A Decade of Atmospheric ν Oscillations with IceCube

Juan Pablo Yáñez

for the IceCube Collaboration

ICECUBE

Neutrino 2024

Milan, Italy

j.p.yanez@ualberta.ca

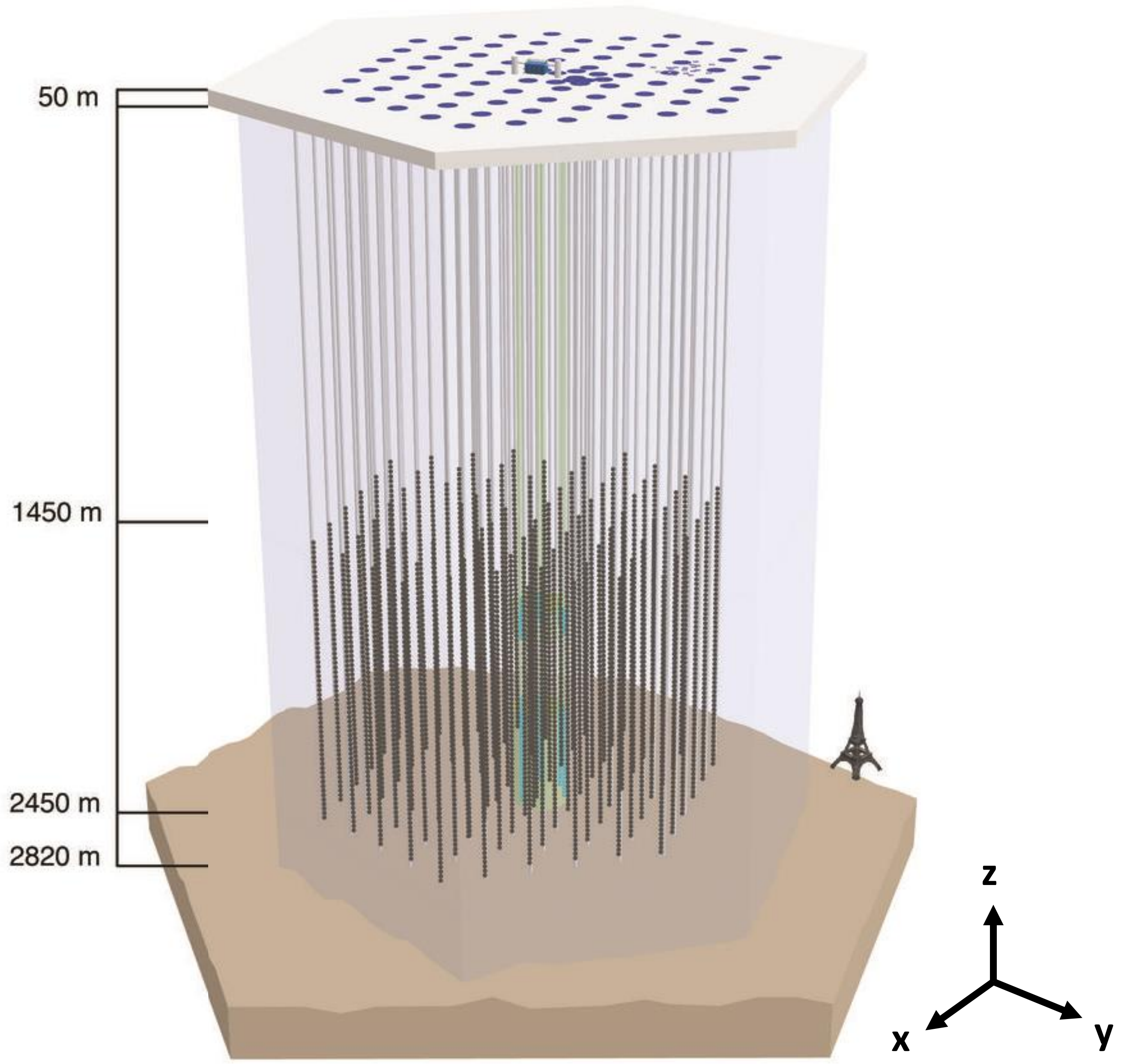
UNIVERSITY OF ALBERTA

N.B. All comparisons are pre-Neutrino 2024

Neutrinos in IceCube

IceCube ν detector

- Ice **Cherenkov ν** detector
- 1.5 – 2.5 km under ice
- 5,160 DOMs on 86 strings
- 1 km^3 volume
- High energy array spacing
  - Δz=17m
  - $\Delta(x, y)$=125m
- LE extension: DeepCore
  - Δz=7m
  - $\Delta(x, y)$=40-70m



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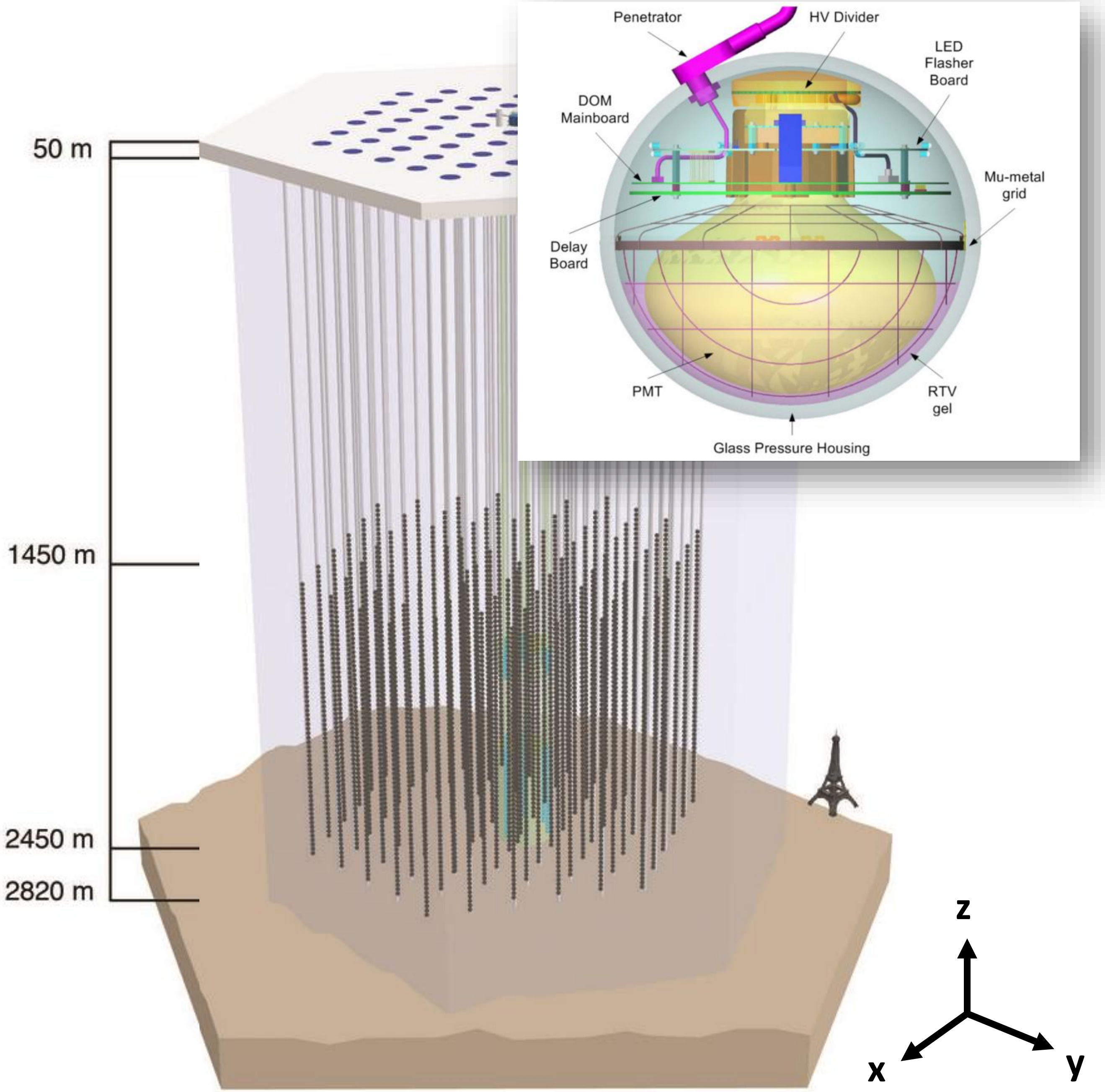

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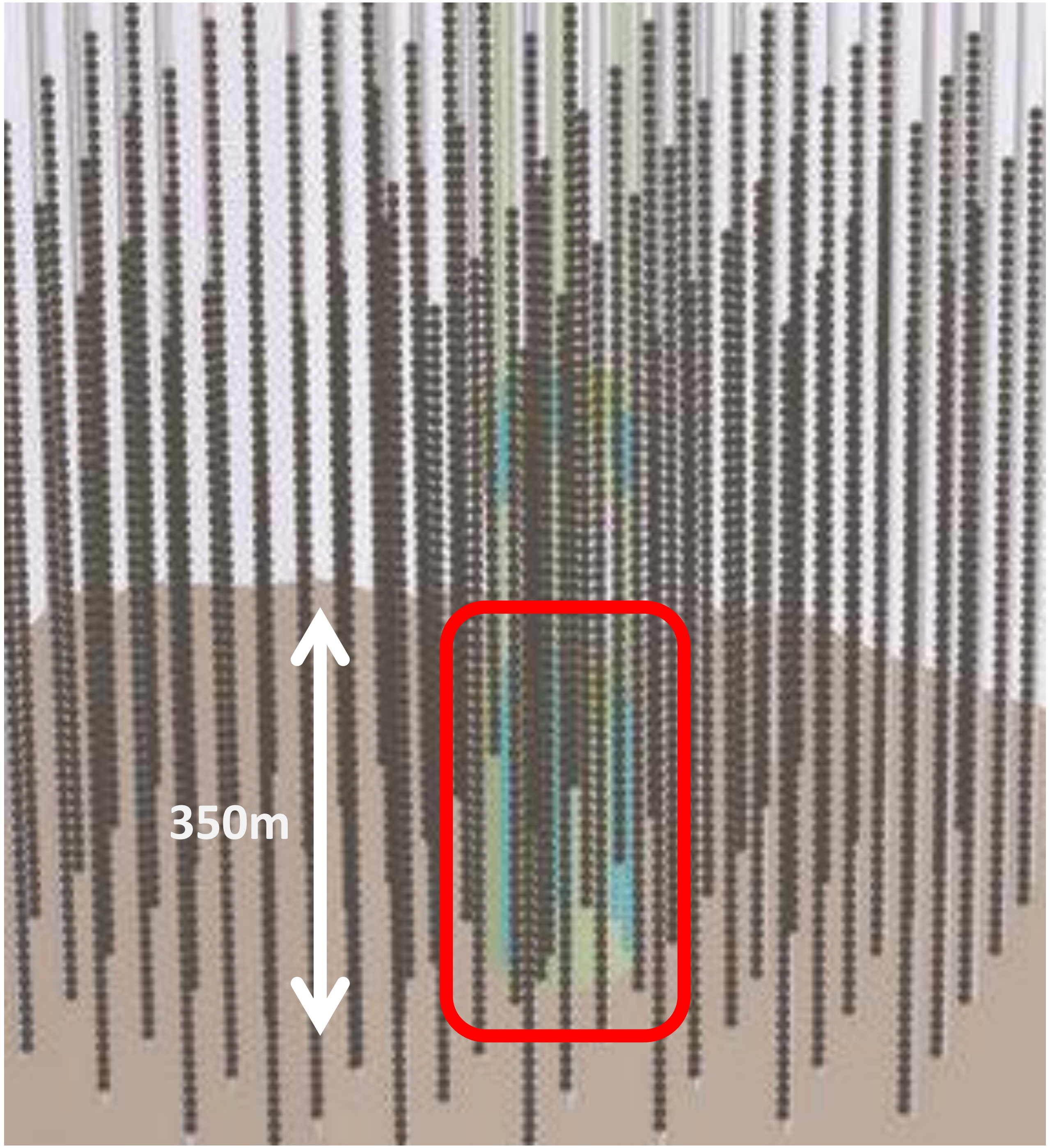
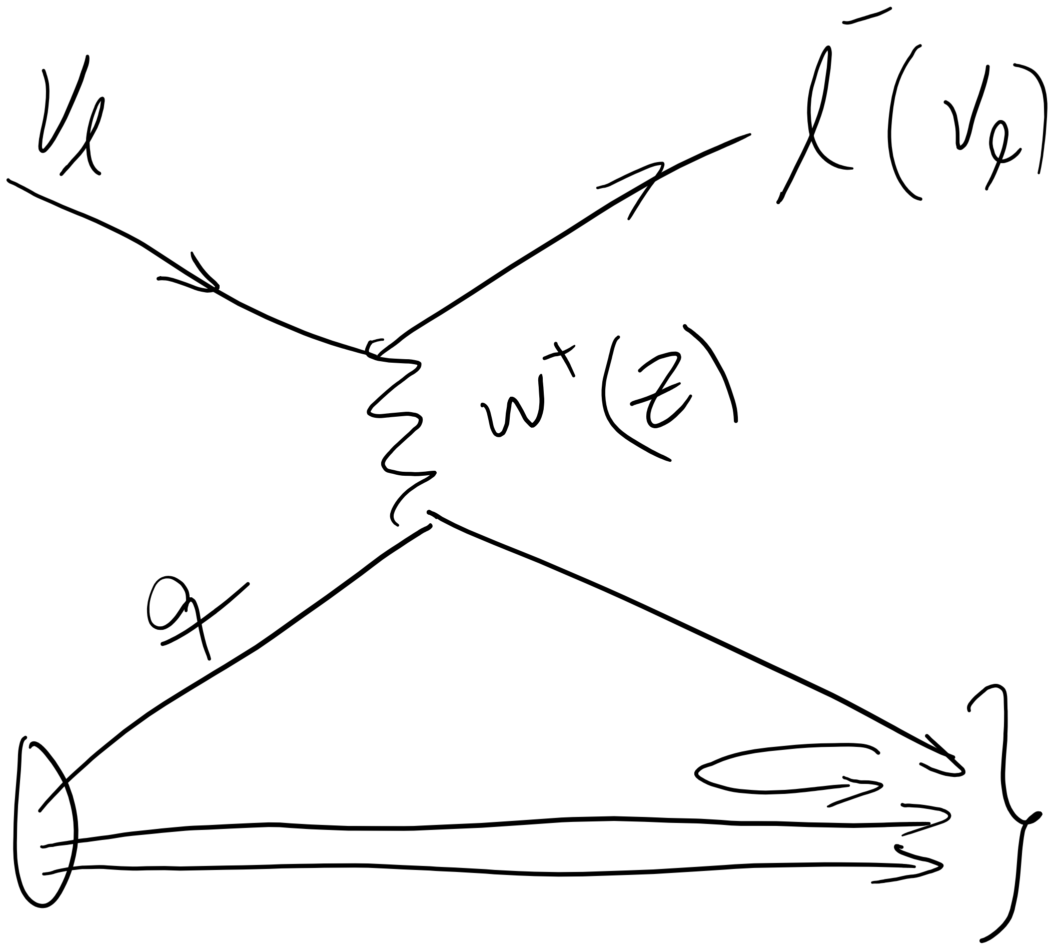


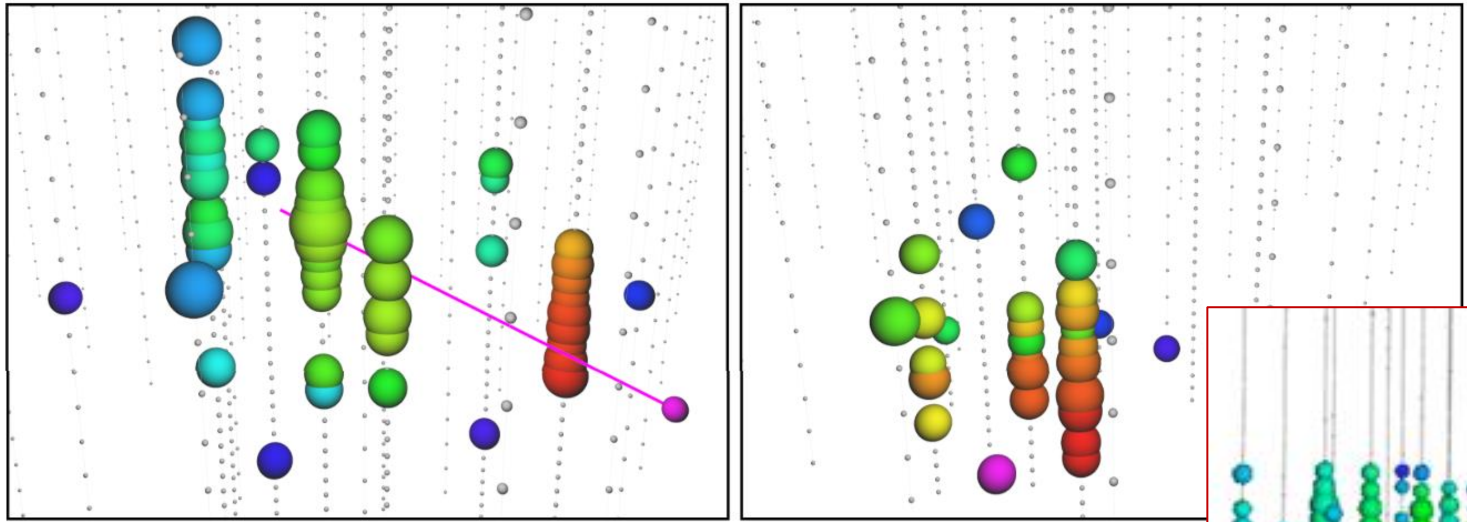
Neutrino **interactions** in IceCube

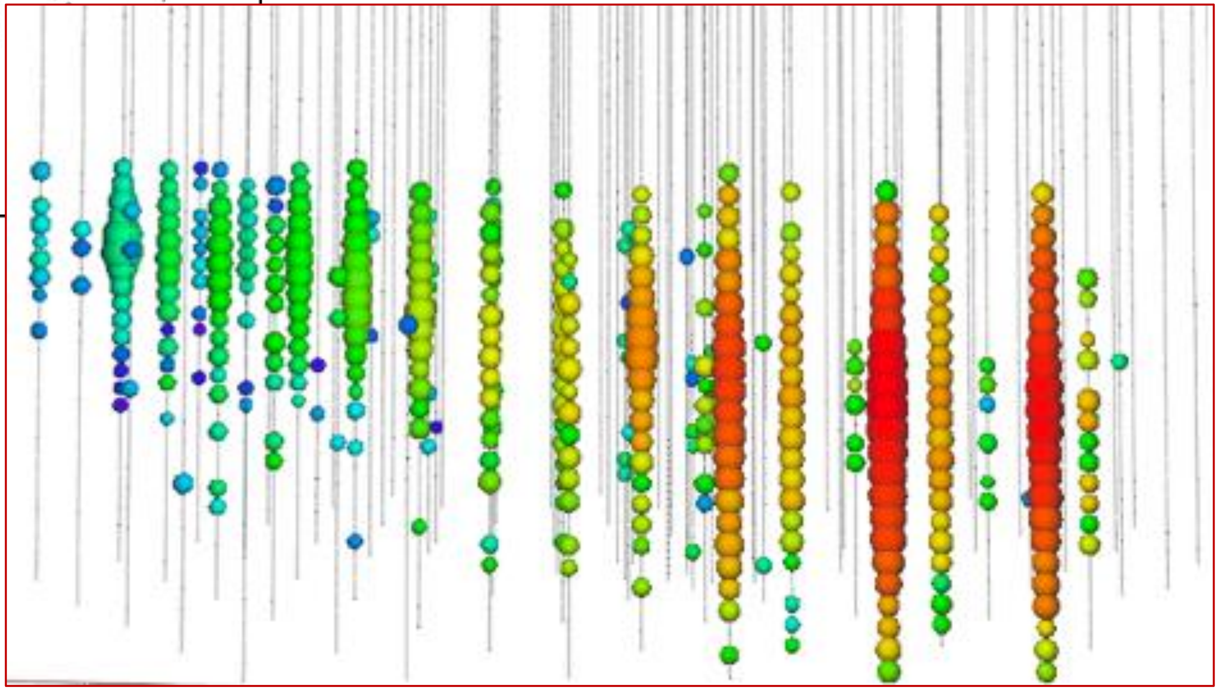


- Energy threshold between a few GeV (DeepCore) and 100 GeV (IceCube)
- Neutrinos mostly interact via Deep Inelastic Scattering (DIS)
  - Hadrons, electrons and most tau leptons produced "localized" particle showers
  - Muons tracks can go kilometers
  - PeV-scale τ tracks hundreds of meters

Events as seen by the detector

GeV events in DeepCore for ν oscillations





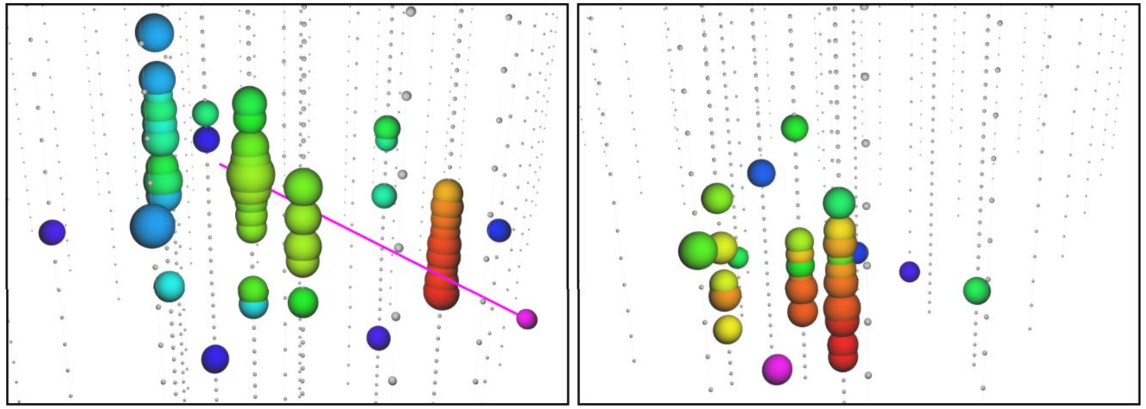
TeV event in IceCube for sterile ν searches

Color indicates time (red=early, blue=late).
Sphere size is proportional to number of photons observed.

Analysis considerations by **energy**

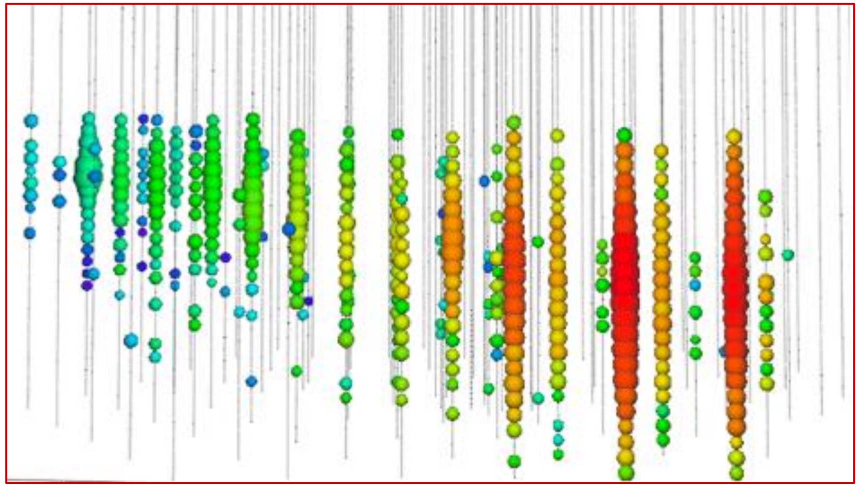
DeepCore (GeV-scale)

- Use events starting in the DeepCore region
  - Strong atm. μ background suppression
  - Mostly contained, good E estimation
  - All flavor, with possibility to tag the presence of a muon (ν_μ-CC)

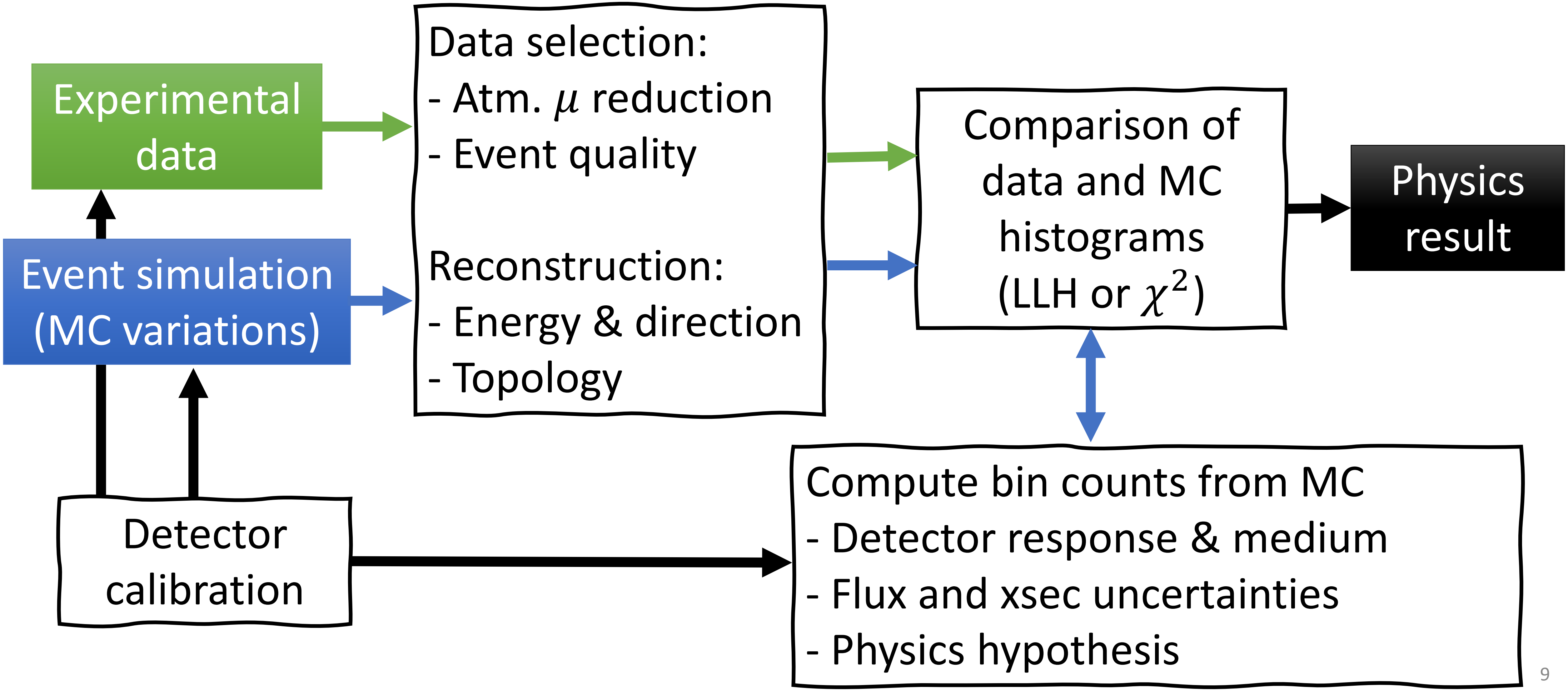


IceCube (TeV scale)

- Use tracks going through the detector
  - No containment, only lower limit on E
  - Sample is ν_μ-CC only
- Excellent pointing
  - Atm. μ bkg suppressed by Earth



Analysis **strategy** for oscillations

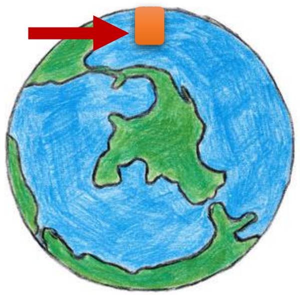


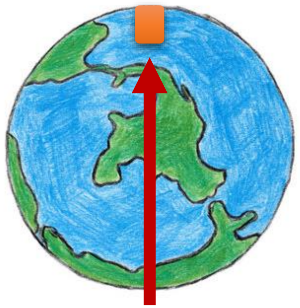
Oscillation results

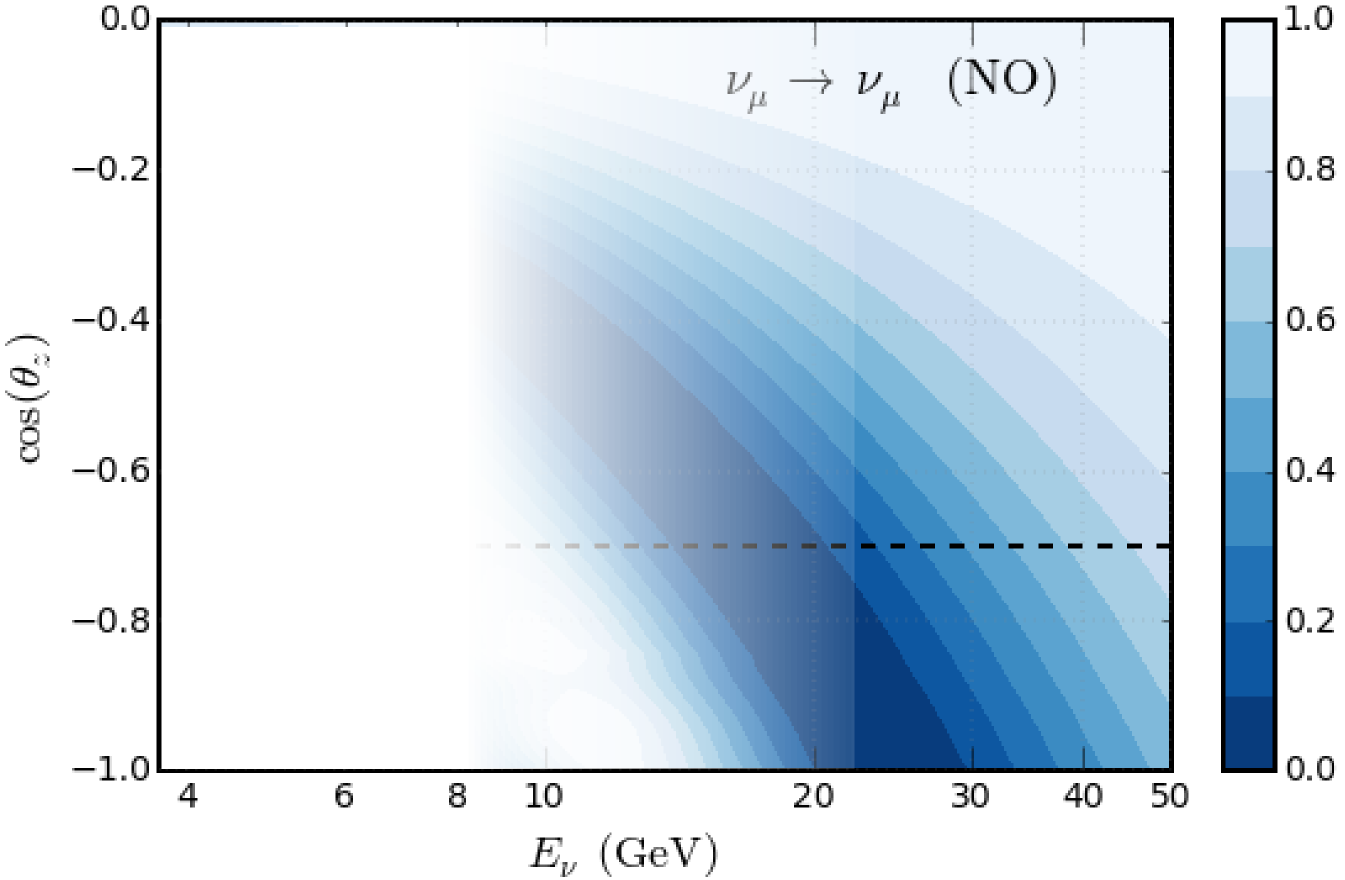
Three flavor paradigm, exotics and steriles

Measurements of neutrino oscillations (DeepCore)

$$P\nu_\mu \to \nu_\mu \simeq 1 - \sin^2 2\theta_{23} \ \sin^2\left(\frac{\Delta m^2_{32}}{4E} L\right)$$

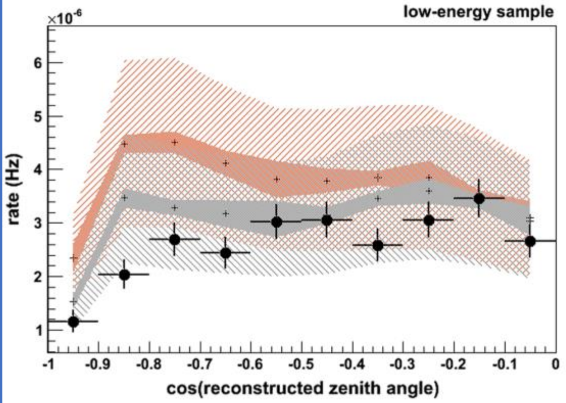


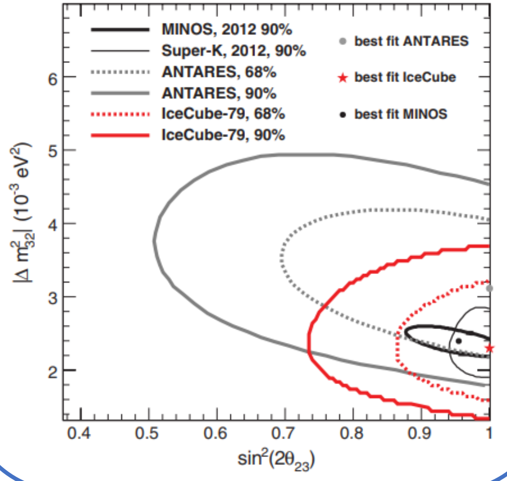




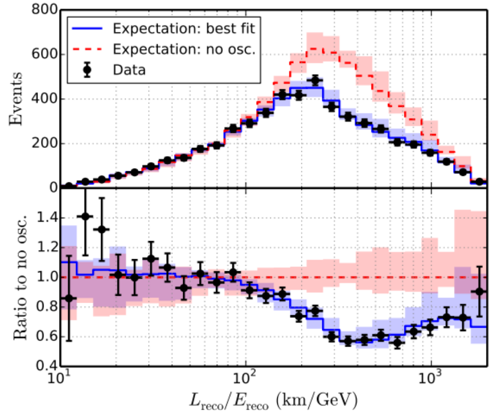
Atmospheric oscillations **progression**

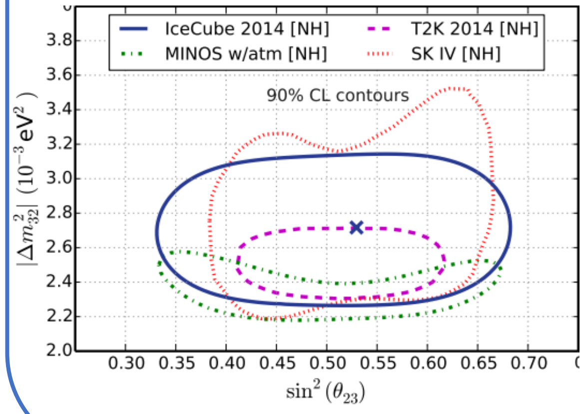
IceCube, PRL 111, 081801 **(2013)**
700 events



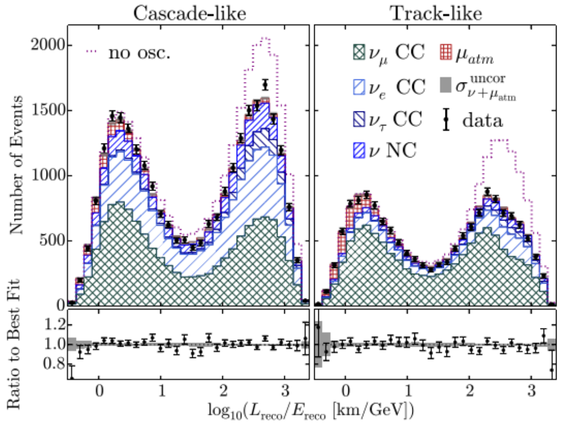


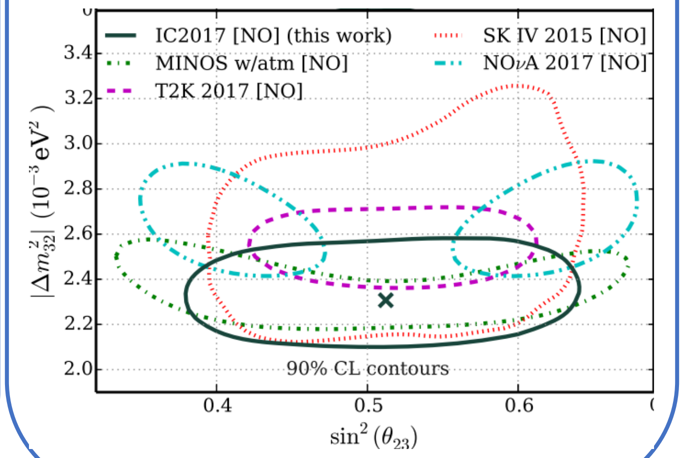
IceCube, PRD 91, 072004 **(2015)**
~5k events, "golden events"



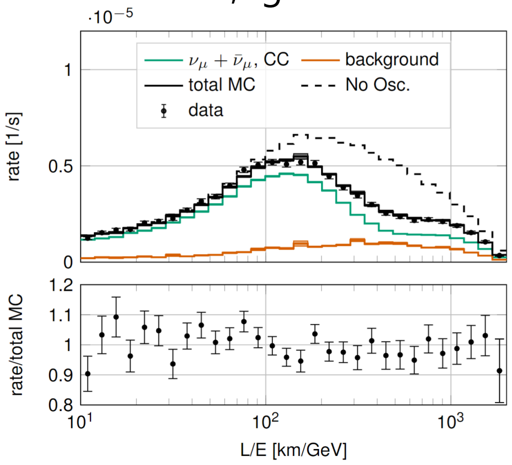


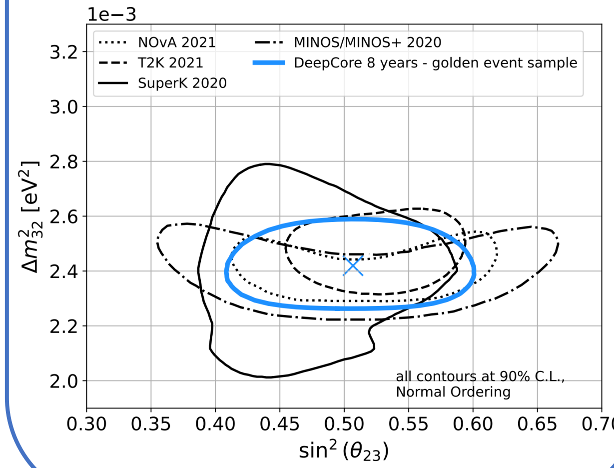
IceCube, PRL 120, 071801 **(2018)**
~35k events, inclusive sample





IceCube, PRD 108, 012014 **(2023)**
~22k events, "golden events"





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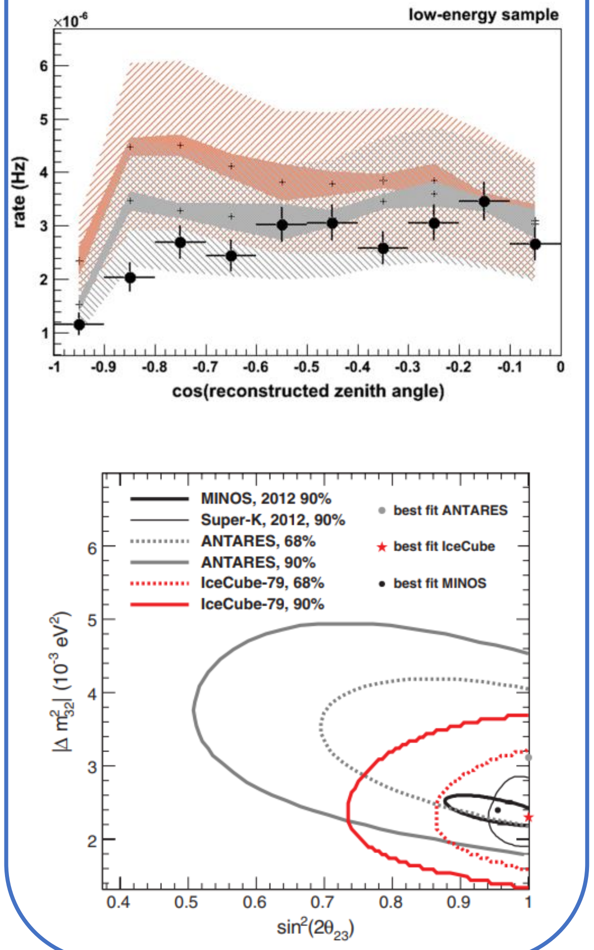

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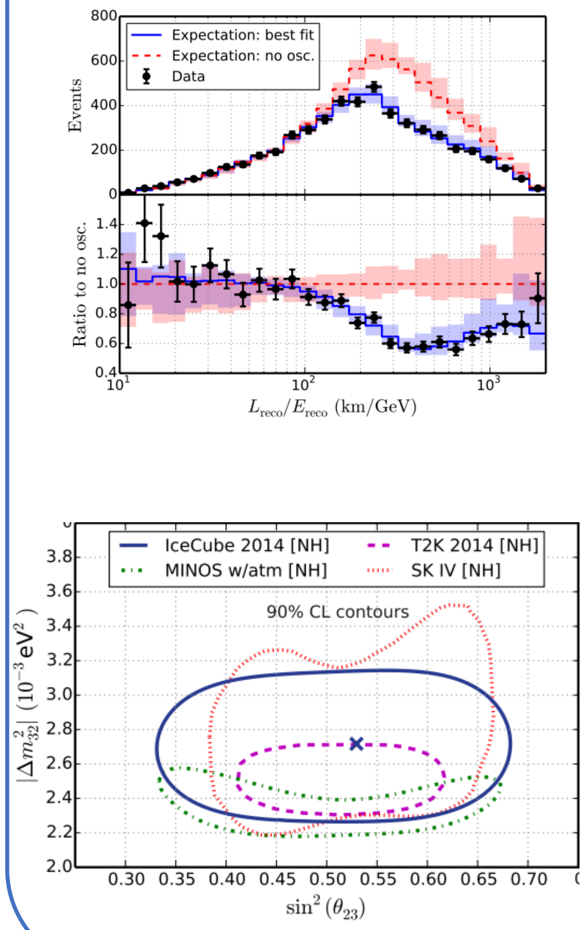

IceCube, PRL 120, 071801 **(2018)**
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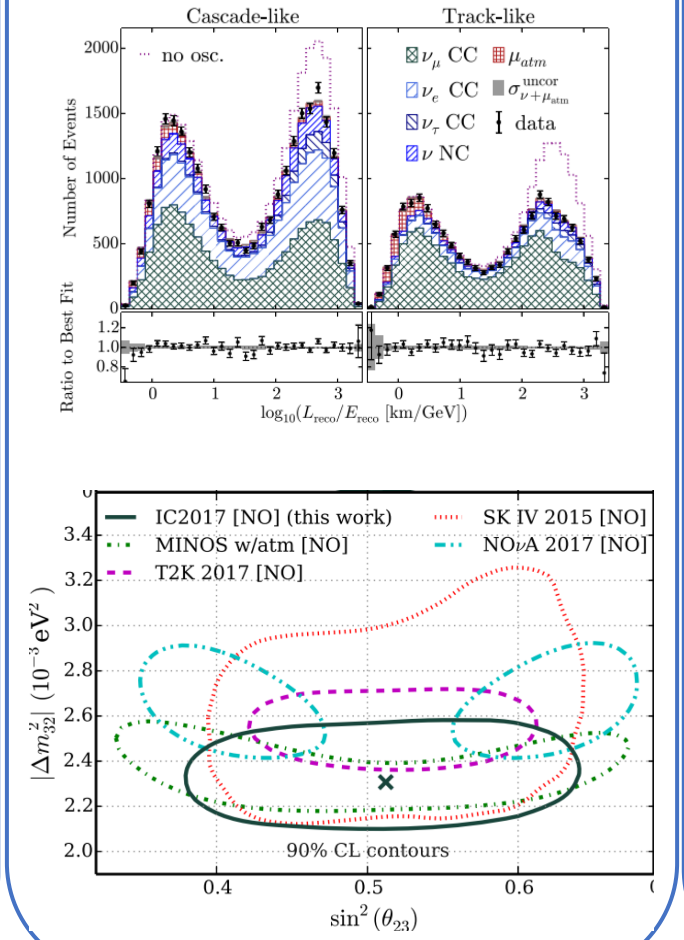

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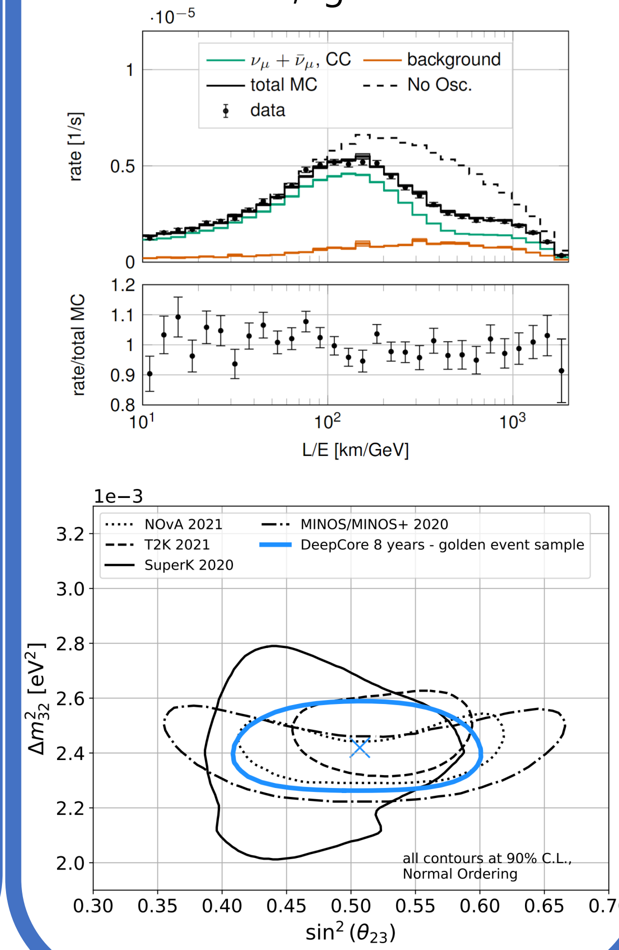
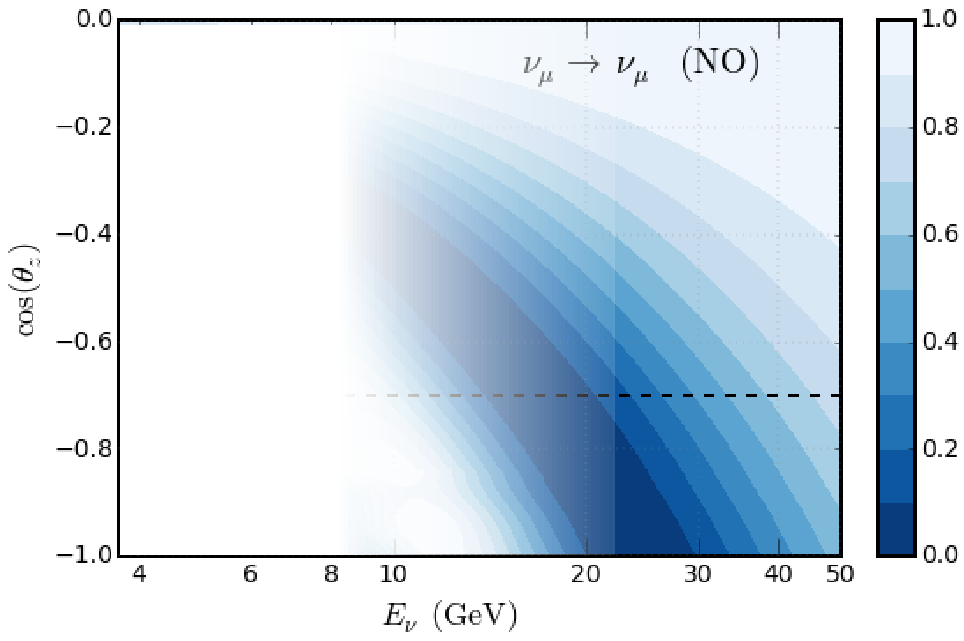
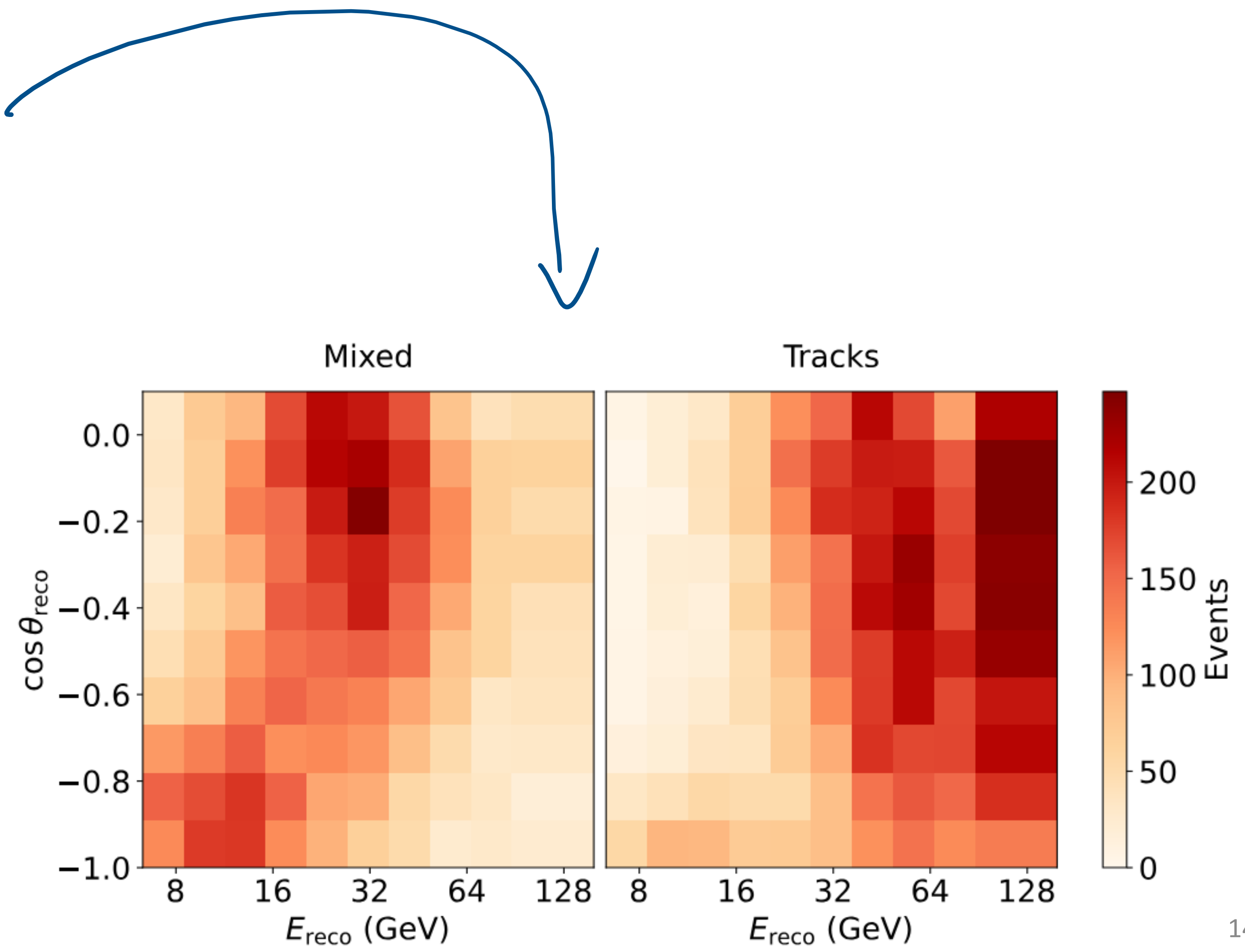


For more details see:
IceCube, PRD 108, 012014 **(2023)**

How? – **strong** signal, multiple **L&E**

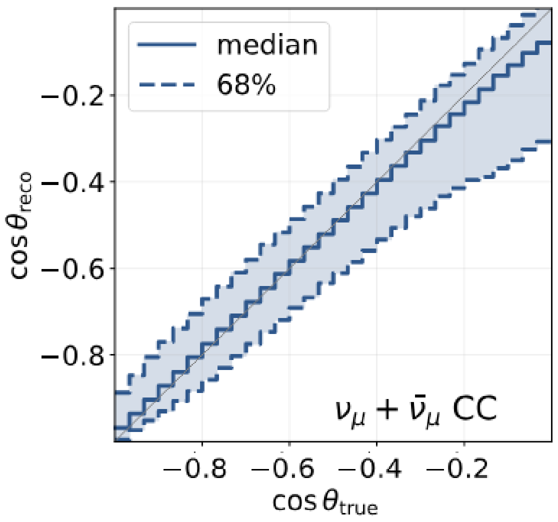


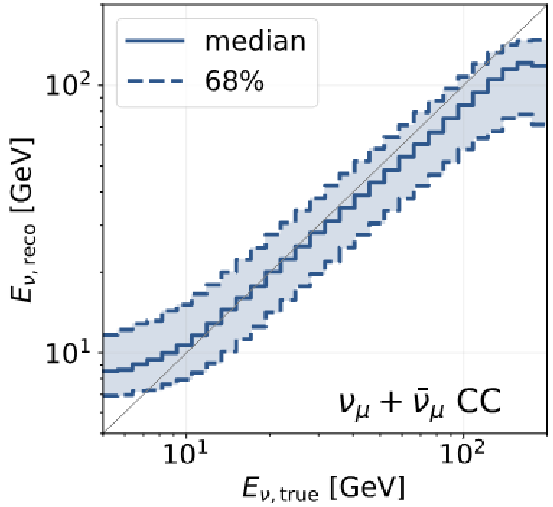


- Broad, single minimum region
  - Visible in the raw data
- Multiple truly long baselines

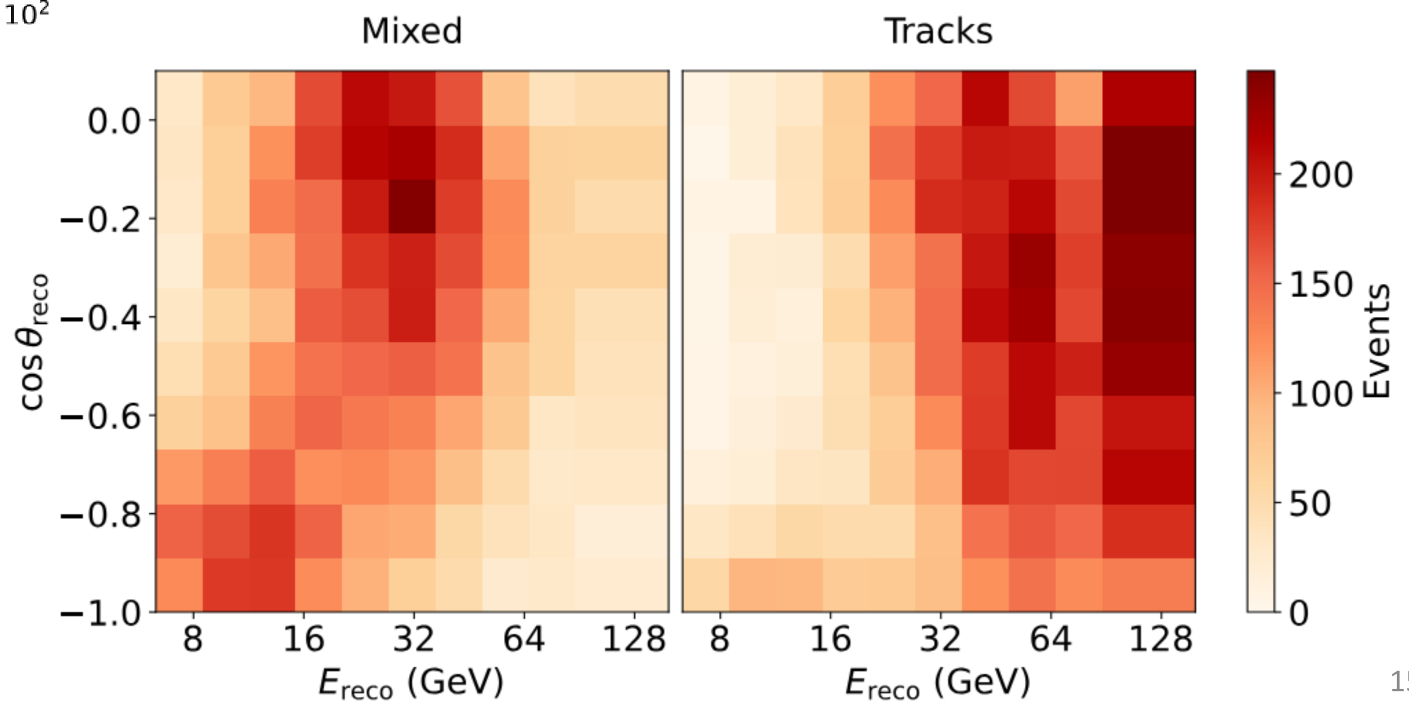
For more details see:
IceCube, PRD 108, 012014 **(2023)**

How? – **resolutions**





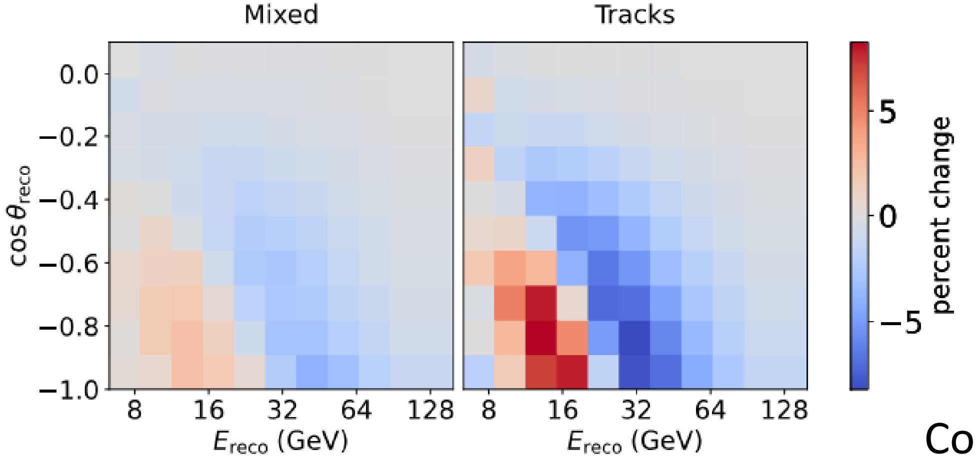
- Sufficiently good resolution in direction and energy to resolve multiple L/E regions



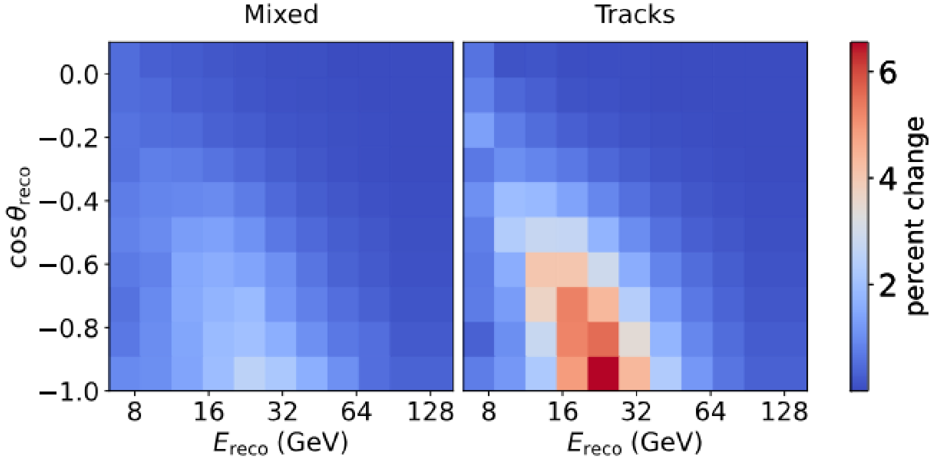
For more details see:
IceCube, PRD 108, 012014 **(2023)**

How? – systematics **handling**

Effects from changing Δm^2_{32}

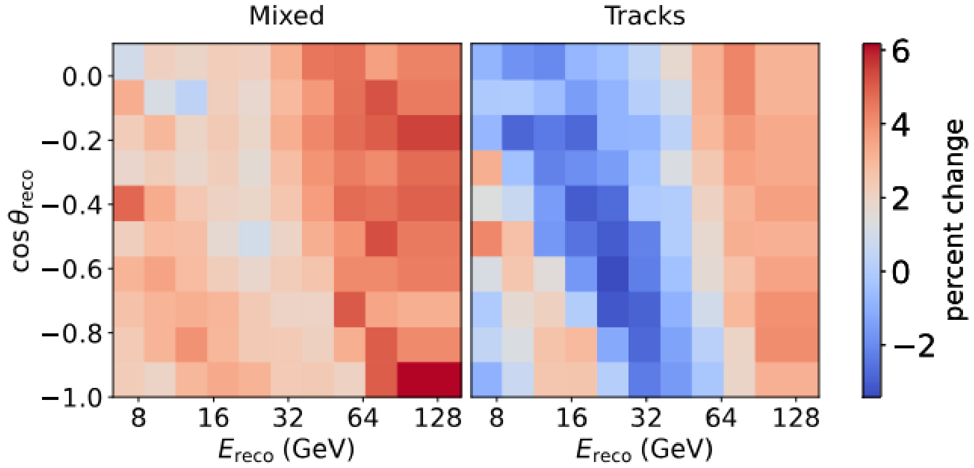


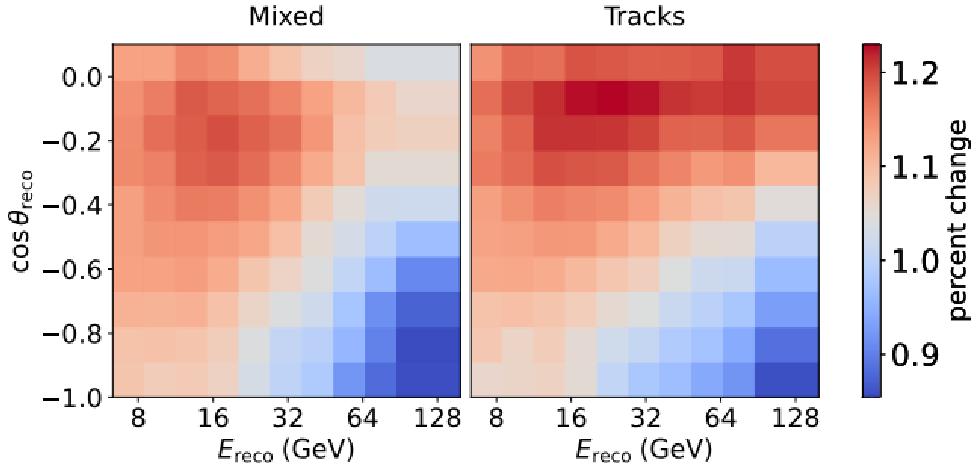
Control regions



Effects from changing θ_{23}

Effects from changing optical efficiency of DOMs (energy scale)





Effect from changing one atm. flux parameter

For more details see:
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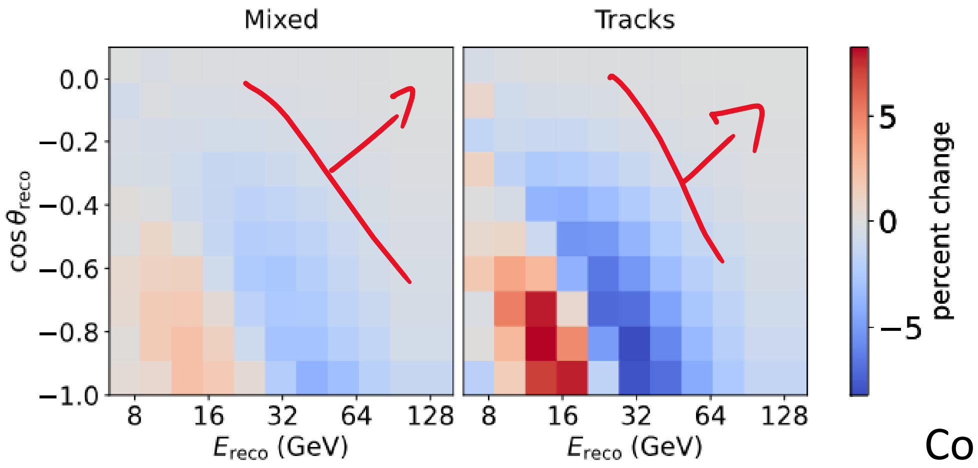

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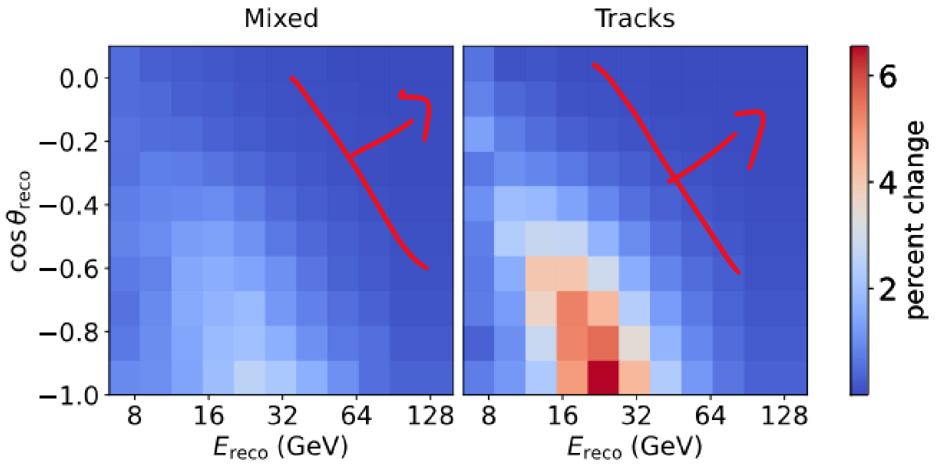

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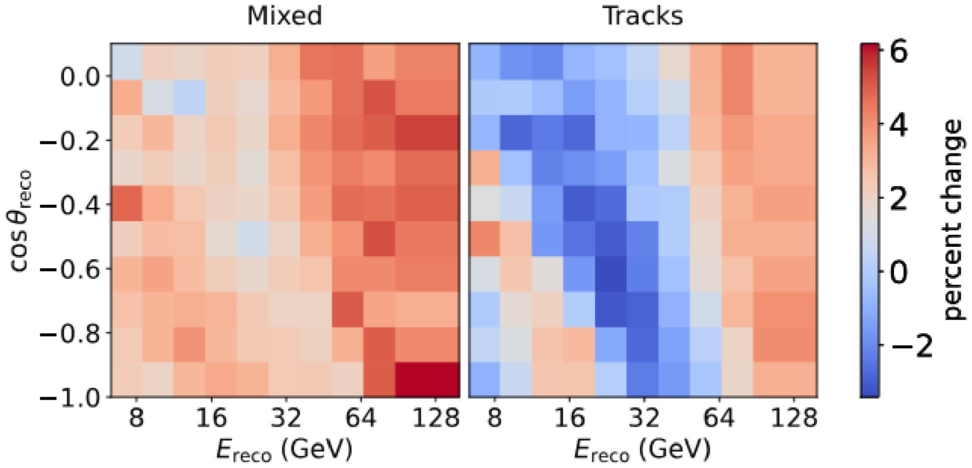
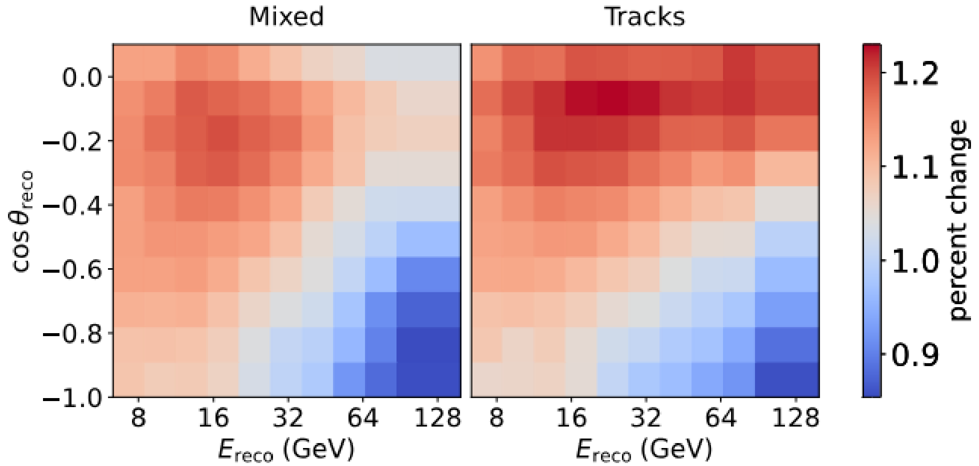




Effect from changing one atm. flux parameter

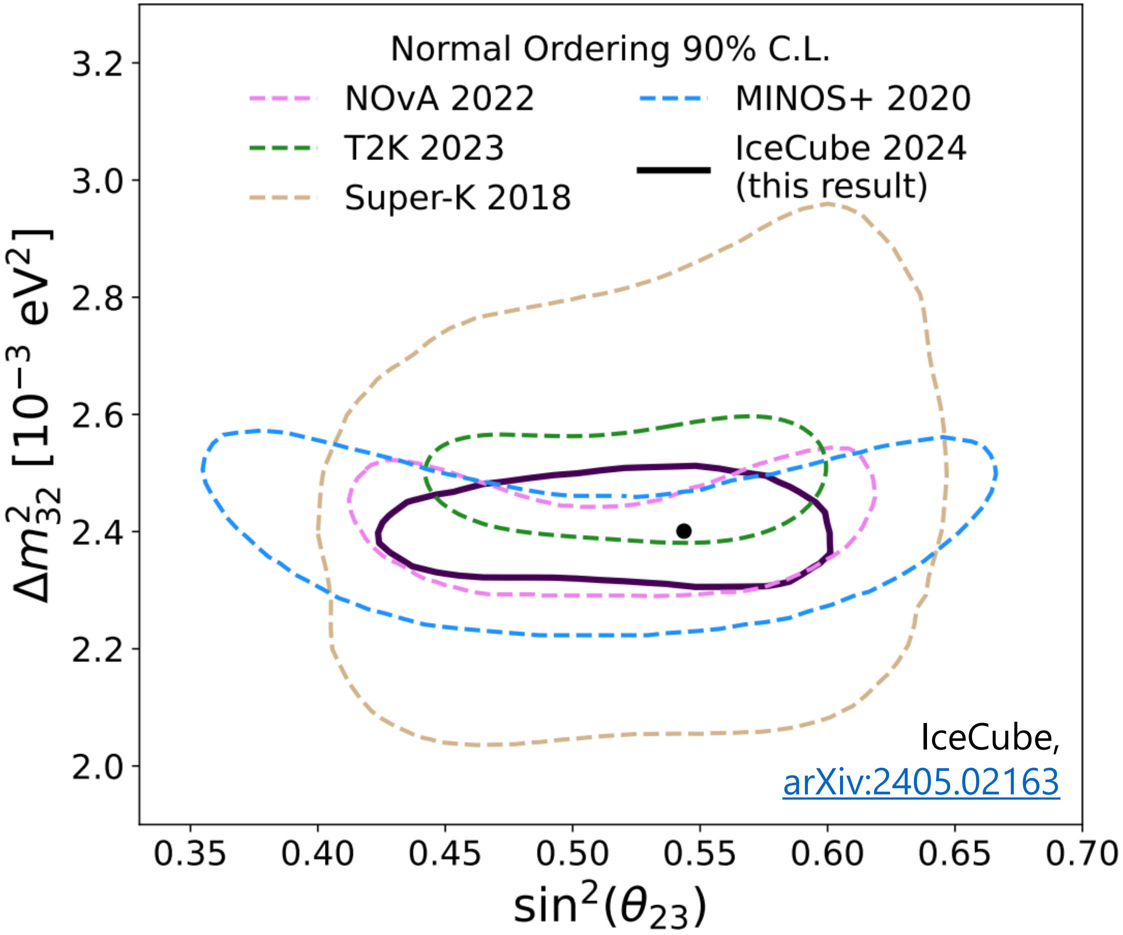
Atm. Osc. - **Newest result**

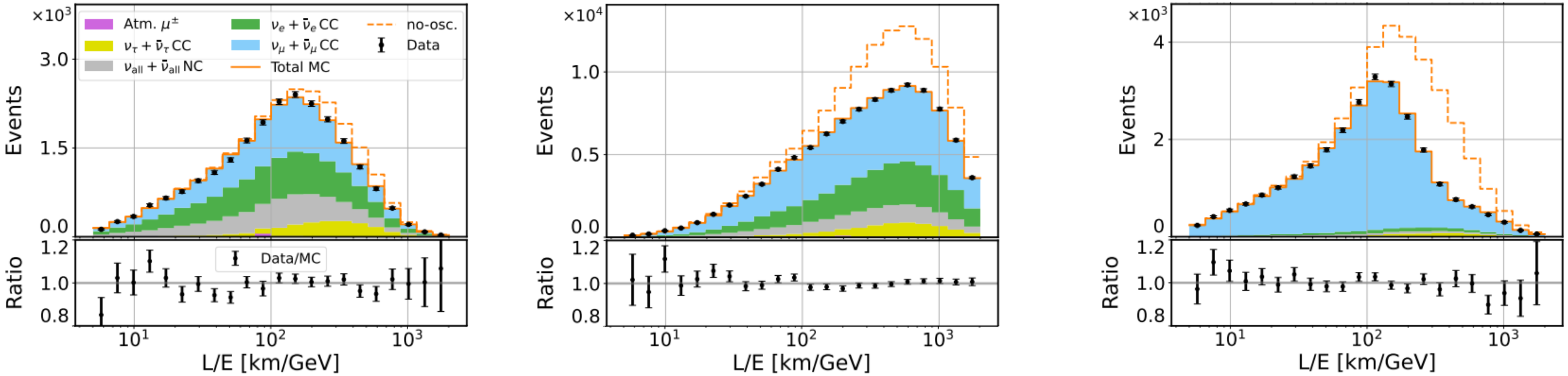
- CNN-based classification and reco
  - Uses inputs that our MC describes well
  - Recovers events that are hard to handle
  - 150,000 ν candidates in 9 years of data
- Best fit

  $\sin^2\theta_{23} = 0.54^{+0.04}_{-0.03}$

  $\Delta m^2_{32} = 2.40^{+0.05}_{-0.04} \times 10^{-3}$ eV^2

  GoF *p*-value: 19%





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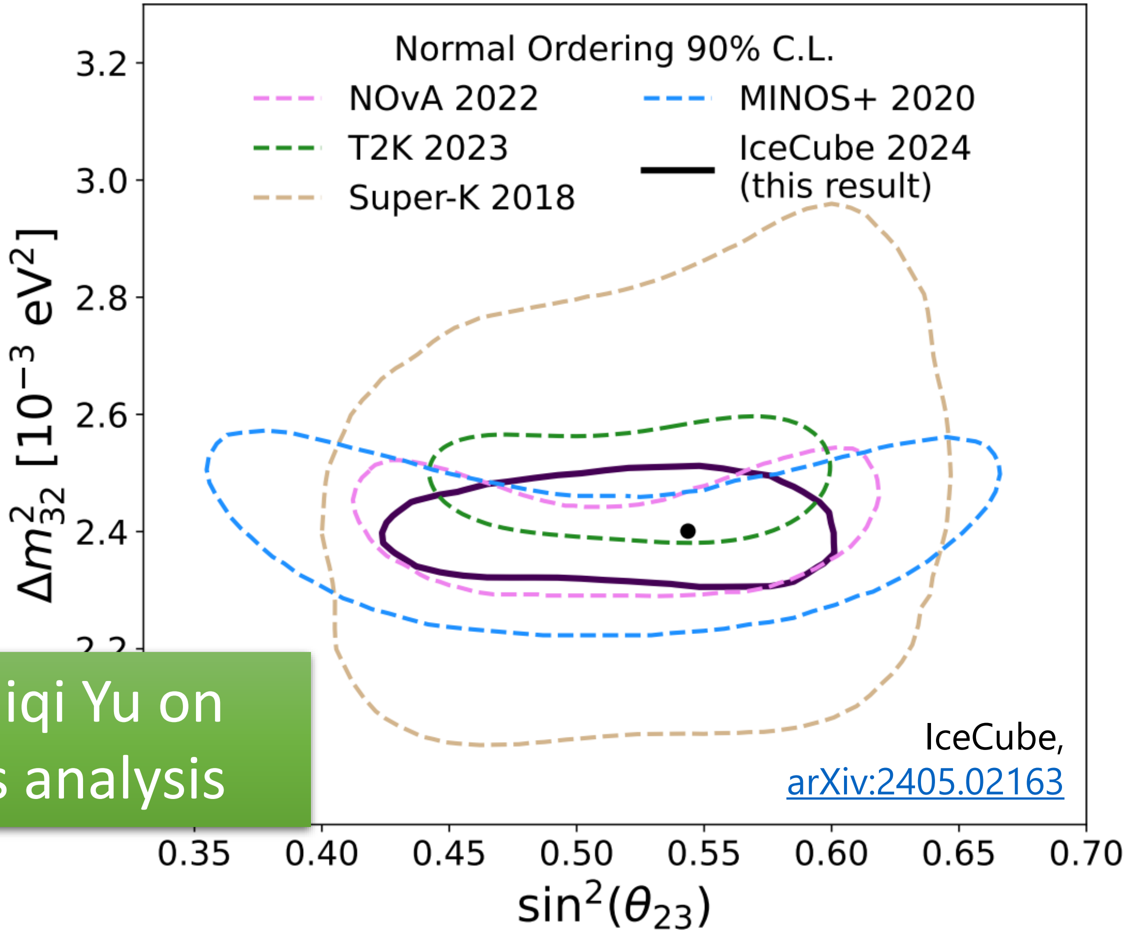
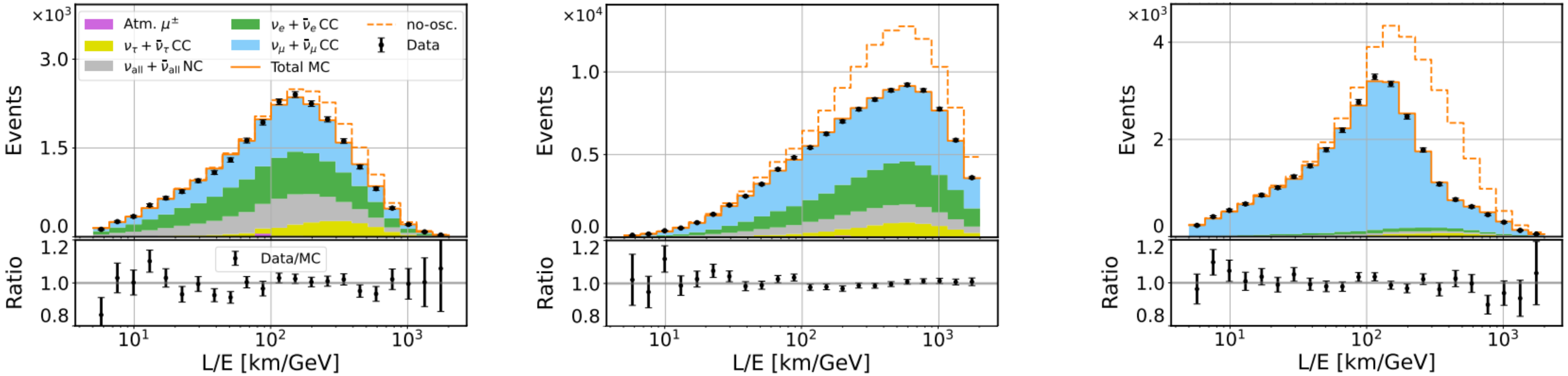


See poster by Shiqi Yu on Friday about this analysis



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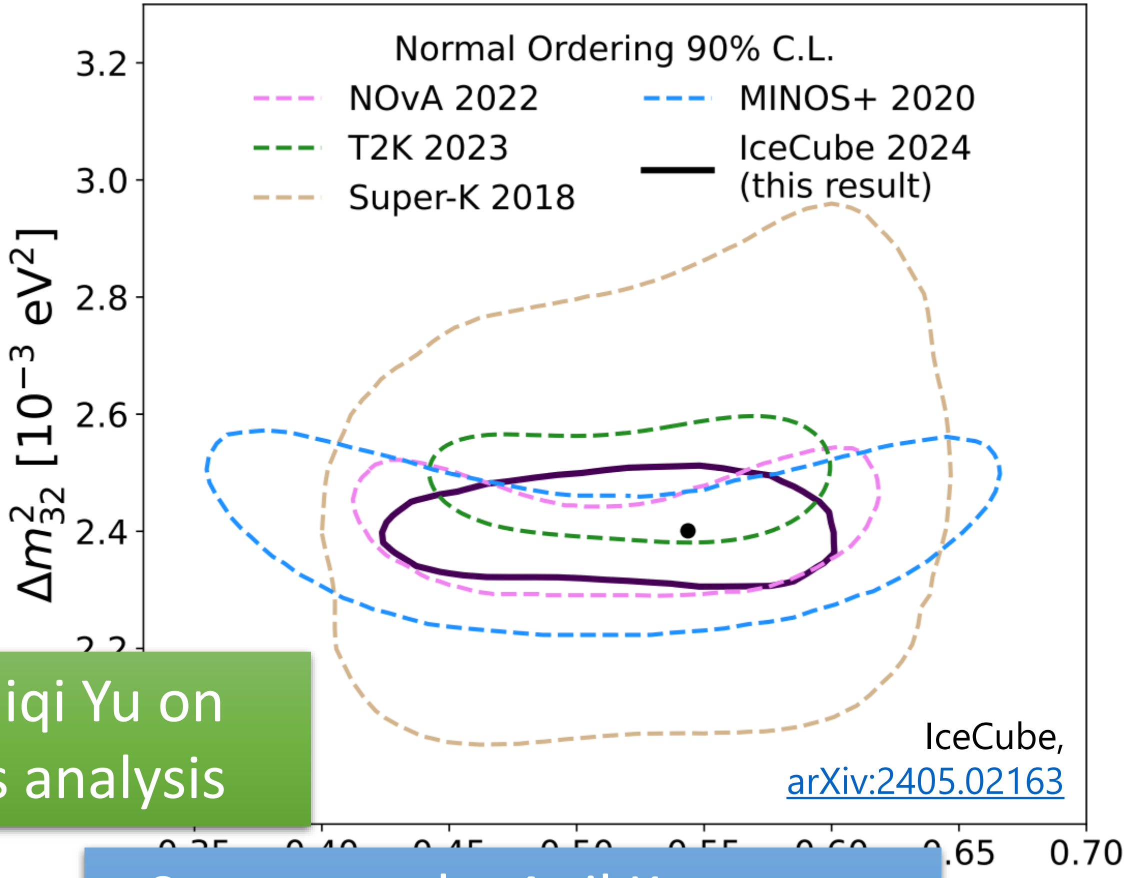
  GoF p value: 10%



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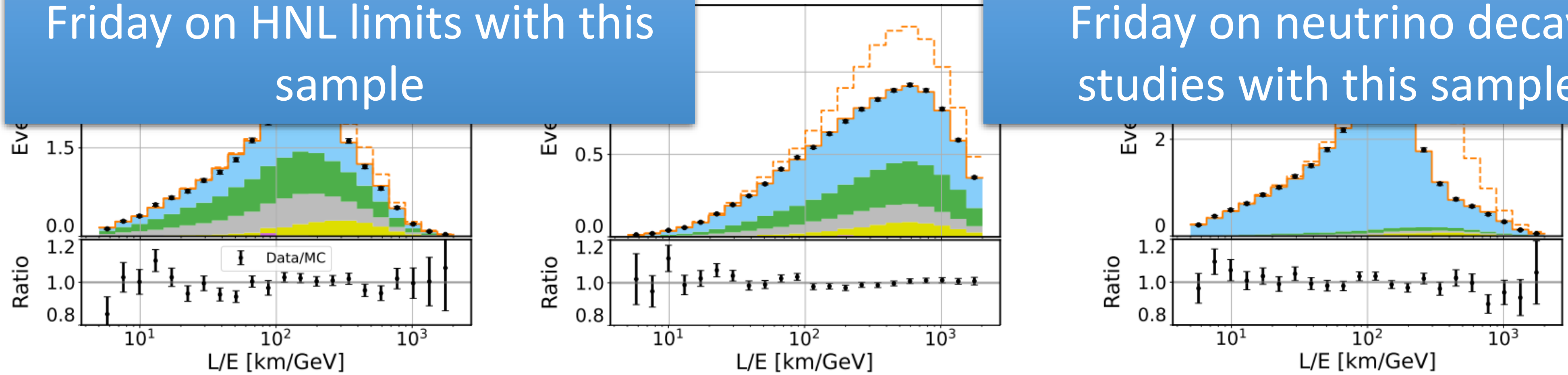


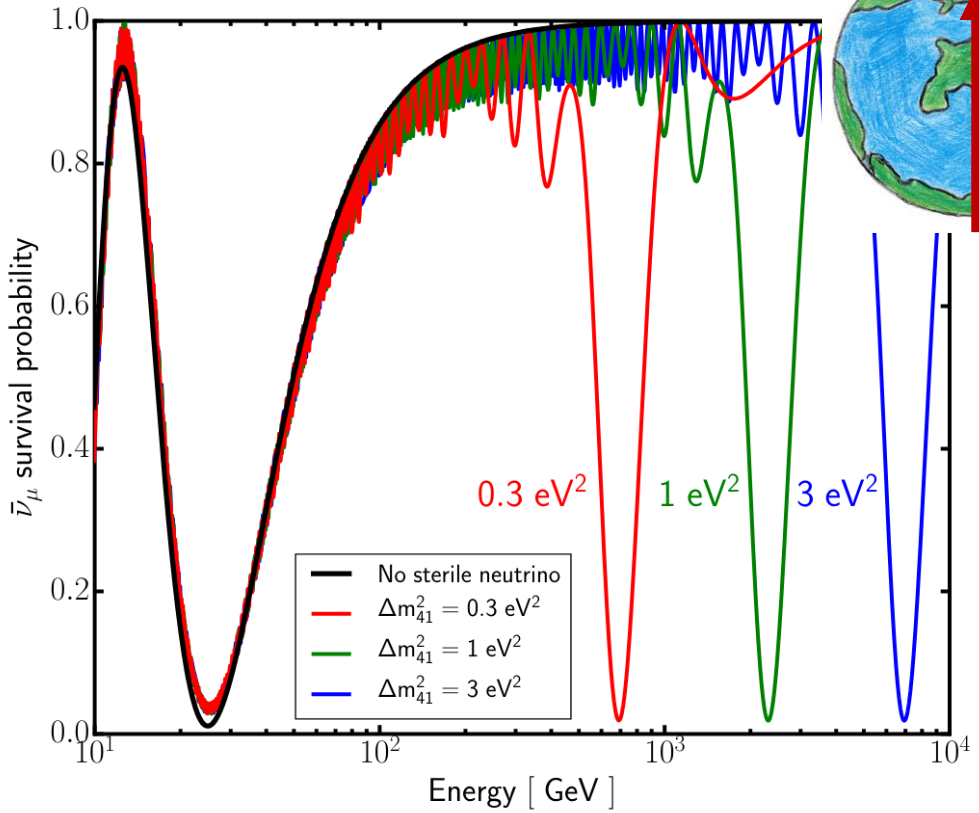
See poster by Julia Book on Friday on HNL limits with this sample

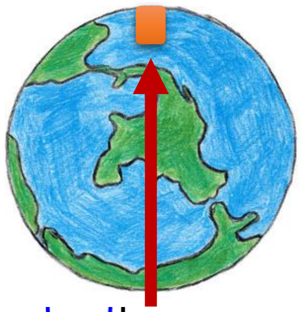
See poster by Anil Kumar on Friday on neutrino decay studies with this sample

Searches for **sterile** neutrinos (DeepCore & IceCube)

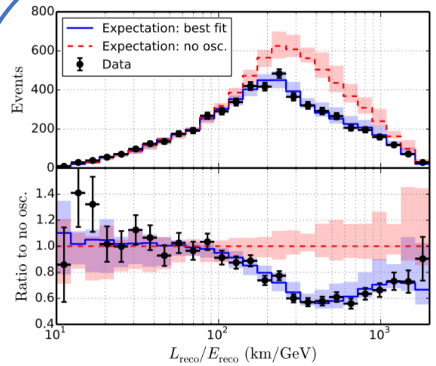
- More elements in the neutrino mixing matrix and a new mass splitting
  - Modulate standard oscillations at GeV energies
  - Can create large oscillations at TeV energies where none are expected
    - Matter effects enhance them even for small mixin
- IceCube tests so far
  - 3+1 model at GeV and TeV energies
  - 3+1+decay at TeV energies

$$\mathbf{U} \equiv \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}.$$



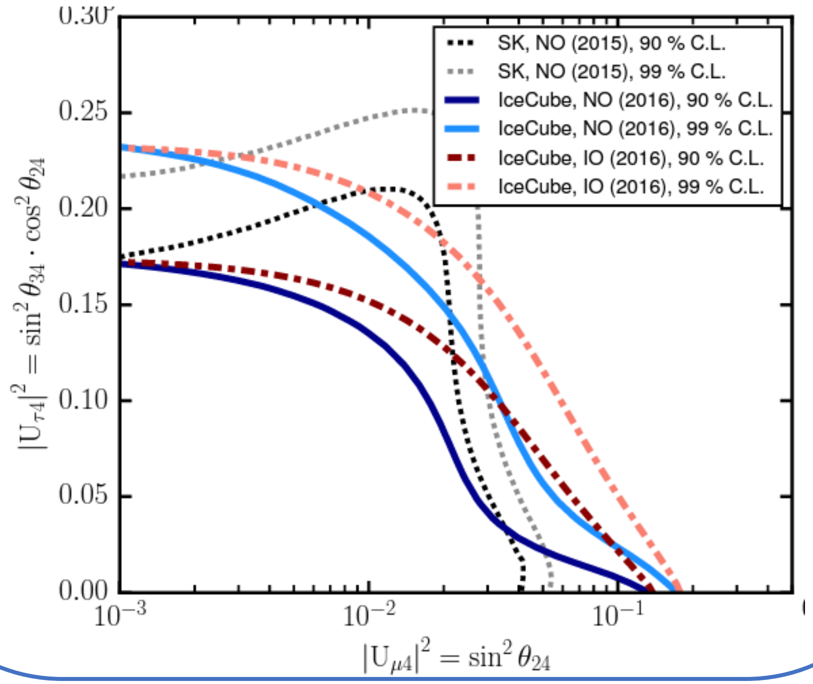


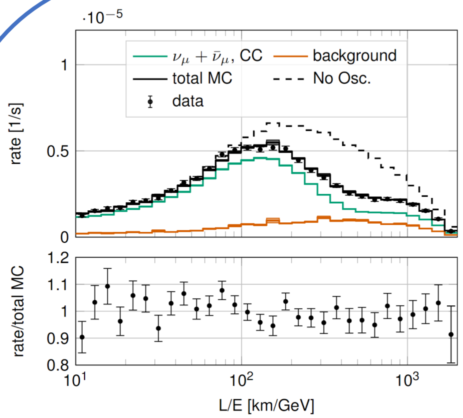
Sterile ν search progression (**GeV** regime)



3+1 $(U_{\mu4}, U_{\tau4})$

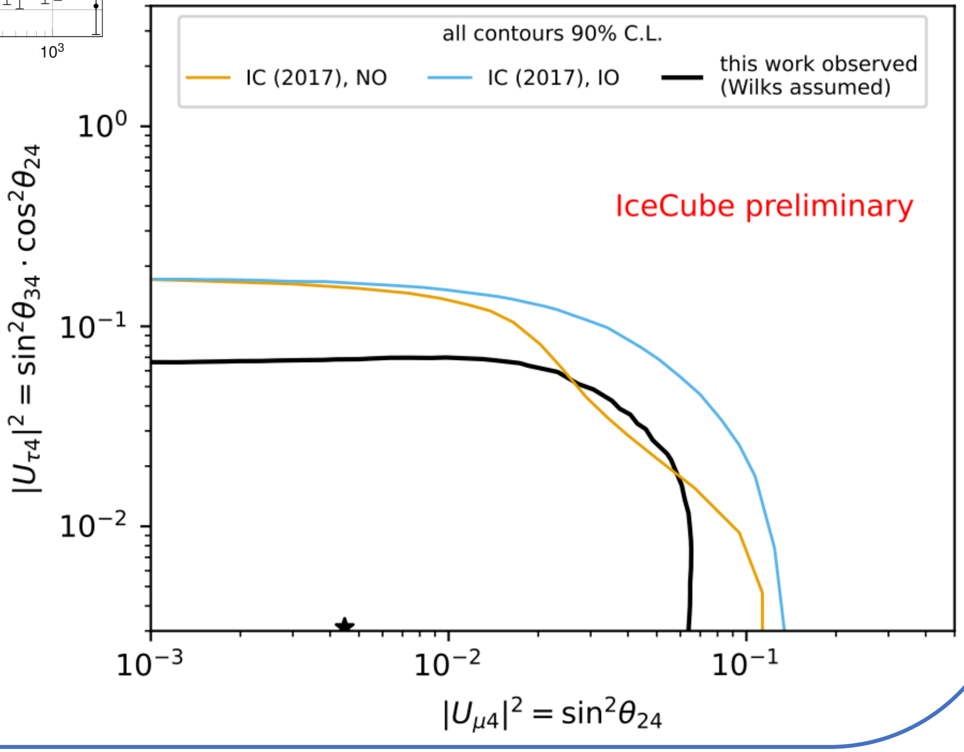
IceCube, PRD 95, 112002 **(2017)**
~5k events



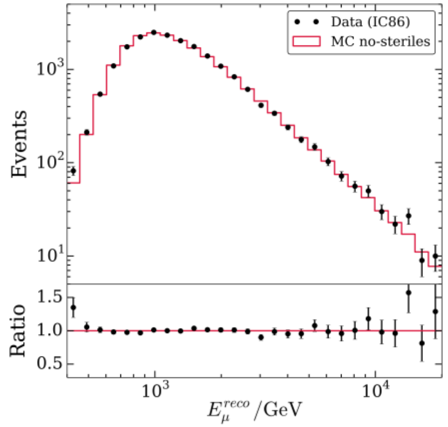


3+1 $(U_{\mu4}, U_{\tau4})$

IceCube, in preparation **(2024)**
~22k events

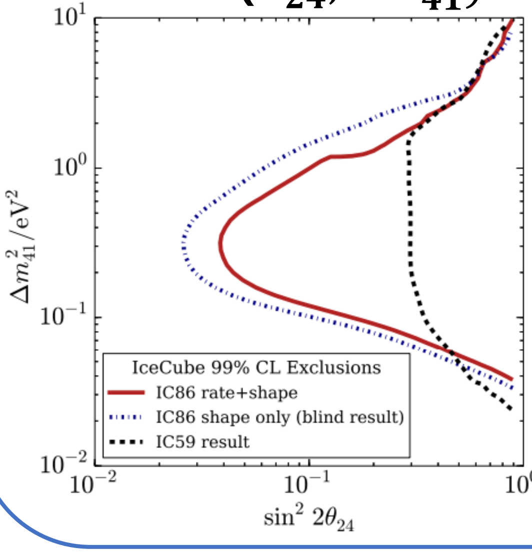


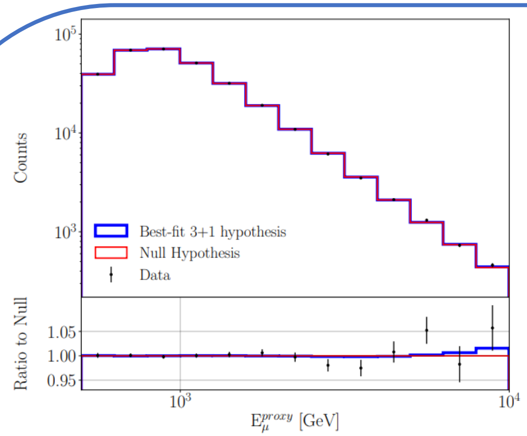
Sterile ν search progression (**TeV** regime)



IceCube, PRL 117, 071801 **(2016)**
~20k events

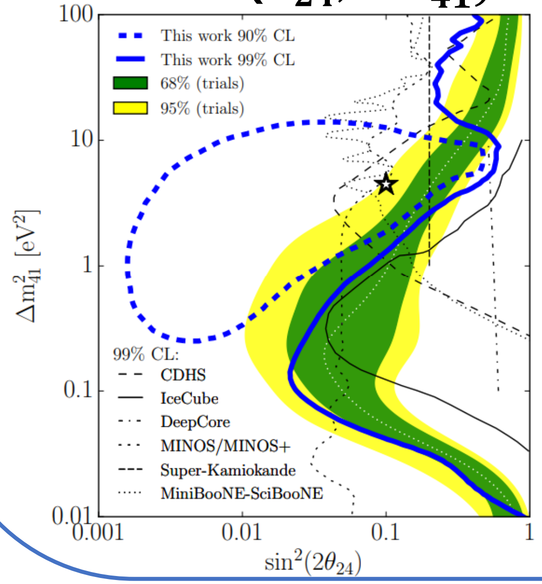
3+1 $(\theta_{24}, \Delta m^2_{41})$





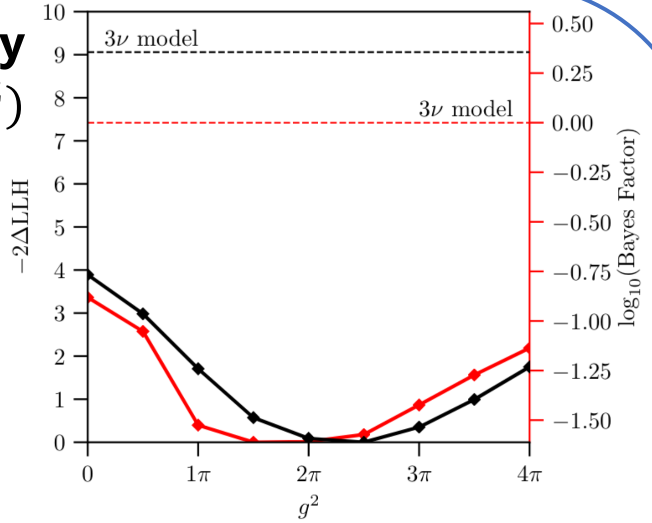
IceCube, PRL 125, 141801 **(2020)**
~300k events

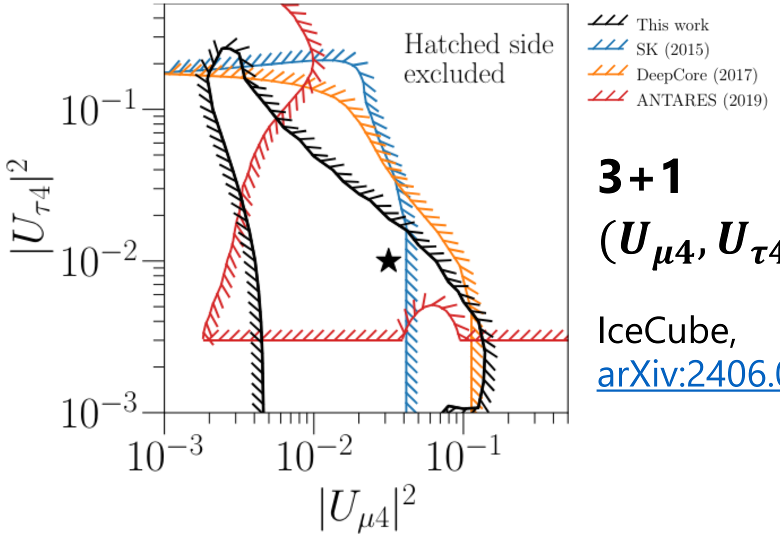
3+1 $(\theta_{24}, \Delta m^2_{41})$



3+1+decay
$(\theta_{24}, \Delta m^2_{41}, g^2)$

IceCube, PRL 129 (2022) 15, 151801





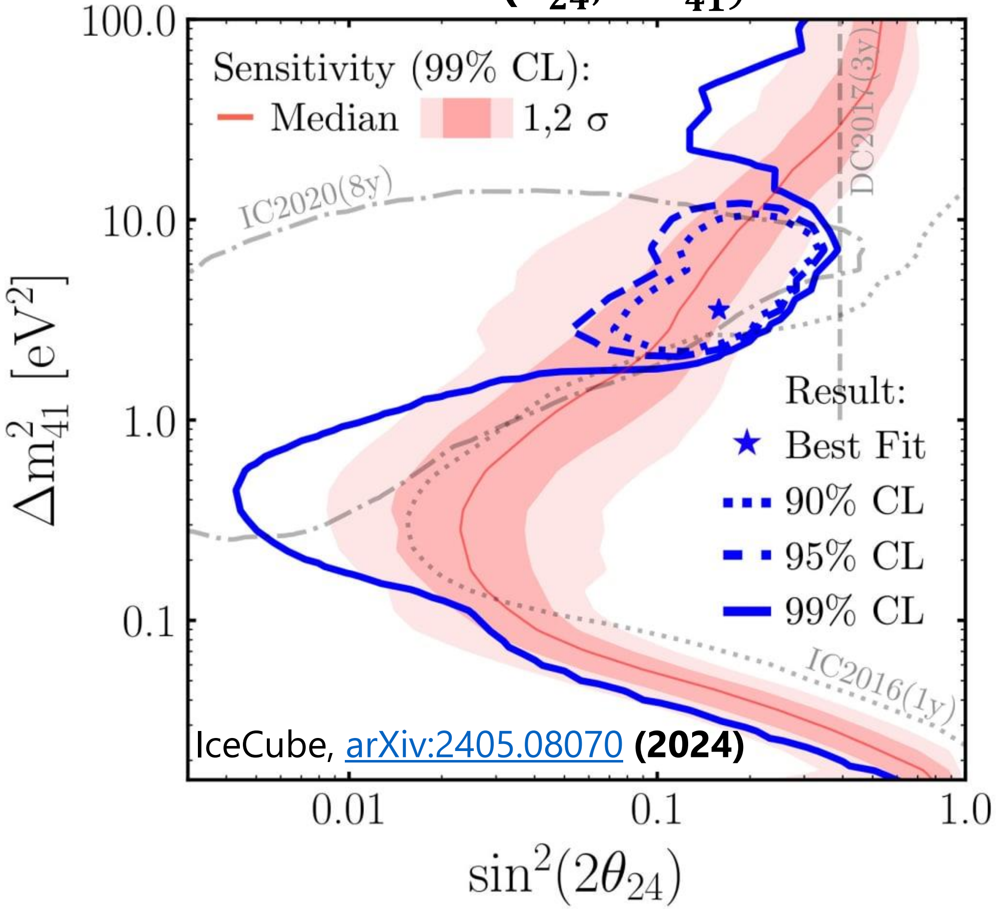
3+1
$(U_{\mu 4}, U_{\tau 4}, \Delta m^2_{41})$

IceCube, arXiv:2406.00905

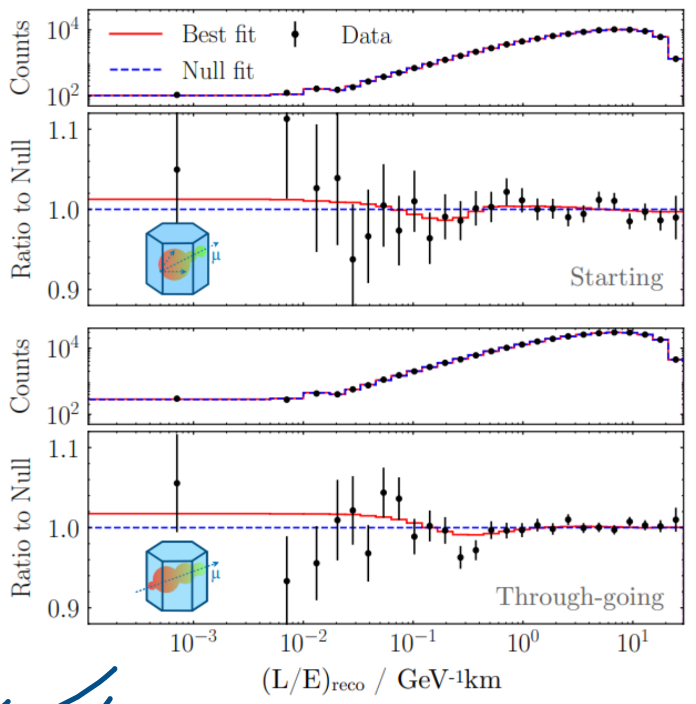
Newest sterile ν search (TeV regime)

- Improved sample
  - 370k events
  - Split starting events
  - Updated flux systematics
- Results
  - No sterile hypothesis p-value = 3%
  - Non-zero fit significance: 2σ
  - Decay scenario disfavored

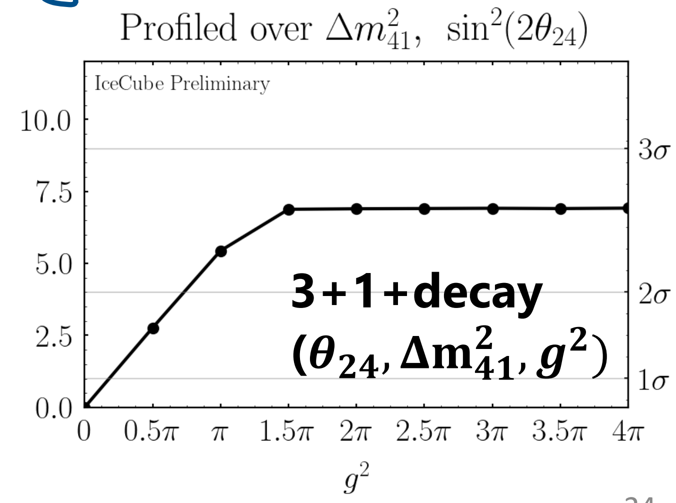
3+1 ($\theta_{24}, \Delta m^2_{41}$)



IceCube, arXiv:2405.08070 **(2024)**



IceCube, in preparation **(2024)**



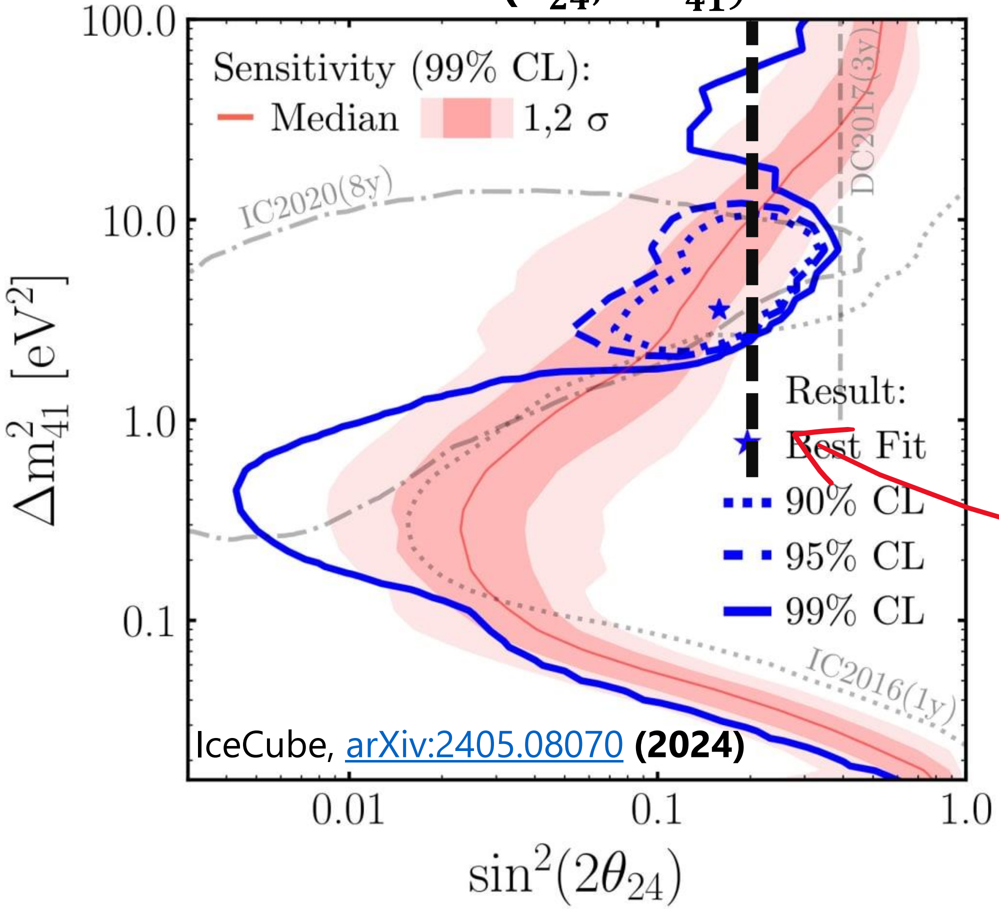
3+1+decay ($\theta_{24}, \Delta m^2_{41}, g^2$)

Comparison of **E regimes**

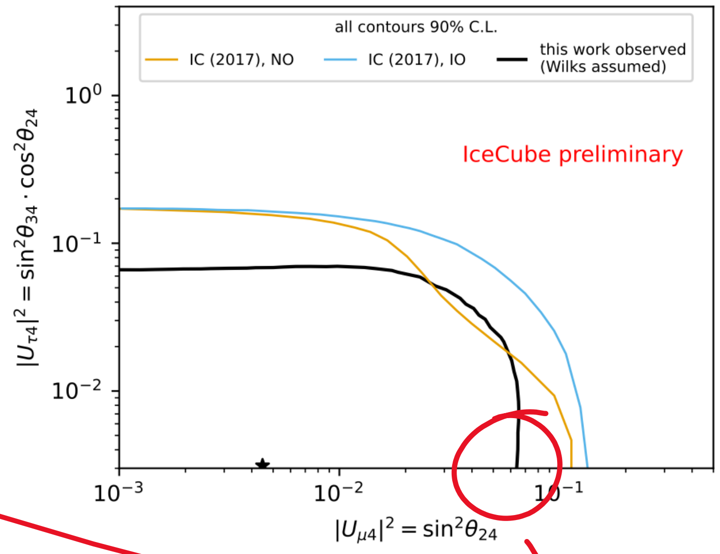
- Improved sample
  - 370k events
  - Split starting events
  - Updated flux systematics

- Results
  - <u>No sterile hypothesis p-value = 3%</u>
  - Non-zero fit significance: 2σ
  - Decay scenario disfavored

3+1 $(\theta_{24}, \Delta m^2_{41})$



IceCube, arXiv:2405.08070 **(2024)**

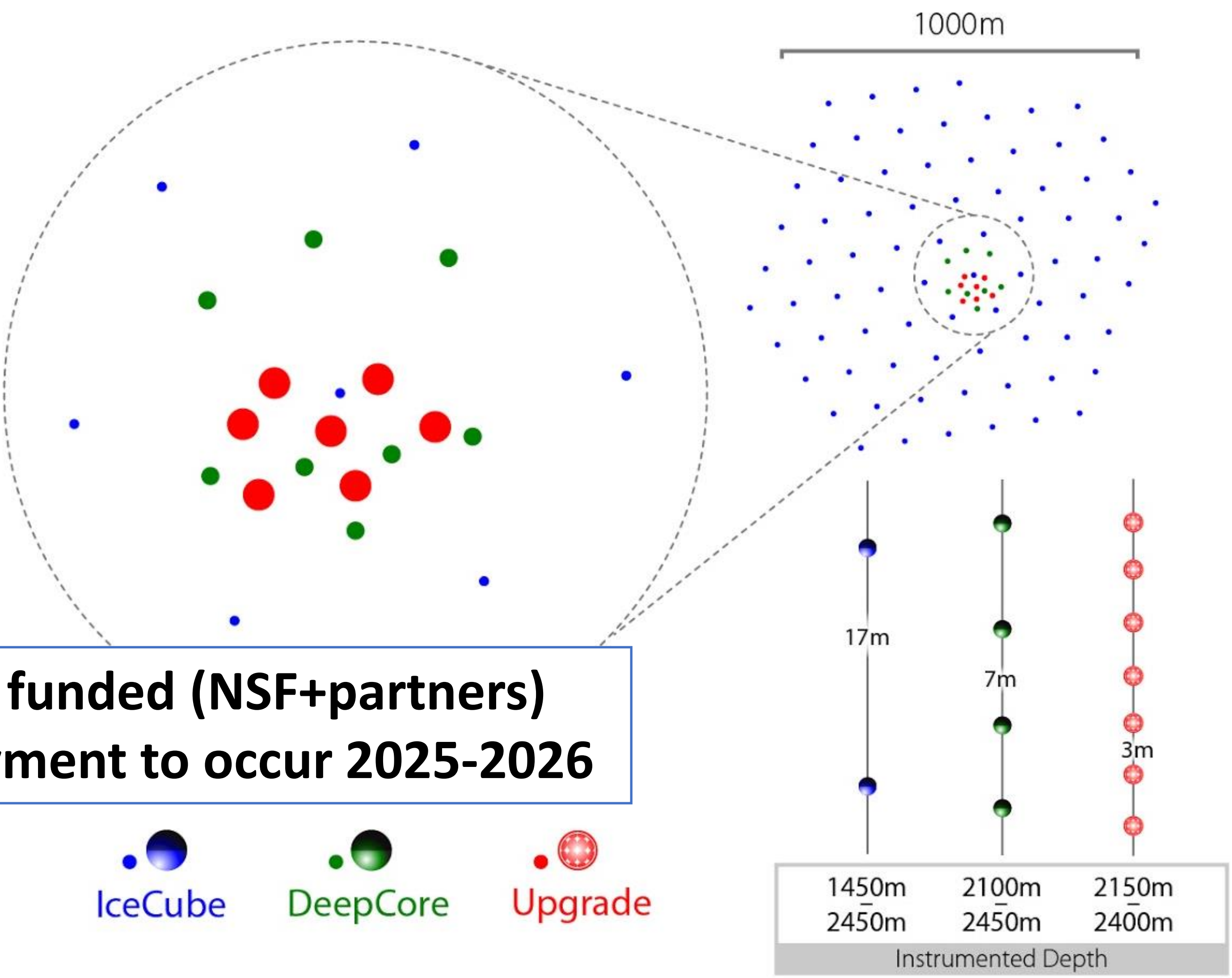


DeepCore sample
All-flavor
3+1 $(U_{\mu4}, U_{\tau4})$

The future

The IceCube **Upgrade**

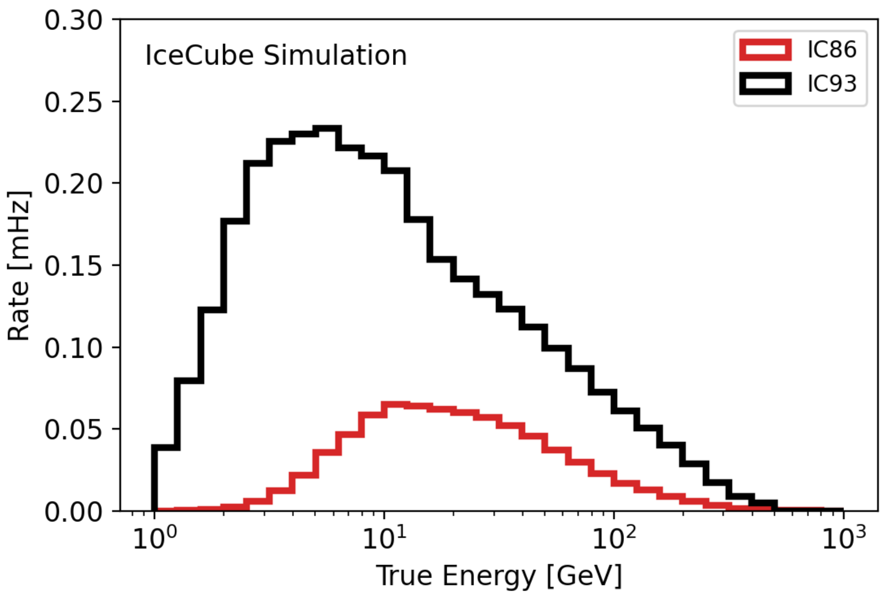
- New devices in the ice
  - Recalibration of all data
  - Lower E threshold for DC

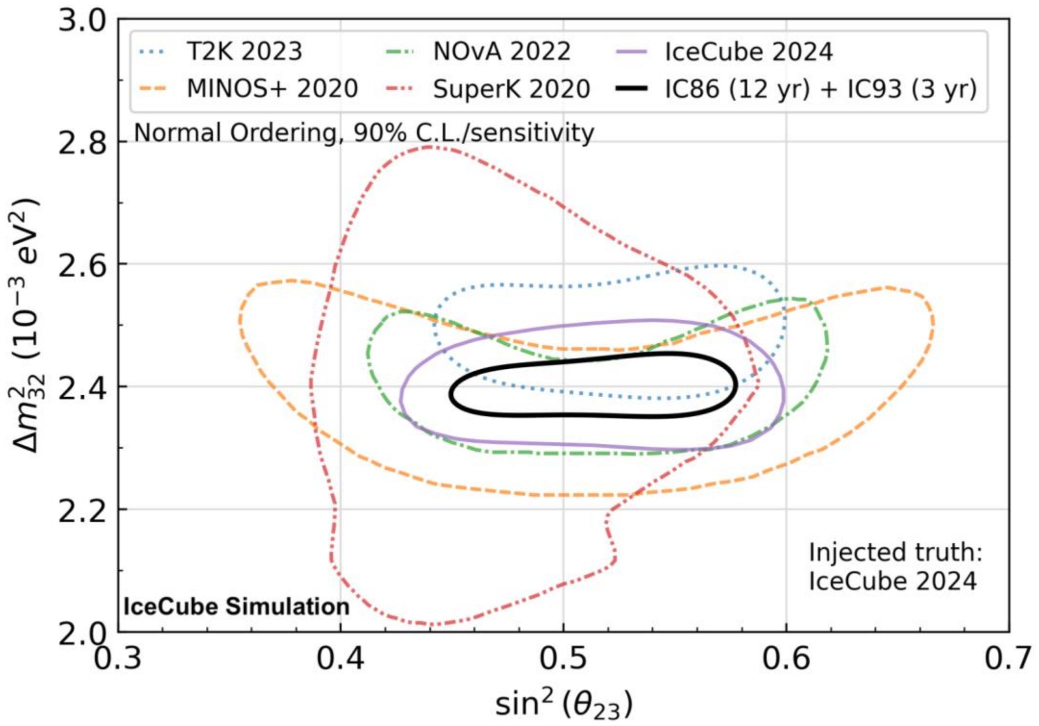


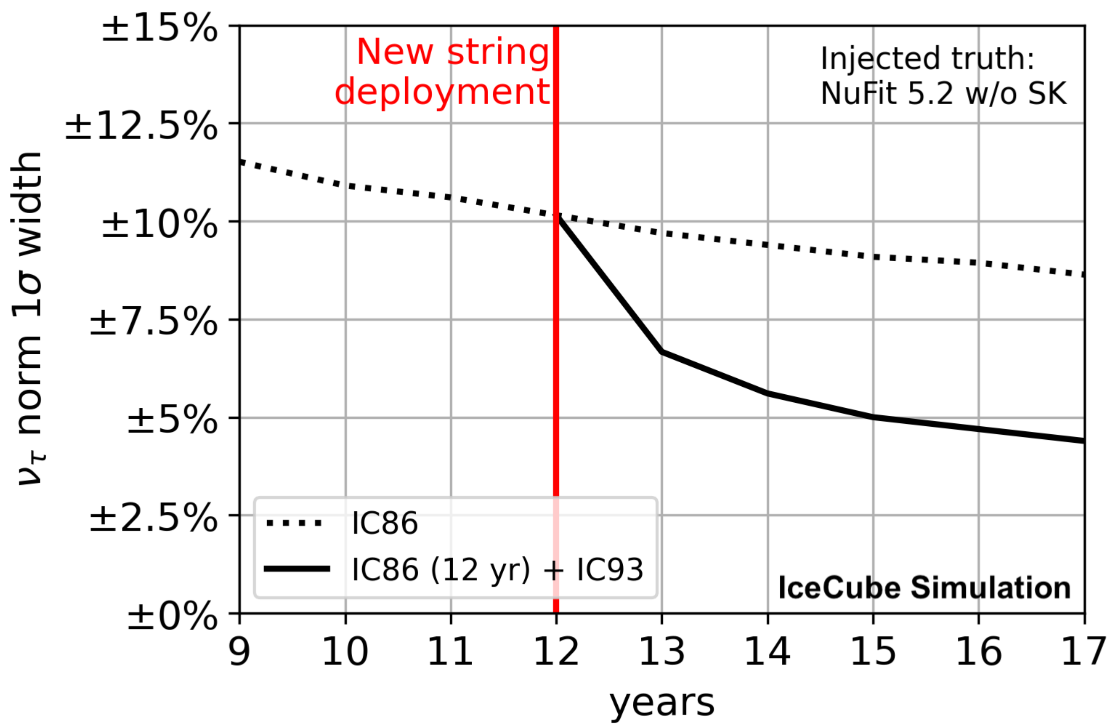
Fully funded (NSF+partners)
Deployment to occur 2025-2026

IceCube Upgrade **potential**

- Significant increase of events at 10 GeV
- Projecting precision on std. oscillations
  - Includes selection, reconstruction and current uncertainties

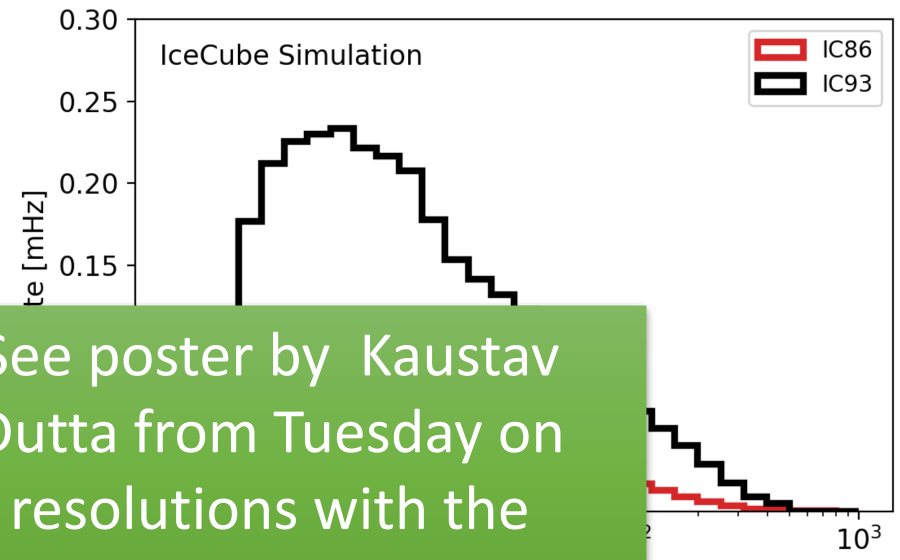




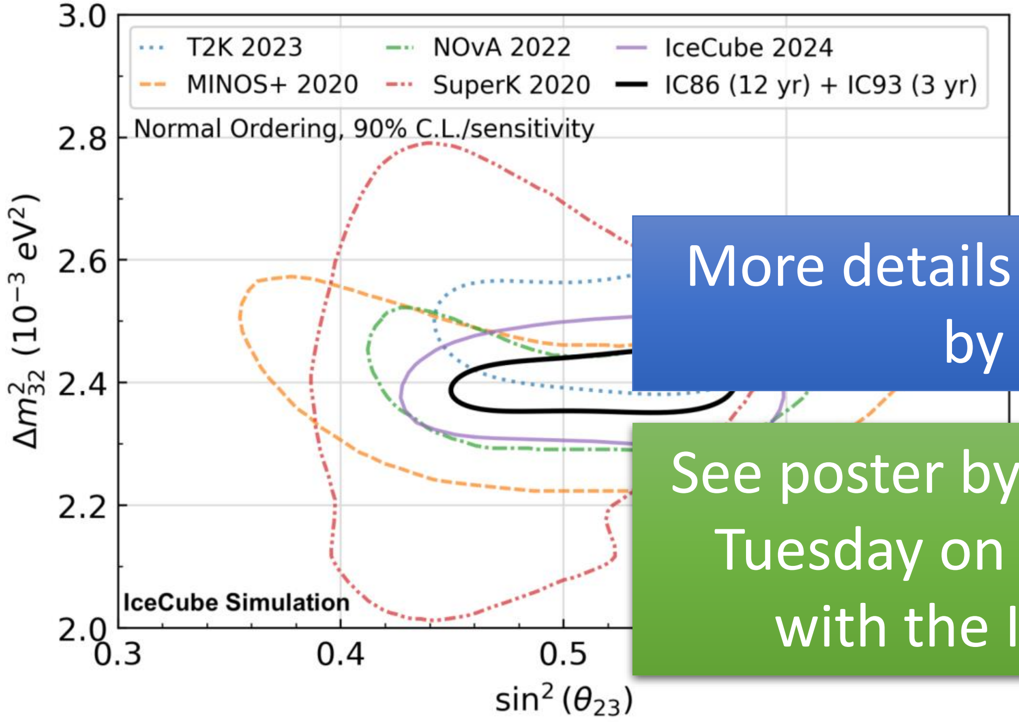


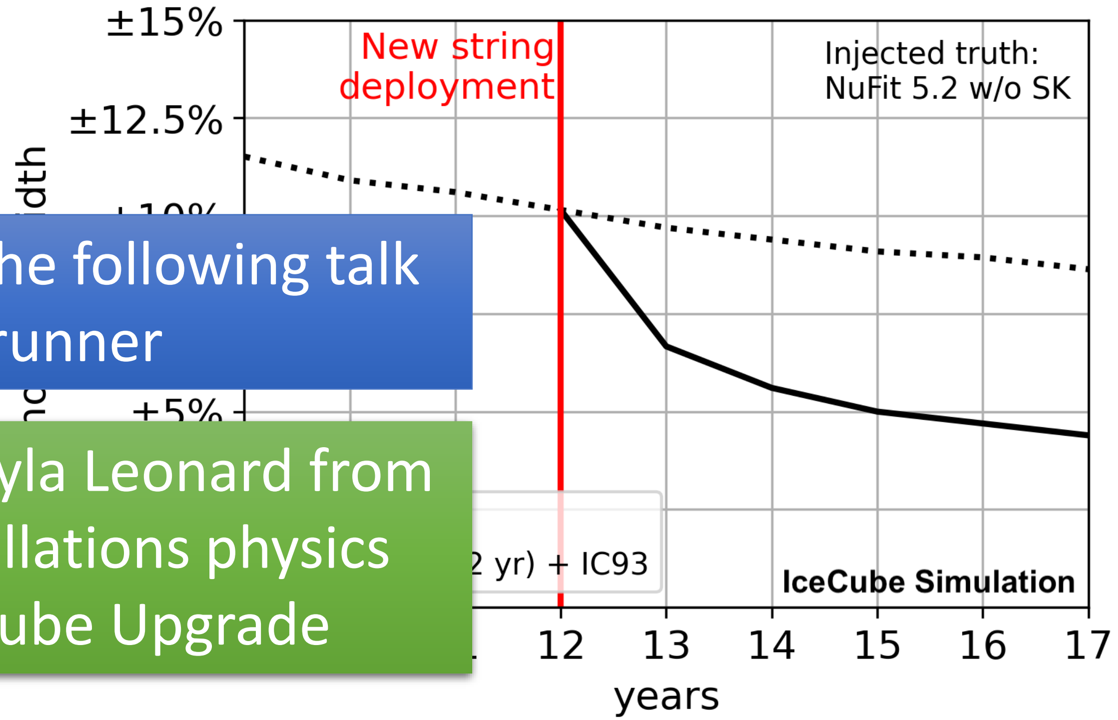
IceCube Upgrade **potential**

- Significant increase of events at 10 GeV
- Projecting precision on std. oscillations
  - Includes selection, reconstruction and current uncertainties



See poster by Kaustav Dutta from Tuesday on resolutions with the IceCube Upgrade





More details in the following talk by J. Brunner

See poster by Kayla Leonard from Tuesday on oscillations physics with the IceCube Upgrade


Thank you for your attention, on behalf of
THE ICECUBE COLLABORATION
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BELGIUM
UCLouvain
Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel
CANADA
Queen's University
University of Alberta–Edmonton
DENMARK
University of Copenhagen
GERMANY
Deutsches Elektronen-Synchrotron
ECAP, Universität Erlangen-Nürnberg
Humboldt–Universität zu Berlin
Karlsruhe Institute of Technology
Ruhr-Universität Bochum
RWTH Aachen University
Technische Universität Dortmund
Technische Universität München
Universität Mainz
Universität Wuppertal
Westfälische Wilhelms-Universität Münster
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REPUBLIC OF KOREA
Chung-Ang University
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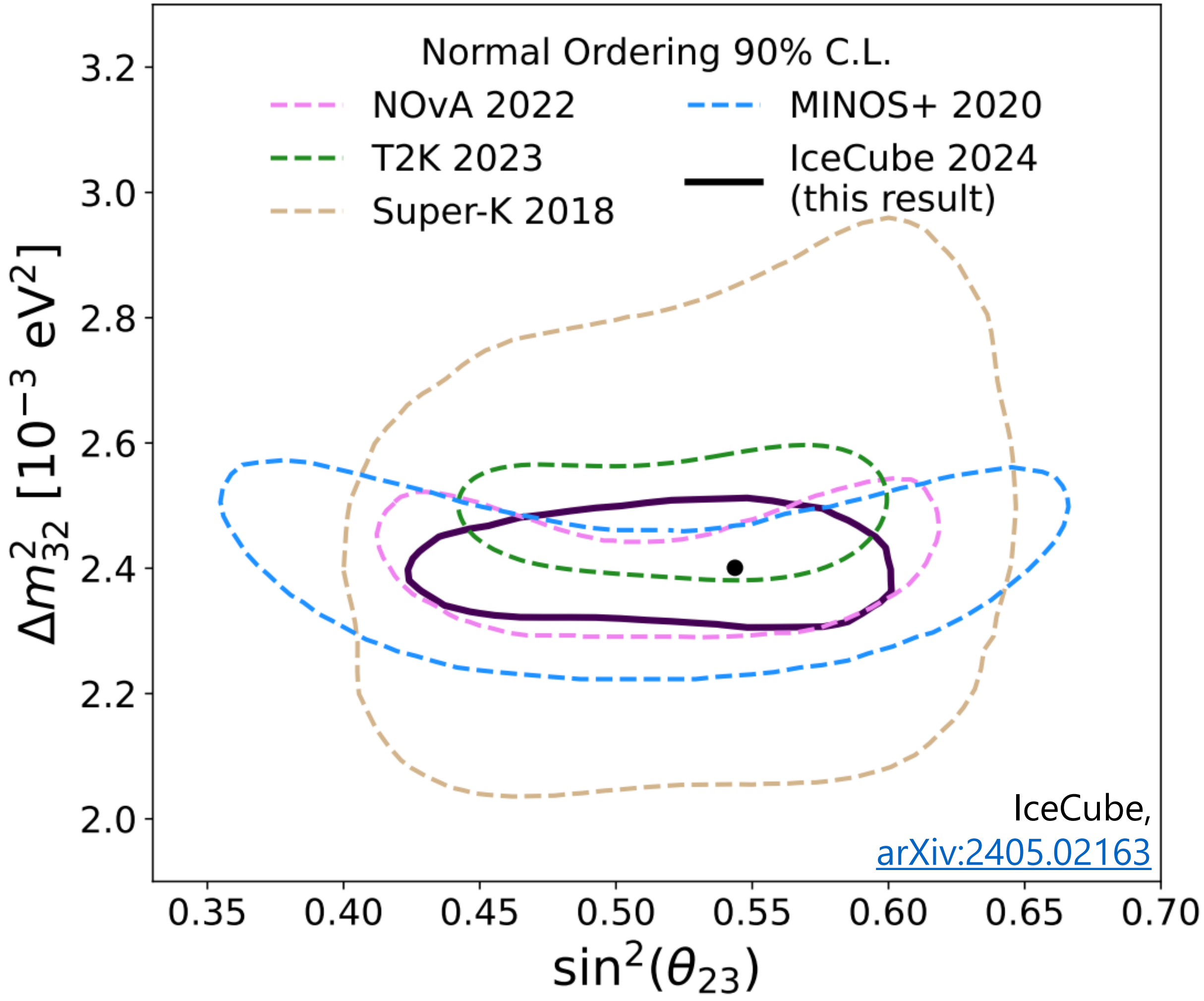
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)
ICECUBE NEUTRINO OBSERVATORY
icecube.wisc.edu

Summary & **Outlook**

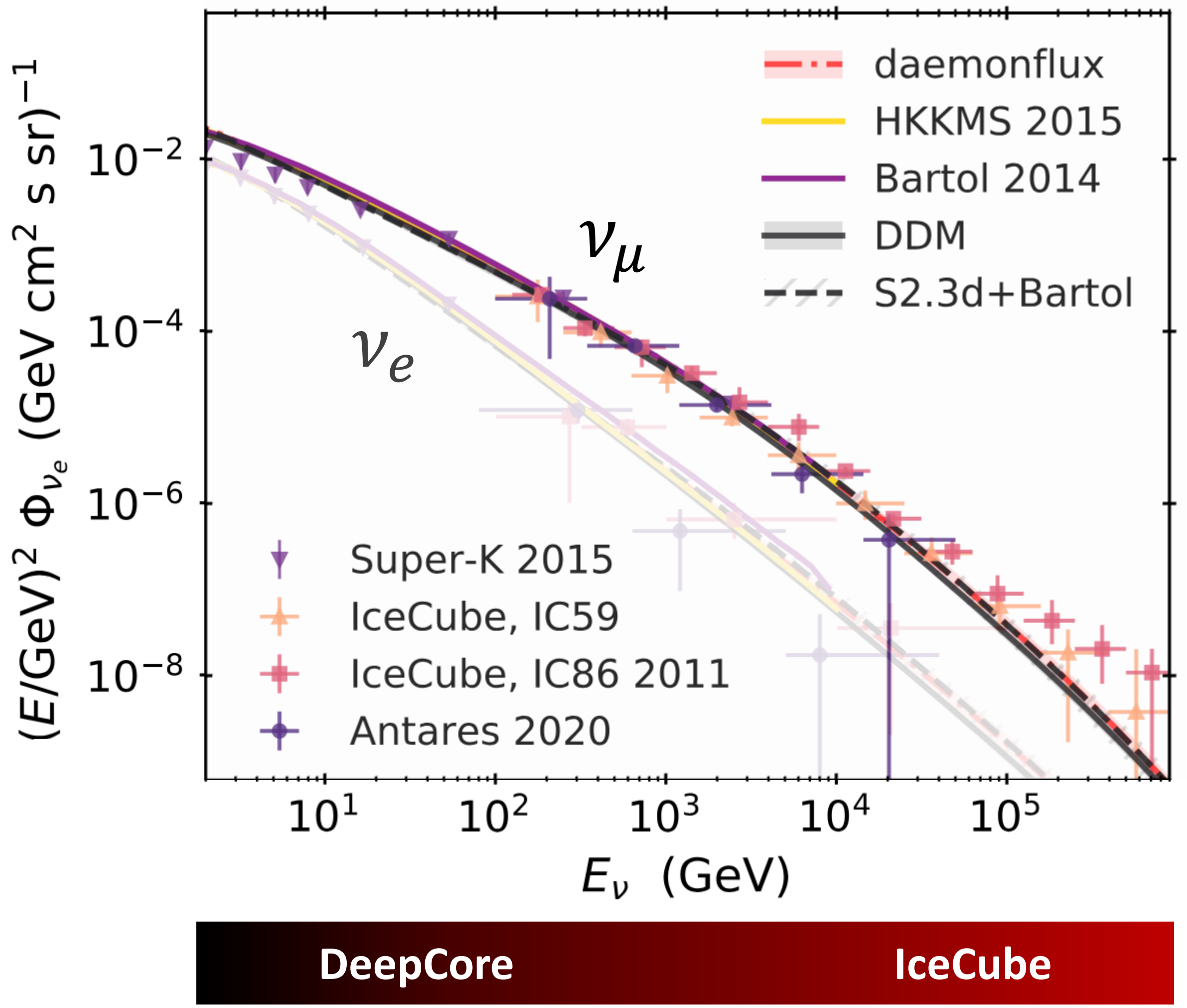
- Precision measurement of atmospheric oscillation parameters
  - Significant progress over the last decade
  - DC data agrees with 3-flavor oscillation paradigm – no evidence for sterile ν's
  - We continue to test for new physics
    - NSI, ν_τ appearance, decoherence
- Upgrade will help both energy regimes
  - Better LE data → improved precision on standard oscillations
  - Recalibration of detector response → better understanding of the HE data



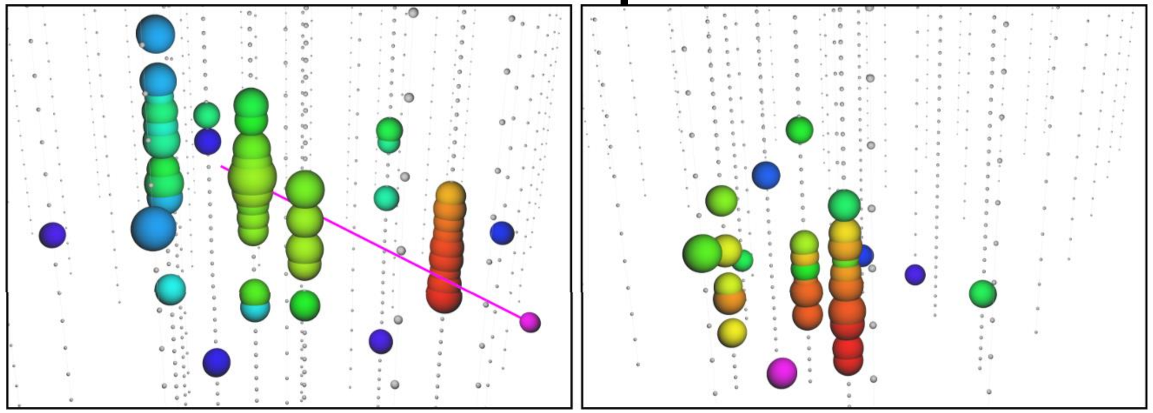
IceCube, arXiv:2405.02163

Additional slides

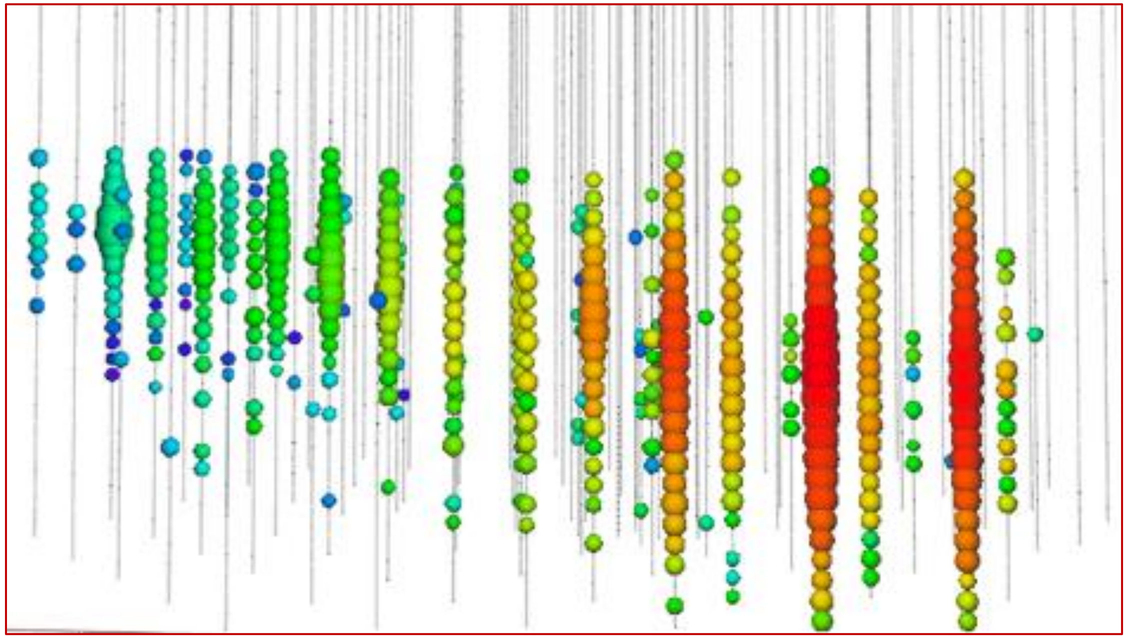
Atmospheric neutrino data



GeV events in DeepCore for ν oscillations



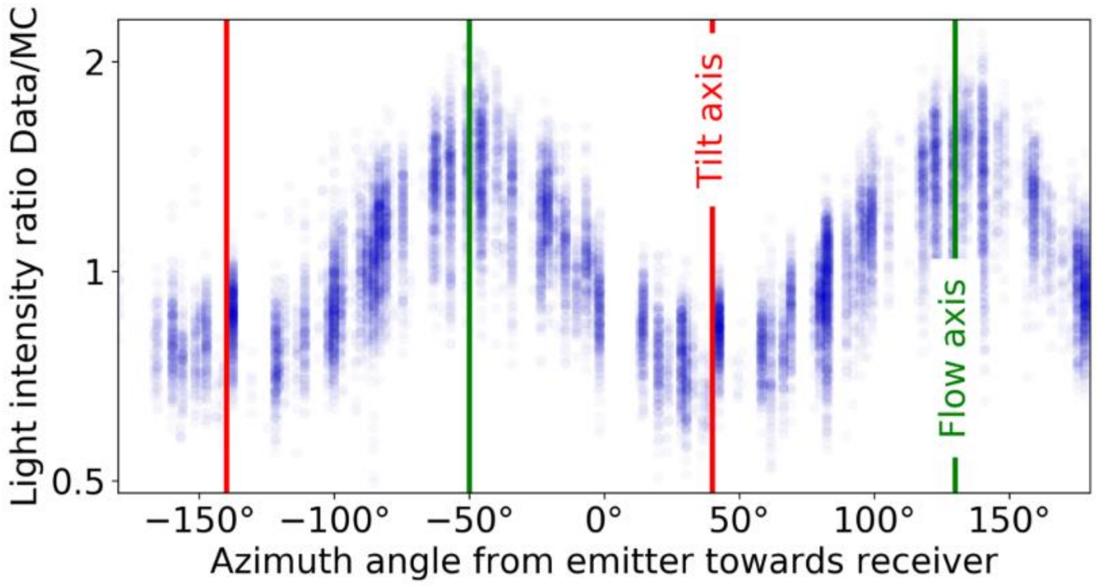
TeV event in IceCube for sterile ν searches

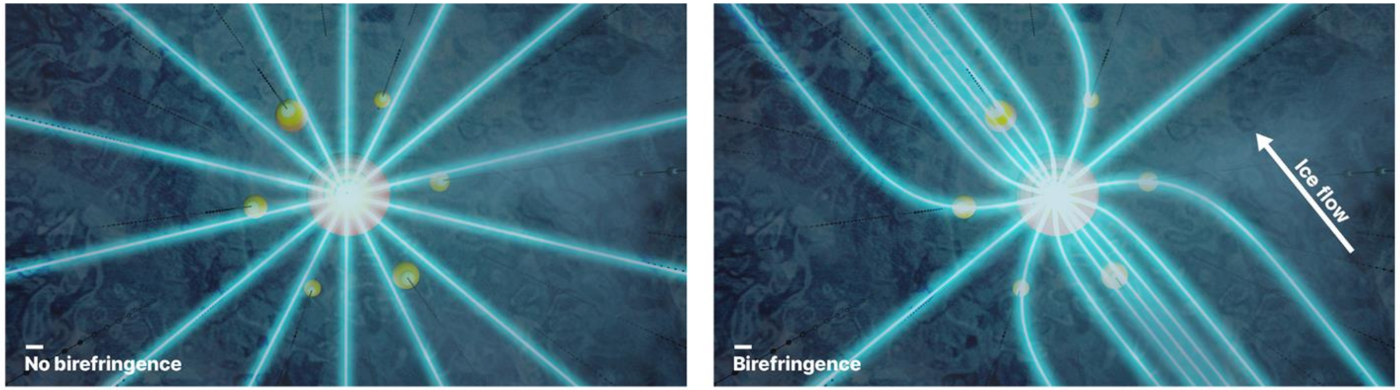


Color indicates time (red=early, blue=late). Sphere size is proportional to number of photons observed.

Detector calibration

- An anisotropy in light yield has been observed for years
  - Limited success explaining it with varying scattering, absorption
- Recent studies show the effect is from birefringence
  - Light rays deflected due to preferred crystal orientations



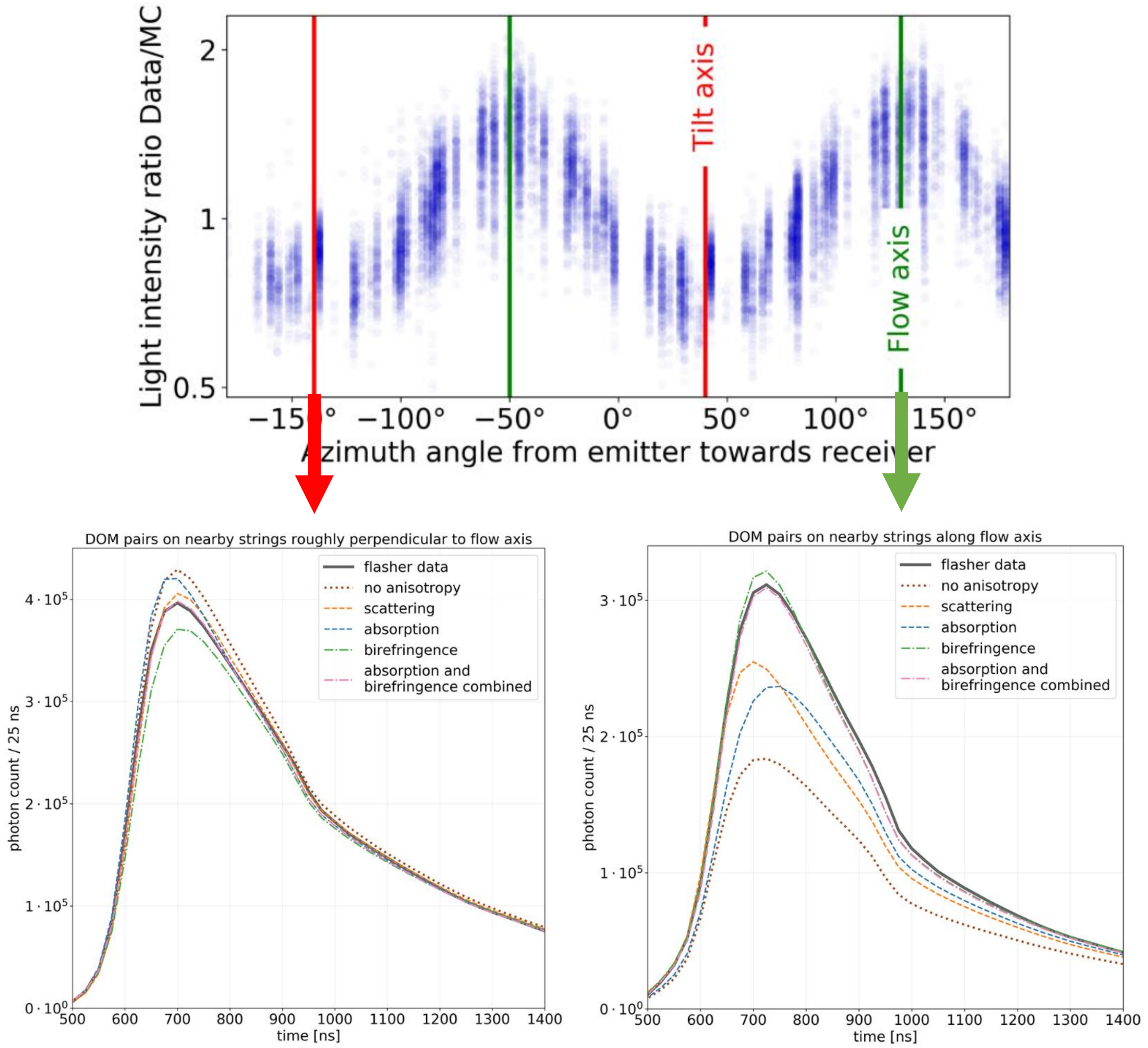


Artist illustration of the deflection

IceCube, The Cryosphere 18 (2024) 1, 75-102

Detector calibration

- An anisotropy in light yield has been observed for years
  - Limited success explaining it with varying scattering, absorption
- Recent studies show the effect is from birefringence
  - Light rays deflected due to preferred crystal orientations
- Effect included in new studies

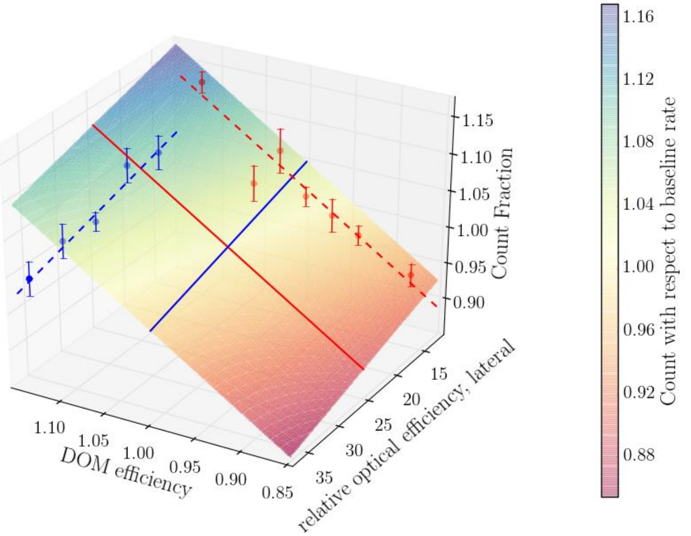


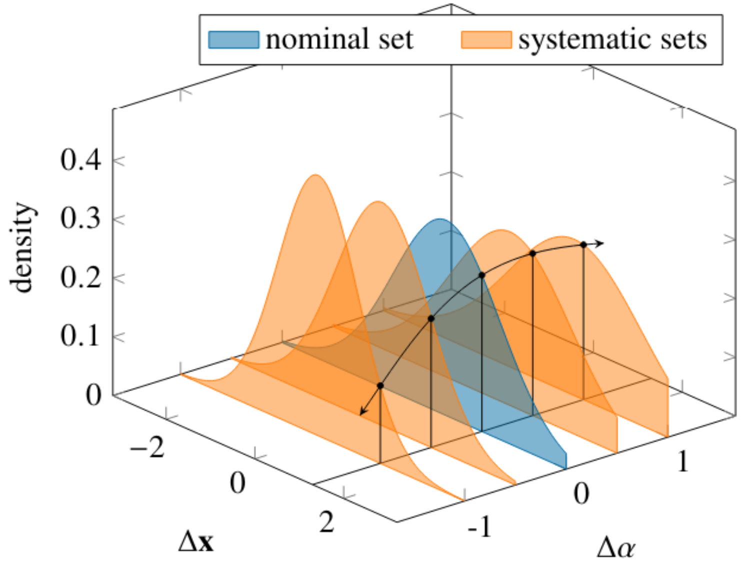
IceCube, The Cryosphere 18 (2024) 1, 75-102

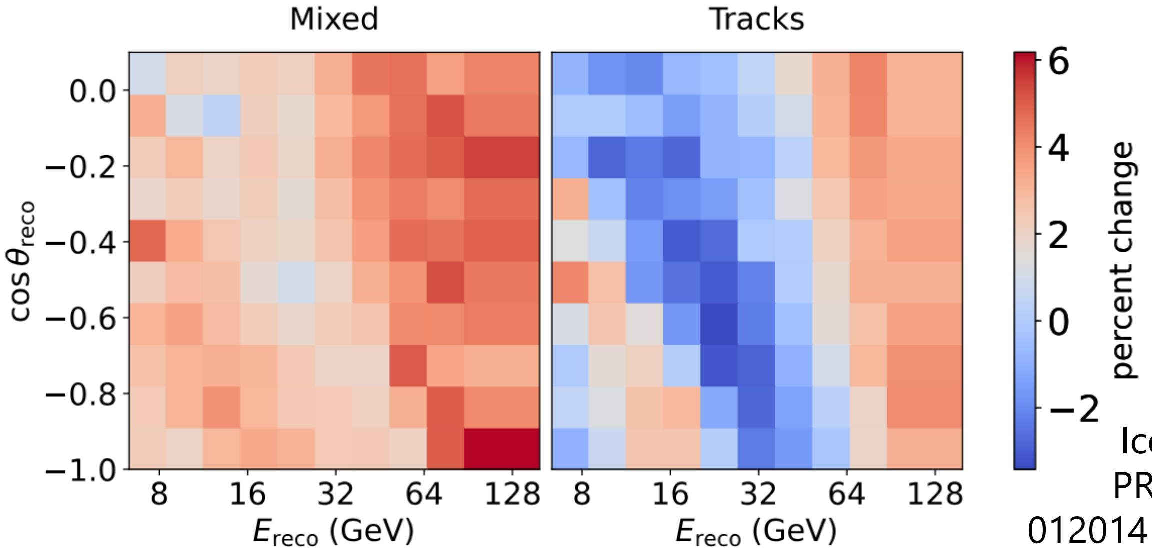
Parameterizing **calibration** information

Fischer, Naab, Trettin
[arXiv:2305.02257](https://arxiv.org/abs/2305.02257)

- Detector-related systematics dominate uncertainty
  - Multiple strategies to account for their impact
- MC production
  - MC at multiple parameter combinations
  - MC with smoothly varying parameters
- Parameterization
  - Gradients obtained from binned MC expectation
  - Event-wise weights from PDFs obtained with ML



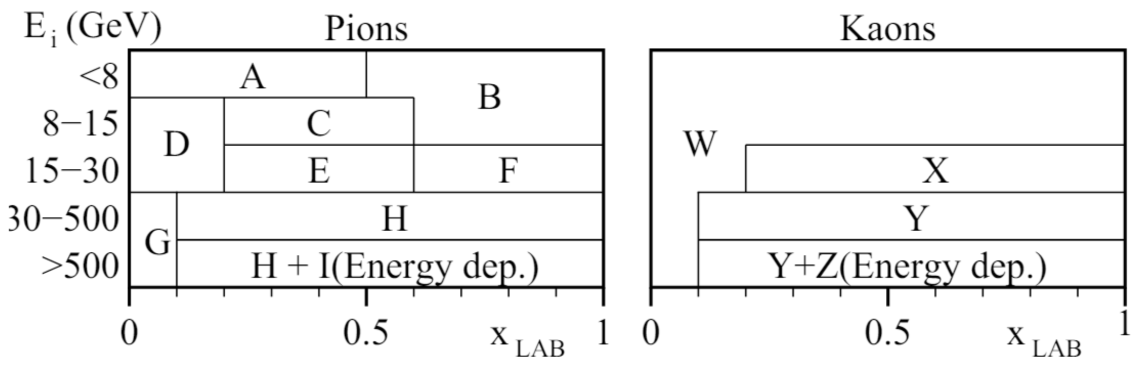




IceCube, PRD 108, 012014 (2023)

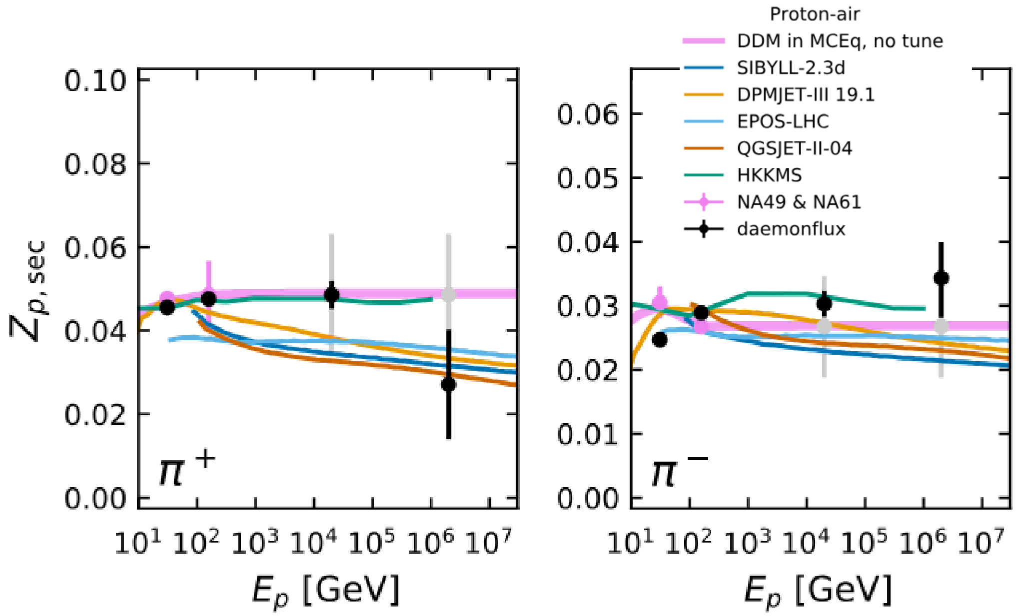
Atmospheric flux uncertainties

- Established method
  - Baseline model + variations based on
  - Using MCEq to predict changes
  - Gradient method to fit parameter

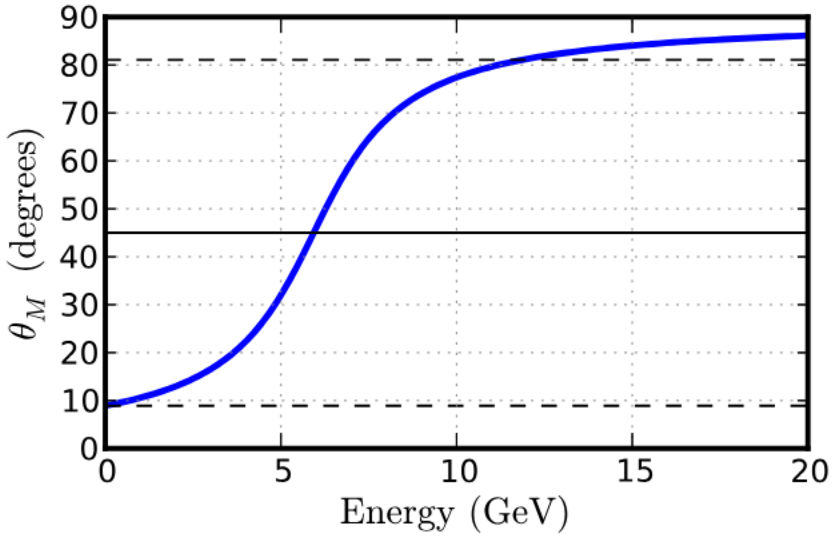


Barr, Gaisser, Robbins, Stanev, PRD 74 094009 (2006)

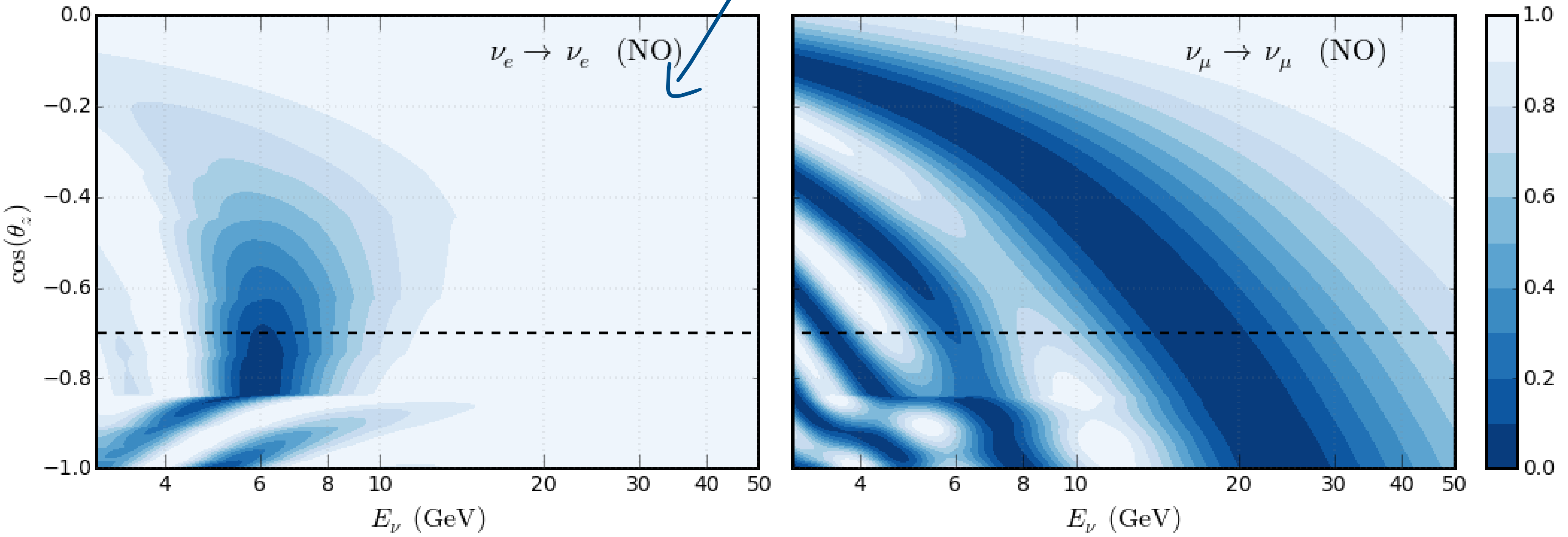
- New strategy
  - daemonflux: self-consistent data-driven flux with uncertainties
  - Key: only fit integral of meson yields, calibrate with μ and fixed target data



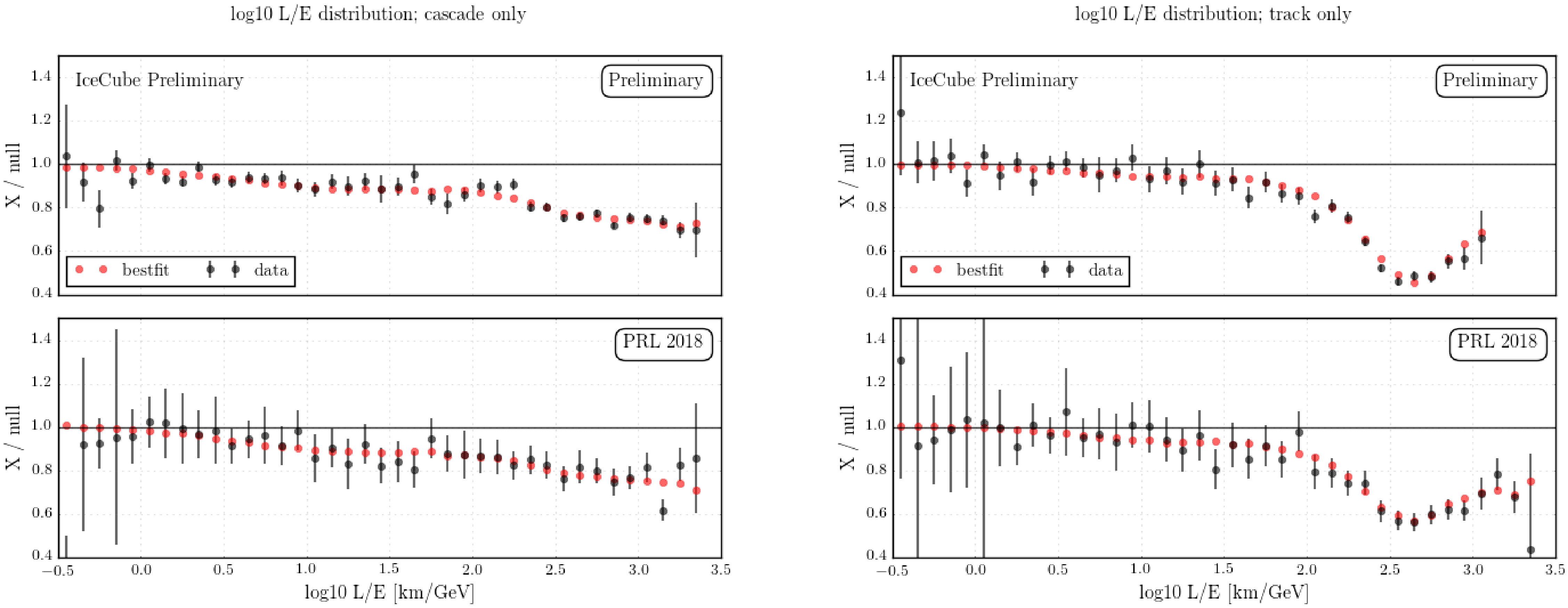
JPY, A. Fedynitch, Phys. Rev. D 107, 123037 (2023)



$$P(\nu_\mu \rightarrow \nu_e) \simeq sin^2(2\theta_{13})sin^2(\theta_{23})sin^2(1.27\Delta m^2_{23}\frac{L}{E})$$

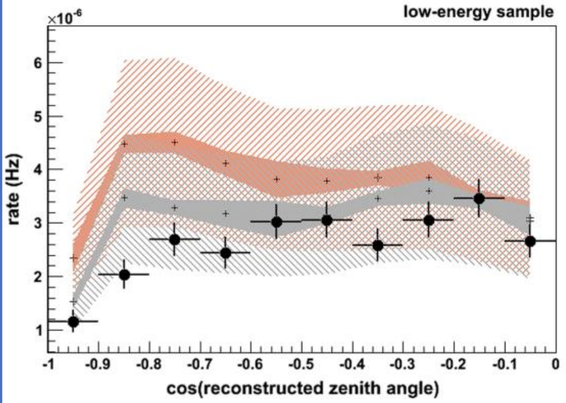


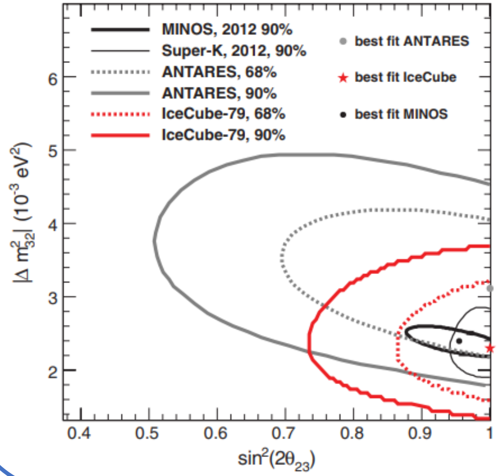
L/E figures for 2018 result



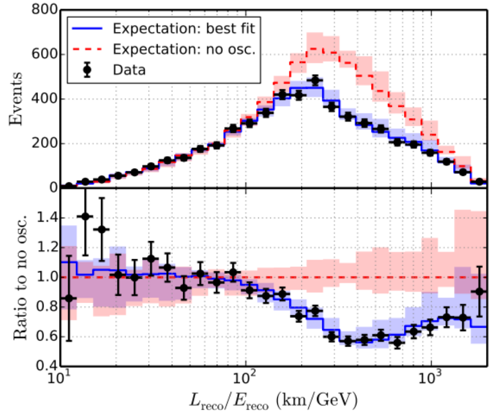
Atmospheric oscillations **progression**

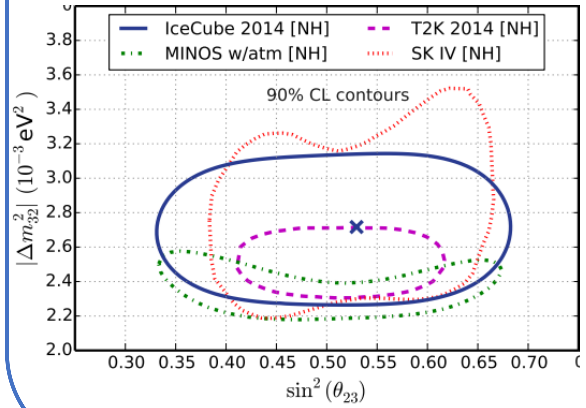
IceCube, PRL 111, 081801 **(2013)**
700 events



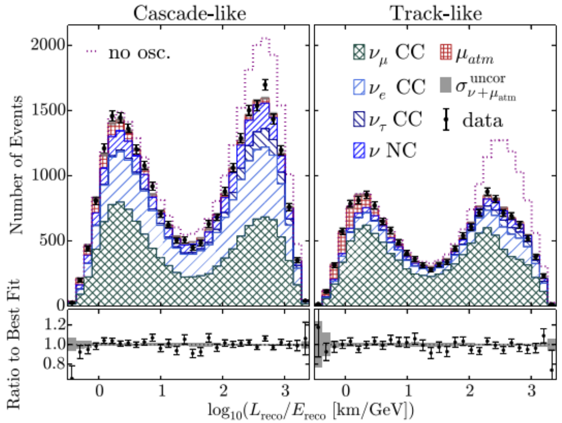


IceCube, PRD 91, 072004 **(2015)**
~5k events, “golden events”

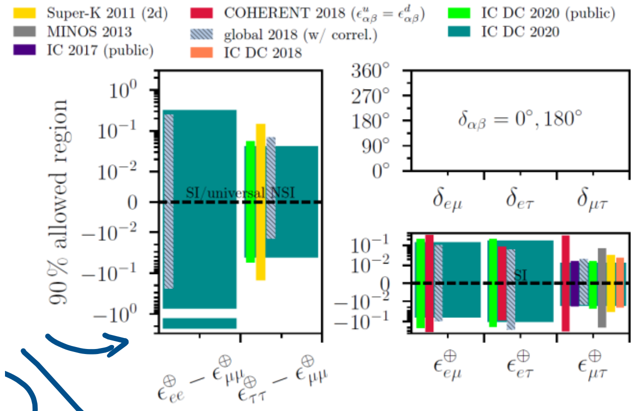


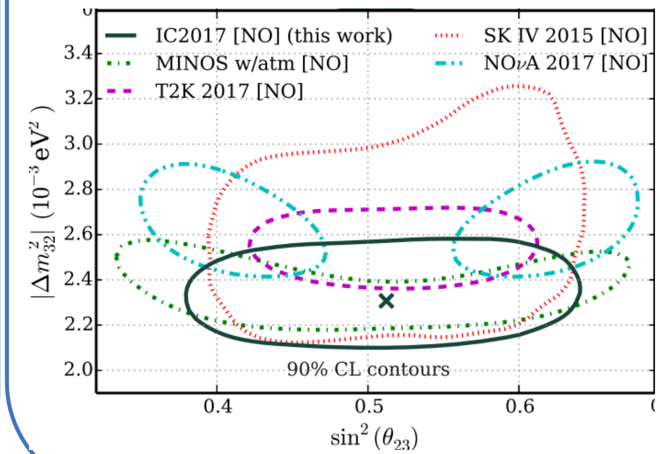


IceCube, PRL 120, 071801 **(2018)**
~35k events, inclusive sample

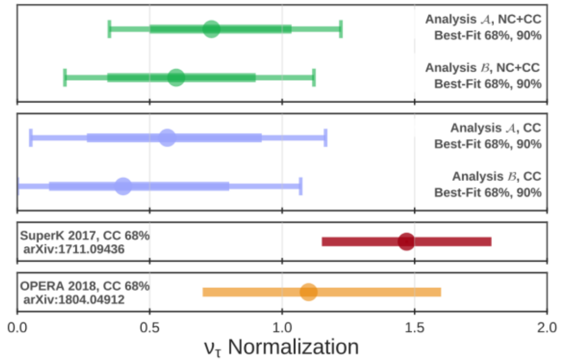


IceCube, PRD 104 **(2021)** 072006



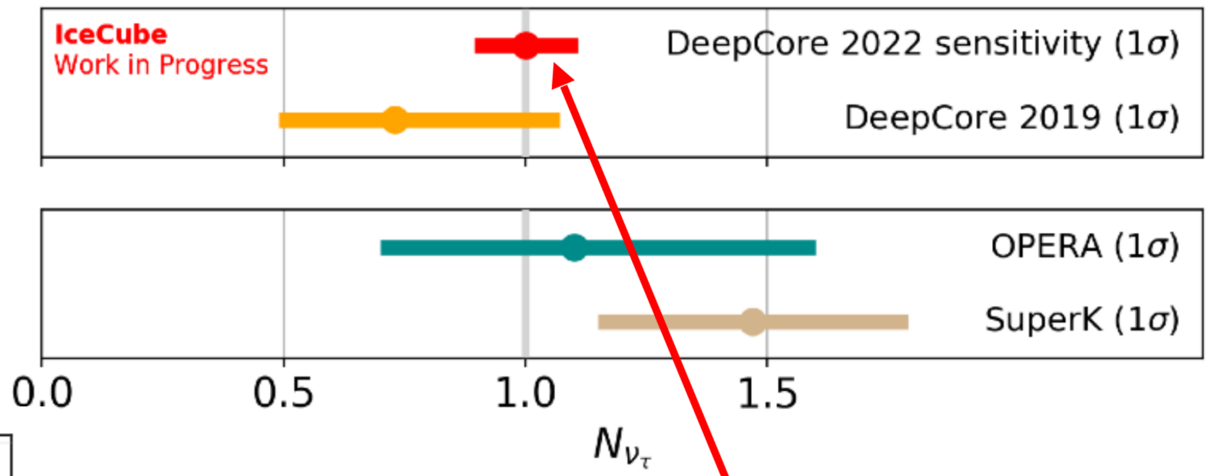


IceCube, PRD 99, 032007 **(2019)**



Standard oscillations (DC) to ν_τ

- Results from older sample
- Analysis with new sample will come next

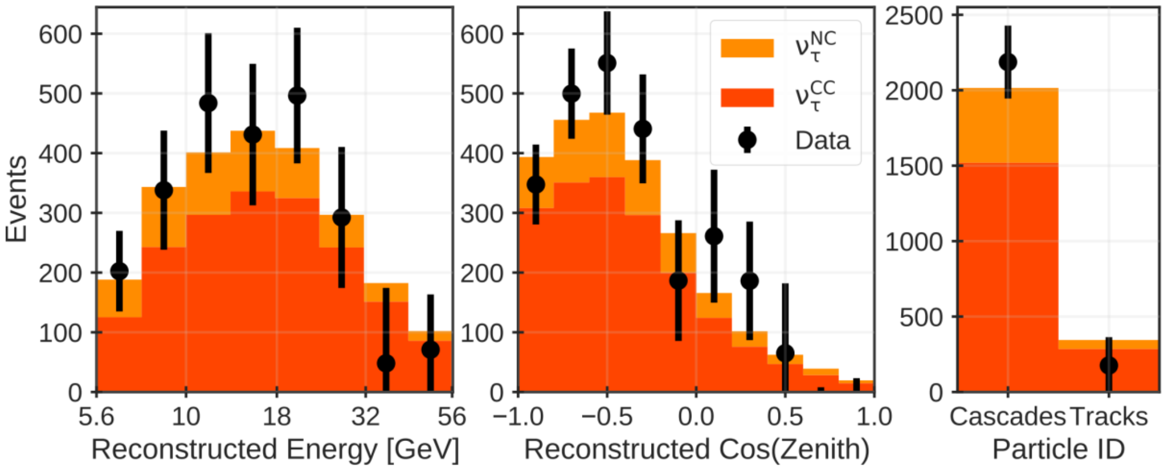


Expecting world-leading 11% precision

~9,700 $\nu_{\tau,CC}$ events expected

Signal is statistical excess of upgoing cascades with suppressed cross section

Tests PMNS unitarity and $\nu_{\tau,CC}$ cross section



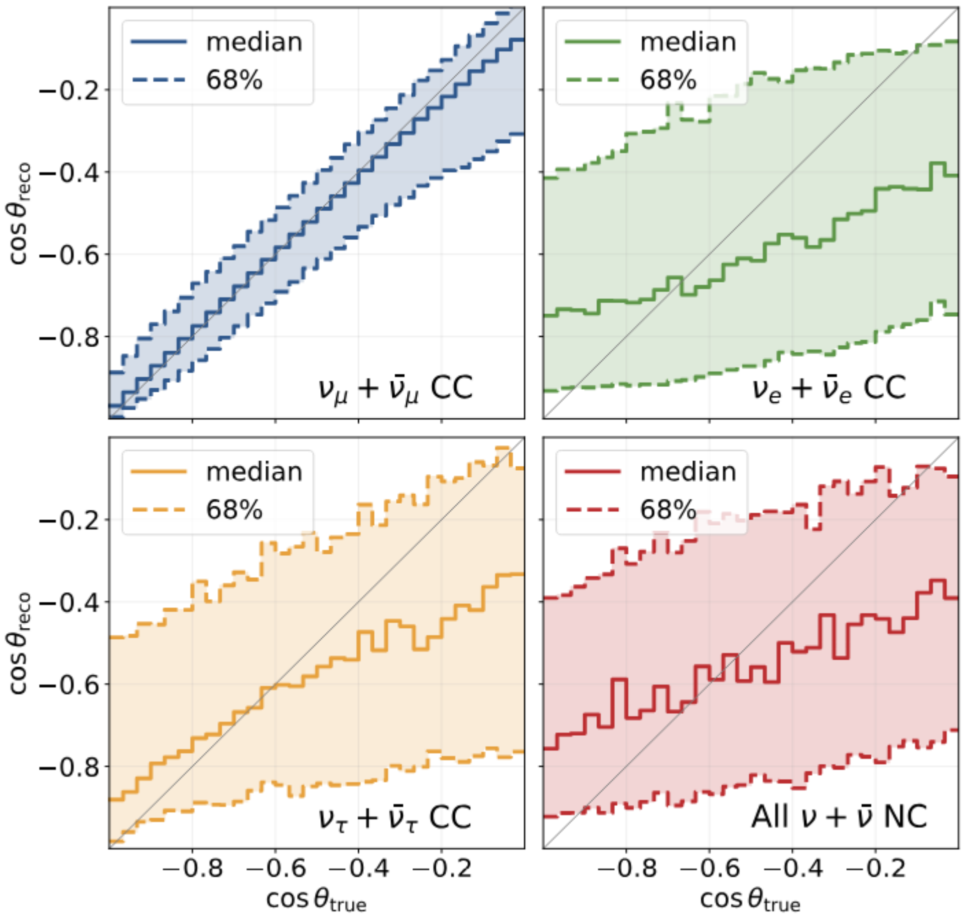
Phys. Rev. D 99, 032007 (2019)

For more details see:
IceCube, PRD 108, 012014 **(2023)**

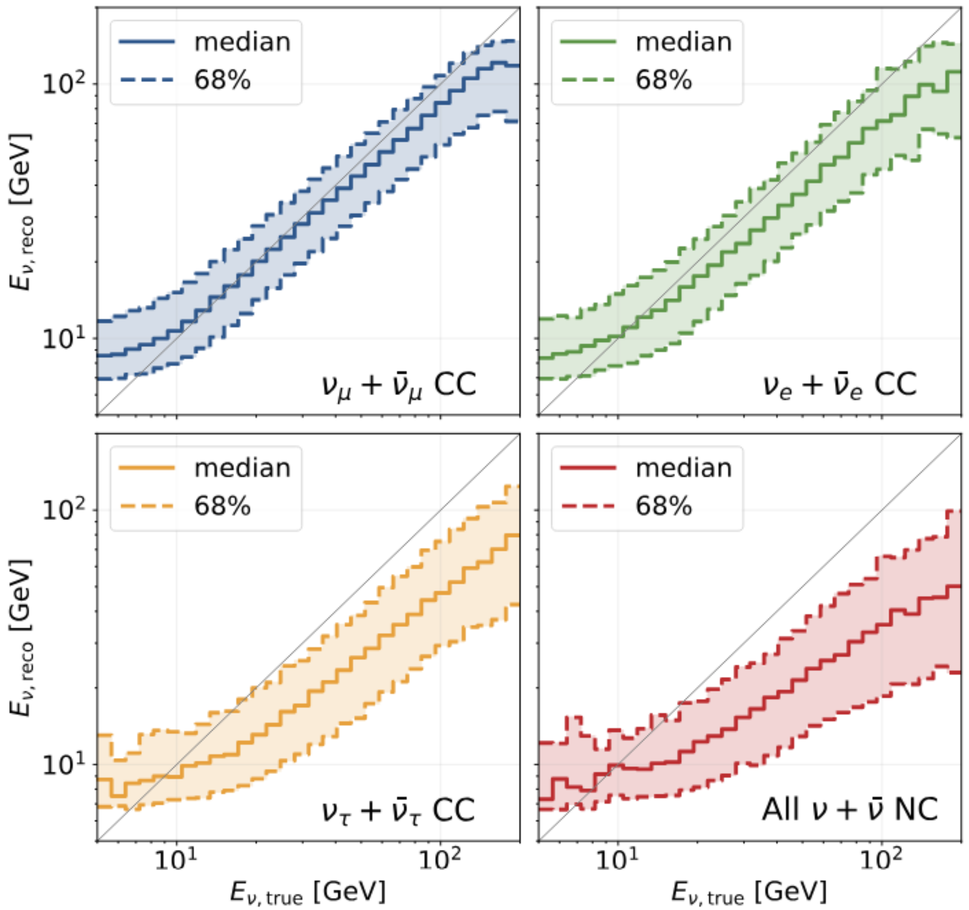
How? – **resolutions**

Relevant events are fully contained

direction



energy

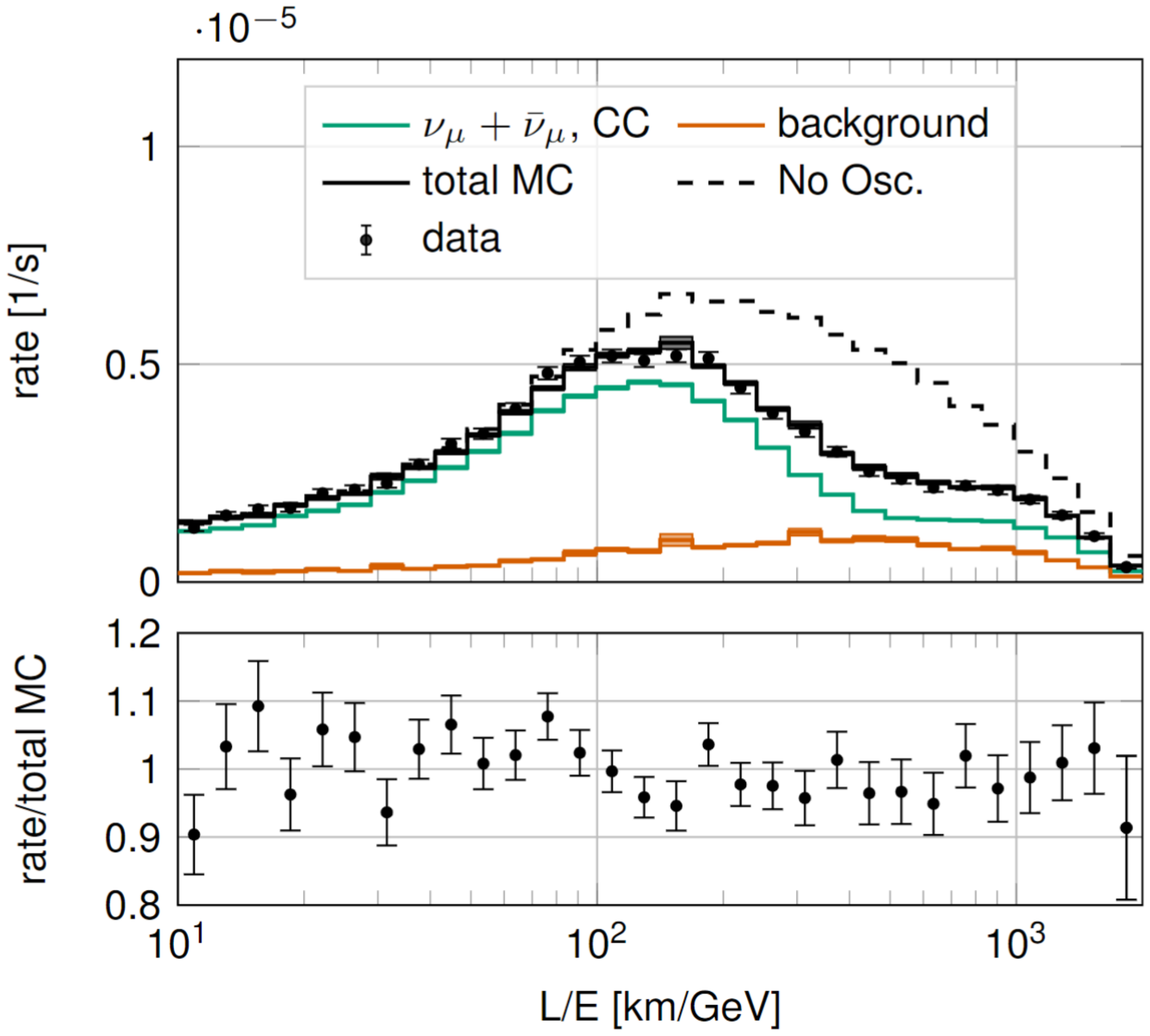


Standard oscillations 2013 (DC)

$$P\nu_\alpha \to \nu_\beta \simeq \sin^2 2\theta \ \sin^2\left(\frac{\Delta m^2}{4E} L\right)$$

- **New sample** incorporating
  - Streamlined event selection, higher efficiency
  - Improved sensor calibration
  - More precise treatment of systematics

- First looked at the **highest quality events**



Phys. Rev. D **108**, 012014

Standard oscillations 2013 (DC)

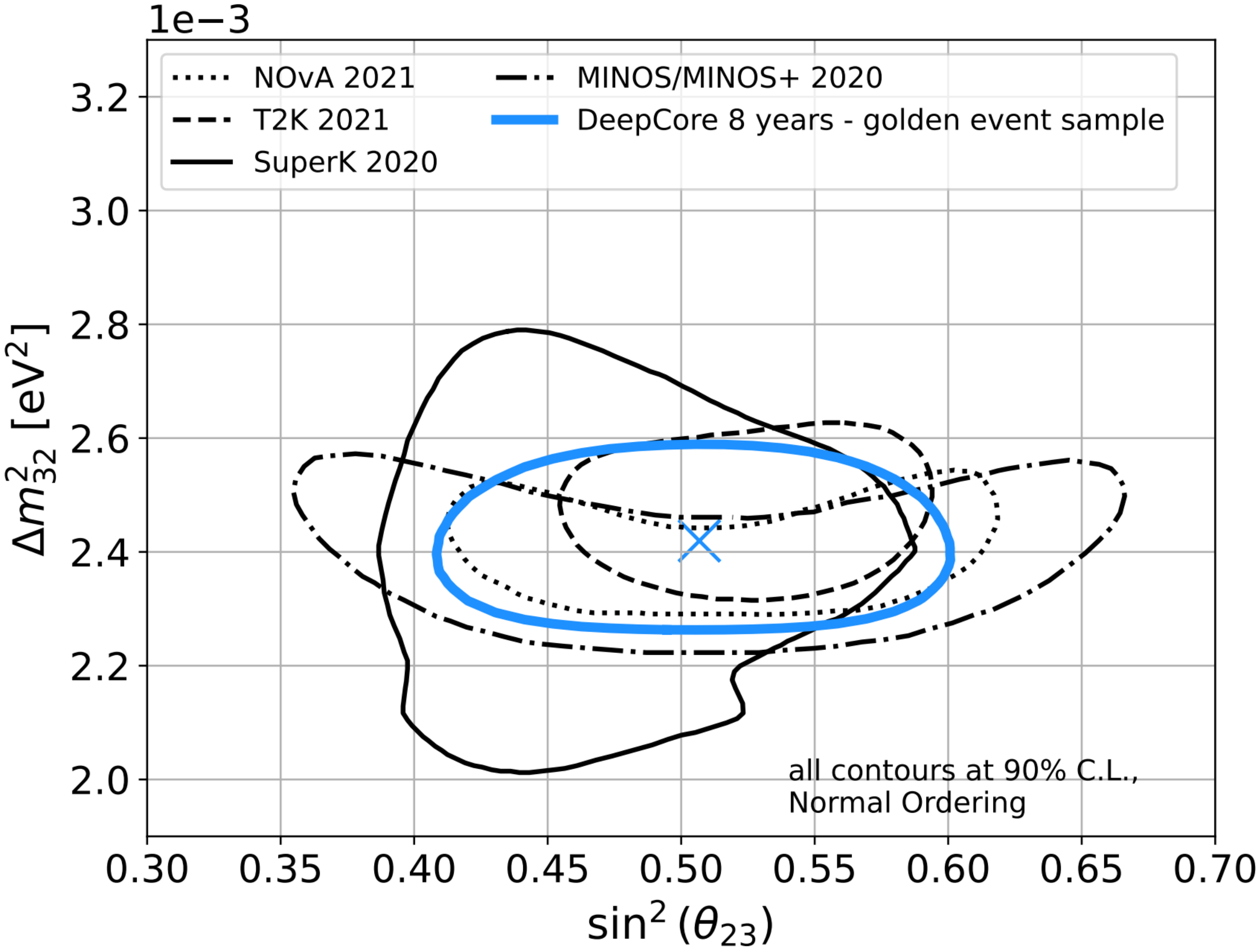
$$P\nu_\alpha \rightarrow \nu_\beta \simeq \sin^2 2\theta \ \sin^2\left(\frac{\Delta m^2}{4E} L\right)$$

- Best fit values

  $\sin^2\theta_{23} = 0.505^{+0.051}_{-0.050}$

  $\Delta m^2_{32} = 2.41 \pm 0.084 \times 10^{-3}$ eV²

- Excellent **agreement** between data/MC



Phys. Rev. D **108**, 012014

Atm. Osc. 2023

Phys. Rev. D **108**, 012014

physics

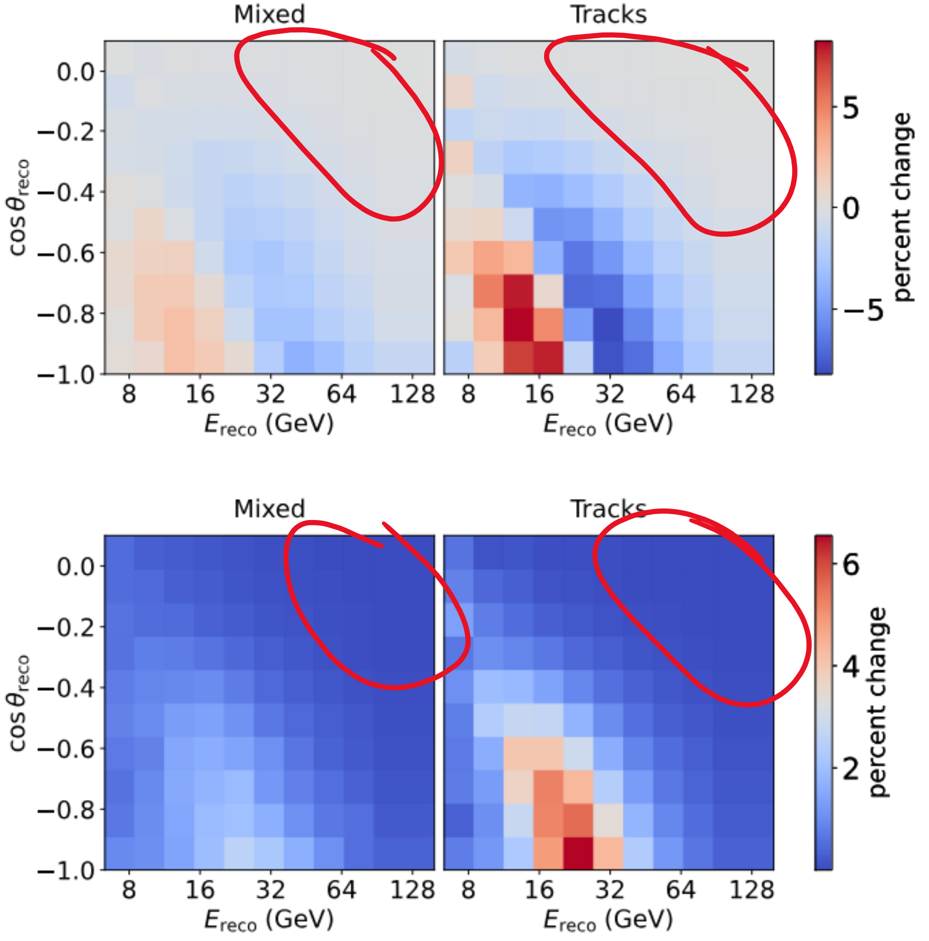


FIG. 18. Change in the expected number of events in the analysis when independently varying the values of Δm^2_{32} (top) and $\sin^2\theta_{23}$ (bottom) to the their 90% confidence level. The mass splitting changes the position of the oscillation probability, while the mixing angle modifies the amplitude. The largest change is observed in the track channel.

systematics

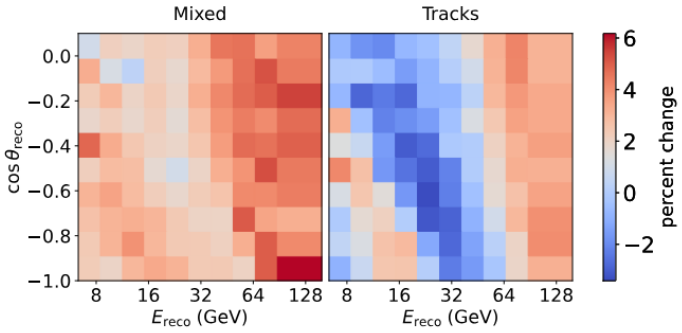


FIG. 28. DOM optical efficiency.

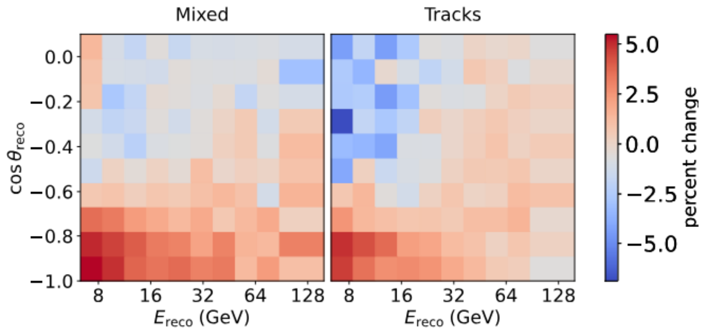


FIG. 29. Hole ice p0.

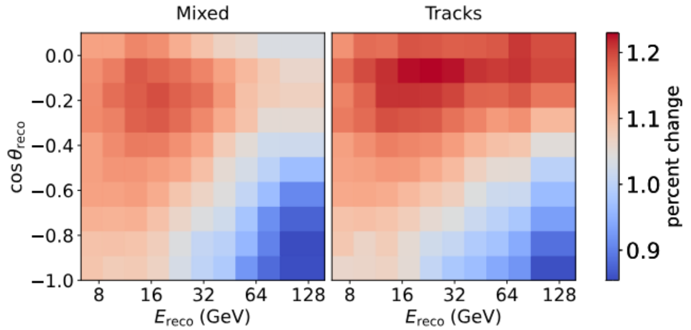
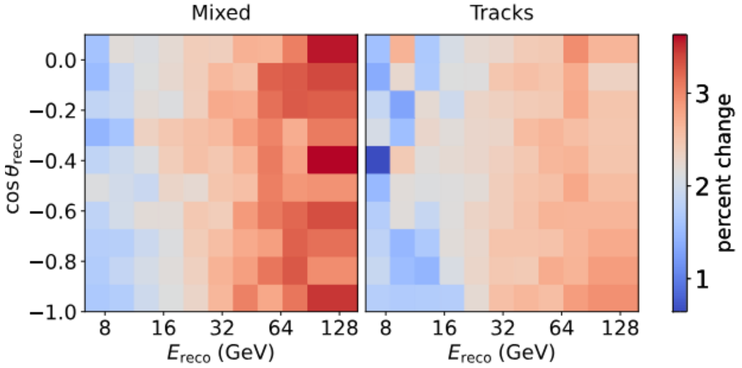


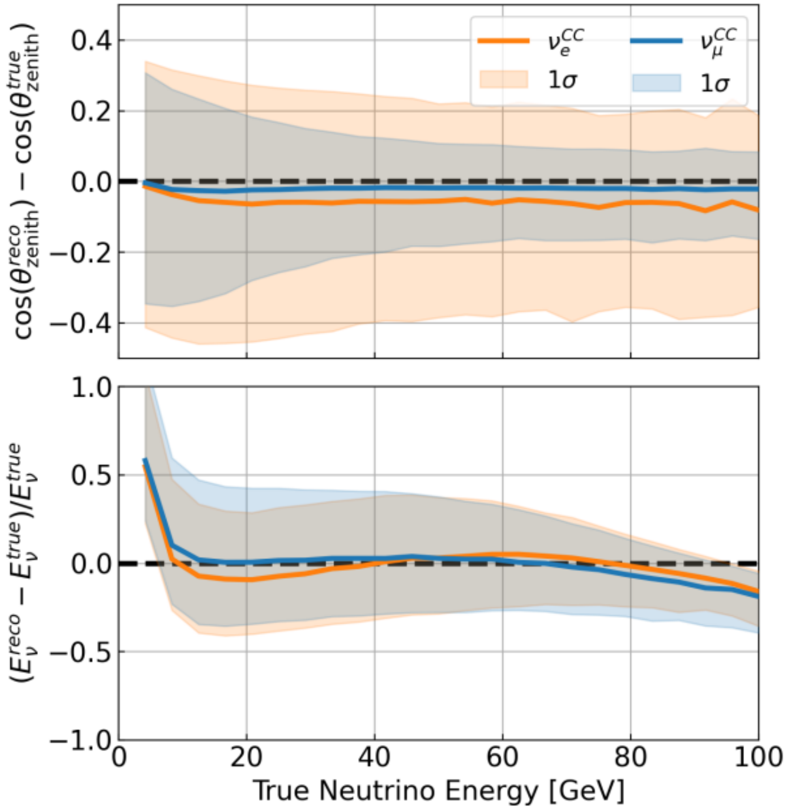
FIG. 35. Atm. flux G parameter.



IG. 42. Deep inelastic scattering correction to CSMS.

Control regions circled

Atm. Osc. 2024



physics

FIG. 7. Difference between the nominal ($\theta_{23} = 45°$) and pulled ($\theta_{23} = 50°$) MC distributions relative to the statistical error of the nominal MC for the analysis sample in analysis binning.

systematics

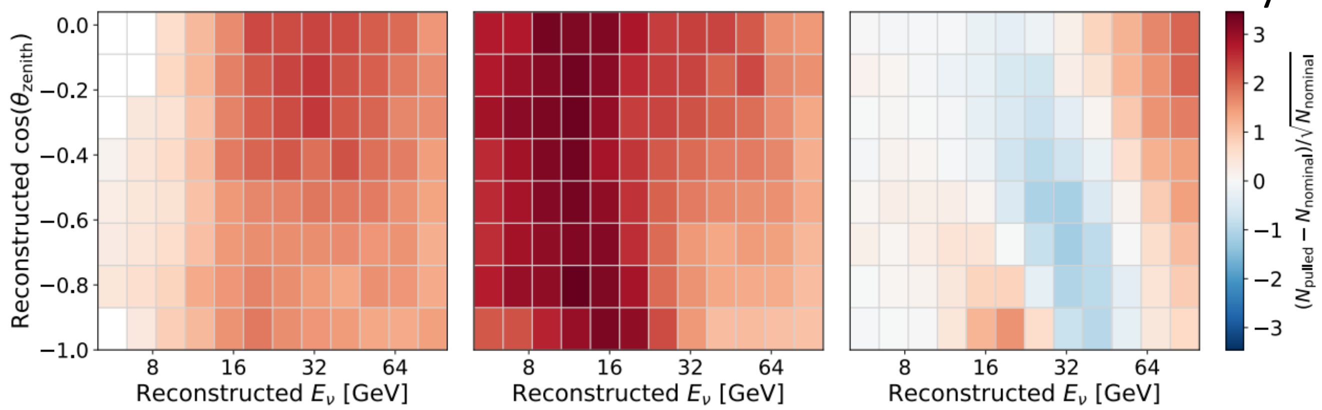
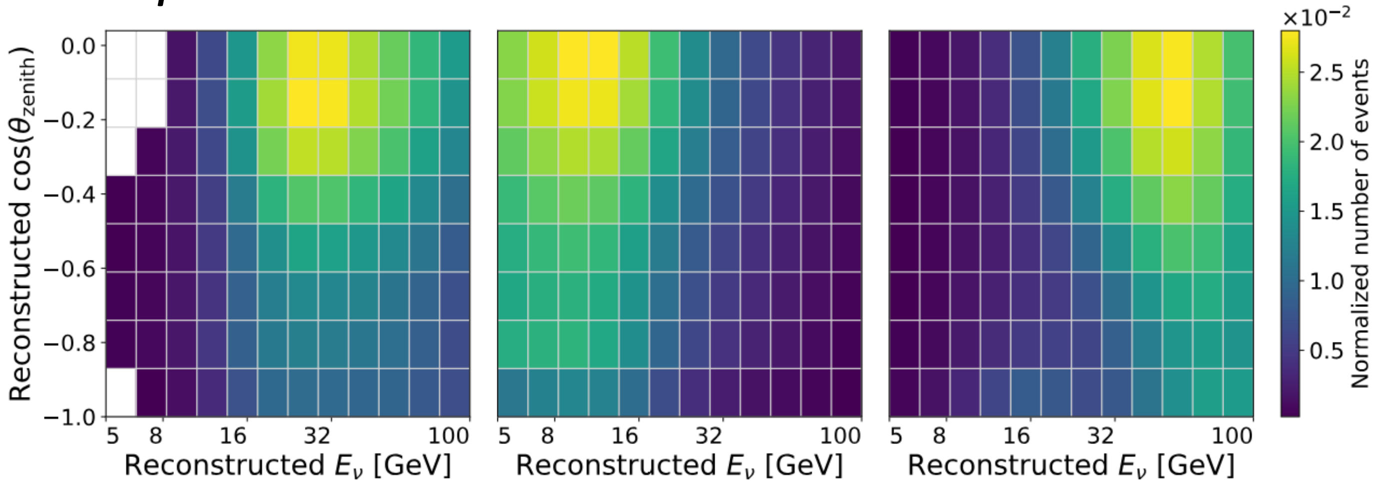


FIG. 8. Difference between the nominal DOM efficiency value and pulled (+10%) MC distributions relative to the statistical error of nominal MC for the analysis sample in analysis binning.

Atm. Osc. 2024

IceCube, arXiv:2405.02163

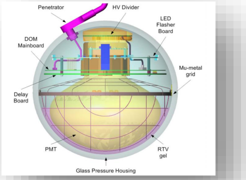
- CNN-based classification and reco
  - Uses inputs that our MC describes well
  - Recovers events that are hard to handle
  - 150,000 ν candidates in 9 years of data
- Best fit
  - $\sin^2\theta_{23} = 0.505^{+0.051}_{-0.050}$
  - $\Delta m^2_{32} = 2.41 \pm 0.084 \times 10^{-3}$ eV²
  - p-value: 19%

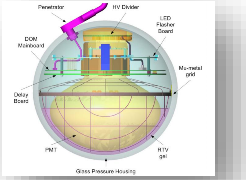


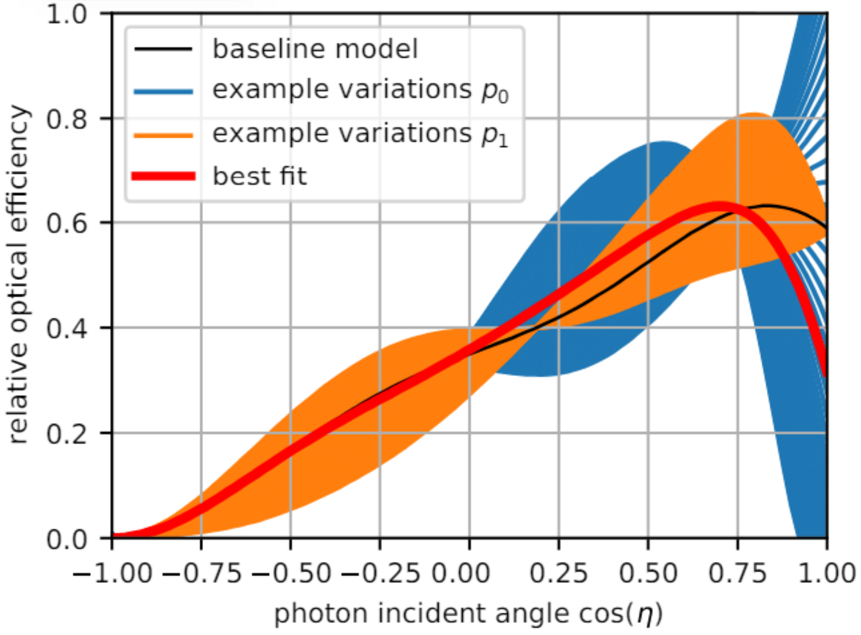
Parameter	Nominal	Prior width	Fit value	Pull (σ)
Detector:				
DOM efficiency	+0%	±10%	+1.8%	0.18
Ice absorption	+0%	±5%	−3.5%	-0.71
Ice scattering	+5%	±10%	+1.8%	-0.32
Rel. eff. p_0	0.10	[-0.6, 0.5]	-0.14	-
Rel. eff. p_1	-0.05	[-0.2, 0.2]	-0.07	-
BFR efficiency	0.0	[0, 1]	0.48	-
Atm. flux:				
$\Delta\gamma_\nu$	0.0	±0.1	-0.011	-0.11
$\Delta\pi^\pm$ yields I	0.0	±61%	+42%	0.68
$\Delta\pi^\pm$ yields G	0.0	±30%	−4.2%	-0.14
$\Delta\pi^\pm$ yields H	0.0	±15%	−12%	-0.81
ΔK^+ yields W	0.0	±40%	+4.2%	0.11
ΔK^+ yields Y	0.0	±30%	−6.9%	-0.23
Cross-section:				
M_A^{CCQE}	0.99 GeV	$^{+25\%}_{-15\%}$	−4.5%	-0.30
M_A^{CCRES}	1.12 GeV	±20%	−3.9%	-0.20
DIS CSMS	0.0	±1.0	0.12	0.12
Normalization:				
A_{eff} scale	+0%	[−90%, +100%]	−10%	-
Atm. muons:				
Atm. μ scale	+0%	±40%	−3.8%	-0.10

Atm. Osc. 2024

IceCube,
arXiv:2405.02163







Parameter	Nominal	Prior width	Fit value	Pull (σ)
Detector:				
DOM efficiency	+0%	±10%	+1.8%	0.18
Ice absorption	+0%	±5%	−3.5%	-0.71
Ice scattering	+5%	±10%	+1.8%	-0.32
Rel. eff. p_0	0.10	[-0.6, 0.5]	-0.14	-
Rel. eff. p_1	-0.05	[-0.2, 0.2]	-0.07	-
BFR efficiency	0.0	[0, 1]	0.48	-
Atm. flux:				
$\Delta\gamma_\nu$	0.0	±0.1	-0.011	-0.11
$\Delta\pi^\pm$ yields I	0.0	±61%	+42%	0.68
$\Delta\pi^\pm$ yields G	0.0	±30%	−4.2%	-0.14
$\Delta\pi^\pm$ yields H	0.0	±15%	−12%	-0.81
ΔK^+ yields W	0.0	±40%	+4.2%	0.11
ΔK^+ yields Y	0.0	±30%	−6.9%	-0.23
Cross-section:				
M_A^{CCQE}	0.99 GeV	$^{+25\%}_{-15\%}$	−4.5%	-0.30
M_A^{CCRES}	1.12 GeV	±20%	−3.9%	-0.20
DIS CSMS	0.0	±1.0	0.12	0.12
Normalization:				
A_{eff} scale	+0%	[−90%, +100%]	−10%	-
Atm. muons:				
Atm. μ scale	+0%	±40%	−3.8%	-0.10

Atm. Osc. 2024

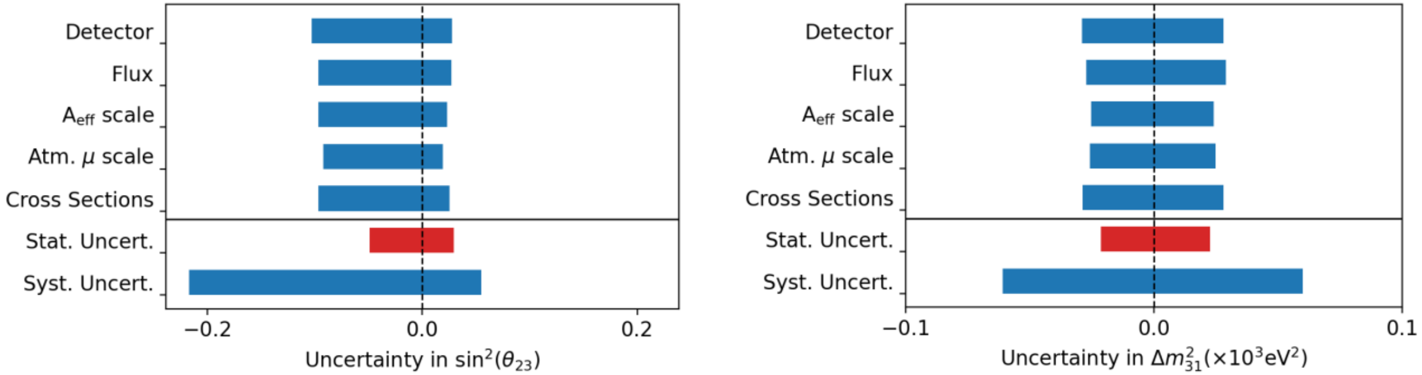
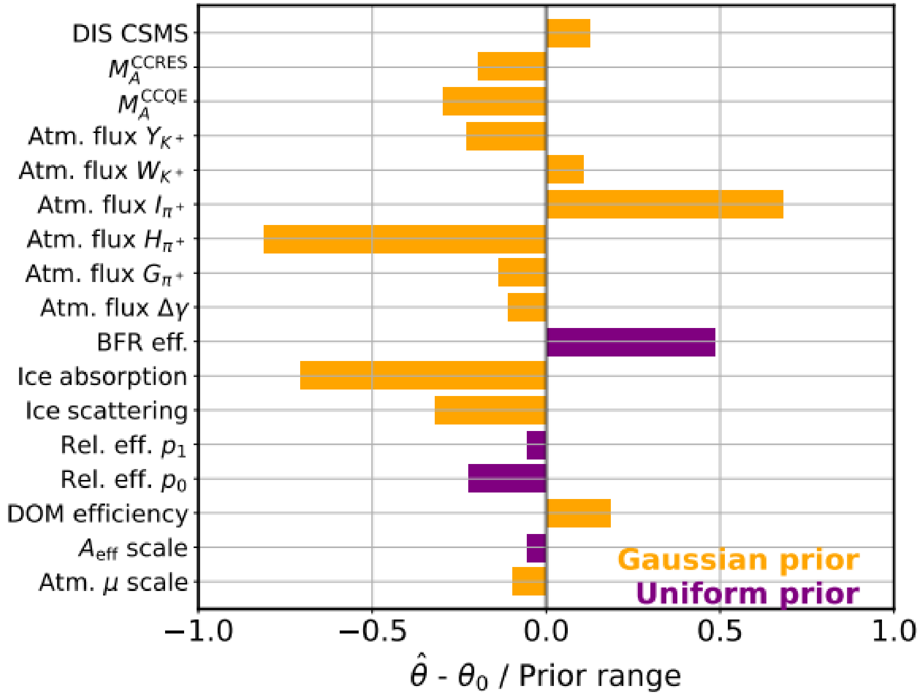
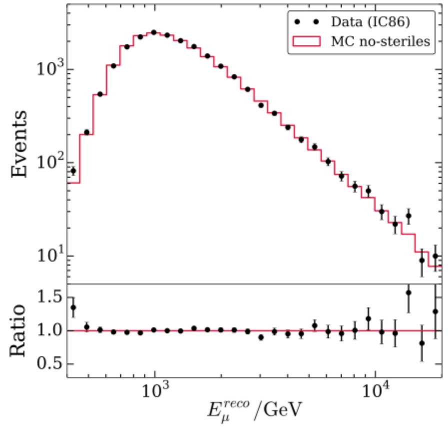


FIG. 10. Expected 1σ uncertainty of the physics parameters by assuming the best-fit values from Table II and fitting for each group of systematic uncertainties independently with the others fixed at their best-fit values compared to statistical uncertainty assuming Wilks' theorem.

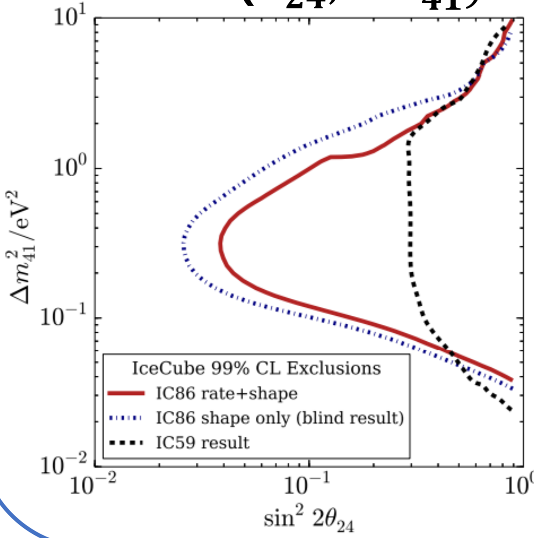


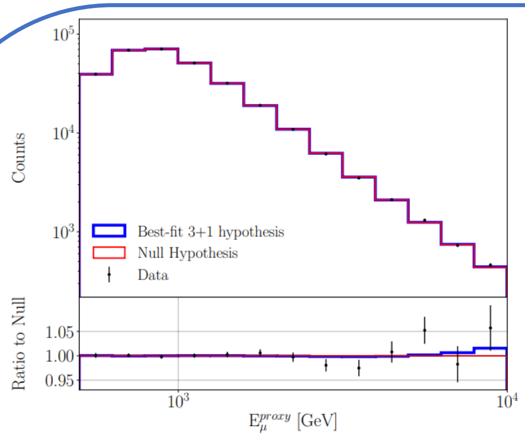
Sterile ν search progression (**TeV** regime)



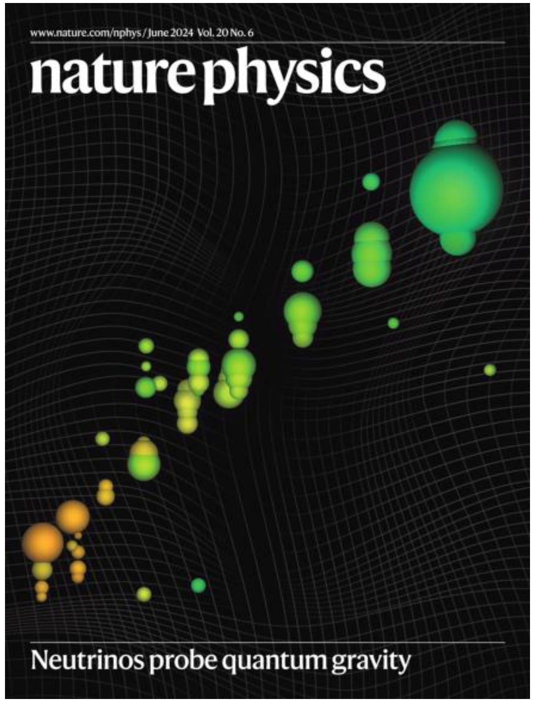
IceCube, PRL 117, 071801 **(2016)**
~20k events

3+1 $(\theta_{24}, \Delta m^2_{41})$

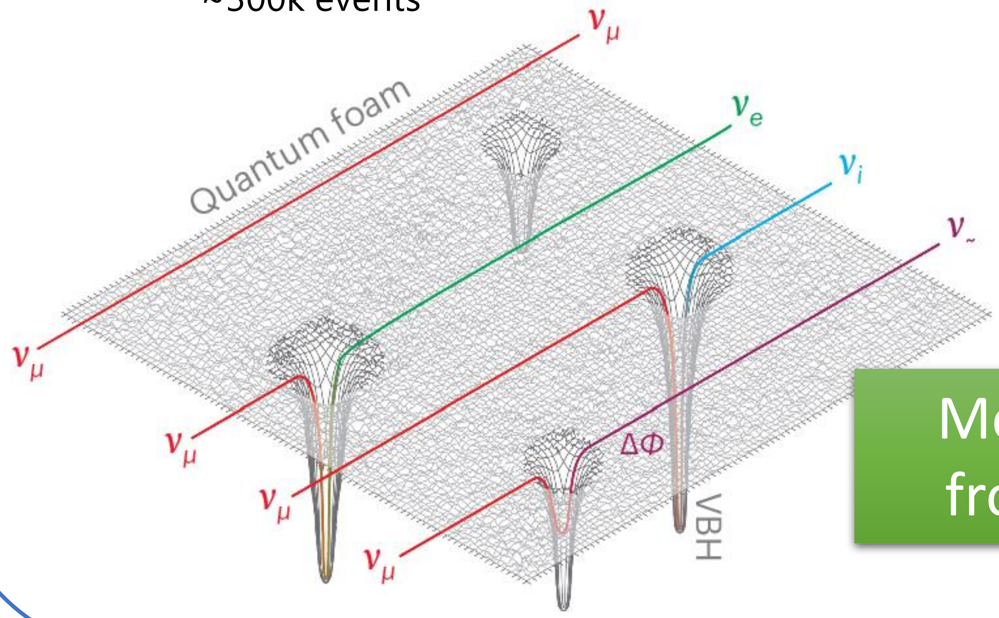




IceCube, PRL 125, 141801 **(2020)**
~300k events

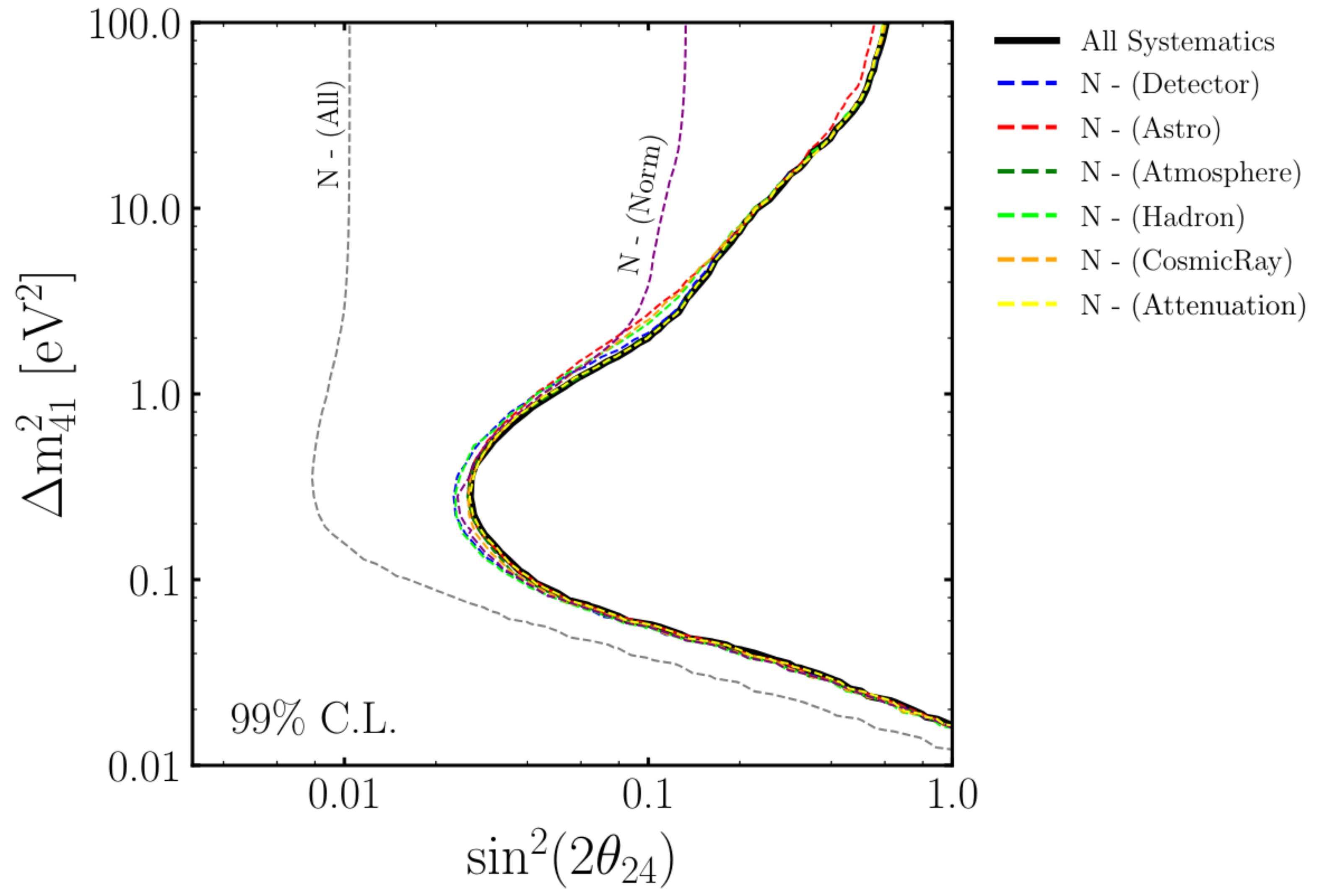


IceCube, Nature Physics volume 20, pages913–920 **(2024)**



More details on the talk from T. Katori on Friday

2024 TeV sterile search - sensitivity



2024 TeV sterile search

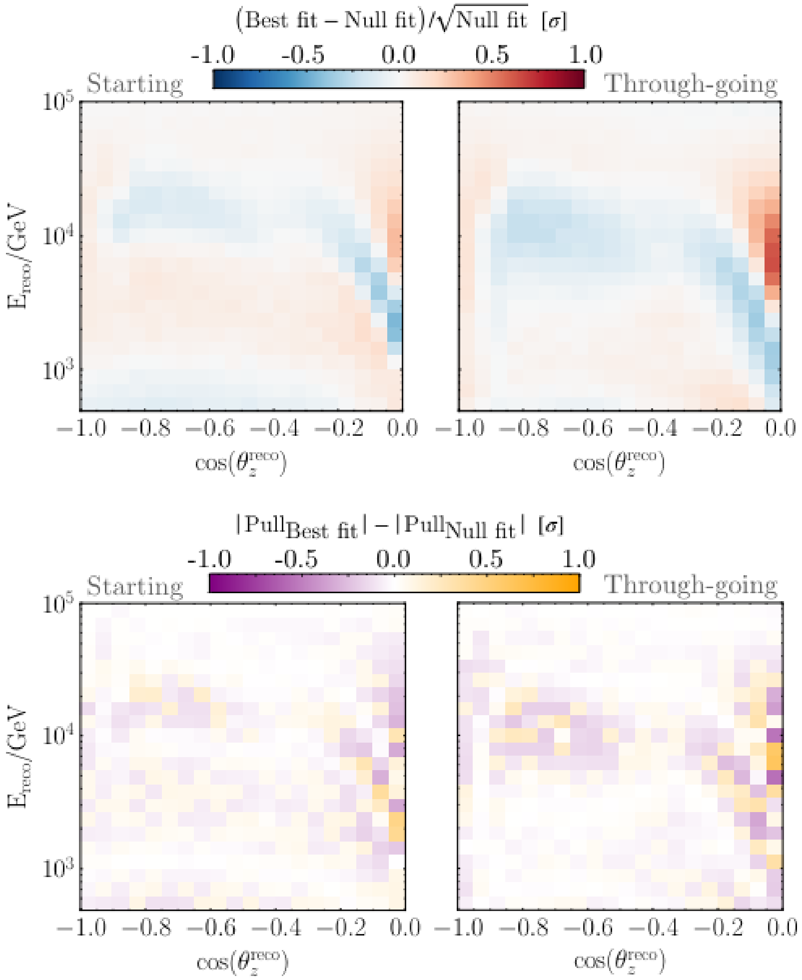
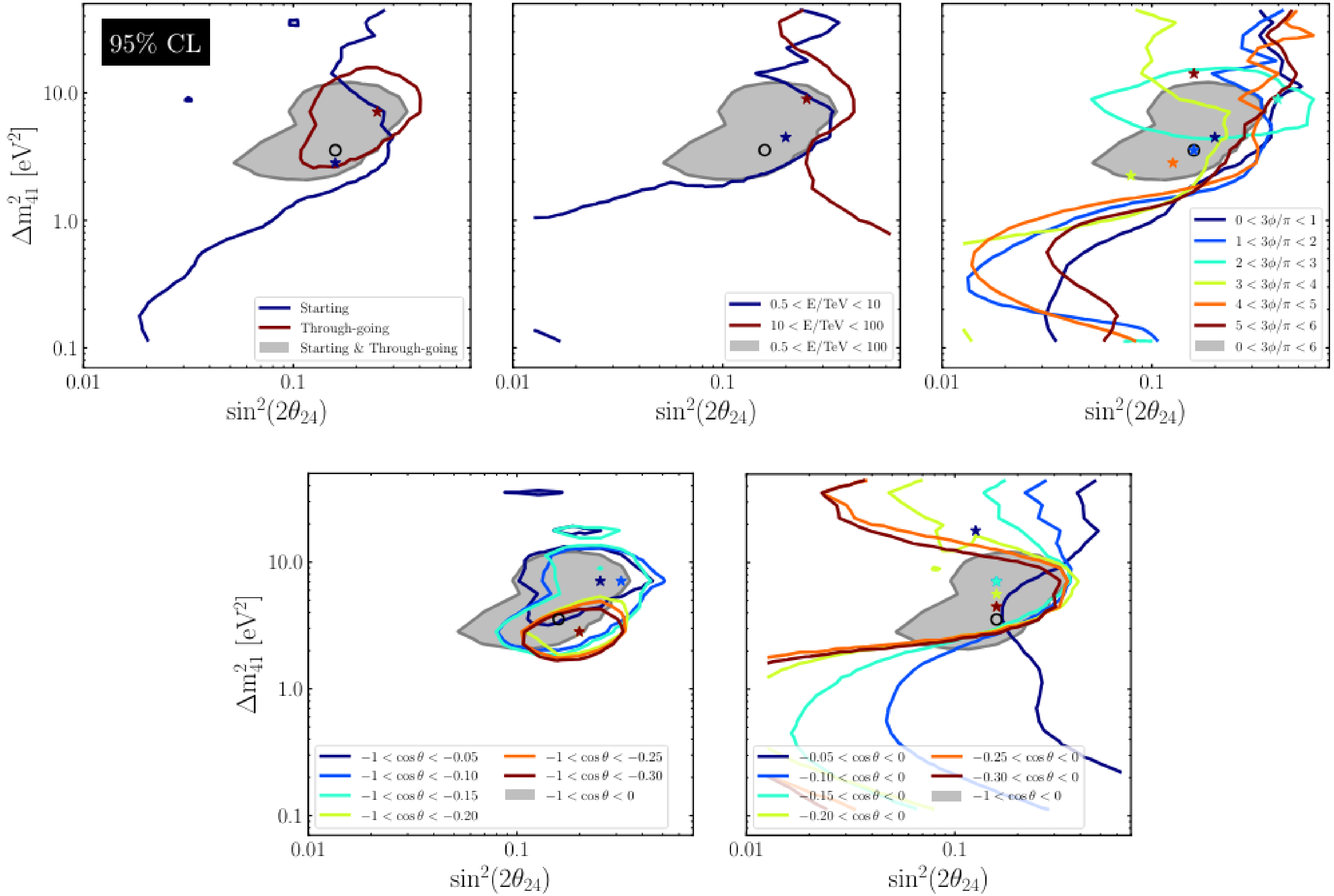


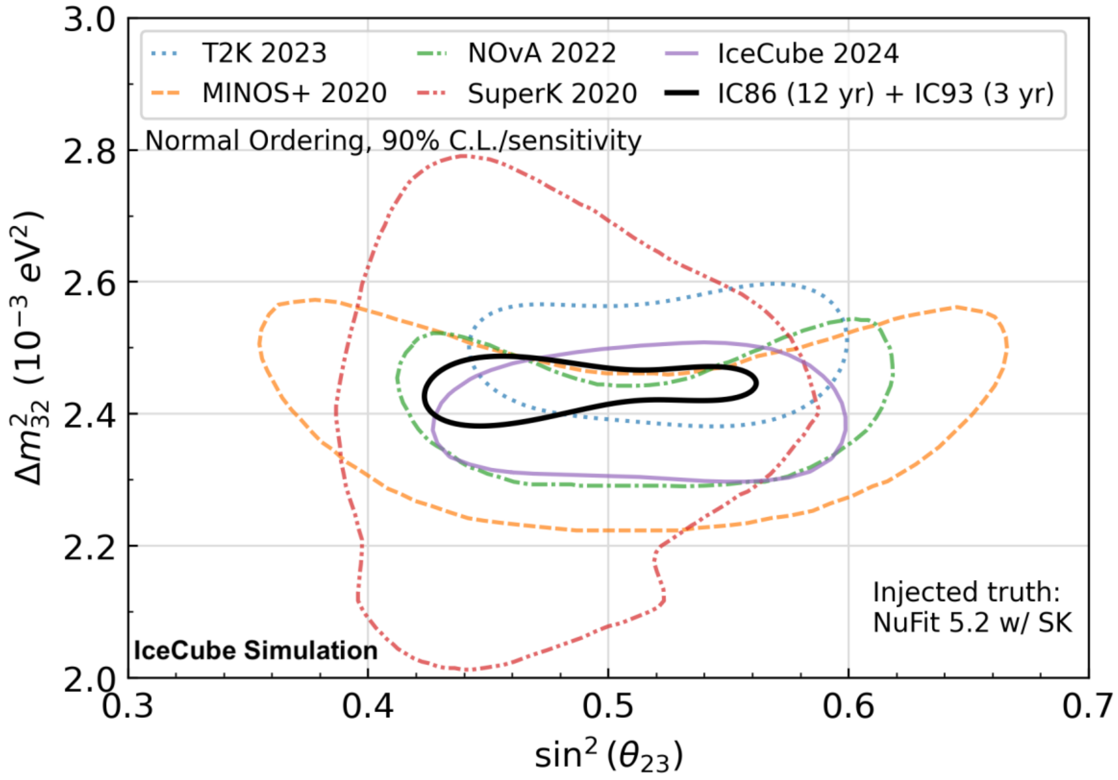
FIG. 11. **Expected and Observed Signal**. *Top panels*: Comparison of the best-fit and null hypothesis expectations for reconstructed starting and through-going events. Red (blue) colors indicate an excess (deficit) of events in the best-fit prediction relative to the null hypothesis. *Bottom panels*: Difference between data pulls for the best-fit values ($\sin^2(2\theta_{24}) = 0.16$ and $\Delta m^2_{41} = 3.5$ eV^2) and null hypotheses for the starting and through-going samples. Purple indicates the best-fit is preferred in a given bin; orange indicates a preference for the null hypothesis.

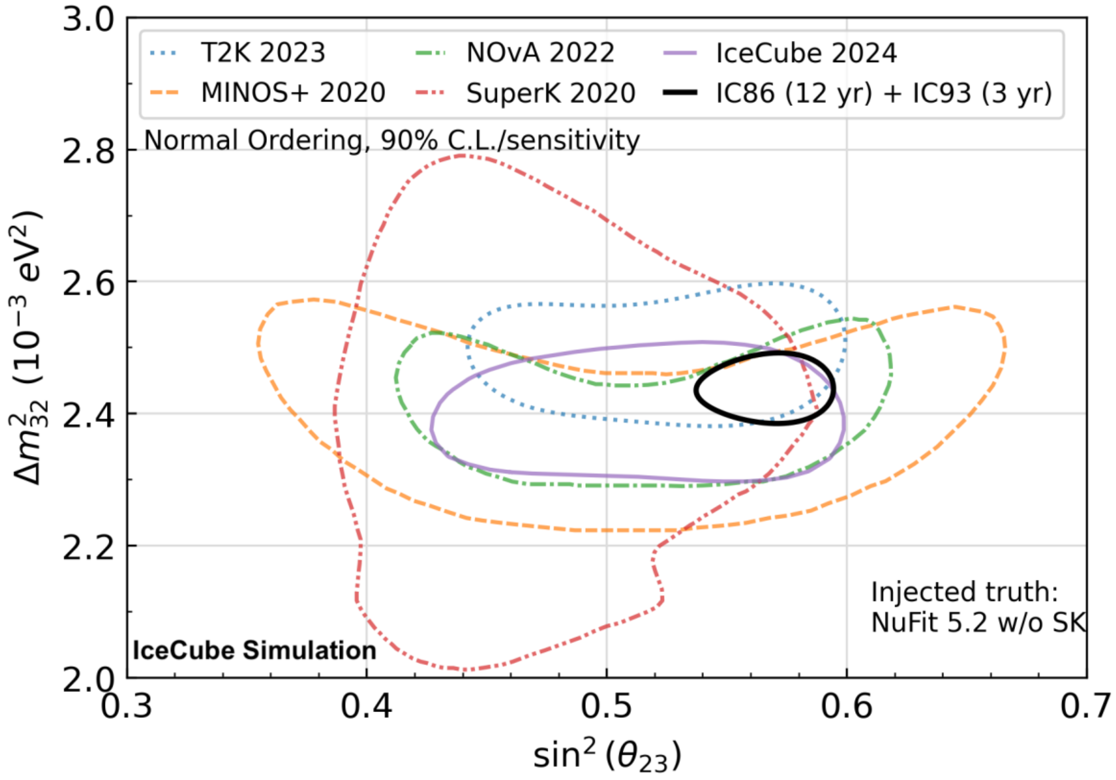
Nuisance parameter	Central value	1σ width of prior	Allowed range	Pull Null Fit (σ)	Pull Best Fit (σ)	Pull Difference |Null-Best Fit| (σ)
Overall normalization (Sec. III C)						
Norm	1.00	0.2	0.10,3.00	-0.05	0.41	0.46
Local response of DOMs (Sec. III E)						
DOM efficiency	1.00	0.10	0.97,1.06	0.02	0.03	0.01
Forward hole ice	-1.00	10.00	-5.35,1.85	0.28	0.27	0.01
Bulk ice (Sec. III D)						
Amplitude 0	0.00	1.00	-3.00,3.00	0.64	0.69	0.05
Amplitude 1	0.00	1.00	-3.00,3.00	1.36	1.19	0.17
Amplitude 2	0.00	1.00	-3.00,3.00	1.35	1.42	0.07
Amplitude 3	0.00	1.00	-3.00,3.00	0.74	0.75	0.01
Amplitude 4	0.00	1.00	-3.00,3.00	1.12	1.16	0.04
Phase 1	0.00	1.00	-3.00,3.00	-1.60	-1.67	0.07
Phase 2	0.00	1.00	-3.00,3.00	-0.59	-0.54	0.05
Phase 3	0.00	1.00	-3.00,3.00	-0.21	-0.08	0.13
Phase 4	0.00	1.00	-3.00,3.00	0.10	0.27	0.17
Conventional flux (Sec. III A)						
Atm. density (ρ_{atm})	0.00	1.00	-3.00,3.00	-0.48	-0.55	0.07
Kaon energy loss ($\sigma_{\text{K-Air}}$)	0.00	1.00	-3.00,3.00	0.66	0.51	0.15
Hadronic production						
K^+_{158G}	0.00	1.00	-2.00,2.00	0.93	0.89	0.04
K^-_{158G}	0.00	1.00	-2.00,2.00	0.29	0.24	0.05
π^+_{20T}	0.00	1.00	-2.00,2.00	0.15	-0.06	0.21
π^-_{20T}	0.00	1.00	-2.00,2.00	0.17	-0.03	0.20
K^+_{2P}	0.00	1.00	-2.00,2.00	0.28	0.09	0.19
K^-_{2P}	0.00	1.00	-1.50,2.00	0.24	0.01	0.23
π^+_{2P}	0.00	1.00	-2.00,2.00	-1.50	-1.23	0.27
π^-_{2P}	0.00	1.00	-2.00,2.00	-1.08	-0.85	0.23
p_{2P}	0.00	1.00	-2.00,2.00	-0.25	-0.18	0.07
n_{2P}	0.00	1.00	-2.00,2.00	-0.17	-0.15	0.02
CR spectrum						
GSF_1	0.00	1.00	-4.00,4.00	-0.33	0.10	0.43
GSF_2	0.00	1.00	-4.00,4.00	-0.12	-0.28	0.16
GSF_3	0.00	1.00	-4.00,4.00	-0.12	-0.05	0.07
GSF_4	0.00	1.00	-4.00,4.00	-0.13	-0.25	0.12
GSF_5	0.00	1.00	-4.00,4.00	1.82	2.24	0.42
GSF_6	0.00	1.00	-4.00,4.00	-1.17	-1.31	0.14
Non-conventional flux (Sec. III B)						
$\Phi^{\text{HE}}/10^{-18}\text{GeV}^{-1}\text{sr}^{-1}\text{s}^{-1}\text{cm}^{-2}$	0.787	0.36	0.00,3.00	0.25	0.61	0.36
$\log_{10}$ of pivot energy, $E^{\text{HE}}_{\text{break}}$/GeV	-	-	4.00,6.00	*4.25	*4.31	N/A, see caption
$\Delta\gamma_1^{\text{HE}}$, tilt from -2.5	0.00	0.36	-2.00,2.00	2.62	2.39	0.23
$\Delta\gamma_2^{\text{HE}}$, tilt from -2.5	0.00	0.36	-2.00,2.00	-0.22	0.10	0.21
Neutrino attenuation (Sec. III F)						
ν attenuation	1.00	0.10	0.82, 1.18	0.12	-0.14	0.26
$\bar{\nu}$ attenuation	1.00	0.10	0.82, 1.18	0.04	-0.02	0.06

2024 Sterile neutrinos split tests

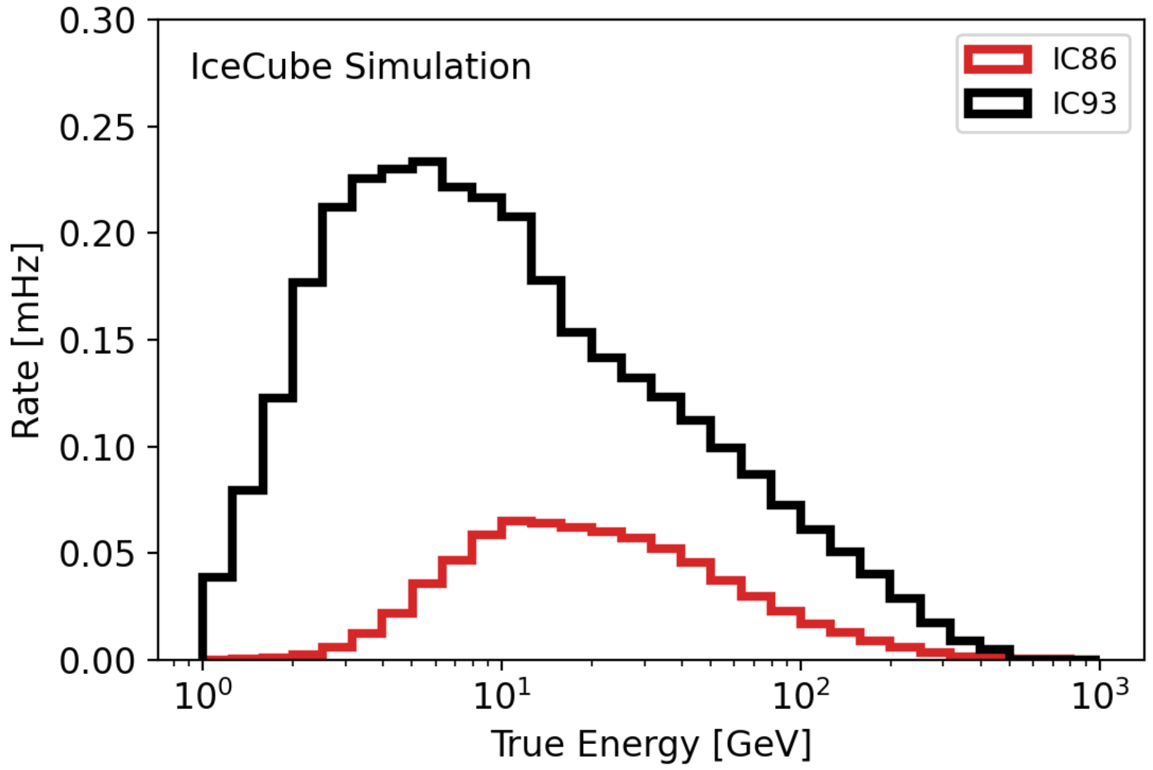


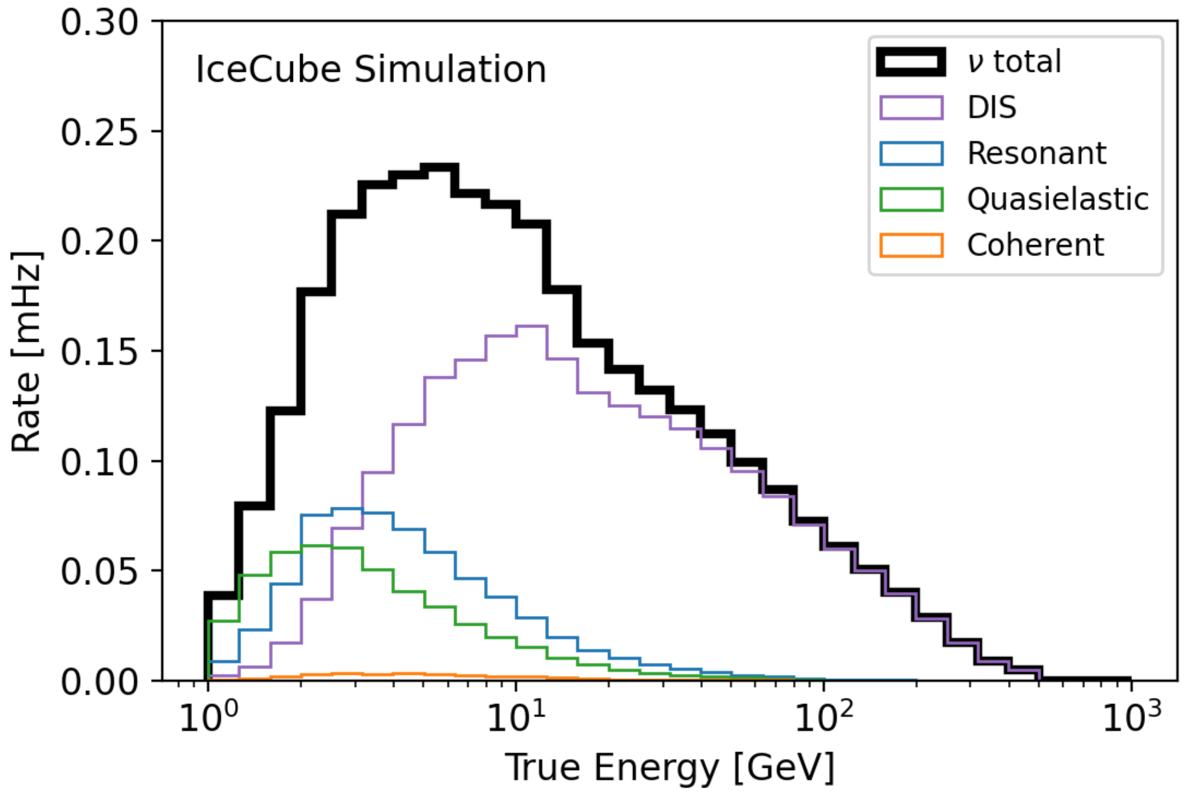
Upgrade: precision oscillations



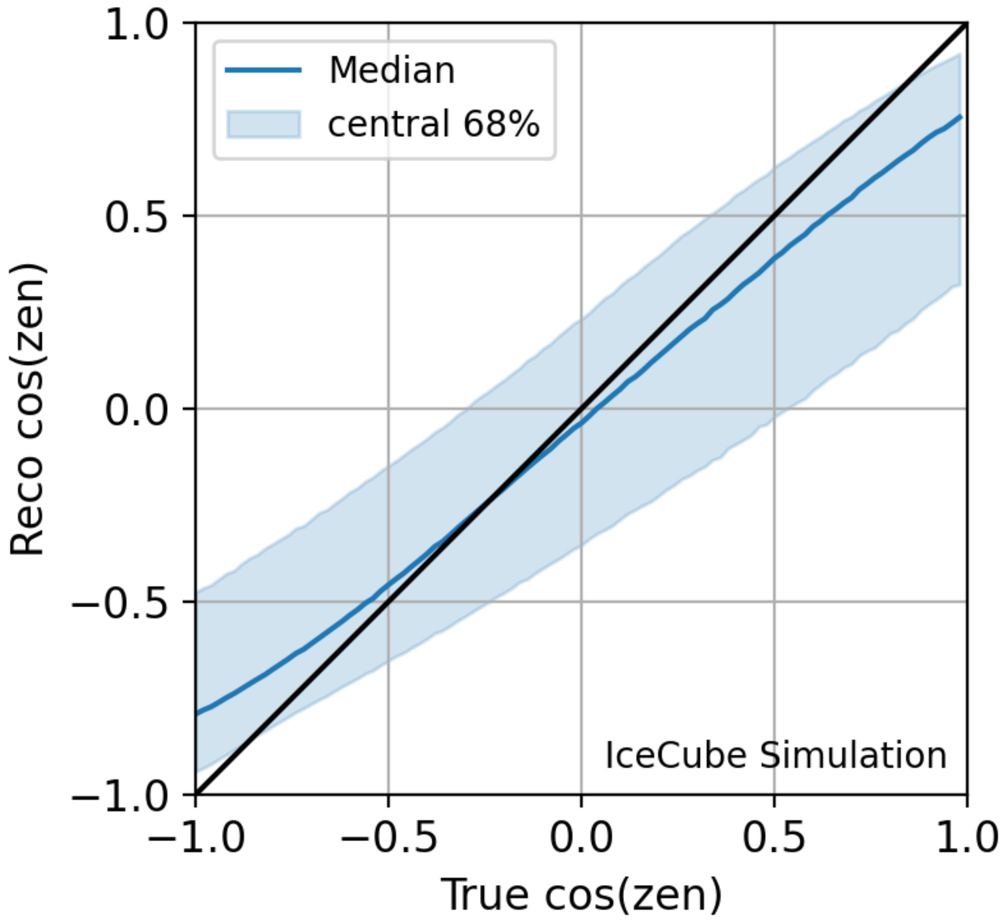


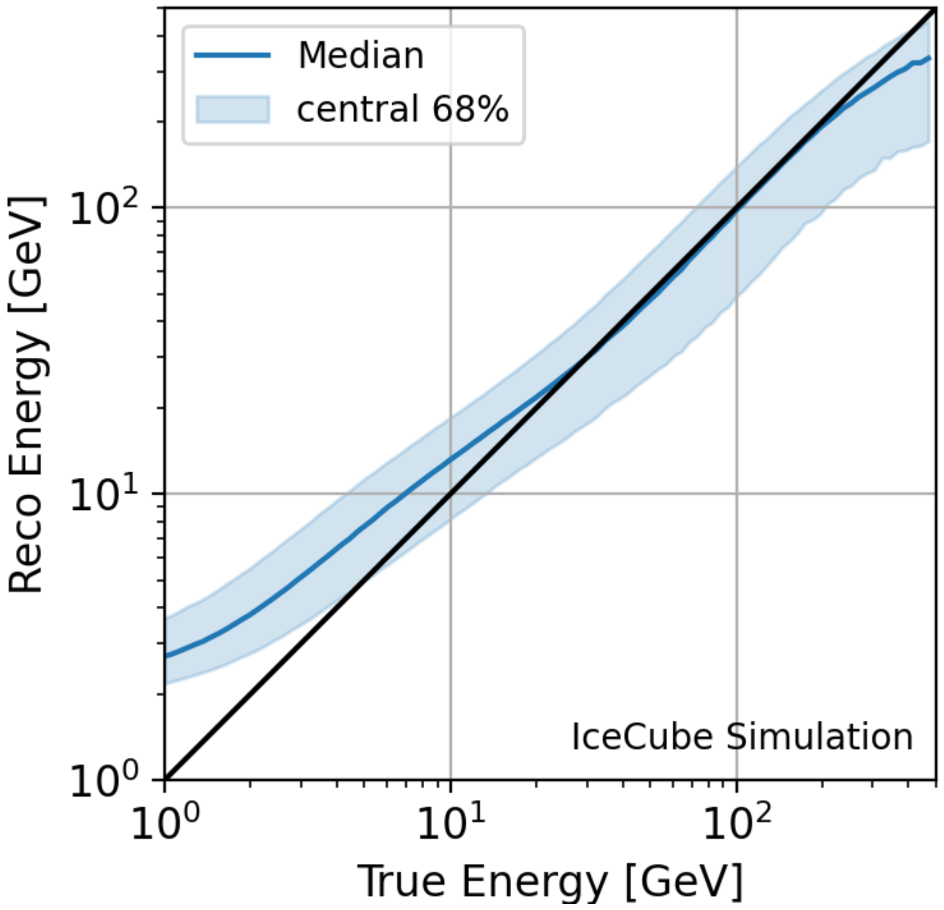
Upgrade: spectrum





Upgrade: resolutions





Steriles in DeepCore

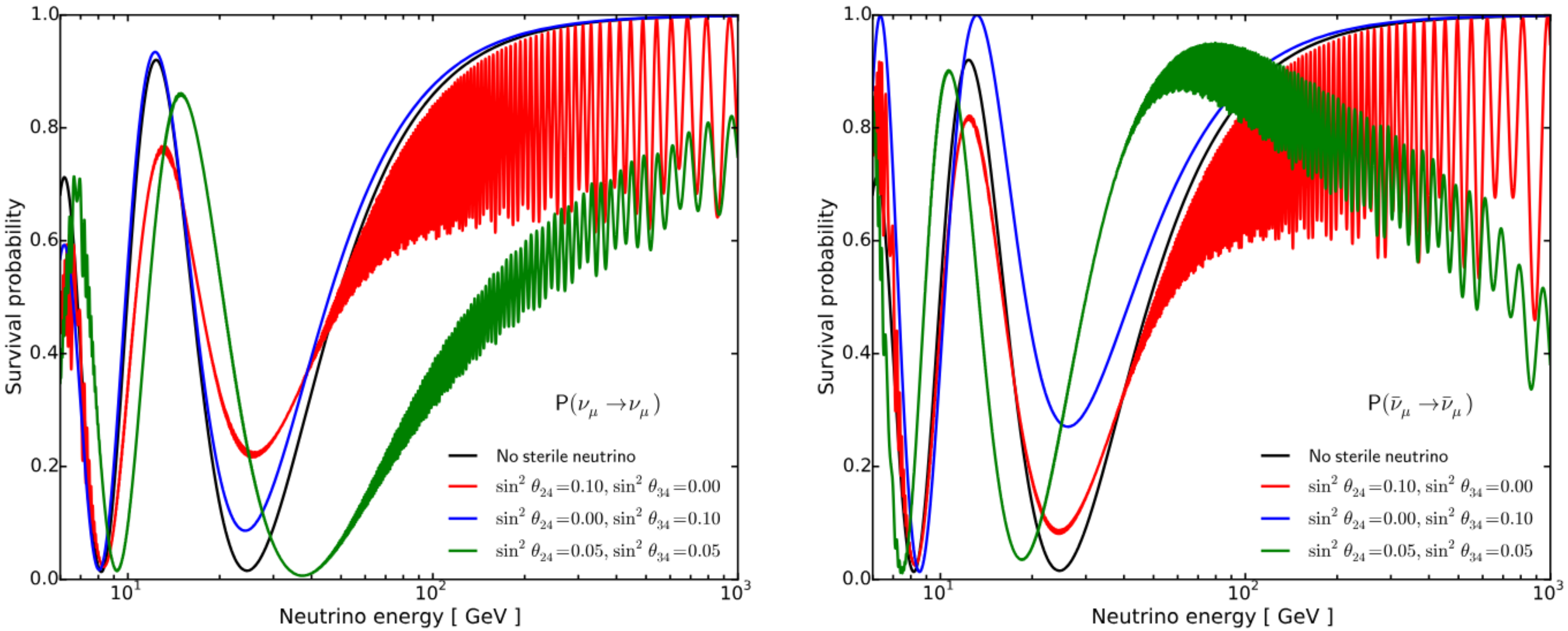


Figure 3.18: The survival probabilities for muon neutrinos (left) and antineutrinos (right) for the standard oscillations (black curve) and various realisations of the sterile neutrino mixing (coloured lines). The parameters of the standard mixing are $\Delta m^2_{31} = 2.515 \cdot 10^{-3}$ eV^2, $\sin^2\theta_{23} = 0.565$, while $\Delta m^2_{41} = 1$ eV^2. The averaging in $\pm 1\%$ window is applied to reduce the effects of the fast oscillating component caused by Δm^2_{41}.

A. Terliuk, PhD thesis