Non-standard neutrino interactions in IceCube

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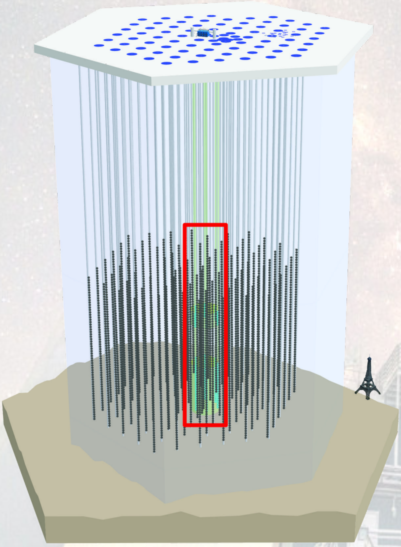
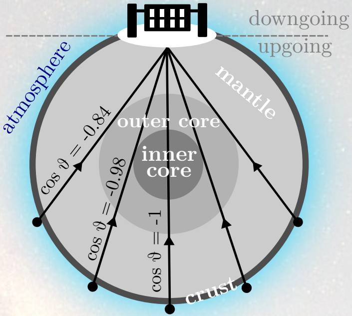
Oscillations analyses in IceCube and DeepCore

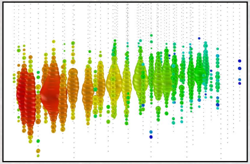


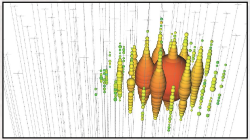


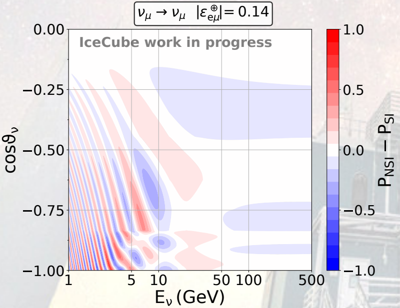
- detecting Cherenkov light from ν charged secondaries
- IceCube detects neutrinos at $E_\nu \gtrsim 100\,\text{GeV}$
- Low-energy extension DeepCore: $E_\nu \gtrsim 5\,\text{GeV}$
- baselines of $\mathcal{O}10\text{-}10^4\,\text{km}$

Low-energy analysis principle

- binning in E_{reco}, $cos\theta_{reco}$ and topology
- compare N events per bin, data vs. Monte Carlo
- re-weight MC for each tested hypothesis via PISA software







- optimize metric in large number of dimensions:
  $\geq$20 nuisance and NSI parameters

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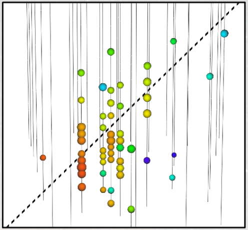
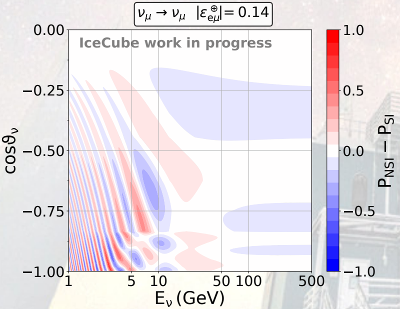
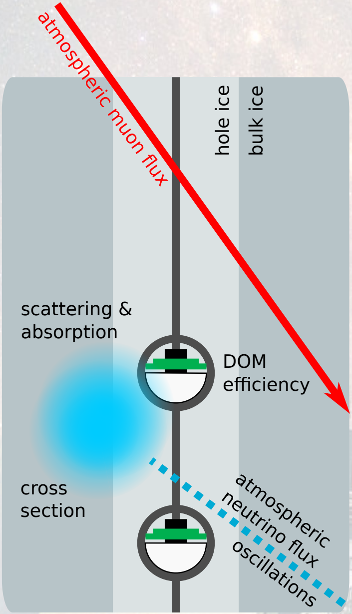




- optimize metric in large number of dimensions: $\geq$20 nuisance and NSI parameters

Nuisance parameters and systematic uncertainties



- detector modules and ice
- atmospheric ν flux using Honda *et al* model [1] and Barr *et al* parameters [2]
- oscillations for low energy samples
- interaction cross sections
- atmospheric μ flux

[1] M. Honda et al, Atmospheric neutrino flux calculation using the NRLMSISE-00 atmospheric model, 2015
[2] G. D. Barr et al, Uncertainties in atmospheric neutrino fluxes, 2006
[3] IceCube Collaboration, Measurement of atmospheric tau neutrino appearance with IceCube DeepCore, 2019

Non-standard neutrino interactions (NSI)

- ν interaction via new heavy mediator
- NC forward scattering of all ν_α at u, d, e^- in Earth matter
- change in matter effects observable in oscillation pattern
- generalized Hamiltonian with effective couplings:

SI ϟ lepton universality ϟ flavor

$$H_{\mathrm{mat}} = \sqrt{2} G_F N_e(x) \begin{pmatrix} 1 + (\epsilon_{ee}^{\oplus} - \epsilon_{\mu\mu}^{\oplus}) & \epsilon_{e\mu}^{\oplus} & \epsilon_{e\tau}^{\oplus} \\ \epsilon_{e\mu}^{\oplus *} & 0 & \epsilon_{\mu\tau}^{\oplus} \\ \epsilon_{e\tau}^{\oplus *} & \epsilon_{\mu\tau}^{\oplus *} & (\epsilon_{\tau\tau}^{\oplus} - \epsilon_{\mu\mu}^{\oplus}) \end{pmatrix}$$

- largely independent from model and mediator mass
- NSI potentially complicates oscillations parameter measurements [1] but resolves tensions [2]

[1] Y. Farzan, M. Tortola, Neutrino Interactions and Non-Standard Interactions, 2018

[2] S. Chatterjee, A. Palazzo, Nonstandard Neutrino Interactions as a Solution to the NOνA and T2K Discrepancy, 2021

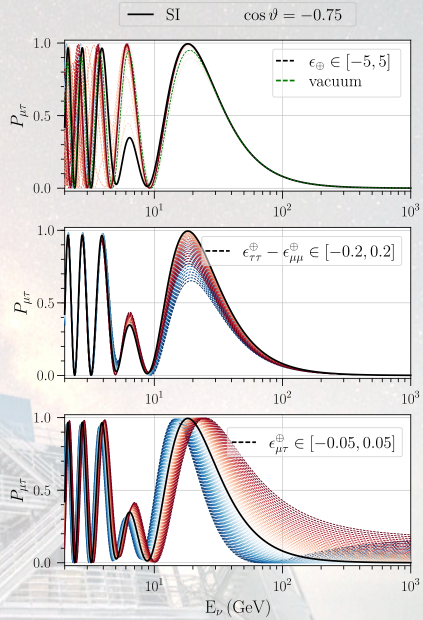
Different IceCube NSI analyses

- IceCube most sensitive to ν_μ

→ earlier low-energy analyses only test for $|\epsilon^{\oplus}_{\mu\tau}|$ [1]

- **newer low-energy analyses** constrain all (complex) NSI parameters [2]
- $\epsilon^{\oplus}_{\mu\tau}$ has strong impact above 100 GeV

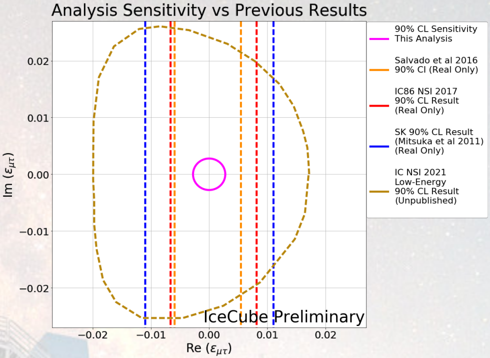
→ high-energy analysis: 500 GeV-1 TeV, $\epsilon^{\oplus}_{\mu\tau}$ only [3]



[1] IceCube Collaboration, Search for nonstandard neutrino interactions with IceCube Deep-Core, 2018
[2] IceCube Collaboration, All-flavor constraints on NSI and GMP with three years of IceCube DeepCore data, 2021
[3] G. Parker for the IceCube Collaboration, Update on the IceCube High Energy Non-Standard Interactions Analysis, VLVnT 2021

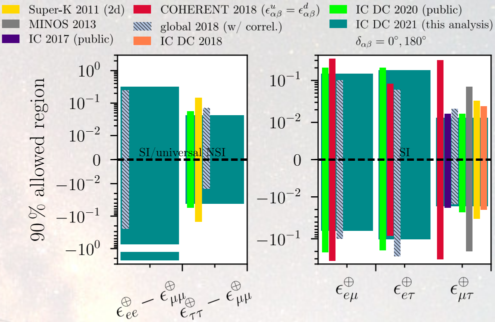
Sensitivity of upcoming high-energy analysis

- 7.5 years of atmospheric $\nu_\mu/\bar{\nu}_\mu$, 500 GeV - 1 TeV [1]
  $\rightarrow$ sensitive to $\epsilon^{\oplus}_{\mu\tau}$
- current median 90% sensitivity:
  $-2.91e-3 \leq |\epsilon^{\oplus}_{\mu\tau}| \leq 2.93e-3$



[1] G. Parker for the IceCube Collaboration, Update on the IceCube High Energy Non-Standard Interactions Analysis, VLVnT 2021

- **recent result:** 3 years DeepCore atmospheric neutrinos sample, $E_\nu \approx 6$ - 100 GeV
- first time constraining all NSI parameters, singly and combined
- up next: **8 year sample**



arXiv.org > hep-ex > arXiv:2106.07755

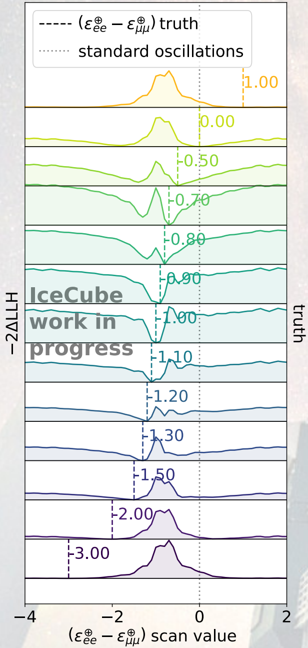
High Energy Physics - Experiment

[Submitted on 14 Jun 2021]

All-flavor constraints on nonstandard neutrino interactions and generalized matter potential with three years of IceCube DeepCore data

IceCube Collaboration: R. Abbasi, M. Ackermann, J. Adams, J. A. Aguilar, M. Ahlers, M. Ahrens, C. Alispach, A. A. Alves Jr., N. M. Amin, R. An, K. Andeen, T. Anderson, I. Ansseau, G. Anton, C. Argüelles, Y. Ashida, S. Axani, X. Bai, A. Balagopal V., A. Barbano, S. W. Barwick, B. Bastian, V. Basu, S. Baur, R. Bay, J. J. Beatty, K.-H. Becker, J. Becker Tjus, C. Bellenghi, S. BenZvi, D. Berley, E. Bernardini, D. Z. Besson, G. Binder, D. Bindig, E. Blaufuss, S. Blot, F. Bontempo, J. Borowka, S. Böser, O. Botner, J. Böttcher, E. Bourbeau, F. Bradascio, J. Braun, S. Bron, J. Brostean-Kaiser, S. Browne, A. Burgman, R. S. Busse, M. A. Campana, C. Chen, D. Chirkin, K. Choi, B. A. Clark, K. Clark, L. Classen, A. Coleman, G. H. Collin, J. M. Conrad, P. Coppin, P. Correa, D. F. Cowen, R. Cross, P. Dave, C. De Clercq, J. J. DeLaunay, H. Dembinski, K. Deoskar, S. De Ridder, A. Desai, P. Desiati, K. D. de Vries, G. de Wasseige, M. de With, T. DeYoung, S. Dharani, A. Diaz, J. C. Díaz-Vélez, H. Dujmovic, M. Dunkman, M. A. DuVernois, E. Dvorak, T.

Challenges for upcoming 8yr low-energy analysis



- 26 + 1 (FD) or 2 (FC) dimensions to minimize
- symmetries in θ_{23}, FD NSI parameters and FC phases
- local minima and flat regions
- e.g. $\epsilon^{\oplus}_{ee} - \epsilon^{\oplus}_{\mu\mu}$ NMO degeneracy:
  SI NO at $\epsilon^{\oplus}_{ee} - \epsilon^{\oplus}_{\mu\mu} = 0$
  SI IO at $\epsilon^{\oplus}_{ee} - \epsilon^{\oplus}_{\mu\mu} = -2$
  $\epsilon^{\oplus}_{ee} - \epsilon^{\oplus}_{\mu\mu} = -1$ mimics vacuum

$\rightarrow$ challenging for (local) minimization

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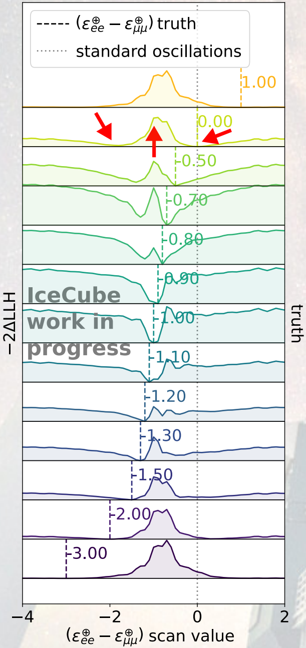

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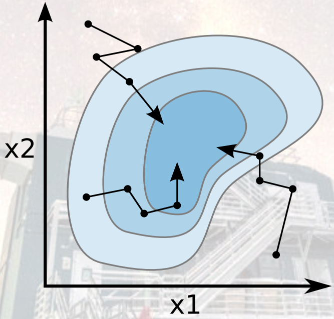
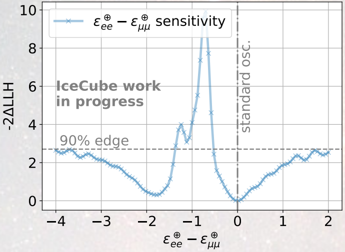
Markov Chain Monte Carlo (MCMC)

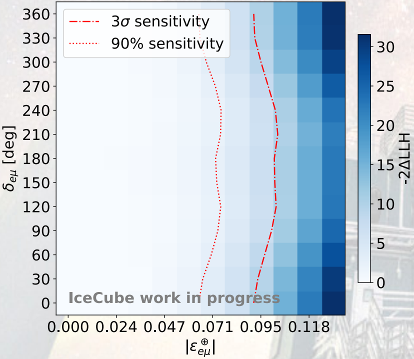
- python emcee package [1], parallelization via openMPI
- multiple interdependent parallel Markov chains
- sample full parameter space based on LLH function
  $\rightarrow$ get best fit *and* allowed ranges
- MCMC copes well with large number of dimensions
  $\rightarrow$ multiple simultaneously free NSI parameters possible



[1] D. Foreman-Mackey et al, emcee: The MCMC Hammer, 2013

Sensitivities of 8 year low-energy sample



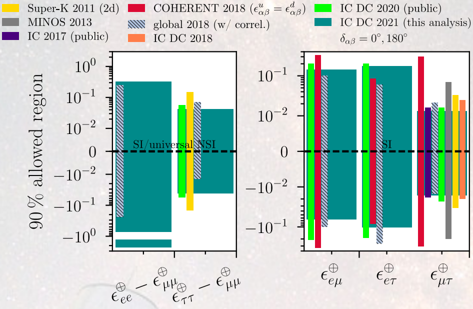


- upcoming analysis: 8 year DeepCore atmospheric neutrinos sample, $E_\nu \approx$ 6 - 300 GeV
- expecting substantial improvement in $\epsilon_{\tau\tau}^{\oplus} - \epsilon_{\mu\mu}^{\oplus}$, $\epsilon_{\mu\tau}^{\oplus}$ and $\epsilon_{e\mu}^{\oplus}$
- little sensitivity to FC parameter phases

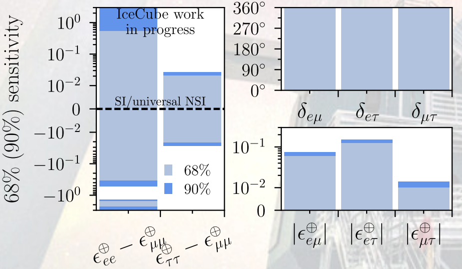
[1] IceCube Collaboration, All-flavor constraints on NSI and GMP with three years of IceCube DeepCore data, 2021

Sensitivities of 8 year low-energy sample

Recent result, 3 year sample



Upcoming analysis, 8 year sample



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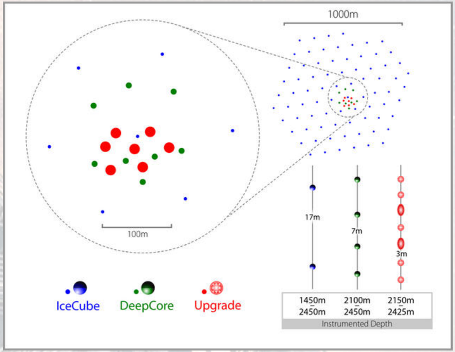
[1] IceCube Collaboration, All-flavor constraints on NSI and GMP with three years of IceCube DeepCore data, 2021

Summary

- multiple analyses at $\mathcal{O}(1-100)$ and $\mathcal{O}(100-1000)$ GeV
- largely model-independent limits on all effective NSI parameters from low-energy data
- stay tuned for next generation of analyses

- On the horizon:
  The IceCube Upgrade [1]
- new, densely packed modules for more events at low(er) energies
- calibration devices improve understanding of systematics

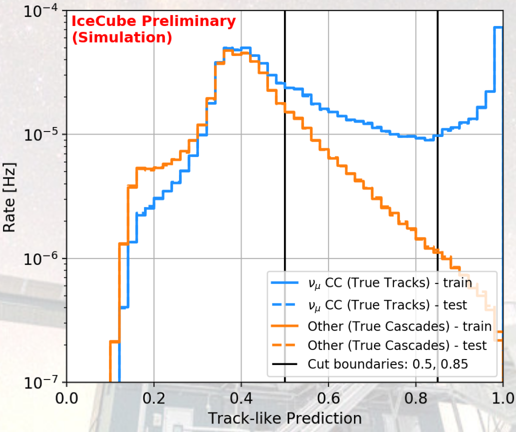


[1] IceCube Collaboration, The IceCube Upgrade - Design and Science Goals, 2021

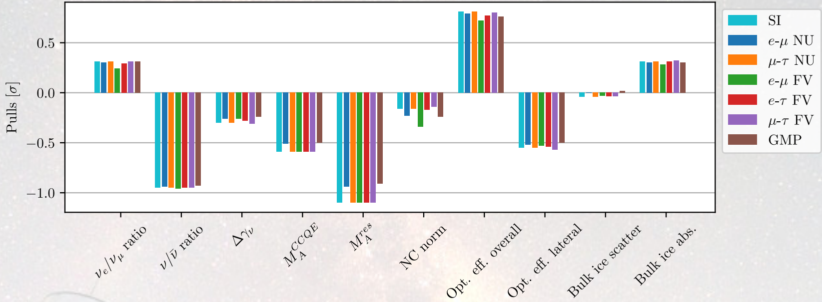
Backup

Low energy event topology binning

- tracks and cascades not easily differentiated
- subdivide topology into 3 bins



Systematics for recent 3 year results



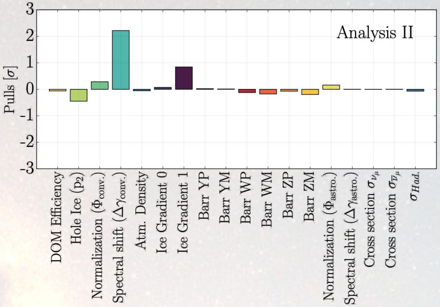
tested hypotheses:

- generalized matter potential (GMP) with 3 free parameters describing mostly model-independent fully free NSI
- one-by-one fits to single NSI parameters as described on slide 3

[1] IceCube Collaboration, All-flavor constraints on NSI and GMP with three years of IceCube DeepCore data, 2021

High-energy analysis

- same sample as in 2020 sterile neutrino search [1]: 7.5 years of Earth-traversing atmospheric $\nu_\mu / \bar{\nu}_\mu$ above 100 GeV
- ice uncertainty modeled using SnowStorm [2]
- neutrino propagation calculated in nuSQuIDS [3]



[1] Searching for eV-scale sterile neutrinos with eight years of atmospheric neutrinos at the IceCube Neutrino Telescope

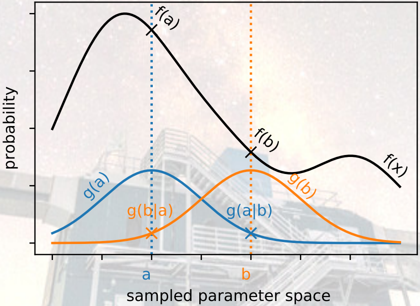
[2] IceCube collaboration, Efficient propagation of systematic uncertainties from calibration to analysis with the SnowStorm method in IceCube

[3] The neutrino Simple Quantum Integro-Differential Solver

Markov Chain Monte Carlo (MCMC)

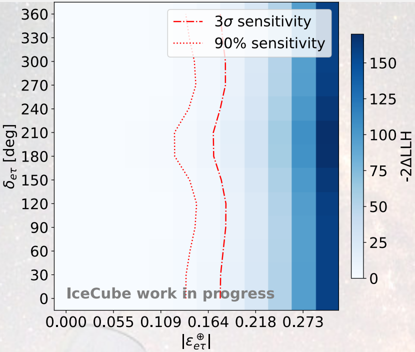
- aim: sample based on unknown true function (LLH)
- start with random sampling to „burn in“ $f(x)$ behavior:

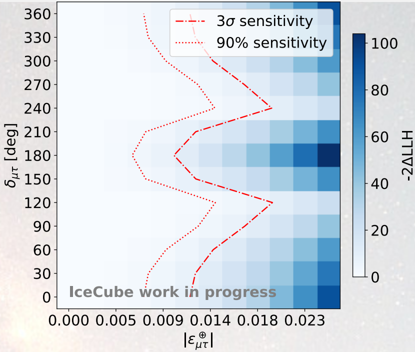
  accept. = $Min\left(1, \frac{f(b)}{f(a)} \times \frac{g(g|b)}{g(b|a)}\right)$ with Gaussian g(x)
- after burn-in: sample equilibrium function $f(x) \propto$ LLH

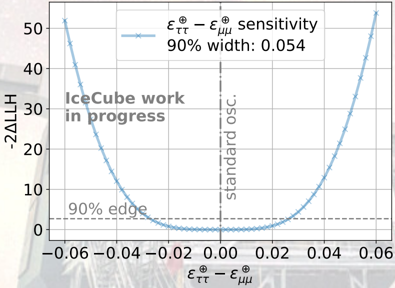


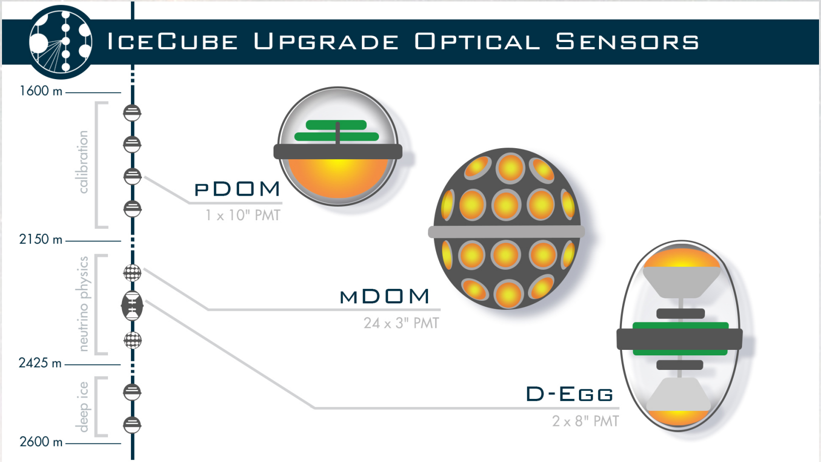
[1] D. Foreman-Mackey et al, emcee: The MCMC Hammer, 2013

8yr low energy sample sensitivities









- additional calibration devices
- more statistics in GeV range