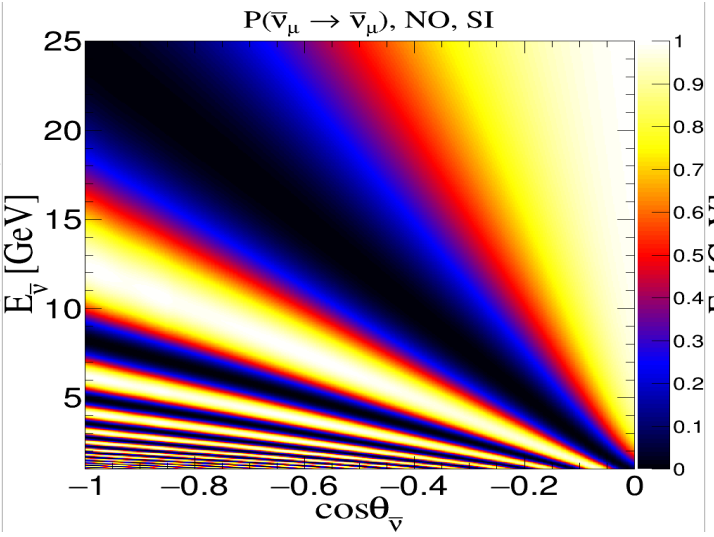
Effect of $a_{\mu\tau}$ on P $(\nu_\mu \to \nu_\mu)$ channel

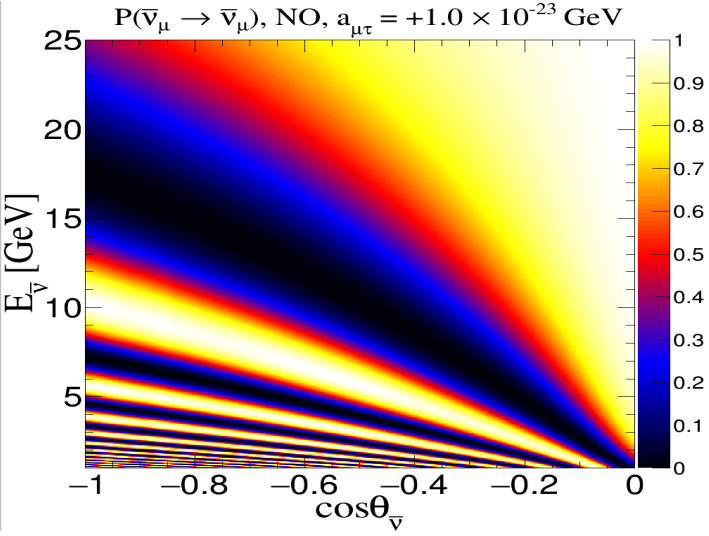




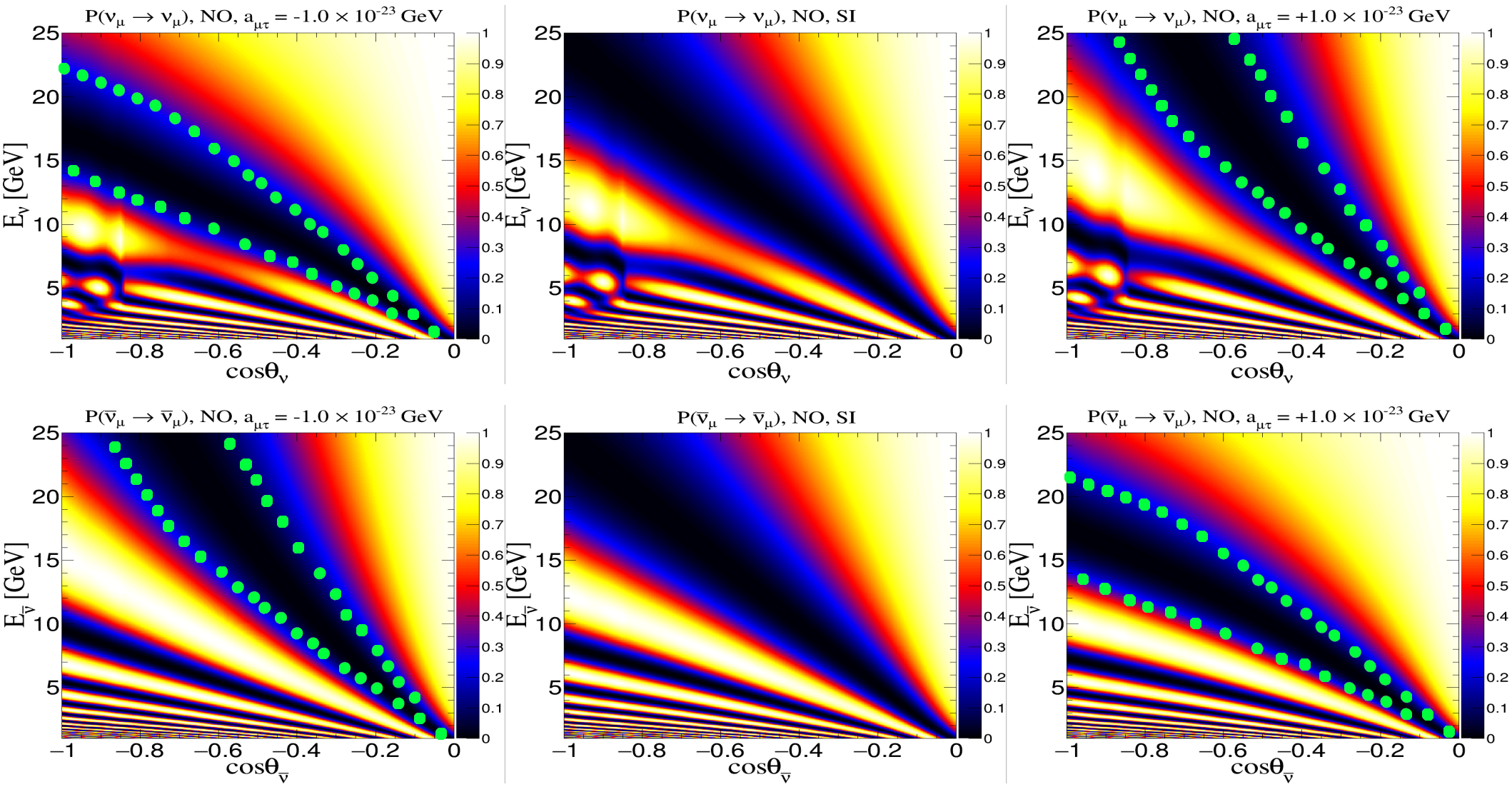








Effect of $a_{\mu\tau}$ on P $(\nu_\mu \to \nu_\mu)$ channel



Brief discussion on Non-Standard Interactions (NSI)

Neutral-current Non-Standard Interactions (NSI)

Neutral-current NSI in propagation through matter.

$$\mathcal{L}_{\text{NC-NSI}} = -2\sqrt{2}G_F\varepsilon^{Cf}_{\alpha\beta}(\bar{\nu}_\alpha\gamma^\rho P_L\nu_\beta)(\bar{f}\gamma_\rho P_C f)$$

where, $P_L = (1-\gamma_5)/2, P_R = (1+\gamma_5)/2$, and $C = L, R$.

For neutral and isoscalar Earth

$\varepsilon_{\alpha\beta} \approx \varepsilon^e_{\alpha\beta} + 3\,\varepsilon^u_{\alpha\beta} + 3\,\varepsilon^d_{\alpha\beta}$

$$\varepsilon_{\alpha\beta} = \sum_{f=e,u,d} \frac{V_f}{V_{CC}}\left(\varepsilon^{Lf}_{\alpha\beta} + \varepsilon^{Rf}_{\alpha\beta}\right)$$

where, $V_{CC} = \sqrt{2}G_F N_e, V_f = \sqrt{2}G_F N_f, f = e, u, d.$

$$H_{mat} = \sqrt{2}G_F N_e \begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau} \end{pmatrix}$$

$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{c^{d=5}}{\Lambda}\mathcal{O}^{d=5} + \frac{c^{d=6}}{\Lambda^2}\mathcal{O}^{d=6} + \cdots$

d=5 Weinberg Operator: LLHH, Λ: New Physics Scale
S. Weinberg, PRL 43 (1979) 1566

NSI appears due to dimension six four fermion operators

hermiticity of the interactions demands $\varepsilon^f_{\beta\alpha,C} = (\varepsilon^f_{\alpha\beta,C})^*$

In atmospheric neutrinos, $\mu - \tau$ channel is dominant, hence, we choose to constrain $\varepsilon_{\mu\tau}$ (only real values)

$$H_{mat} = \sqrt{2}G_F N_e \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & \varepsilon_{\mu\tau} \\ 0 & \varepsilon^*_{\mu\tau} & 0 \end{pmatrix}$$

Effective Hamiltonian for NSI

$$H_\nu = \frac{1}{2E} U M^2 U^\dagger + \sqrt{2} G_F N_e \tilde{I} + \sqrt{2} G_F N_e \mathcal{E}$$

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$$\varepsilon_{\alpha\beta} \approx \varepsilon^e_{\alpha\beta} + 3\varepsilon^u_{\alpha\beta} + 3\varepsilon^d_{\alpha\beta}$$

$$\sqrt{2} G_F N_e \approx 7.6 \times 10^{-23} \cdot Y_e \cdot \rho \left(g/cm^3 \right) \text{GeV}$$

Effective Hamiltonian for NSI

$$H_{\bar{\nu}} = \frac{1}{2E} U^* M^2 U^T - \sqrt{2} G_F N_e \tilde{I} - \sqrt{2} G_F N_e \mathcal{E}^*$$

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Oscillation Parameters

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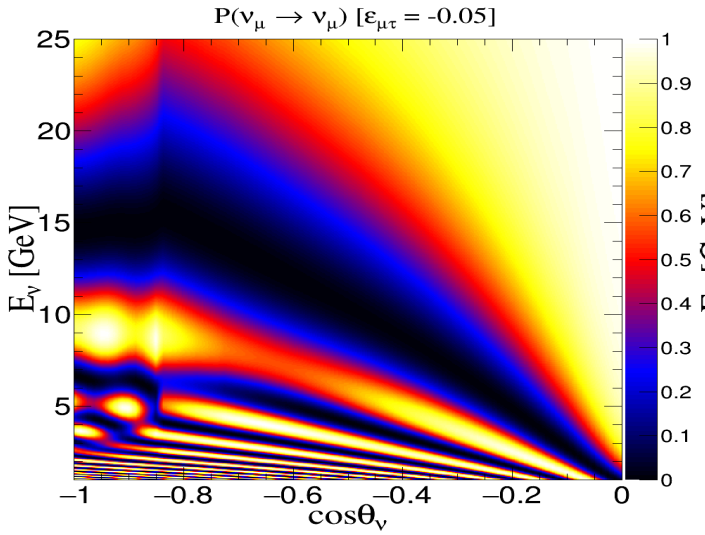
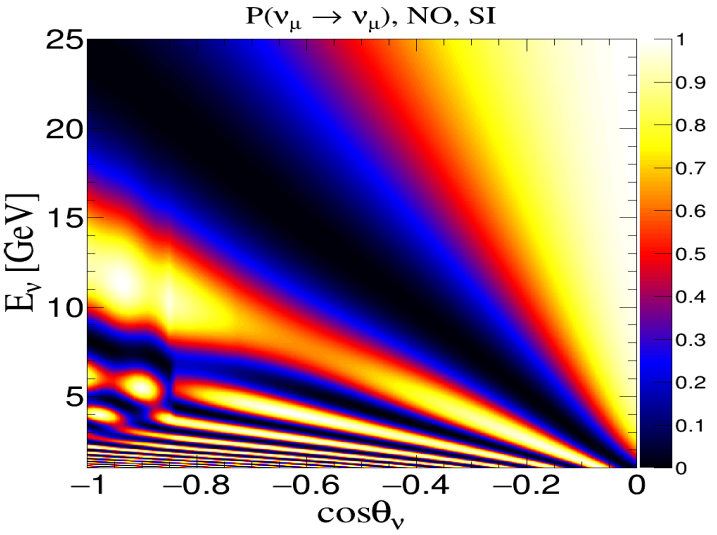
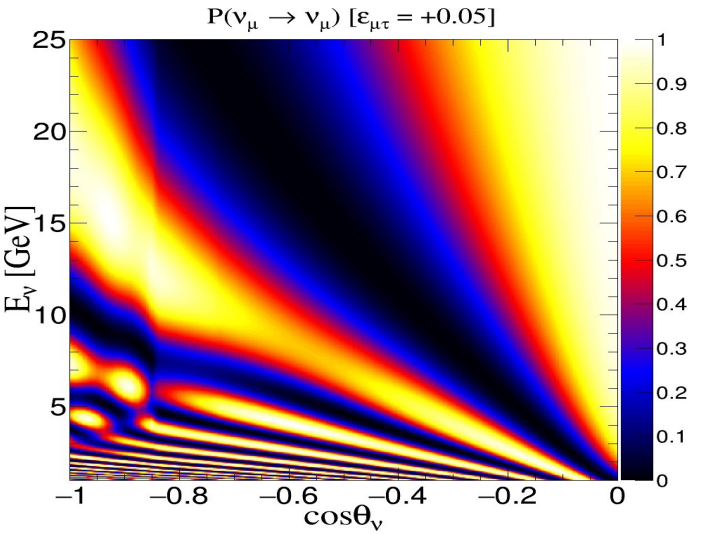
Current Constraints on LIV and NSI Parameters from Atmospheric Neutrino Experiments

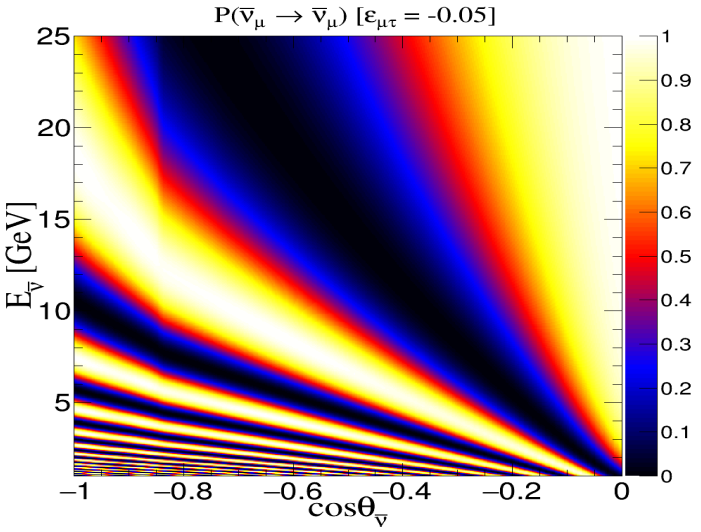
Current Experimental Constraints on NC-NSI parameters ($a_{\mu\tau}$)			
Experiments	Expt. Conventions	Scale factor	Our Conventions
Super-K [1109.1889]	$\lvert\varepsilon_{\mu\tau}\rvert < 0.011$	3 (d-quark)	$\lvert\varepsilon_{\mu\tau}\rvert < 0.033$
IceCube [1609.03450]	$-6.0 \times 10^{-3} < \varepsilon_{\mu\tau} < 5.4 \times 10^{-3}$ (90% C.L)	3 (d-quark)	$-1.8 \times 10^{-2} < \varepsilon_{\mu\tau} < 1.6 \times 10^{-2}$ (90% C.L)
DeepCore [1709.07079]	$-6.7 \times 10^{-3} < \varepsilon_{\mu\tau} < 8.1 \times 10^{-3}$ (90% C.L)	3 (d-quark)	$-2.0 \times 10^{-2} < \varepsilon_{\mu\tau} < 2.4 \times 10^{-2}$ (90% C.L)
DeepCore [2106.07755]	$\lvert\varepsilon_{\mu\tau}\rvert \leq 0.0232$ (90% C.L)	$\frac{3.000}{3.051}(N_n/N_e)$	$\lvert\varepsilon_{\mu\tau}\rvert \leq 0.0228$ (90% C.L)
ANTARES [2112.14517]	$-4.7 \times 10^{-3} < \varepsilon_{\mu\tau} < 2.9 \times 10^{-3}$ (90% C.L)	3 (d-quark)	$-1.4 \times 10^{-2} < \varepsilon_{\mu\tau} < 0.87 \times 10^{-2}$ (90% C.L)

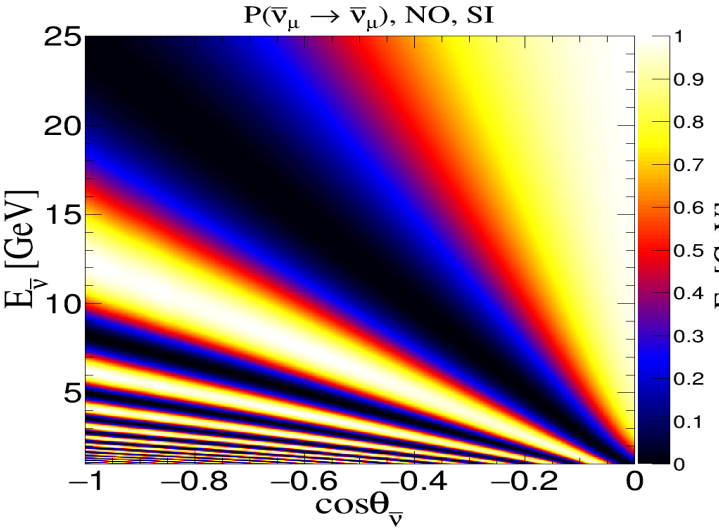
Effect of $\varepsilon_{\mu\tau}$ on P $(\nu_\mu \to \nu_\mu)$ channel

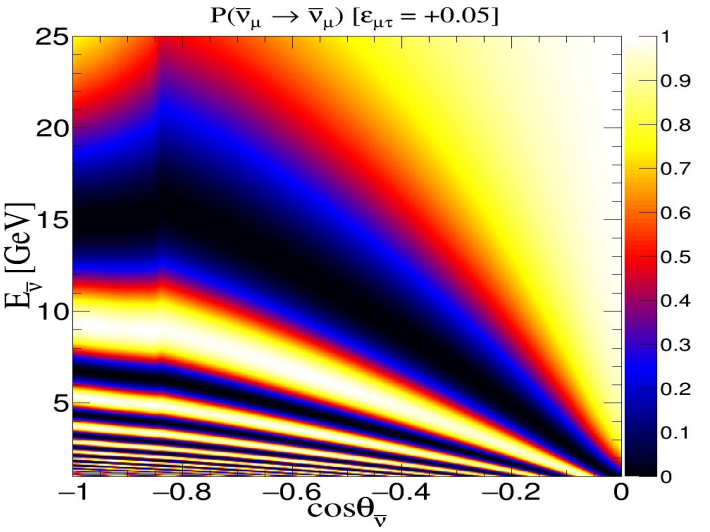




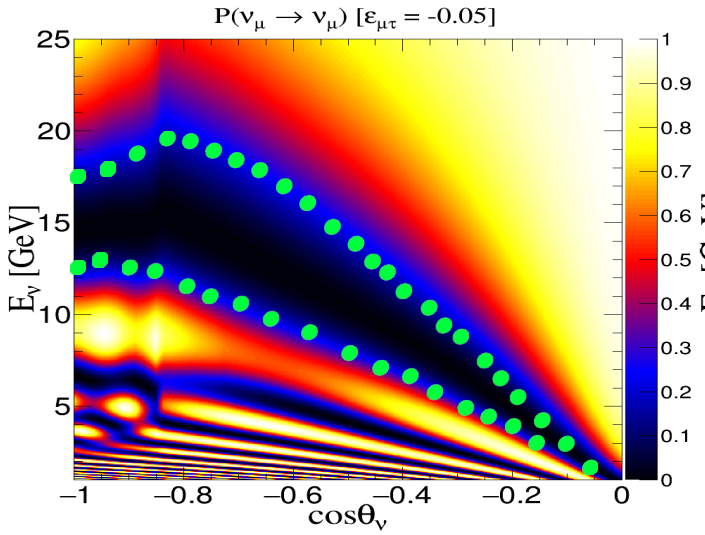


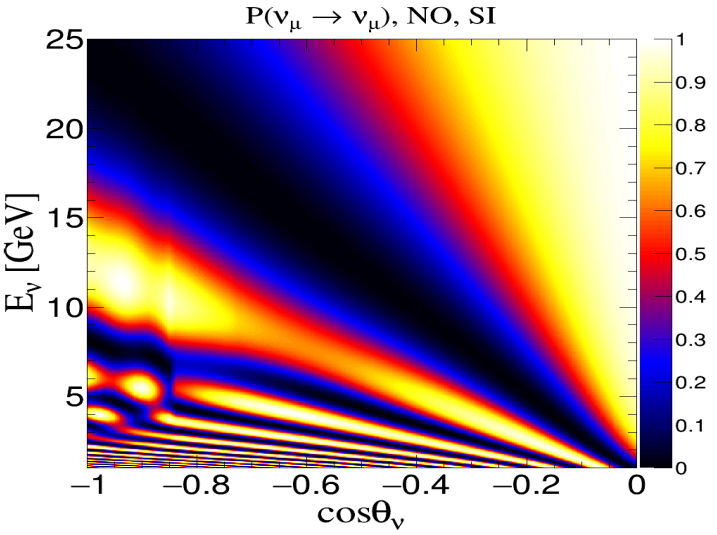


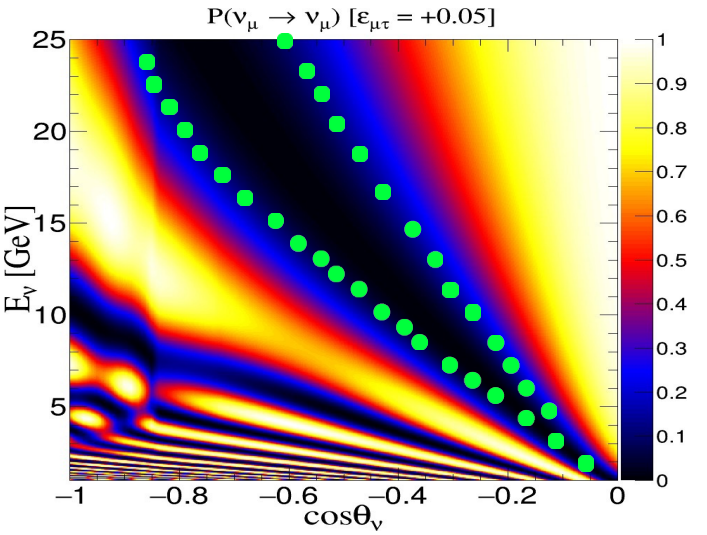


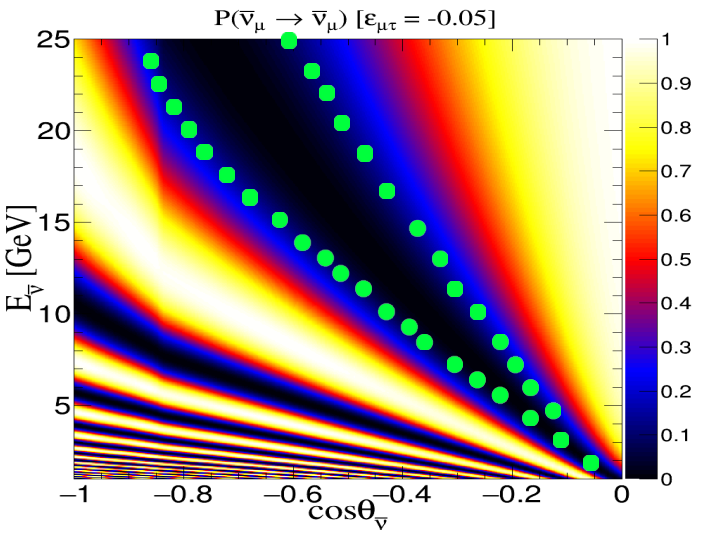


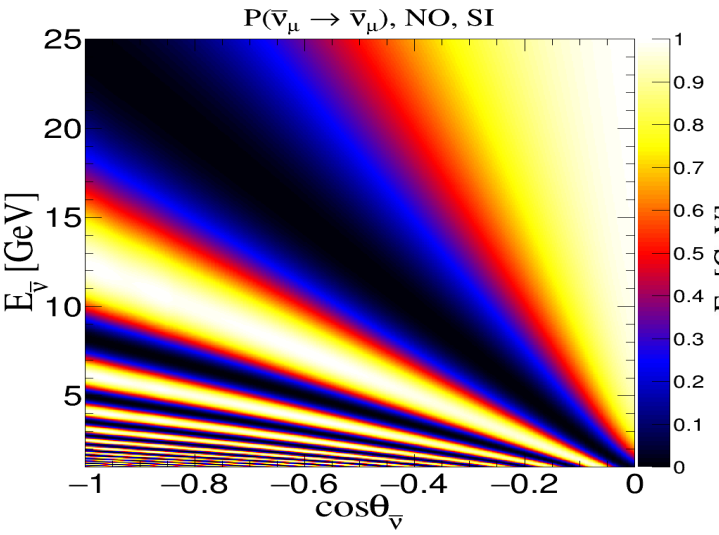
Effect of $\varepsilon_{\mu\tau}$ on P $(\nu_\mu \to \nu_\mu)$ channel

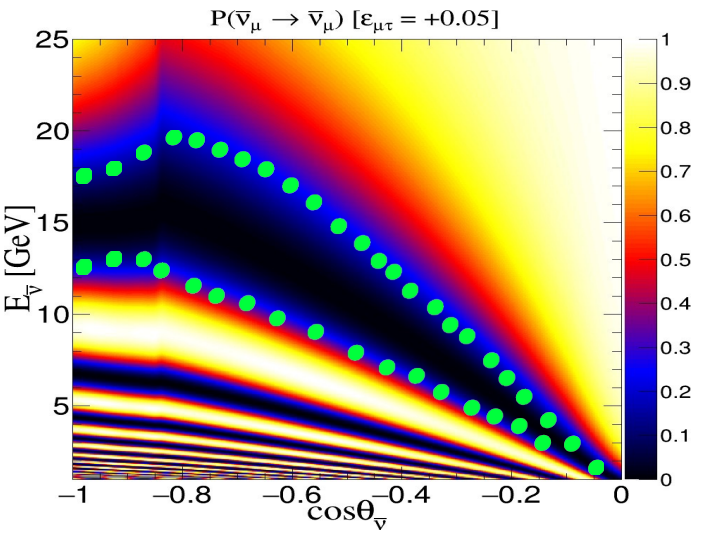












Degeneracy between LV and NSI

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Degeneracy between LV and NSI

$$\mathring{A} = \sqrt{2} G_F N_e \mathcal{E}$$

Degeneracy between LV and NSI

$$\mathring{A} = \sqrt{2} G_F N_e \mathcal{E}$$

If this condition gets satisfied,

then there is a degeneracy between "LV" and "NSI" parameters.

This is also true for the case of antineutrino

Degeneracy between LV and NSI

$$\mathring{A} = \sqrt{2} G_F N_e \mathcal{E}$$

Such degeneracy is obvious for the current and future

"fixed-baseline neutrino oscillation experiments",

where the line-averaged constant matter density approximation holds well.

Core-Passing Neutrinos: A unique tool to break this degeneracy between LV and NSI

Degeneracy between LV and NSI

A case-study with representative value of LV $\mathrm{a}_{\mu\tau} = 10^{-23}\mathrm{GeV}$

$\underline{Case - I}$

- Fixed-baseline (DUNE)

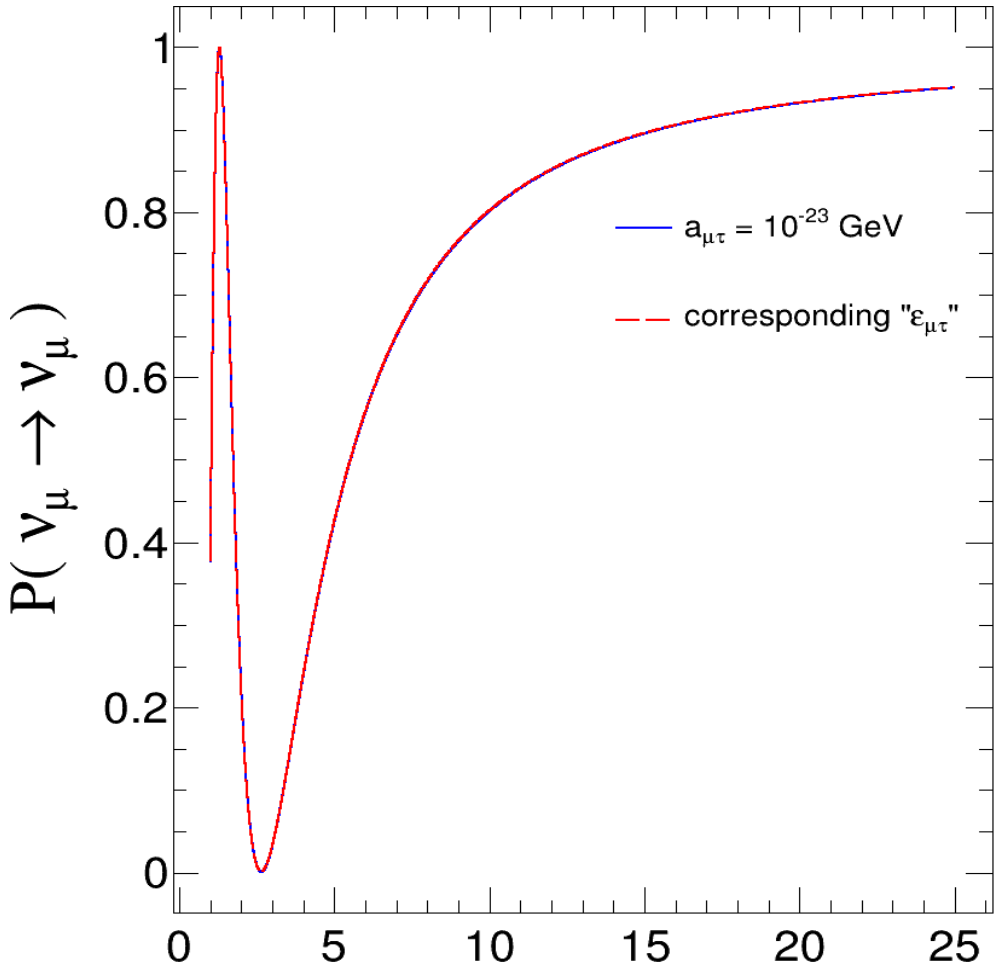
- $L = 1284.9\,\mathrm{km}$
- $\rho_{\mathrm{avg}}^{\mathrm{DUNE}} = 2.848\,g/cm^3$

arXiv : 2103.04797

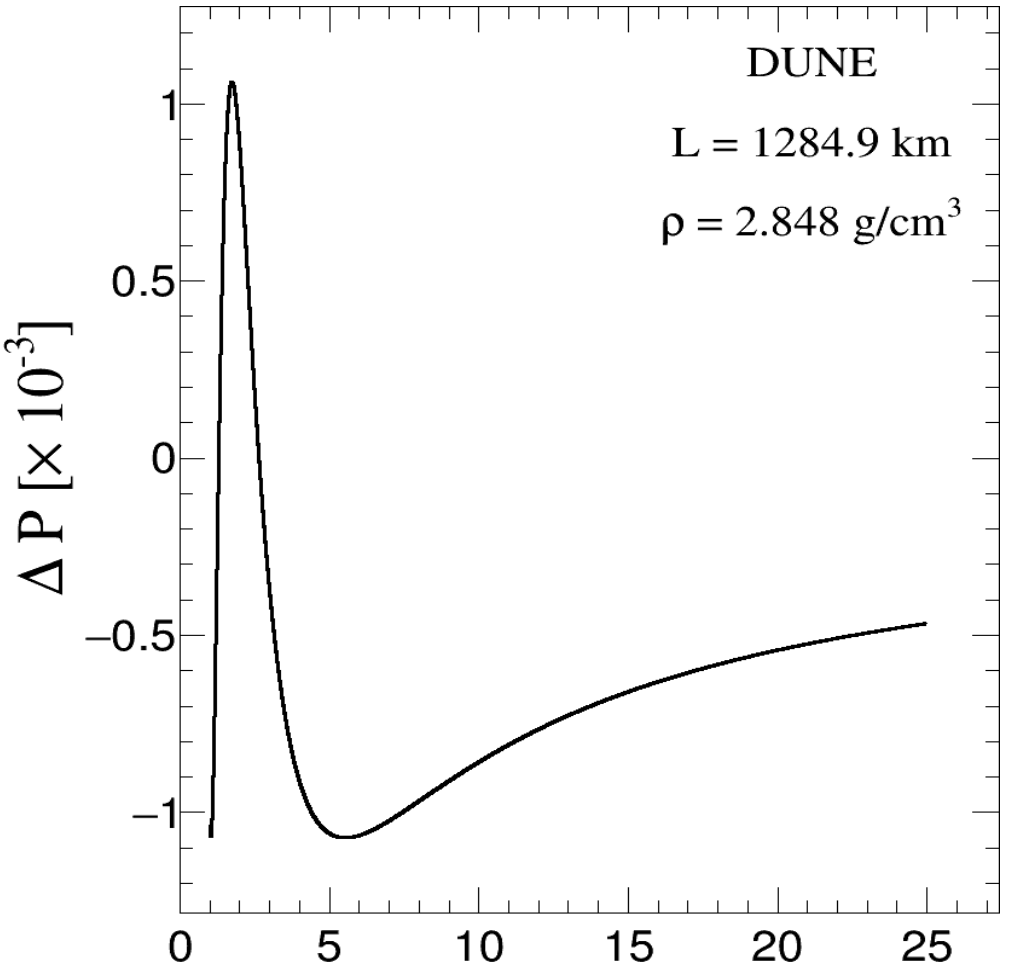
- $\mathcal{E}_{\mu\tau} = 0.092$

$$\Delta P = P\,(\mathrm{SI} + \mathrm{LV}) - P\,(\mathrm{SI} + \mathrm{NSI})$$

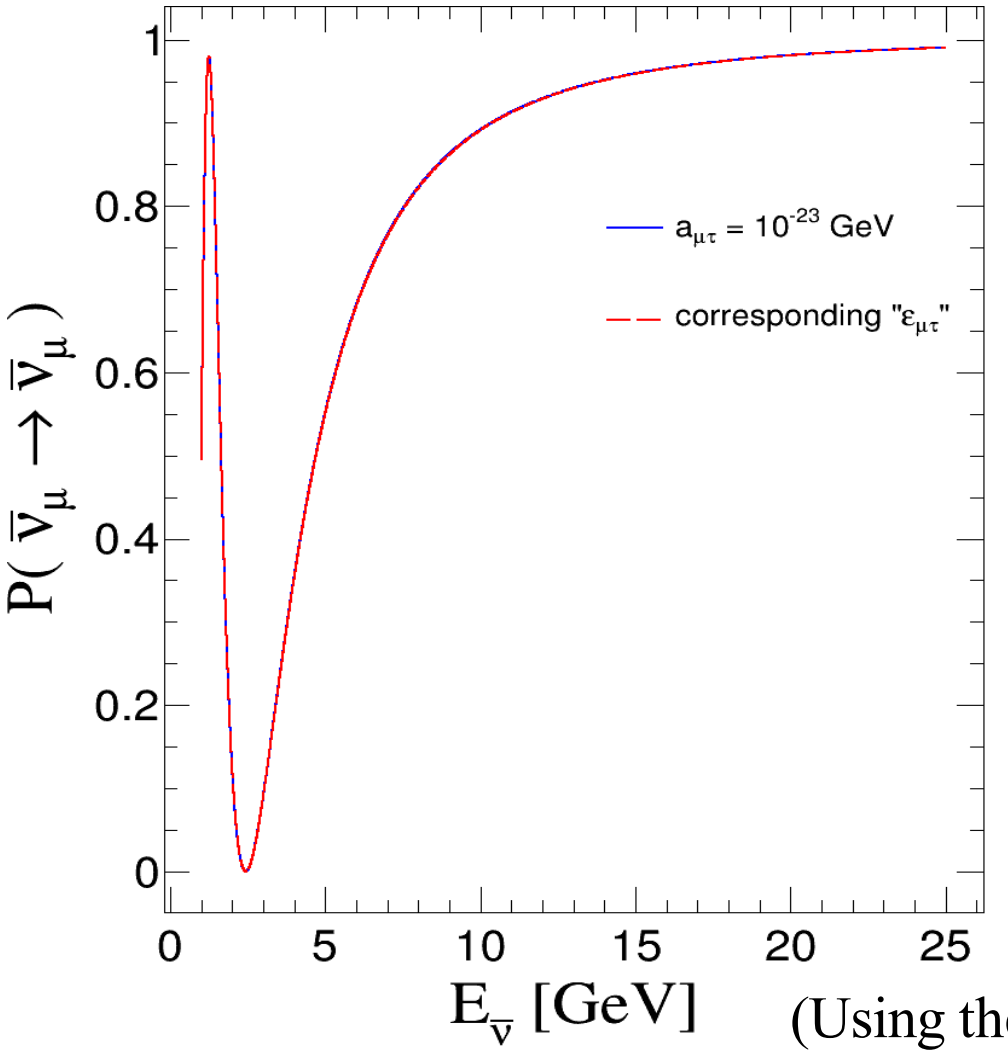
$Case - I$



(Using the PREM profile)



$Case - I$



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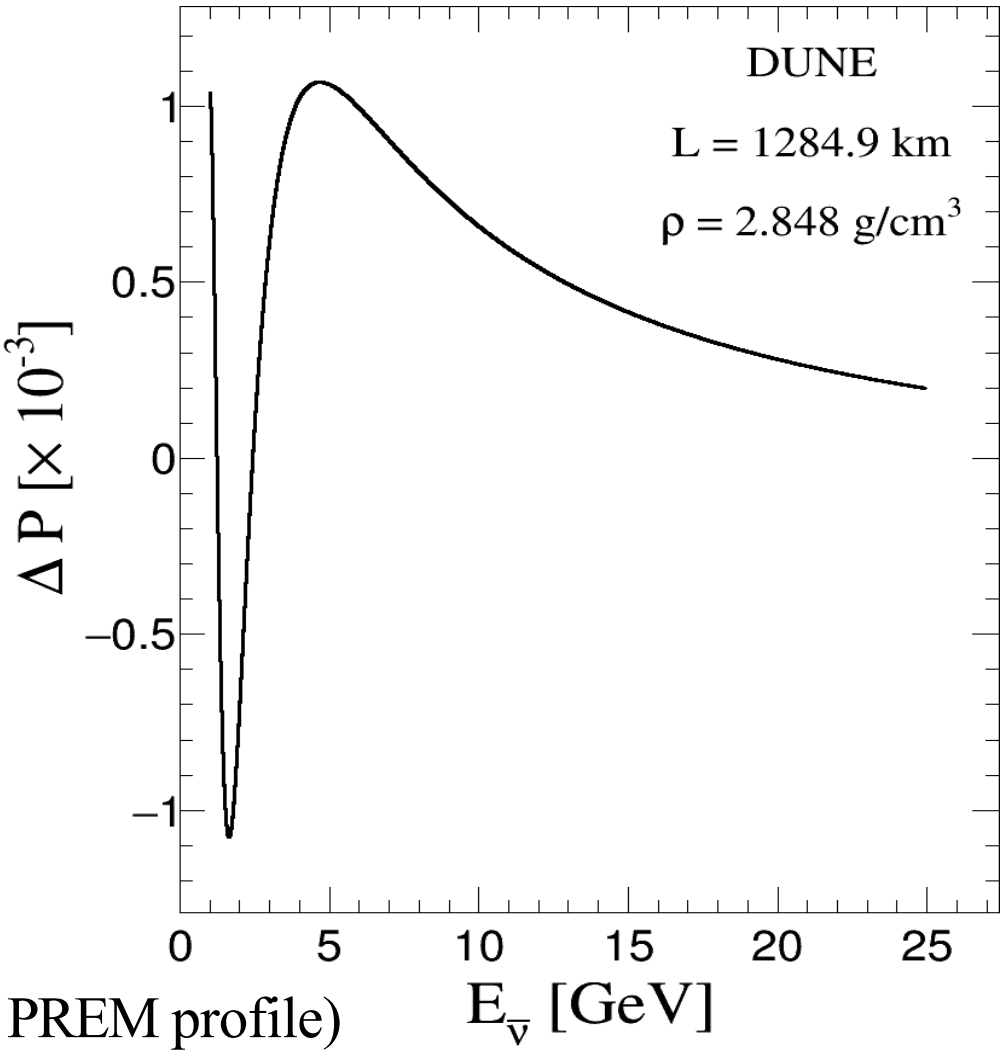


Degeneracy between LV and NSI

A case-study with representative value of LV $\mathrm{a}_{\mu\tau} = 10^{-23}\mathrm{GeV}$

$Case - I$

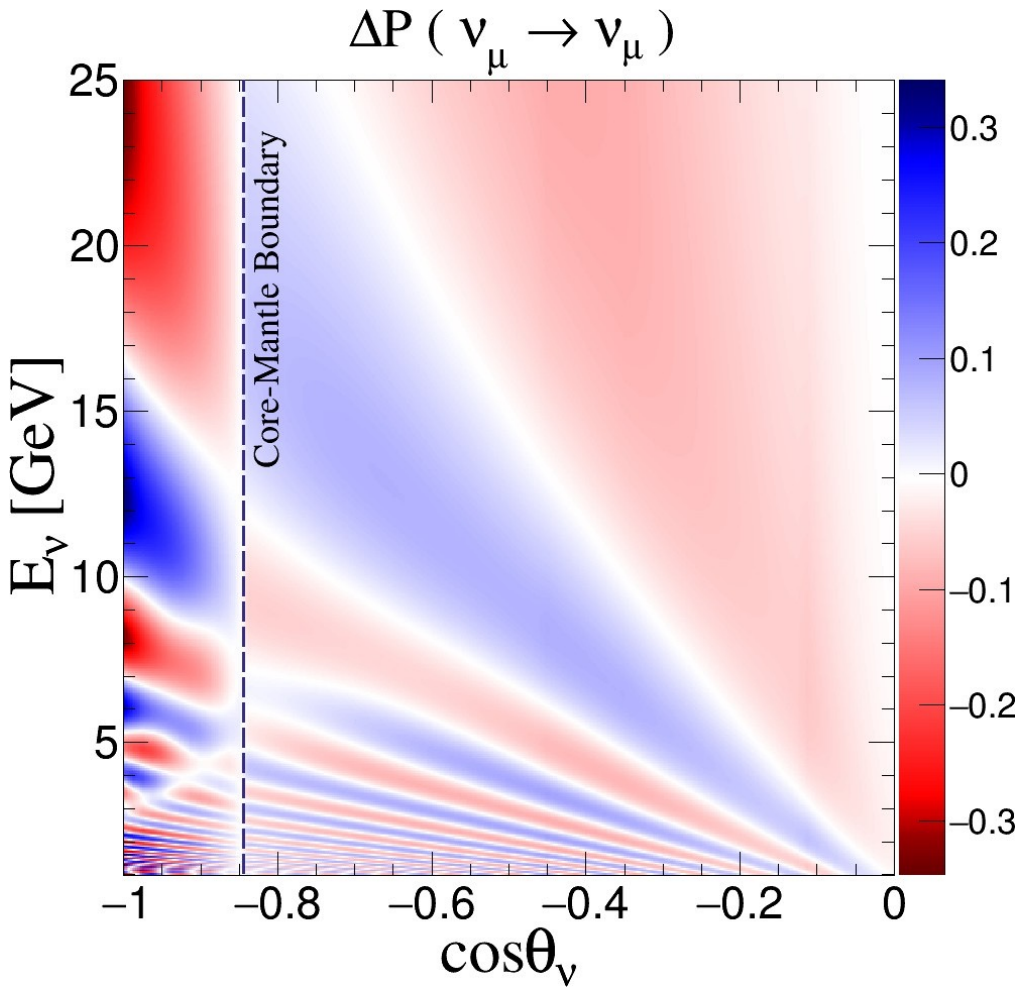
- Fixed-baseline (DUNE)
- $L = 1284.9\,\mathrm{km}$
- $\rho_{\mathrm{avg}}^{\mathrm{DUNE}} = 2.848\,g/cm^3$
- $\mathcal{E}_{\mu\tau} = 0.092$

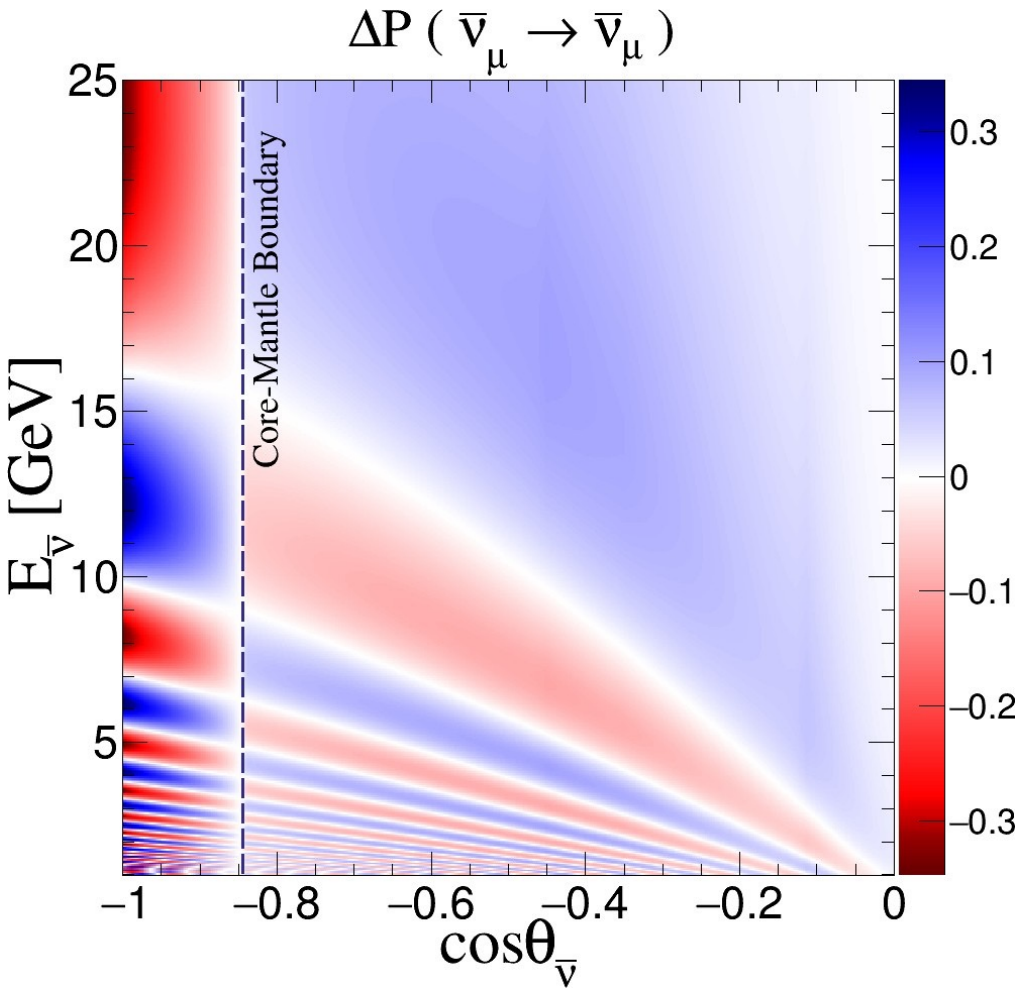
$Case - II$

- Atmospheric Experiments
- $L \in [15,\ 12757]\ \mathrm{km}$
- $\rho_{\mathrm{avg}}^{\mathrm{Earth}} = 5.513\,g/cm^3$
- $\mathcal{E}_{\mu\tau} = 0.0475$

$$\Delta P = P\,(\mathrm{SI} + \mathrm{LV}) - P\,(\mathrm{SI} + \mathrm{NSI})$$

$Case - II$





(Using the PREM profile)

Degeneracy between LV and NSI

A case-study with representative value of LV $a_{\mu\tau} = 10^{-23}\text{GeV}$

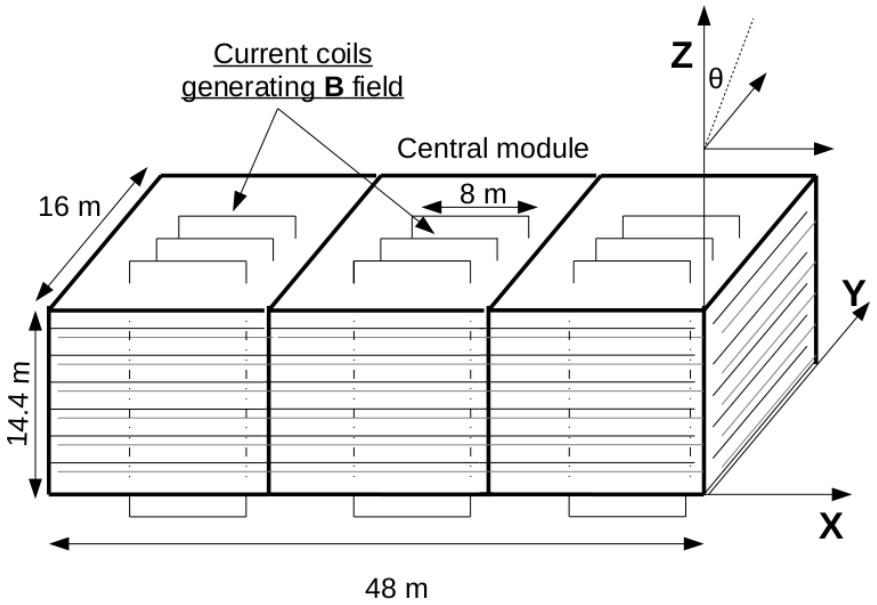
$Case - I$

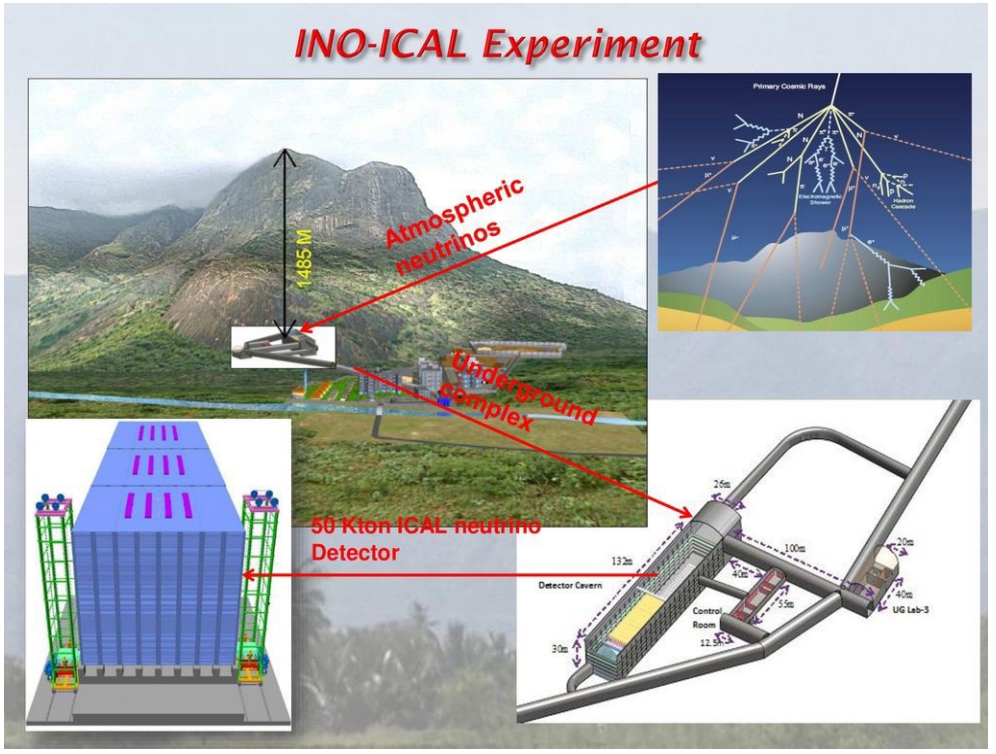
- Fixed-baseline (DUNE)
- $L = 1284.9\,\text{km}$
- $\rho_{\text{avg}}^{\text{DUNE}} = 2.848\,g/cm^3$
- $\mathcal{E}_{\mu\tau} = 0.092$
- $\Delta P_{\text{max}} < |0.0012|$

$Case - II$

- Atmospheric Experiments
- $L\,\epsilon\,[15,\,12757]\,\text{km}$
- $\rho_{\text{avg}}^{\text{Earth}} = 5.513\,g/cm^3$
- $\mathcal{E}_{\mu\tau} = 0.0475$
- $\Delta P_{\text{max}} \approx |0.34|$

Iron Calorimeter (ICAL) detector at India-based Neutrino Observatory (INO)





- 50 kt Magnetized Iron Calorimeter (ICAL) detector with magnetic field strength ~ 1.3 Tesla, enables to distinguish atmospheric neutrino and antineutrino events, separately.
- It has ~10% resolution of muon momentum ranging 1 to 25 GeV and ~1° zenith angle resolution over 15 to 12800 km range of baselines

Hadron energy resolution: 85% at 1 GeV and 36% at 15 GeV

Binning Scheme:

Observable	Range	Bin width	Total bins	
E_μ^{rec} (GeV)	$[1, 6]$	0.5	10	19
	$[6, 12]$	1	6	
	$[12, 15]$	3	1	
	$[15, 25]$	5	2	
$\cos\theta_\mu^{\text{rec}}$	$[-1.0, -0.85]$	0.0125	12	39
	$[-0.85, -0.4]$	0.025	18	
	$[-0.4, 0.0]$	0.1	4	
	$[0.0, 1.0]$	0.2	5	
$E'^{\text{rec}}_{\text{had}}$ (GeV)	$[0, 2]$	1	2	4
	$[2, 4]$	2	1	
	$[4, 25]$	21	1	

- NUANCE, Honda 3D Flux
- 20 years of Exposure
- Fixed Oscillation Parameters

D. Casper, arXiv: hep-ph/0208030

HAKKM, Phys. Rev. D 92, 023004

Method of χ^2 Analysis:

$$\chi^2_{\pm} = \min_{\zeta_l} \sum_{i=1}^{N_{E_{\rm had}}} \sum_{j=1}^{N_{E_{\mu^{\pm}}}} \sum_{k=1}^{N_{\cos\theta_\mu}} 2\left[N^{\rm test}_{ijk} - N^{\rm true}_{ijk} - N^{\rm true}_{ijk} \ln\left(\frac{N^{\rm test}_{ijk}}{N^{\rm true}_{ijk}}\right)\right] + \sum_{l=1}^{5} \zeta_l^2$$

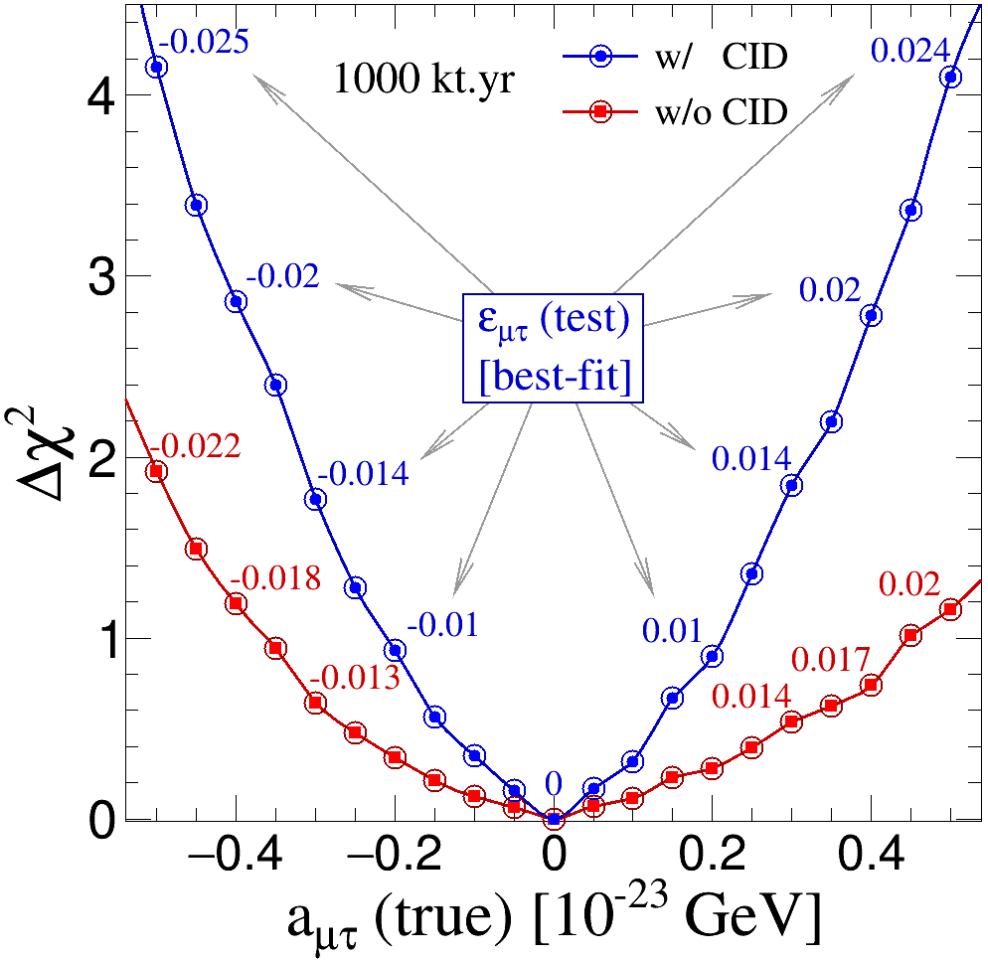
arXiv:1406.3689v1

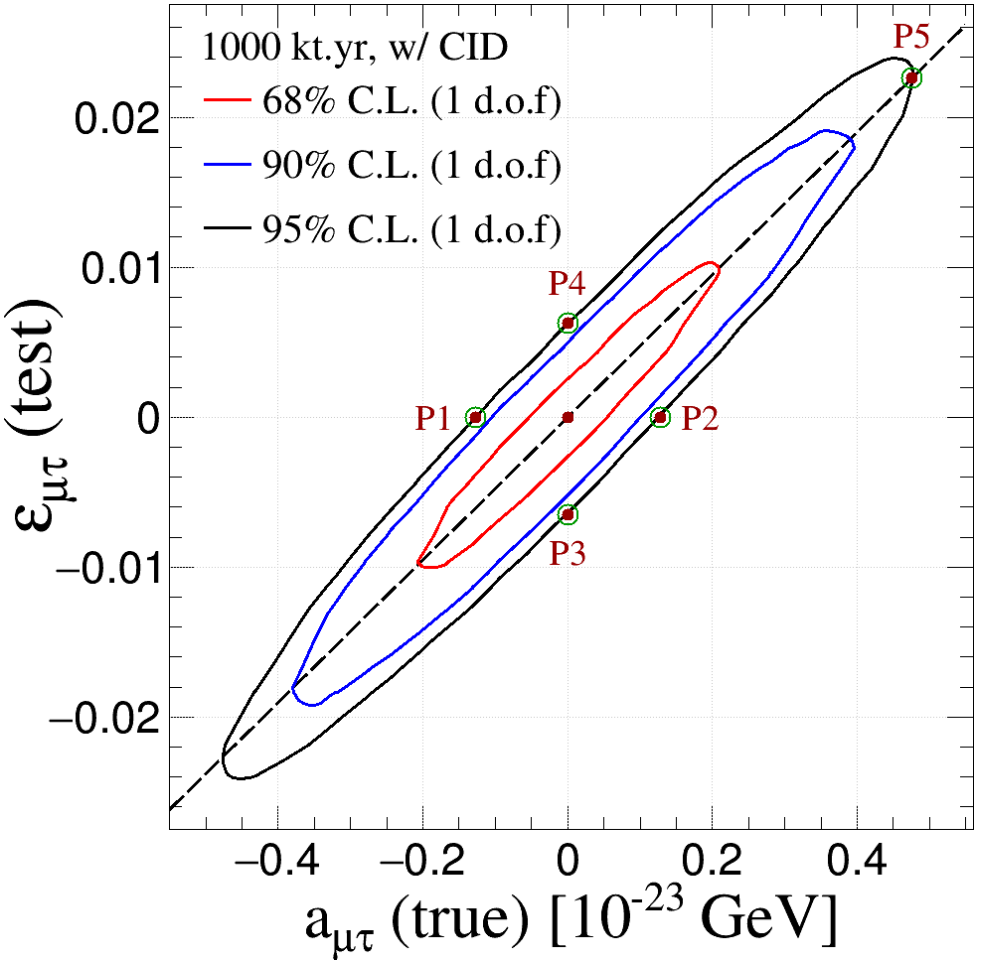
$$N^{\rm test}_{ijk} = N^0_{ijk}\left(1 + \sum_{l=1}^{5} \pi^l_{ijk}\zeta_l\right);$$

- Flux Normalization Error = 20%
- Interaction Cross section Error = 10%
- Energy Tilt Error = 5%
- Zenith Angle Error = 5%
- Overall Systematic Error = 5%

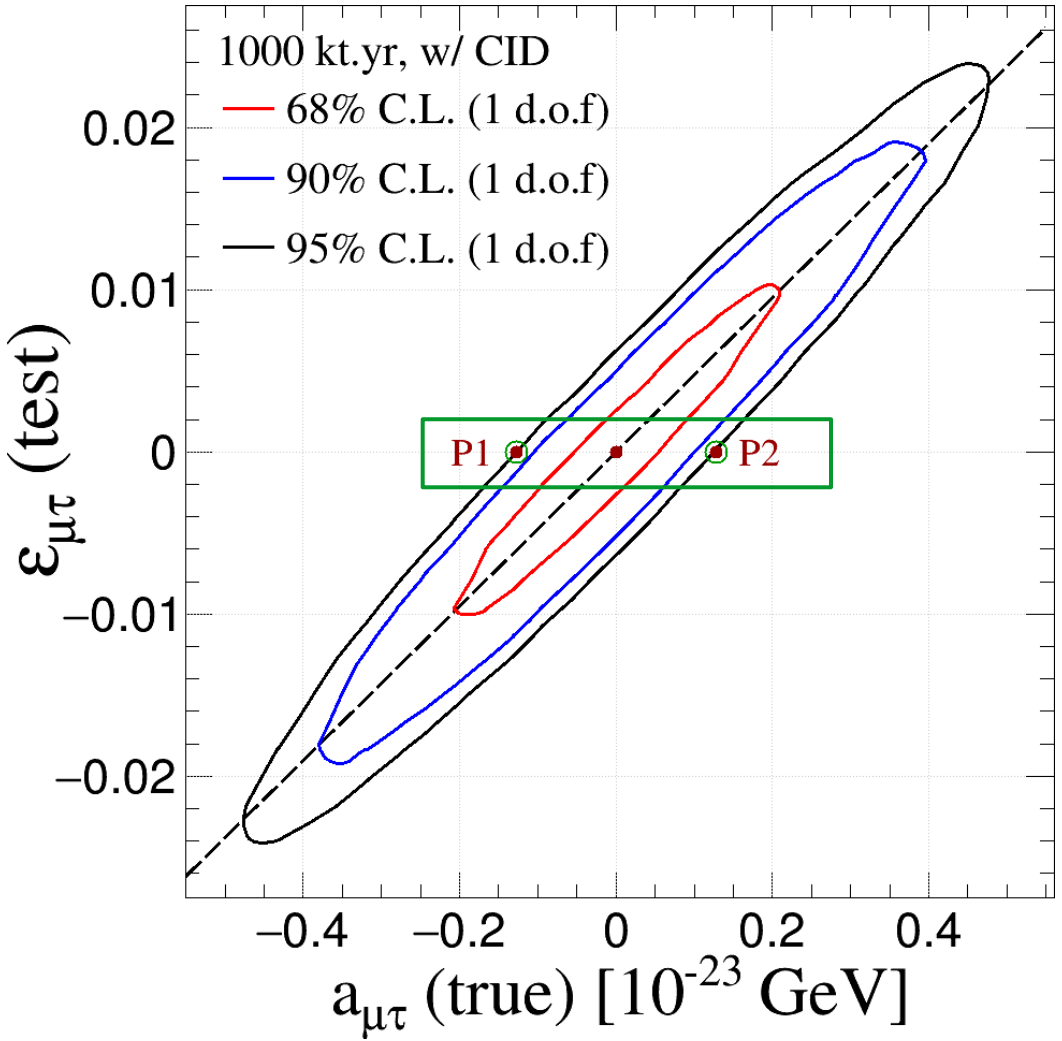
$$\Delta\chi^2 = \chi^2\left(\mathrm{a}^{\rm test}_{\mu\tau} = 0,\ \varepsilon^{\rm test}_{\mu\tau}\right) - \chi^2\left(\mathrm{a}^{\rm true}_{\mu\tau},\ \varepsilon^{\rm true}_{\mu\tau} = 0\right)$$

Results :


1000 kt.yr
w/ CID
w/o CID
$\varepsilon_{\mu\tau}$ (test)
[best-fit]
-0.025
-0.02
-0.014
-0.01
0
0.01
0.014
0.02
0.024
-0.022
-0.018
-0.013
0.014
0.017
0.02
$\Delta\chi^2$
$a_{\mu\tau}$ (true) [10^{-23} GeV]


1000 kt.yr, w/ CID
68% C.L. (1 d.o.f)
90% C.L. (1 d.o.f)
95% C.L. (1 d.o.f)
P1
P2
P3
P4
P5
$\varepsilon_{\mu\tau}$ (test)
$a_{\mu\tau}$ (true) [10^{-23} GeV]

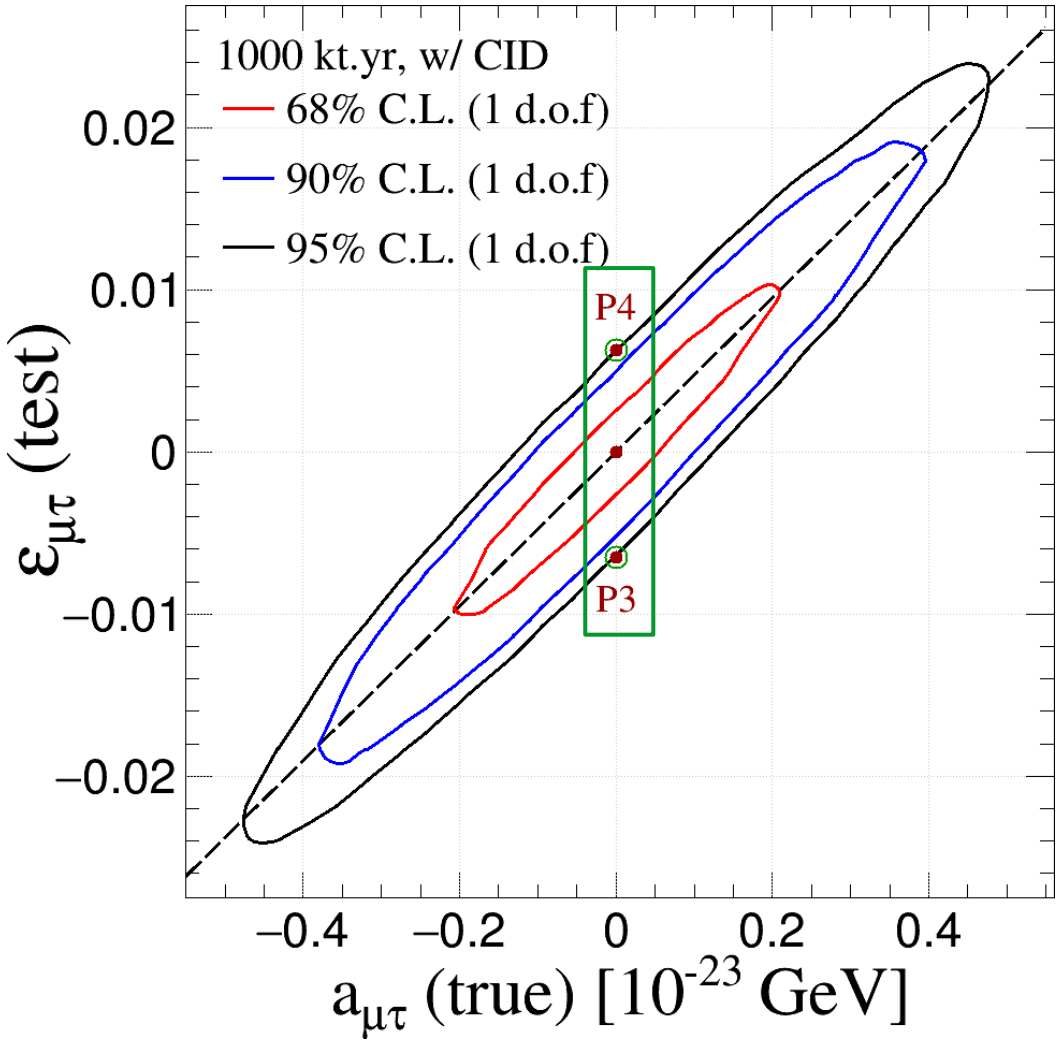
Results :



P1 - P2 disfavours SM when "$a_{\mu\tau}$" has non-zero values

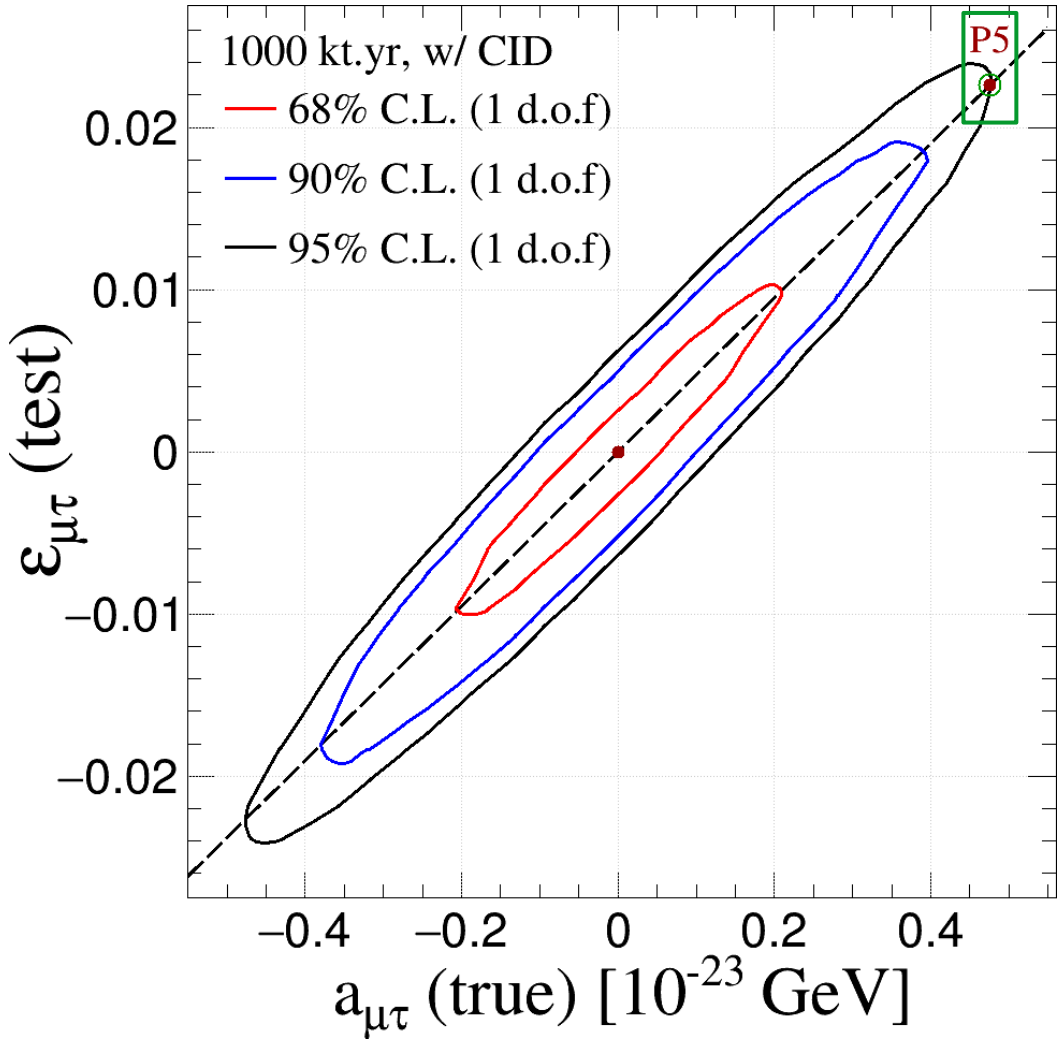
Beyond P1 - P2, SM gets disfavored at > 95% C.L.

Results :



P3 - P4 constrains the hypothesis of non-zero values of "$\varepsilon_{\mu\tau}$" at 95% C.L.

Results :



- The common major axis informs, the best-fit values of $\varepsilon_{\mu\tau}$ that can mimic the non- zero values of $a_{\mu\tau}$.
- P5 discards any values of $\varepsilon_{\mu\tau}$ including the mimicking value with $a_{\mu\tau} = 0.475 \times 10^{-23}$ GeV at $\geq 95\%$ C.L.

Concluding Remarks:

- The Core-passing atmospheric neutrinos and antineutrino can distinguish between the two popular beyond the Standard Model (BSM) scenarios, LV and NSI.
- The Charge Identification Capability (CID) of ICAL detector improves the power to discriminate between these two BSM scenarios.
- High-precision atmospheric neutrino data from currently running experiments like Super-K, IceCube, and ORCA and upcoming experiments like Hyper-K, DUNE, and P-ONE will certainly help to improve such discrimination.

Thank You

Hamiltonian in Standard Model Extension

$$H_{ij} = E\delta_{ij} + \frac{m^2_{ij}}{2E} + \frac{1}{E}\left(a^{\mu}_{L} p_{\mu} - c^{\mu\nu}_{L} p_{\mu} p_{\nu}\right)_{ij}$$

$p \equiv (E, -E\hat{p})$

$i, j \rightarrow$ flavour indices

$\mu, \nu \rightarrow$ space time indices

$m^2_{ij} \rightarrow$ mass squared splitting in flavour indices

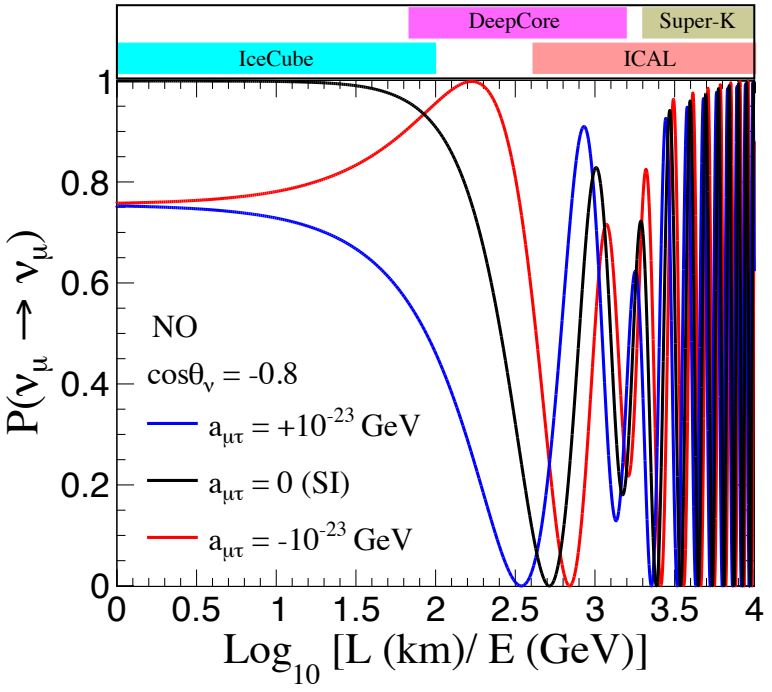
In our work, we only focus on CPT-violating LIV parameters $(a^{\mu})_{ij}$ where μ is the spacetime index and i, j are flavor indices. The couplings of $(a^{\mu})_{ij}$ with neutrinos are flavor-dependent.

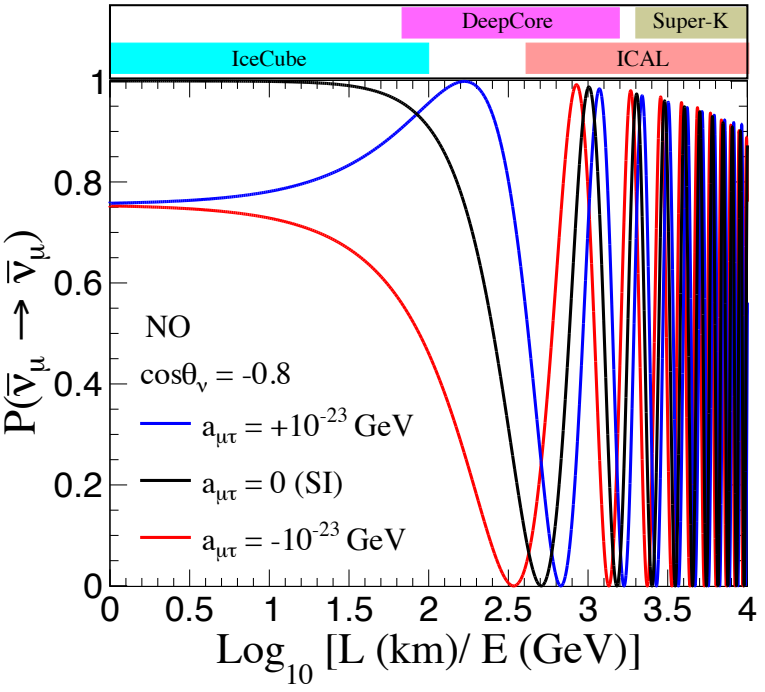
Remember, here, we consider a scenario in which the Lorentz symmetry is broken spontaneously, giving nonzero vev to a 4-vector $(a^{\mu})_{ij}$. Here $(a^{\mu})_{ij}$ combines the information on the vev and couplings of a^{μ} with neutrinos.

We work in an approximately inertial frame and consider only the timelike (isotropic) component of the LIV parameters to be nonzero ($a^{o} \neq 0$ and $p^{o} = E$).

The Sun-centered celestial-equatorial (SCCE) frame can be taken to be such a frame when the small effects due to gravity and boost due to the Earth's motion are ignored.

Oscillation Dip in presence of LIV





$\Delta m^2_{21} L/(4E) \ll \Delta m^2_{32} L/(4E)$

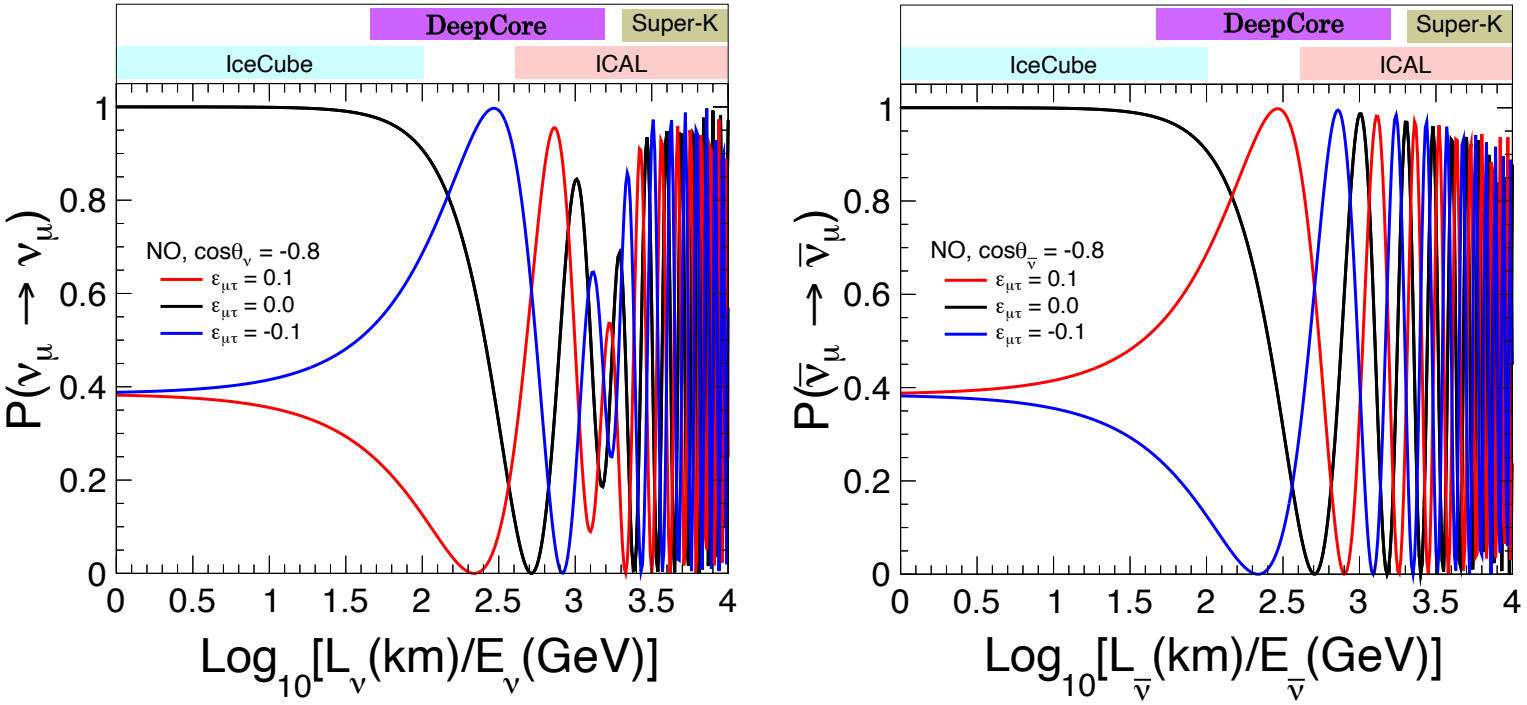
$\theta_{13} \to 0 \quad \theta_{23} = 45°$

Normal ordering

$$P(\nu_\mu \to \nu_\mu) = \cos^2\left[L_\nu\left(\frac{\Delta m^2_{32}}{4E_\nu} + \omega\, a_{\mu\tau}\right)\right]$$

ω = +1 (-1) for neutrino (antineutrino)

Oscillation Dip in presence of NSI



$$\Delta m^2_{21} L/(4E) \ll \Delta m^2_{32} L/(4E)$$

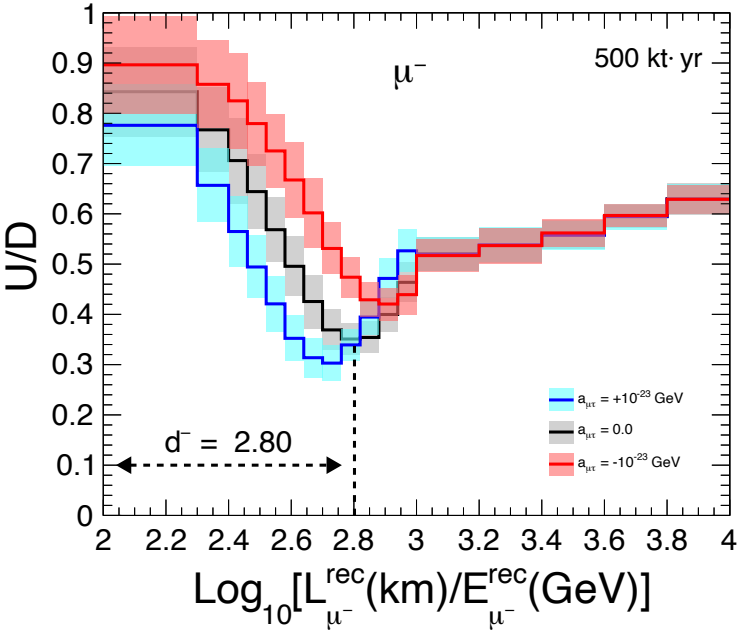
$$\theta_{13} \to 0 \quad \theta_{23} = 45^\circ$$

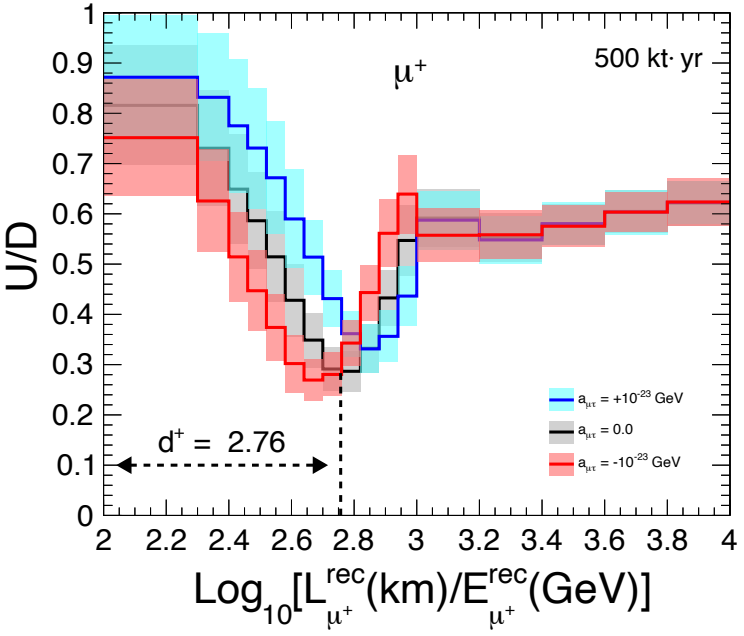
Normal ordering

$$P_{\nu_\mu \to \nu_\mu} = \cos^2 \left[L_\nu \left(\frac{\Delta m^2_{32}}{4E_\nu} + \varepsilon_{\mu\tau} V_{CC} \right) \right]$$

V_{CC} = +1 (-1) for neutrino (antineutrino)

Identifying LIV through the Shift in oscillation Dip Location





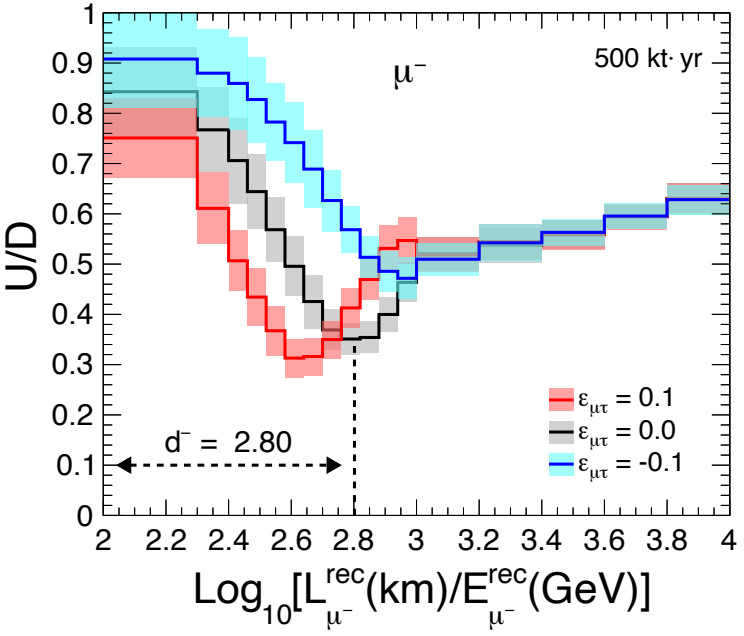
Sahoo, Kumar, Agarwalla, Dighe, work in progress

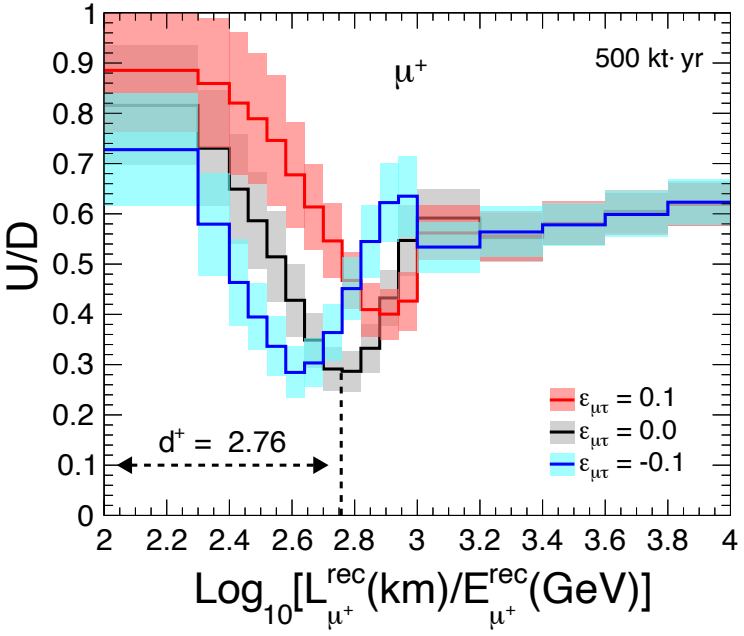
$$\mathrm{U/D}(E_\mu^{\mathrm{rec}}, \cos\theta_\mu^{\mathrm{rec}}) \equiv \frac{N(E_\mu^{\mathrm{rec}}, -|\cos\theta_\mu^{\mathrm{rec}}|)}{N(E_\mu^{\mathrm{rec}}, |\cos\theta_\mu^{\mathrm{rec}}|)}$$

→ It reduces the impact of systematic uncertainties like flux normalization, cross sections, overall detection efficiency, & energy dependent tilt error

The statistical fluctuations shown by shaded boxes are the root-mean-square deviation of 100 independent distributions of U/D ratio, each for 10 years, whereas the mean of these distributions are shown by solid lines. Even after detector smearing and statistical fluctuations, the oscillation dip is visible in ICAL and shift in oscillation dip location may hint towards LIV. Note that the shift occurs in the opposite direction for neutrinos and antineutrinos for a given LIV parameter. Also, the dip is deeper for antineutrino as compared to neutrino due less inelasticity in antineutrino events

Identifying NSI through the Shift in oscillation Dip Location





Kumar, Khatun, Agarwalla, Dighe, JHEP 04 (2021) 159

$$U/D(E_\mu^{rec}, \cos\theta_\mu^{rec}) \equiv \frac{N(E_\mu^{rec}, -|\cos\theta_\mu^{rec}|)}{N(E_\mu^{rec}, |\cos\theta_\mu^{rec}|)}$$

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