First Constraints on Long-Range Neutrino Interactions using IceCube DeepCore

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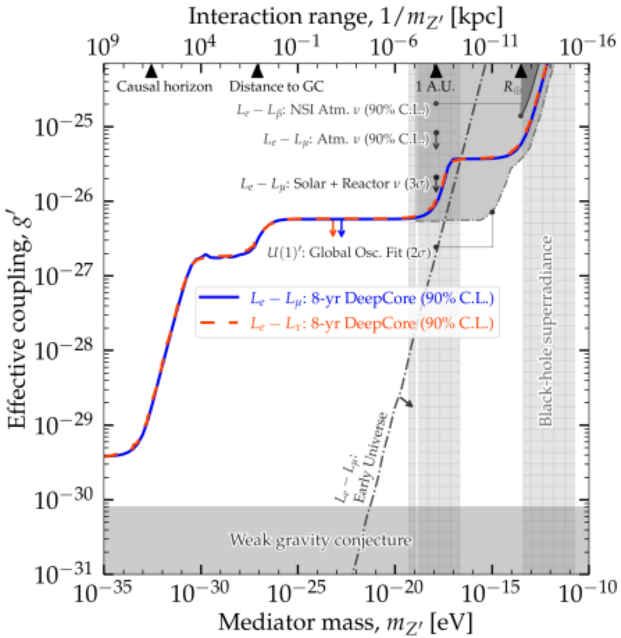
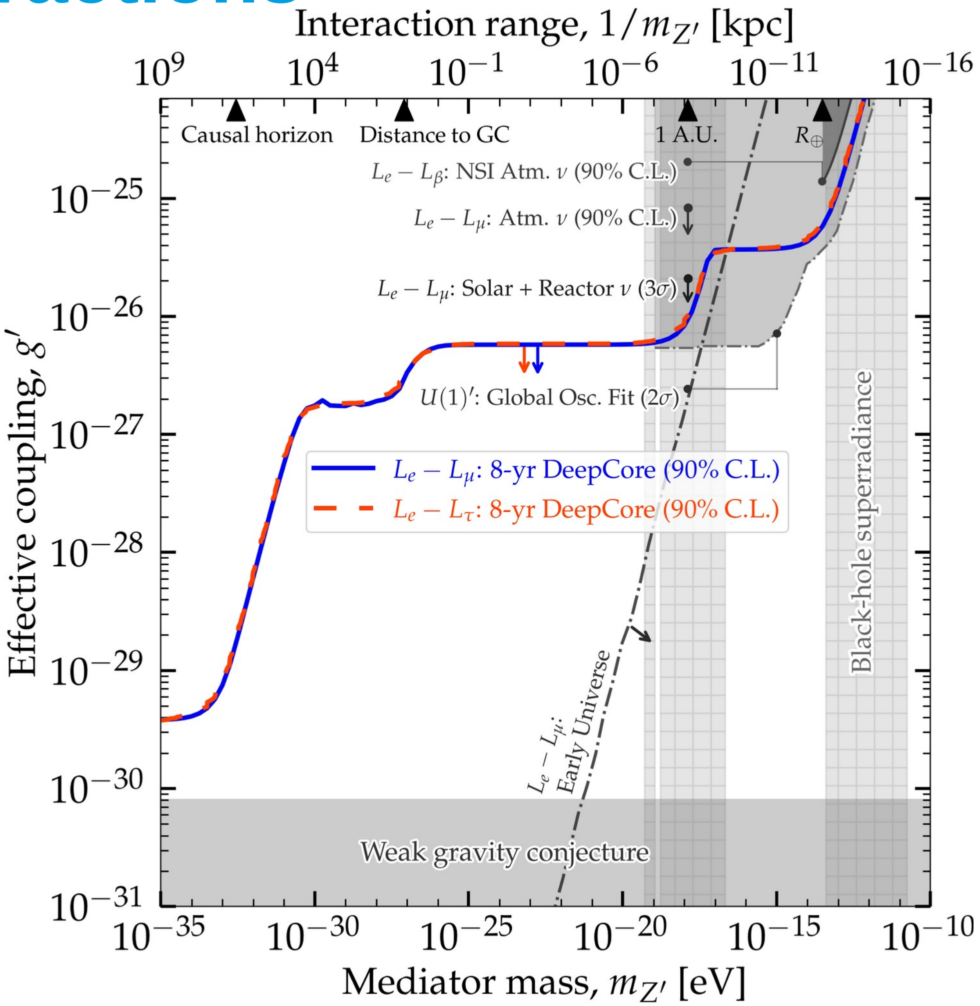
We present the first search for new flavor-dependent long-range interactions (LRI) of neutrinos using publicly available 8 years of high-purity ν_μ CC data from IceCube DeepCore. These interactions are mediated by ultra-light gauge bosons with masses below 10^{-10} eV, which can arise due to a new lepton-number gauge symmetry, such as $L_e - L_\mu$ or $L_e - L_\tau$. These long-range interactions induce matter potential between neutrinos and abundant electrons present in distant astrophysical sources. These LRI potentials could modify neutrino oscillation probabilities. By probing the effects of LRI on atmospheric neutrino oscillations at IceCube DeepCore, we place world-leading constraints on the coupling strength of these interactions.

Introduction.— The discovery of neutrino oscillations [1–5] established that neutrinos possess nonzero masses and undergo flavor mixing, highlighting the need for an extension of the Standard Model (SM) of particle physics. This makes neutrinos a unique probe to search for potential signatures of physics beyond the Standard Model (BSM). A broad class of proposed BSM models predicts new flavor-dependent interactions for leptons. Since neutrinos with different flavors experience these interactions differently, the oscillation patterns get modified, which can be seen in neutrino oscillation experiments. Over the years, various neutrino experiments have investigated the possibility of such BSM interactions and placed limits on their coupling strengths, including studies with atmospheric [6, 7], solar and reactor [8–10], long-baseline [11–15], astrophysical neutrinos [16, 17], as well as with their combinations [18–24]. Also, there are other complementary constraints on these BSM interactions from phenomena not involving neutrinos [25–30]. In this letter, we use weakly interacting neutrinos produced in the atmosphere of Earth to search for such lepton flavor-dependent BSM interactions. These atmospheric



Long-Range Neutrino Interactions

- Long-range interactions (LRI) of neutrinos
- Mediated by a new neutral vector boson
- Test the possibility of LRI and put the bound on mass-coupling of the gauge boson
- Use 8 years of publicly available IceCube DeepCore data



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

- Standard Model is a gauge theory based on,

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

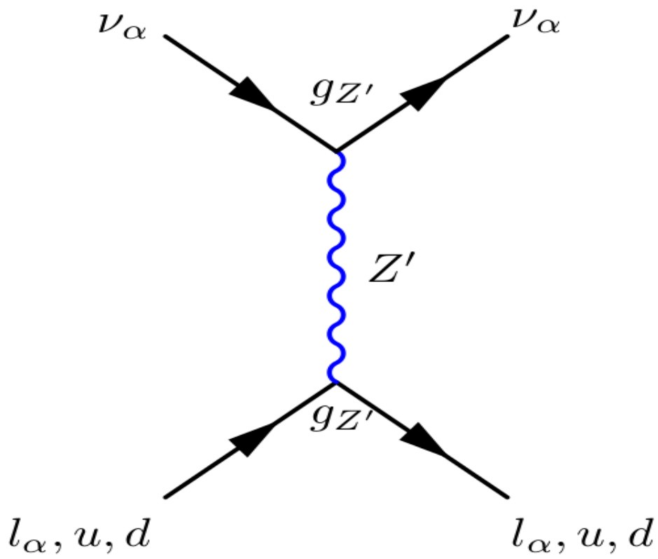
- It requires an extension to accommodate unexplained issues such as neutrino mass, baryon asymmetry, dark matter, etc.

- One possible way to expand it, is by an additional U(1)' symmetry,

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

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)

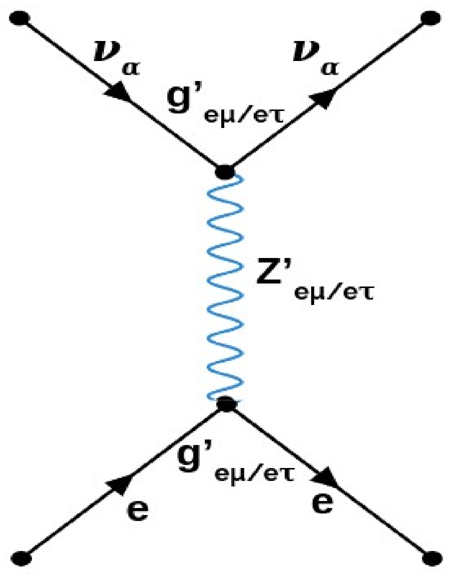
❖ A. Khatun, T. Thakore, & S. K. Agarwalla, JHEP04(2018)023

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

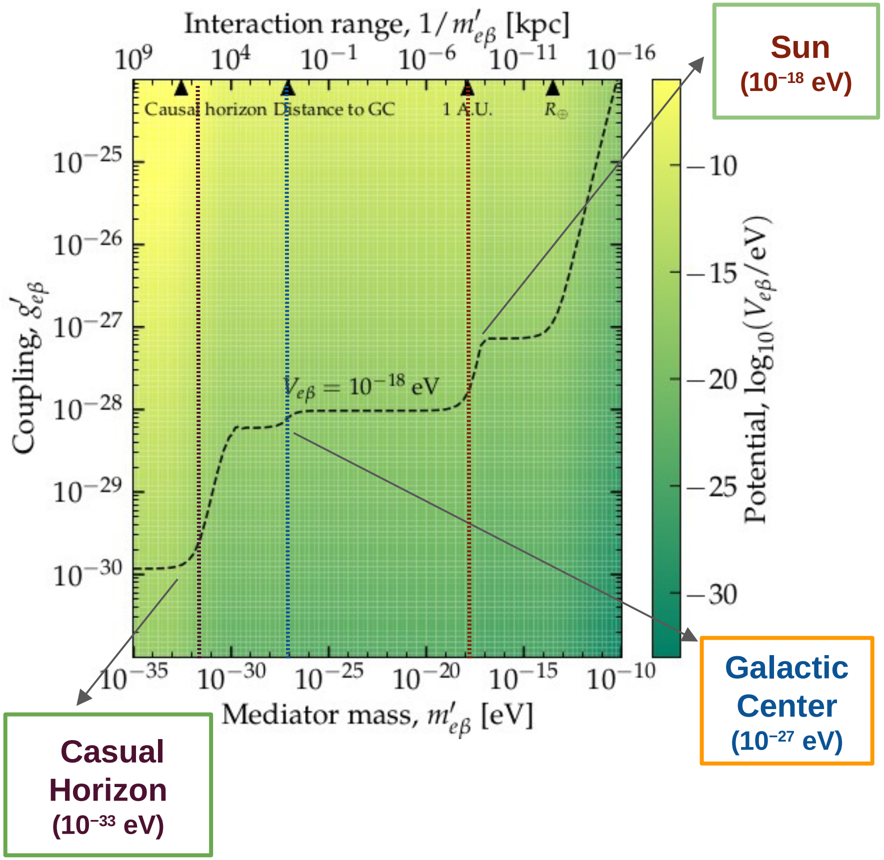
❖ S. K. Agarwalla, et. al, JHEP08(2023)113

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

- Out of L_e- L_μ & L_e- L_τ, only one symmetry can be gauged in an anomaly free way at a time
- An additional flavor-dependent neutral current interaction
- Z' may be very heavy or very light in nature
- A very light Z' gauge boson ($m_{Z'} \lesssim 10^{-18}$ eV) gives rise to leptonic **flavor-dependednt Long Range neutrino interactions**



Long-Range Interaction (LRI)



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

- 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,

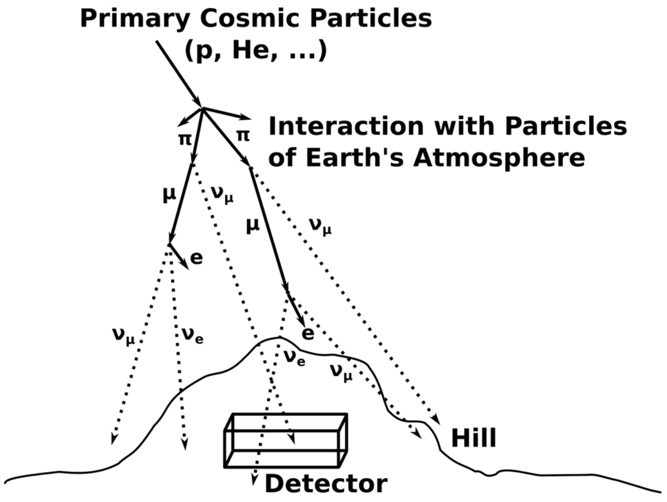
$$V_{e\beta} = G'^2_{e\beta} \frac{N_e}{4\pi d} e^{-m'_{e\beta} d}$$

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

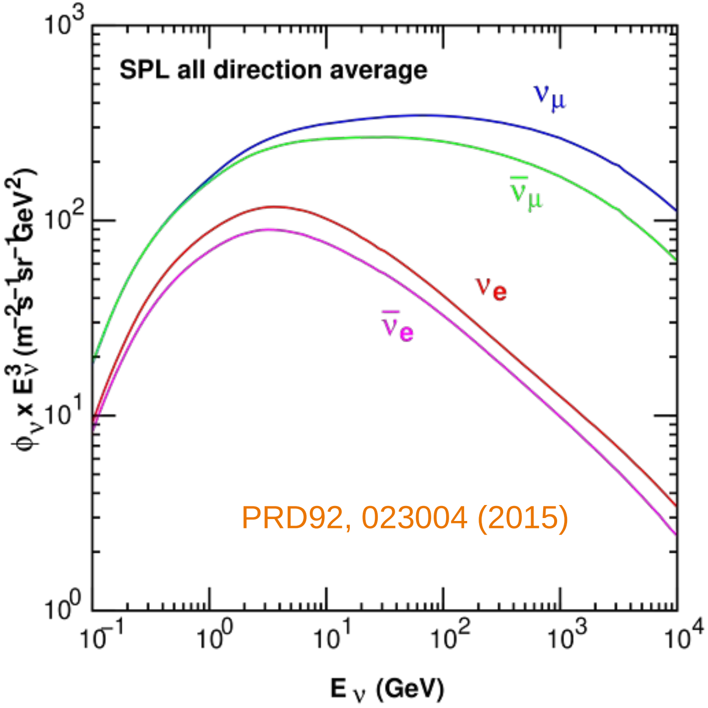
- LRI strength depends on the electron content of the celestial objects within the interaction range d
- Step-like transitions in potential is due to the contributions from various sources at different distances

Can we probe these flavor-dependent neutral-current long-range interactions using atmospheric neutrino oscillations at IceCube DeepCore?

Atmospheric Neutrinos



$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$
$$\pi^- \to \mu^- + \bar{\nu}_\mu$$
$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$$



- Baselines: ~ 20 km to 12700 km
- Wide energy range: few MeV to more than TeV

- In the GeV range, initial atmospheric neutrino flux is almost isotropic (up-down symmetric)
- Steeply falling power-law spectra ($\sim E^{-2.7}$) in the GeV range

Neutrino Oscillations

Neutrino flavor eigenstates ν_α as superposition of mass eigenstates ν_i

$$\nu_\alpha = \sum_i U_{\alpha i} \nu_i$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

where, $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$.

Osc. Params.	Nominal
θ_{12}	33.41
θ_{13}	8.58
δ_{CP}	0
Δm^2_{21}	7.41e-05

Probability of oscillation of flavor α to β:

$$P(\nu_\alpha \to \nu_\beta) = \left| U_{\beta 1} U^*_{\alpha 1} + U_{\beta 2} U^*_{\alpha 2} e^{-i2\alpha\Delta} + U_{\beta 3} U^*_{\alpha 3} e^{-i2\Delta} \right|^2$$

where, $\Delta = \frac{\Delta m^2_{31} L_\nu}{4E_\nu}$, $\Delta m^2_{ij} = m^2_i - m^2_j$, and $\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$

This analysis is performed assuming normal mass ordering.

Coherent elastic scattering with ambient electrons inside the Earth leads to resonance in the oscillation probabilities.

- Normal Ordering (NO): $(m_3 > m_2 > m_1)$
- Inverted Ordering (IO): $(m_2 > m_1 > m_3)$

Long-Range Interaction (LRI) Hamiltonian

The effective Hamiltonian in the flavor basis in presence of LRI,

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

Where,

$$V_{CC} = \pm\sqrt{2} G_F N_e$$

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

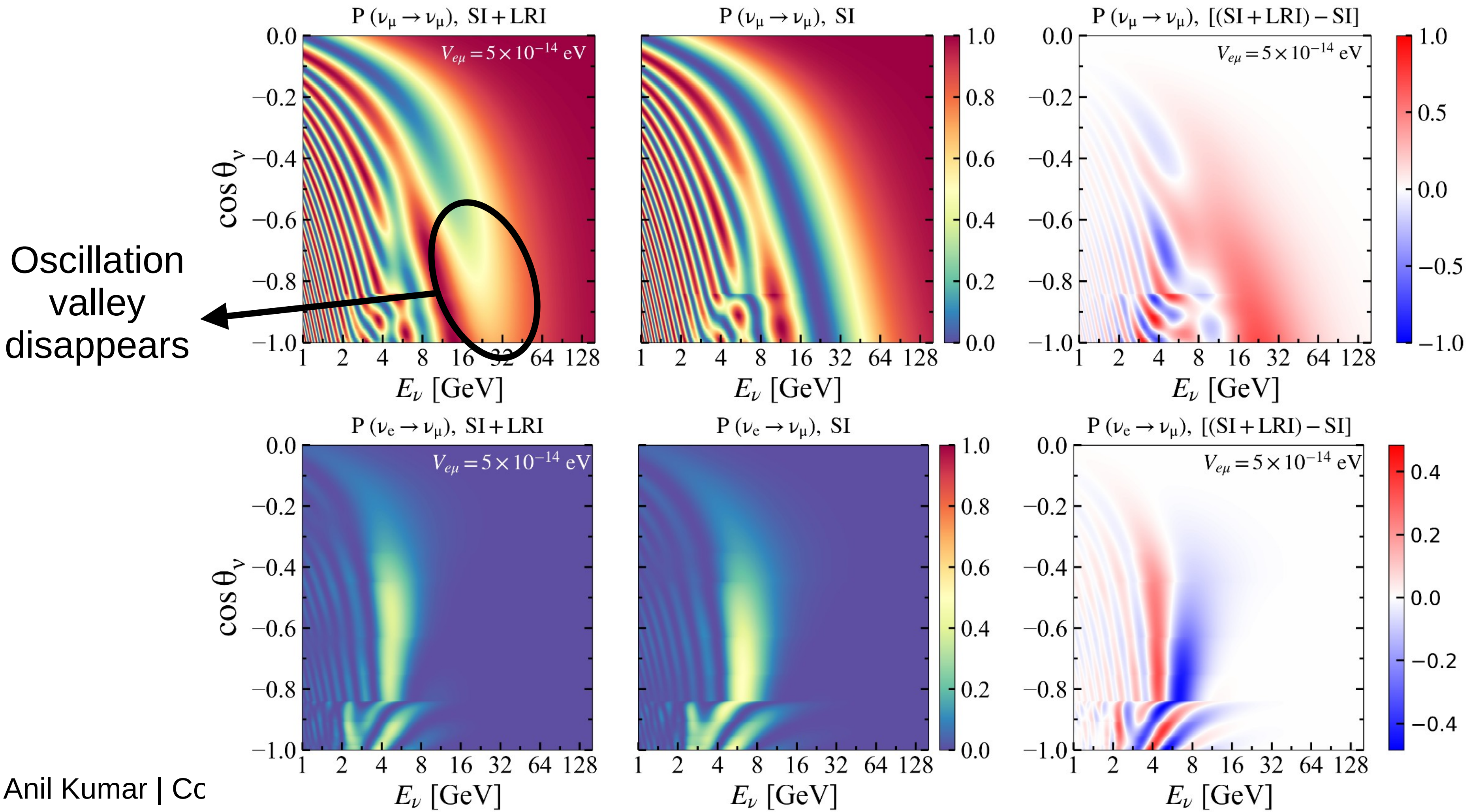
For $L_e - L_\mu$ symmetry, $\zeta = V_{e\mu}$, $\xi = -V_{e\mu}$ & = 0

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

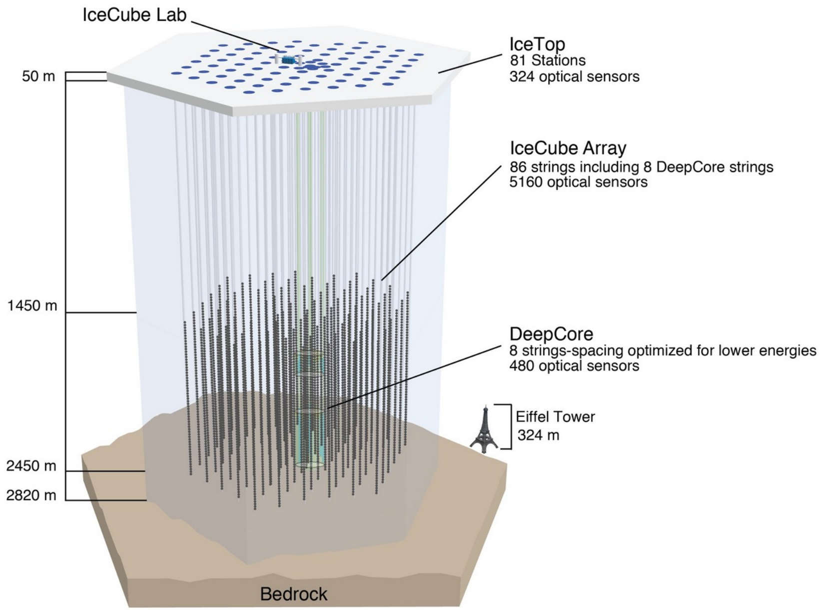
$$V_{LRI} = \begin{cases} \text{Diag}\,(V_{e\mu}, -V_{e\mu}, 0) \\ \text{Diag}\,(V_{e\tau}, 0, -V_{e\tau}) \end{cases}$$

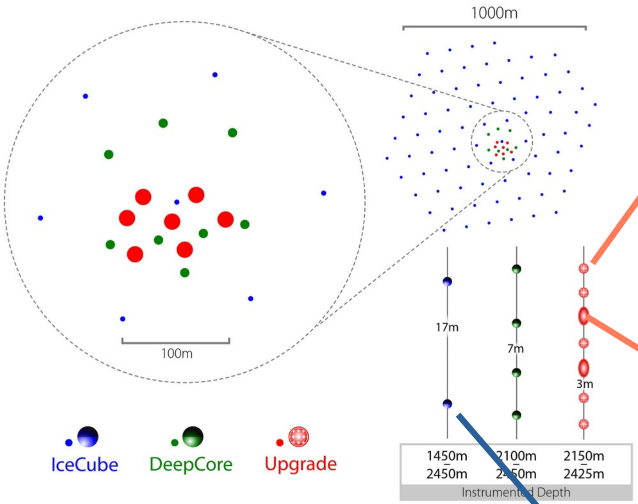
- For antineutrinos, V_{CC} & $V_{e\mu / e\tau}$ change their sign
- When $V_{e\mu/e\tau} \approx \Delta m^2_{31} / E \approx V_{CC} \approx 10^{-13}$ eV, its effect can be observed in atmospheric neutrino oscillations

Effect of L_e- L_μ on Probability Oscillograms



IceCube Neutrino Observatory





mDOM

D-Egg

DOM

- **Neutrino interactions ⟶ Cherenkov photons ⟶ DOMs**
- **IceCube**: up to **PeV energies**
- **DeepCore: GeV-scale**
- IceCube **Upgrade:** Energy threshold of a few GeV

Events at DeepCore

Red = Early Hits
Blue = Late Hits

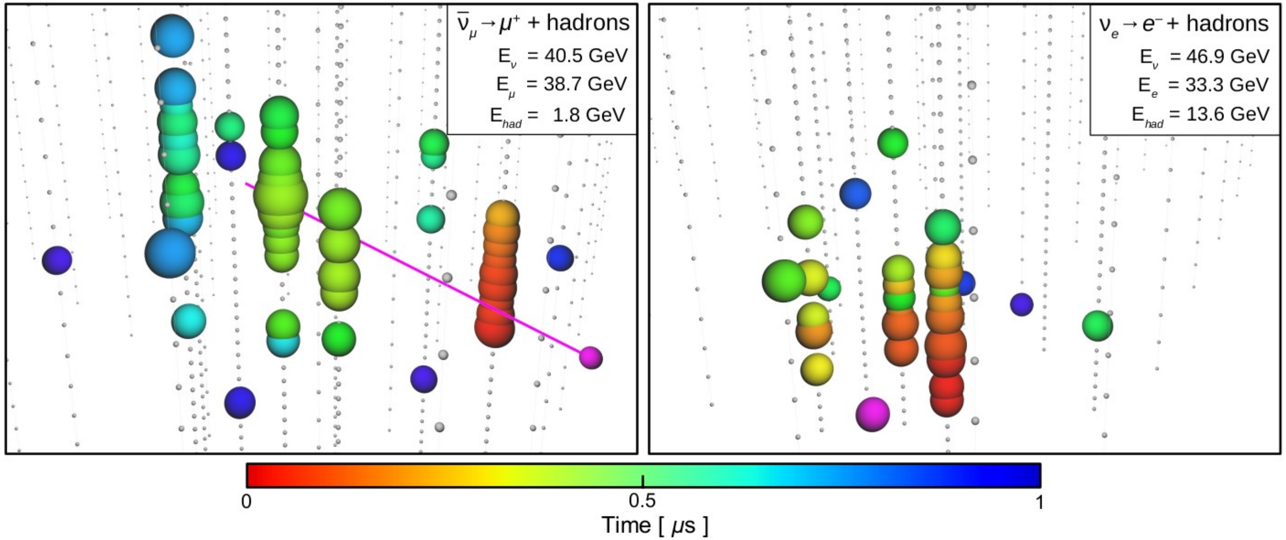
Signals:

- ν_μ, ν_e, ν_τ
- Predominantly DIS interactions
- Operate above τ production threshold of 3.5 GeV

Backgrounds:

- Atmospheric muons
- Random detector noise

Tracks | **Cascades**

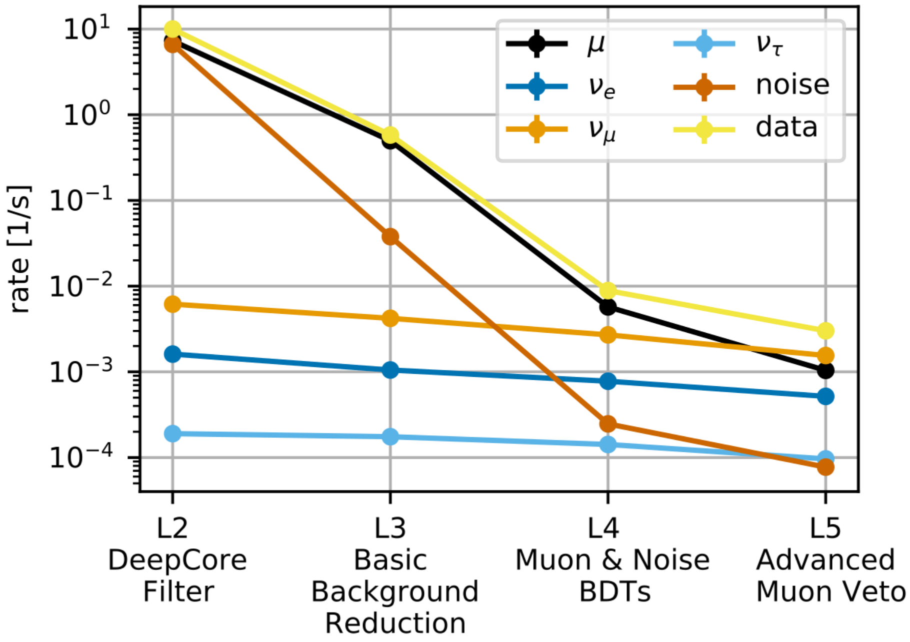


mostly ν_μ^{CC} | $\nu_{\mathrm{e}}^{\mathrm{CC}}, \nu_\tau^{\mathrm{CC}}, \nu^{\mathrm{NC}}$

A. Terliuk, Ph.D. thesis (2018)

Event Selection and Reconstruction

PRD 108, 012014 (2023)



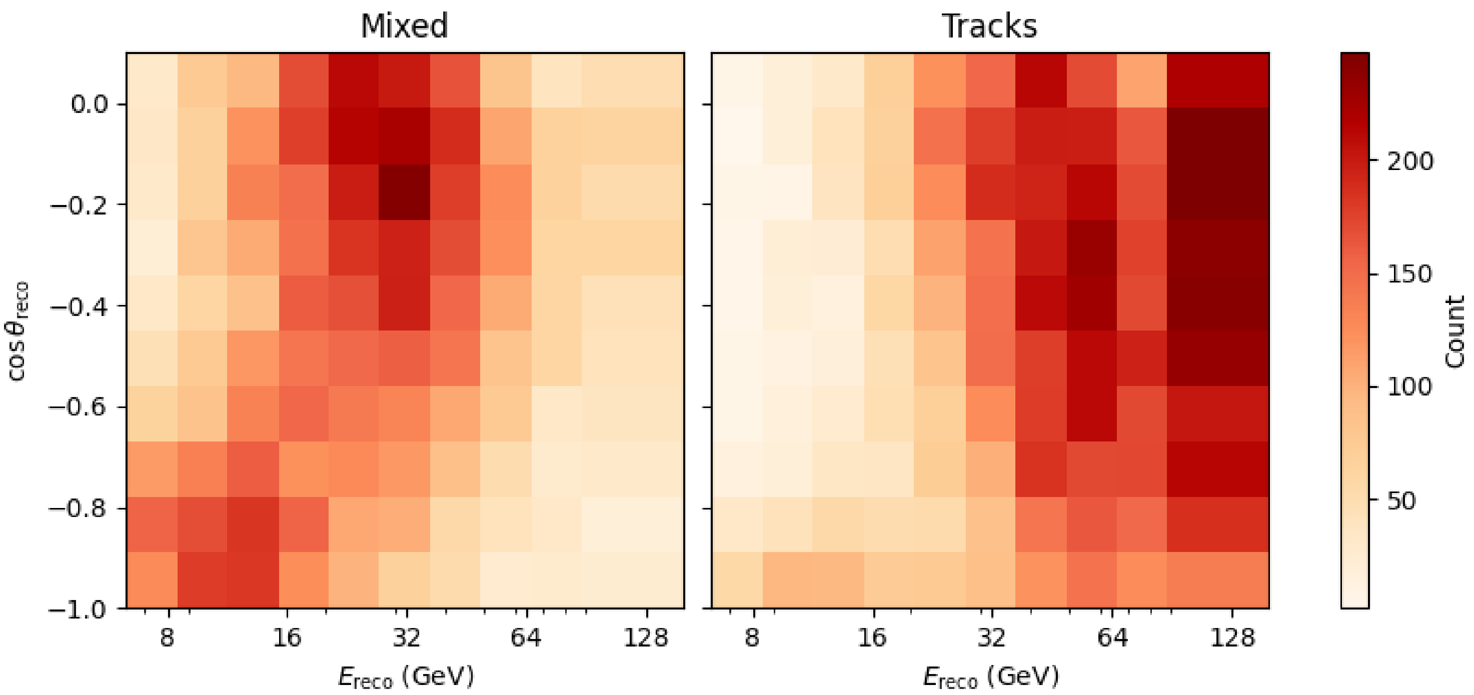
Filters at various levels reduce backgrounds such as noise and atmospheric muons below 1% of signal.

Publicly available golden event sample

- 2011-2019 : 8 years of DeepCore data
- Quick reconstruction for events with only unscattered photon
- Computationally less expensive
- Clean events
- Lower statistics (~22k)
- High purity ν_μ CC event sample
- Analysis using track-like events only
- Assume normal mass ordering

8-year Golden Event Sample

PRD 108, 012014 (2023)

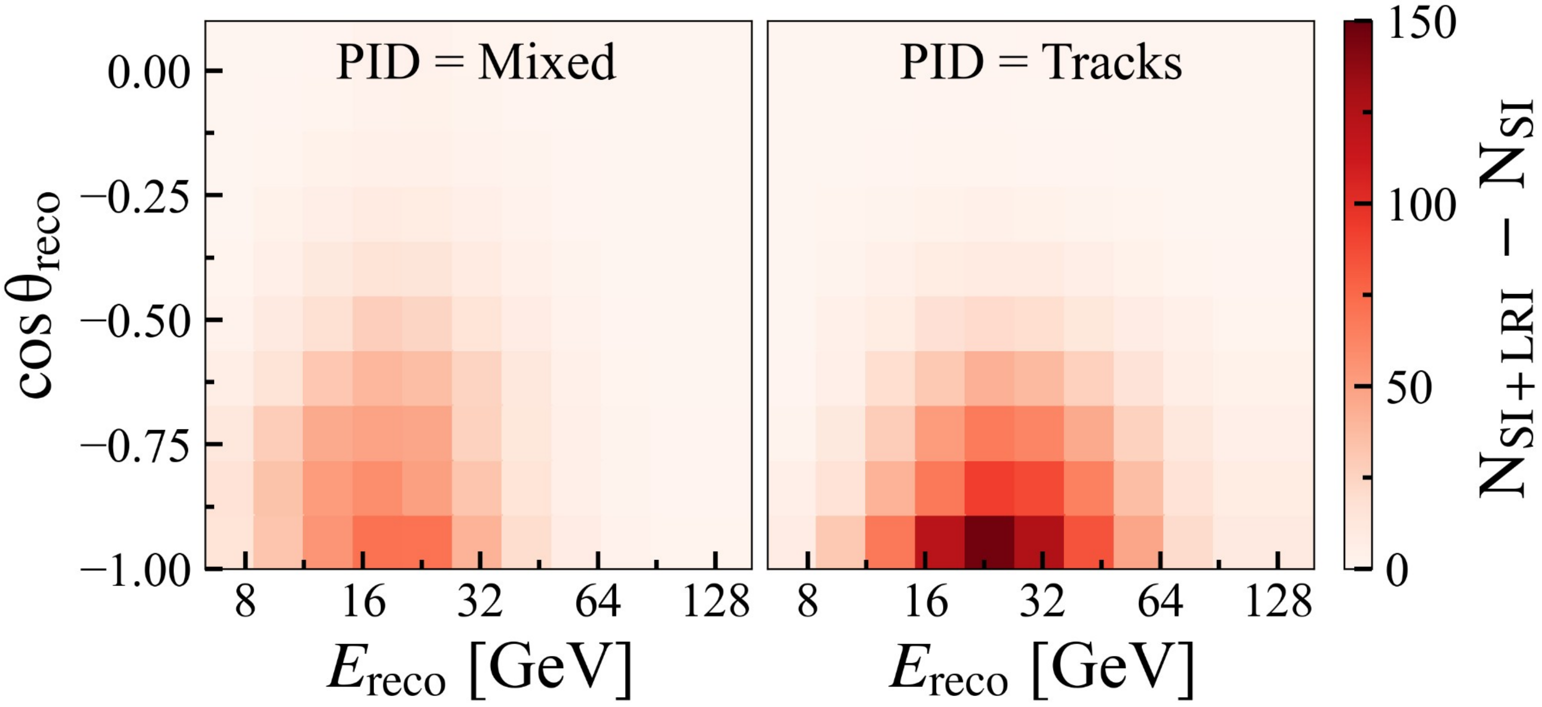


Binning Scheme :

- Energy – 10 log bins in [6.3 – 158.5] GeV
- Zenith – 10 linear bins in [-1, 0.1]
- PID – Mixed : [0.55, 0.75] & Tracks [0.75, 1]

Particle Identification (PID) score is the probability for an event to be ν_μ CC

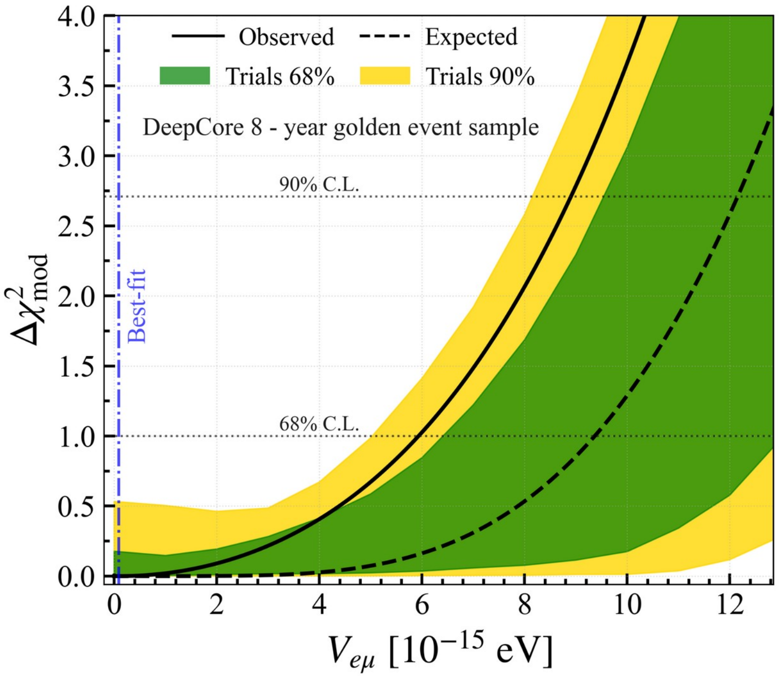
Effect of $L_e - L_\mu$ on Expected Events

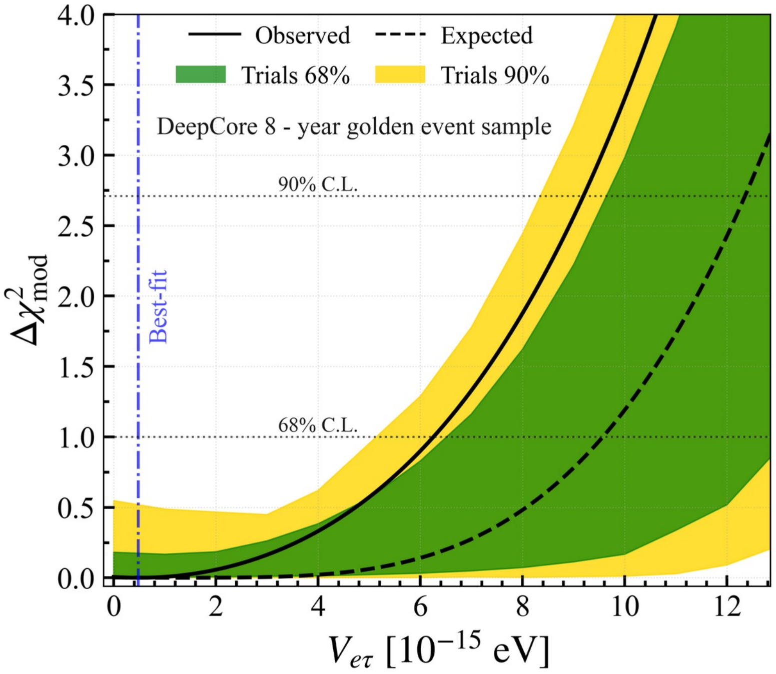


The difference of expected MC events at DeepCore for SI + LRI ($V_{e\mu} = 5 \times 10^{-14}$ eV) and SI scenarios.

Results

$\Delta\chi^2_{mod} = \chi^2_{mod}\,(V_{LRI}\text{ fixed}) - \chi^2_{mod}\,(V_{LRI}\text{ free})$





- The best-fit values are : **$V_{e\mu} = 8.9 \times 10^{-17}$ eV, $V_{e\tau} = 4.8 \times 10^{-16}$ eV (consistent with no LRI)**
- The 90% upper bounds are : **$V_{e\mu} < 8.9 \times 10^{-15}$ eV, $V_{e\tau} < 9.2 \times 10^{-15}$ eV**

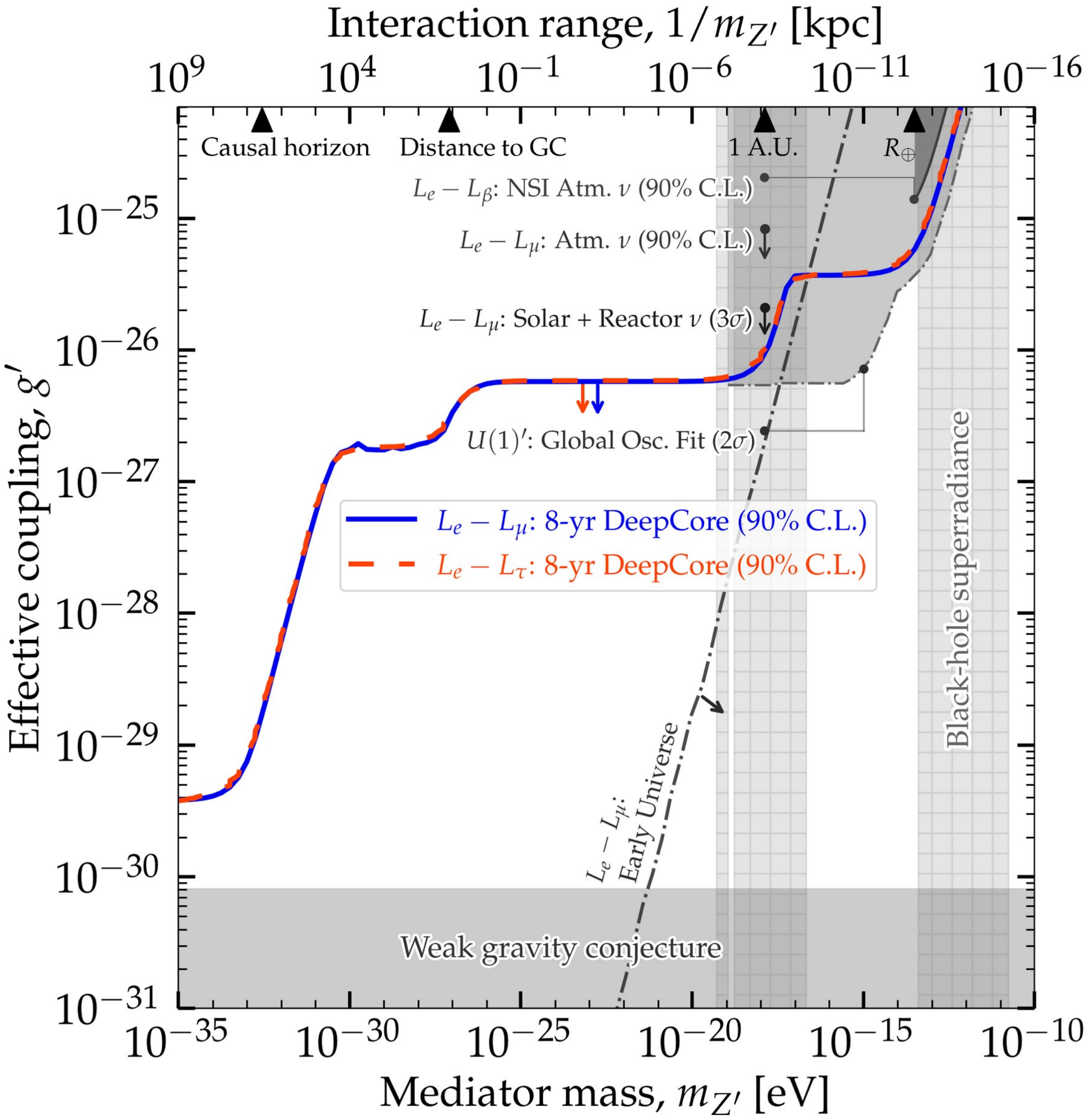
Results

- Constraints on LRI potentials for $L_e - L_\mu$ & $L_e - L_\tau$ symmetries in terms of the coupling strength g' & the mediator mass $m_{Z'}$ at 90% C.L.

- DeepCore put the most stringent experimental bounds on such long-range interactions using neutrino data

References:

- global oscillation fit: JHEP 01 (2021) 114,
- atmospheric neutrinos: PLB 584 (2004) 103-108,
- solar and reactor neutrinos: PRD 75 (2007) 093005,
- non-standard interaction searches PRD 84 (2011) 113008, Rept.Prog.Phys. 76 (2013) 044201, JHEP 09 (2013) 152
- Indirect limits [JHEP 06 (2018) 053] from
  - black-hole superradiance: PRD 96 (2017) 3, 035019
  - the early Universe: PRD 101 (2020) 9, 095013
  - compact binaries: PRD 100 (2019) 12, 123023
  - the weak gravity conjecture: JHEP 06 (2007) 060



Summary

- The 8-year high-purity ν_μ CC golden event sample of IceCube DeepCore can be used to test various BSM models
- We explore the U(1)’ symmetry using DeepCore data
- We put the best constraint on LRI potential using the DeepCore data
- We also put the bounds on mass and coupling of ultra-light gauge boson

Thank You

Backup

NSI and LRI

- NSI is a short range interaction while LRI is a long range interaction
- LRI depends on the type of symmetry
- NSI hamiltonian can have both real and imaginary terms
- LRI Hamiltonian has only diagonal terms which can be only real
- NSI depends on the density of ambient electrons present inside the Earth
- LRI is sourced by the electrons present in large celestial objects

$$H = U \begin{bmatrix} 0 & 0 & 0 \\ 0 & k_{21} & 0 \\ 0 & 0 & k_{31} \end{bmatrix} U^{\dagger} + V_{CC} \begin{bmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^{*}_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^{*}_{e\tau} & \varepsilon^{*}_{\mu\tau} & \varepsilon_{\tau\tau} \end{bmatrix}$$

NSI Hamiltonian

$$H_f = \left(U \begin{bmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} \end{bmatrix} U^{\dagger} + \begin{bmatrix} V_{CC} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} + \begin{bmatrix} V_{e\mu} & 0 & 0 \\ 0 & -V_{e\mu} & 0 \\ 0 & 0 & 0 \end{bmatrix} \right)$$

LRI Hamiltonian

Long-Range Interaction (LRI)

- The Solar electrons can generate a flavor-dependent long-range potential $V_{e\mu\,/\,e\tau}$ at the Earth's surface as,

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

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 ($\approx 1.5 \times 10^{13}$ cm $= 7.6 \times 10^{26}$ GeV^{-1})

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

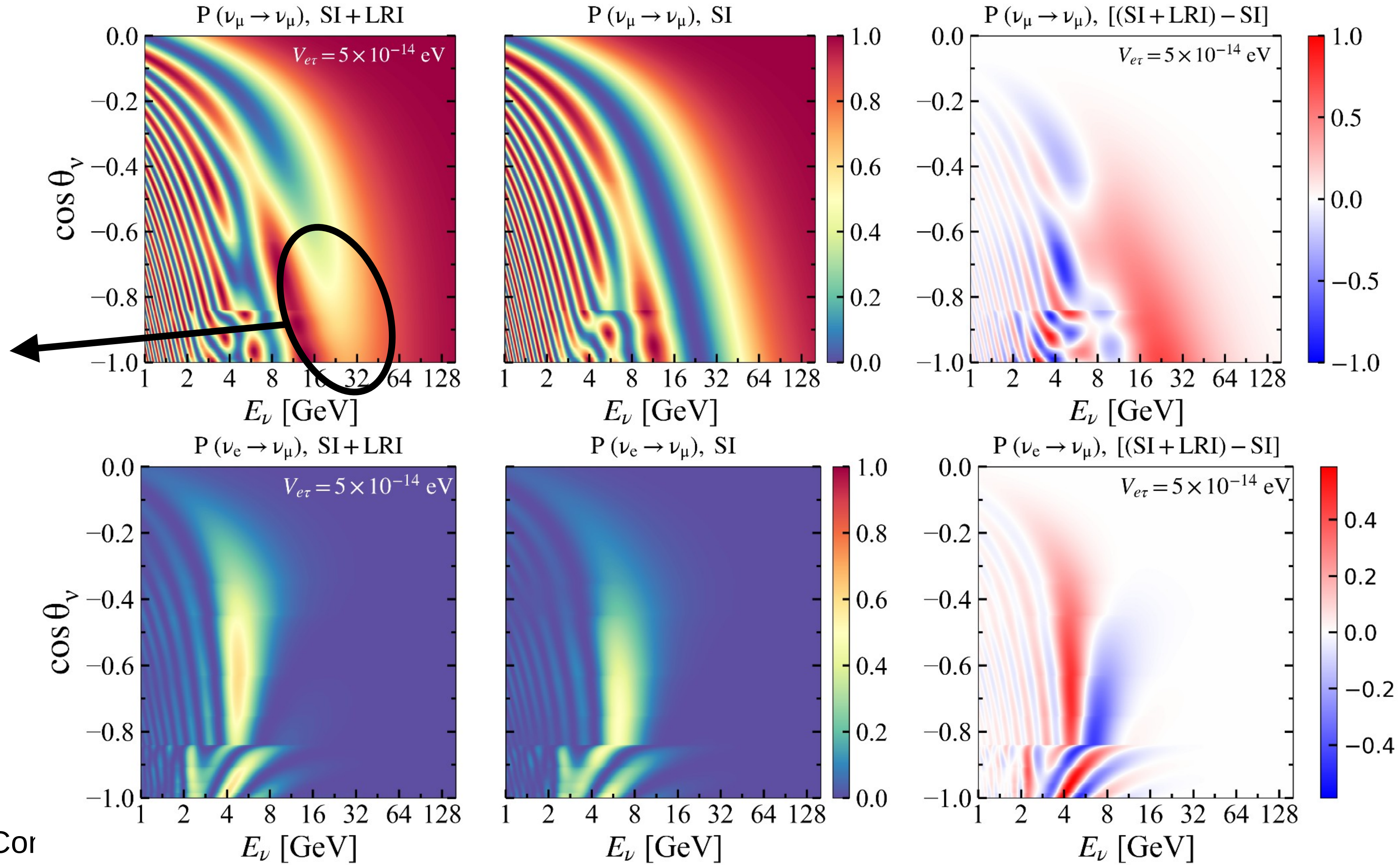
$$V_{e\mu/e\tau}(R_E) \approx 0.05\, V_{e\mu/e\tau}(R_{SE})$$

Present Bounds

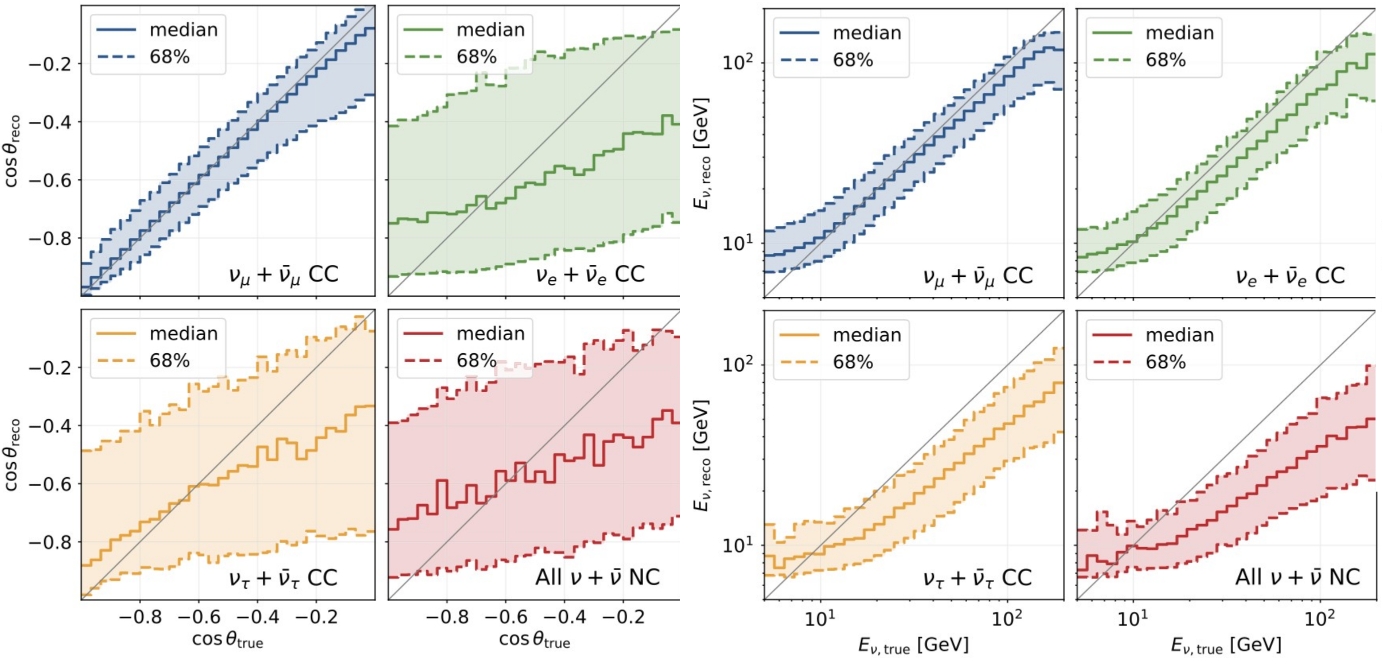
Experiment	LRI Potential $V_{e\mu / e\tau}$ (eV)	Reference
IceCube DeepCore**	$V_{e\mu} < 0.89 \times 10^{-14}$ (90% CL) $V_{e\tau} < 0.92 \times 10^{-14}$ (90% CL)	**Present work constraints****
Super-Kamiokande*	$V_{e\mu} < 5.5 \times 10^{-13}$ (90% CL) $V_{e\tau} < 6.4 \times 10^{-13}$ (90% CL)	A. Joshipura & S. Mohanty PLB 584 (2004)
Solar + KamLAND*	$V_{e\mu} < 4.4 \times 10^{-14}$ (3σ) $V_{e\tau} < 3.3 \times 10^{-14}$ (3)	A. Bandyopadhyay, A. Dighe, & A. S. Joshipura PRD 75 093005 (2007)
ICAL-INO (500 kt.yr)	$V_{e\mu/e\tau} < 1.6 \times 10^{-14}$ (90% CL)	A. Khatun, T. Thakore, & S. K. Agarwalla JHEP 04 (2018) 023
DUNE + T2HK	$V_{e\mu} < 1.56 \times 10^{-14}$ (3) $V_{e\tau} < 1.32 \times 10^{-14}$ (3)	S. K. Agarwalla, et. al, JHEP 09 (2024) 055

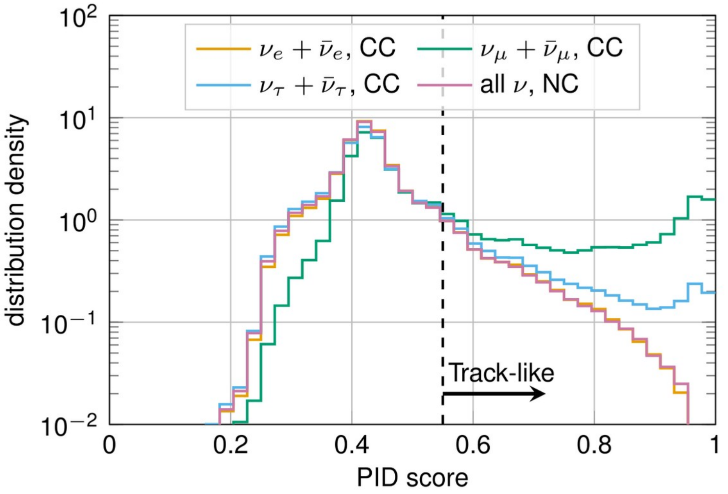
Effect of L_e- L_τ on Probability Oscillograms

Oscillation valley disappears



Final Level Resolutions - Golden Sample





Particle Identification (PID) score is the probability for an event to be ν_μ CC

PID classification

- Track-like: 0.75 < PID < 1.00
- Mixed: 0.55 < PID < 0.75

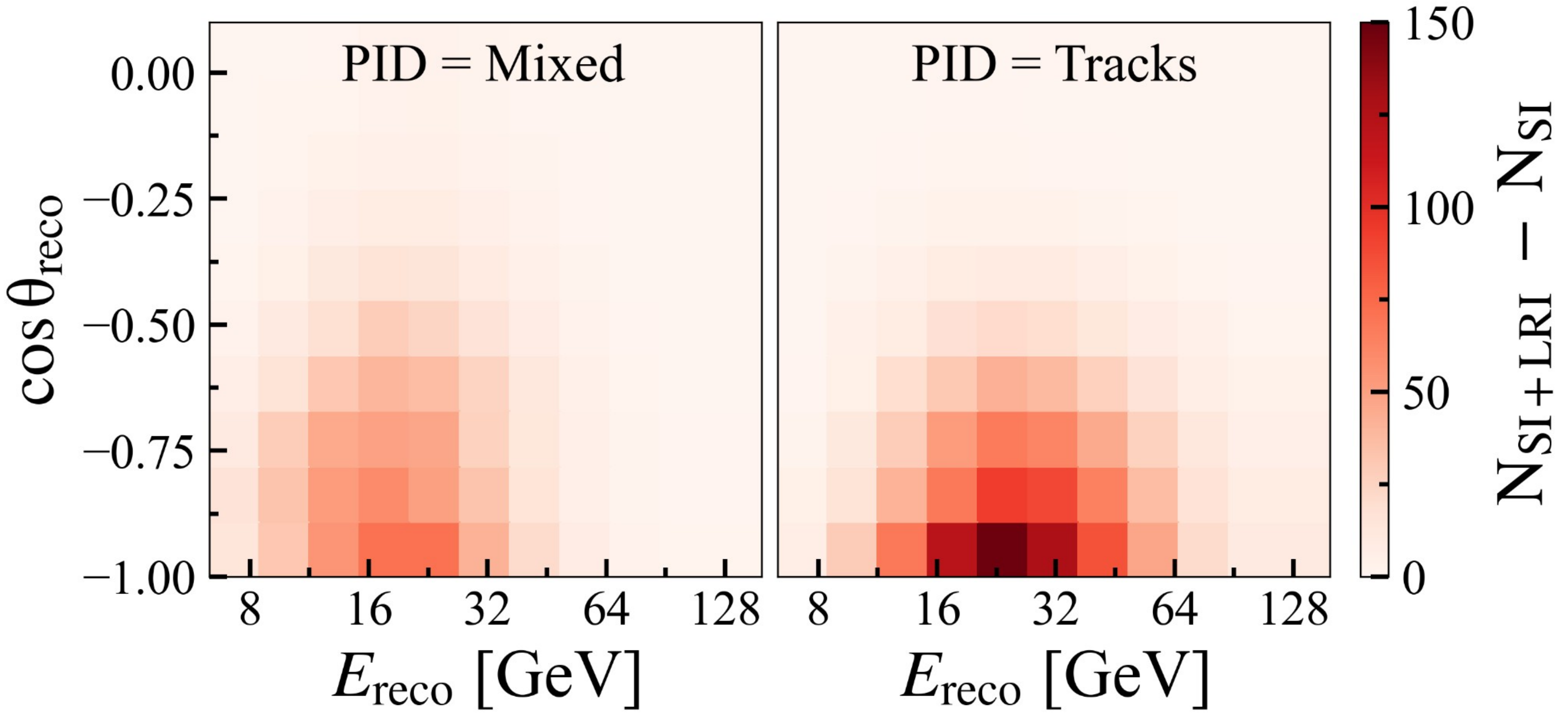
ν_μ CC events have better energy and direction resolutions than ν_e CC and ν NC events

PRD 108, 012014 (2023)

Event Sample

Type	Events	Rates [1/10^6 s]
$\nu_\mu + \bar{\nu}_\mu$ CC	17656	75.03
$\nu_e + \bar{\nu}_e$ CC	1820	7.74
$\nu_\tau + \bar{\nu}_\tau$ CC	603	2.56
$\nu_{all} + \bar{\nu}_{all}$ NC	1222	5.19
Atmospheric μ	711	3.02
Total (best-fit)	22012	93.54
Observed	21914	93.08

Effect of L_e- L_τ on Event Level



The difference of expected MC events at DeepCore for SI + LRI ($V_{e\tau} = 5 \times 10^{-14}$ eV) and SI scenarios.

Systematic Treatment

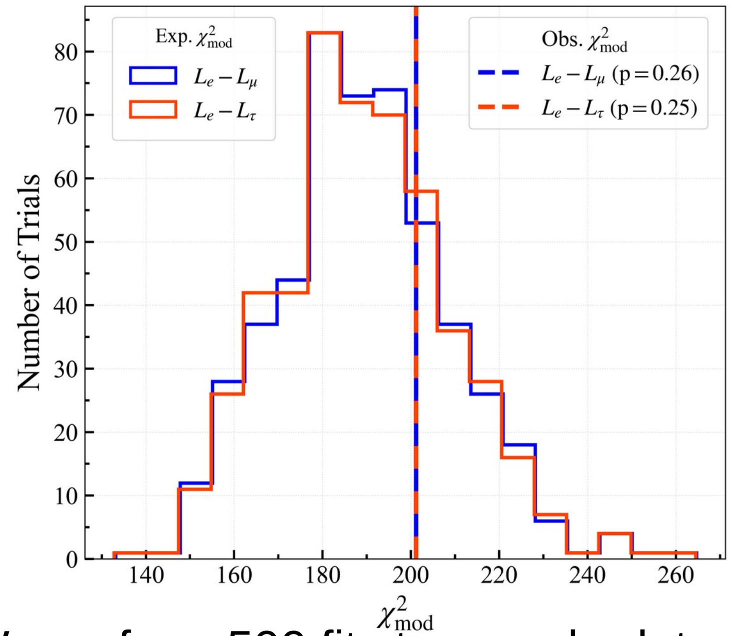
- **Flux uncertainties** [Pion & Kaon production uncertainties (**Barr et al., Phys. Rev. D 74, 094009**)]
- **Cross section** [Axial mass uncertainty for resonance and quasielastic events, GENIE - CSMS transition for DIS (**JHEP 08, 042 (2011)**)]
- **Detector & Ice properties** [Better treatment for modeling the optical properties of ice, PMT charge calibration]
- **Oscillation parameters**
- **Atmospheric muon (scale)** [**Gaisser et al.**+ **Sibyll2.1**]
- **Normalization of neutrino event counts** [calibration + flux models]

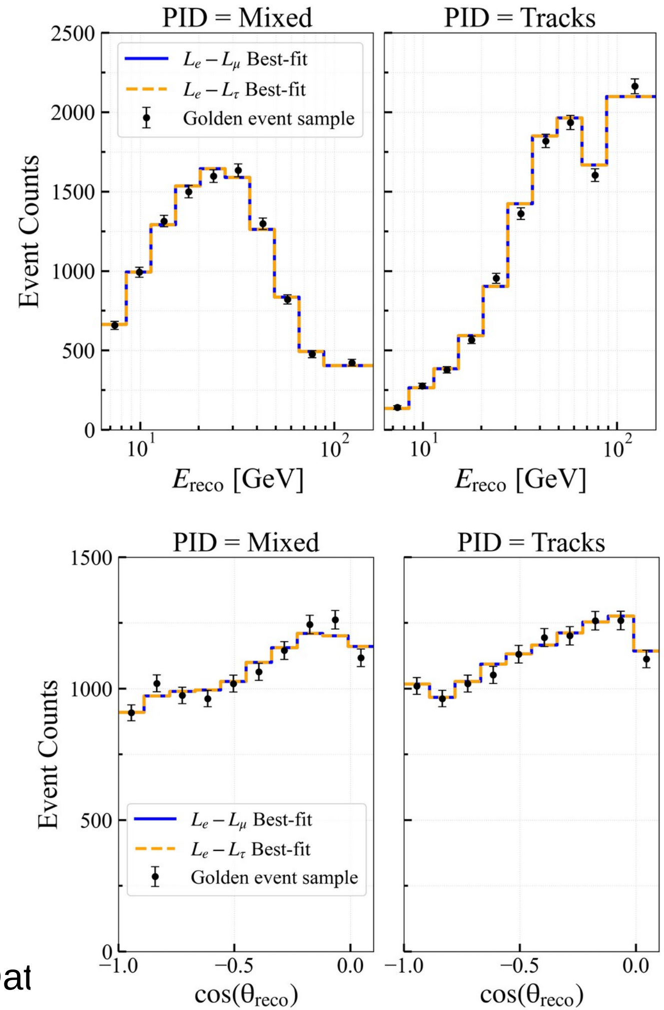
Total number of free systematics: 18

For more details, please see:
arXiv:2304.12236v1

Parameter	Best-fit ($V_{e\mu}$)	Best-fit ($V_{e\tau}$)	Nominal value	Prior	Range
Detector:					
DOM efficiency	1.064	1.064	1.0	± 0.1	[0.8, 1.2]
Ice absorption	0.974	0.974	1.0	-	[0.9, 1.1]
Ice scattering	0.988	0.988	1.05	-	[0.95, 1.15]
Relative eff. p_0	-0.269	-0.269	0.10	-	[-0.2, 0.6]
Relative eff. p_1	-0.043	-0.043	-0.05	-	[-0.2, 0.2]
Atmospheric flux:					
$\Delta\gamma_\nu$	0.064	0.064	0.0	± 0.1	[-0.5, 0.5]
$\Delta\pi^\pm$ yields [A-F]	0.061	0.061	0.0	± 0.3	[-1.5, 1.5]
$\Delta\pi^\pm$ yields G	-0.055	-0.055	0.0	± 0.15	[-1.5, 1.5]
$\Delta\pi^\pm$ yields H	-0.018	-0.018	0.0	± 0.15	[-0.75, 0.75]
ΔK^+ yields W	0.085	0.085	0.0	± 0.4	[-2.0, 2.0]
ΔK^+ yields Y	0.107	0.108	0.0	± 0.3	[-1.5, 1.5]
ΔK^- yields W	-0.009	-0.009	0.0	± 0.4	[-2.0, 2.0]
Cross-section:					
M_A^{CCQE} (in σ)	0.062	0.062	0.0	± 1.0	[-2.0, 2.0]
M_A^{CCRES} (in σ)	0.606	0.606	0.0	± 1.0	[-2.0, 2.0]
DIS CSMS	0.034	0.035	0.0	± 1.0	[-3.0, 3.0]
$\sigma_{\mathrm{NC}}/\sigma_{\mathrm{CC}}$	1.127	1.127	1.0	± 0.2	[0.5, 1.5]
Normalization:					
A_{eff} scale	0.824	0.824	1.0	-	[0.6, 1.4]
Atmospheric muons:					
Atm. μ scale	1.365	1.365	1.0	-	[0.7, 1.5]
Oscillations:					
θ_{23}	45.385°	45.297°	45.573°	-	[38°, 52°]
Δm^2_{31}	0.002489 eV^2	0.002489 eV^2	0.002484 eV^2	-	[0.002, 0.003] eV^2

Goodness of fit and Data - MC Agreement





- We perform 500 fits to pseudo-data trials that are generated by fluctuating best fit template
- Observed χ^2_{mod} has a p-value of ~25 %, indicating good agreement between simulation and data