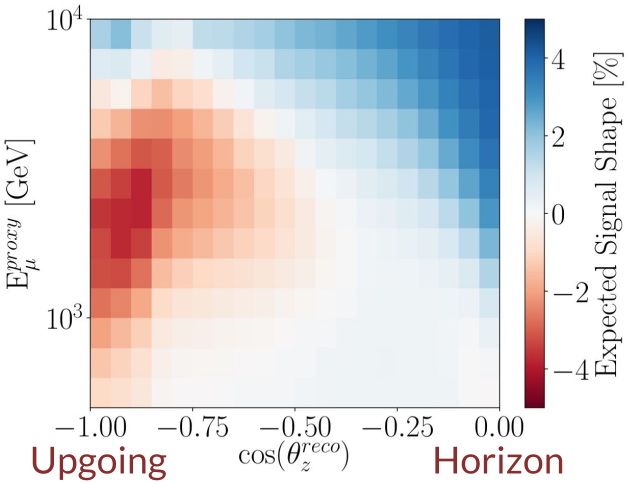
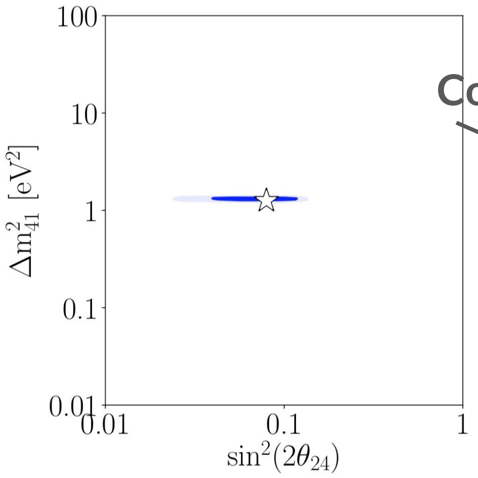
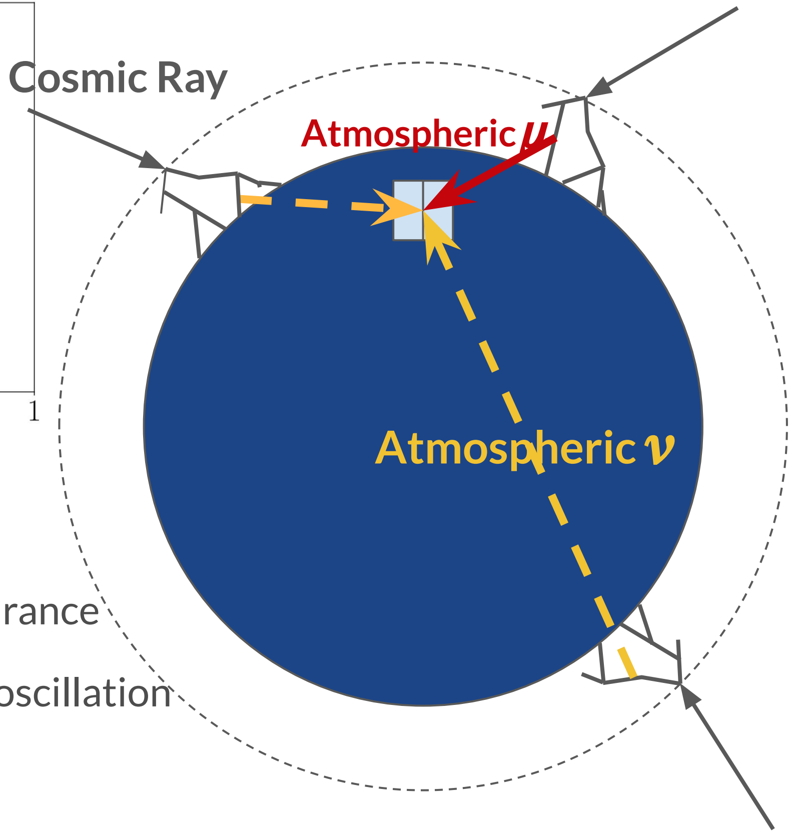
Sterile neutrino prospects with atmospheric neutrinos in DUNE

Austin Schneider | Barbara Skrzypek | Carlos Argüelles | Janet Conrad

Atmospheric neutrinos



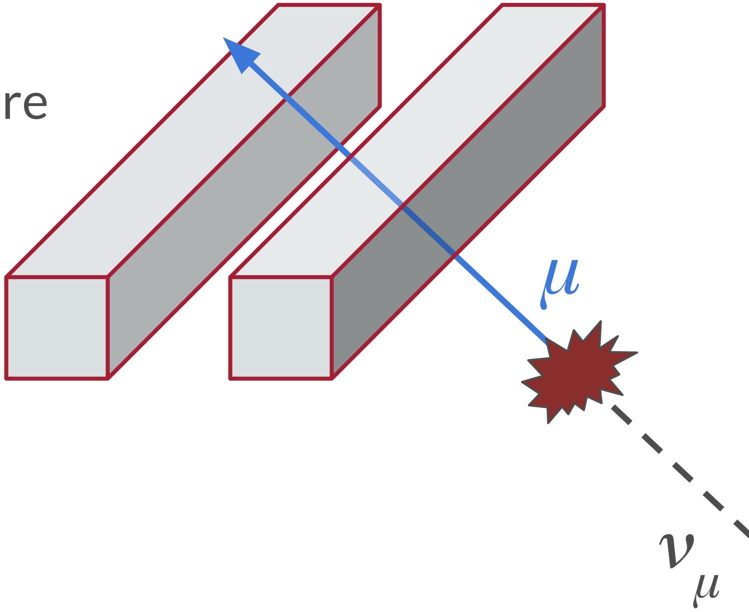




- Many baselines and energies
- Upgoing muons ⇒ sensitivity to muon neutrino disappearance
- Used by IceCube and others for both standard and BSM oscillation measurements/searches

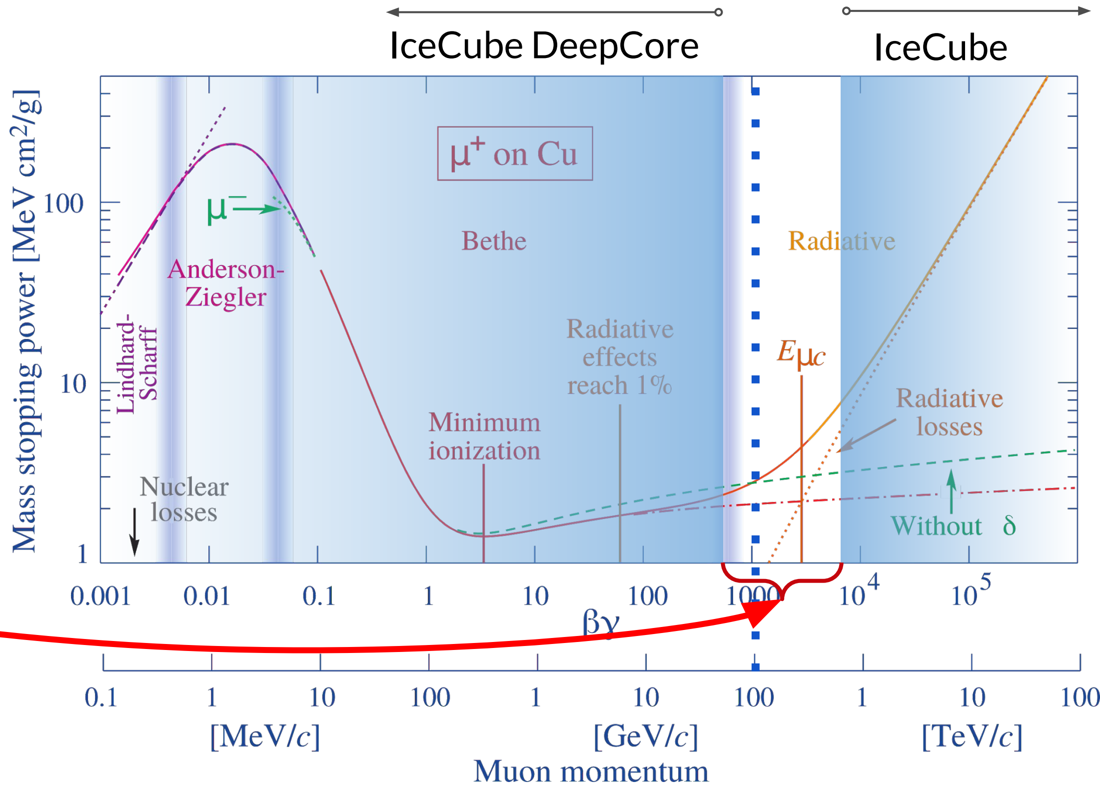
Through-going atmospheric neutrinos

- Initial look at through-going atmospheric muons/neutrinos in DUNE
- Muons from NuMu CC DIS interactions outside fiducial volume
- Effective volume ~10x the fiducial volume
- DUNE far detector data will be available before the beam is online

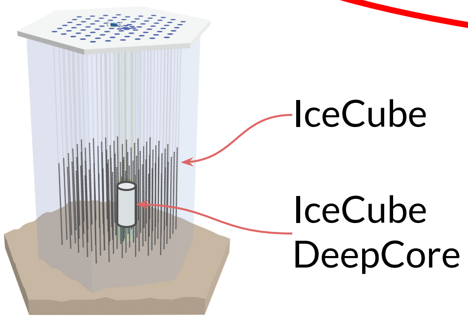


Radiative losses

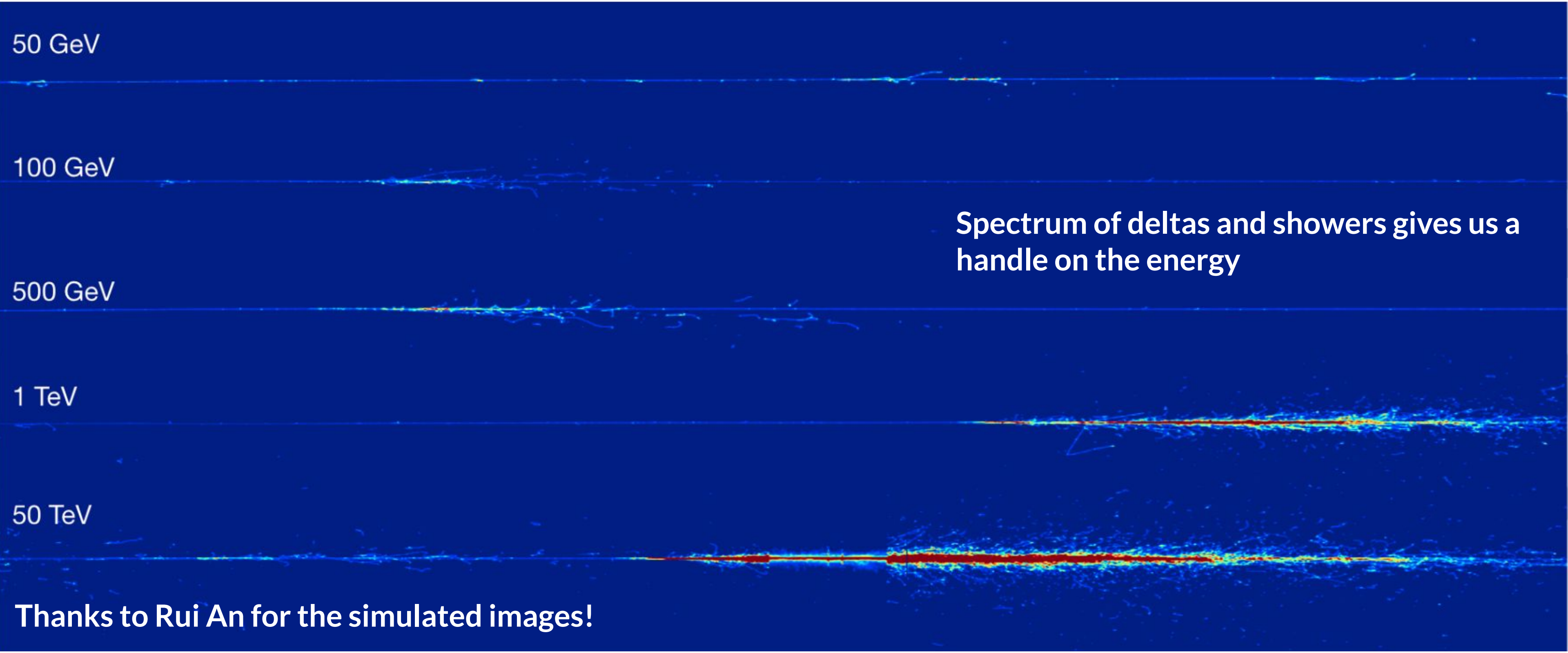
- Cannot measure incoming MIP energy
- Need radiative energy losses
- Above ~100 GeV may be measurable in LArTPC
- IceCube cannot measure energy in this regime
- Sweet spot for DUNE through-going muons



M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018).



Muons in DUNE

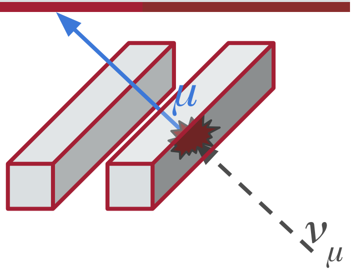


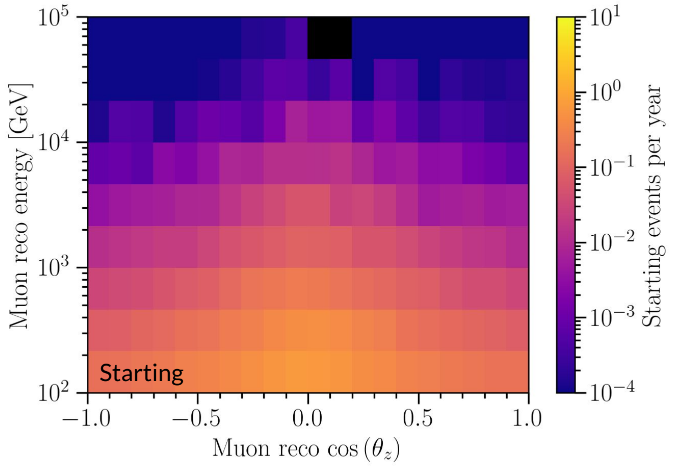
Spectrum of deltas and showers gives us a handle on the energy

Thanks to Rui An for the simulated images!

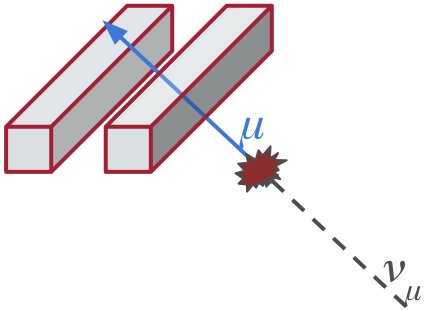
Muons expected in DUNE

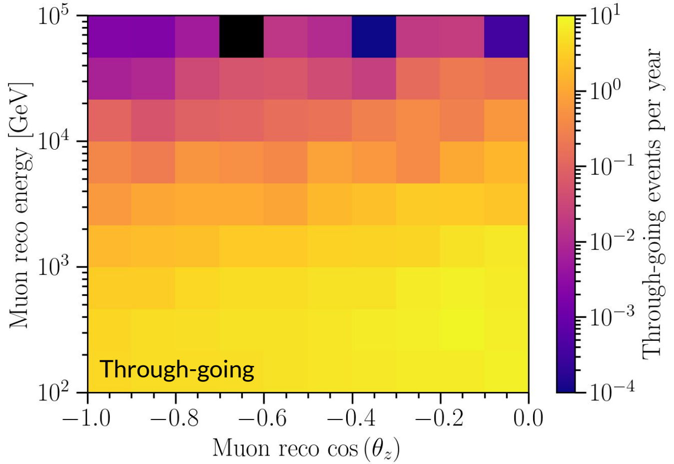
- ~14 starting muons per year per module above 100 GeV
- Assume 10% energy resolution for contained vertex neutrinos*





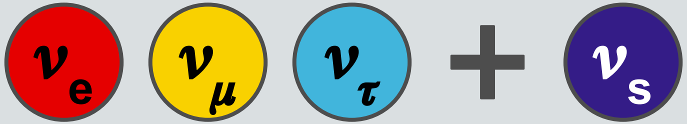
- ~230 upgoing through-going muons per year per module above 100 GeV
- Assume 20% energy resolution for through-going muons*
- **Will show results for 9 module years as an example (~5 years of running)**

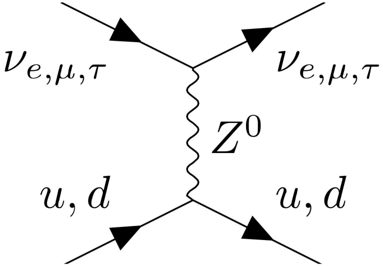


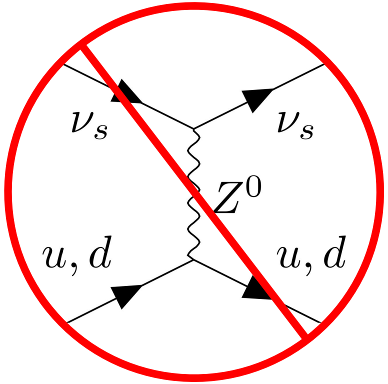


*a 0.1° directional error is assumed

Sterile neutrinos

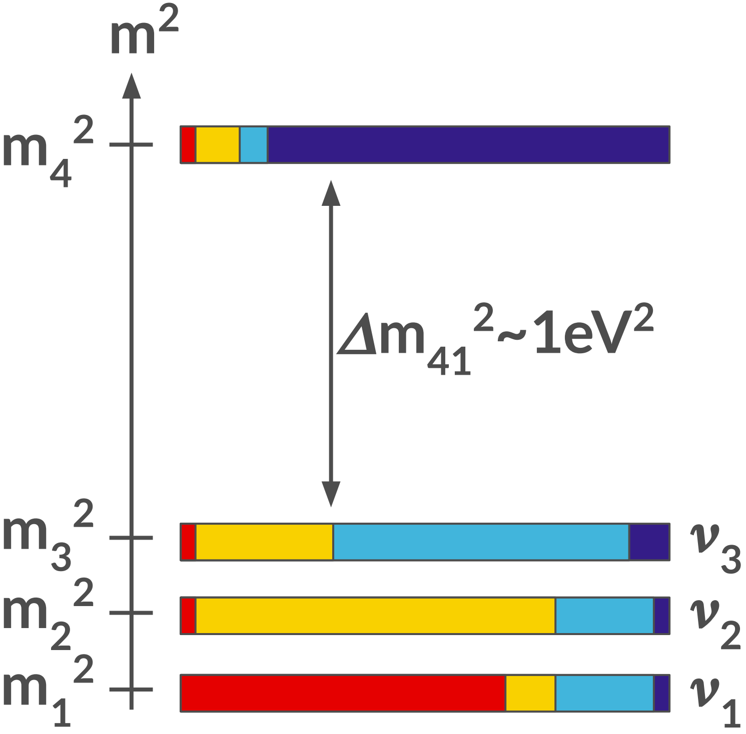






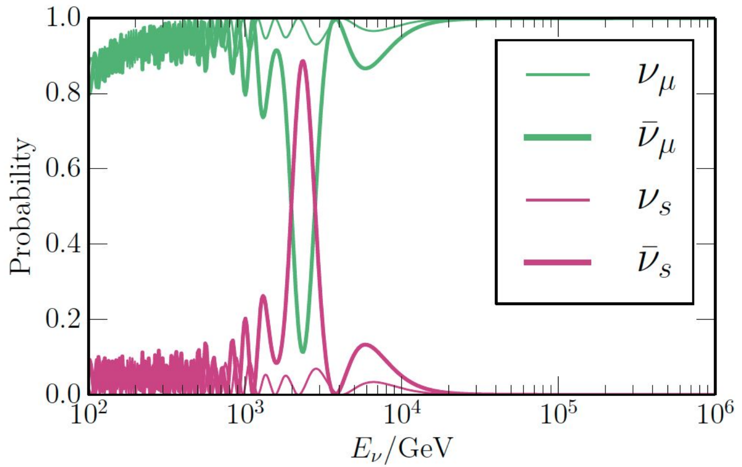
$$U_{3+1} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ \vdots & & \vdots & U_{\mu 4} \\ \vdots & & \vdots & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix}$$

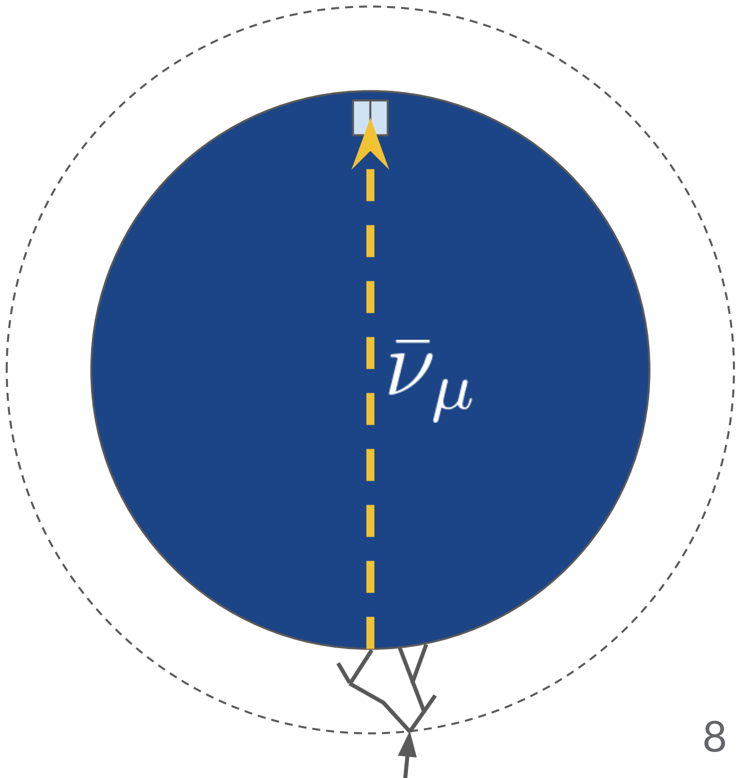
$$\begin{aligned}
\sin^2 2\theta_{ee} &= \sin^2 2\theta_{14} && = 4(1 - |U_{e4}|^2)|U_{e4}|^2 \\
\sin^2 2\theta_{\mu\mu} &= 4\cos^2\theta_{14}\sin^2\theta_{24}(1 - \cos^2\theta_{14}\sin^2\theta_{24}) && = 4(1 - |U_{\mu 4}|^2)|U_{\mu 4}|^2 \\
\sin^2 2\theta_{\tau\tau} &= 4\cos^2\theta_{14}\cos^2\theta_{24}\sin^2\theta_{34}(1 - \cos^2\theta_{14}\cos^2\theta_{24}\sin^2\theta_{34}) && = 4(1 - |U_{\tau 4}|^2)|U_{\tau 4}|^2 \\
\sin^2 2\theta_{\mu e} &= \sin^2 2\theta_{14}\sin^2\theta_{24} && = 4|U_{\mu 4}|^2|U_{e4}|^2 \\
\sin^2 2\theta_{e\tau} &= \sin^2 2\theta_{14}\cos^2\theta_{24}\sin^2\theta_{34} && = 4|U_{e4}|^2|U_{\tau 4}|^2 \\
\sin^2 2\theta_{\mu\tau} &= \sin^2 2\theta_{24}\cos^4\theta_{14}\sin^2\theta_{34} && = 4|U_{\mu 4}|^2|U_{\tau 4}|^2
\end{aligned}$$



Sterile neutrino signature

- Matter effects produce resonance in muon antineutrino disappearance
- Produces a sharp feature in energy and zenith angle!
- **Δm^2_{41}** = 1 eV^2, $\sin^2(2\theta_{24})$ = 0.1:

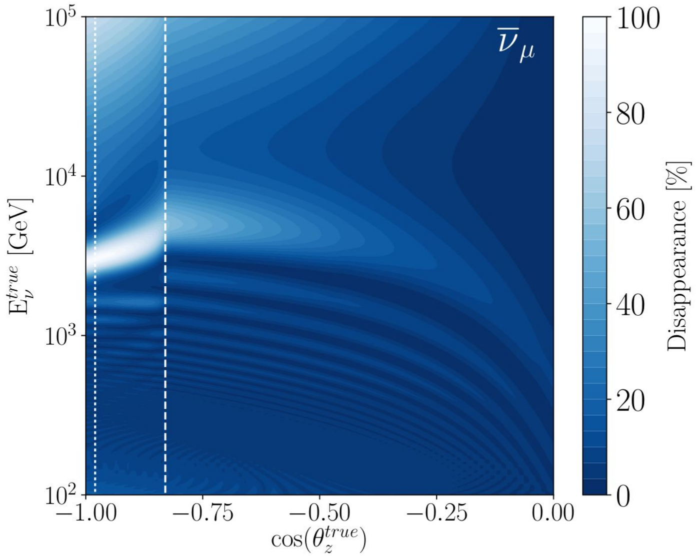


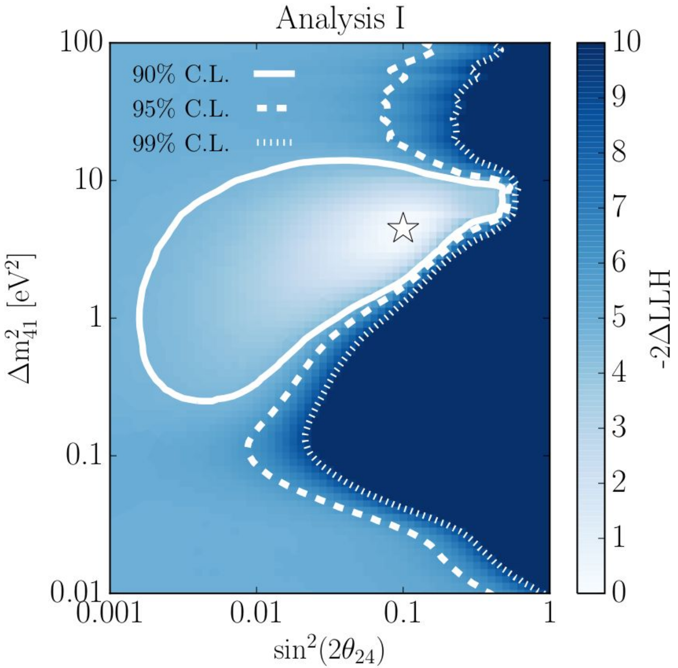


Sterile neutrino signature and IceCube result

- Search for 3+1 matter resonance
- Scan in $\sin^2(2\theta_{24})$ and Δm^2
- θ_{34} is fixed to zero

$$E^M_{\mathrm{crit}} = \frac{\Delta m^2 \cos(2\theta)}{\sqrt{2} G_F n_e} \approx \frac{\Delta m^2 \cos(2\theta)}{0.038(\rho[g/cm^3])}$$

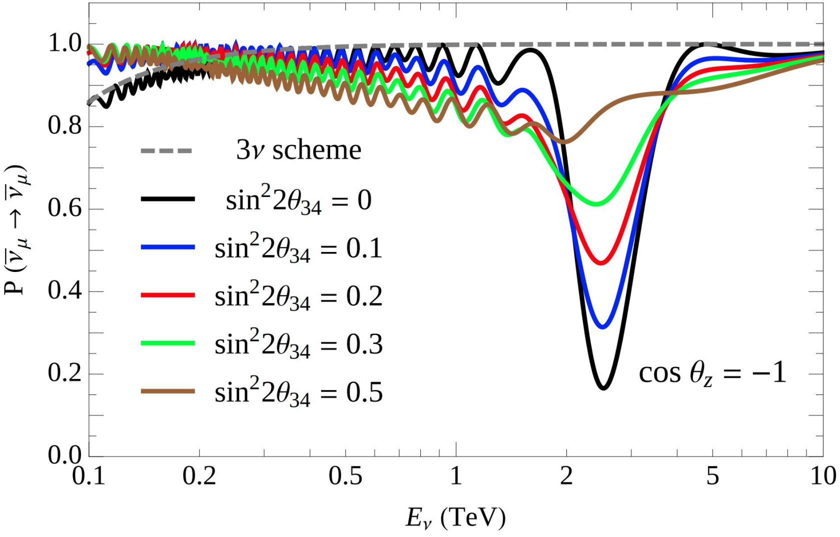




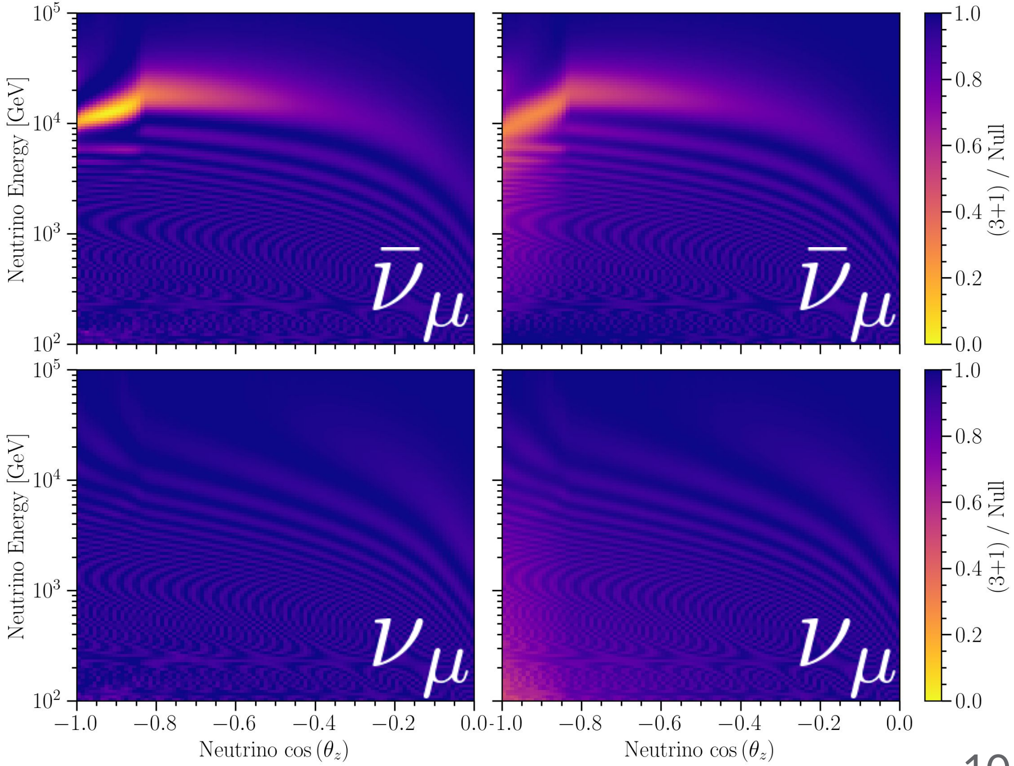
IceCube Collaboration, Phys. Rev. Lett. 125, 141801
https://doi.org/10.1103/PhysRevLett.125.141801

IceCube Collaboration, Phys. Rev. D 102, 052009
https://doi.org/10.1103/PhysRevD.102.052009

Effect of θ_{34}



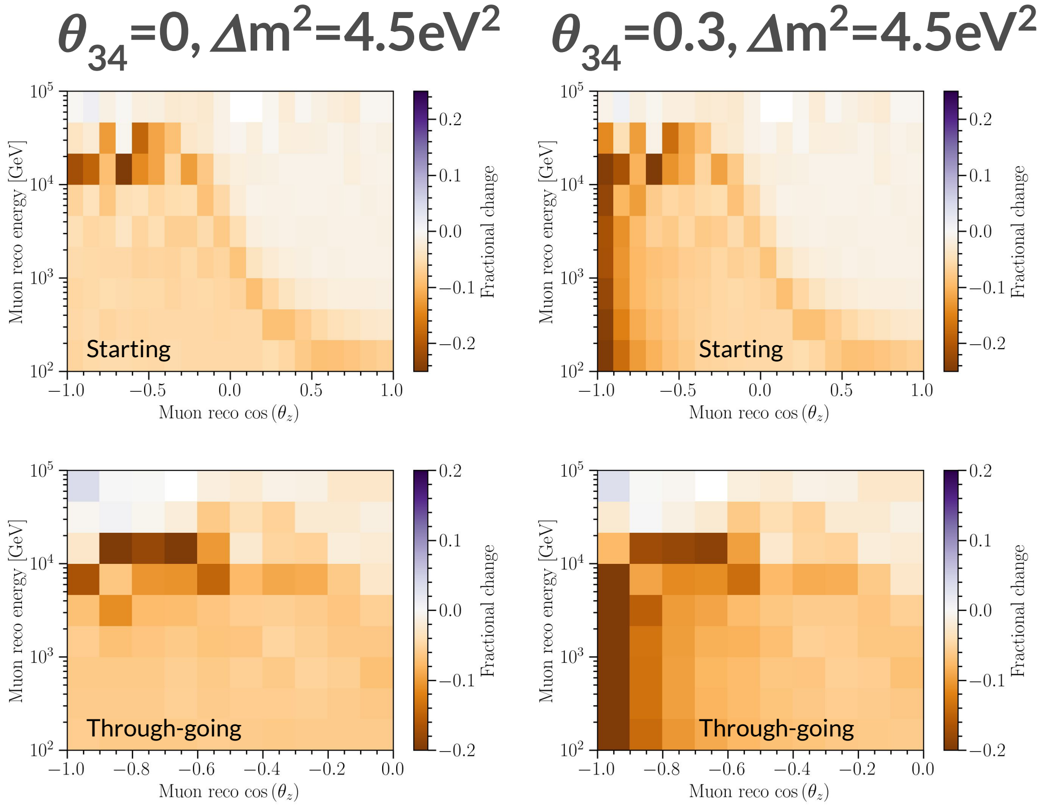
θ_{34}=0, Δm^2=4.5eV^2 θ_{34}=0.3, Δm^2=4.5eV^2



Esmaili, A., Smirnov, A.Y., *J. High Energ. Phys.* 2013, 14 (2013). https://doi.org/10.1007/JHEP12(2013)014

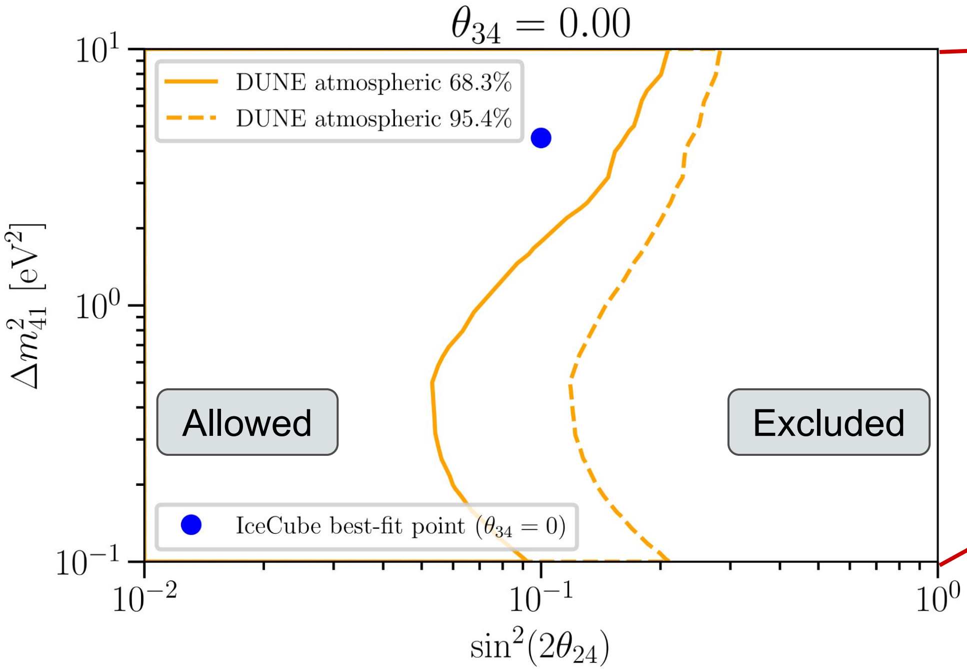
3+1 signature in DUNE

- Prevalent in DUNE atmospheric neutrino energy regime
- Figure: (3+1) neutrino expectation over 3 neutrino expectation
    - Left: θ_{34}=0
    - Right: θ_{34}=0.3
- Detector resolution preserves the strength of the oscillation effect

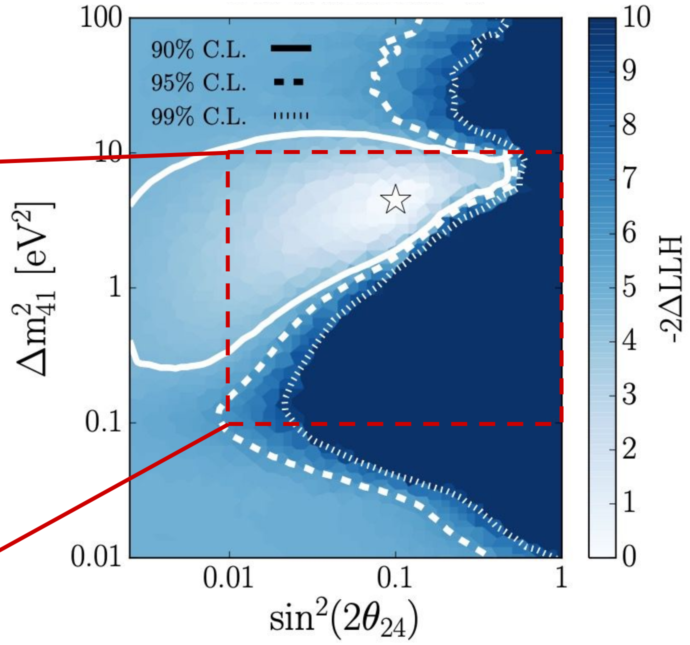


Sensitivity to 3+1 scenario

- 9 module-years (first ~5 years of operation)
- 5% normalization uncertainty, 0.01 CR spectral uncertainty
- 3 neutrino oscillation parameters fixed
- Wilks' w/ 3 degrees of freedom (using Asimov data)



IceCube results θ_{34}=0
8 years of data



IceCube Collaboration, Phys. Rev. D 102, 052009
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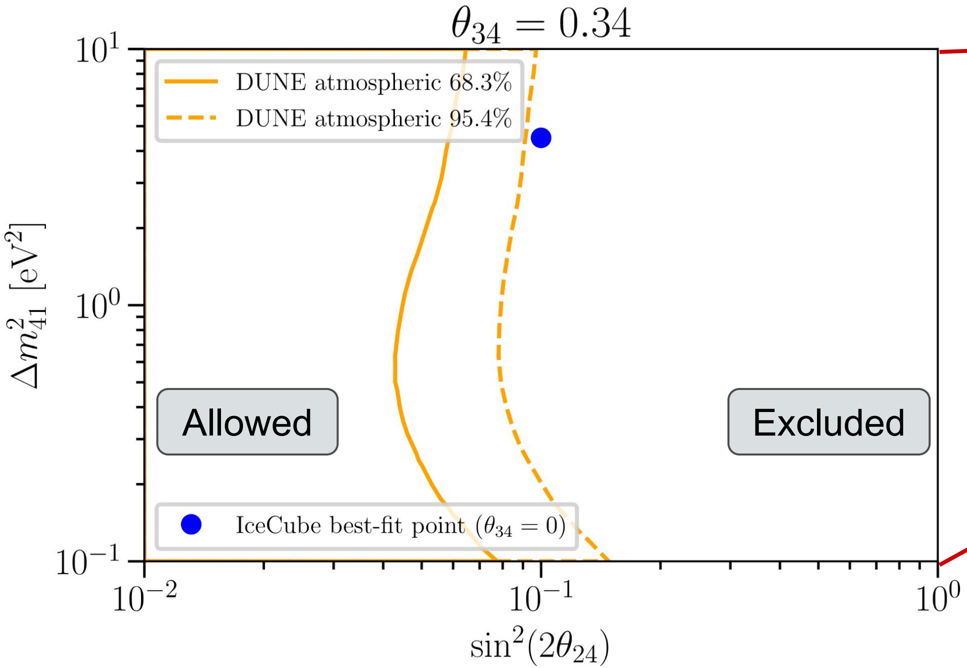

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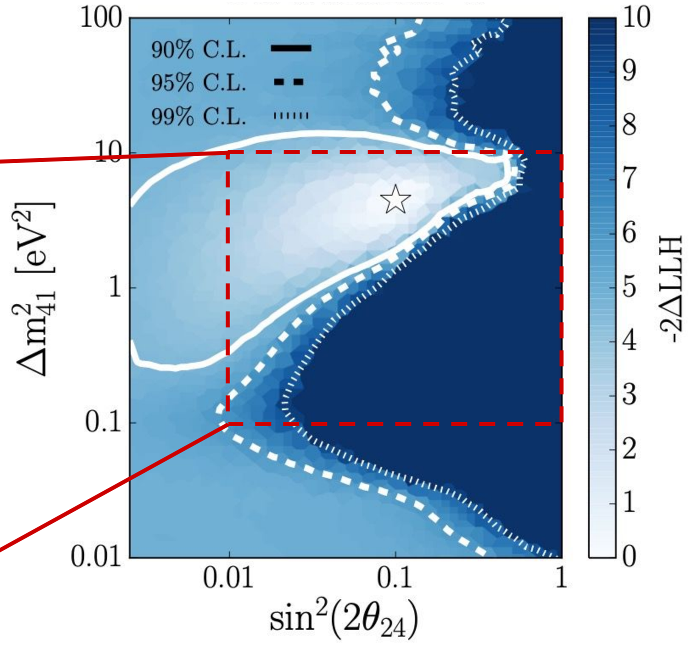


IceCube Collaboration, Phys. Rev. D 102, 052009
https://doi.org/10.1103/PhysRevD.102.052009

Other opportunities

- Recent workshop explored BSM synergies in atmospheric neutrinos between IceCube and DUNE
- Workshop summary: https://harvard-neutrinos.rc.fas.harvard.edu/event/5/sessions/4/#20210618
- Promising topics to explore:
  - Cross section and inelasticity measurements in the gap region
  - Z-prime model constraints
  - Sidereal Lorentz violation
  - Heavy neutral leptons
  - Millicharged particles
  - Staus
  - Boosted dark matter
  - Unitarity tests

IceDUNE

JUNE 16-18, 2021

ICECUBE SOUTH POLE NEUTRINO OBSERVATORY

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

Summary

- Through-going muons provide ~10x effective volume boost
- DUNE far detector is sensitive to a challenging energy regime
- Sensitivity to 3+1 is complementary to other experiments
- More to see with other BSM physics scenarios

Next steps:

- Developing reconstruction techniques for muons in LArTPCs
- Exploring new scenarios
- Complementarity with other neutrino experiments

This work: https://arxiv.org/abs/2106.01508

Bonus slides

Lorentz violation

- Add higher dimensional operators to effective Hamiltonian

$$H \sim \frac{m^2}{2E} + \mathring{a}^{(3)} - E \cdot \mathring{c}^{(4)} + E^2 \cdot \mathring{a}^{(5)} - E^3 \cdot \mathring{c}^{(6)} \cdots$$

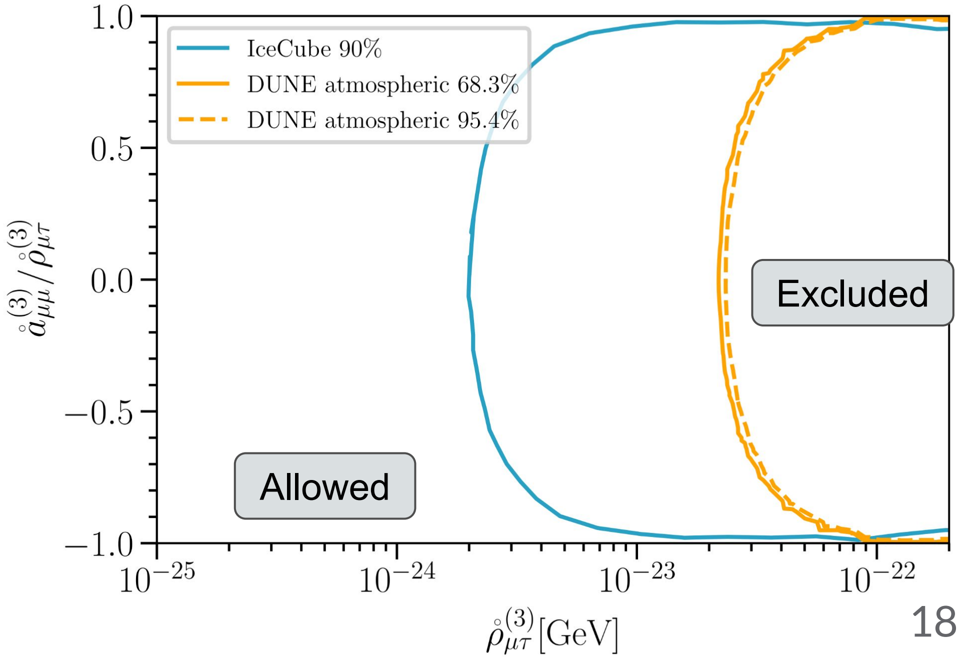
- Causes neutrino disappearance
- Focus on mu/tau mixing ⇒ muon neutrino and muon antineutrino disappearance
- Parameterization:
  - Strength of LV $\rho^{(3)} = \sqrt{(\mathring{a}^{(3)}_{\mu\mu})^2 + (\mathrm{Re}[\mathring{a}^{(3)}_{\mu\tau}])^2 + (\mathrm{Im}[\mathring{a}^{(3)}_{\mu\tau}])^2}$
  - Fraction on the diagonal $\mathring{a}^{(3)}_{\mu\mu}/\rho^{(3)}$

$$\mathring{a}^{(3)} = \begin{pmatrix} a_{ee} & a_{e\mu} & a_{e\tau} \\ a^*_{e\mu} & a_{\mu\mu} & a_{\mu\tau} \\ a^*_{e\tau} & a^*_{\mu\tau} & a_{\tau\tau} \end{pmatrix} \qquad a_{\tau\tau} = -a_{ee} - a_{\mu\mu}$$

Lorentz violation dimension 3 sensitivity

- DUNE atmospheric neutrinos less sensitive to Lorentz violation strength
- More sensitive in the region of minimal flavor violation

- 9 module-years (first ~5 years of operation)
- 5% normalization uncertainty, 0.01 CR spectral uncertainty
- 3 neutrino oscillation parameters fixed
- Wilks' w/ 2 degrees of freedom



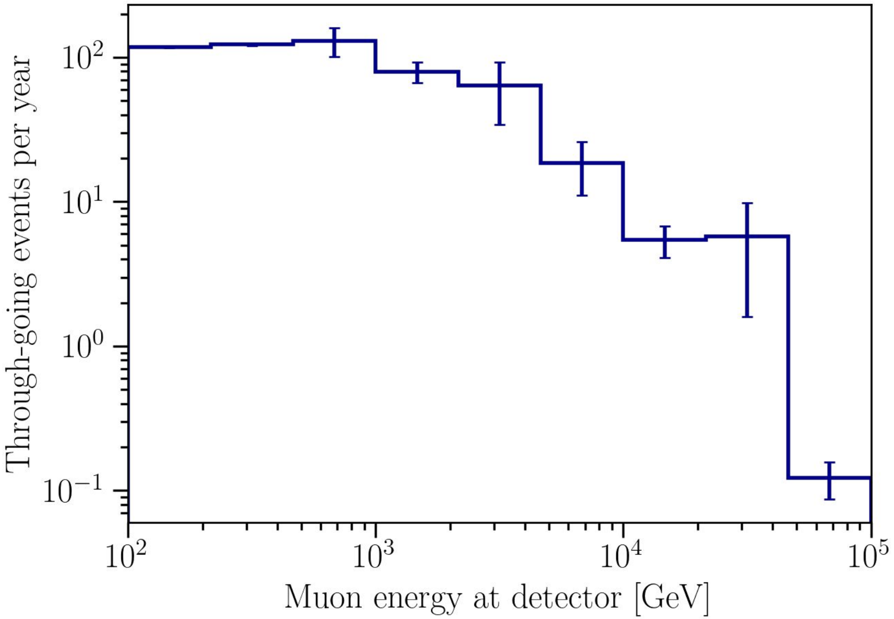
Analysis details/assumptions

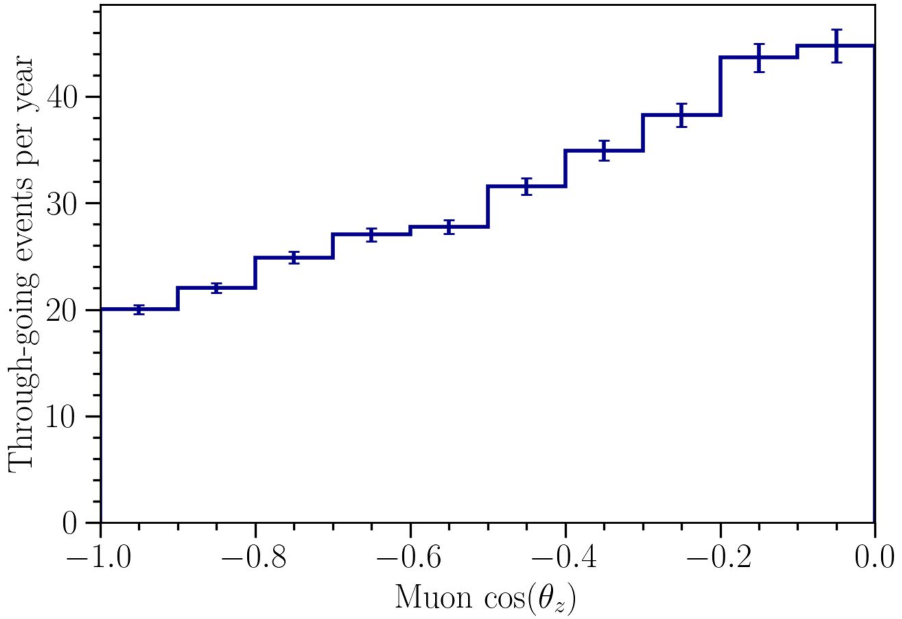
1. 3 neutrino oscillation parameters fixed
2. Directional reconstruction error negligible
3. Energy resolution of muons is 10% and 20% for starting and through-going events respectively (log-normal distributed)
4. Simple model for rock
5. 14m x 58.2m x 12m liquid argon
6. 13.9m x 58.1m x 11.9m fiducial volume
7. H3a_SIBYLL23C conventional atmospheric flux (from nuflux [https://github.com/icecube/nuflux])
8. Only numu / numubar CC DIS final states assuming CSMS cross sections
9. Total interaction cross section from CSMS (CC + NC DIS)
10. Oscillation probability computed with tau regeneration and Glashow resonance
11. Oscillation probability computed on 1 GeV to 1 PeV 101 point log energy grid * 100 point cos zenith grid
12. Detector center at -1480m from surface (perhaps this should be the top or bottom of the detector?)
13. ~250,000 simulation events at final level
14. MC statistical errors accounted for via likelihood technique [https://austinschneider.github.io/MCLLH/]

Software details

- LeptonInjector for neutrino injection (actually using a custom modified version)
    - [https://github.com/icecube/LeptonInjector]
- LeptonWeighter for weighting (actually using a python re-implementation: LWpy)
    - [https://github.com/austinschneider/LWpy]
    - [https://github.com/IceCubeOpenSource/LeptonWeighter/]
- nuSQuIDS for oscillation (some modifications for Lorentz violation)
    - [https://github.com/austinschneider/nuSQuIDS_LV]
- PROPOSAL for muon propagation (modified for bug-fixes and extra material defs.)
    - [https://github.com/austinschneider/PROPOSAL]
- Custom analysis software used for likelihood problem and nuisance weighting
    - [https://github.com/austinschneider/DUNEAtmo/]

Energy and zenith distribution





Muon energy losses in liquid argon

- Liquid argon density
  - 1.401 g/cm^3
- Total energy loss at 50 GeV
  - 2 MeV cm^2 g^{-1} * rho = 2.8 MeV/cm
- Radiative energy loss at 50 GeV
  - 0.2 MeV cm^2 g^{-1} * rho = 0.28 MeV/cm