Probing Lorentz invariance violation using atmospheric and accelerator neutrinos at upcoming neutrino detectors: INO-ICAL, DUNE, and T2HK

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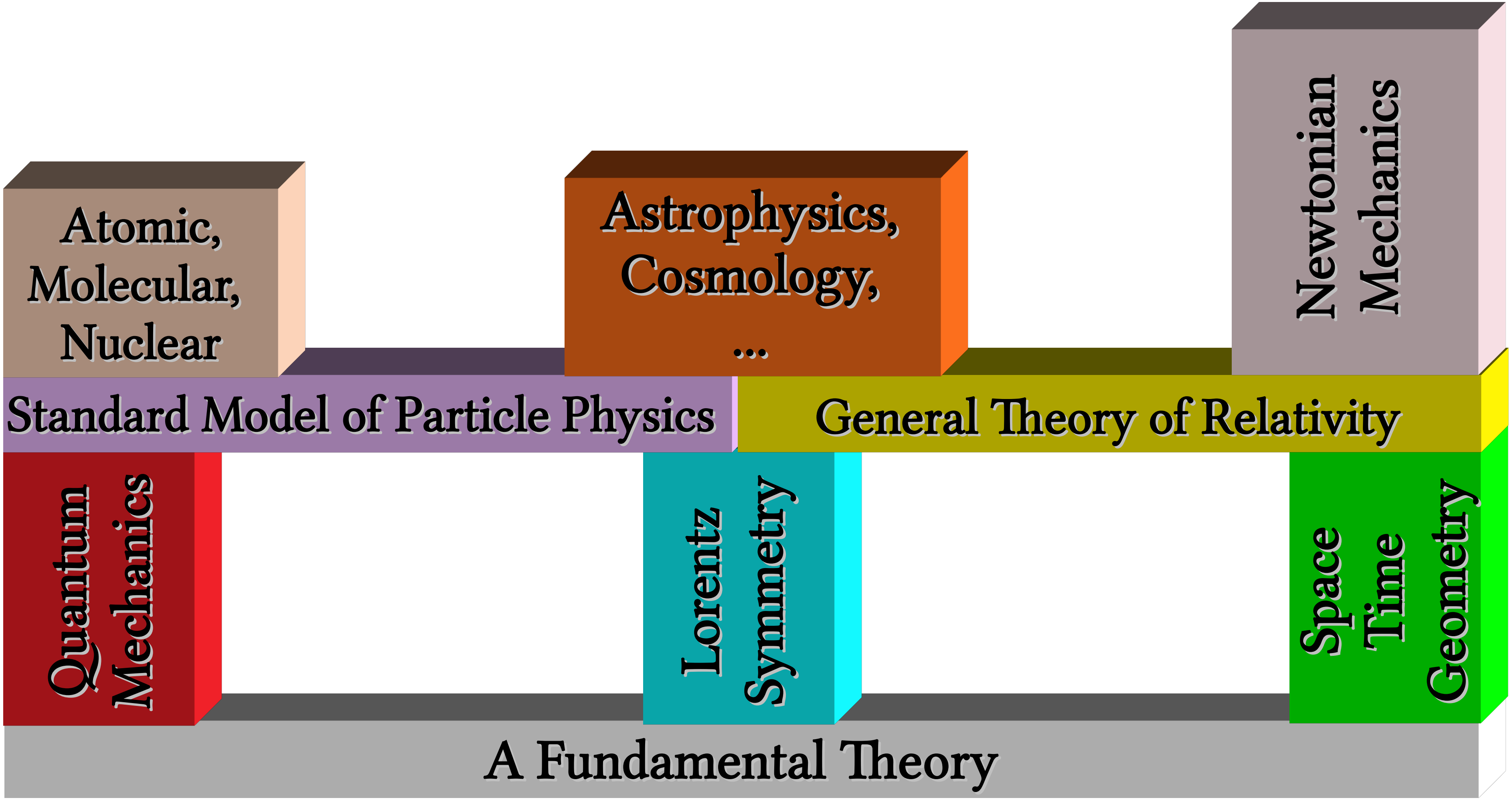
Based on two papers:
JHEP 03 (2022) 050 (S Sahoo, A Kumar, and S K Agarwalla)
&
arXiv: 2302.12005 [accepted in JHEP] (S K Agarwalla, S Das, S Sahoo, and P Swain)

Motivation to Lorentz Invariance Violation



Atomic, Molecular, Nuclear

Astrophysics, Cosmology, …

Newtonian Mechanics

Standard Model of Particle Physics

General Theory of Relativity

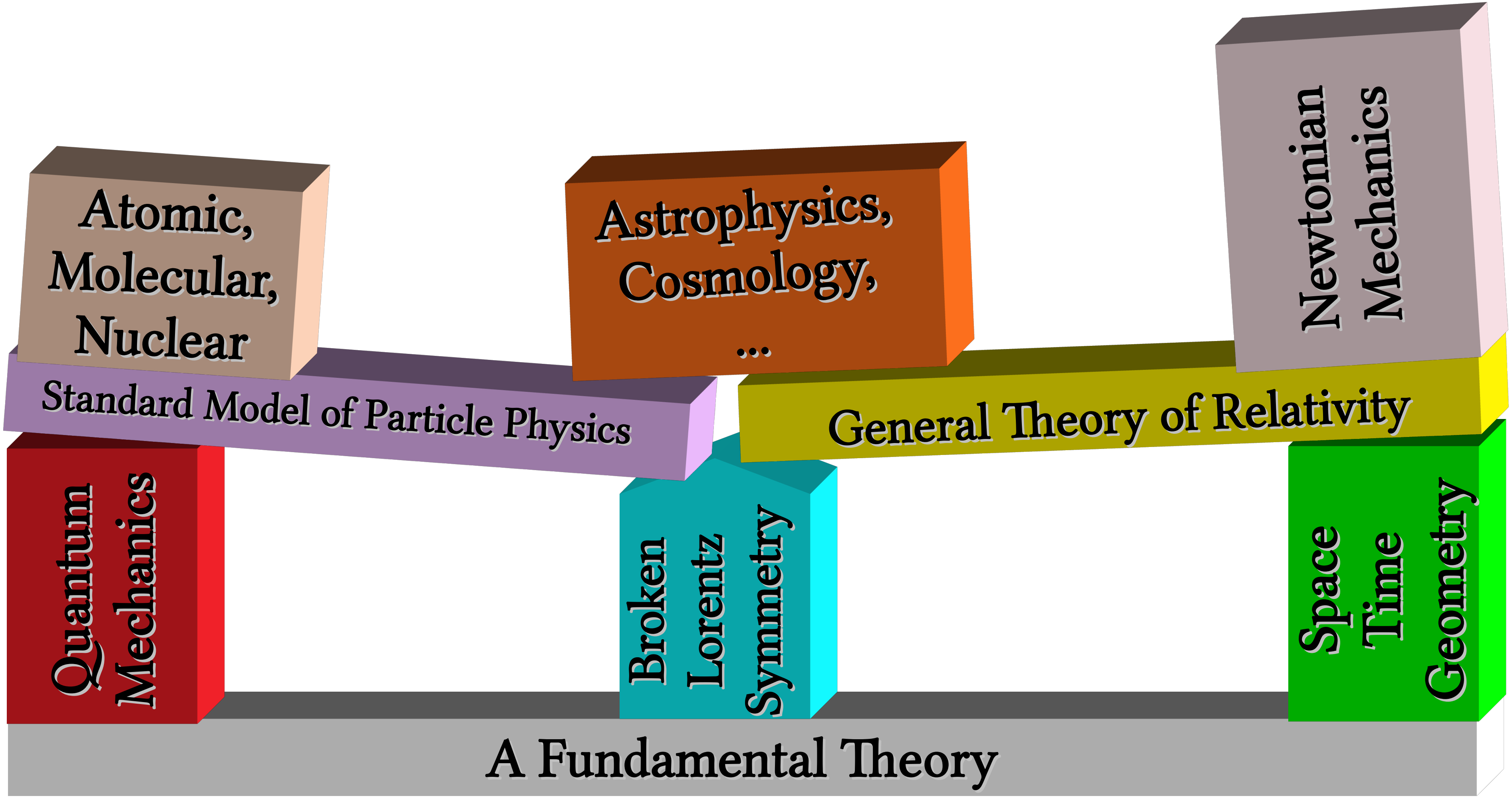
Quantum Mechanics

Lorentz Symmetry

Space Time Geometry

A Fundamental Theory

Original: M. Mathew



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Newtonian
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Standard Model of Particle Physics

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Quantum
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Broken
Lorentz
Symmetry

Space
Time
Geometry

A Fundamental Theory

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Breaking of Lorentz Symmetry

↓

Explicit ← Breaking → Spontaneous

Spontaneous Lorentz Symmetry Breaking
&
Standard Model Extension

Basic Hypothesis of Spontaneous Lorentz Symmetry Breaking

- At Planck Scale ($M_P \sim 10^{19}$ GeV), there is possibility of breaking of Lorentz , and Charge-Parity-Time (CPT) Symmetry at a higher dimension of space-time (> 4).

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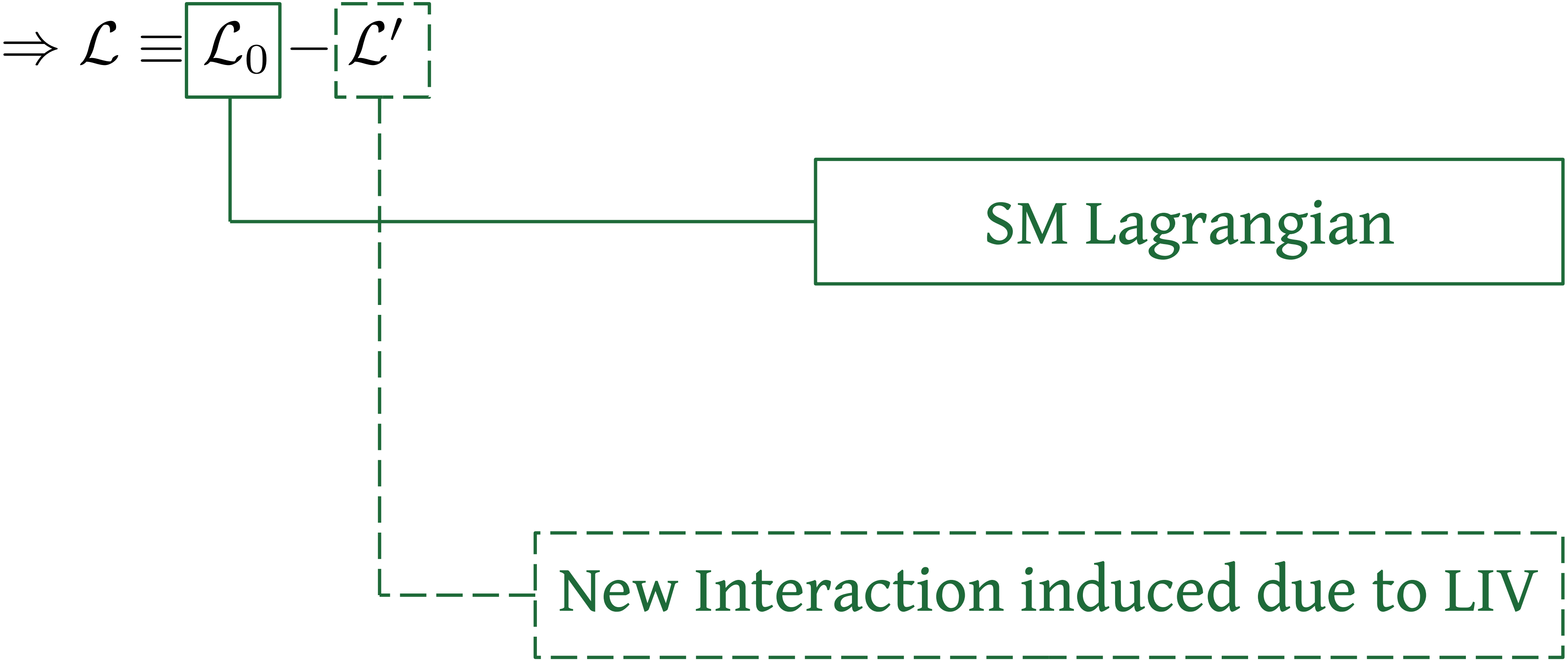
- Such a violation in Lorentz and CPT symmetry may be realised in Nature, i.e., in realistic dimension 4 space-time.
- Using effective field theory formulation, such effect can be treated as a new interaction in a minimal extension Standard Model of Particle Physics.
- However, the strength of such interaction would be expected to be suppressed by $1/M_P$

Spontaneous Lorentz Symmetry Breaking



$$\Rightarrow \mathcal{L} \equiv \boxed{\mathcal{L}_0} - \boxed{\mathcal{L}'}$$

SM Lagrangian

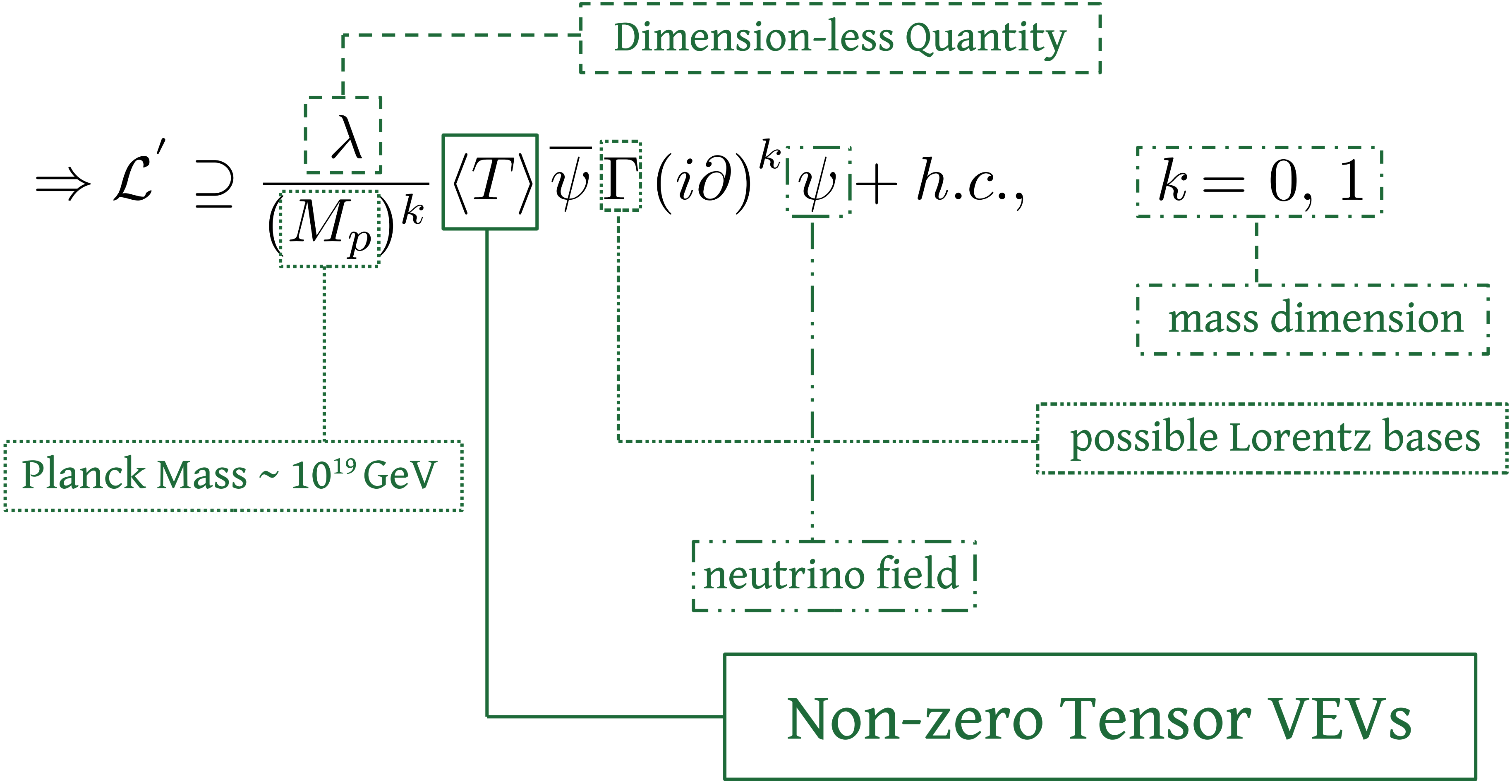
New Interaction induced due to LIV

Spontaneous Lorentz Symmetry Breaking

$$\Rightarrow \mathcal{L}^{'} \supseteq \frac{\lambda}{(M_p)^k} \langle T \rangle \, \overline{\psi} \, \Gamma \, (i\partial)^k \, \psi + h.c., \qquad k = 0,\, 1$$

CPT violation and the standard model
Don Colladay and V. Alan Kostelecký
Phys. Rev. D 55, 6760 – Published 1 June 1997

Spontaneous Lorentz Symmetry Breaking



Dimension-less Quantity

$$\Rightarrow \mathcal{L}' \supseteq \frac{\lambda}{(M_p)^k}\boxed{\langle T\rangle}\,\overline{\psi}\,\Gamma\,(i\partial)^k\psi + h.c., \qquad k = 0,\, 1$$

mass dimension

possible Lorentz bases

Planck Mass ~ 10^{19} GeV

neutrino field

Non-zero Tensor VEVs

Spontaneous Lorentz Symmetry Breaking

$$\mathcal{L}' \supseteq \frac{\lambda}{(M_p)^k} \langle T \rangle \, \overline{\psi} \, \Gamma \, (i\partial)^k \, \psi + h.c., \qquad k = 0,\, 1$$

$$\mathrm{k} = 0,\ \langle T \rangle \sim \left(\frac{m^2}{M_p} \right); \ (\, \text{leads to CPT} - \text{violating LIV})$$

$$\mathrm{k} = 1,\ \langle T \rangle \sim m; \qquad (\, \text{leads to CPT} - \text{conserving LIV})$$

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

Hamiltonian in Minimal Standard Model Extension

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

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

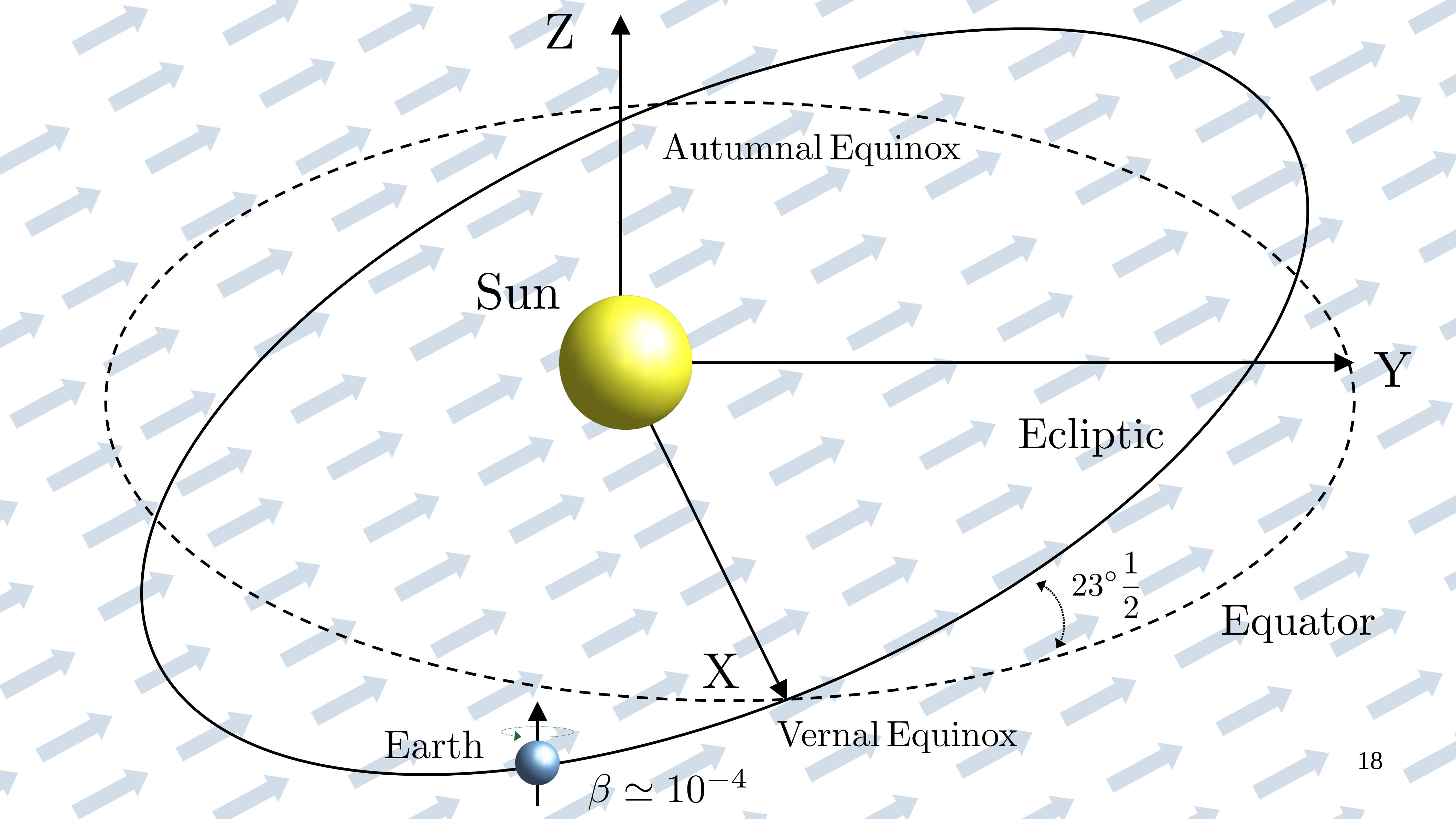
$i,\ j$ → Flavour indices

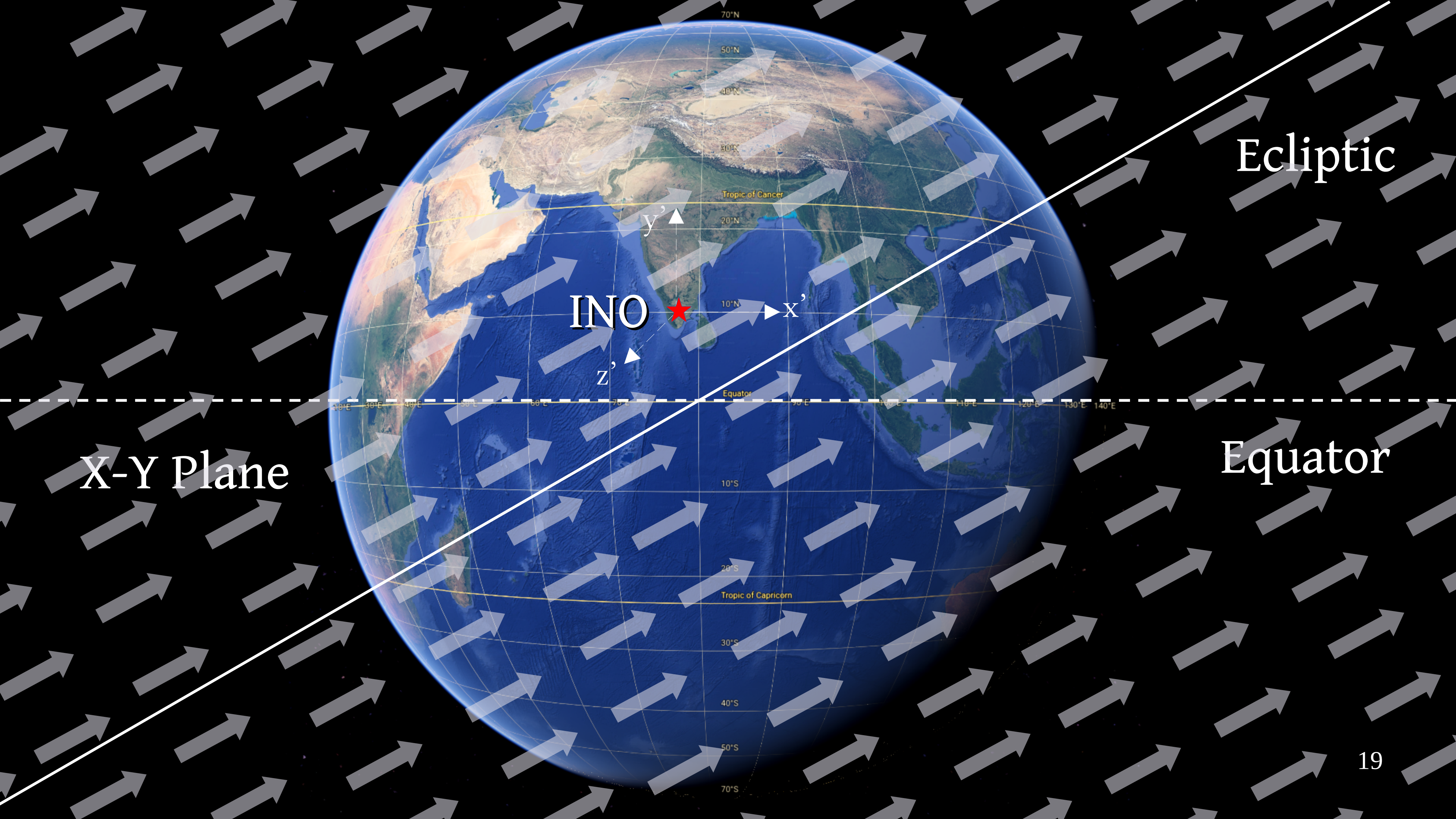
$\mu,\ \nu$ → Space-time indices

m^2_{ij} → Mass-squared splitting in flavour bases

PhysRevD.69.016005, A., Kostelecky and M., Matthew

Choice of Inertial Frame of Reference


Z
Autumnal Equinox
Sun
Y
Ecliptic
$23^\circ\frac{1}{2}$
Equator
X
Vernal Equinox
Earth
$\beta \simeq 10^{-4}$


Ecliptic
INO
y'
x'
z'
X-Y Plane
Equator
70°N
50°N
40°N
30°N
Tropic of Cancer
20°N
10°N
Equator
10°S
20°S
Tropic of Capricorn
30°S
40°S
50°S
70°S

Effect of LIV on atmospheric neutrino oscillation

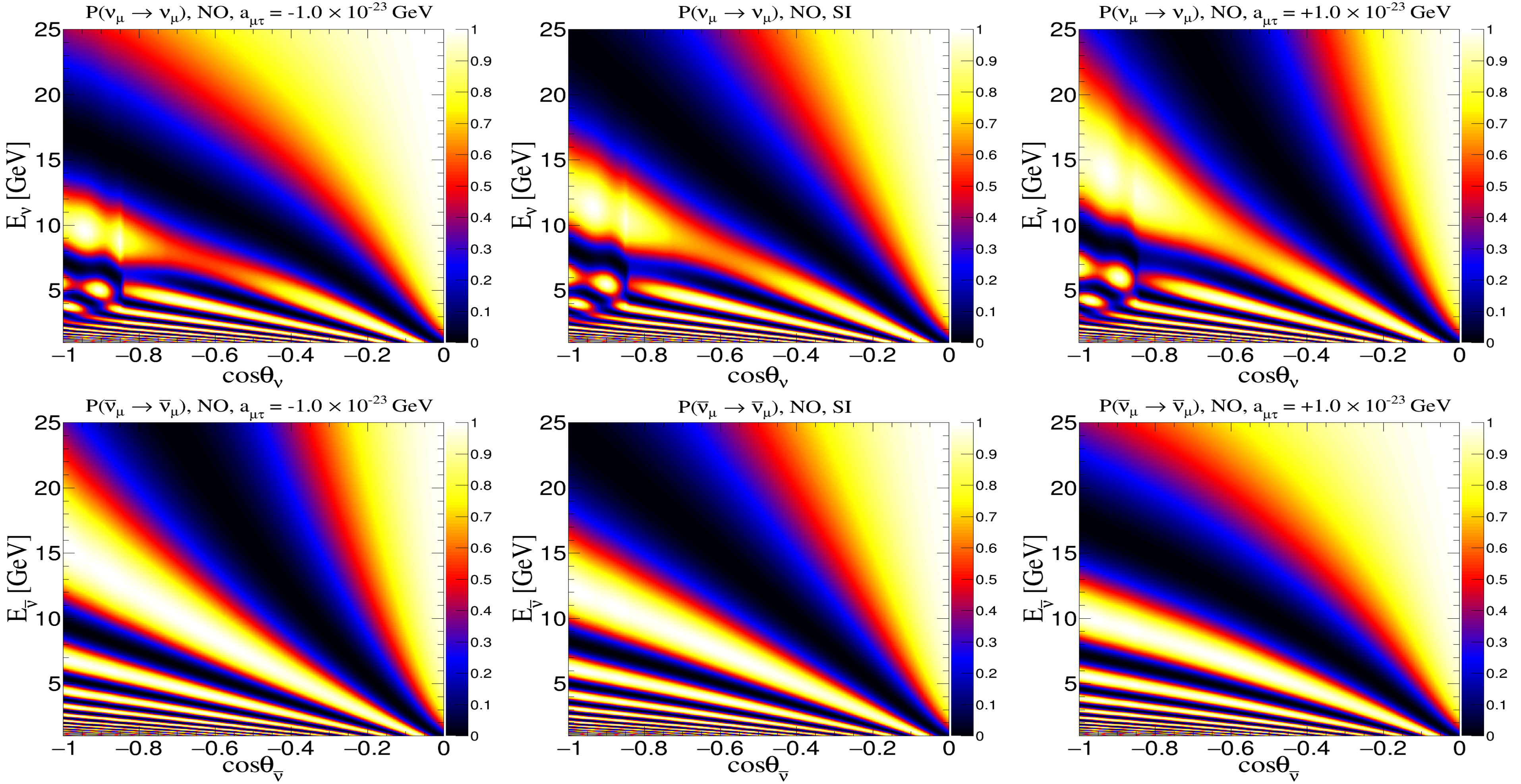
$$H = \frac{1}{2E} U \begin{bmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{bmatrix} U^\dagger \pm \begin{bmatrix} \mathrm{a}_{ee} & \mathrm{a}_{e\mu} & \mathrm{a}_{e\tau} \\ \mathrm{a}^*_{e\mu} & \mathrm{a}_{\mu\mu} & \mathrm{a}_{\mu\tau} \\ \mathrm{a}^*_{e\tau} & \mathrm{a}^*_{\mu\tau} & \mathrm{a}_{\tau\tau} \end{bmatrix}_0 \pm \sqrt{2} G_F \begin{bmatrix} N_e & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

- CPT-Violating parameter “a” with isotropic components
- “+” sign is assigned for neutrino and “-” sign for antineutrino
- $\sqrt{2}G_F N_e$ is standard matter interaction potential of neutrino and antineutrino

Benchmark Oscillation Parameters

$\sin^2 2\theta_{12}$	$\sin^2 \theta_{23}$	$\sin^2 2\theta_{13}$	$\Delta m^2_{\mathrm{eff}}$ (eV^2)	Δm^2_{21} (eV^2)	δ_{CP}	Mass Ordering
0.855	0.5	0.0875	2.49×10^{-3}	7.4×10^{-5}	0	Normal (NO)

Effect of $a_{\mu\tau} = \pm 1.0 \times 10^{-23}$ GeV on Muon Survival Channel

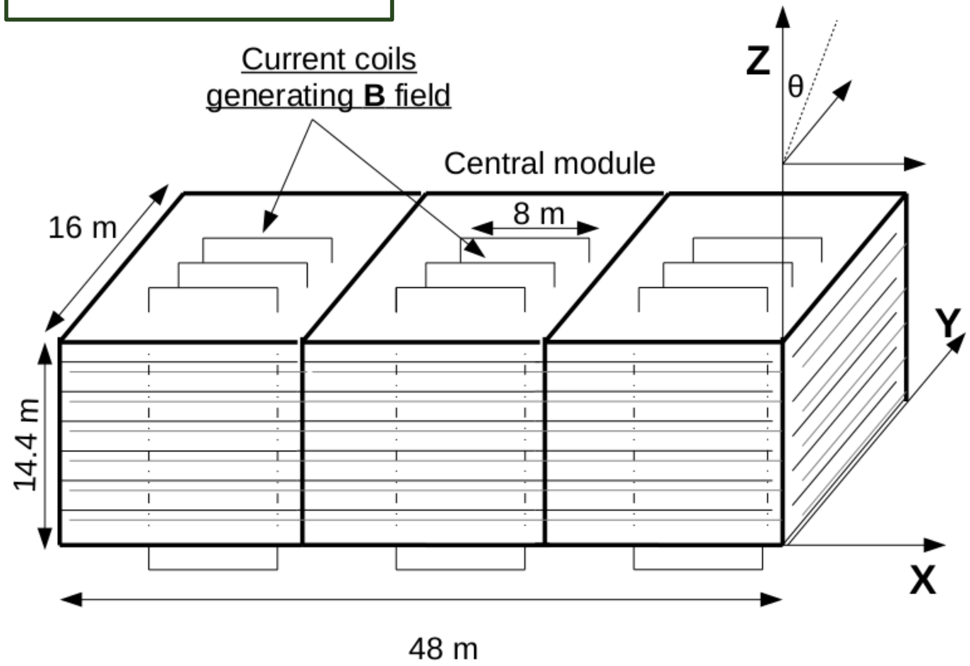


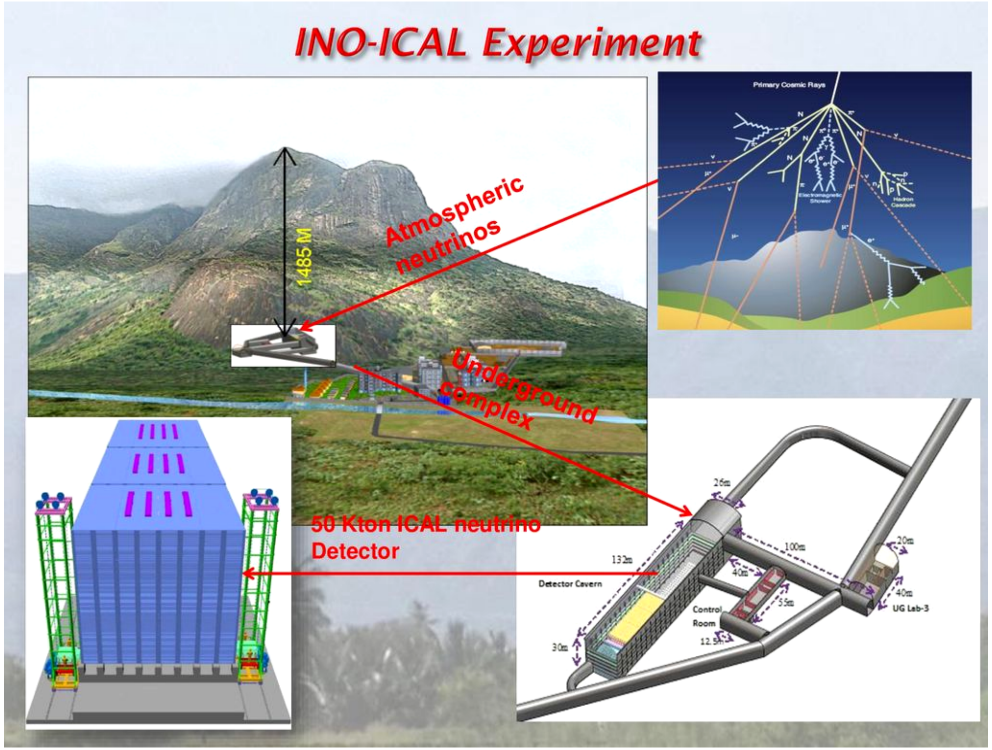
The Oscillation valley bends, when $a_{\mu\tau}$ has a non-zero value

Exploring LIV at INO-ICAL

JHEP 03 (2022) 050 (S Sahoo, A Kumar, and S K Agarwalla)

INO-ICAL :

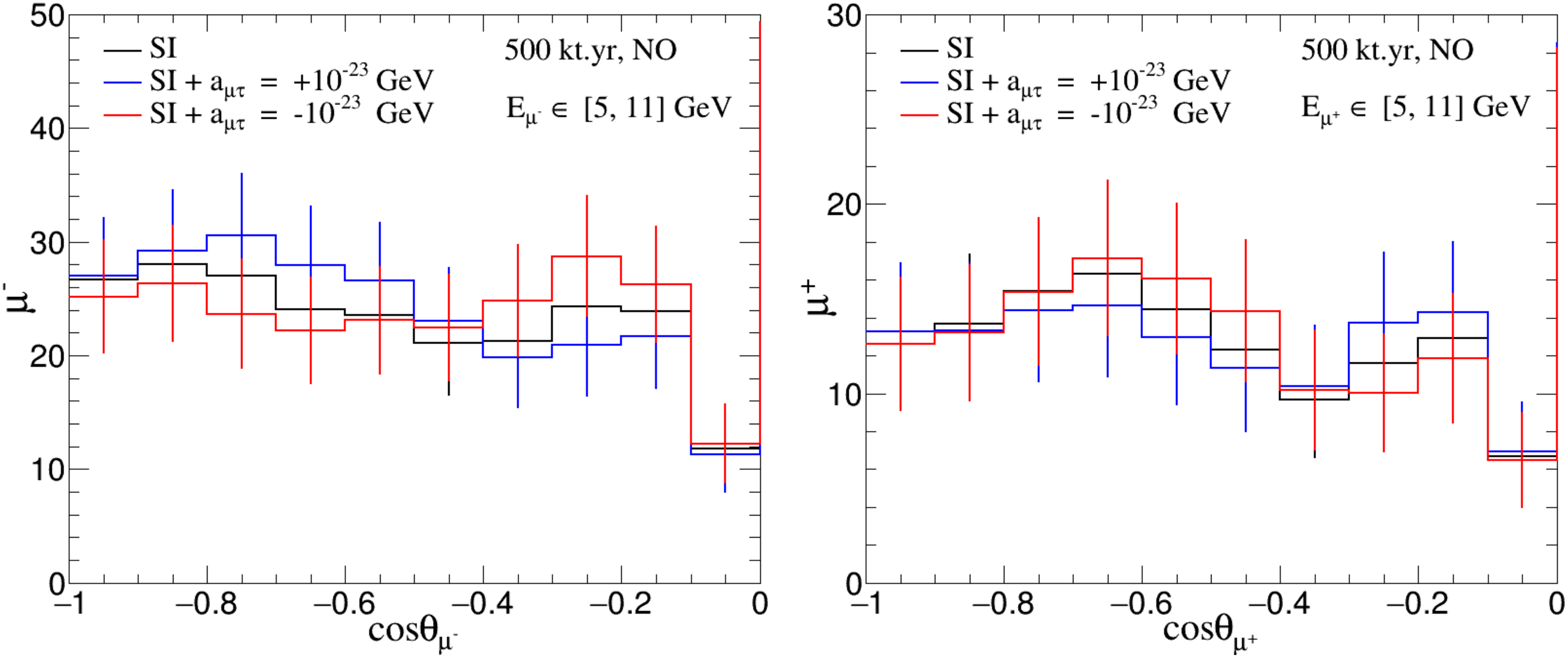




- 50 kt Magnetized Iron Calorimeter (ICAL) of field strength ~1.3 Tesla, enables to distinguish atmospheric neutrino and antineutrino events, separately.
- ICAL has ~10% resolution of muon momentum ranging 1-25 GeV and ~1° zenith angle resolution over 15-12800 km range of baselines

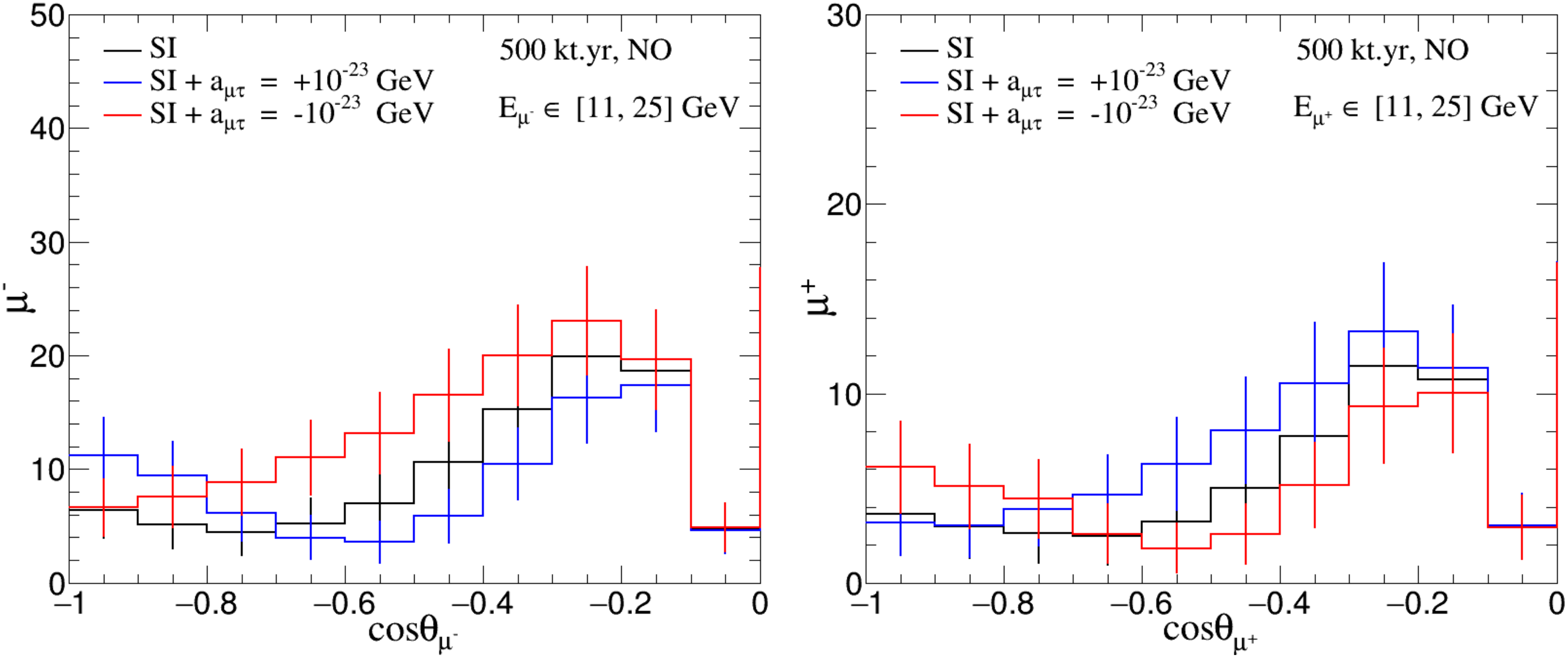
ICAL Collaboration (White Paper): Pramana 88 (2017) 5, 79

Impact of non-zero ($a_{\mu\tau}$) on Event Distribution :



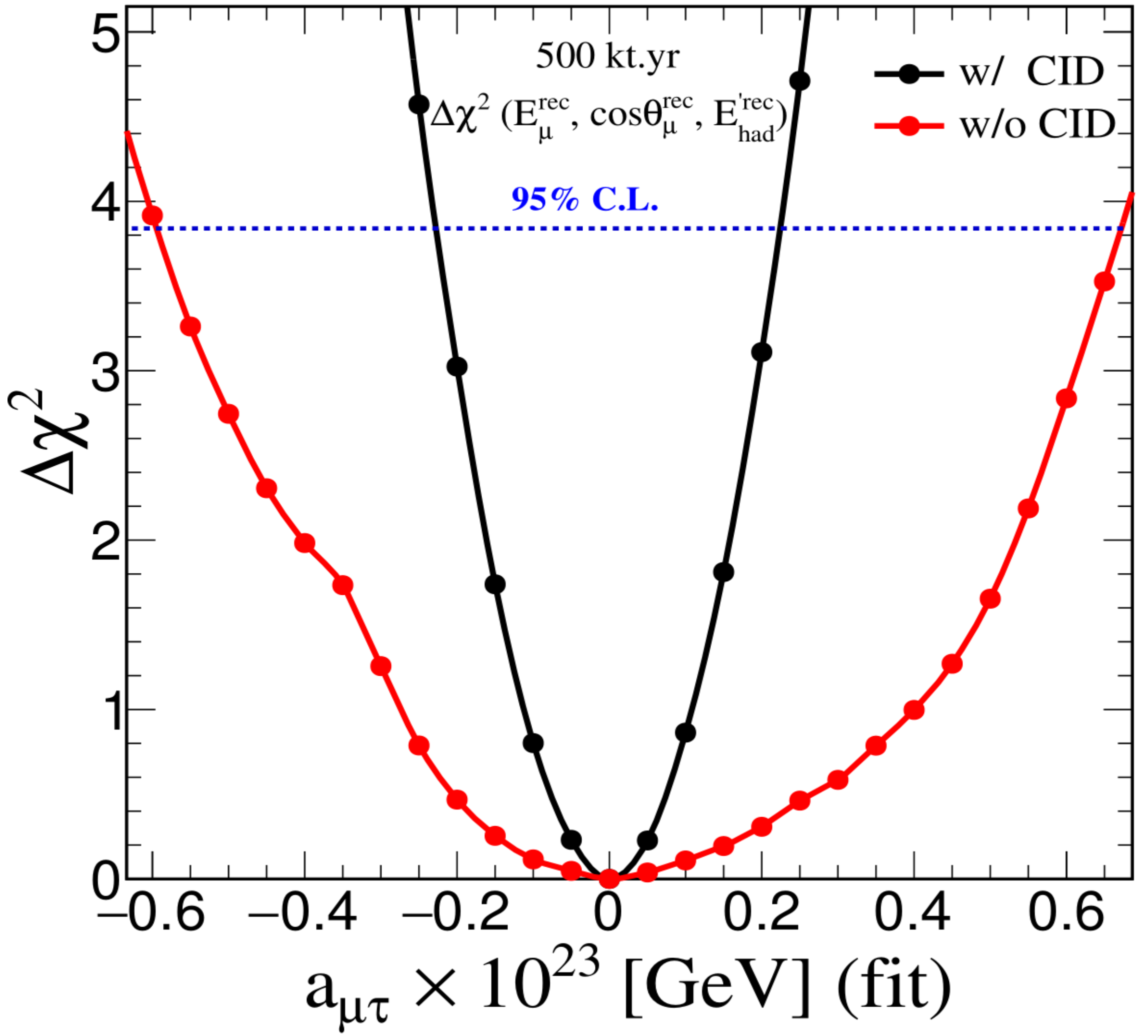
For a given $a_{\mu\tau}$: The event distributions of μ^- and μ^+ flip around the SI scenario

Impact of non-zero ($a_{\mu\tau}$) on Event Distribution :



For a given $a_{\mu\tau}$: The event distributions of μ^- and μ^+ flip around the SI scenario

Bounds of CPT-Violating parameters with Charge Identification Capability



- Expected bound is placed with an exposure of 500 kt.yr of ICAL simulation data
- Minimized over $\sin^2\theta_{23}$, Δm^2_{32}, and Mass Orderings (NO and IO).
- Red curve without CID and Blue curve with CID.
- Using CID improves the sensitivity significantly.

JHEP 03 (2022) 050
S Sahoo, A Kumar, and S K Agarwalla

Comparison of ICAL LIV Sensitivity with the Current Experimental Limits

Constraints on CPT-violating LIV parameters				
Experiments		$a_{\mu\tau}[10^{-23}\ \text{GeV}]$	$a_{e\mu}[10^{-23}\ \text{GeV}]$	$a_{e\tau}[10^{-23}\ \text{GeV}]$
IceCube (99% C.L.)		$\lvert\text{Re}(a_{\mu\tau})\rvert < 0.29$ $\lvert\text{Im}(a_{\mu\tau})\rvert < 0.29$	–	–
Super-K (95% C.L.)		$\text{Re}(a_{\mu\tau}) < 0.65$ $\text{Im}(a_{\mu\tau}) < 0.51$	$\text{Re}(a_{e\mu}) < 1.8$ $\text{Im}(a_{e\mu}) < 1.8$	$\text{Re}(a_{e\tau}) < 4.1$ $\text{Im}(a_{e\tau}) < 2.8$
ICAL (95% C.L.)	w/o CID	$-0.59 \leq \text{Re}(a_{\mu\tau}) \leq 0.67$	$-3.97 \leq \text{Re}(a_{\mu\tau}) \leq 3.37$	$-4.71 \leq \text{Re}(a_{\mu\tau}) \leq 3.96$
	w/ CID	$-0.23 \leq \text{Re}(a_{\mu\tau}) \leq 0.22$	$-1.97 \leq \text{Re}(a_{\mu\tau}) \leq 1.34$	$-2.80 \leq \text{Re}(a_{\mu\tau}) \leq 1.58$

JHEP 03 (2022) 050 (This Work)
S Sahoo, A Kumar, and S K Agarwalla

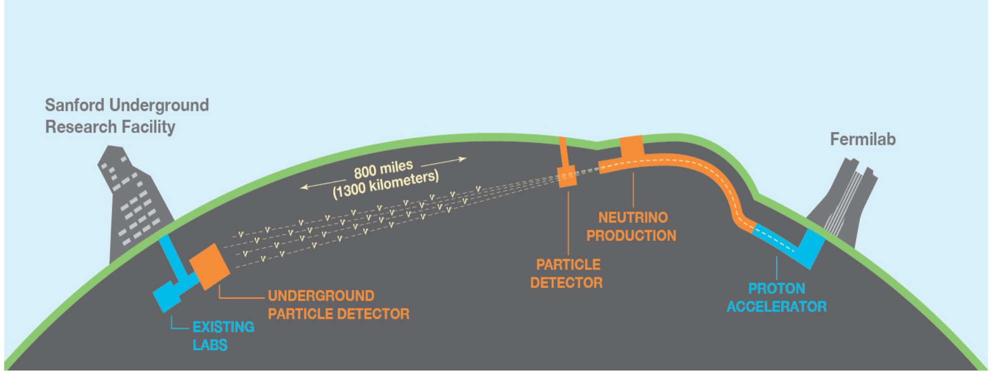
Nature Phys. 14 (2018) 9, 961-966
IceCube Collaboration

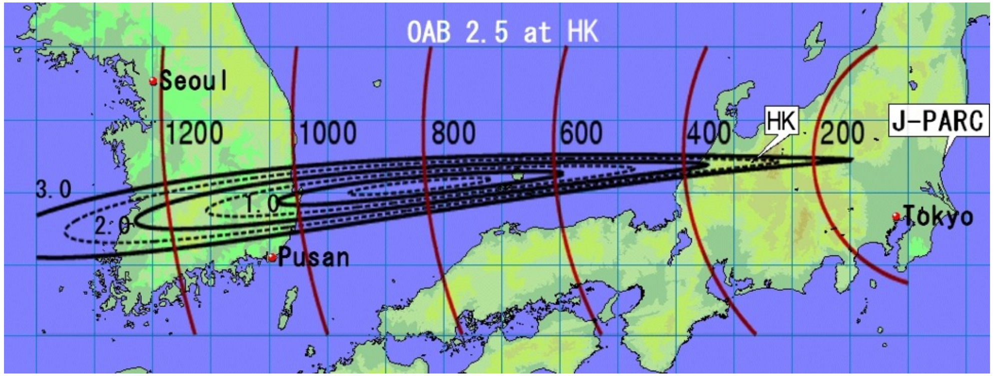
Phys.Rev.D 91 (2015) 5, 052003
Super-K Collaboration

Exploring LIV at future LBL Experiments

arXiv: 2302.12005 (S K Agarwalla, S Das, S Sahoo, and P Swain)

Brief description on next generation LBL Experiments: DUNE and T2HK





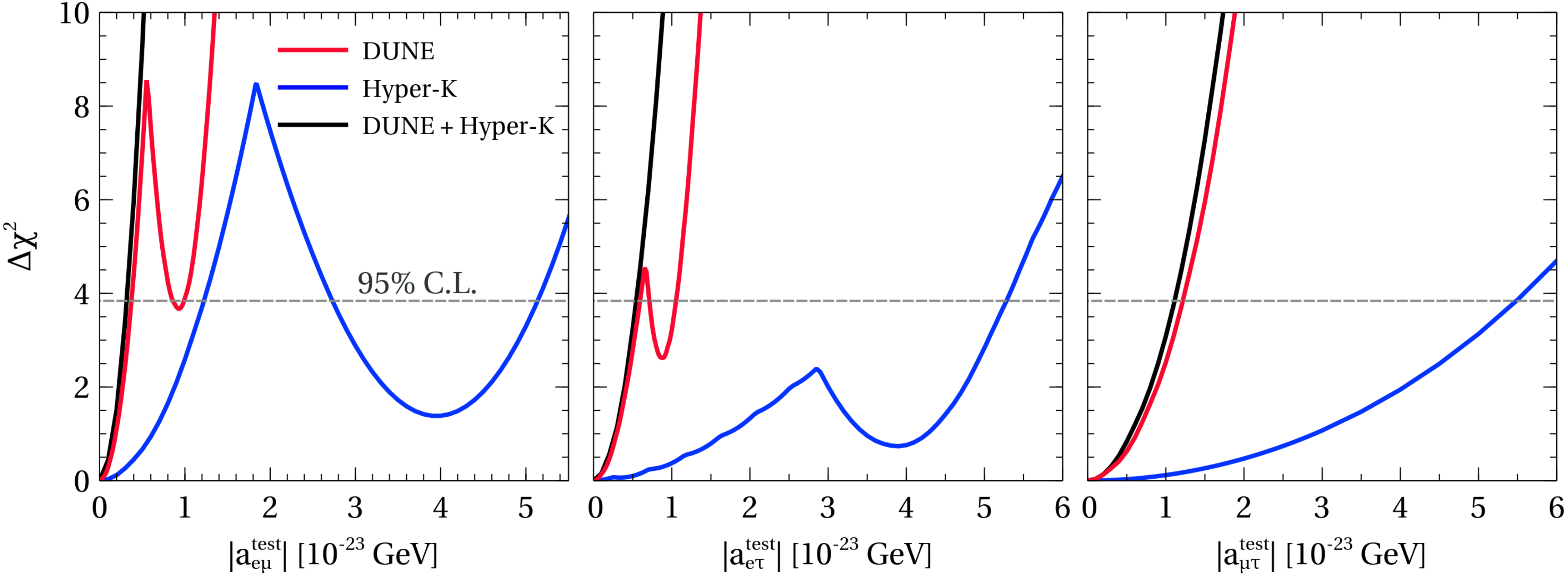
	DUNE	T2HK
Detector Mass	40 kt LArTPC	187 kt WC
Baseline	1285 km	295 km
Proton Energy	120 GeV	80 GeV
Beam type	Wide-band, on-axis	Narrow-band, off-axis (2.5°)
Beam power	1.2 MW	1.3 MW
P.O.T./year	1.1×10^{21}	2.7×10^{21}
Run time $(\nu + \bar{\nu})$	5 yrs + 5 yrs	2.5 yrs + 7.5 yrs
Normalization error	2% (app.) 5% (disapp.)	5% (app.), 3.5% (disapp.)

JINST 15 (2020) 08, T08008
DUNE Collaboration

arXiv: 1805.04163
Hyper-K Collaboration

Bounds on LIV parameters with LBL Expt: DUNE, T2HK, and DUNE + T2HK

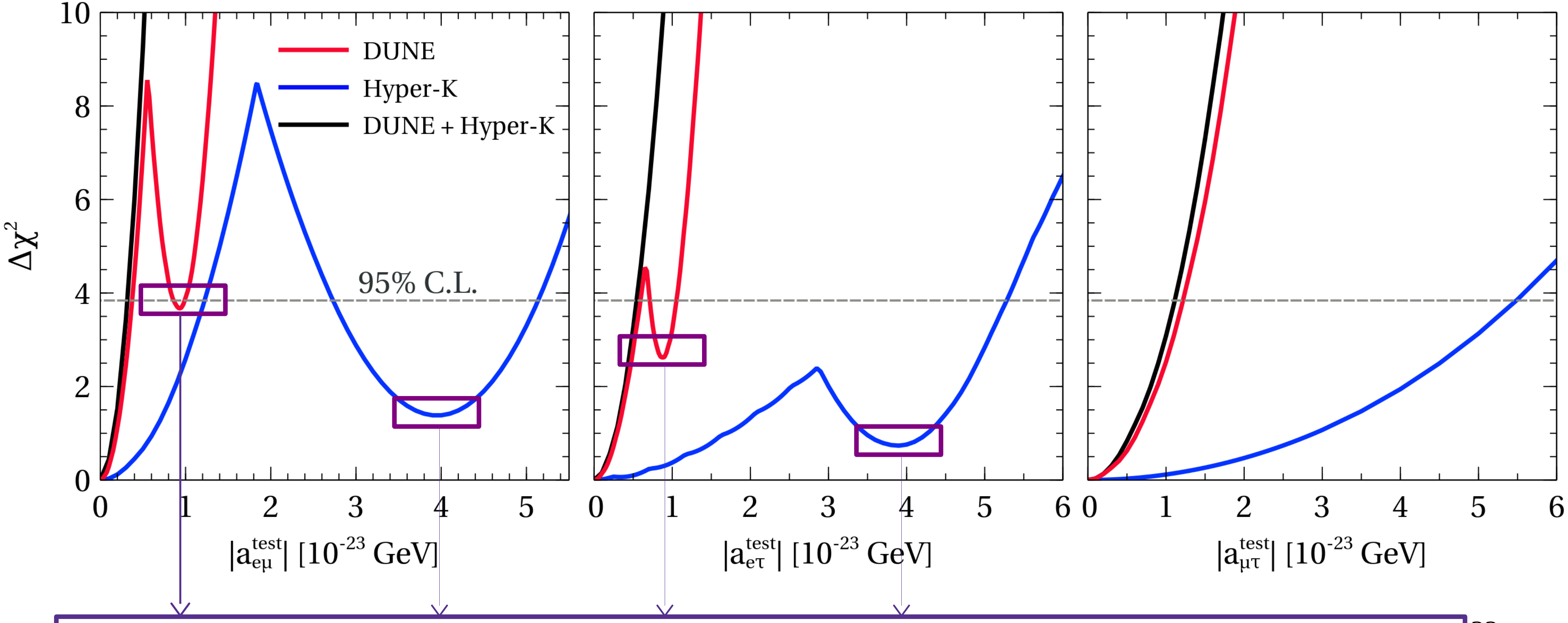
CPT-violating LIV off-diagonal parameters



Representation of LIV parameters as: $a_{\alpha\beta} = |a_{\alpha\beta}| \cdot e^{-i\Phi}$

Bounds on LIV parameters with LBL Expt: DUNE, T2HK, and DUNE + T2HK

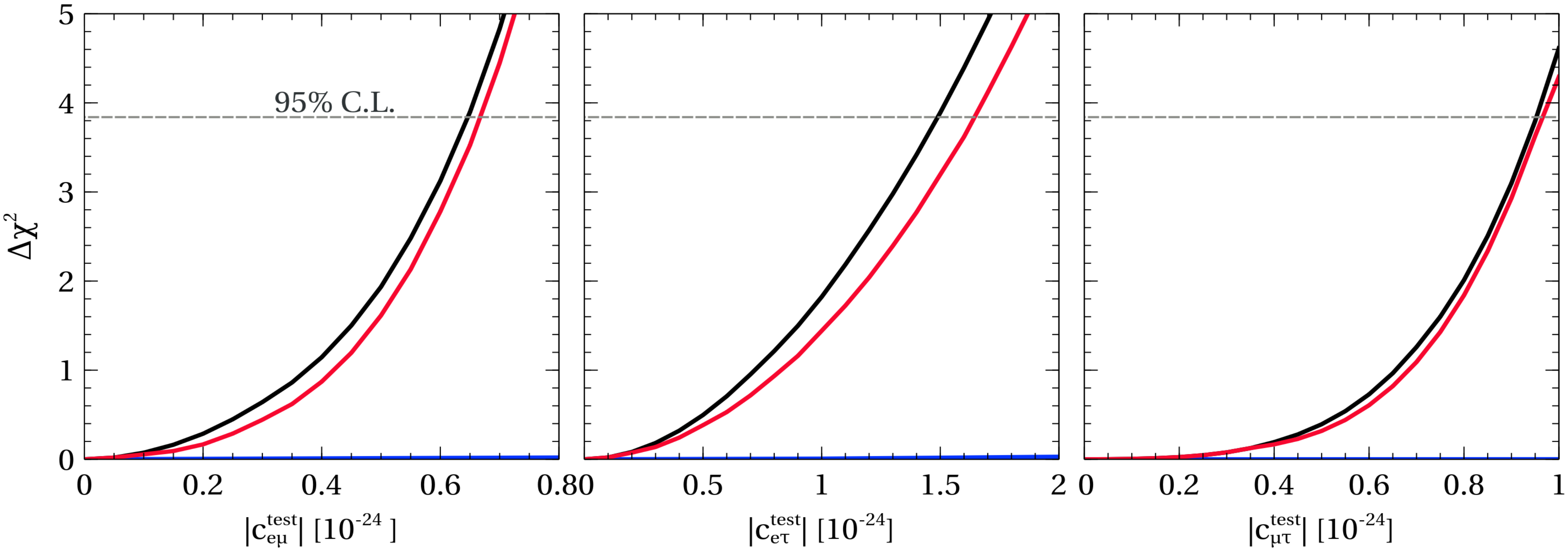
CPT-violating LIV off-diagonal parameters



Local Minima obtained due to degeneracy among θ_{23}, δ_{CP}, and $\Phi_{\alpha\beta}$

Bounds on LIV parameters with LBL Expt: DUNE, T2HK, and DUNE + T2HK

CPT-conserving LIV off-diagonal parameters



Representation of LIV parameters as: $c_{\alpha\beta} = |c_{\alpha\beta}| \cdot e^{-i\Phi}$

Bounds on LIV parameters with LBL Expt: DUNE, T2HK, and DUNE + T2HK

	DUNE	T2HK	DUNE+T2HK
$\lvert a_{e\mu}\rvert$ $[10^{-23}$ GeV$]$	< 1.0	< 5.15	< 0.32
$\lvert a_{e\tau}\rvert$ $[10^{-23}$ GeV$]$	< 1.05	< 5.3	< 0.55
$\lvert a_{\mu\tau}\rvert$ $[10^{-23}$ GeV$]$	< 1.26	< 5.5	< 1.1
$\lvert c_{e\mu}\rvert$ $[10^{-24}]$	< 0.66	< 17.1	< 0.64
$\lvert c_{e\tau}\rvert$ $[10^{-24}]$	< 1.65	< 71.1	< 1.49
$\lvert c_{\mu\tau}\rvert$ $[10^{-24}]$	< 0.97	< 42.4	< 0.95

arXiv: 2302.12005
S K Agarwalla, S Das, S Sahoo, and P Swain

Bounds on LIV parameters at 95% C.L. with 1 d.o.f

Summary & Remark

- The upcoming magnetised ICAL detector at INO can play a crucial role to establish three-flavour neutrino oscillation framework by observing atmospheric neutrino and antineutrino separately, in the multi-GeV energy range over a wide range of baselines.
- Using its excellent muon detection sensitivity, for an exposure of 500 kt·yr we calculate the expected limits on CPT-violating LIV parameters ($a_{\mu\tau}$, $a_{e\mu}$, $a_{e\tau}$), one-at-a-time at 95% C.L. (1 d.o.f), which is slightly better than the current Super-K limits.
- We calculate the expected limits on LIV parameters using the detector sensitivity of future long-baseline neutrino oscillation experiments: DUNE and T2HK.
- For the first time, we place the expected bounds on CPT-conserving LIV parameters using DUNE and T2HK detector sensitivities.
- We demonstrate that how the combined sensitivity of DUNE and T2HK would enhance the limits on LIV parameters.

Thanking You !!!

Back Up

INO-ICAL :

- NUANCE MC Generator using Neutrino Flux (Honda) at INO site
- Three-Flavour Oscillation Framework; PREM profile; 500 kt·yr (10 yr)
- Migration matrices from ICAL-Geant4 simulation [arXiv:1304.5115, 1405.7243]

Observable	Range	Bin width	Total bins	
$E_\mu^{\rm rec}$ (GeV)	$[1, 11]$	1	10	13
	$[11, 21]$	5	2	
	$[21, 25]$	4	1	
$\cos\theta_\mu^{\rm rec}$	$[-1.0, 0.0]$	0.1	10	15
	$[0.0, 1.0]$	0.2	5	
$E'^{\rm rec}_{\rm had}$ (GeV)	$[0, 2]$	1	2	4
	$[2, 4]$	2	1	
	$[4, 25]$	21	1	

Method of χ^2 Analysis:

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

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

$$N_{ijk}^{\text{theory}} = N_{ijk}^{0}\left(1 + \sum_{l=1}^{5} \pi_{ijk}^{l} \zeta_l\right);$$

$$\chi^2 = \chi^2_{-} + \chi^2_{+}$$

$$\Delta\chi^2 = \chi^2_{\text{std+liv}} - \chi^2_{\text{std}}$$

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

arXiv:1406.3689v1 (Moon Moon Devi, Tarak Thakore, Sanjib Kumar Agarwalla, Amol Dighe)