Exploring flavor-dependent long-range interactions in atmospheric neutrino oscillations at DeepCore

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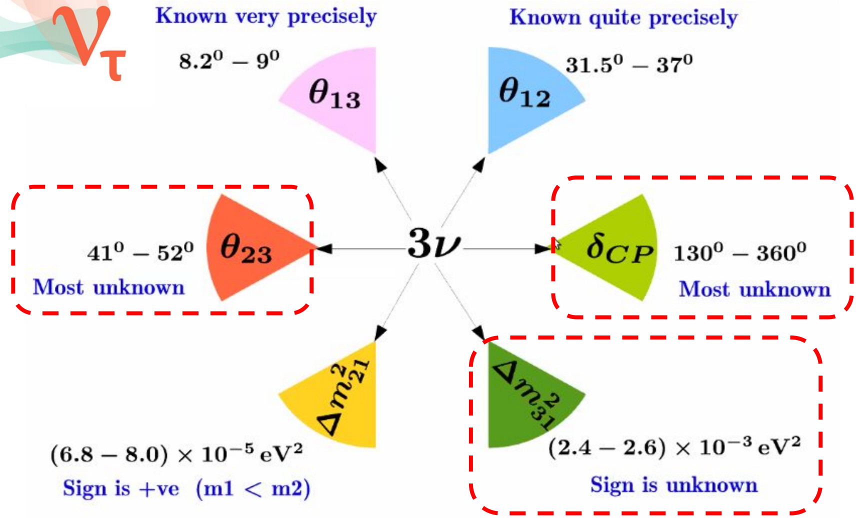
17th International Conference on Interconnections between Particle Physics and Cosmology

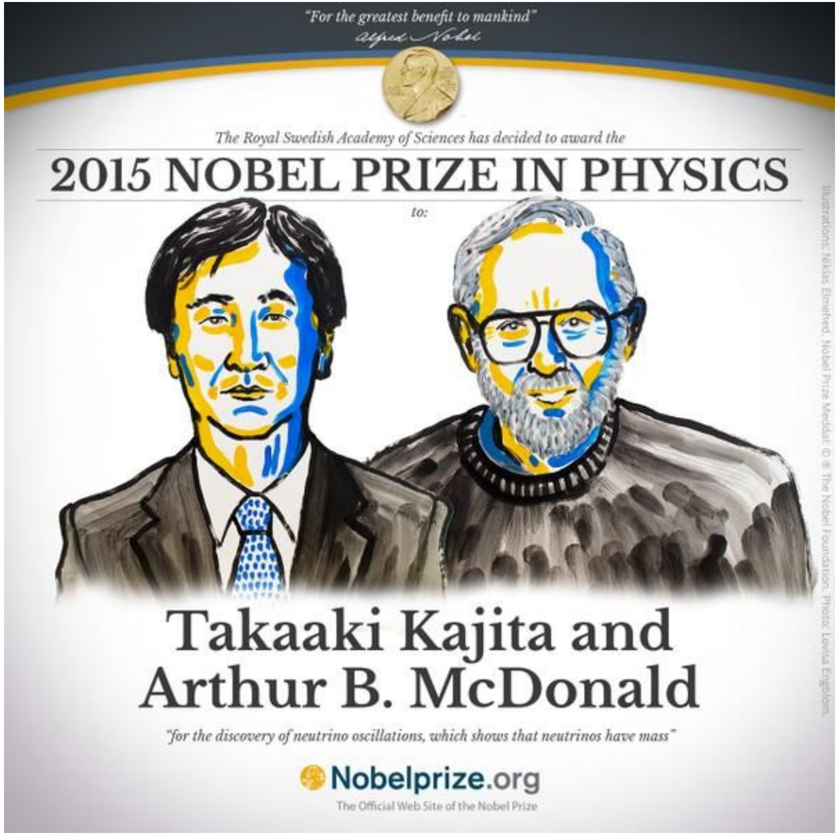
IIT Hyderabad, India

Department of Science & Technology, Government of India

IceCube Neutrino Observatory

Neutrino Flavor Oscillations





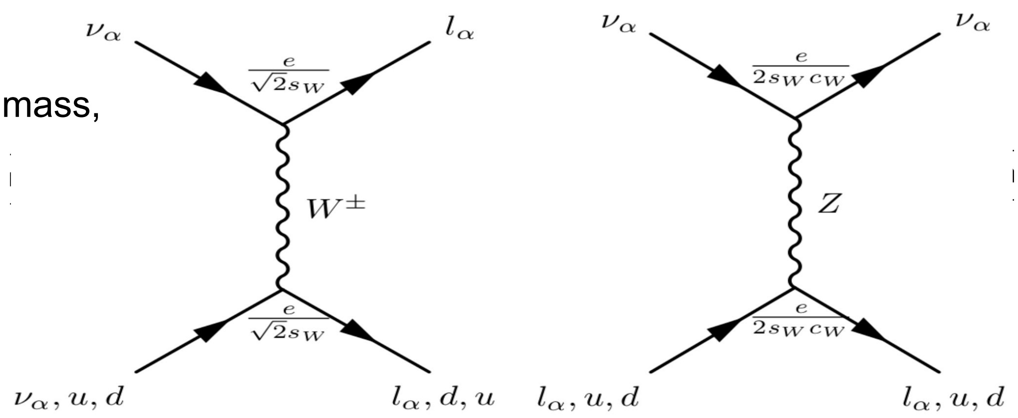
- Neutrino flavor changes as it propagates in space
- First experimental proof for existence of BSM physcis
- We have a great precision on oscillation parameters value
- Offers an unparallel window to probe subtle BSM scenarios

U(1)’ Extension of Standard Model (SM)

- Standard Model is a gauge theory based on,

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$$

- It requires extension to accommodate neutrino mass, mixing, baryon asymmetry, dark matter, etc.



U(1)' Extension of Standard Model (SM)

- Standard Model is a gauge theory based on,

  $$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$$

- It requires extension to accommodate neutrino mass, mixing, baryon asymmetry, dark matter, etc.

- It can be expanded by an additional U(1)' symmetry,

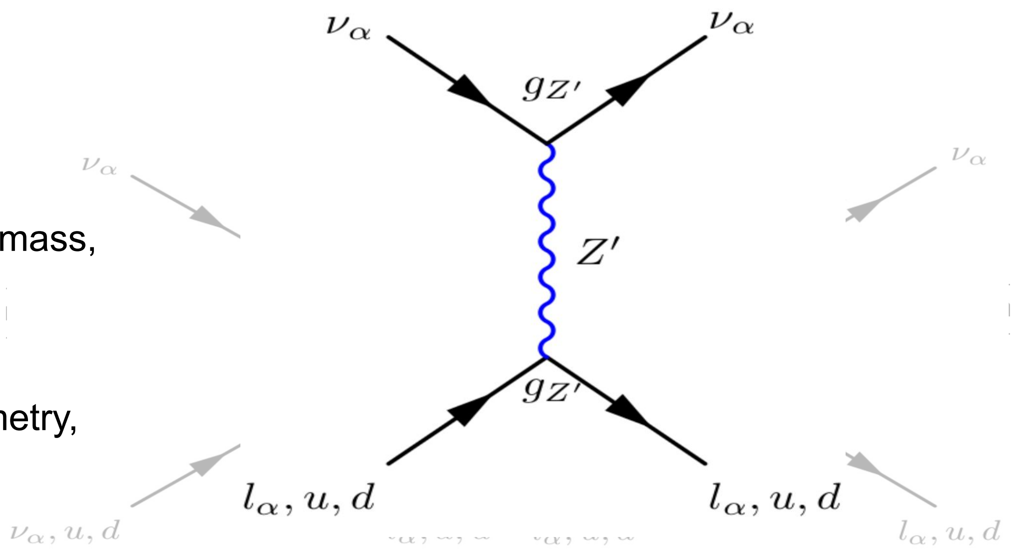
  $$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)'_X$$

  where, $X = L_e - L_\mu$ & $L_e - L_\tau$

- These are abelian flavor-dependent symmetries

- This model does not require any exotic particles

- These symmetries are sourced by the electrons



❖ M. Bustamante & S. K. Agarwalla, PRL122(2019)

❖ X.-G. He, G.C. Joshi, H. Lew, R. R. Volkas, PRD 43 R22 (1991)

❖ A. Khatun, T. Thakore, & S. K. Agarwalla, JHEP04(2018)023

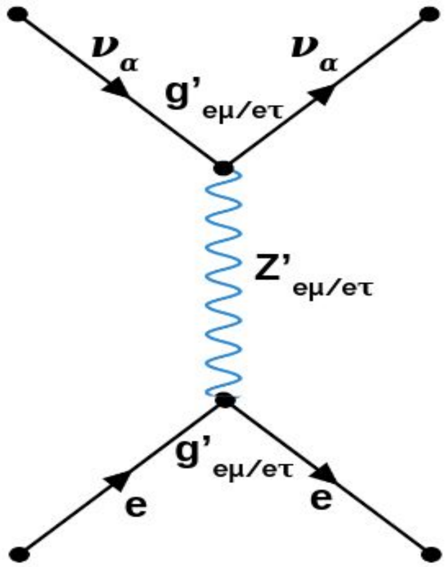
❖ S. S. Chatterjee, A. Dasgupta, S. K. Agarwalla, JHEP12(2015)167

❖ M. Singh, M. Bustamante, S. K. Agarwalla, JHEP08(2023)101

❖ S. K. Agarwalla, et. al, JHEP08(2023)113

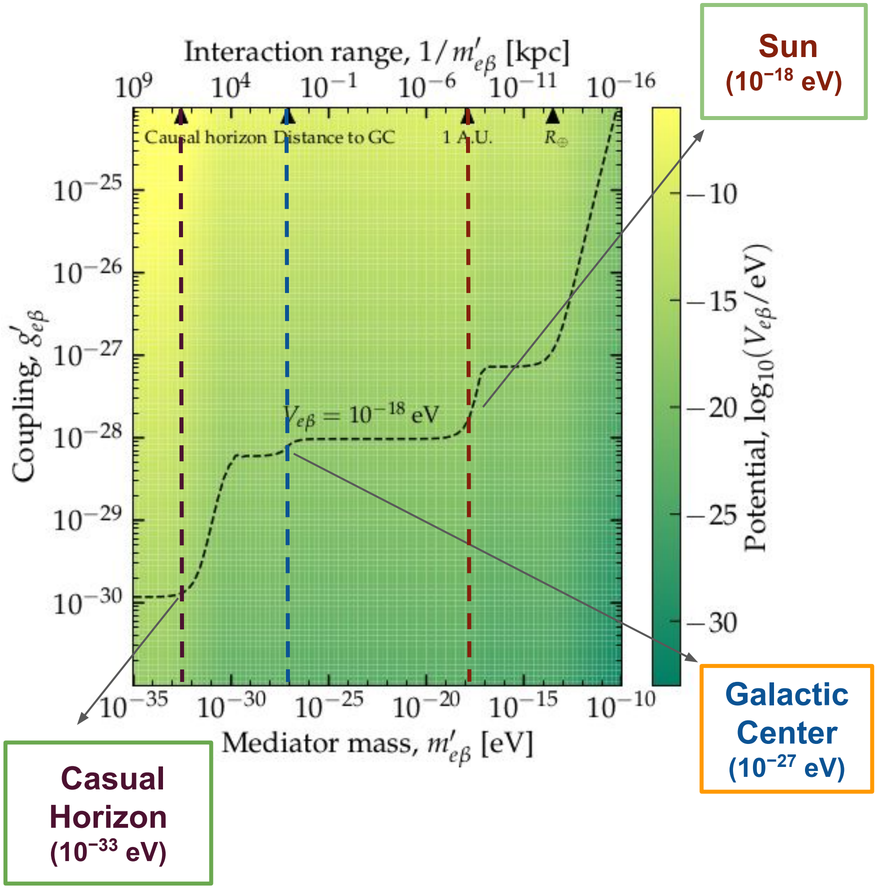
U(1)’ Extension of Standard Model (SM)

- $U(1)'_X$ must break down to accommodate neutrino mixing
- Only one symmetry can be gauged in an anomaly free way at a time
- Gives rise to an additional flavor-dependent neutral current interaction
- Interaction lagrangian, $\mathcal{L} = g' \bar{\psi} \gamma^{\alpha} Z'_{\alpha} \psi$
- Z' gauge boson may be very heavy or very light in nature
- Z’ can also act as a dark matter candidate
- A very light Z' gauge boson ($m_{Z'} \lesssim 10^{-18}$ eV) gives rise to leptonic
  flavor-dependednt Long Range neutrino interactions



Can we constrain / discover the flavor-dependent neutral current long-range interactions using neutrino oscillations in IceCube DeepCore?

Long-Range Interaction (LRI)



- Under $L_e - L_\beta$ ($\beta = \mu, \tau$) symmetry, a neutrino located at a distance d from a collection of N_e electrons experiences a Yukawa like potential,

$$V_{e\beta} = G'^2_{e\beta} \frac{N_e}{4\pi d} e^{-m'_{e\beta} d}$$

where $m'_{e\beta}$ is the mass of mediating $Z'_{e\beta}$ boson

- LRI strength depends on the electron content of the celestial objects within the interaction range d
- Step-like transitions in potential is due to the contributions from various sources at different distances

❖ M. Bustamante & S. K. Agarwalla, PRL122(2019)

Long-Range Interaction (LRI)

- The electrons inside the Sun can generate a flavor-dependent long-range potential $V_{e\mu / e\tau}$ at the Earth's surface which has the following form,

$$V_{e\mu/e\tau}(R_{SE}) = \alpha_{e\mu/e\tau} \frac{N_e^{\odot}}{R_{SE}} \approx 1.3 \times 10^{-14}\,\text{eV} \left(\frac{\alpha_{e\mu/e\tau}}{10^{-53}}\right)$$

where, $N_e^{\odot}$ denotes the total number of electrons ($\approx 10^{57}$) inside the Sun,

$\alpha_{e\mu/e\tau} = g^2_{e\mu/e\tau}/4\pi$ is the fine structure constant of the coupling,

R_{SE} is the Sun - Earth distance ($\approx 1.5 \text{ x } 10^{13}$ cm $= 7.6 \text{ x } 10^{26}$ GeV^{-1})

- LRI potential due to the Earth can be neglected safely as,

$$V_{e\mu/e\tau}(R_E) \approx 0.05\, V_{e\mu/e\tau}(R_{SE})$$

- We can neglect the contribution to LRI from earth's electron

❖ A. Khatun, T. Thakore, & S. K. Agarwalla, JHEP04(2018)023

LRI Hamiltonian

- The effective Hamiltonian for neutrino propagation in Earth matter in the flavor basis in presence of LRI,

$$H_f = U \begin{bmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} \end{bmatrix} U^\dagger + \begin{bmatrix} V_{CC} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} + \begin{bmatrix} \zeta & 0 & 0 \\ 0 & \xi & 0 \\ 0 & 0 & \eta \end{bmatrix}$$

Vacuum **Std. Matter** **V (LRI)**

- For L_e - L_μ symmetry, $\zeta = V_{e\mu}$, $\xi = -V_{e\mu}$ & $\eta = 0$

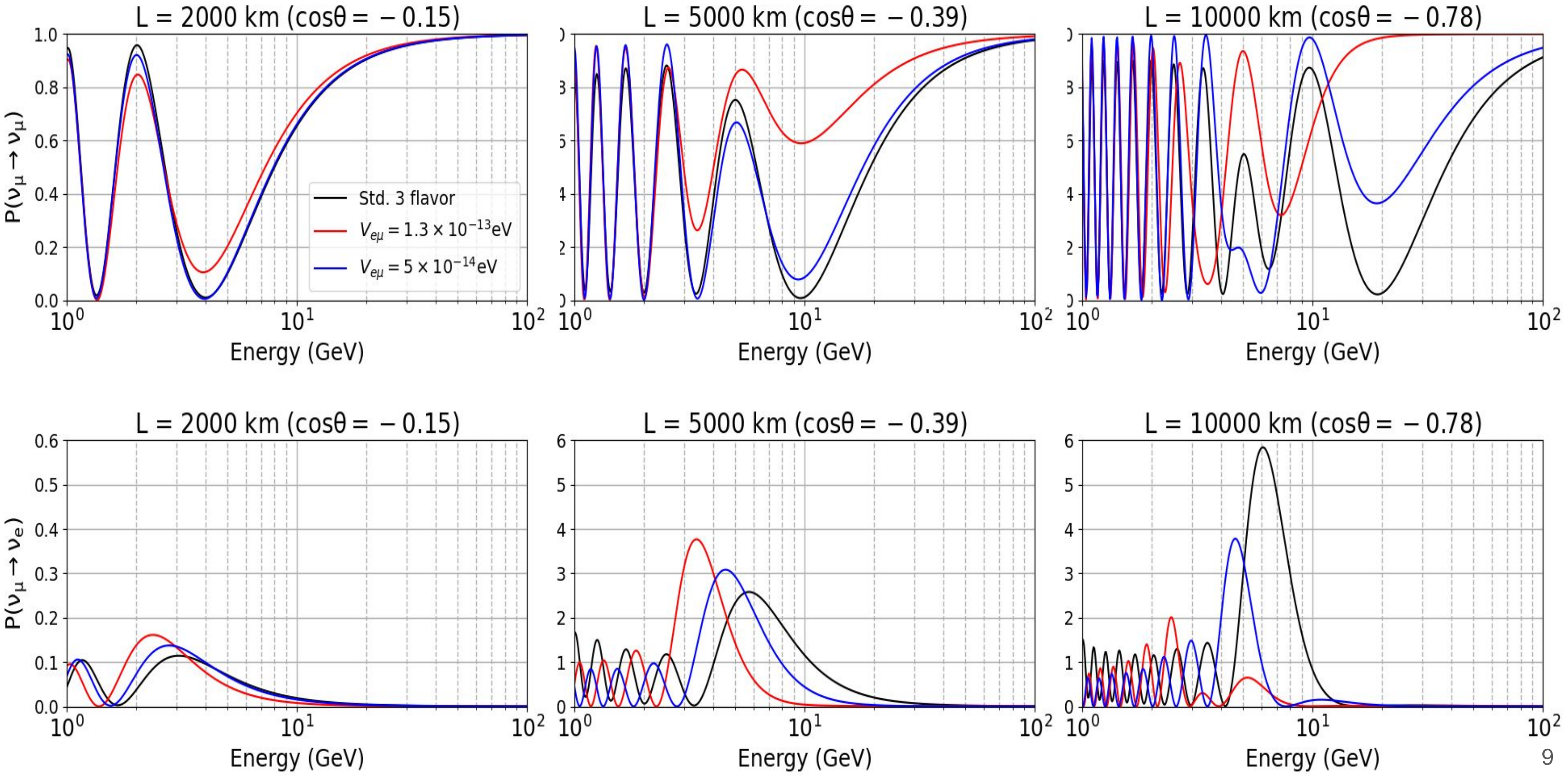
- For L_e - L_τ symmetry, $\zeta = V_{e\tau}$, $\xi = 0$ & $\eta = - V_{e\tau}$

$$V_{LRI} = \begin{cases} \text{Diag}\,(V_{e\mu}, -V_{e\mu}, 0) \\ \text{Diag}\,(V_{e\tau}, 0, -V_{e\tau}) \end{cases}$$

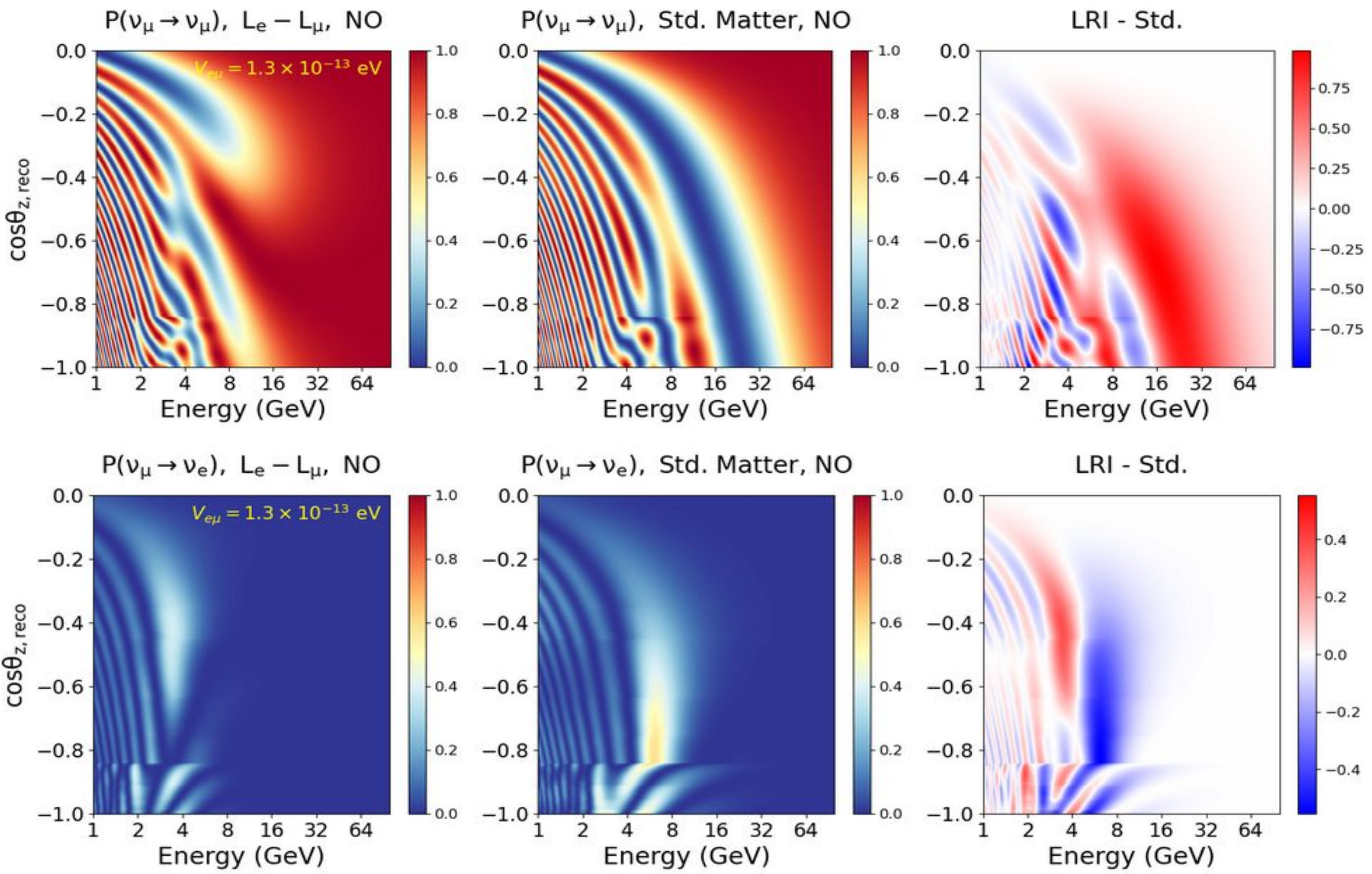
- For antineutrinos, V_{CC} & $V_{e\mu\,/\,e\tau}$ change their sign

- When $V_{e\mu/e\tau} \approx \Delta m^2_{31} / E \approx V_{CC} \approx 10^{-13}$ eV, its effect can be observed in atmospheric neutrino oscillations

Effect of $L_e - L_\mu$ on Oscillation Probabilities

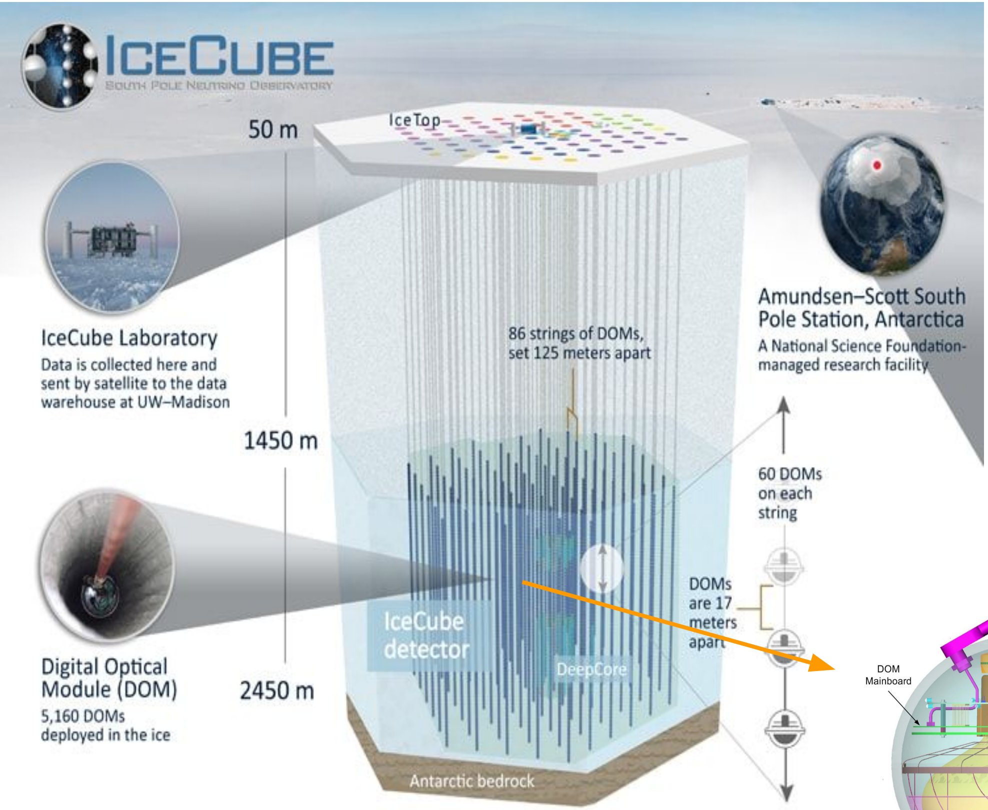


Effect of L_e - L_μ on Oscillograms

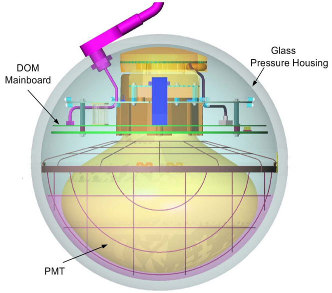


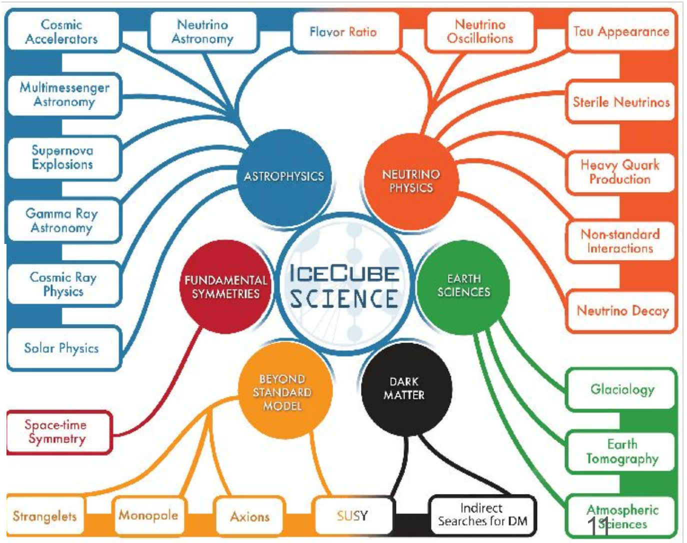
- $V_{e\mu} = 1.3 \times 10^{-13}$ eV
- Oscillation valley gets almost disappeared in presence of LRI
- Larger difference is at larger baseline and lower & intermediate energy region

IceCube Neutrino Observatory



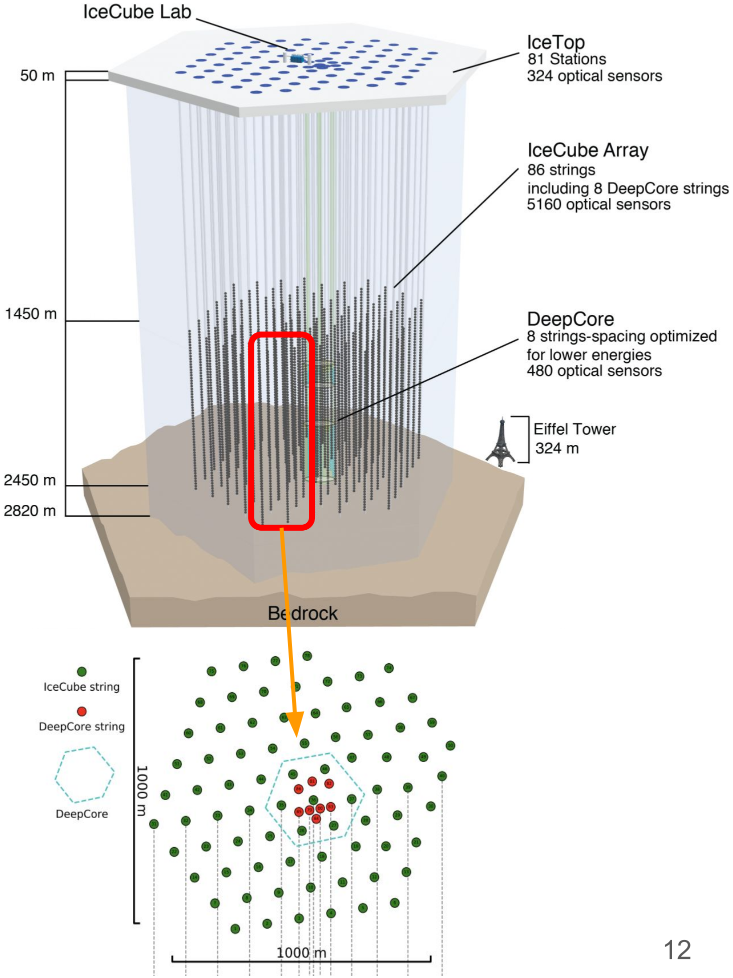
- $1\ \mathrm{km}^3$ neutrino observatory at South Pole
- Priory built for (> 100 GeV) high energy ν's
- ~100's / year astrophysical ν's
- 5160 DOMs on 86 vertical strings inside the ice



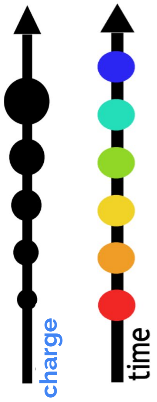


IceCube DeepCore

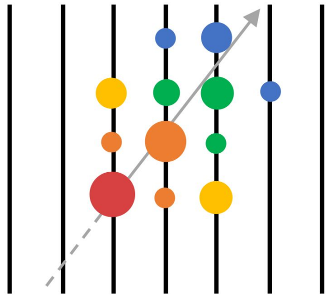
- Bottom central region of IceCube with 8 extra strings
- Large Fiducial volume → more number of events
- Denser spacing → reduces the threshold ~ few GeV
- Higher quality PMTs → better identification of events
- Improved angular resolution → better reconstruction
- For atmospheric neutrino oscillation studies
- To perform Earth’s tomography related studies
- Search for BSM scenarios like NSI, LRI, stetrile neutrino existence etc.
- To explore the diffuse and point source ν emission



Event Signatures at IceCube DeepCore

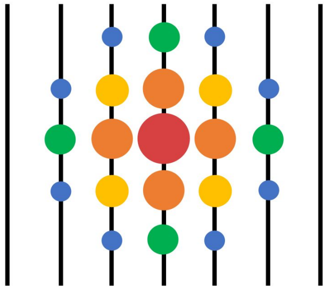


Track-like events

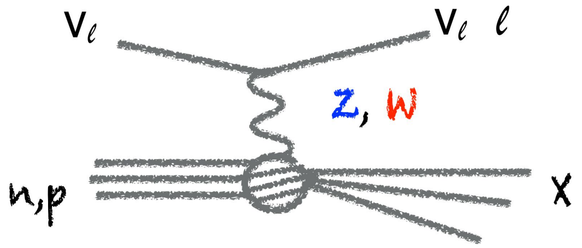


- Elongated track
- ν_μ CC

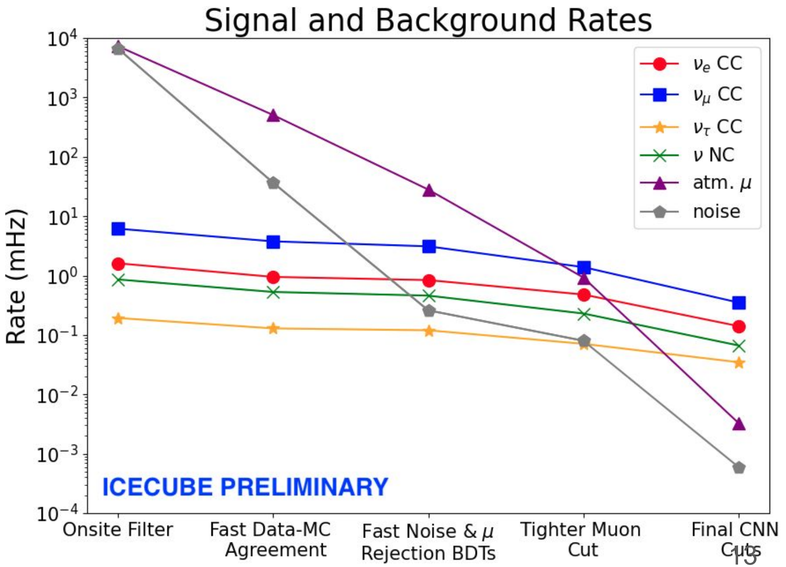
Cascade-like events



- Spherical shape
- ν_e CC, ν_τ CC, all NC

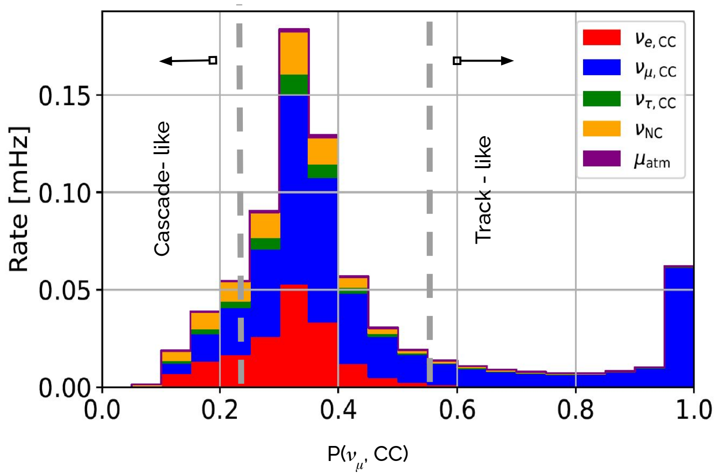


- CNN based reconstruction method
- 9.28 years of MC data sample (2012 - 2021)
- ~ 192k event statistics
- Various filters to eliminate noise and atm. μ contamination



Analysis Setup

Observables	No. of bins	Range	Step
Energy	12	[5, 100]	log
Zenith	10	[0, -1]	linear
PID	3	[0.0, 0.25,0.55,1]]	linear



Oscillation Param.	Nominal	Range	Fixed/Free
θ_{12}	33.41	[31.31, 35.74]	Fixed
θ_{13}	8.58	[8.19, 8.89]	Fixed
θ_{23}	47.5047	[38, 52]	Free
δ_{CP}	0	[0, 360]	Fixed
Δm^2_{21}	7.41e-05	[6.82e-05,8.03e-05]	Fixed
Δm^2_{31}	2.47467e-03	[0.001, 0.004]	Free

$$\chi^2_{\text{mod}} = \sum_{i \in \text{bins}} \frac{(N_i^{\text{exp}} - N_i^{\text{obs}})^2}{N_i^{\text{exp}} + (\sigma_i^{\text{exp}})^2} + \sum_{j \in \text{syst}} \frac{(s_j - \hat{s_j})^2}{\sigma_{s_j}^2}$$

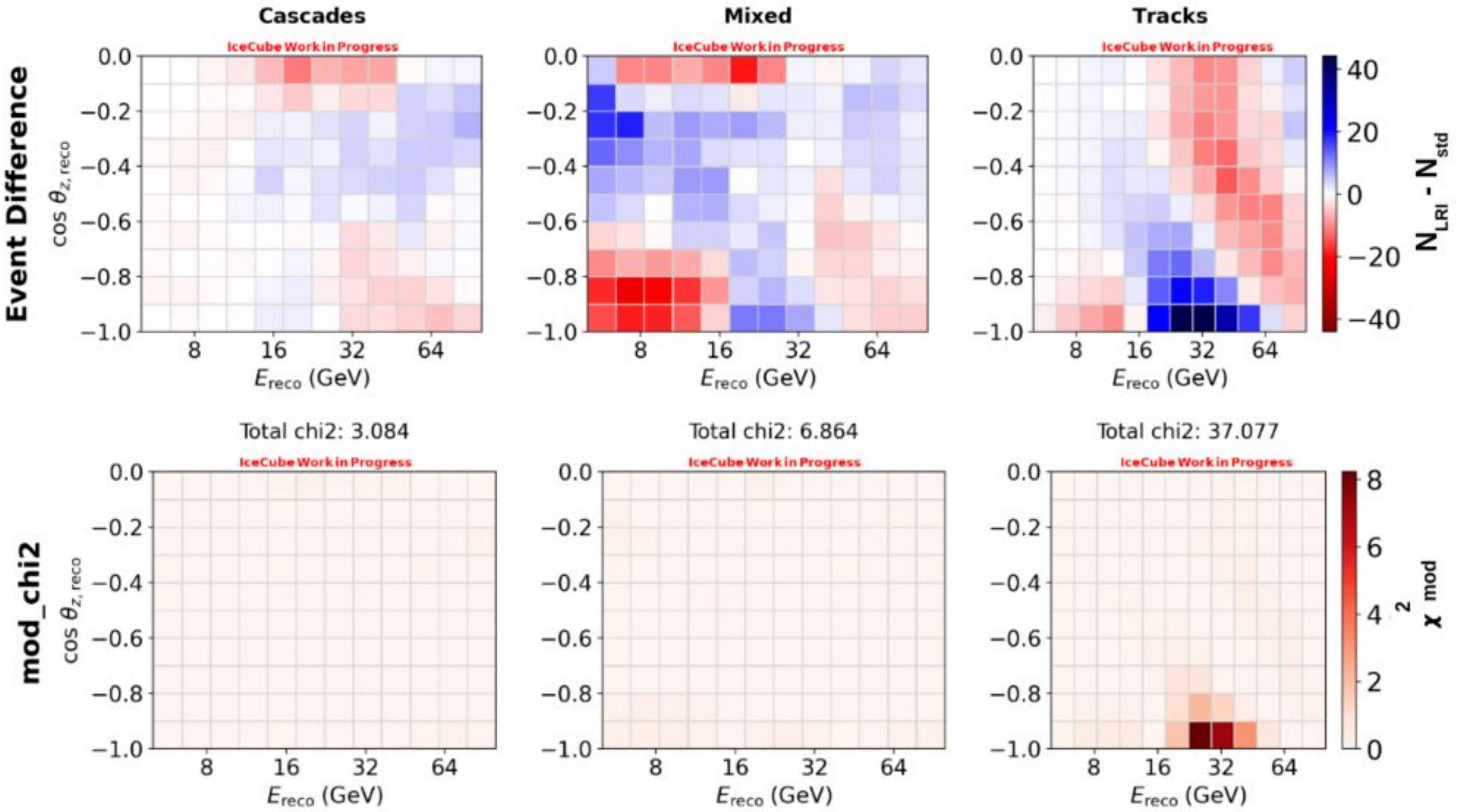
$$\Delta\chi^2 = \min_{\{sys\}} [\chi^2 (\text{SM} + \text{LRI}) - \chi^2 (\text{SM})]$$

Systematic Uncertainties

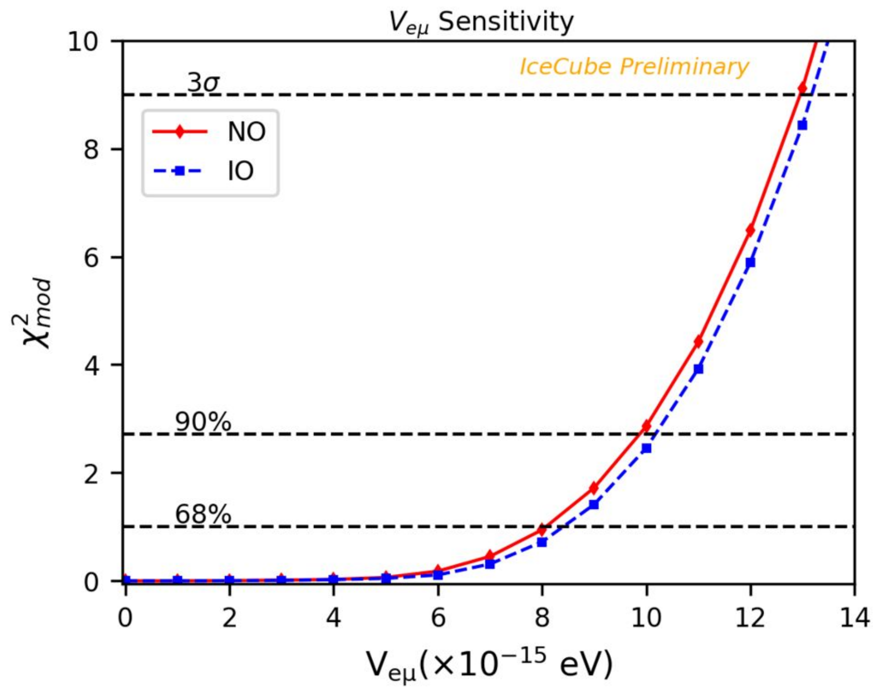
- **Honda flux uncertainties**
  - Cosmic ray spectrum
  - Pion & Kaon production uncertainties
- **Osc parameters uncertainties**
  - θ_{23} & Δm^2_{31} uncertainty
- **Cross section uncertainties**
  - Axial mass uncertainty for resonance and quasielastic events
  - GENIE - CSMS transition for DIS
- **Detector and Ice uncertainties**
  - Optical efficiency of the photo sensor
  - Ice scattering and absorption
  - Birefringence (double refraction of light due to anisotropy of ice)
  - Muon Light Yield (photon propagation in the ice from muons)
- **Atmospheric muon scale**
- **Neutrino event counts normalization**

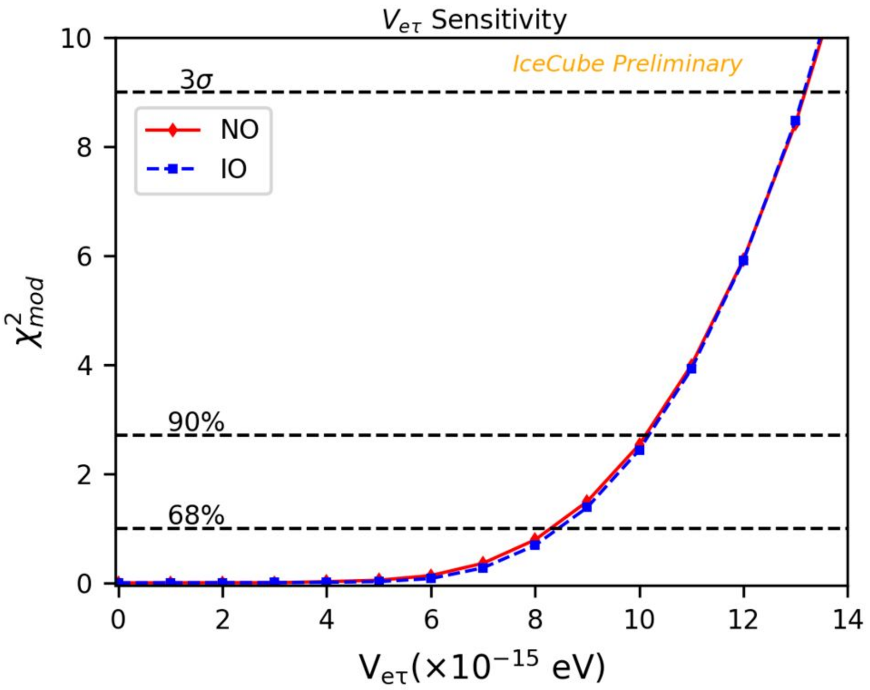
❖ Phys.Rev.D 108 (2023) 1, 012014

Simulated Event difference and χ^2 Distribution for L_e - L_μ



Sensitivity Results





- **MC Data :** SI ($V_{LRI} = 0$)
- **Test :** SI + LRI
- Minimizing over systematic parameters

	68% C.L.	90% C.L.
$V_{e\mu}$(x 10^{-15} eV)	8.03	9.82
$V_{e\tau}$(x 10^{-15} eV)	8.05	10.12

Present Experimental Bounds on LRI

Experiment	Bounds on LRI Potential $V_{e\mu\,/\,e\tau}$ (eV)	Reference
Super-Kamiokande*	$V_{e\mu} < 5.5 \times 10^{-13}$ (90% CL) $V_{e\tau} < 6.4 \times 10^{-13}$ (90% CL)	A. Joshipura & S. Mohanty PLB 584 (2004)
Solar + KamLAND*	$V_{e\mu} < 4.4 \times 10^{-14}$ (3σ) $V_{e\tau} < 3.3 \times 10^{-14}$ (3σ)	A. Bandyopadhyay, A. Dighe, & A. S. Joshipura PRD 75 093005 (2007)
IceCube DeepCore**	$V_{e\mu} < 0.98 \times 10^{-14}$ (90% CL) $V_{e\tau} < 1.01 \times 10^{-14}$ (90% CL)	Present work sensitivity**

- * These results are not from the collaborations rather an independent study with various approximations like $\theta_{13} = 0$ & $\theta_{23} = 45$
- **** First full-fledged LRI analysis from any collaboration in the context of neutrino oscillations**

Take Home Messages

- The huge statistics of DeepCore allows us to identify subtle deviation from the Standard Model.
- We are exploring the U(1)’ symmetry using DeepCore data sample.
- For the first time, we are showing that DeepCore has the ability to constrain the Long range interactions.
- We can put the best constrain using the DeepCore’s 9.28 years of low energy data sample.

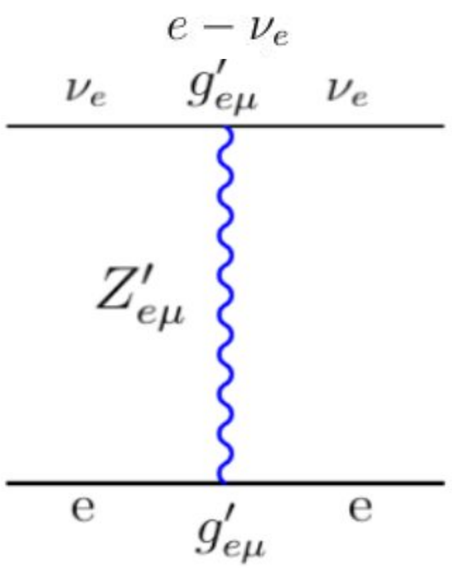
Thank you !

Backup slides

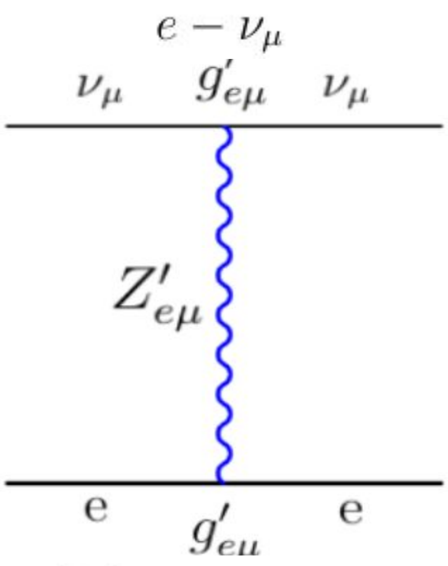
Effective Neutrino-Matter Interactions

- U(1)' Lagrangian for propagation in ordinary matter has the most general form,

$$\mathrm{L}_{Z'}^{matter} = -g'\left(a_u\,\bar{u}\gamma^\alpha u + a_d\,\bar{d}\gamma^\alpha d + a_e\,\bar{e}\gamma^\alpha e + b_e\,\bar{\nu}_e\gamma^\alpha P_L\nu_e + b_\mu\,\bar{\nu}_\mu\gamma^\alpha P_L\nu_\mu + b_\tau\,\bar{\nu}_\tau\gamma^\alpha P_L\nu_\tau\right)Z'_\alpha$$

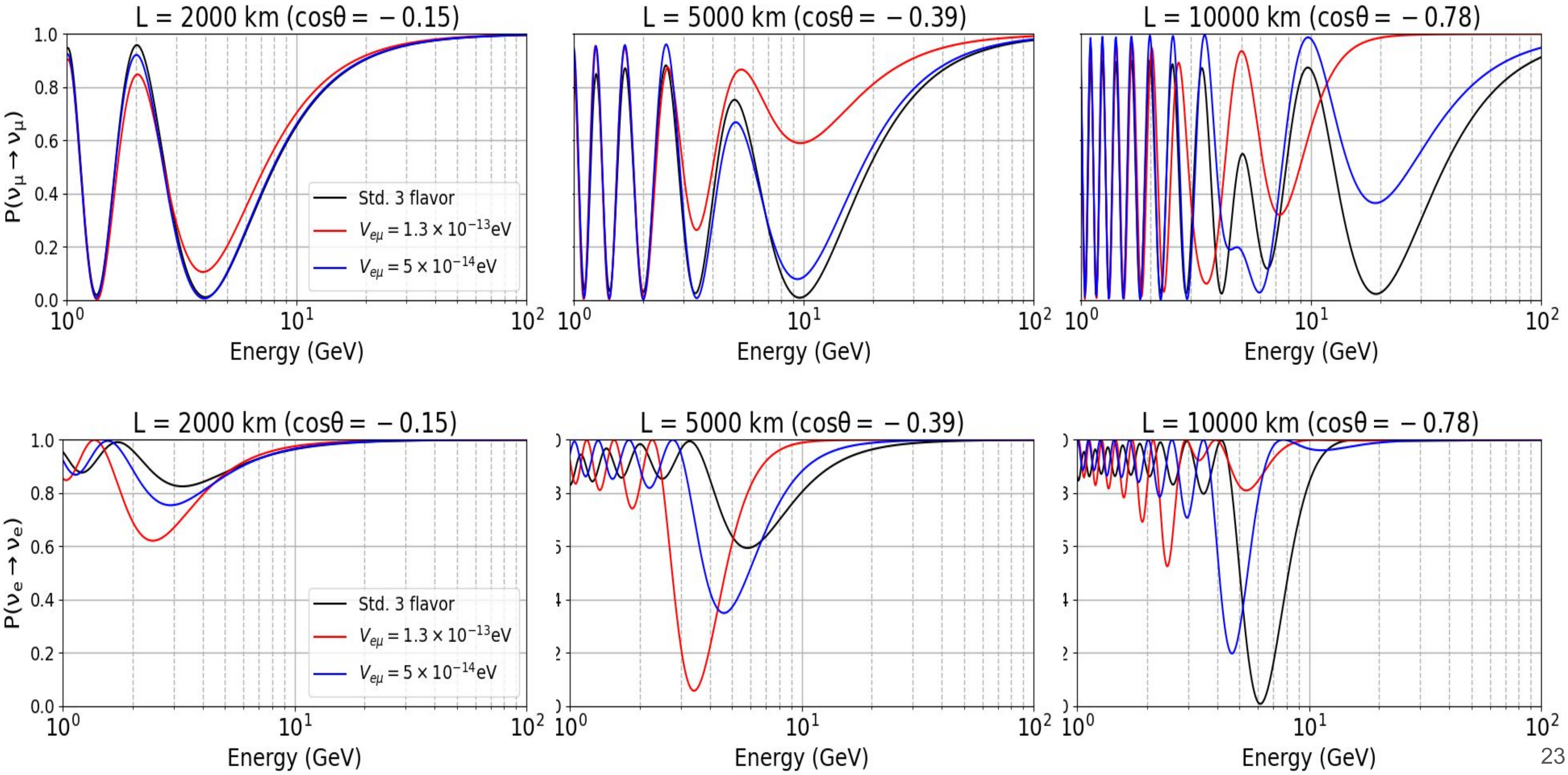


$$\mathcal{L}_{Z'} = g'_{e\mu}(\bar{e}\gamma^\alpha e + \bar{\nu}_e\gamma^\alpha P_L\nu_e)Z'_\alpha$$

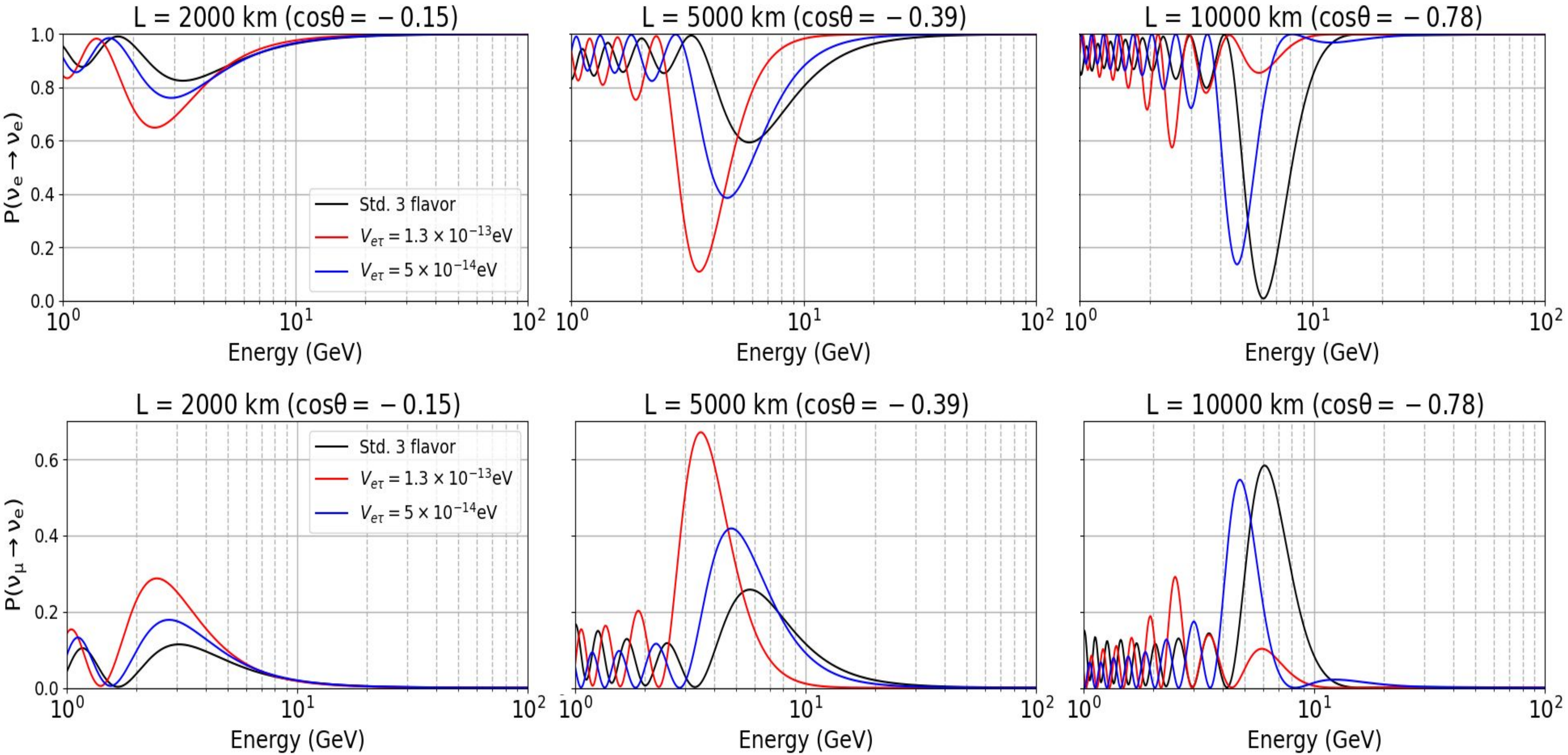


$$\mathcal{L}_{Z'} = g'_{e\mu}(\bar{e}\gamma^\alpha e - \bar{\nu}_\mu\gamma^\alpha P_L\nu_\mu)Z'_\alpha$$

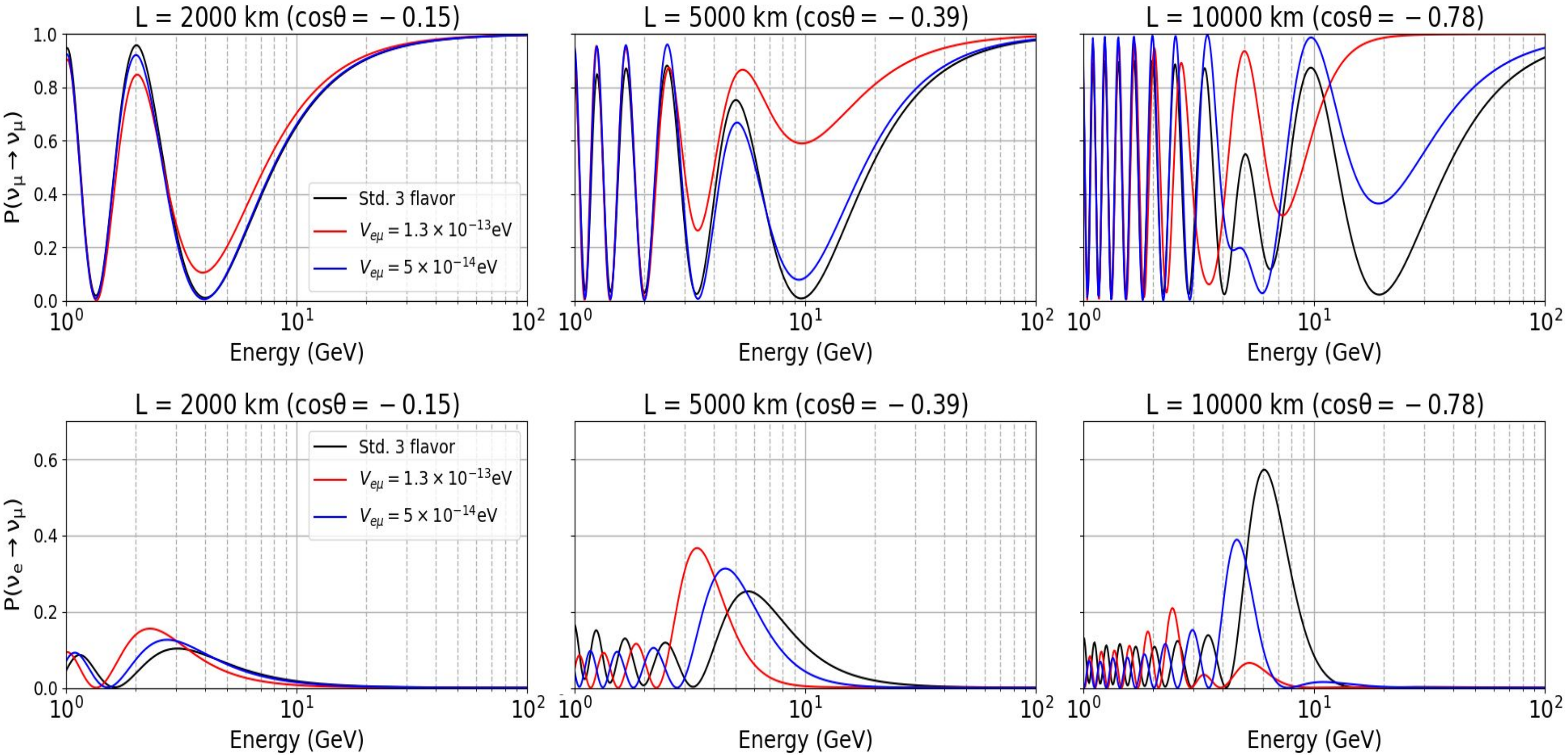
Effect of $L_e - L_\mu$ on Oscillation Probabilities



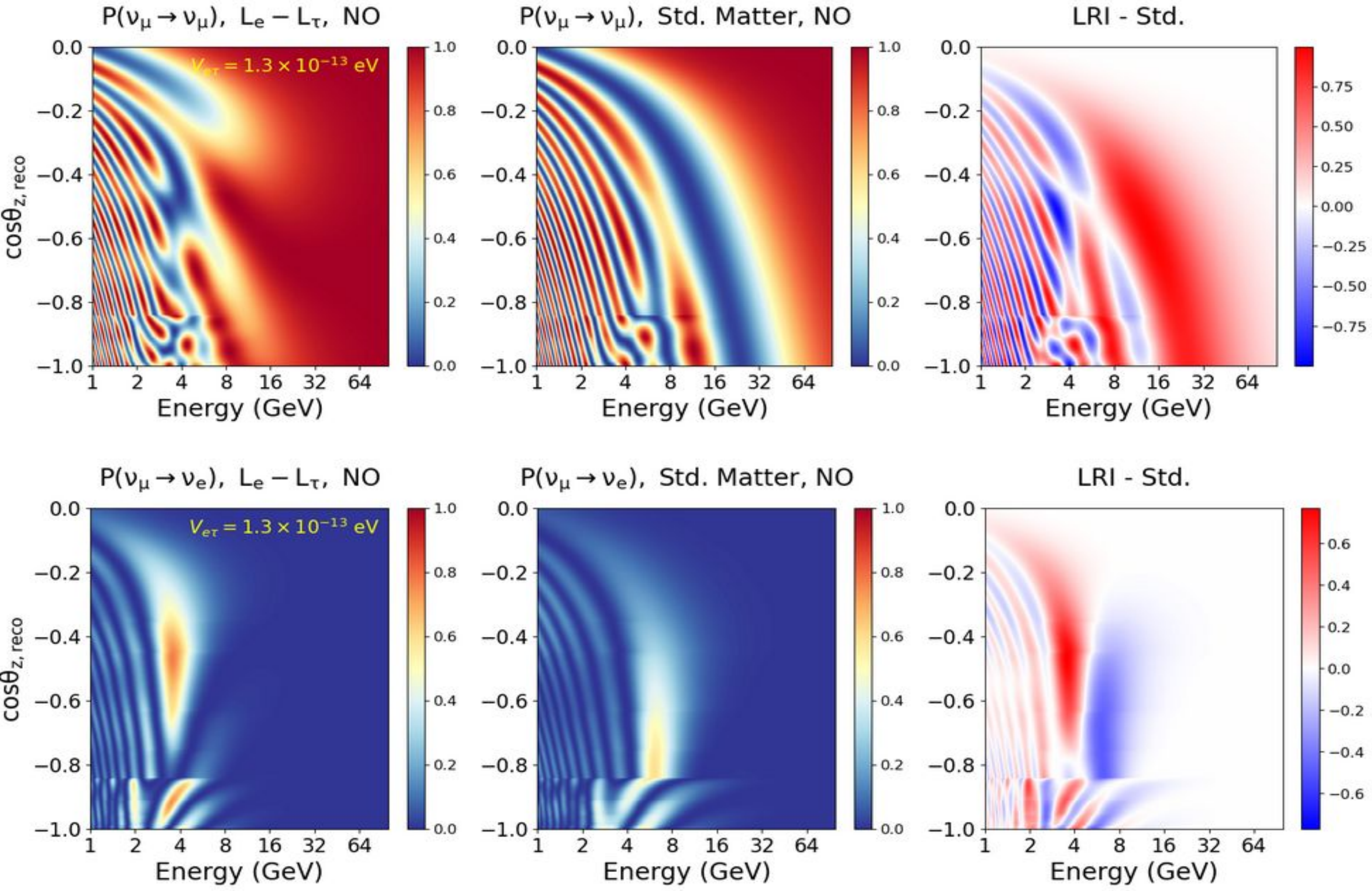
Effect of $L_e - L_\tau$ on Oscillation Probabilities (cascade-like)



Effect of $L_e - L_\tau$ on Oscillation Probabilities (track-like)

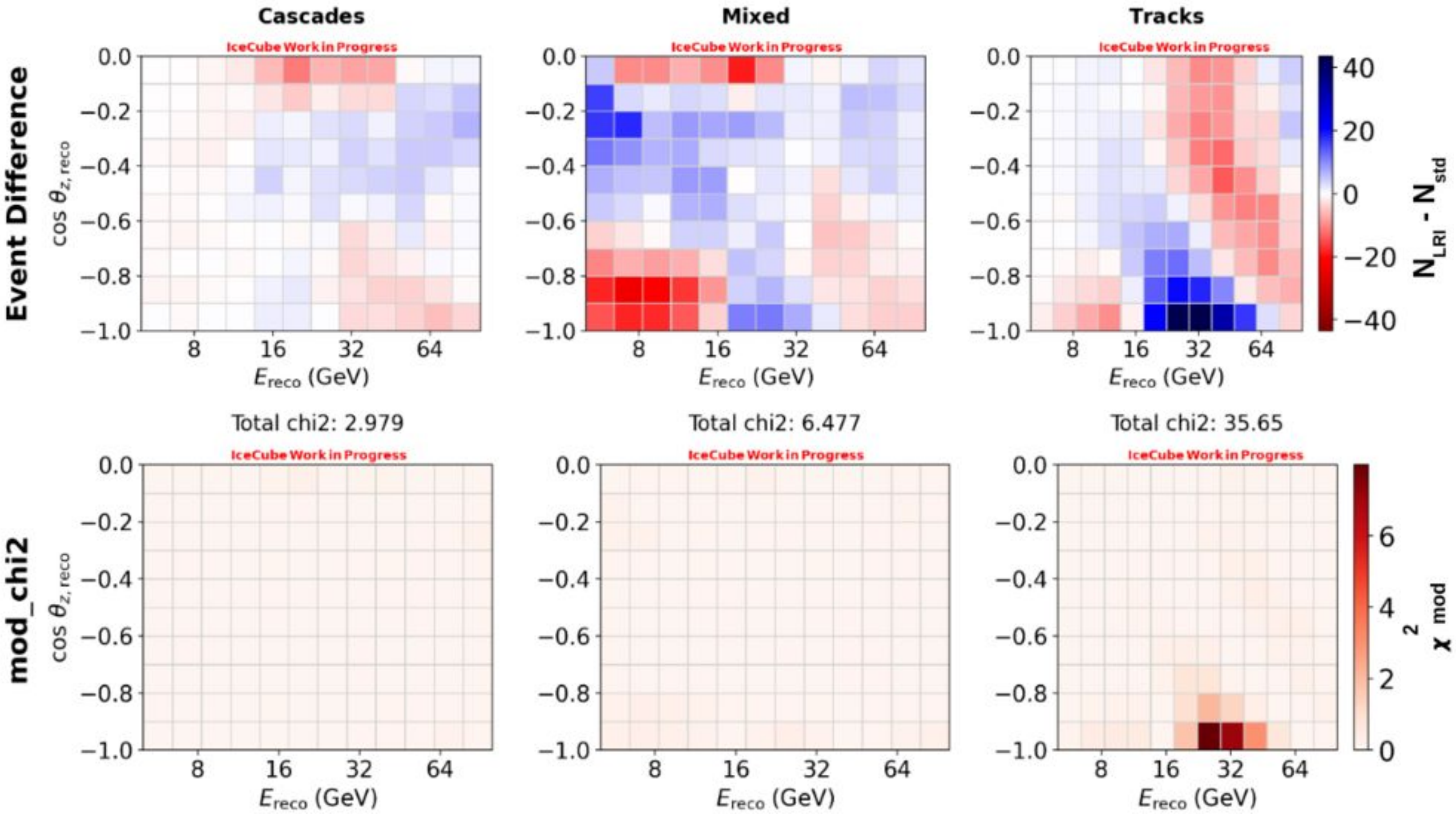


Effect of $L_e - L_\tau$ on Oscillograms

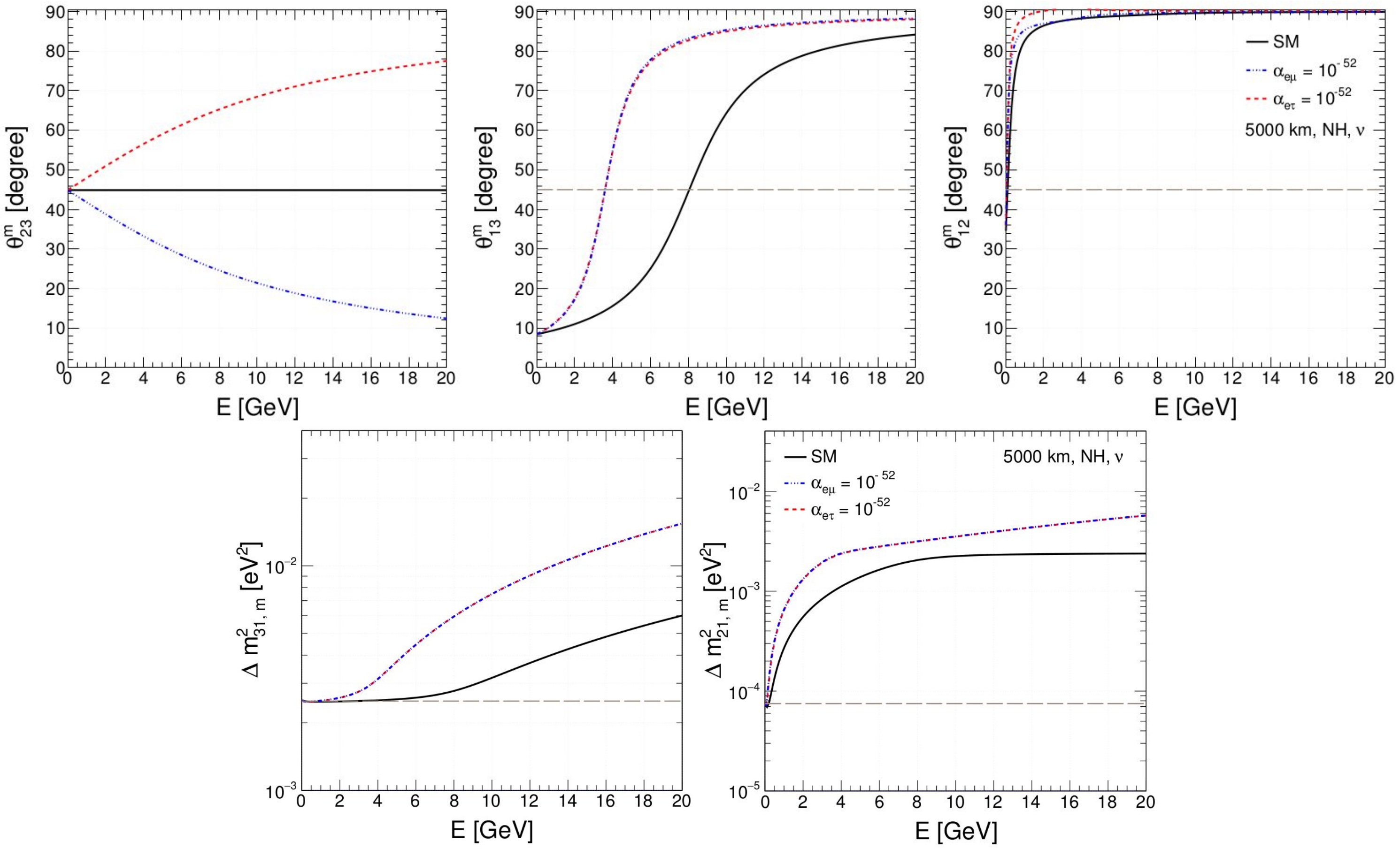


- $V_{e\tau} = 1 \times 10^{-13}$ eV
- Again the oscillation valley gets almost disappeared in presence of LRI
- Both the symmetries have different impacts on both the channels

Simulated Event difference and χ^2 Distribution for $L_e - L_\tau$



Effect of LRI on Oscillation Parameters



❖ A. Khatun, T. Thakore, & S. K. Agarwalla, JHEP04(2018)023