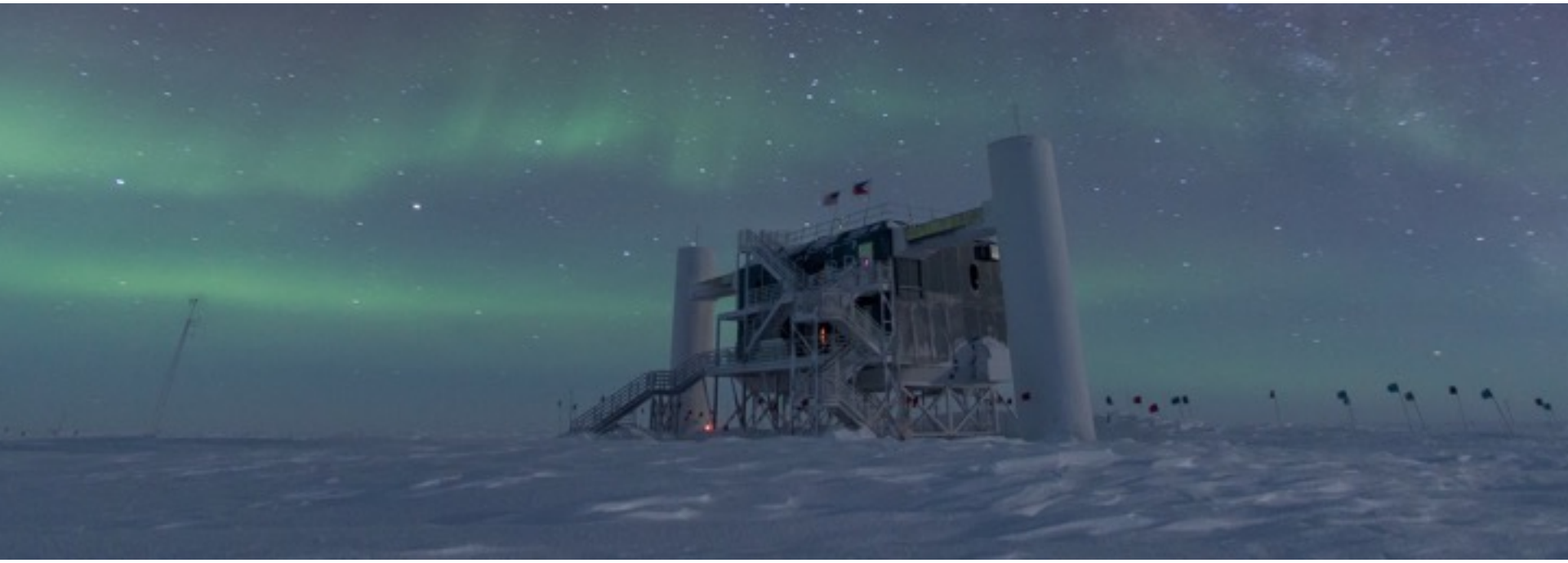


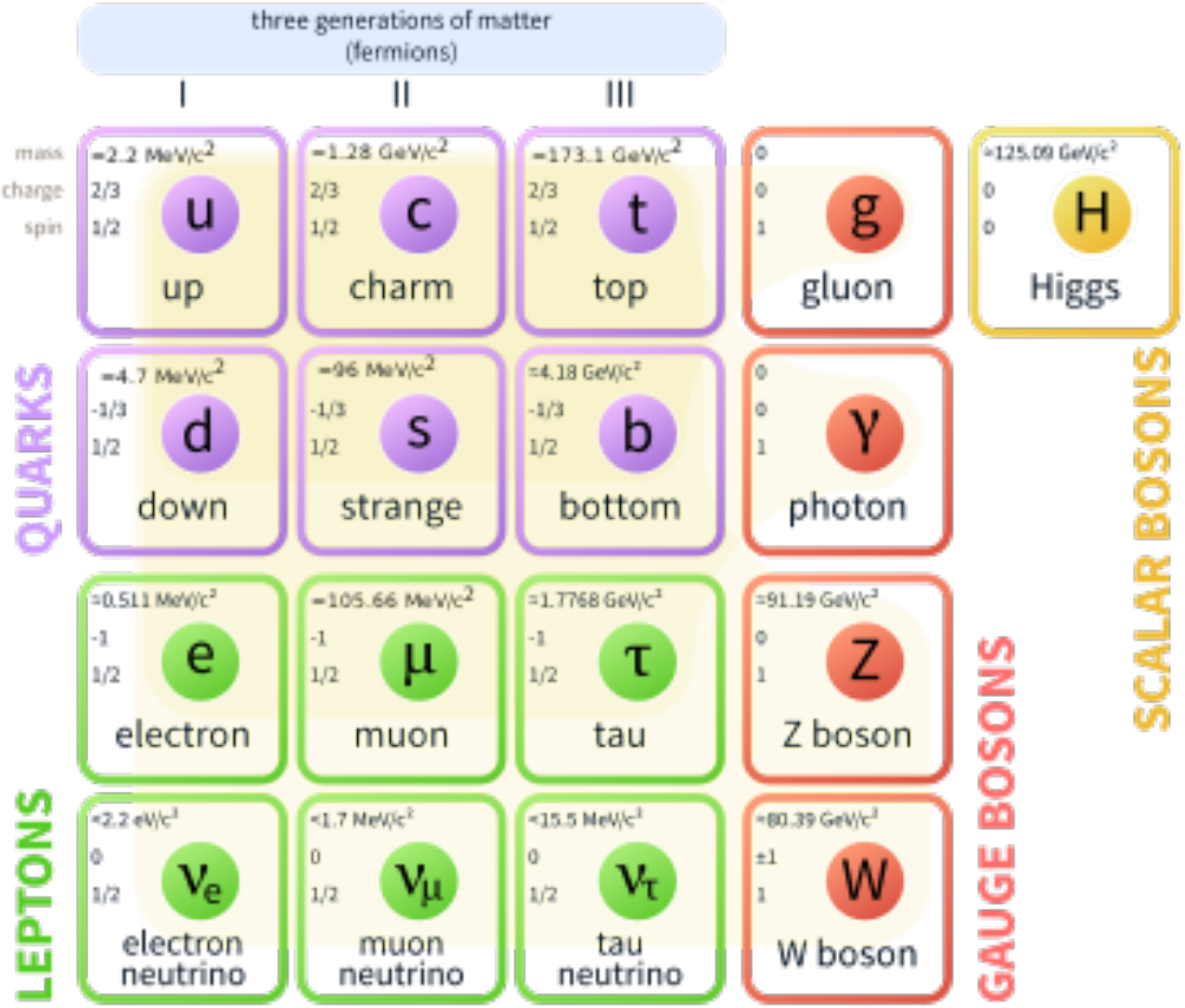
Searches for Tau Neutrinos from Oscillations with IceCube/DeepCore

Michael Larson

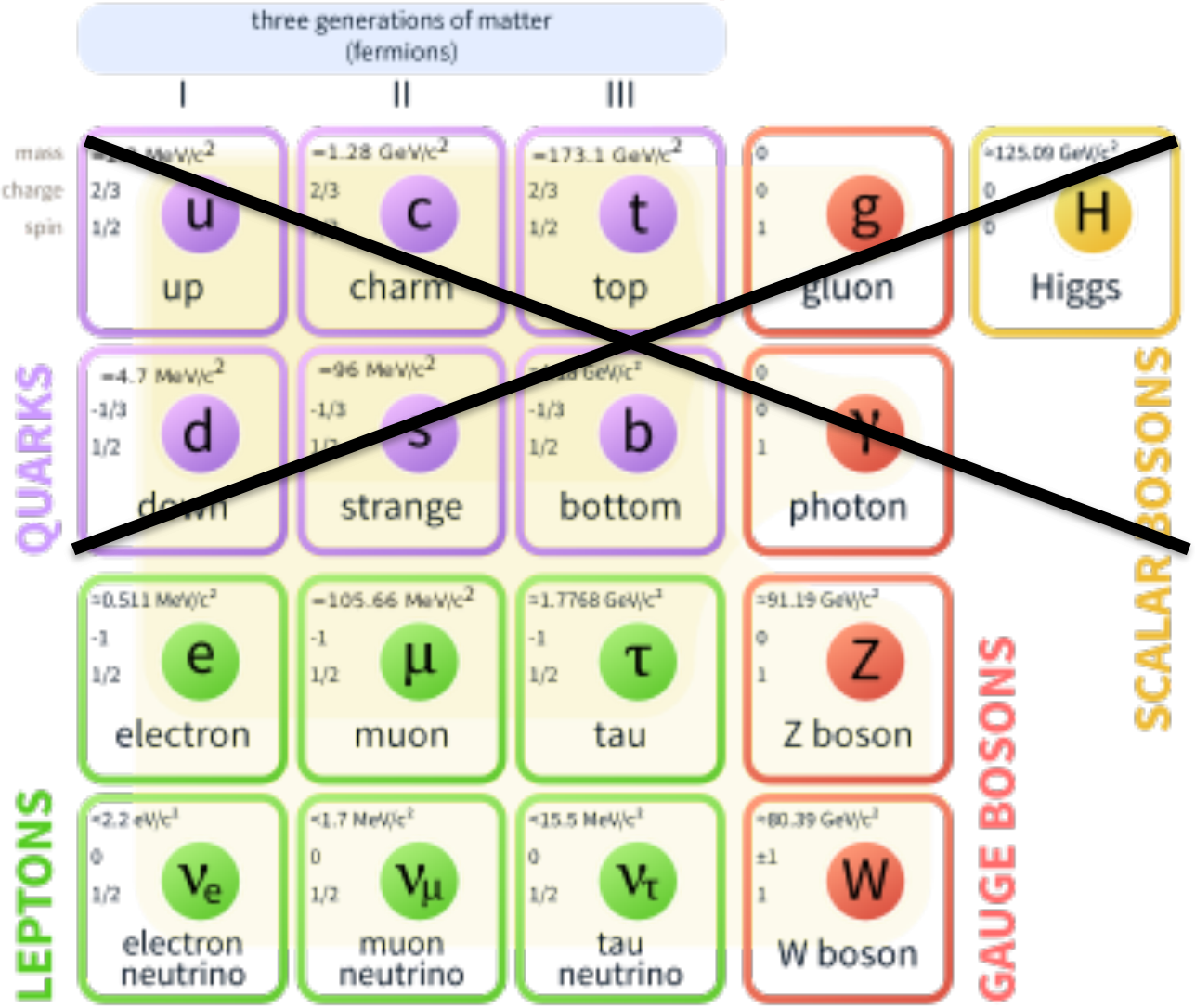
PhD Defense

13 June 2018

The Standard Model of Particle Physics

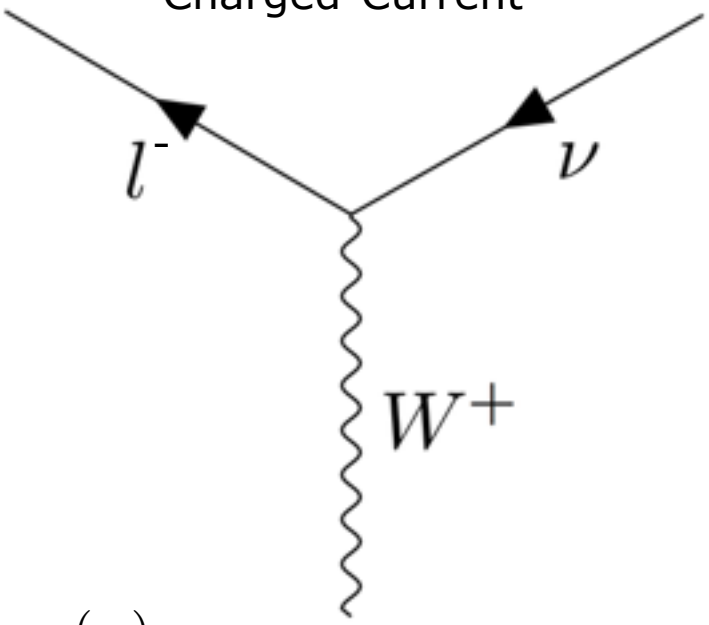


The Standard Model of Particle Physics



Neutrino Interactions

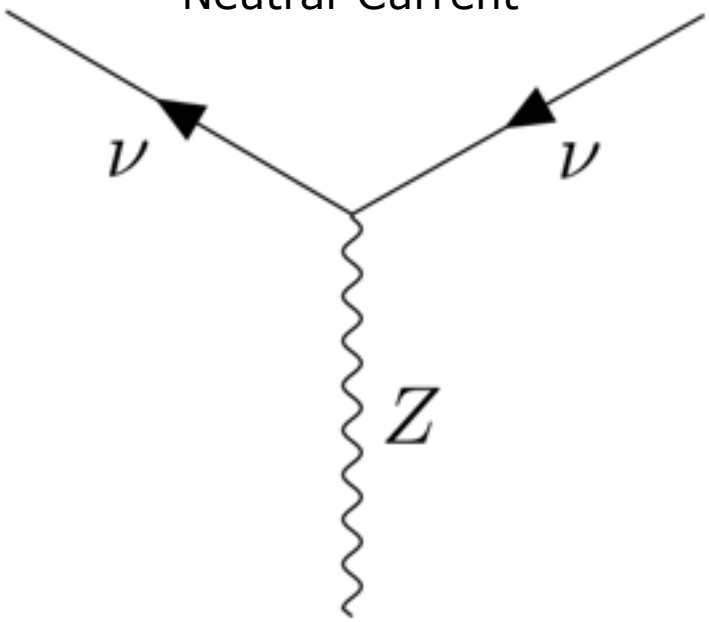
Charged-Current



$$\overset{(-)}{\nu} + X \rightarrow l^{\pm} + X$$

Can identify flavor

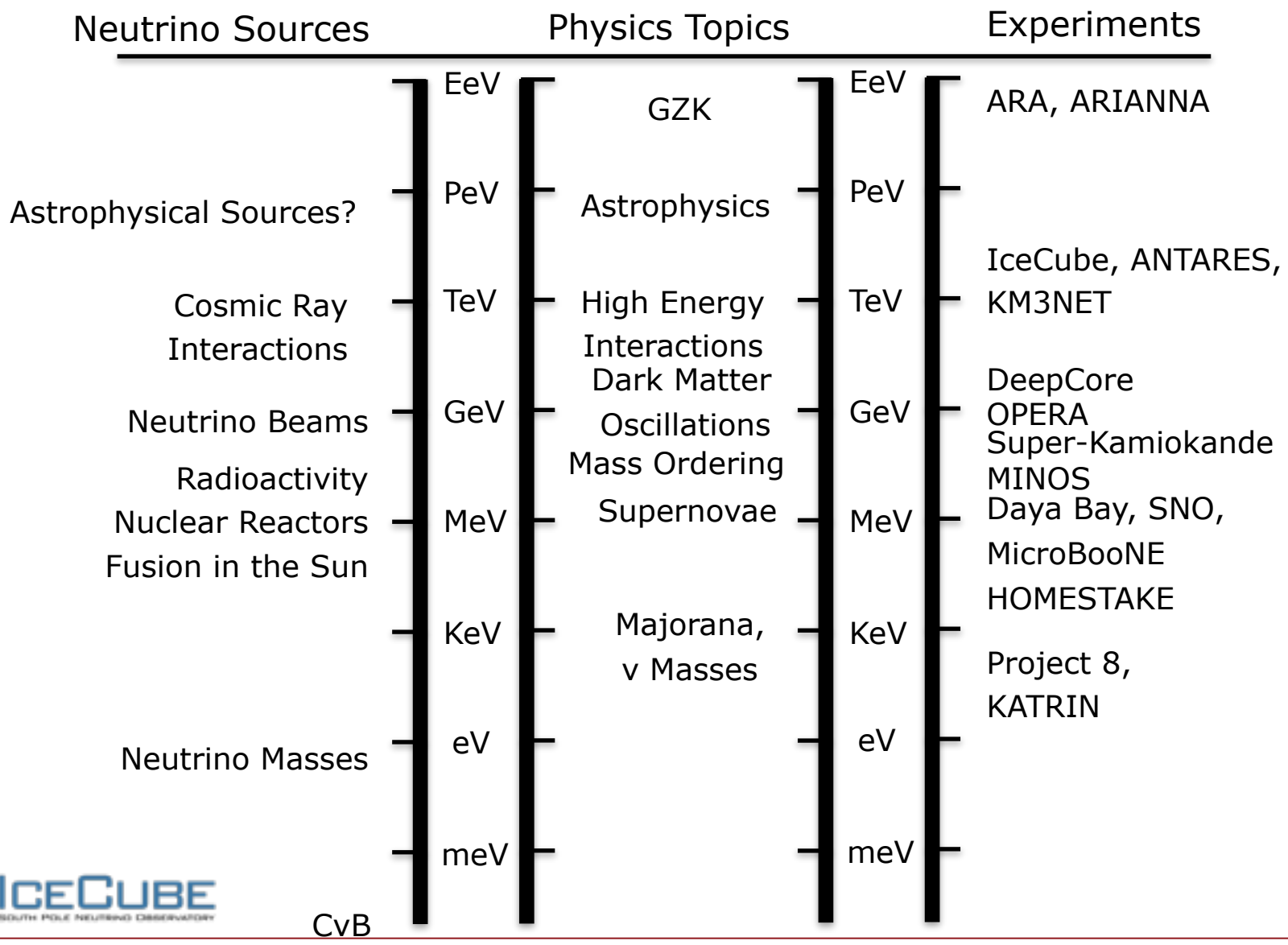
Neutral-Current



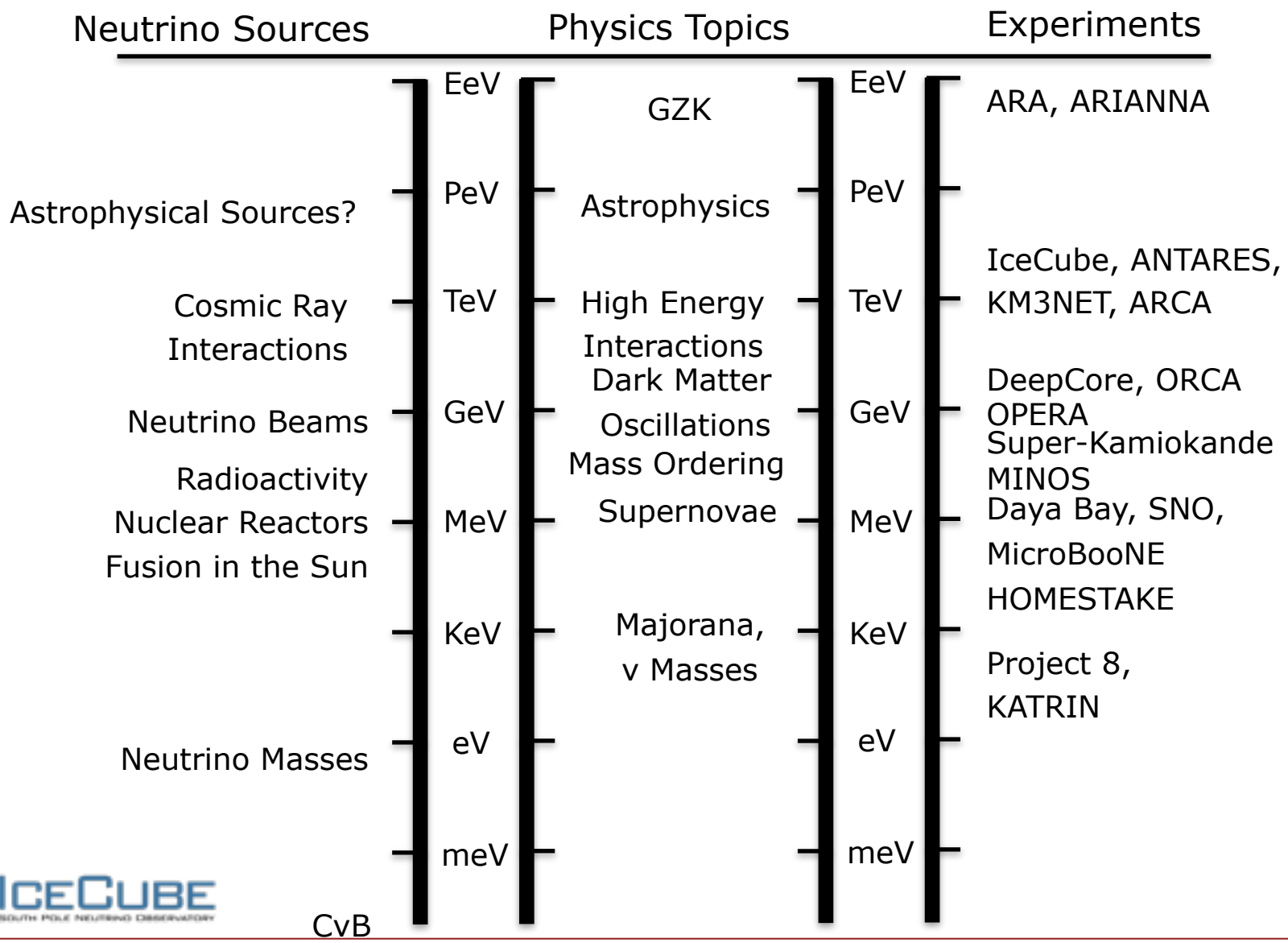
$$\overset{(-)}{\nu} + X \rightarrow \overset{(-)}{\nu} + X$$

Cannot identify flavor

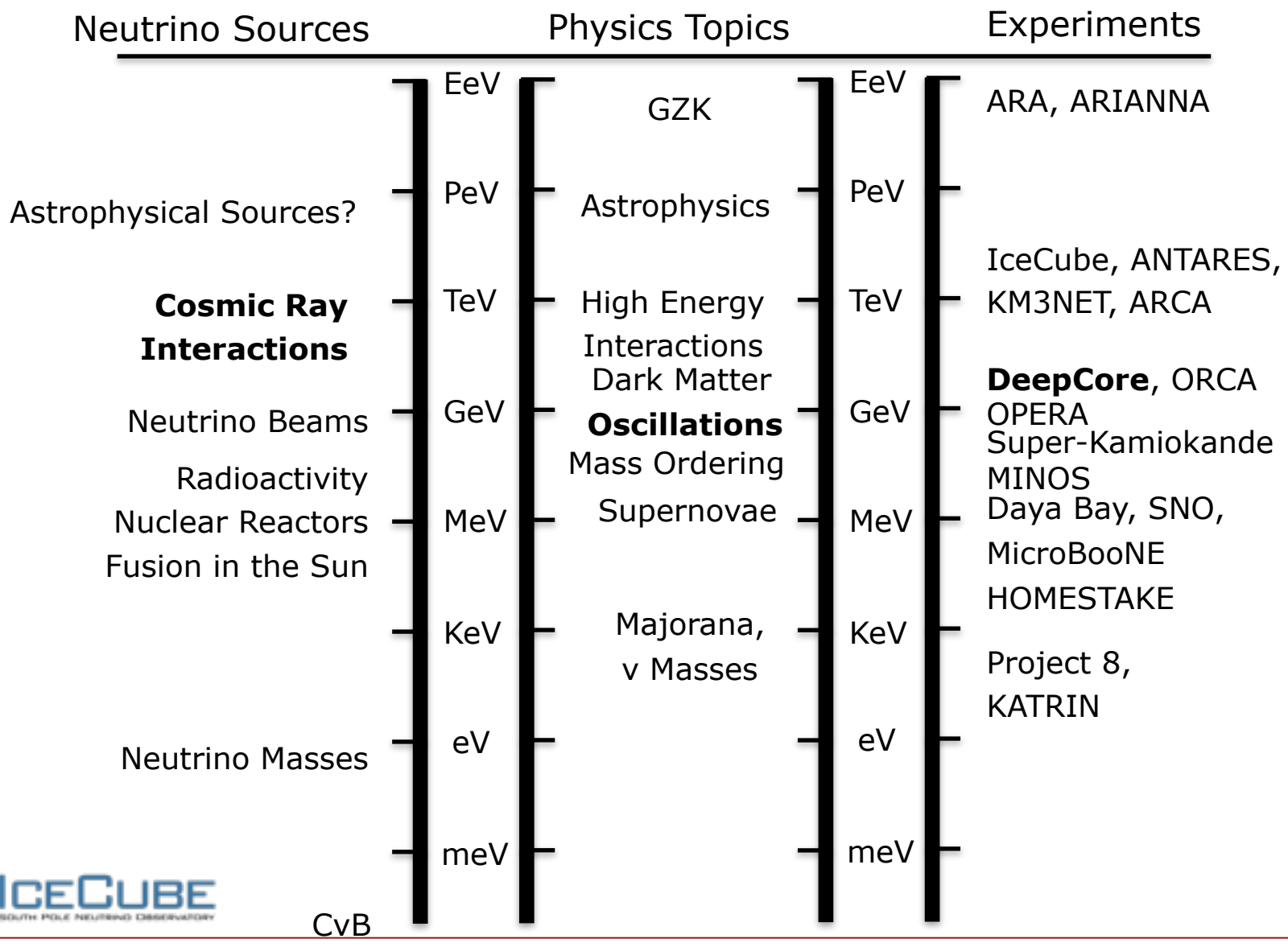
Physics Topics with Neutrinos



Physics Topics with Neutrinos

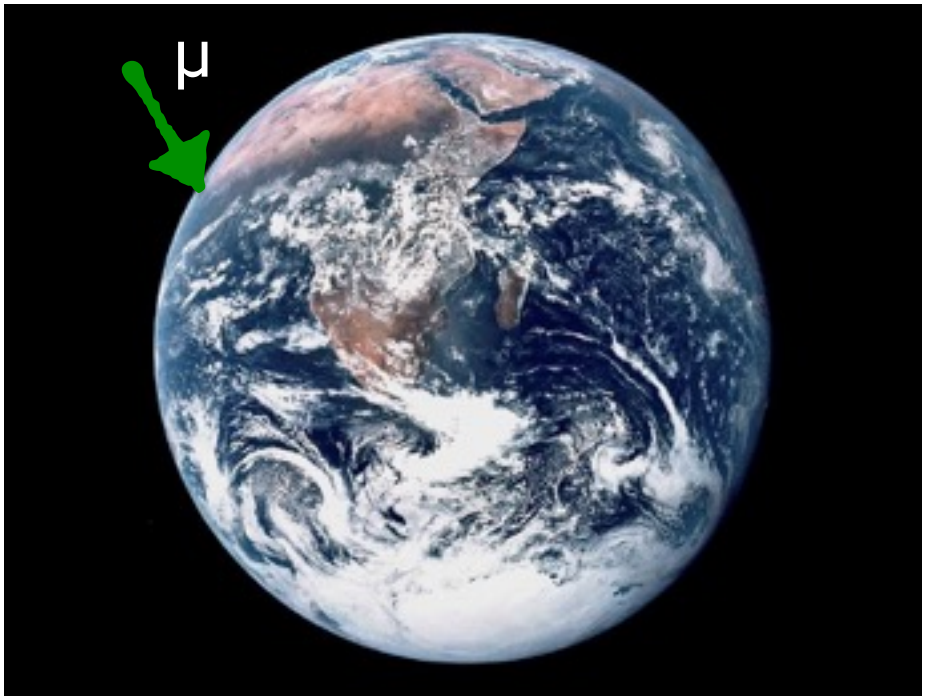


Physics Topics with Neutrinos

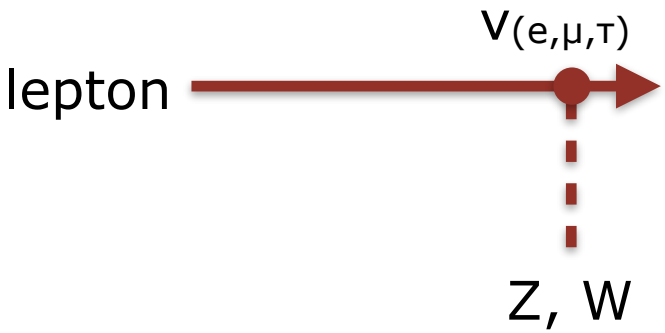


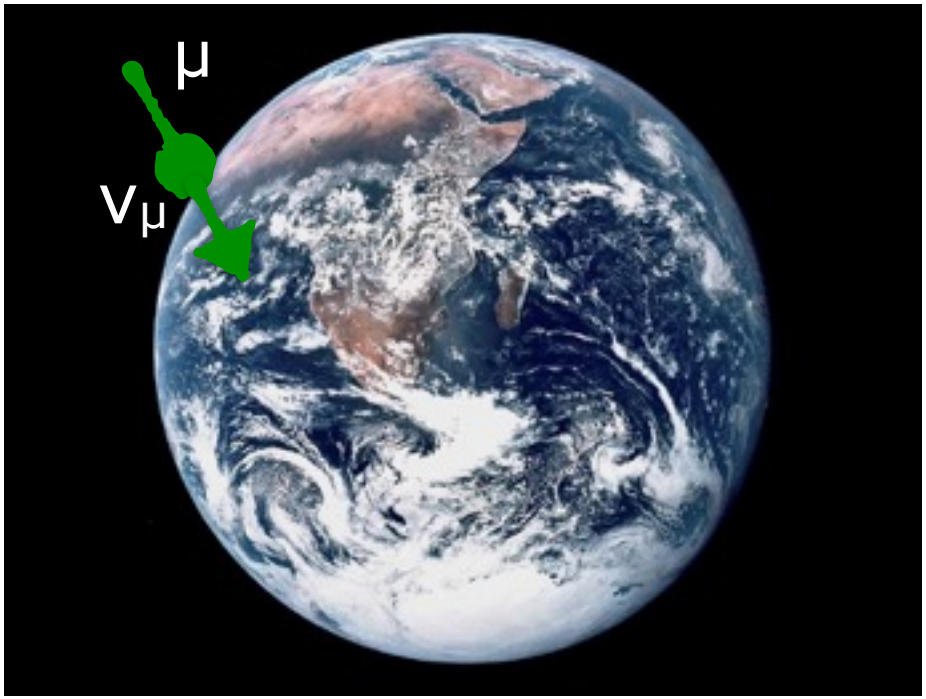
Atmospheric Neutrino Oscillations

lepton →

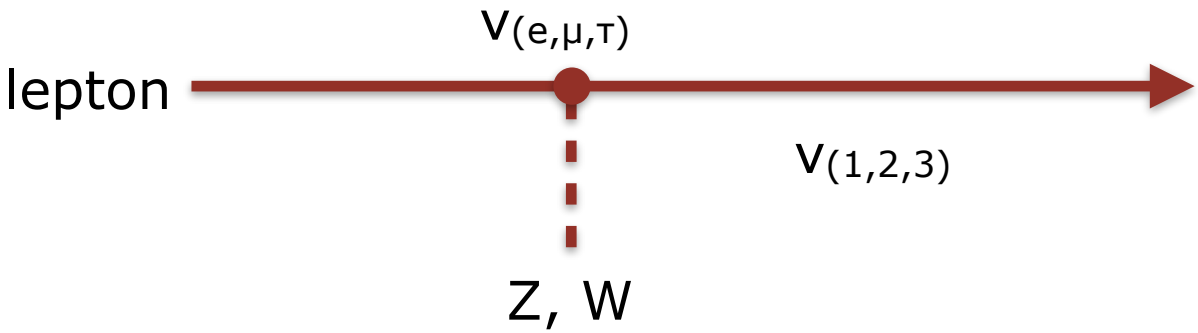


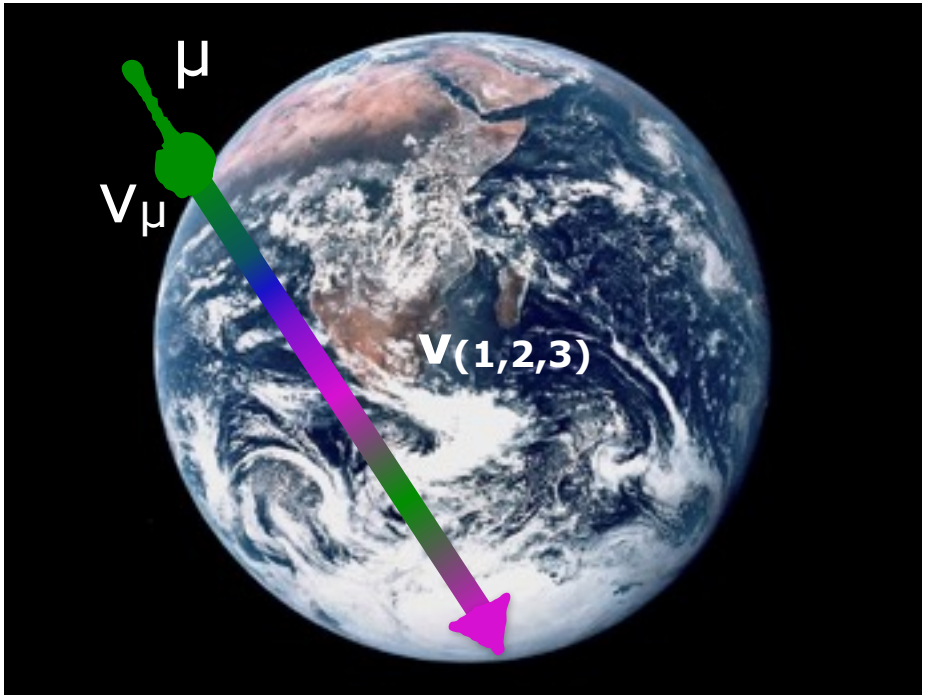
Atmospheric Neutrino Oscillations



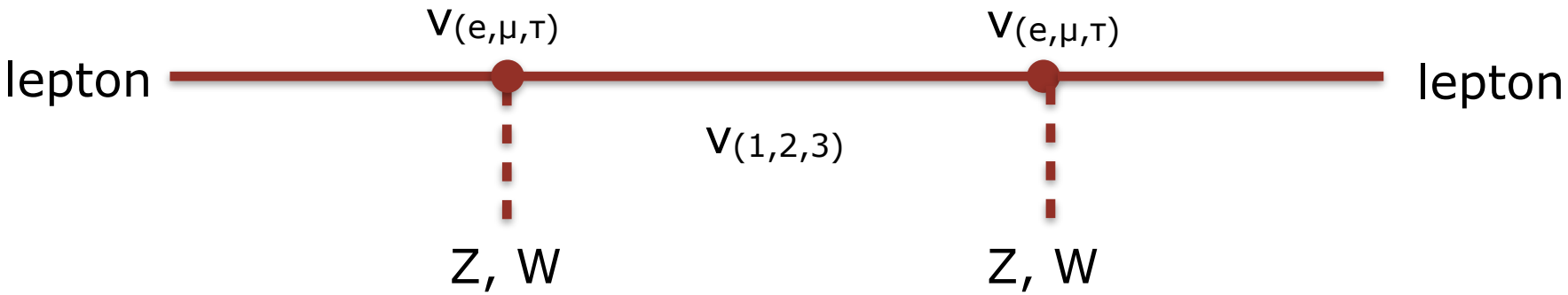


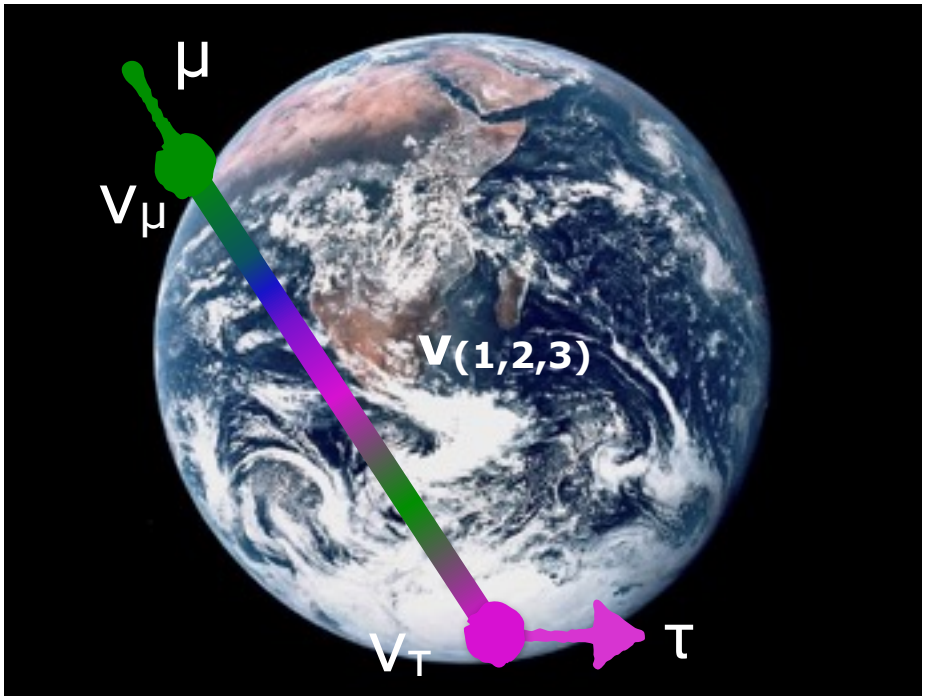
Atmospheric Neutrino Oscillations



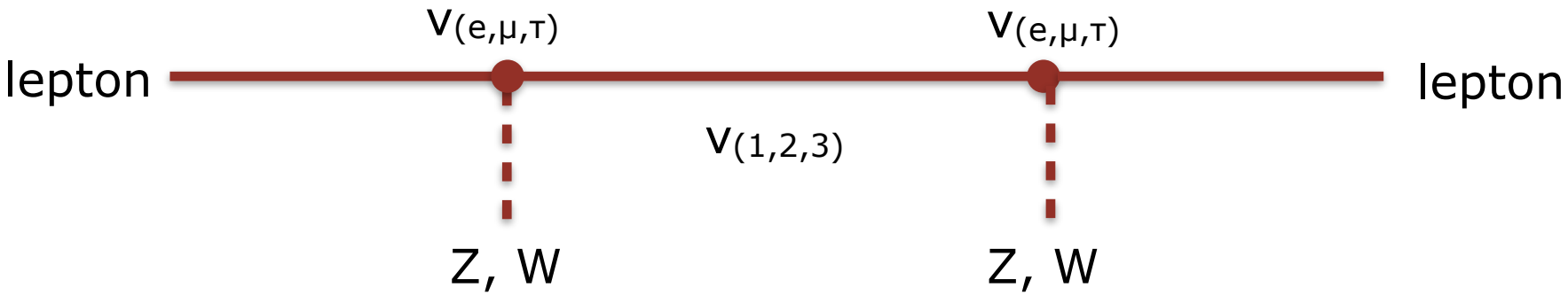


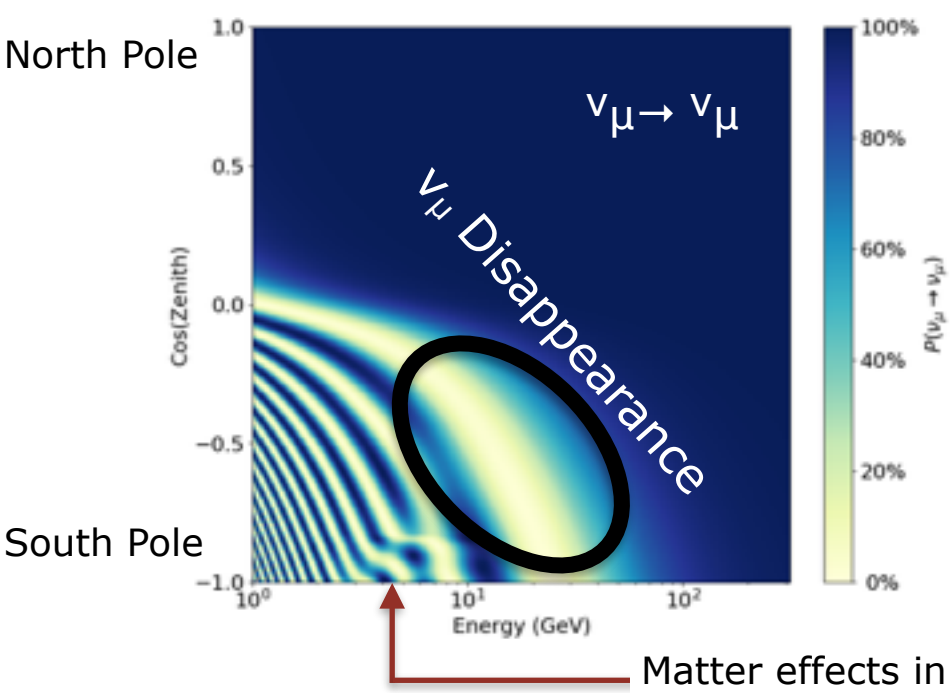
Atmospheric Neutrino Oscillations

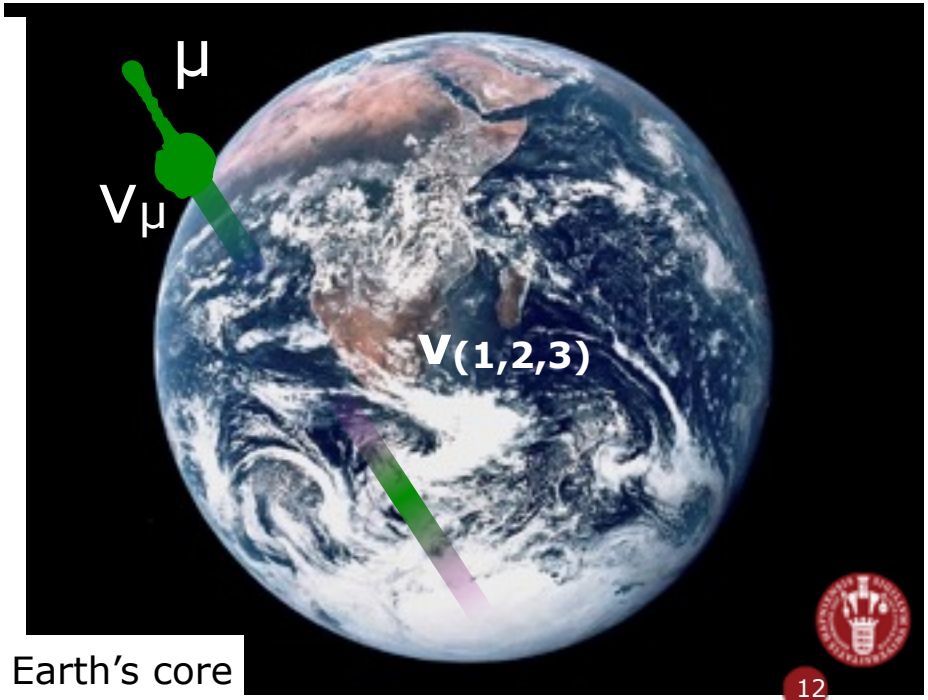




Atmospheric Neutrino Oscillations

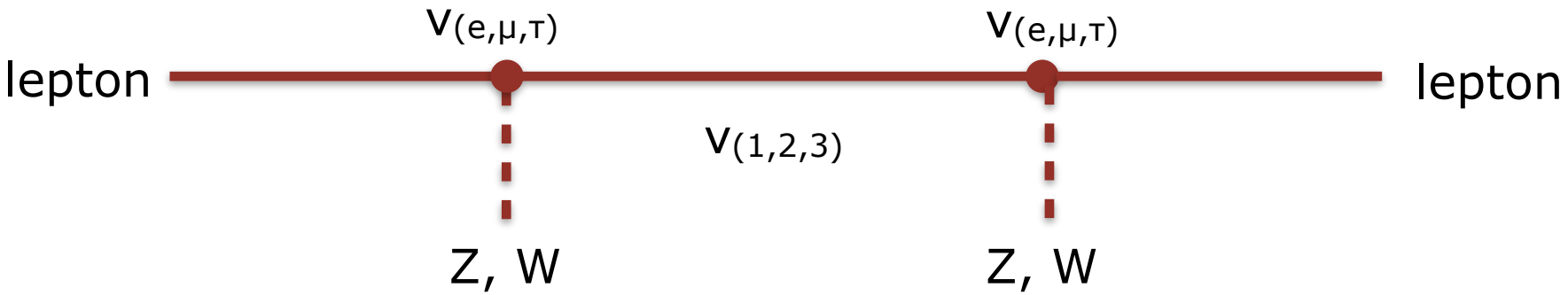






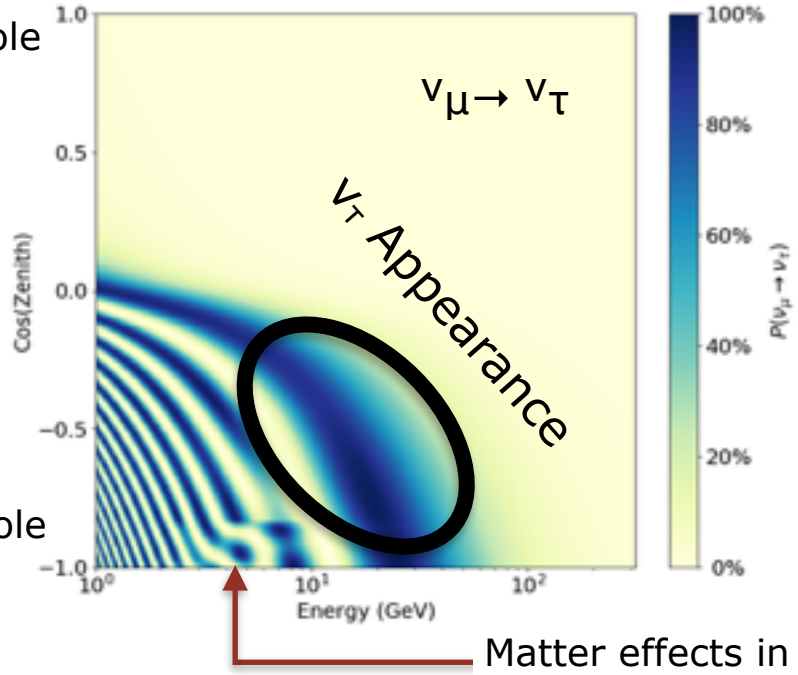
Matter effects in Earth's core

Atmospheric Neutrino Oscillations



North Pole

South Pole



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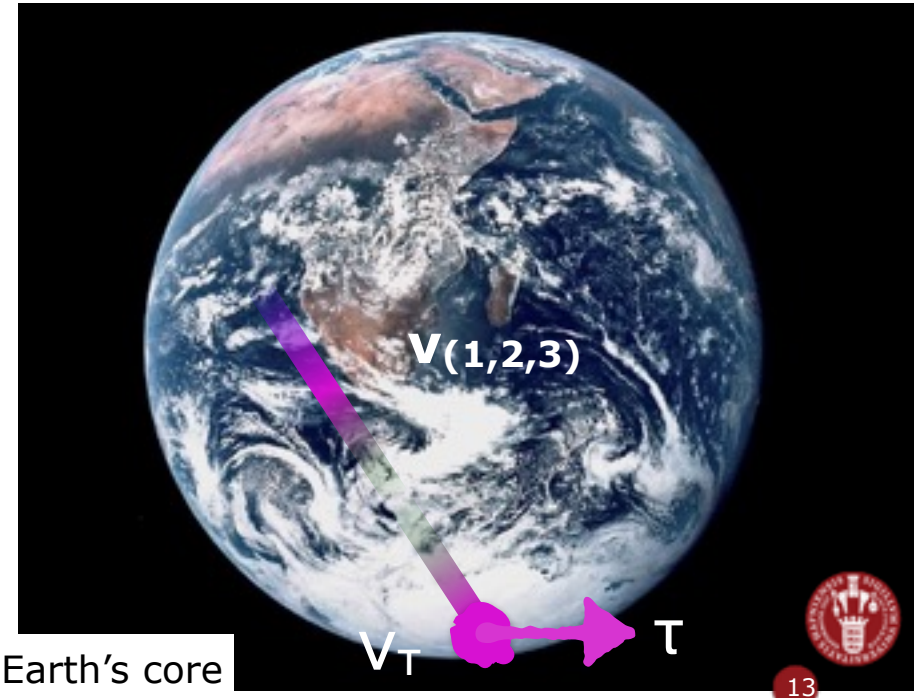


Atmospheric Neutrino Oscillations

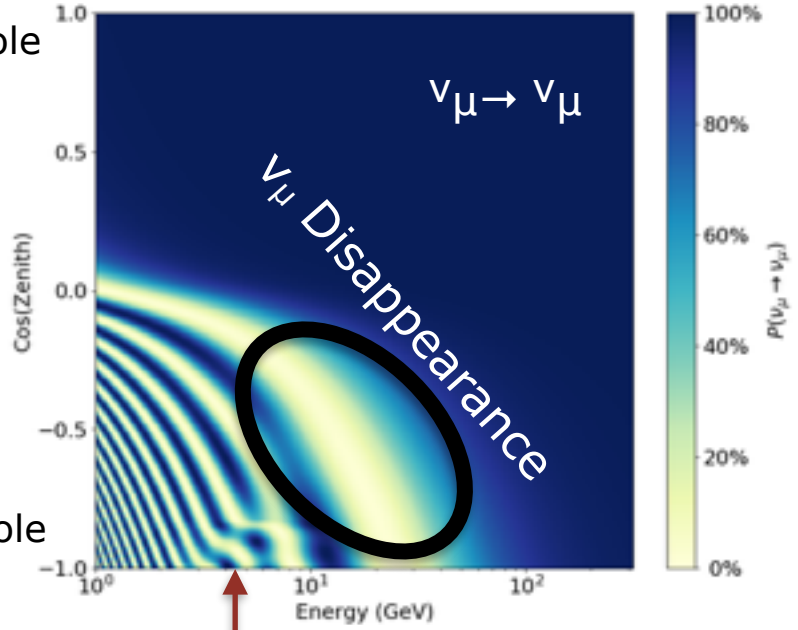
- Approximately parametrized in terms of mixing angles and mass splittings

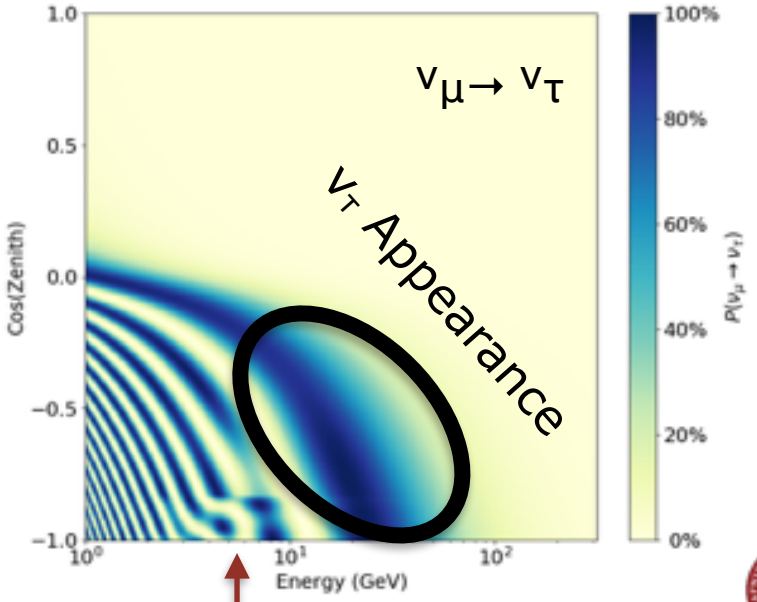
$$P\left(\nu_\mu \to \nu_\mu\right) \approx 1 - \sin^2 2\theta_{23}\, sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

$$P\left(\nu_\mu \to \nu_\tau\right) \approx \sin^2 2\theta_{23}\, sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

North Pole

South Pole

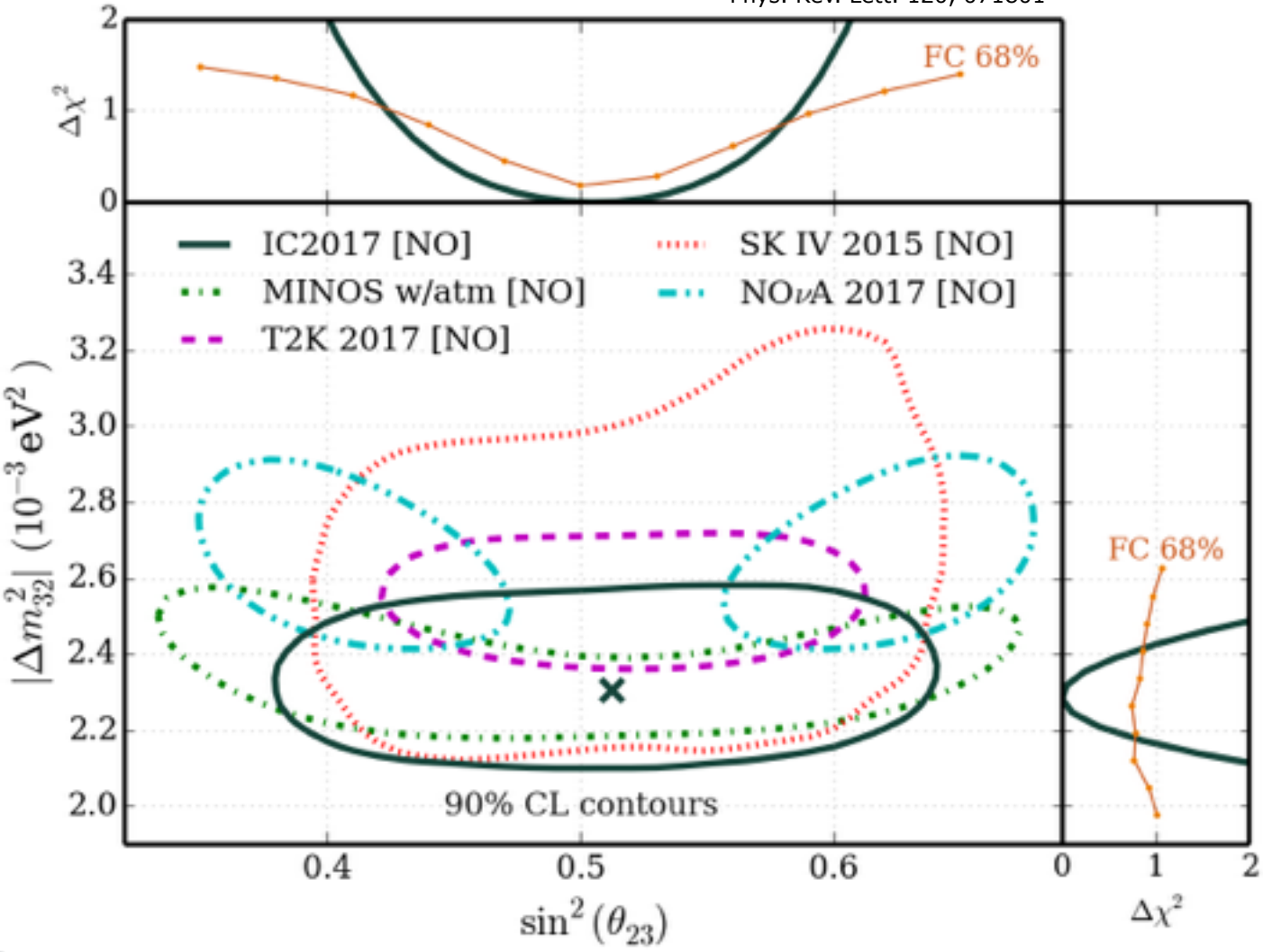




Matter effects in Earth's core

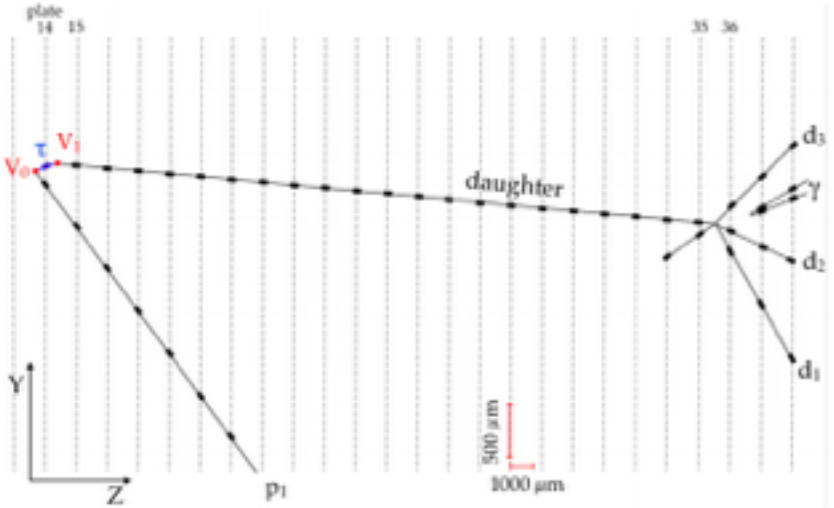
Measurements of ν_μ Disappearance

Phys. Rev. Lett. 120, 071801



Measurements of ν_τ Appearance

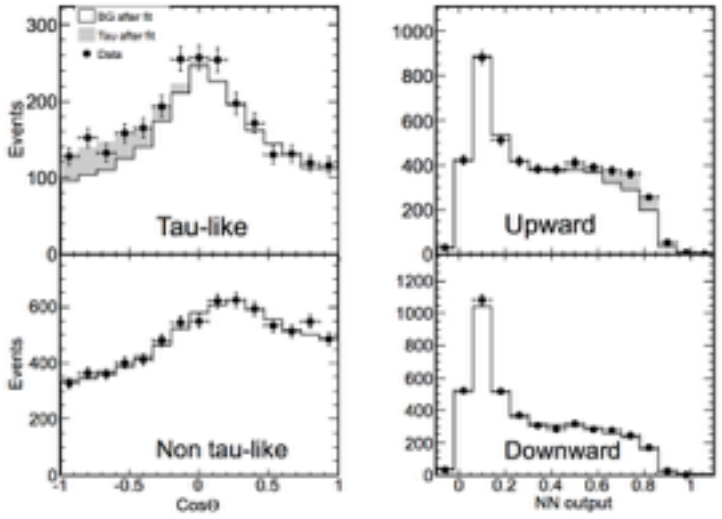
OPERA



Phys. Rev. Lett. 115, 121802 (2015)
Phys. Rev. Lett. 120, 211801 (2018)

- Measurement of individual ν_τ events
- Identified 10 events
- 6.1σ rejection of no-appearance
- Found $1.1^{+0.5}_{-0.4}$ x expectation

Super-Kamiokande

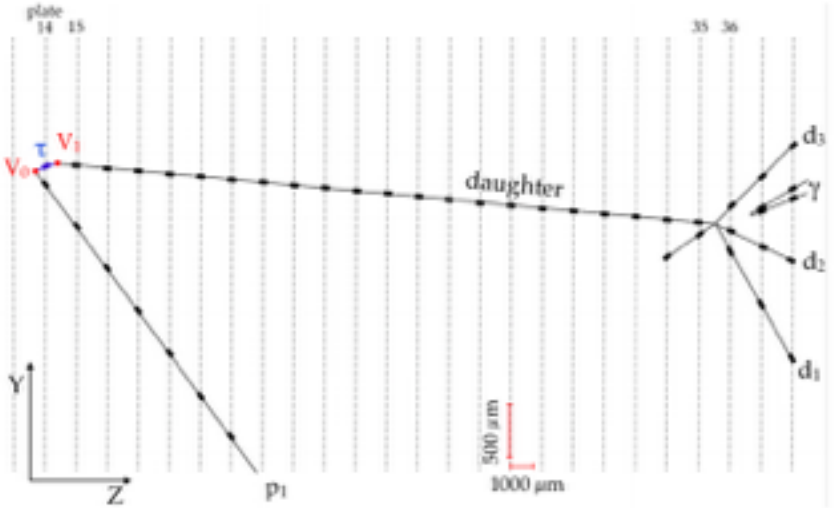


arXiv:1711.09436

- Statistical fit to identify ν_τ events
- 338 ± 72 CC $\nu\tau$ events
- Found 1.47±0.32 x expectation

Previous Limits on Appearance

OPERA



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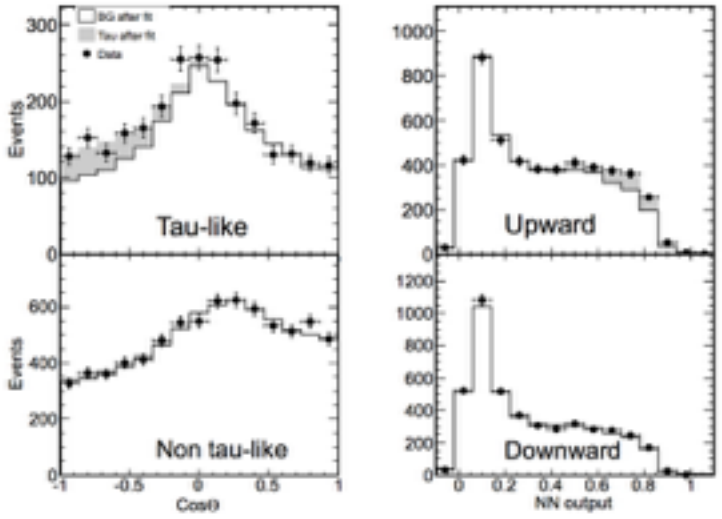

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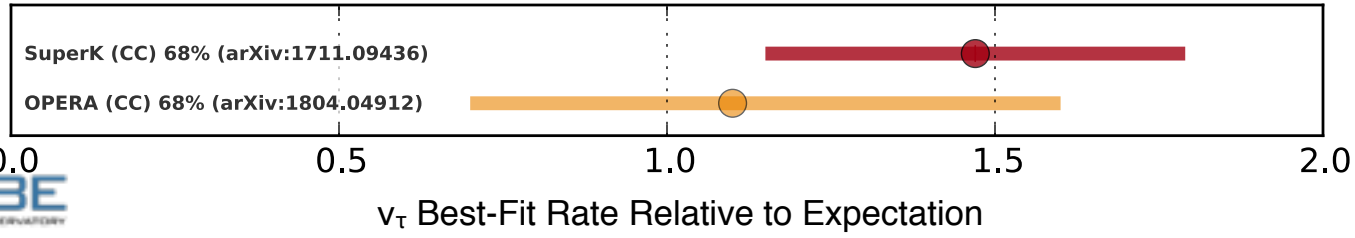


GRECO:
GeV Reconstructed Events with Containment for Oscillations

- An Oscillation Sample for IceCube-DeepCore

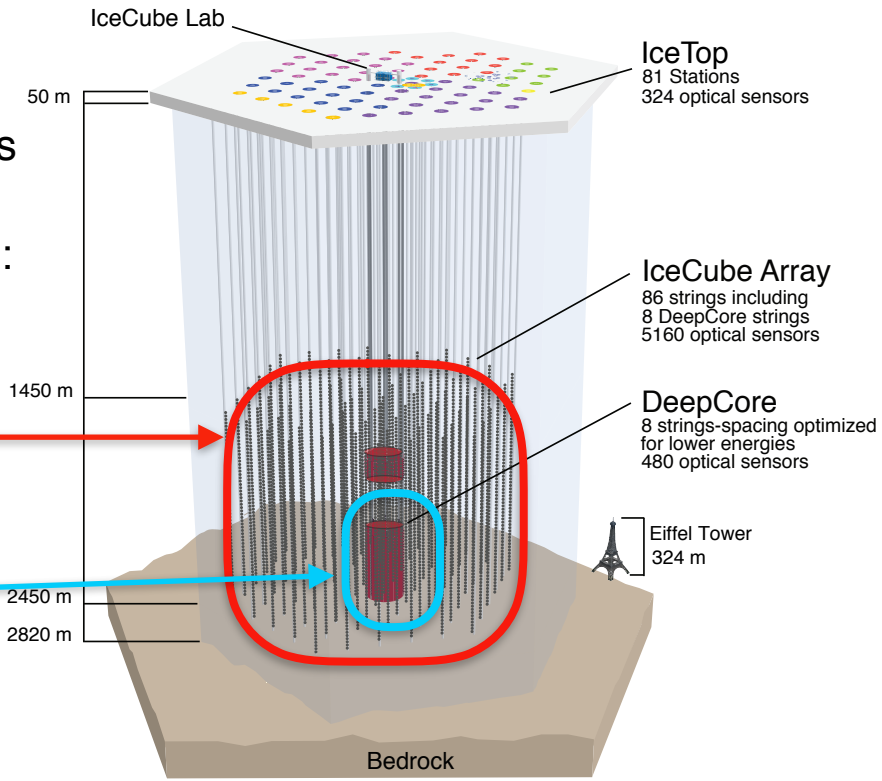
The IceCube-DeepCore Detector

- Neutrino detector built at the South Pole
- Sensitive to a wide range of physics goals
  - Atmospheric neutrinos at low energies
  - Astrophysical neutrinos at higher energies

- Two major parts of the detector buried in the ice:

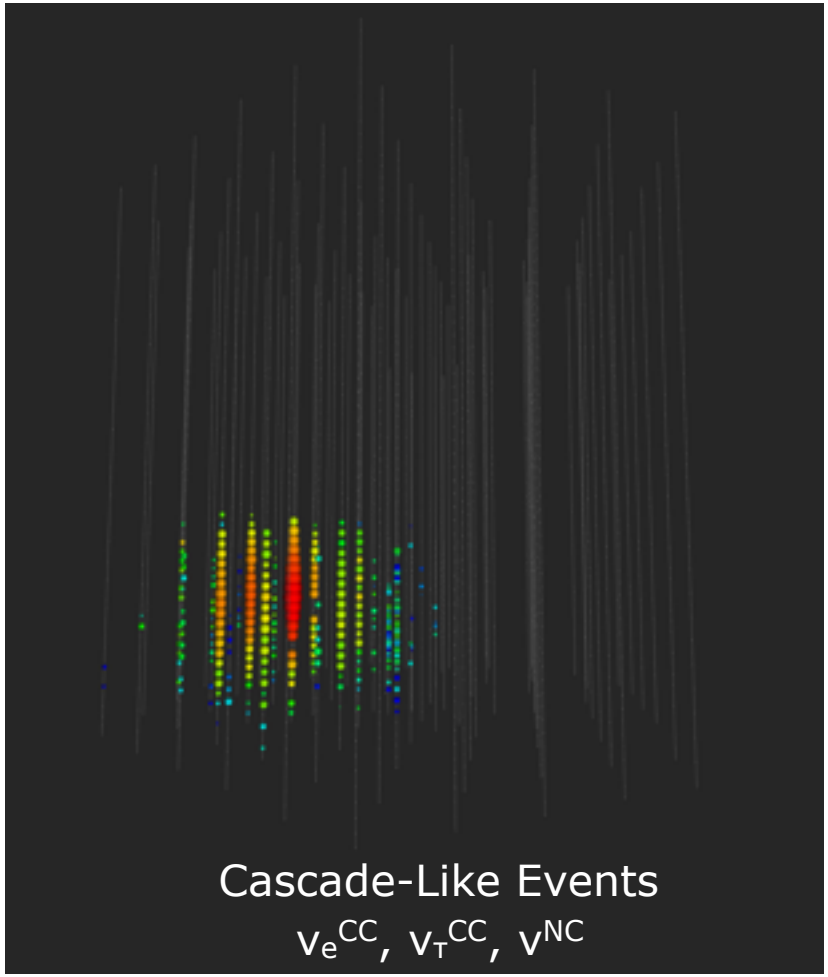
IceCube:
- Primarily optimized for TeV energies
- Provides active veto for DeepCore

DeepCore:
- Denser string, PMT spacing
- Clearest ice available
- Sensitive to ~5 GeV neutrinos



IceCube Neutrino Event Topologies

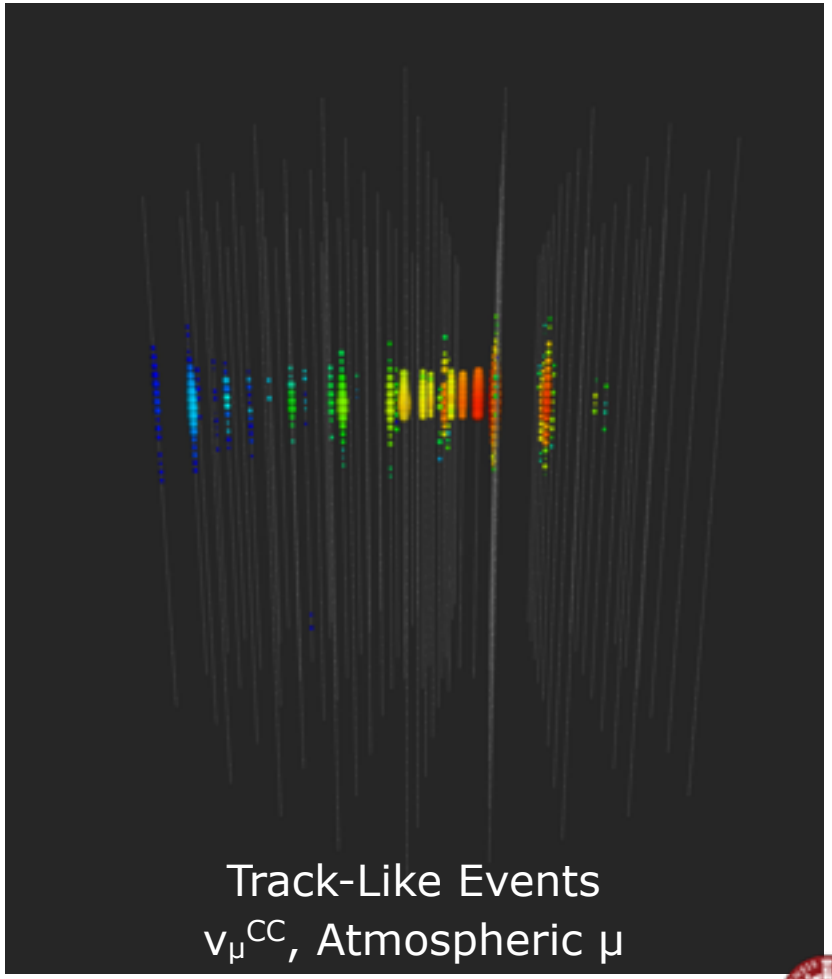
IceCube HESE Event 9 — Data, Cascade-like, E=63.2 TeV



Cascade-Like Events

ν_e^{CC}, ν_τ^{CC}, ν^{NC}

IceCube HESE Event 5 — Data, Track-like, E=71.4 TeV



Track-Like Events

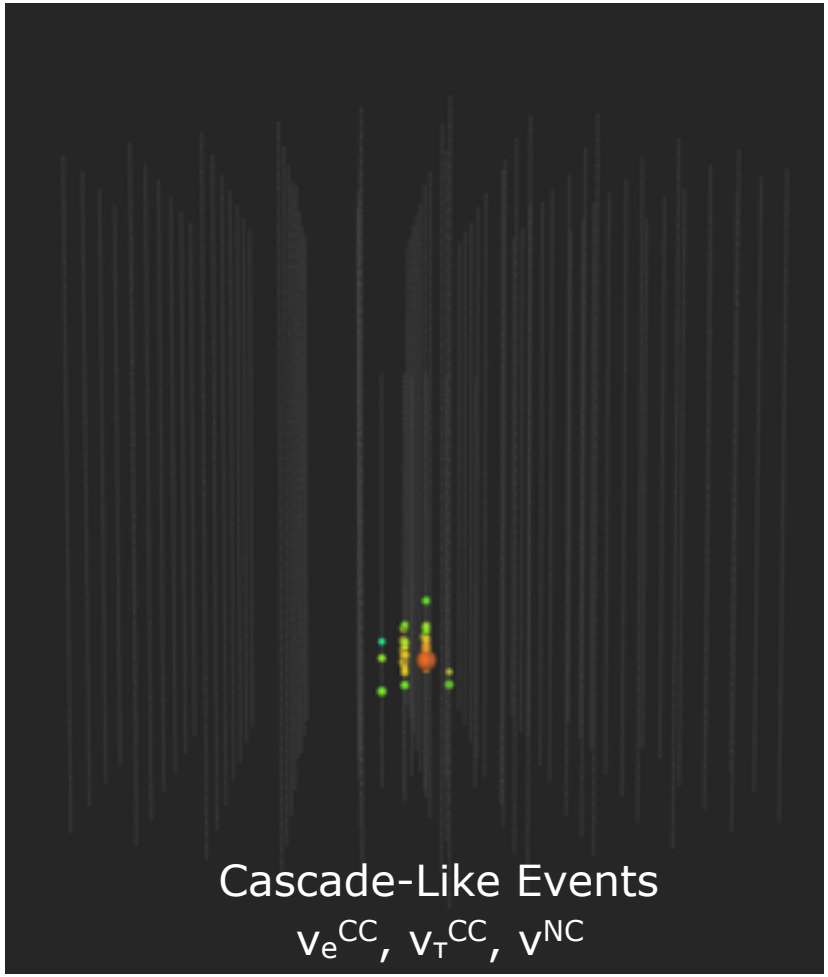
ν_μ^{CC}, Atmospheric μ

IceCube South Pole Neutrino Observatory

DeepCore Neutrino Event Topologies

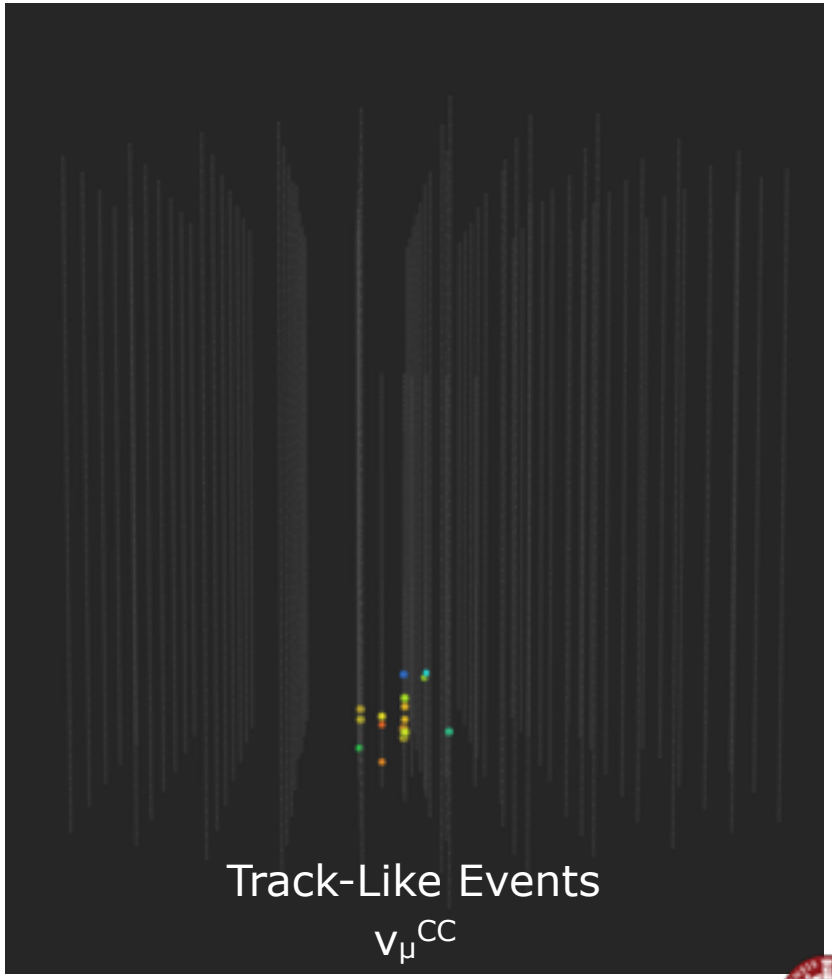
GRECO NuE CC

GENIE Simulation, E=30 GeV



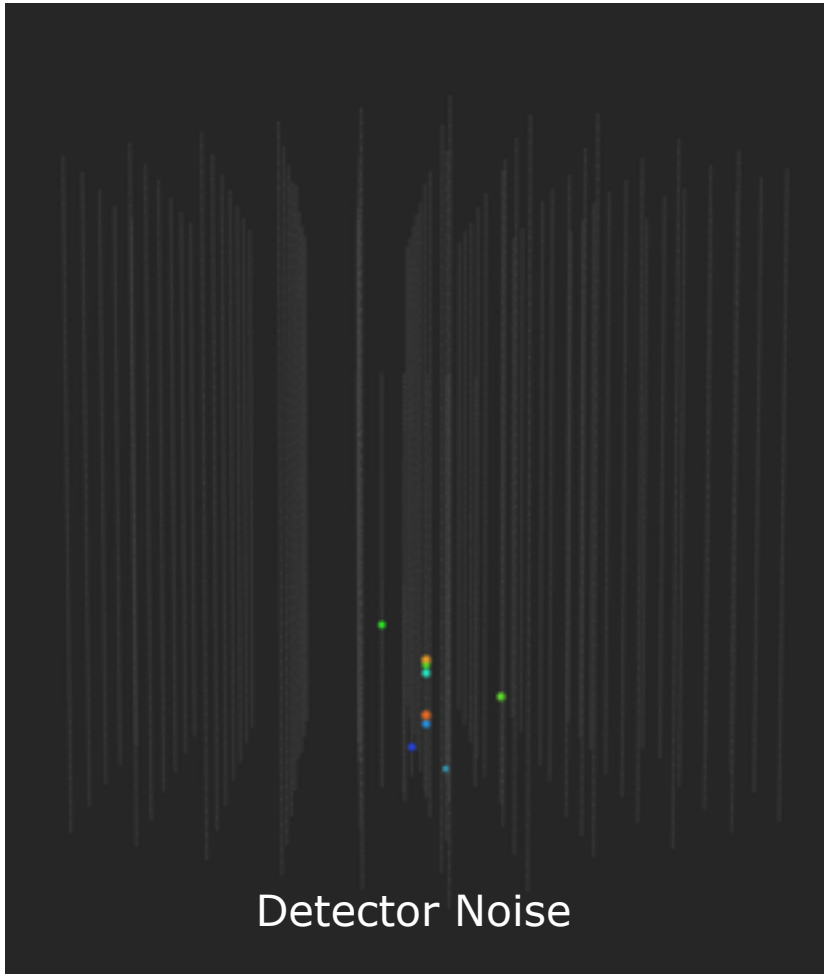
GRECO NuMu CC

GENIE Simulation, E=21 GeV

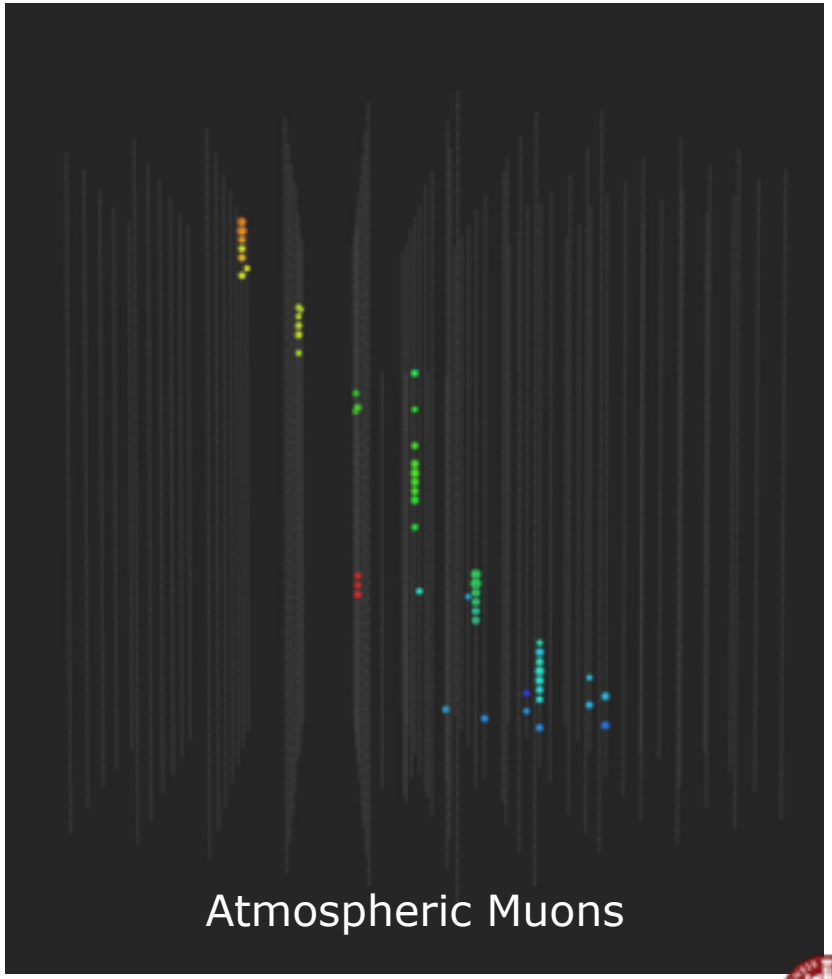


DeepCore Background Event Topologies

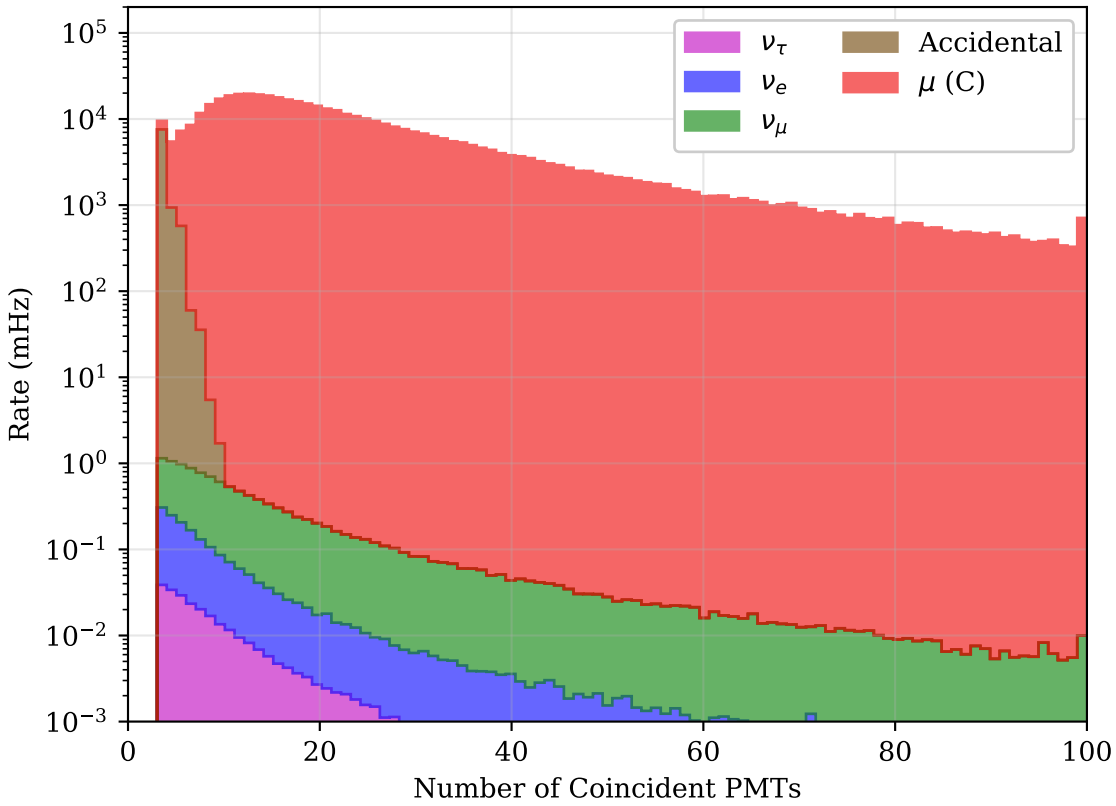
Simulation, Final Level



CORSIKA Simulation

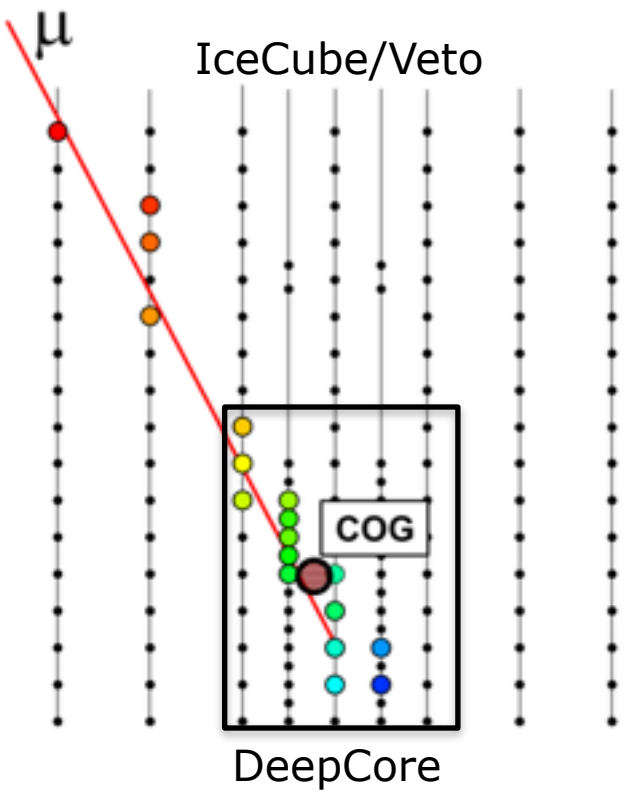


IceCube Backgrounds

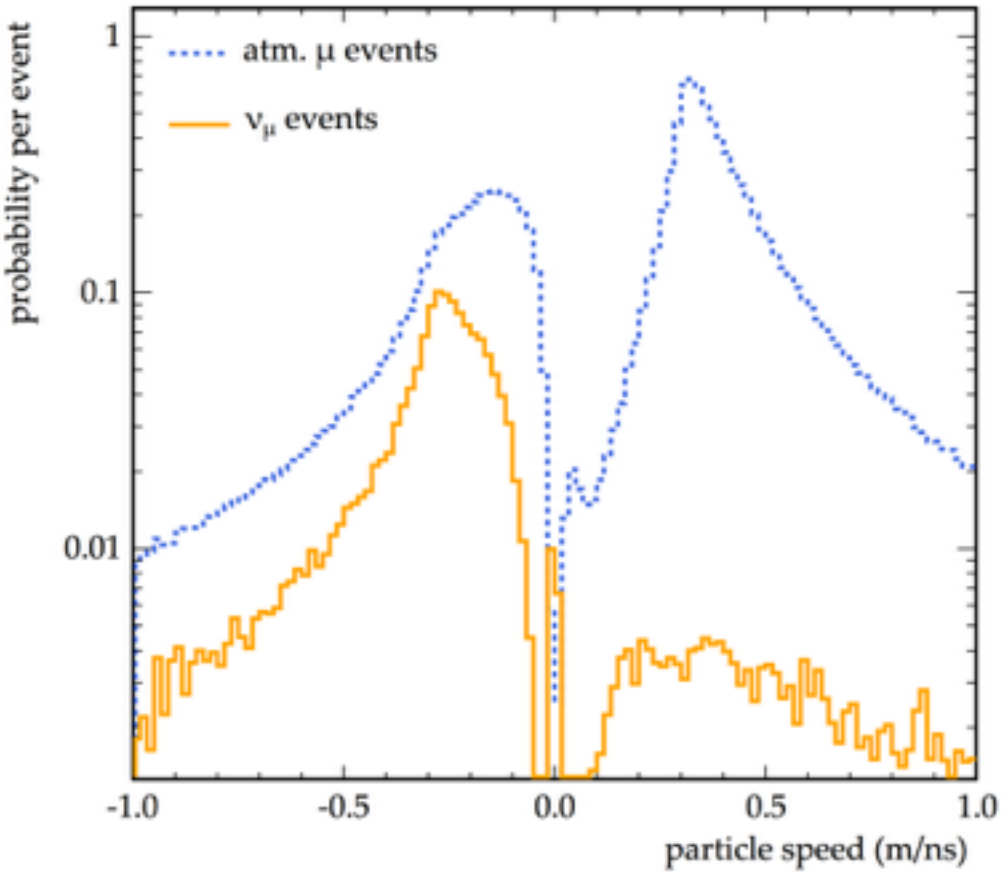


- Primarily dominated by muons created in air showers
- Random noise can also trigger detector
    - "Accidental" rate is 4 orders of magnitude larger than neutrinos

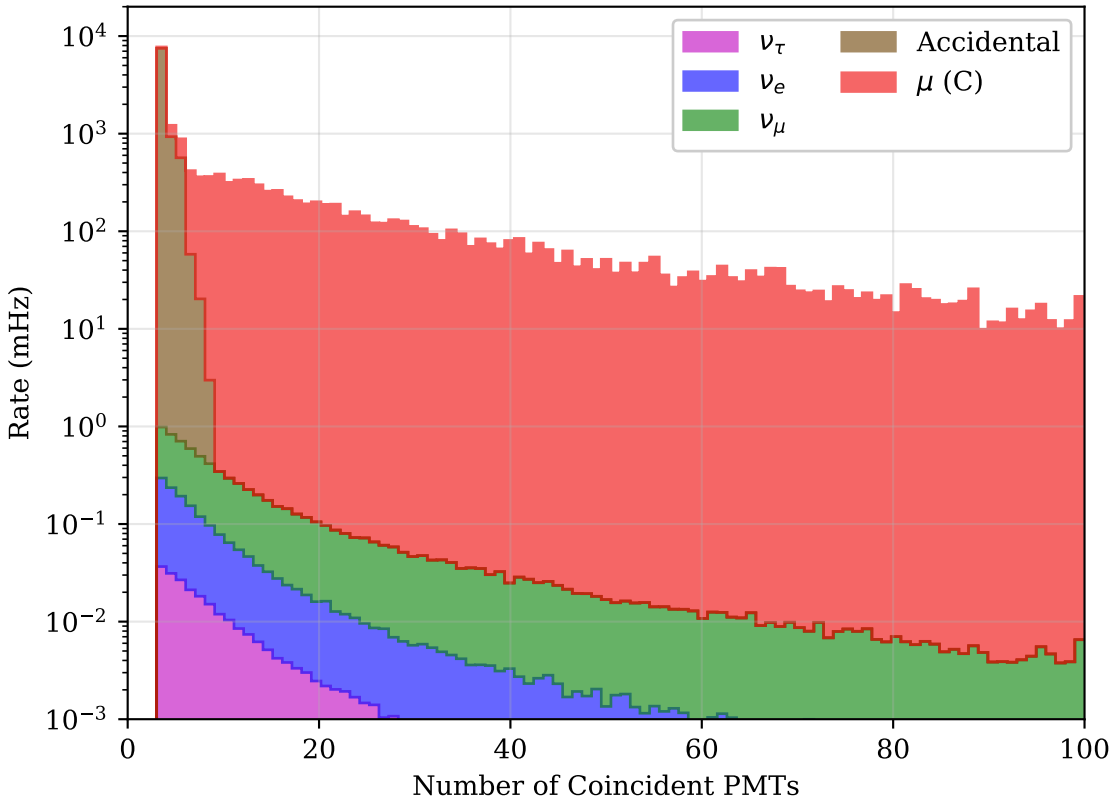
Identifying DeepCore Neutrinos



Astropart. Phys., 35 (2012), p. 615



DeepCore Backgrounds



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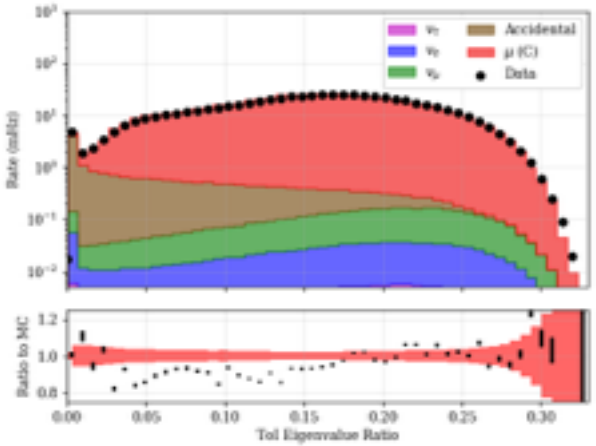
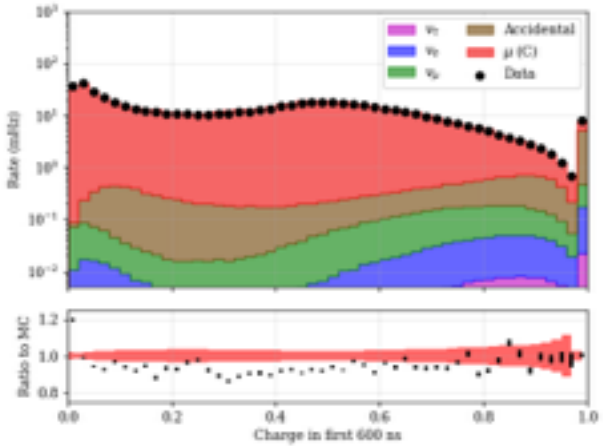
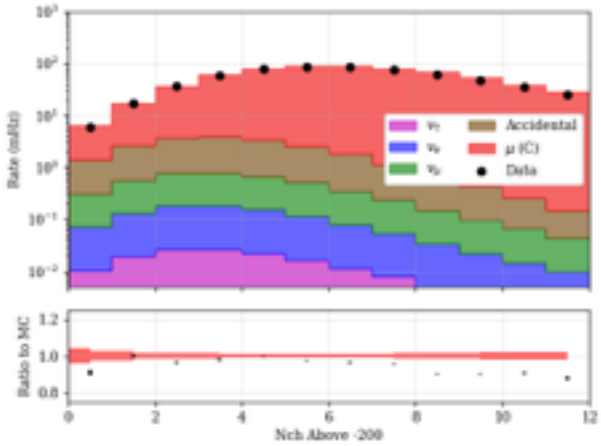
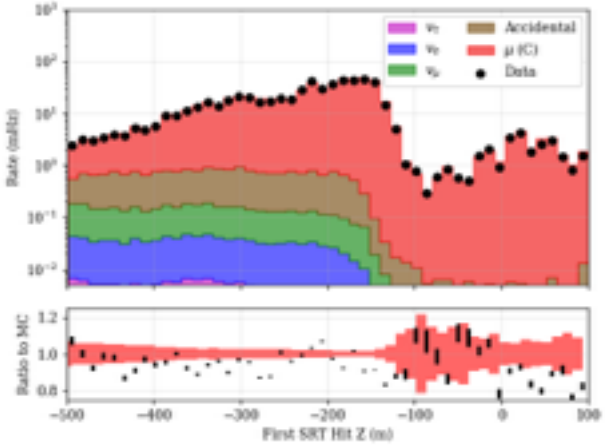
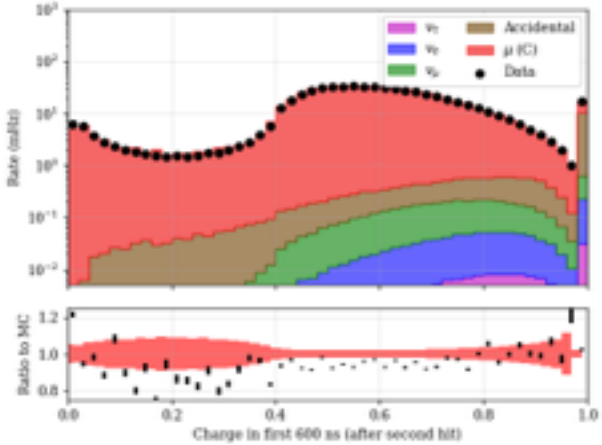
Muon Rejection with BDTs - GRECO Level 4

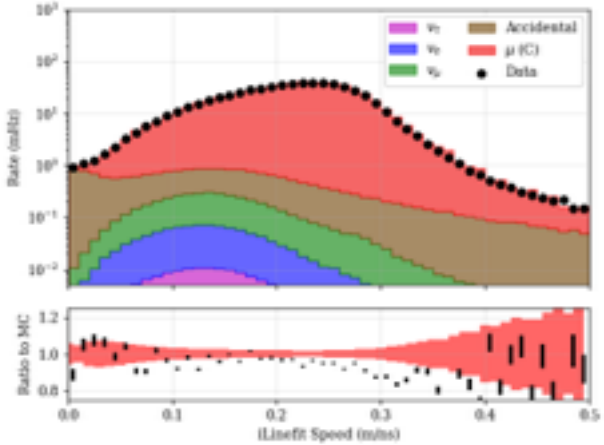




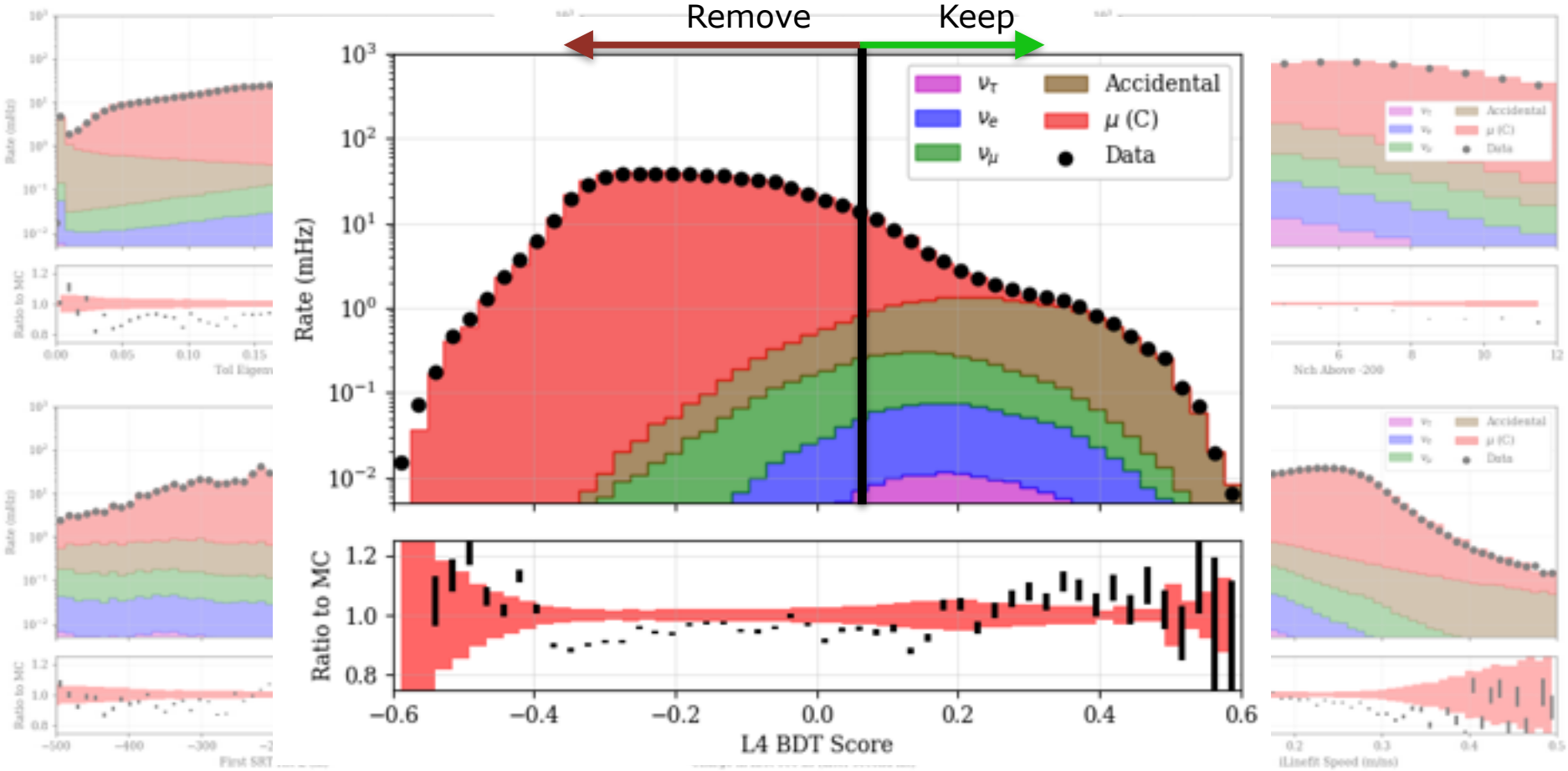




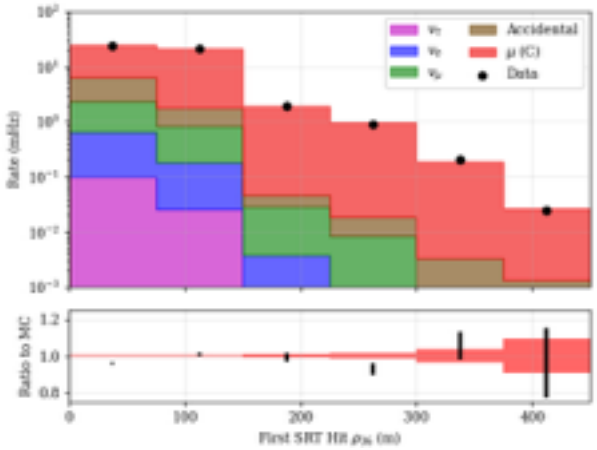


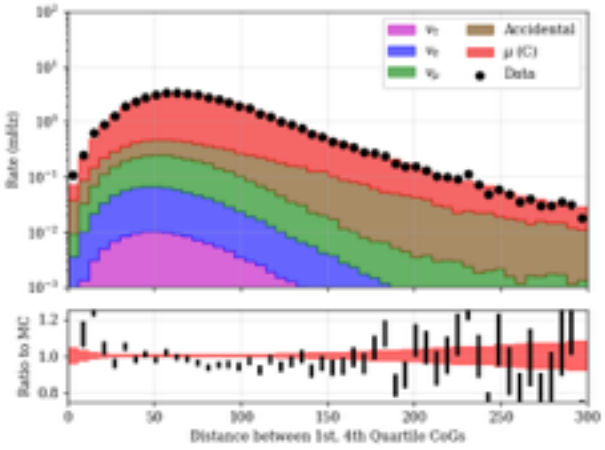


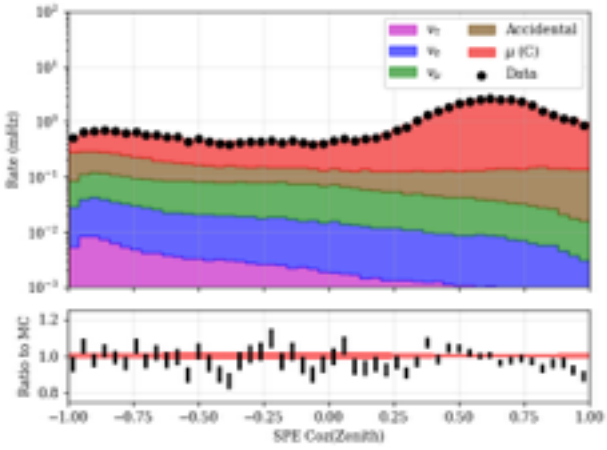
Muon Rejection with BDTs - GRECO Level 4

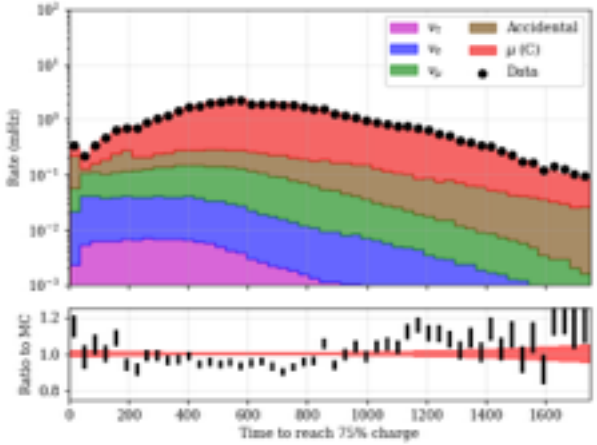


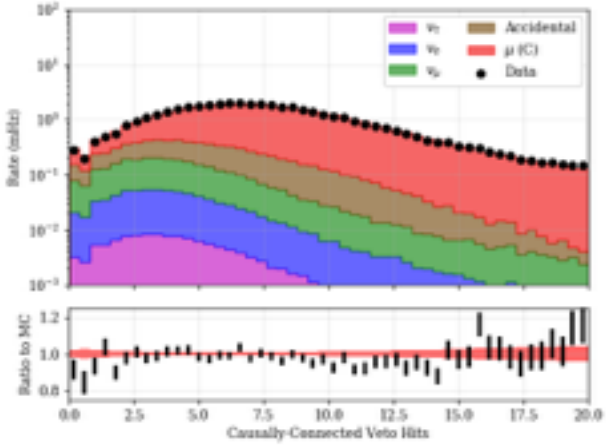
Muon Rejection with BDTs - GRECO Level 5

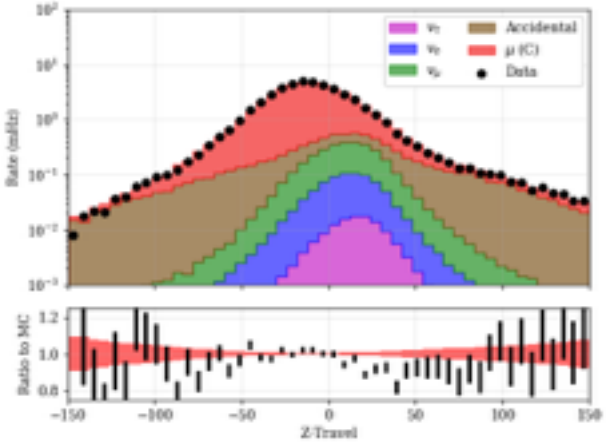




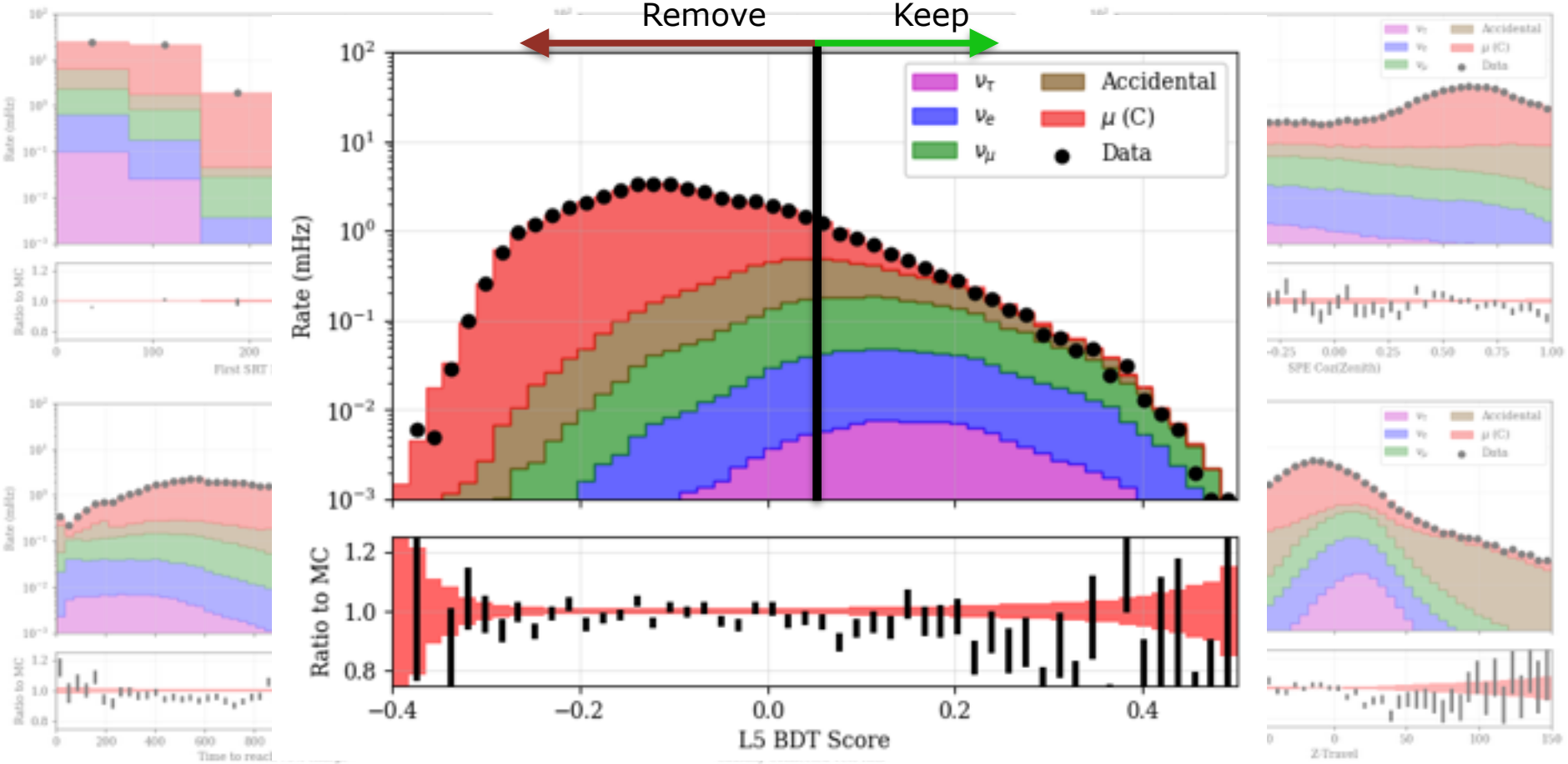




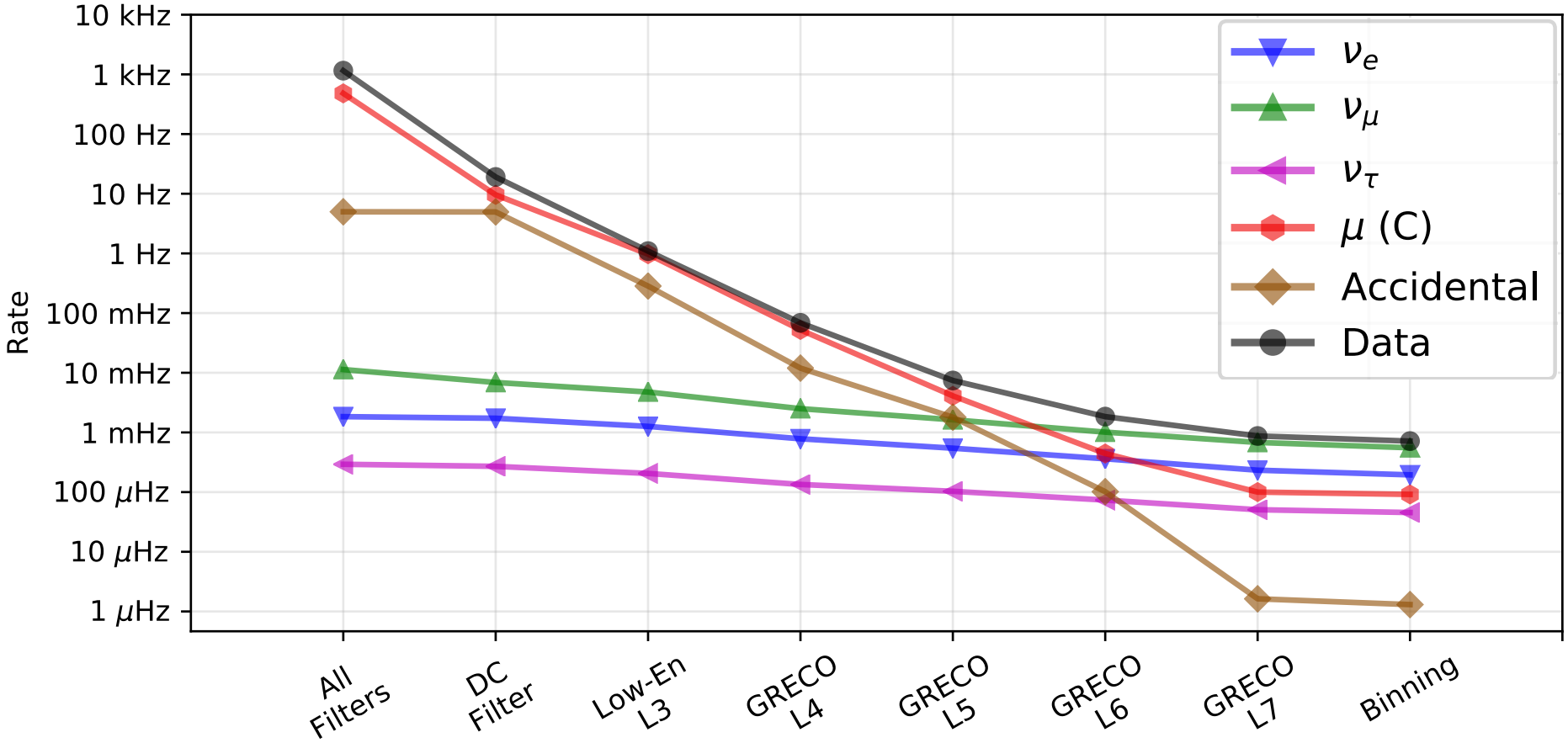




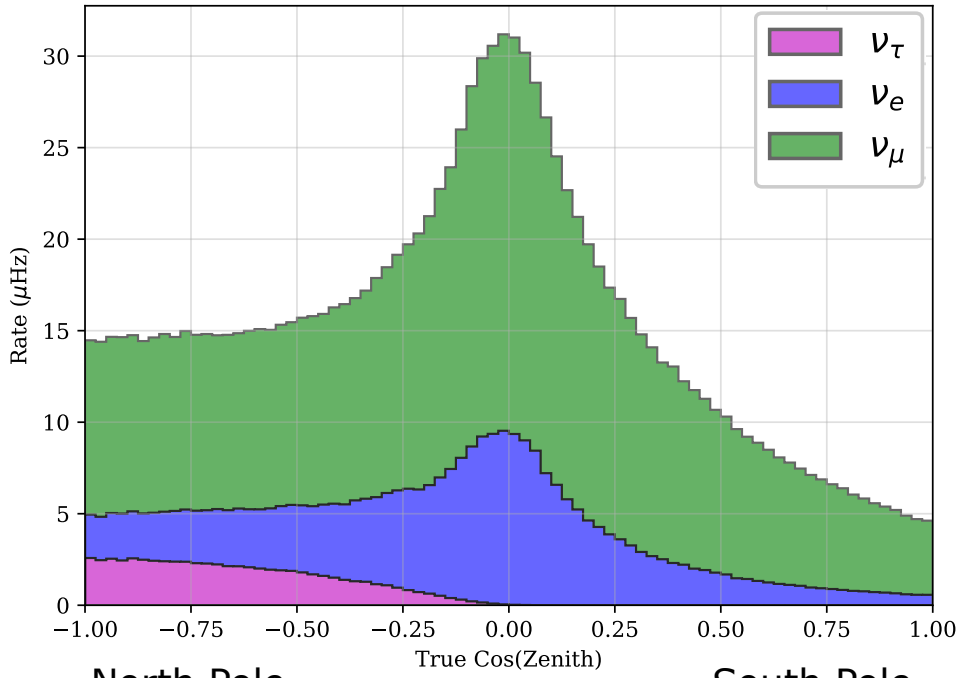
Muon Rejection with BDTs - GRECO Level 5

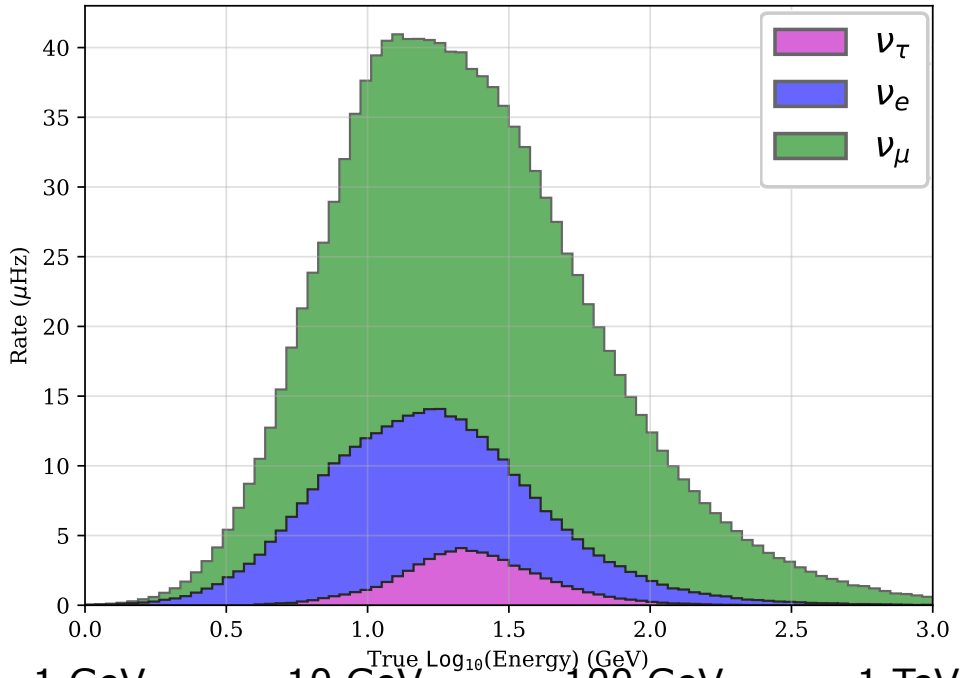


Background Rejection in GRECO Sample

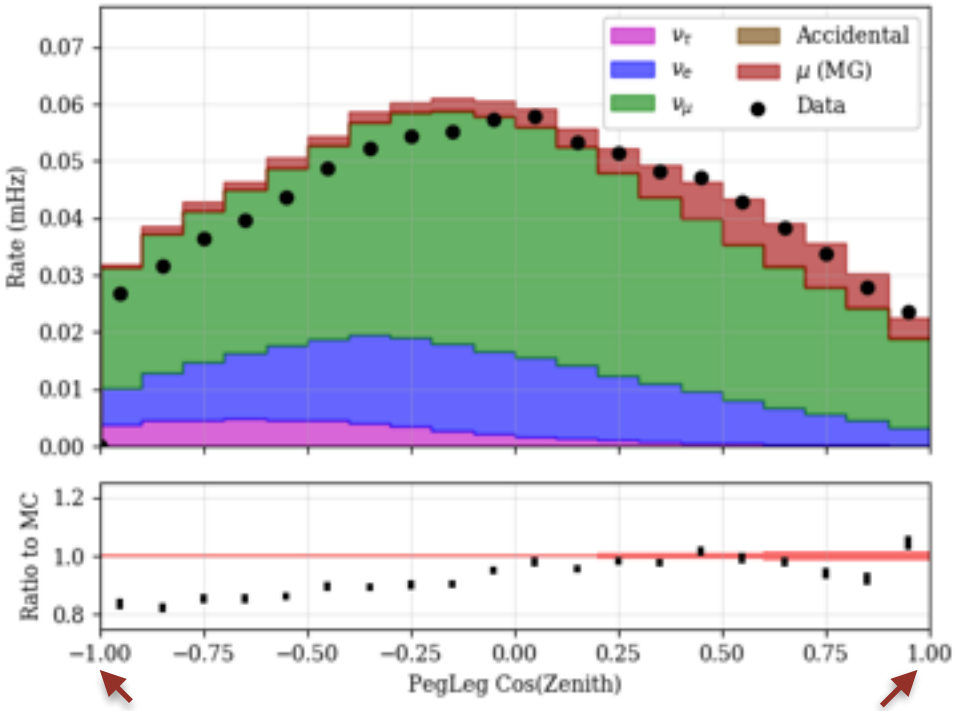


Neutrino Events from 1 GeV to 1 TeV



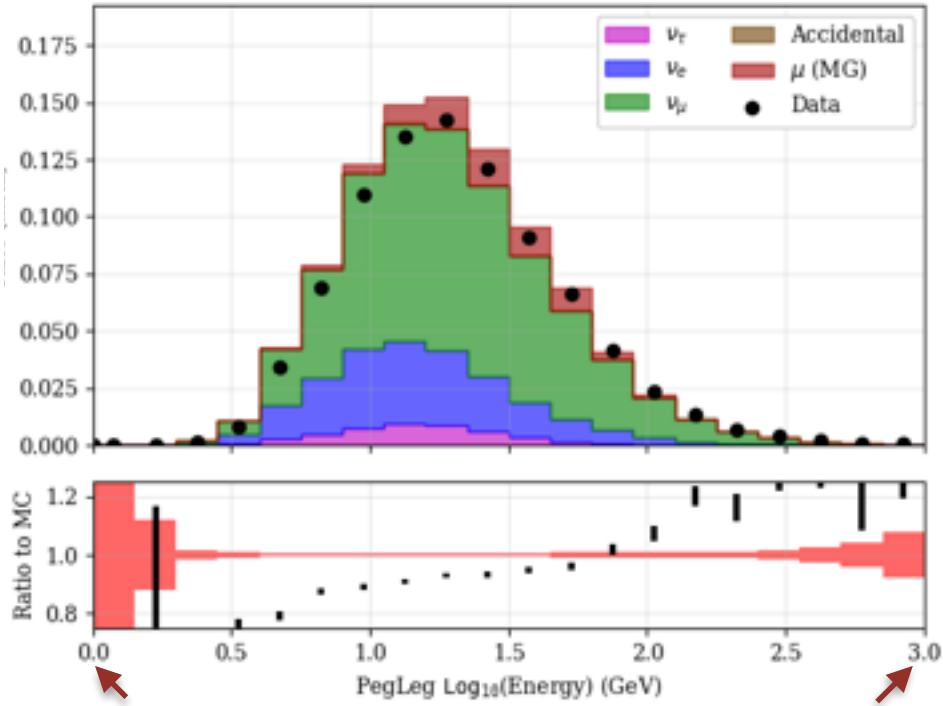


The Reconstructed Event Sample (Binning)



North Pole

South Pole



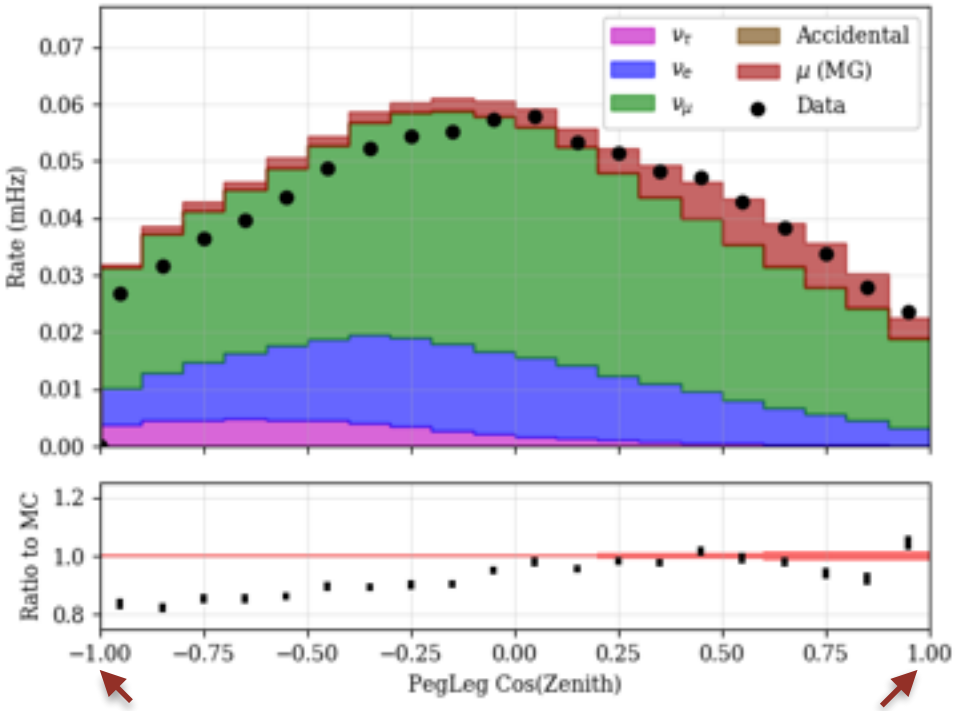
1 GeV

10 GeV

100 GeV

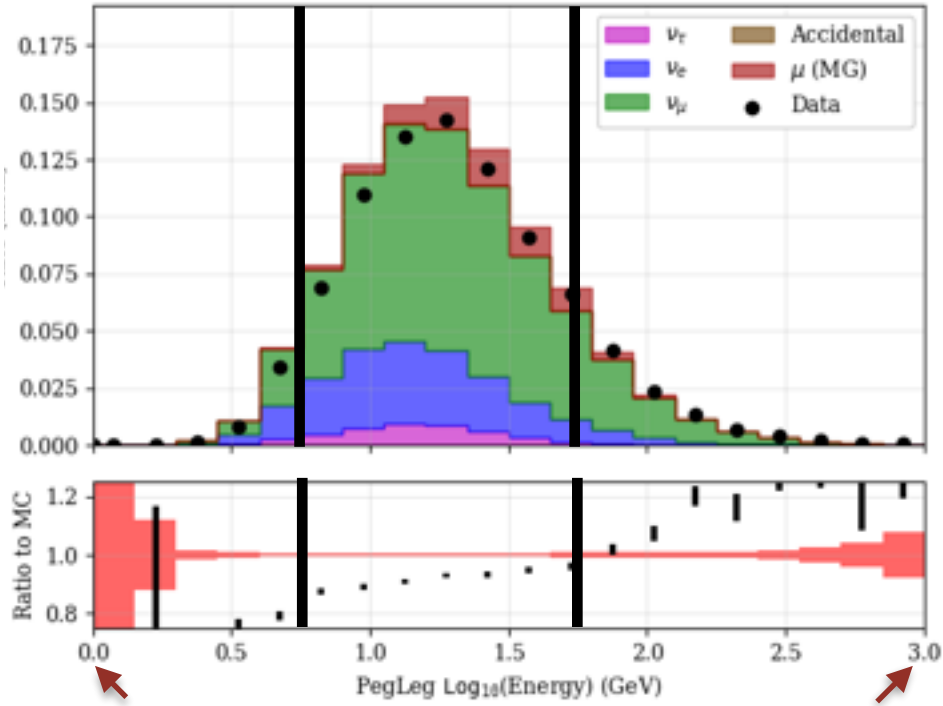
1 TeV

The Reconstructed Event Sample (Binning)



North Pole

South Pole



1 GeV

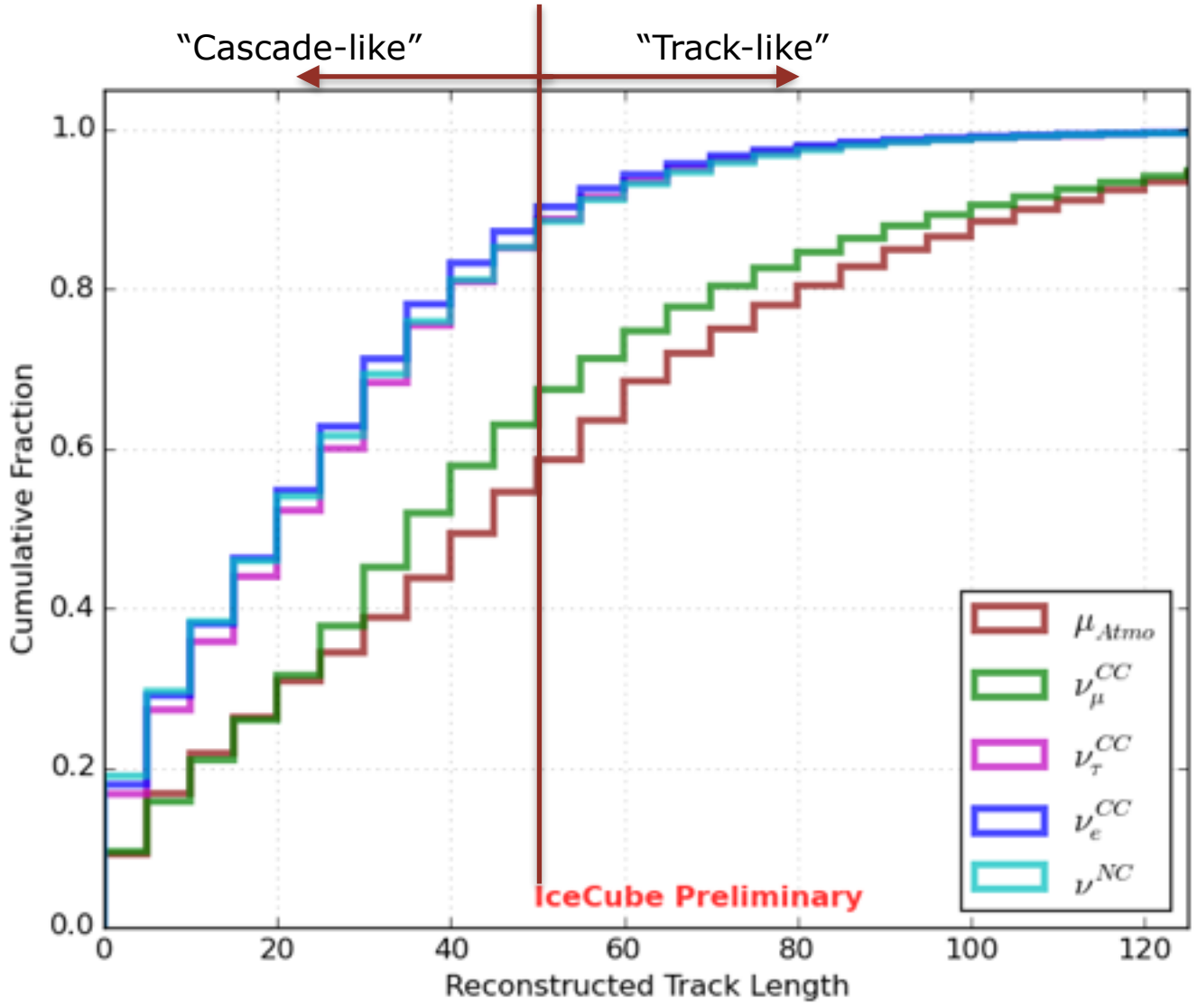
10 GeV

100 GeV

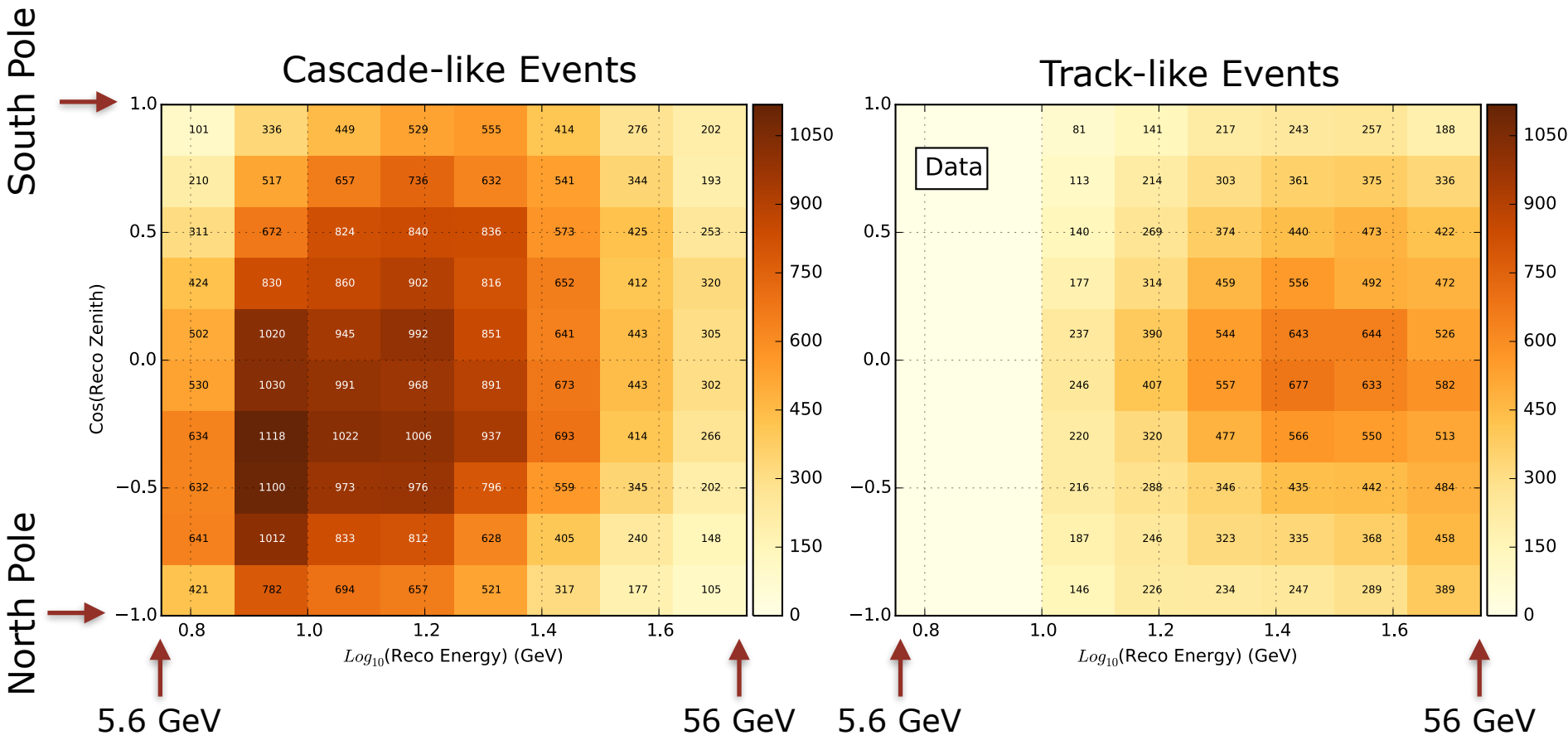
1 TeV

Energy range selected to match previous IceCube results

Particle Identification

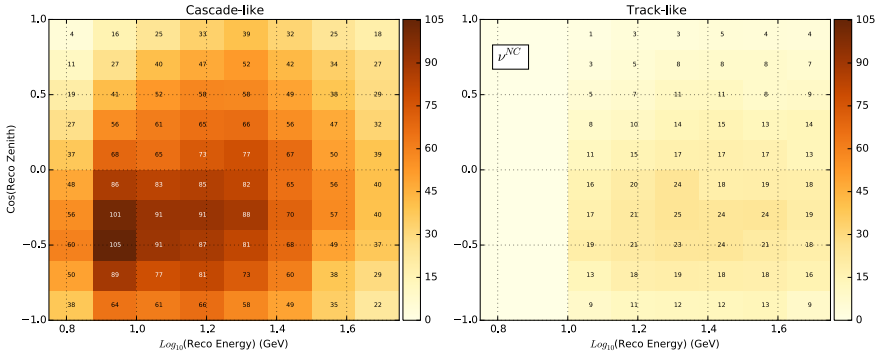


Reconstructed Event Distributions - Data

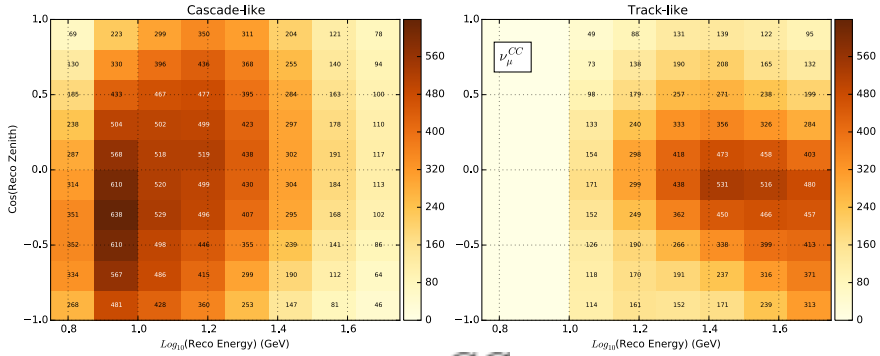


3 years of data included (2012-2015)

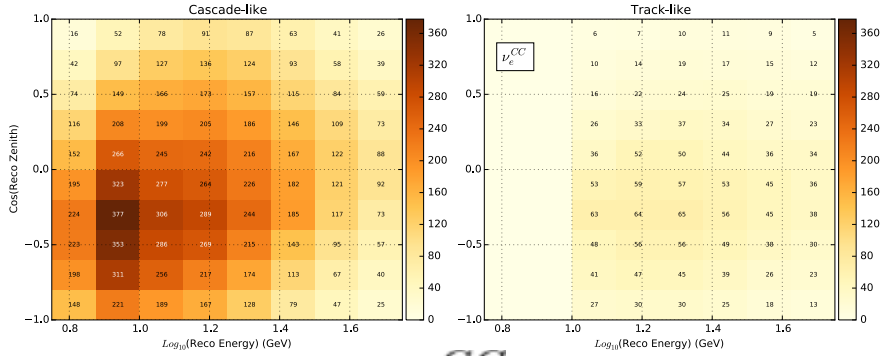
Reconstructed Event Distributions - Neutrinos



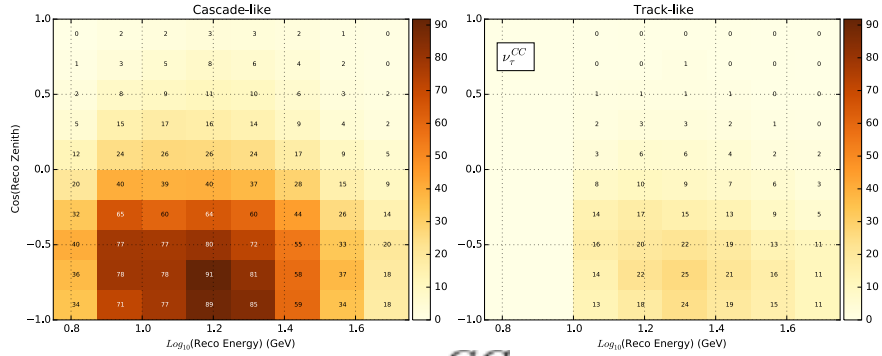
ν^{NC}



ν_μ^{CC}



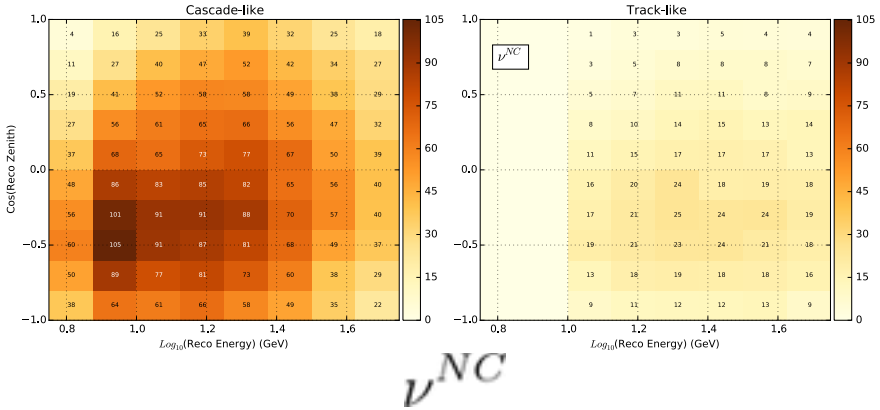
ν_e^{CC}



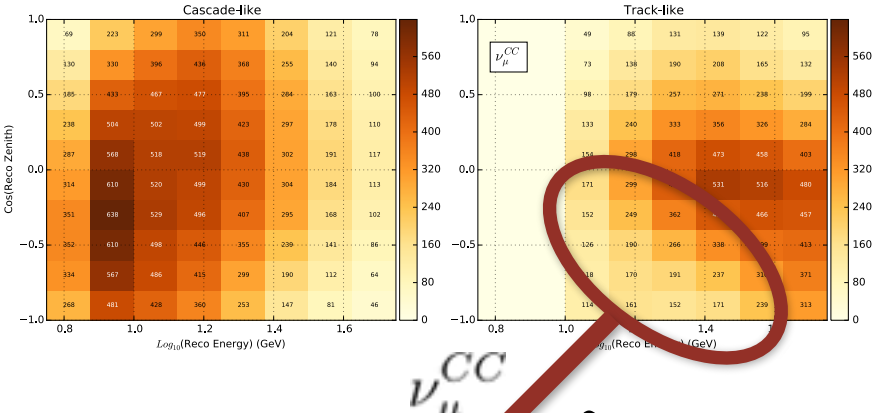
ν_τ^{CC}

Signal

Reconstructed Event Distributions - Neutrinos

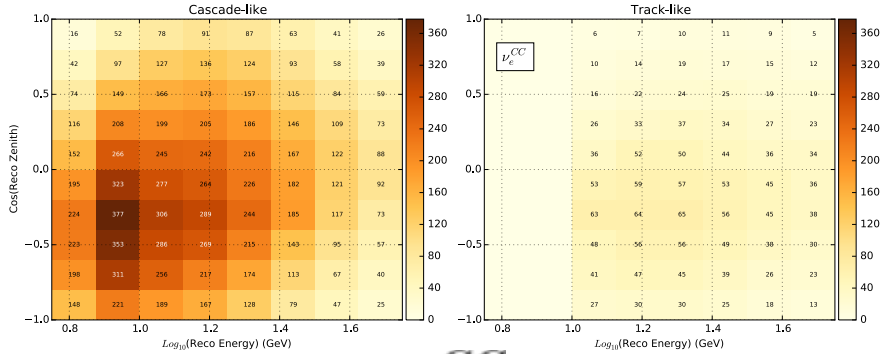


ν^{NC}

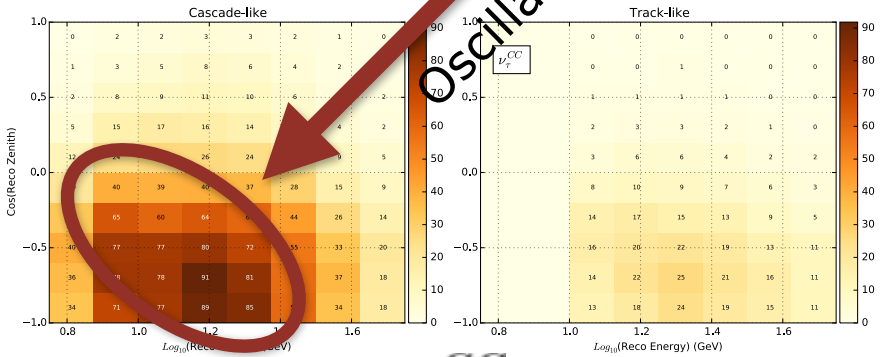


ν_{μ}^{CC}

Oscillation



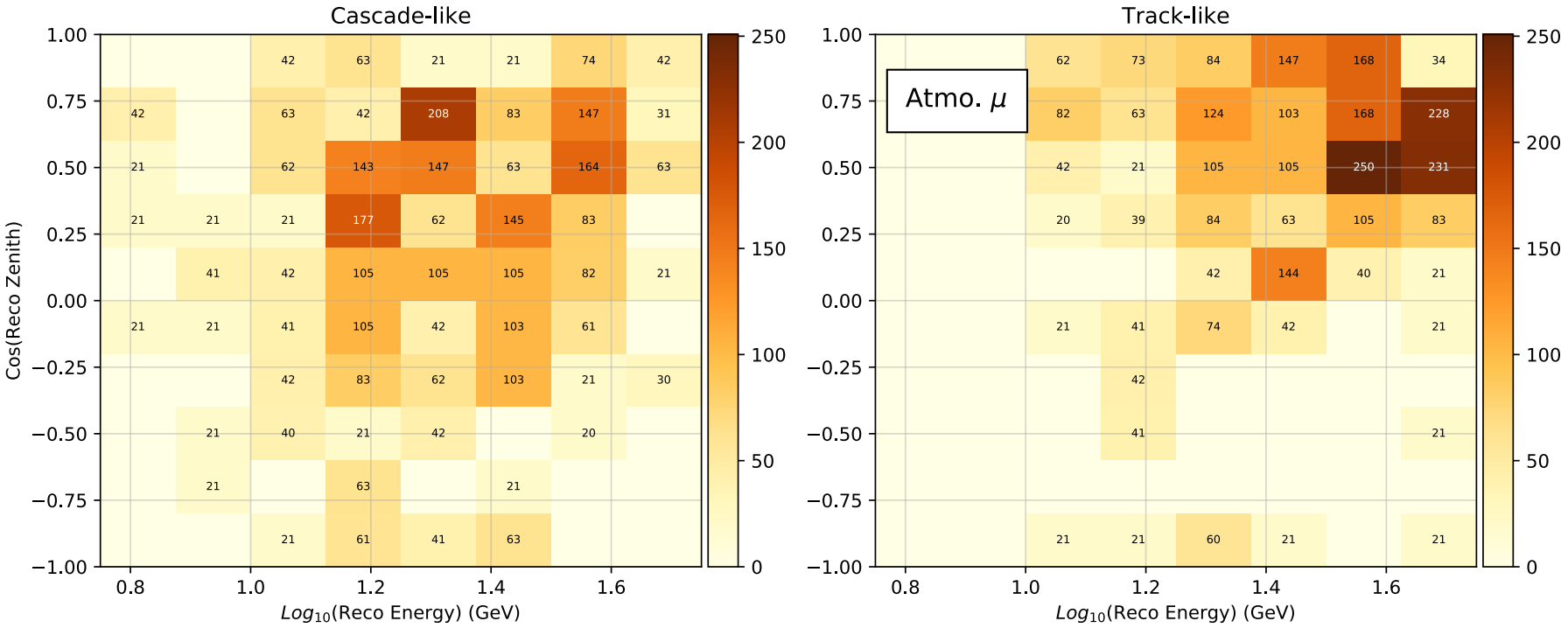
ν_{e}^{CC}



ν_{τ}^{CC}

Signal

Reconstructed Event Distributions - Muons



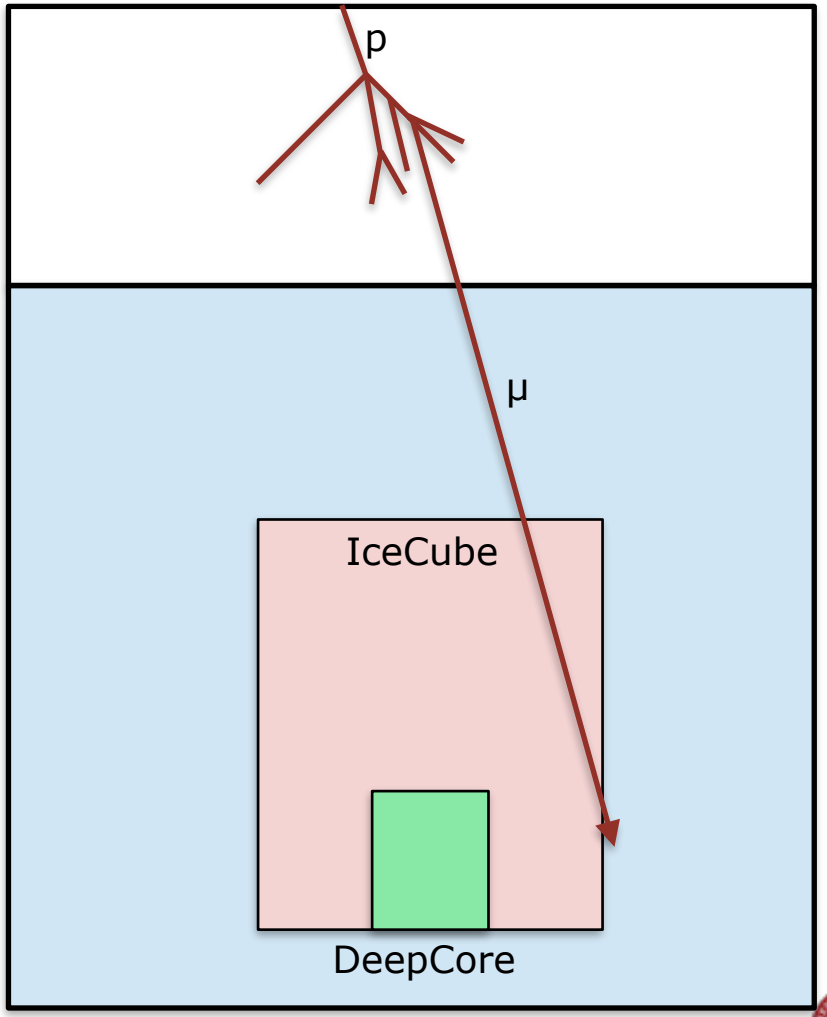
- Combined multiple large IceCube background simulation sets
  - Simulation predicts 7415 ± 448 events in sample
  - Only 284 simulated atmospheric muon events remain
- Shape of atmospheric muons is statistically unreliable.

Increasing Background Statistics

- Typical simulation chain:
  - Start with cosmic ray
  - Produce air shower
  - Propagate muon to IceCube
  - Propagate light in detector
  - Run trigger simulation

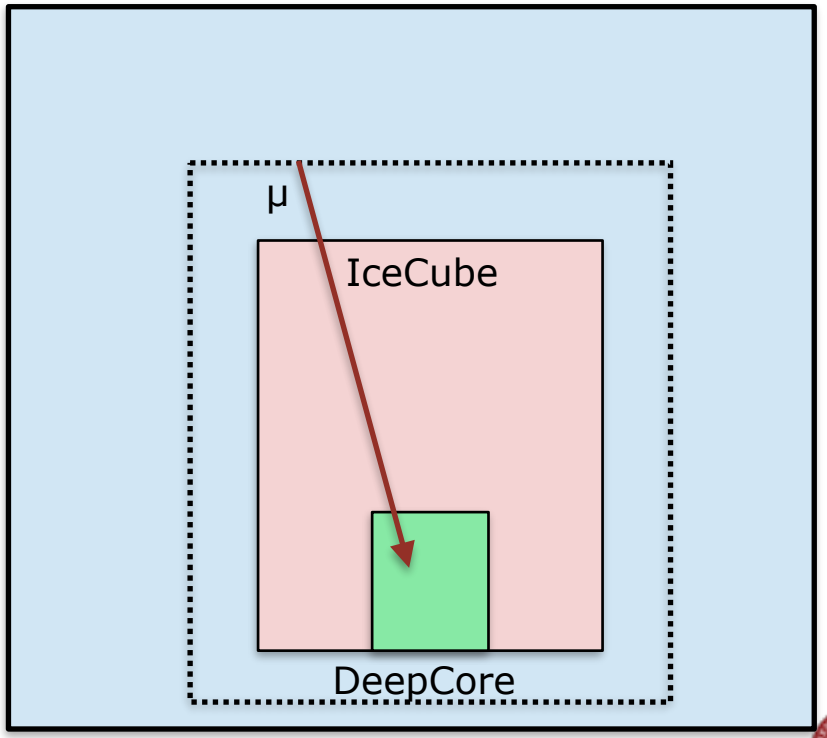
- No control over whether event is good for analysis

- **On average, 1.20 useful events per processing year**

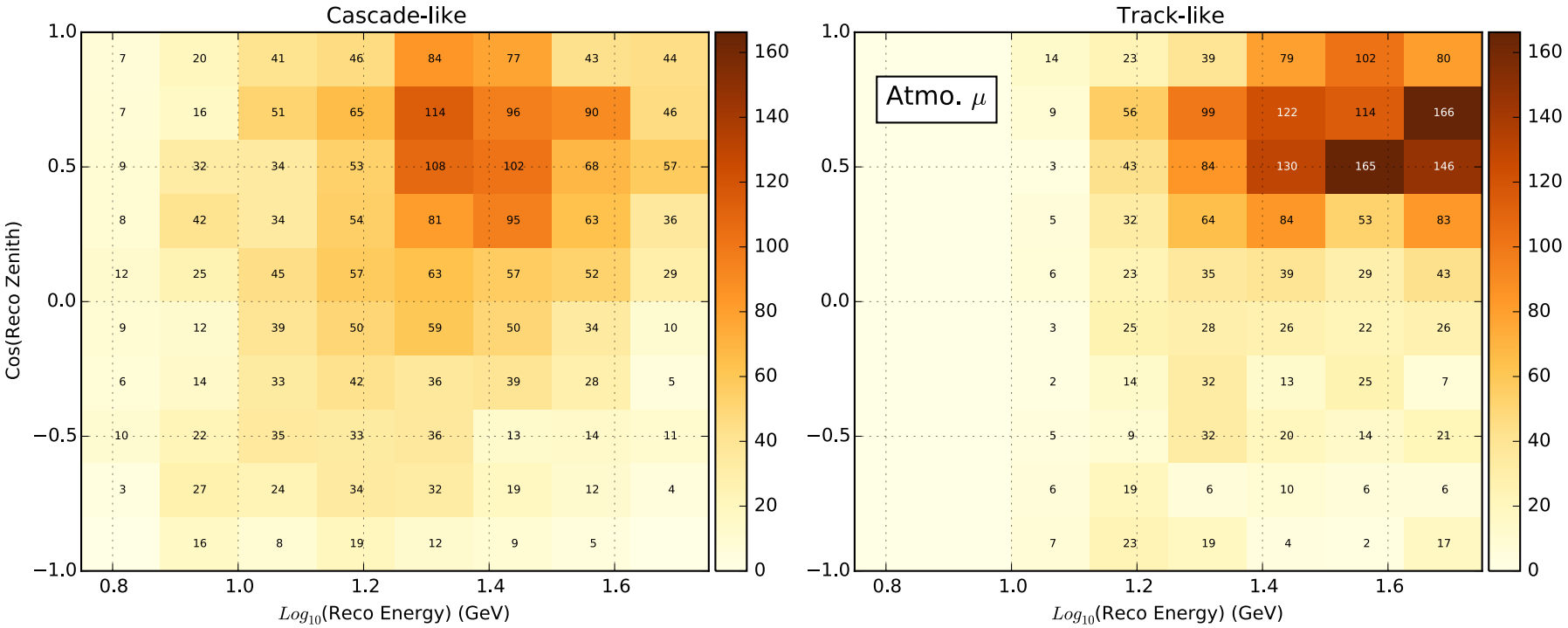


Increasing Background Statistics

- New simulation chain:
  - Start with muon near IceCube
  - Propagate light in detector
  - Run trigger simulation
- Able to aim muons only at DeepCore volume!
- **On average, 111 useful events per processing year**
- Further improvements possible
  - Not discussed today



Reconstructed Event Distributions - Muons



- Had 284 simulated events at final level

- Now have 2486 simulated events to use
  - Significantly smaller background uncertainties
  - More events possible with more processing time

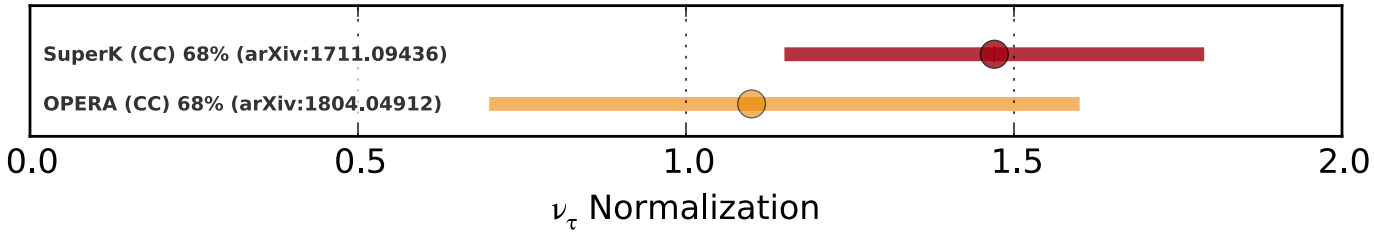
A Search for Tau Neutrino Appearance with DeepCore

Parametrizing ν_τ Appearance

- Define "tau normalization", N_{ν_τ}, as modification of expected tau neutrino event rate from standard muon neutrino flux, cross section, oscillations, etc.

$$\text{Observed } \nu_\tau = N_{\nu_\tau} \times (\text{Expected } \nu_\tau)$$

$$R'_{\nu_\tau} = N_{\nu_\tau}\, R_{\nu_\tau}(\theta_{23}, \theta_{13}, \Delta m^2_{31}, \ldots)$$



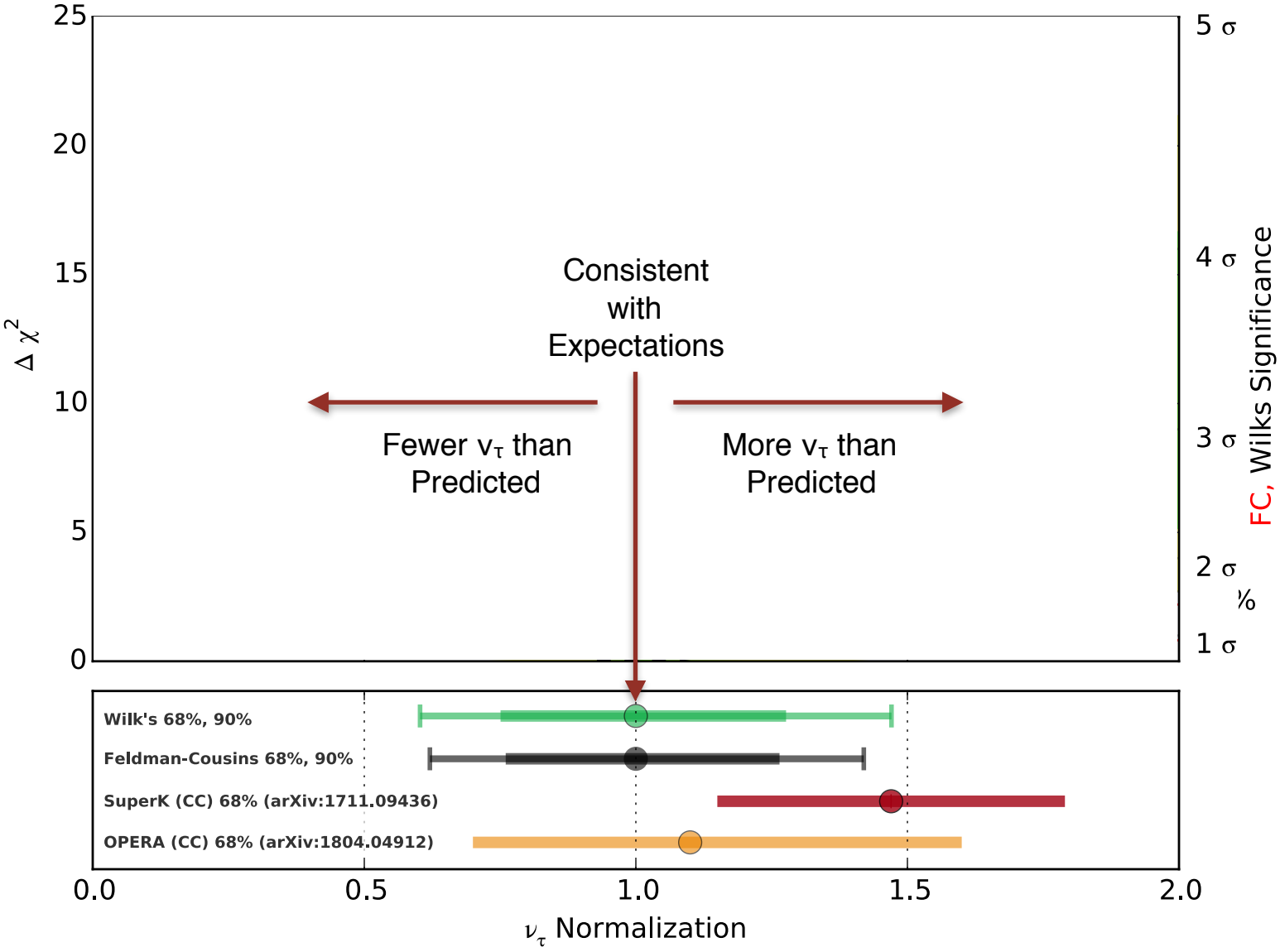
- Can apply this to just CC ν_τ or both (NC+CC) ν_τ interactions
  - Super-K, OPERA performed CC-only measurement
  - Focusing on the NC+CC measurement today

Systematics Included for Appearance Fits

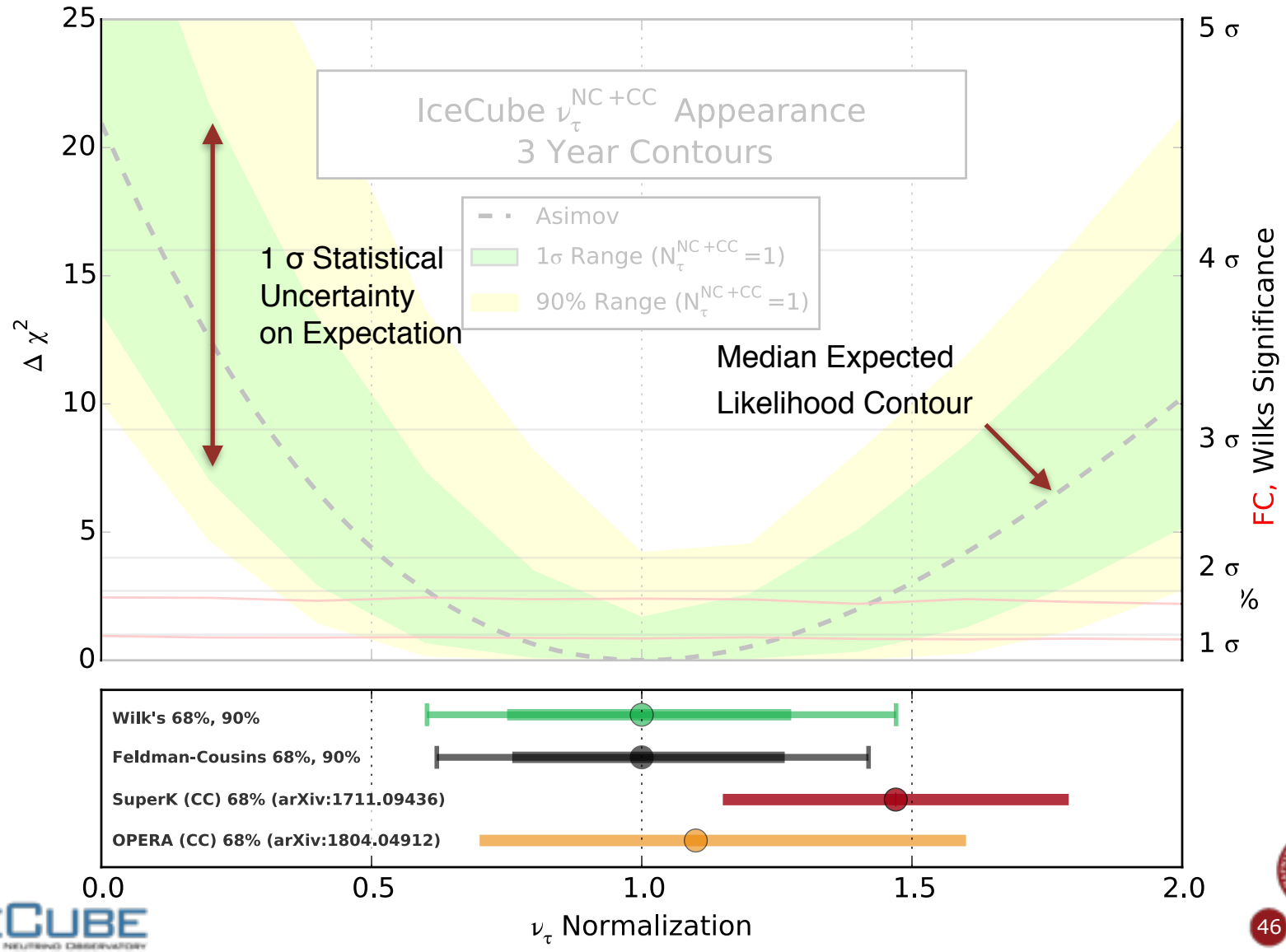
Parameter Type	Fit Parameter
Oscillations	Δm^2_{32}
	$\sin^2(\theta_{23})$
	N_τ
Cross-section	Axial Mass (QE)
	Axial Mass (RES)
	N_{NC}/N_{CC}
Neutrino Flux	ν_μ Normalization
	ν_e/ν_μ Ratio
	γ_ν
	$\nu/\bar{\nu}$ Ratio
	Up/Horizontal Ratio
	$f_{Coincident}$
Muon Flux	μ Norm
	γ_{CR}
Detector	DOM Efficiency
	Lateral Sensitivity
	Forward Sensitivity
	Absorption
	Scattering

- Wide range of systematics included
- Similar to previous IceCube oscillation analyses
- Most important systematics:
  - Oscillation parameters
  - "Hole Ice" parameters

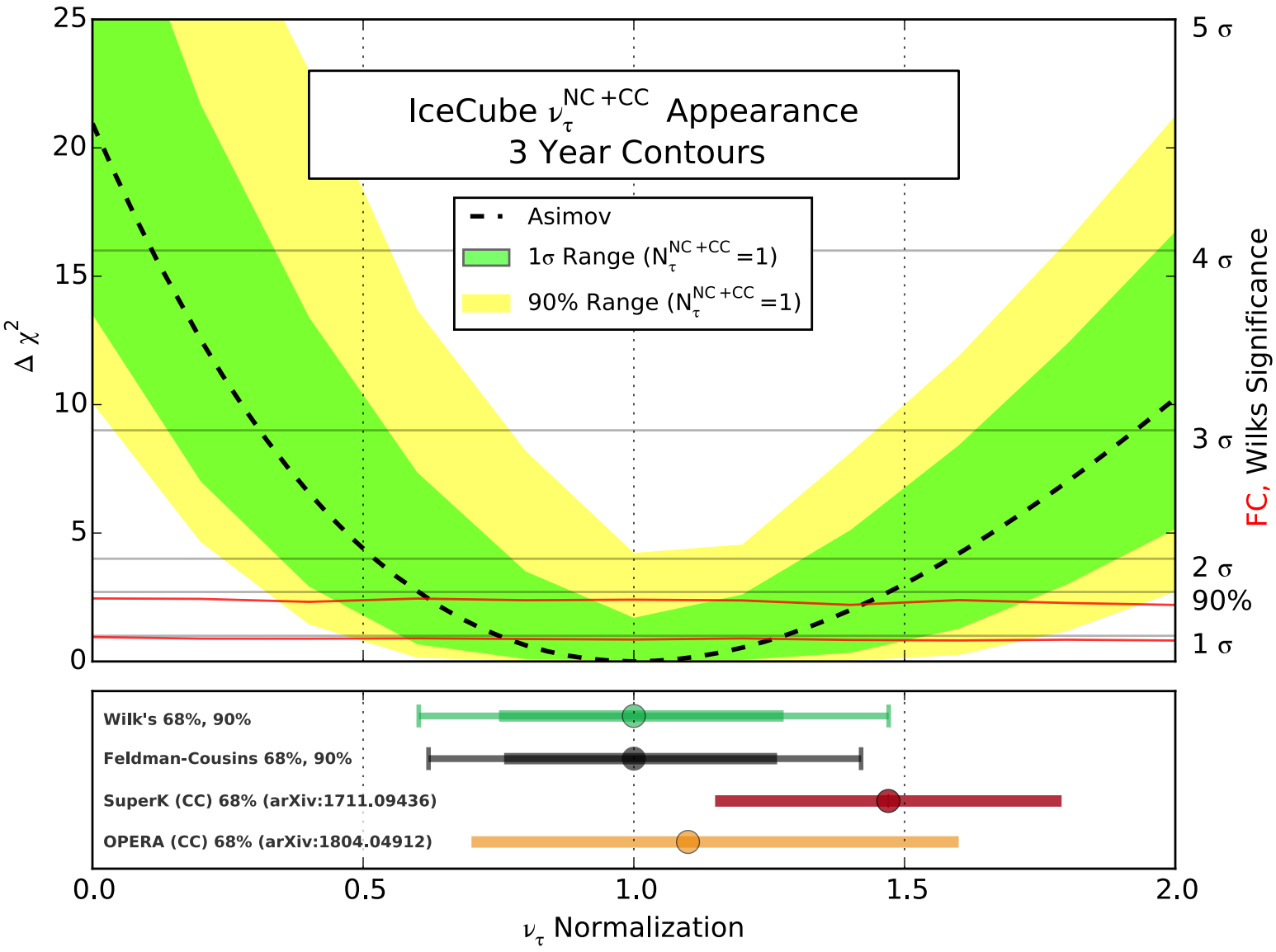
Expected Precision of the Two Analyses



Expected Precision of the Two Analyses



Expected Precision of the Two Analyses



Checking Data/MC Agreement

Checking Data/MC Agreement :(

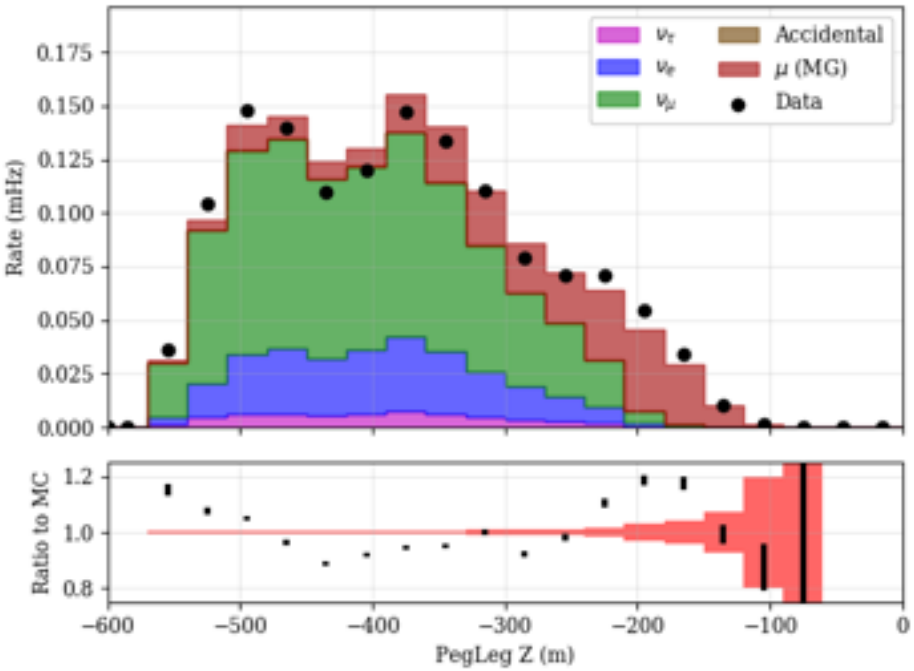
- Initial Goodness-of-fit $p=10^{-7}$

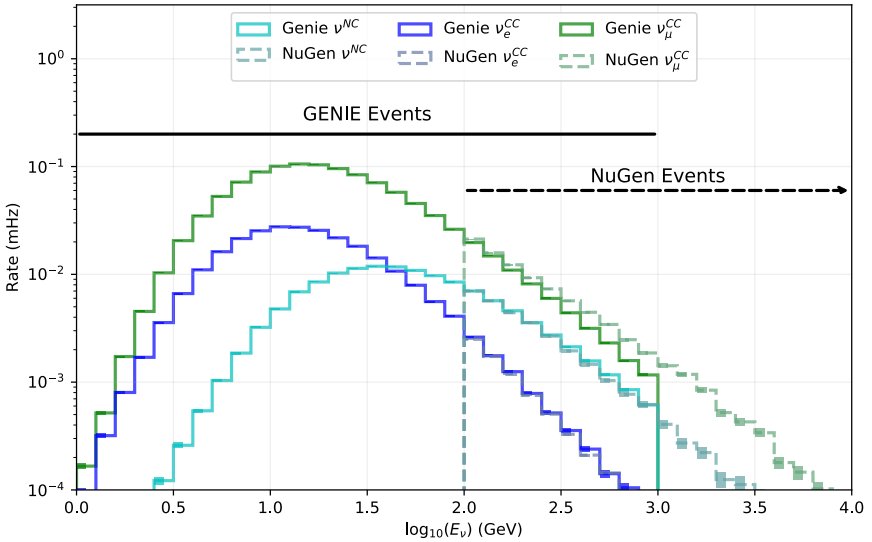
Sudden Detour to Antarctica

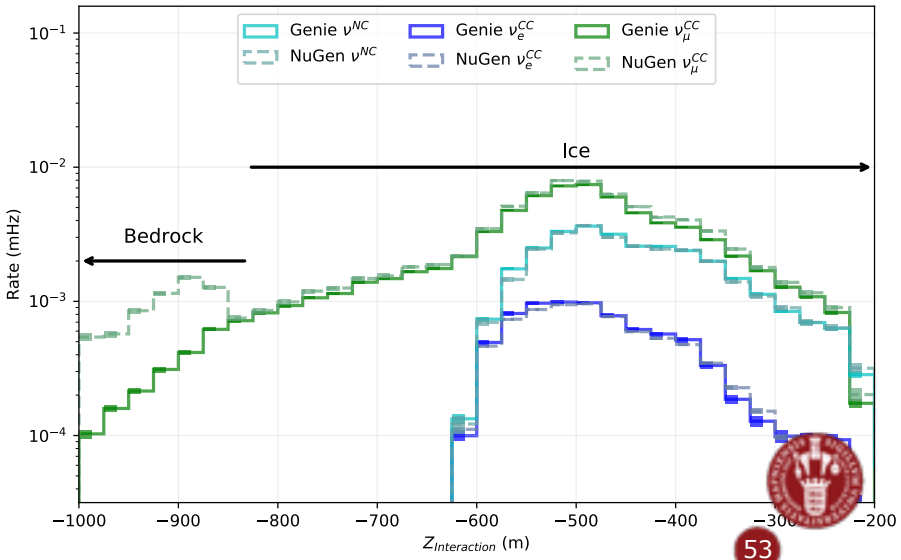
Sudden Detour to Antarctica

Identifying Data/MC Disagreement

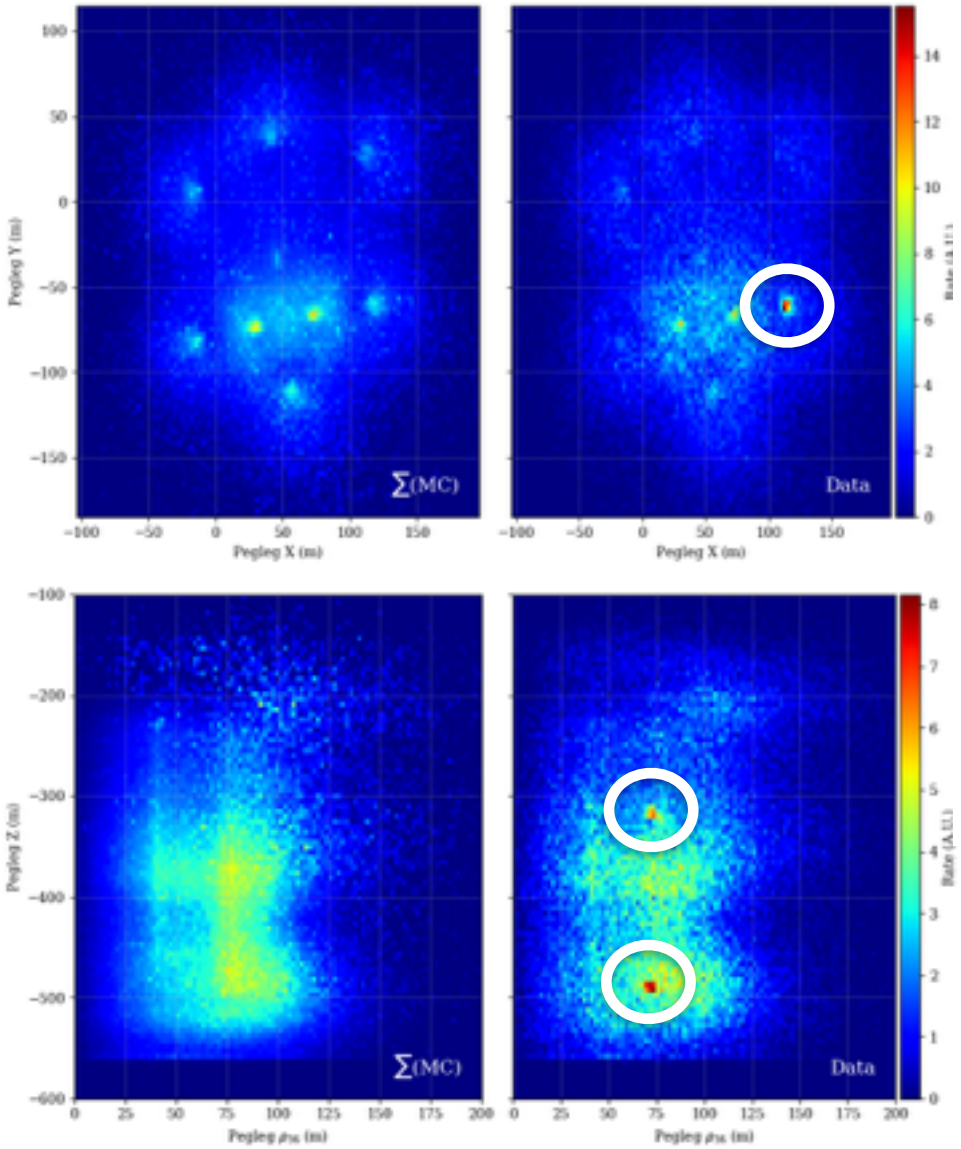
Calibration Discoveries with this Selection

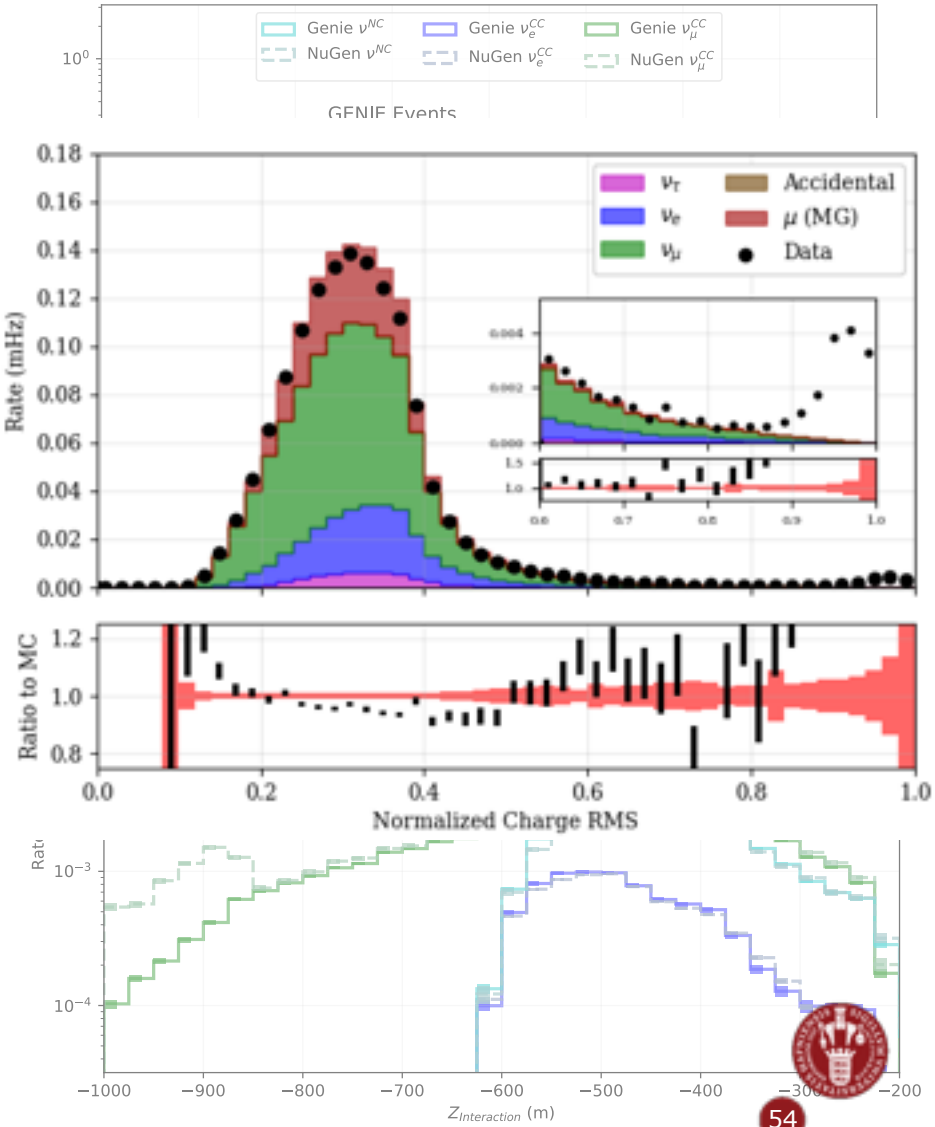






Calibration Discoveries with this Selection





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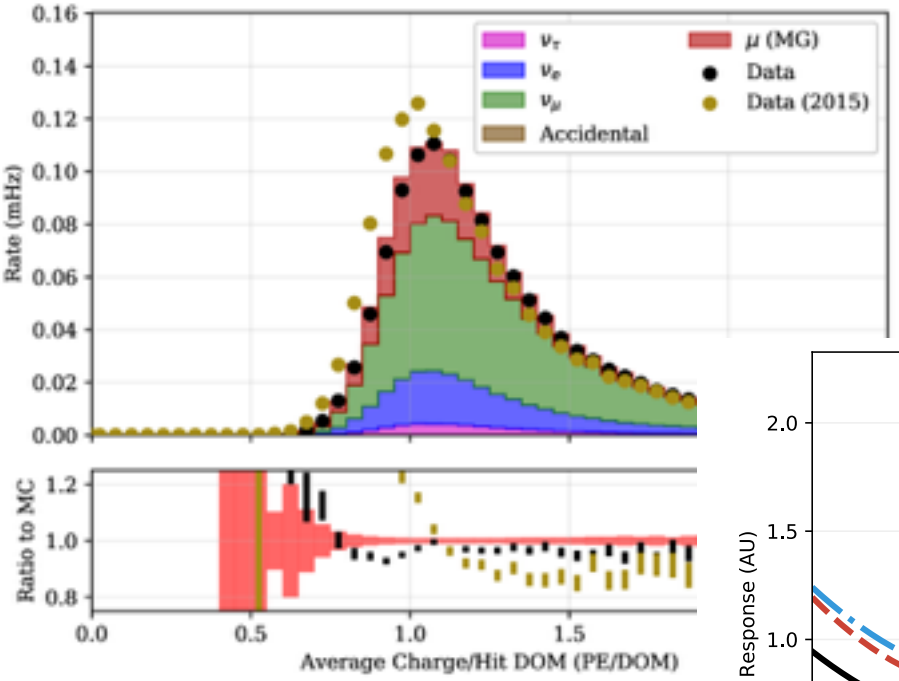
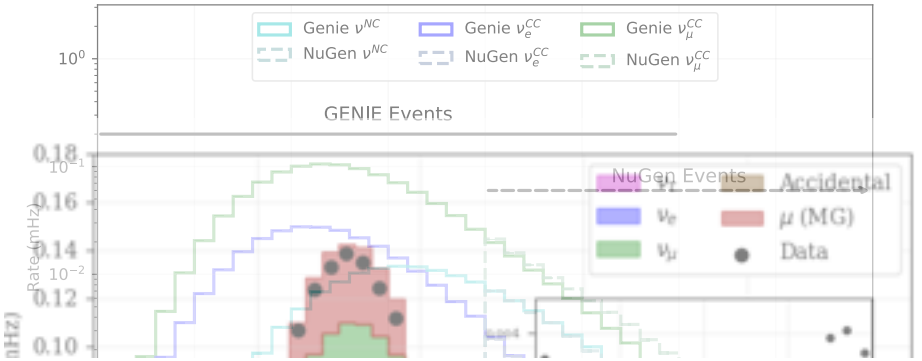
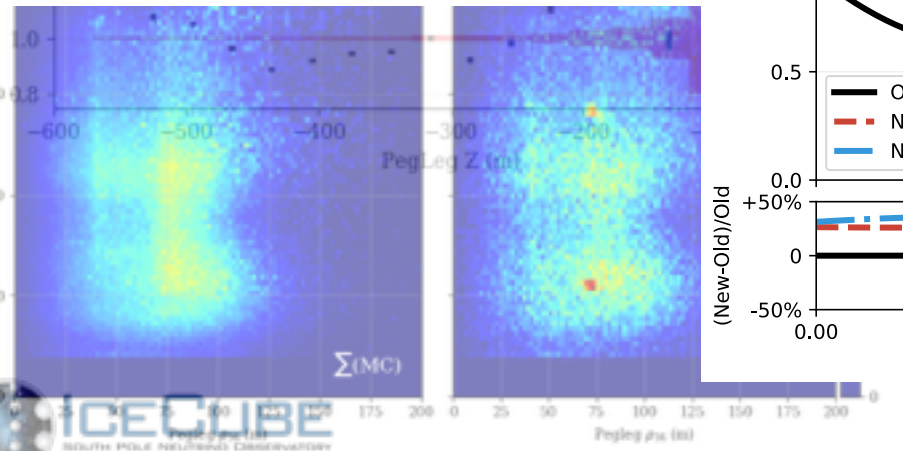
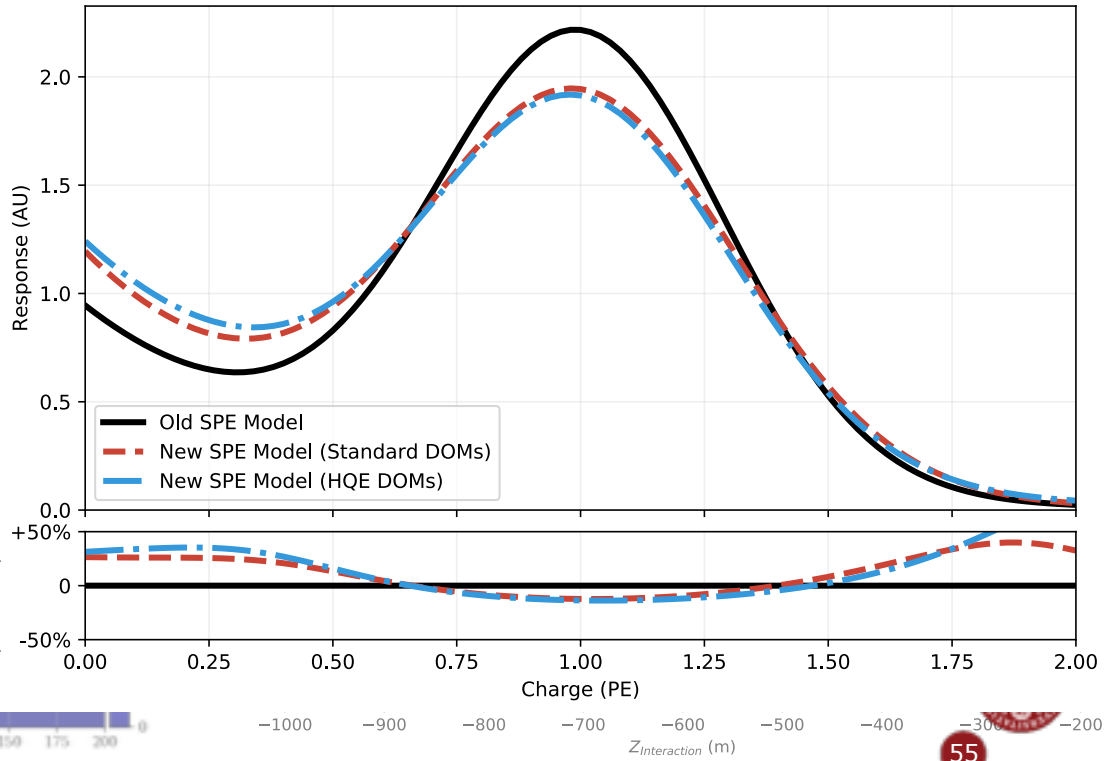
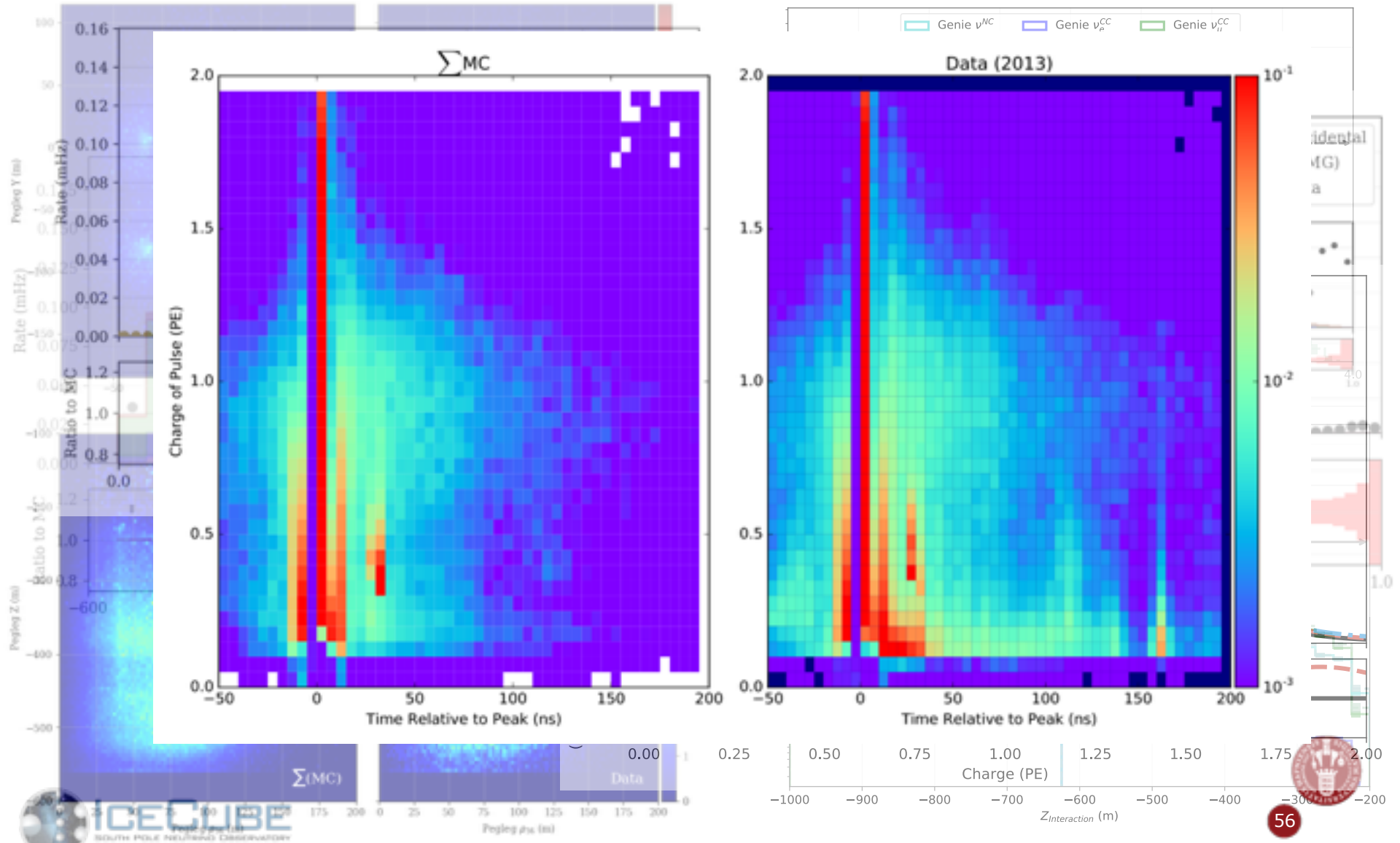








Calibration Discoveries with this Selection



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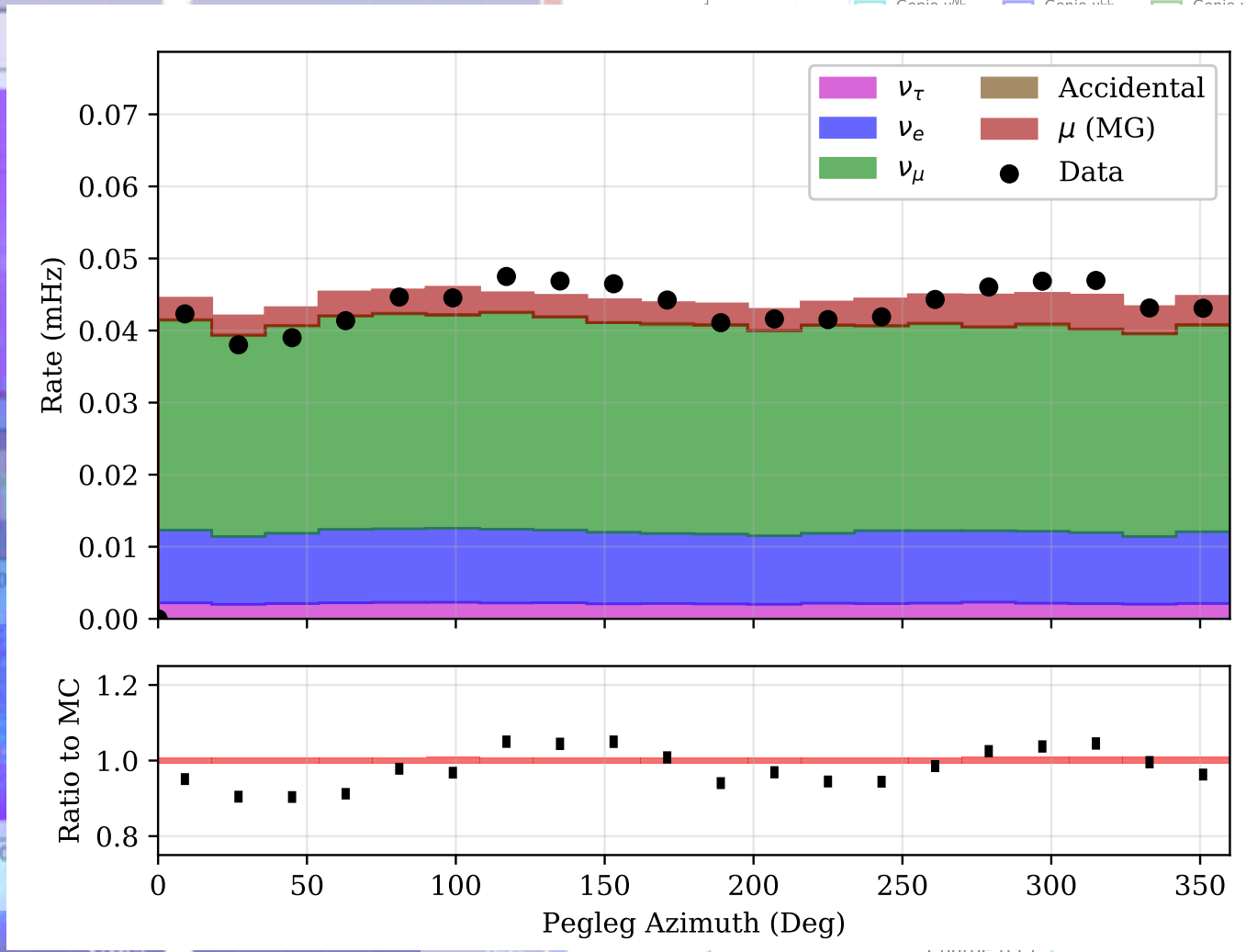
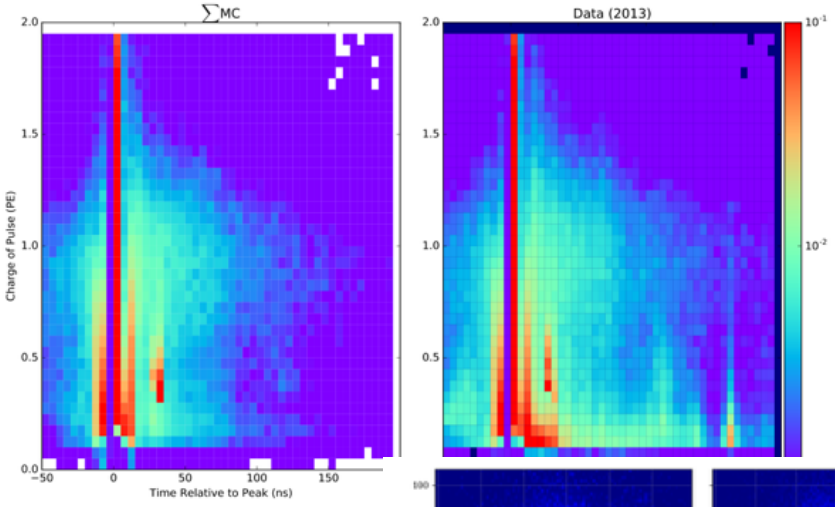
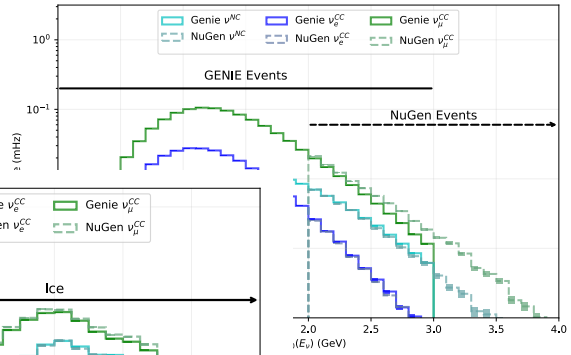
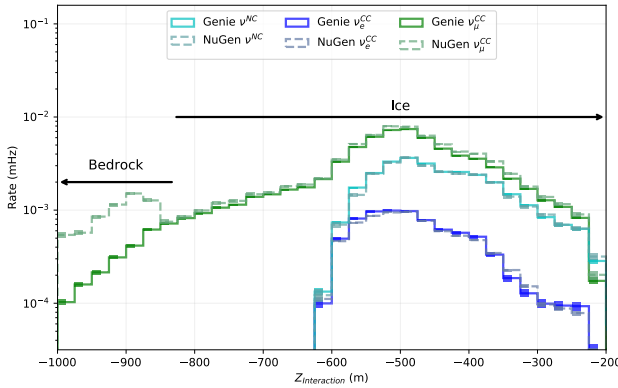
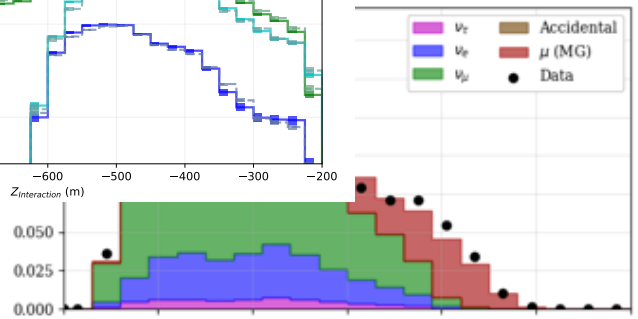


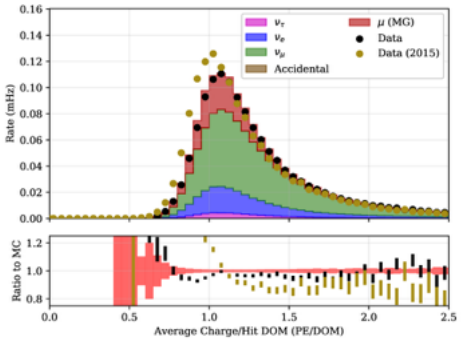
Calibration Discoveries with this Selection

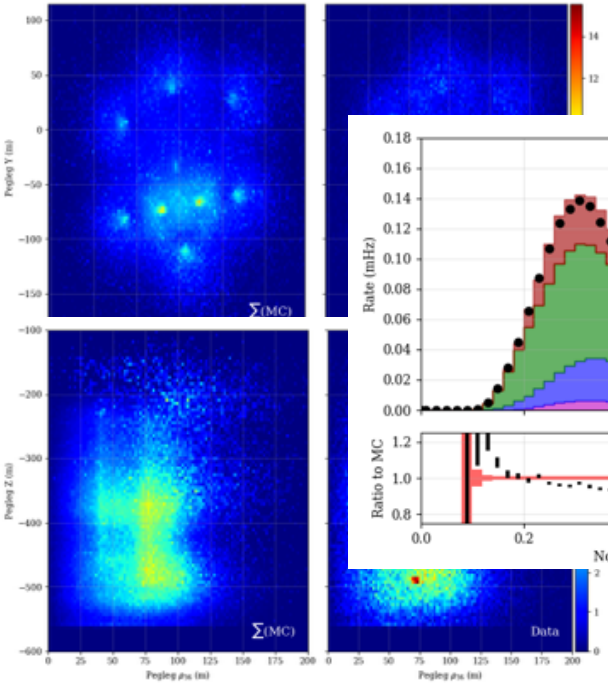


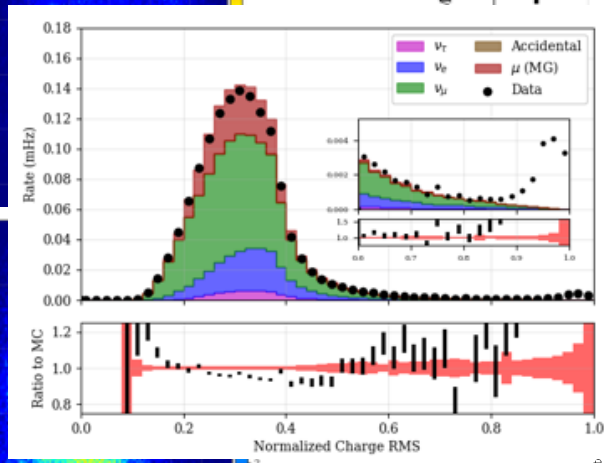


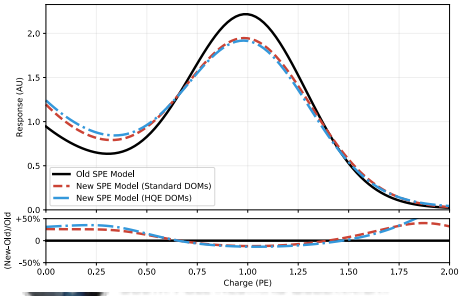


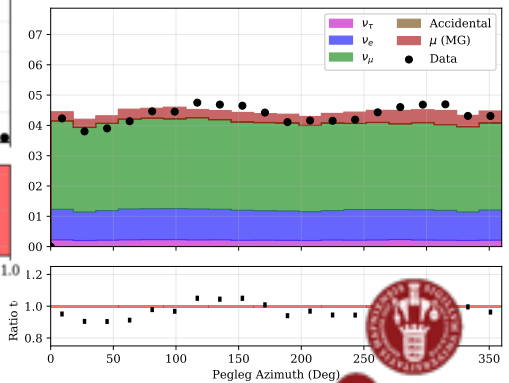










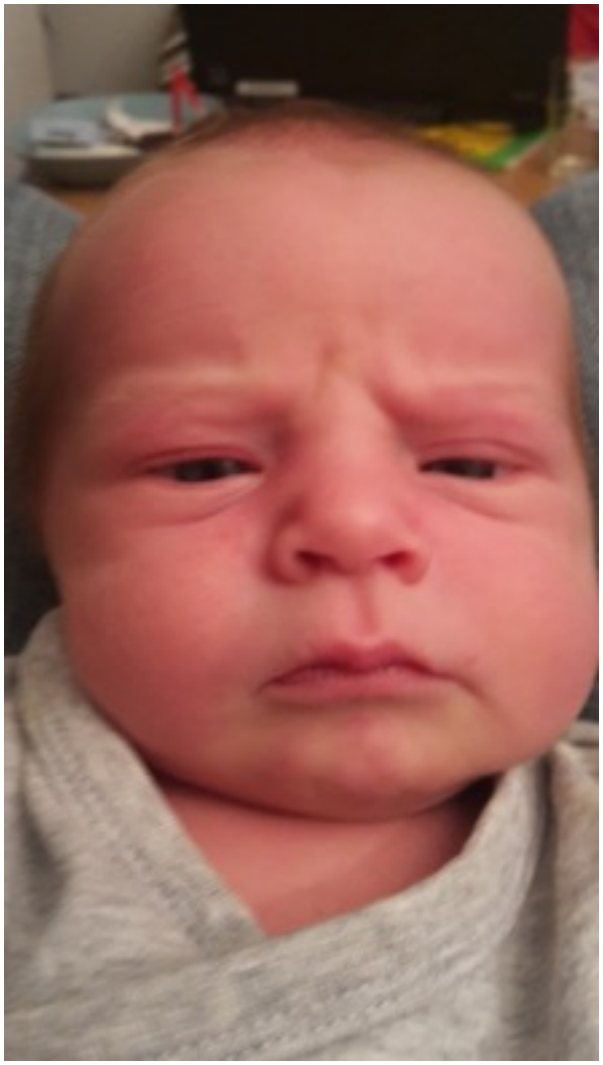


Problems Fixed: Unblinding Approval

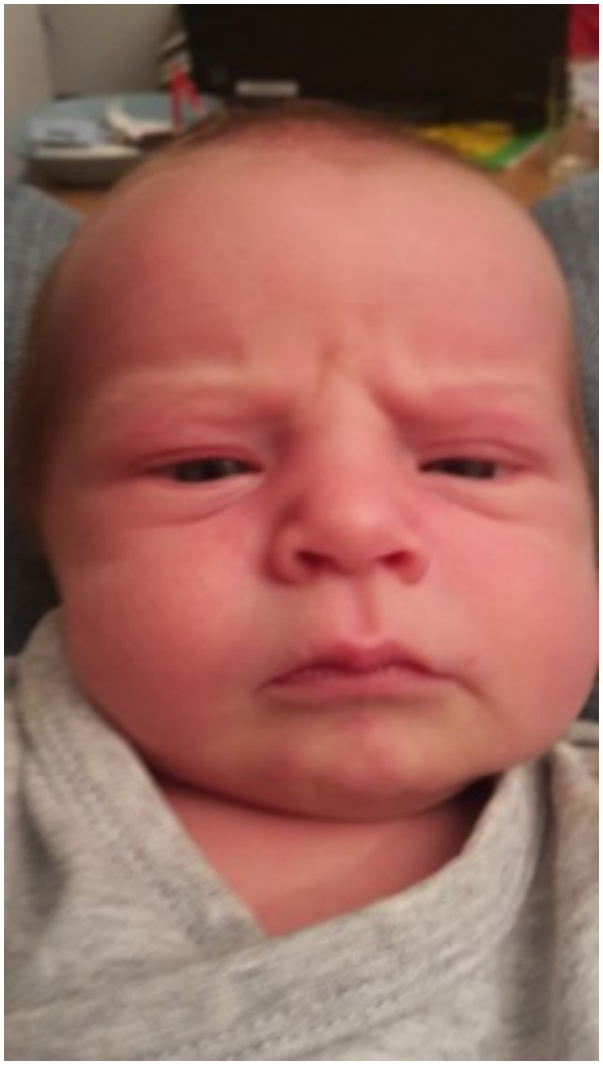
- New Goodness-of-fit p=58%

4 Days after Unblinding Approval

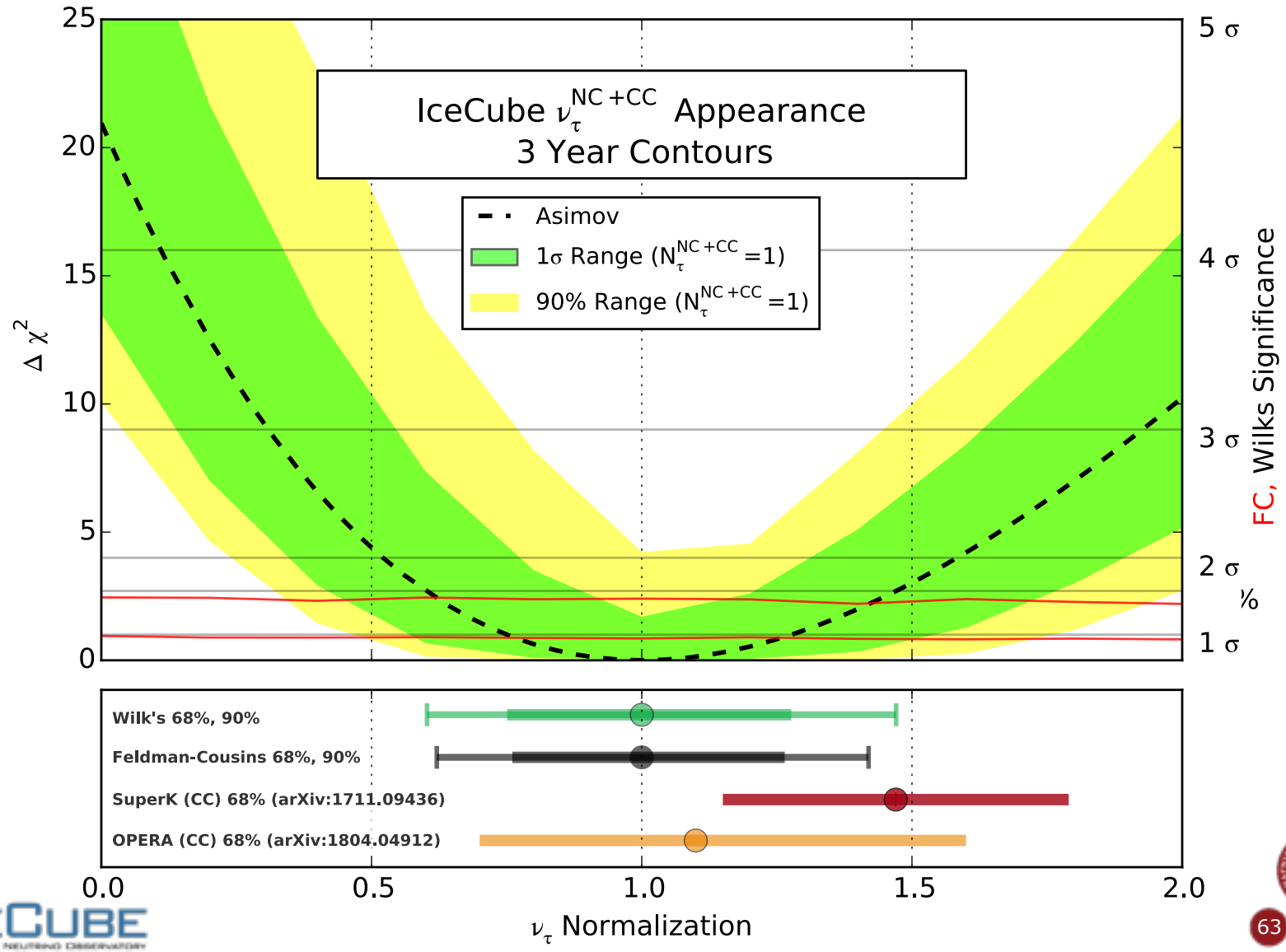
"Why are you still a student?"



"You were supposed to be done by now"


Expected Precision of the Analysis



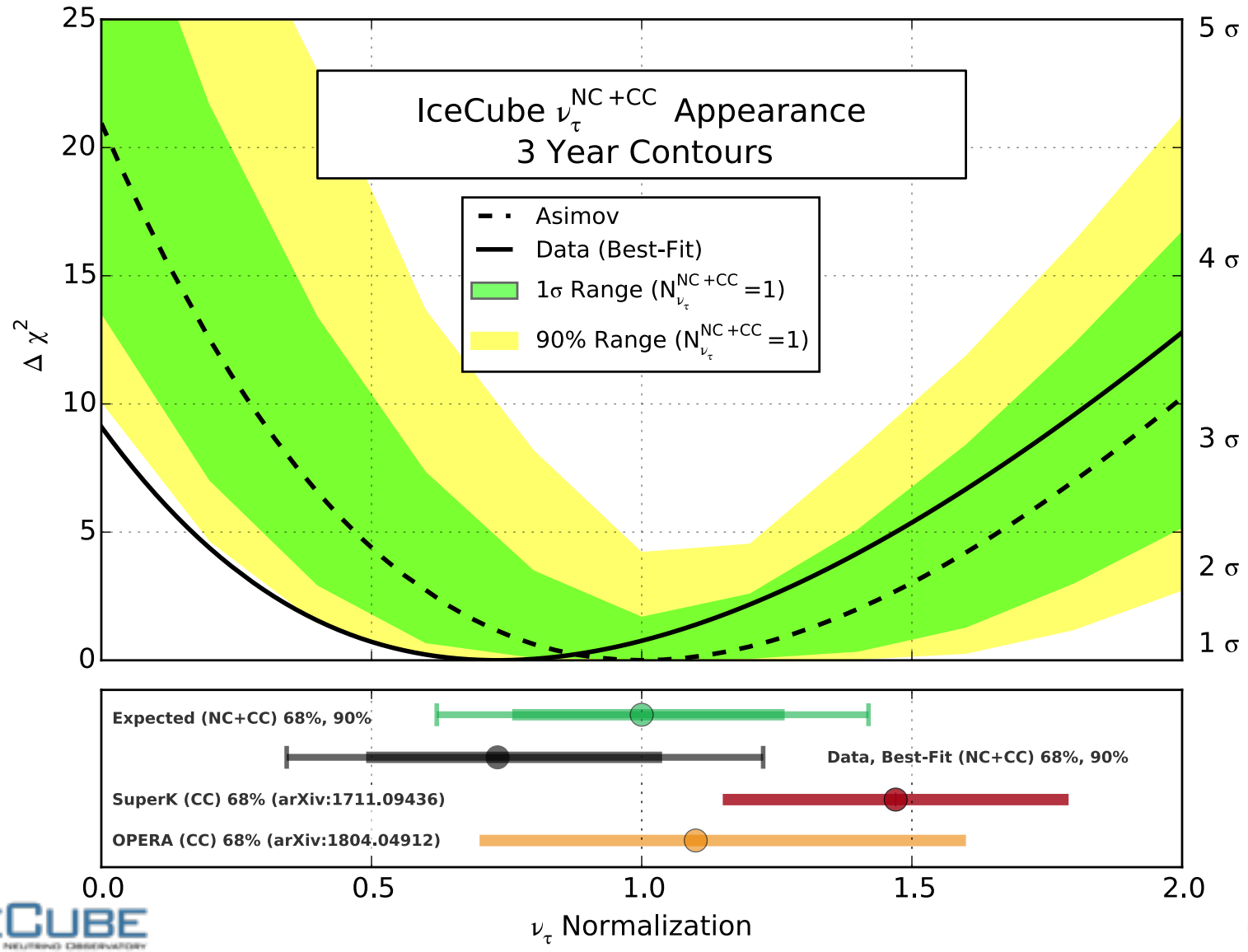
Best-Fit Event Rates (NC+CC Fit)

- Expected 2461 CC ν_τ + 1035 NC ν_τ
- Found **1804 CC ν_τ + 759 NC ν_τ** (NC+CC Fit)

- Previous Experiments:
  - Super-Kamiokande: **338 ± 72 CC ν_τ** (arXiv:1711.09436)
  - OPERA: **10 CC ν_τ** (Phys. Rev. Lett. 120, 211801)

Type	This Work Events	$+1\sigma$
$\nu_e + \bar{\nu}_e$ CC	13462	29
$\nu_\mu + \bar{\nu}_\mu$ CC	35706	48
$\nu_e + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu$ NC	5559	21
$\nu_\tau + \bar{\nu}_\tau$ CC	1804	9
$\nu_\tau + \bar{\nu}_\tau$ NC	759	5
Atmospheric μ	5023	167
Accidental Triggers	93	27
Total Expected (NC+CC Best Fit)	62406	180
Observed	62112	249

Appearance Best-Fit Values from DeepCore



Tau Appearance Results from DeepCore

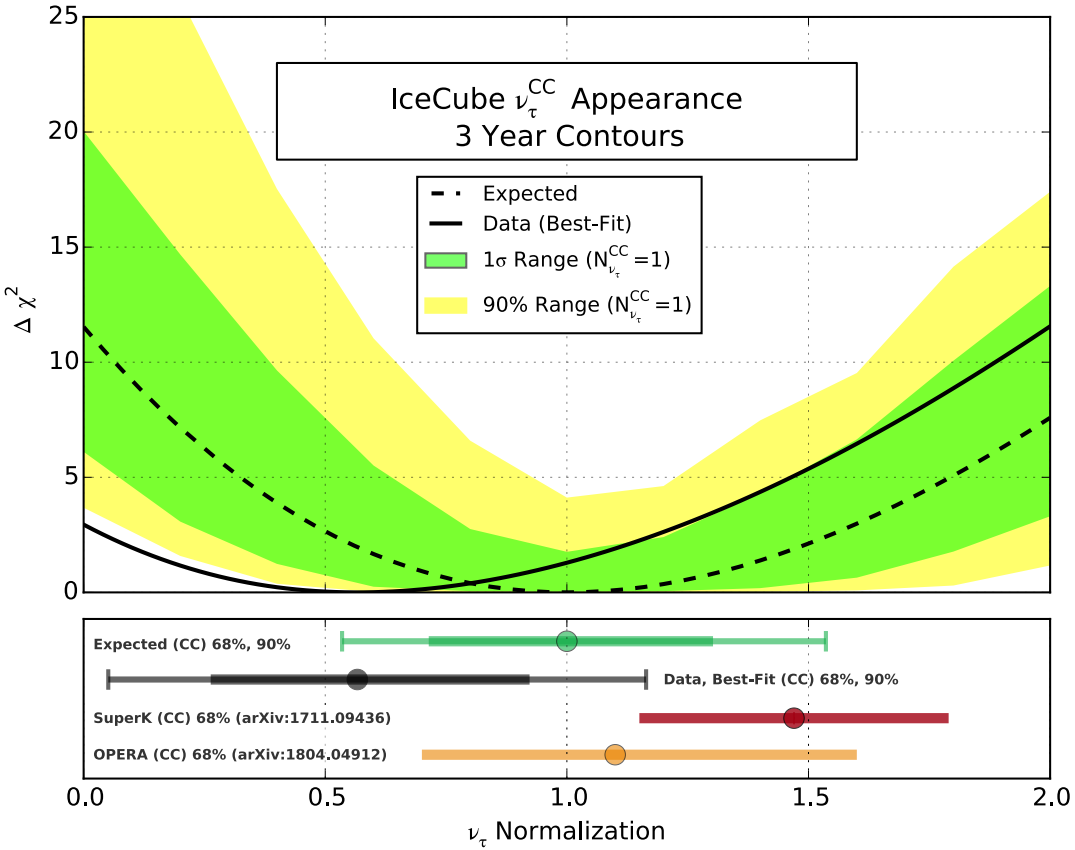
- Using CC as signal

$$N_\tau^{CC} = 0.57^{+0.36}_{-0.30}$$

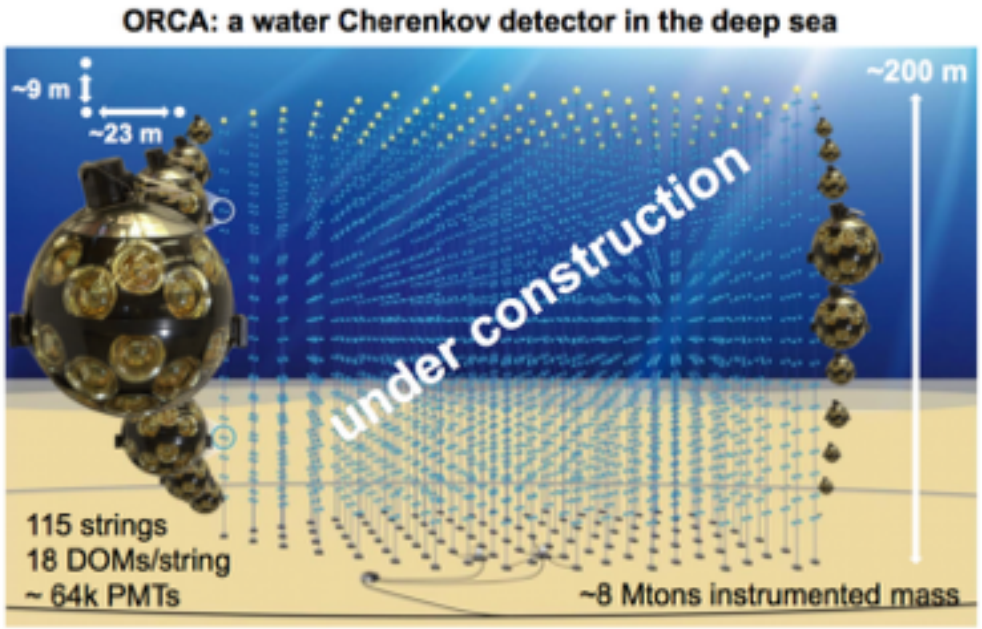
- Using CC+NC as signal

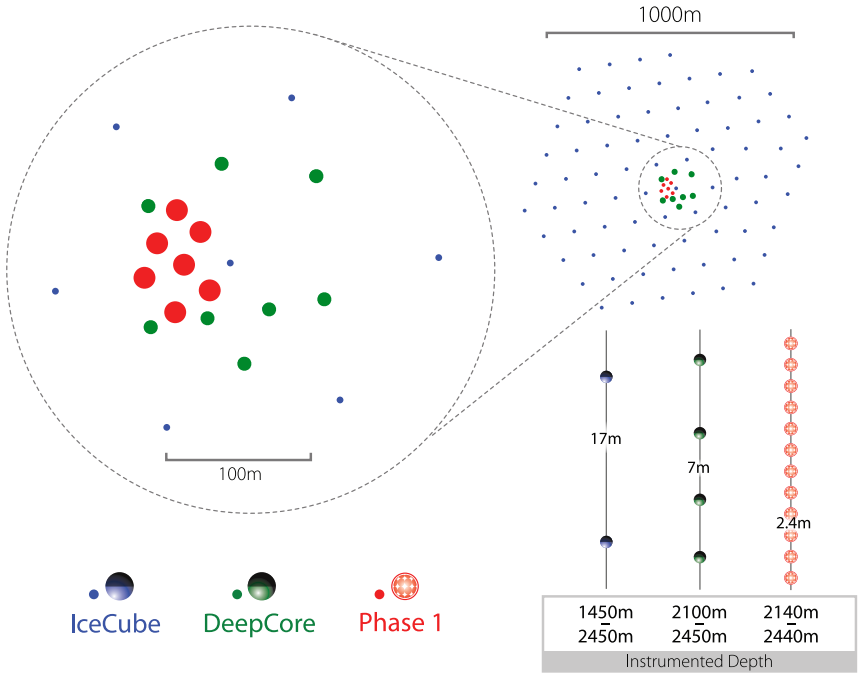
$$N_\tau^{NC+CC} = 0.73^{+0.31}_{-0.24}$$

- Consistent results from both analyses
- First results with $N_\tau < 1$
- Results consistent with unitary oscillations, cross section, ect



Future Analyses





- Mediterranean Neutrinos: ORCA
- New location
- Deployed: 7 strings
- Expected 115 strings by ~2020

- South Pole Neutrinos: IceCube-Upgrade
- Built inside DeepCore
- Just funded!
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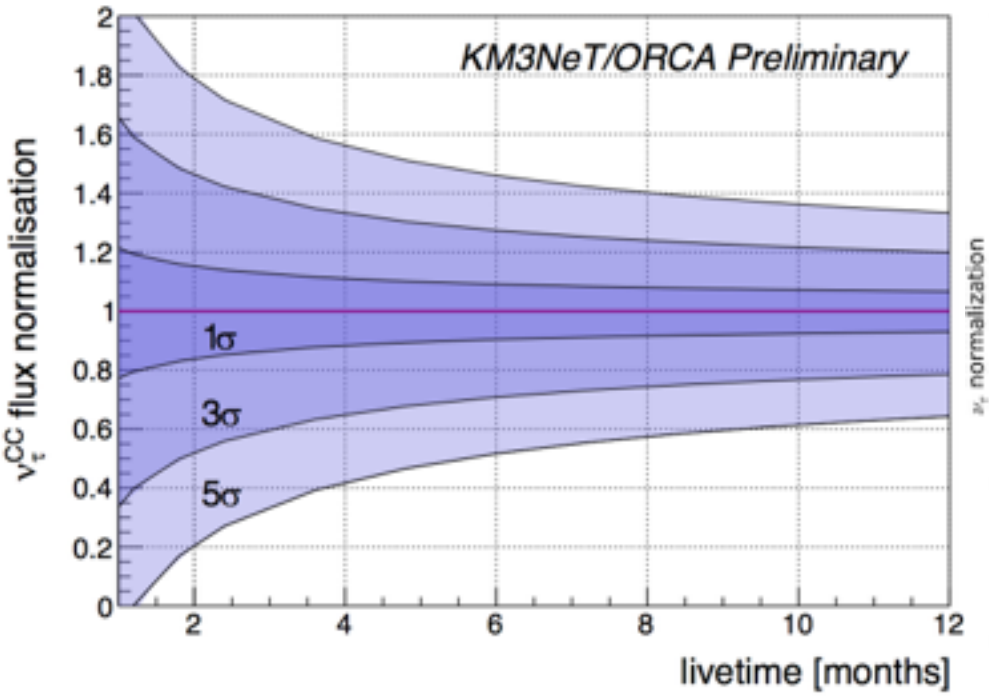
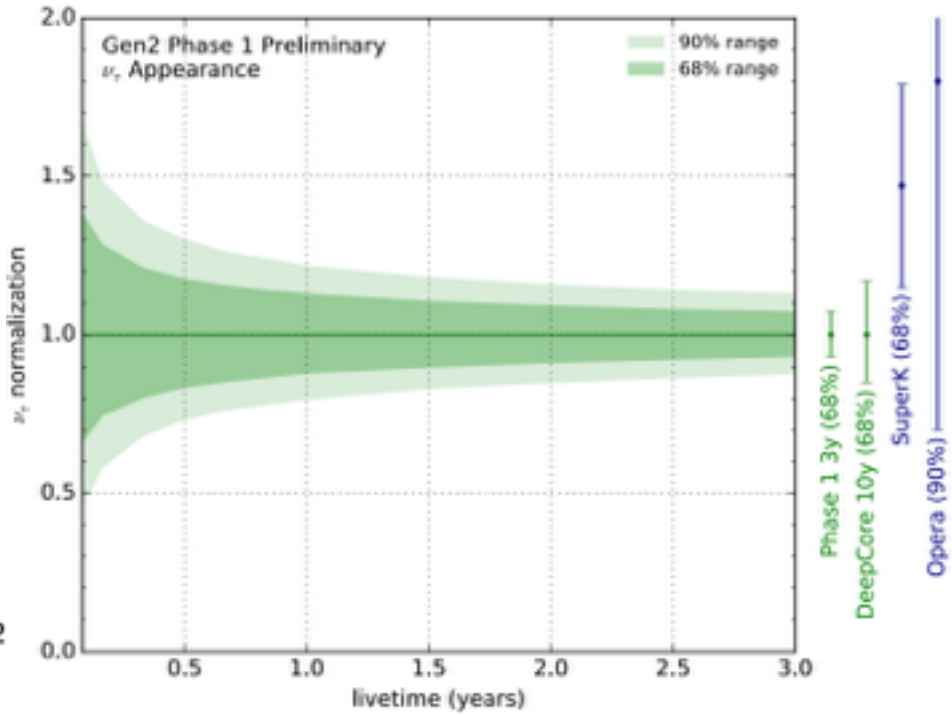
Future Analyses





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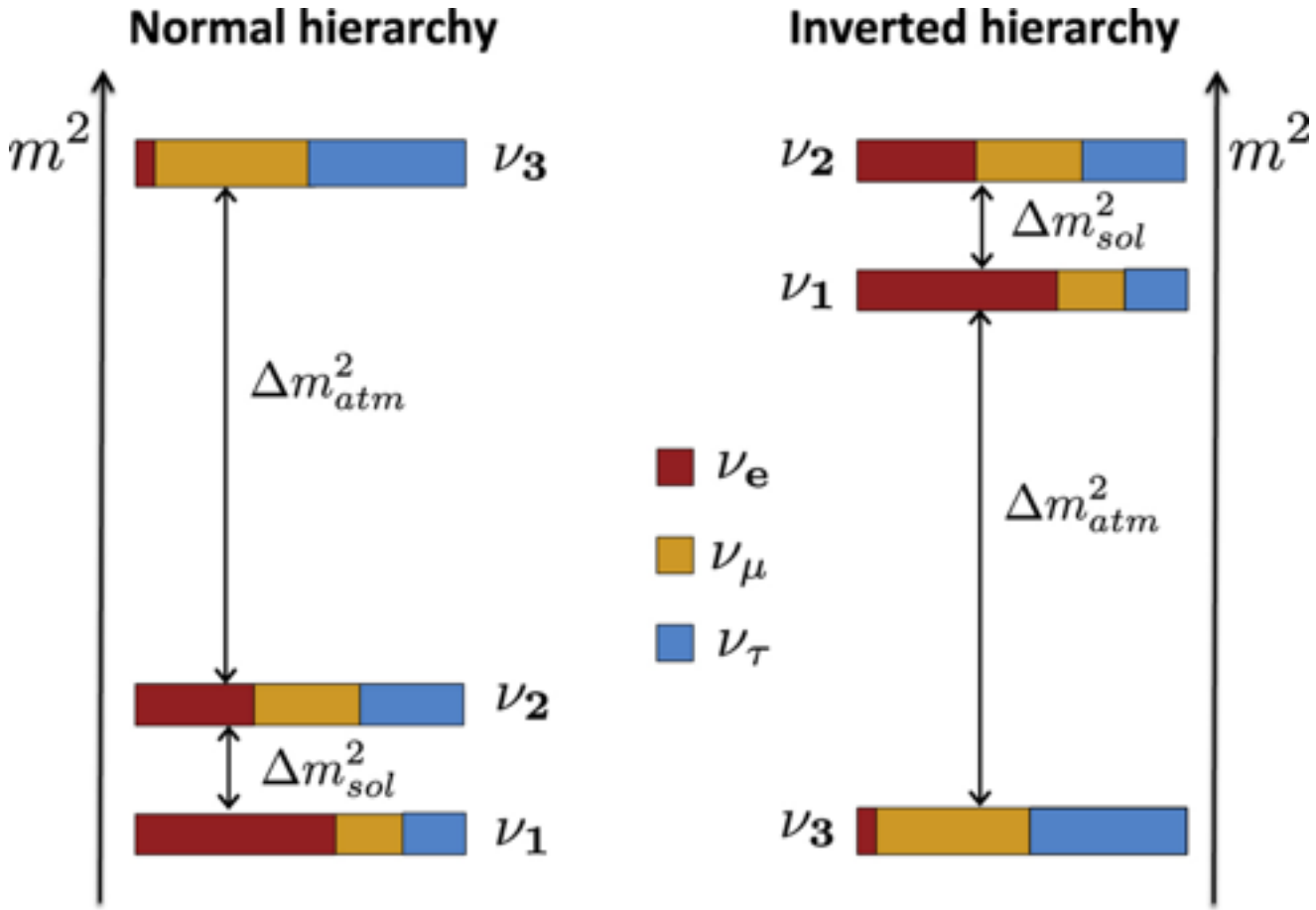
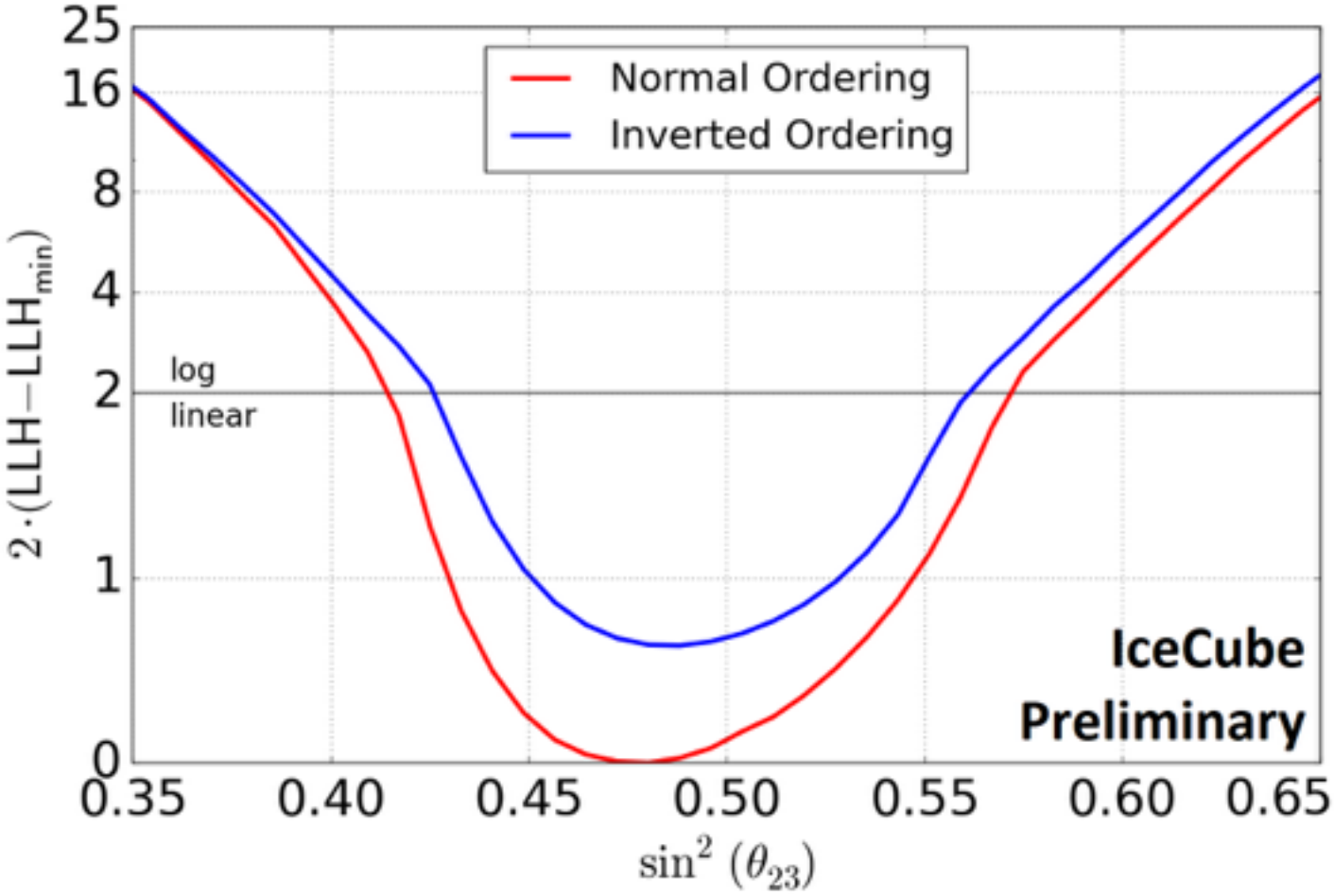
The End

Backup Slides

Neutrino Mass Ordering



Neutrino Mass Ordering with GRECO

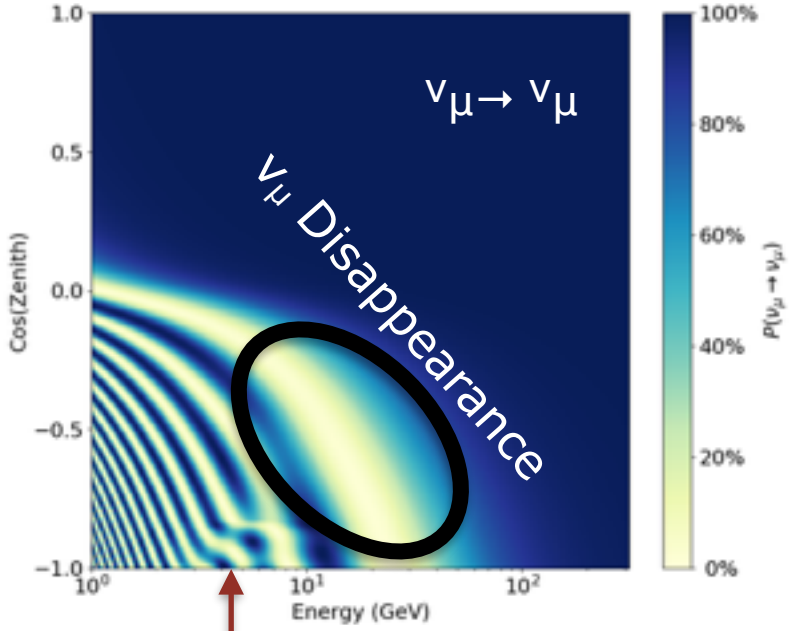


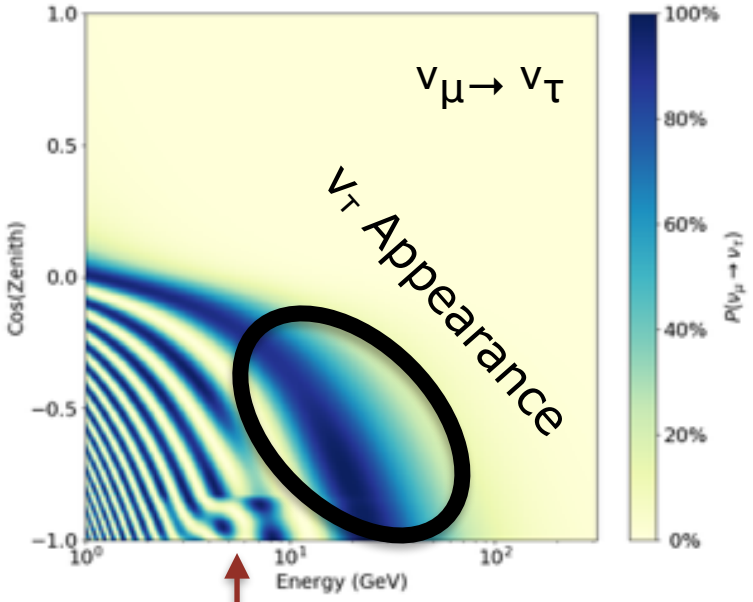
Why Measure Tau Neutrinos?

- **Approximately** parametrized in terms of mixing angles and mass splittings

$$P\left(\nu_\mu \to \nu_\mu\right) \approx 1 - \sin^2 2\theta_{23}\, sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

$$P\left(\nu_\mu \to \nu_\tau\right) \approx \sin^2 2\theta_{23}\, sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$





Matter effects in Earth's core

Why Measure Tau Neutrinos?

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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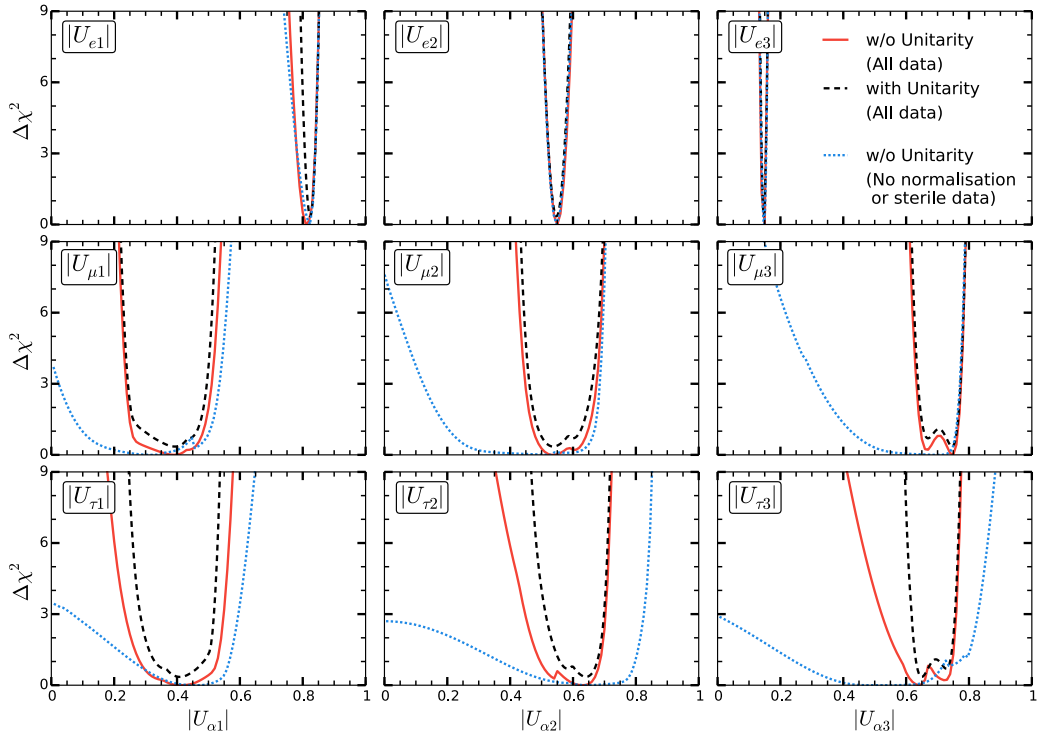
Parke and Ross-Lonergan,
Phys. Rev. D 93, 113009 (2016)



- Strong experimental constraints on ν_e and ν_μ terms
- Large uncertainties on ν_τ related terms

Why Measure Tau Neutrinos?

Atmospheric ν_μ Disappearance

$$P\left(\nu_\mu \to \nu_\mu\right) = 1 - \left| \sum_i U^*_{\mu i} U_{\mu i} e^{-i m_i^2 L/2E} \right|^2$$

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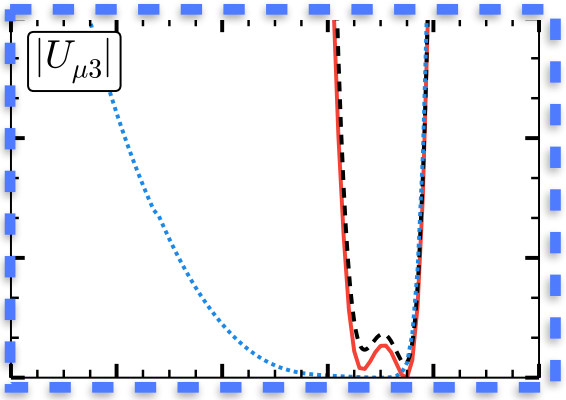

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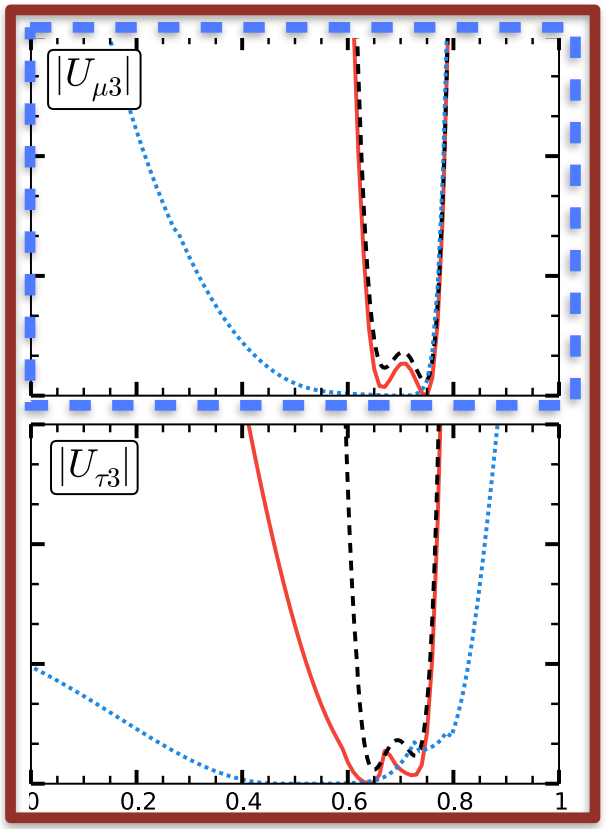
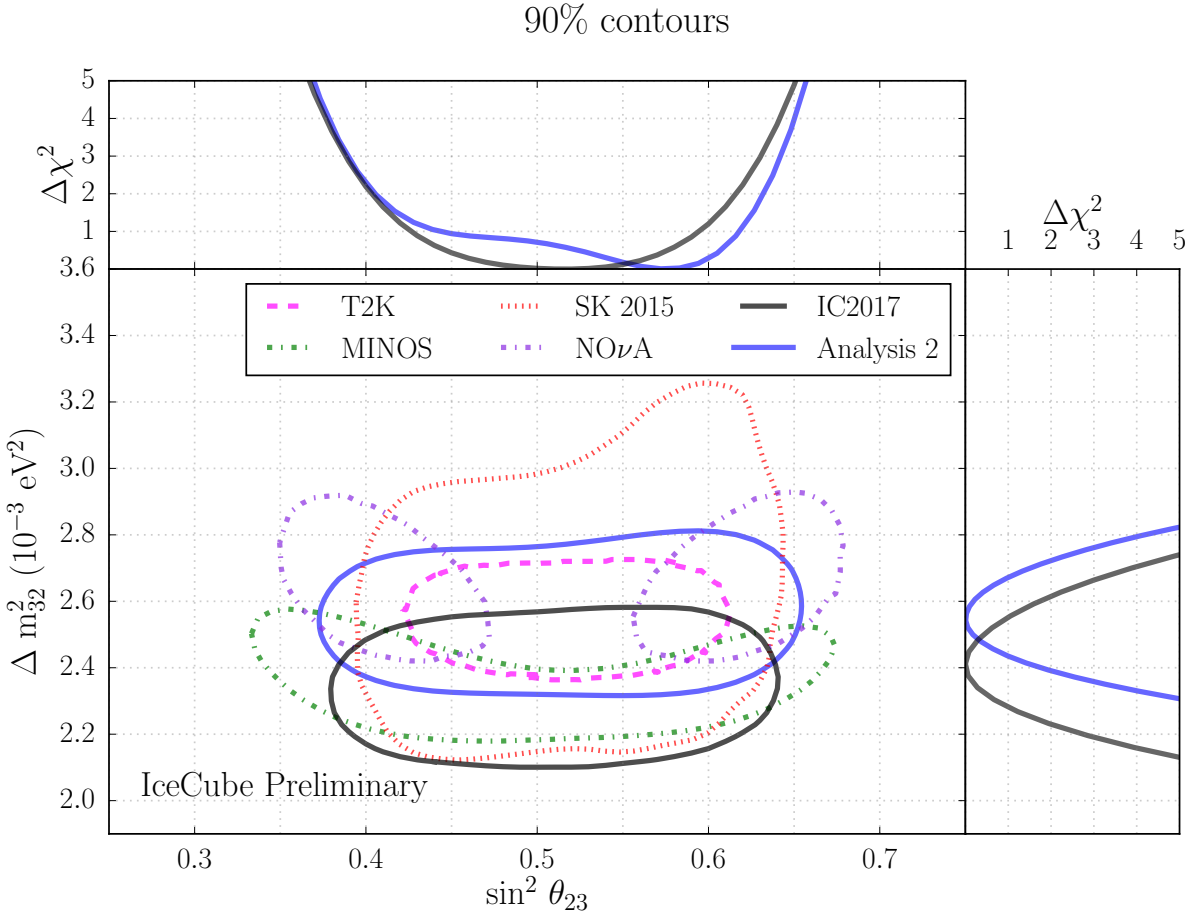


- Appearance and disappearance are sensitive to different elements
  - Appearance depends on multiple elements
  - Measure both simultaneously in full 3-flavor framework

Disappearance with the New Sample

- Disappearance also fit with new selection
- Improved sensitivity over published result
- Details at Neutrino 2018
- Results in good agreement with other experiments
- First DeepCore results off maximal mixing



Tau Appearance Results from DeepCore

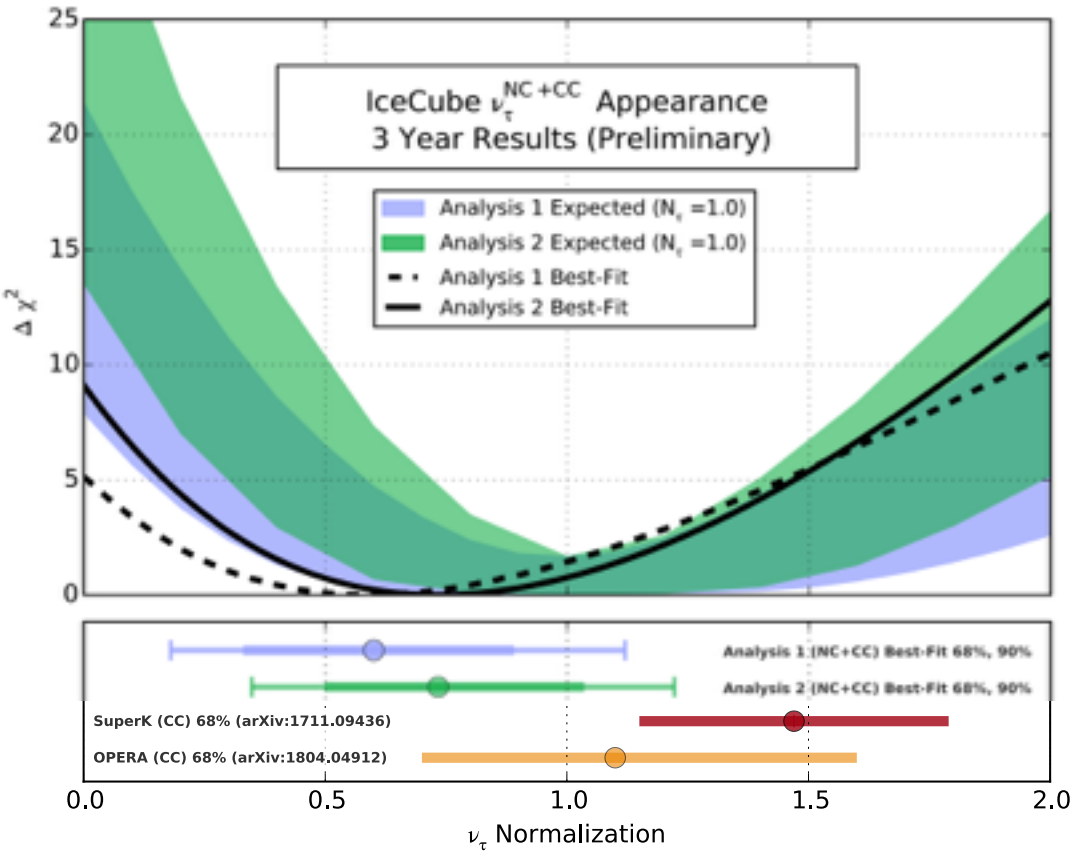
- Analysis 1:

$$N_\tau^{NC+CC} = 0.58^{+0.31}_{-0.25}$$

- GRECO (This work):

$$N_\tau^{NC+CC} = 0.73^{+0.31}_{-0.24}$$

- Consistent results from both analyses
- First results with $N_\tau < 1$
- Results consistent with unitary oscillations, cross section, ect



CC-Only Results

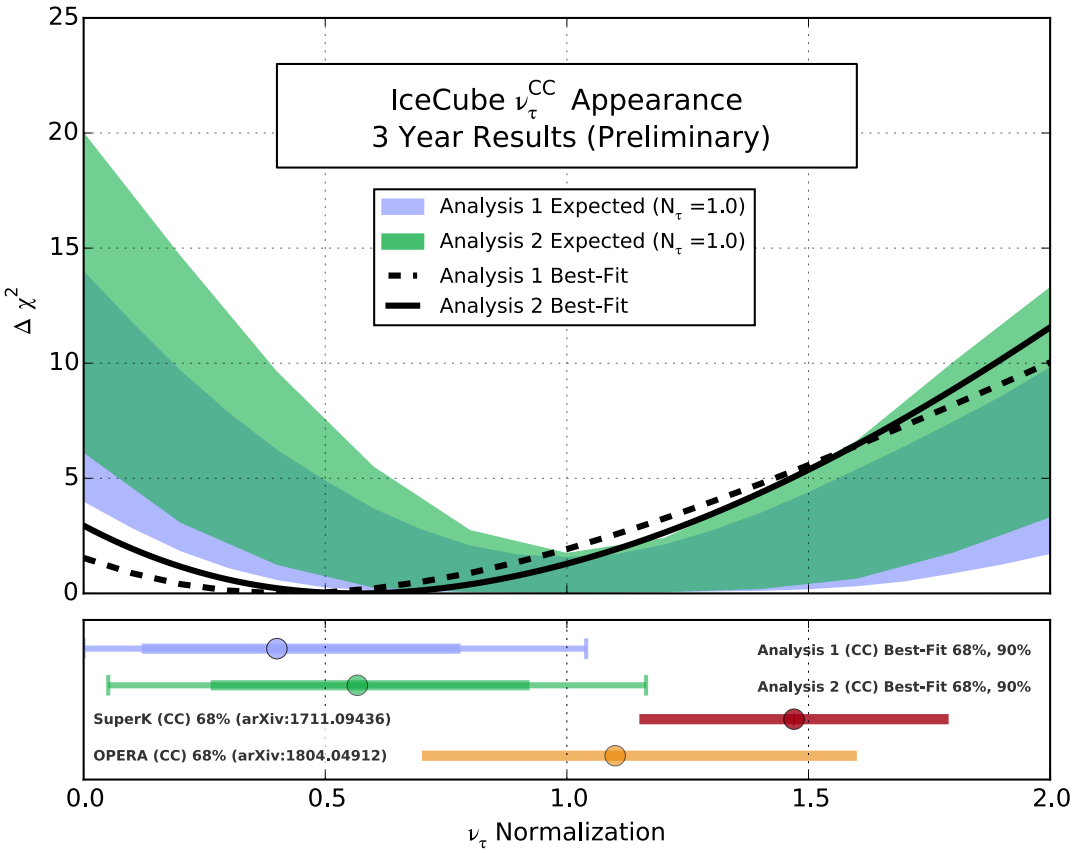
- Weaker sensitivity than NC+CC
- Analysis 1:

$$N_\tau^{CC} = 0.43^{+0.35}_{-0.31}$$

- GRECO (This work):

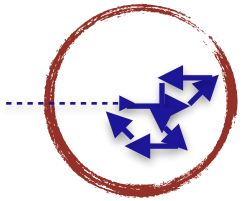
$$N_\tau^{CC} = 0.57^{+0.36}_{-0.30}$$

- Consistent results from both analyses
- Results consistent with unitary oscillations

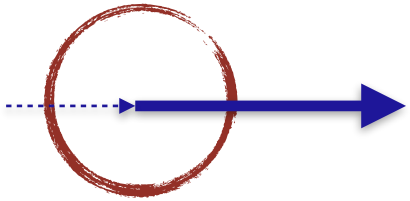


Reconstructing Events in DeepCore

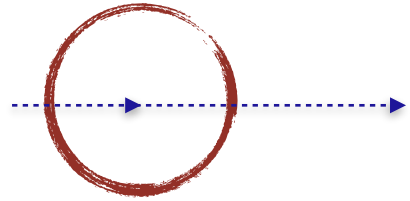
$$\overset{(-)}{\nu}_e + X \rightarrow e^{\pm} + h$$



$$\overset{(-)}{\nu}_\mu + X \rightarrow \mu^{\pm} + h$$



$$\overset{(-)}{\nu} + X \rightarrow \overset{(-)}{\nu} + h$$

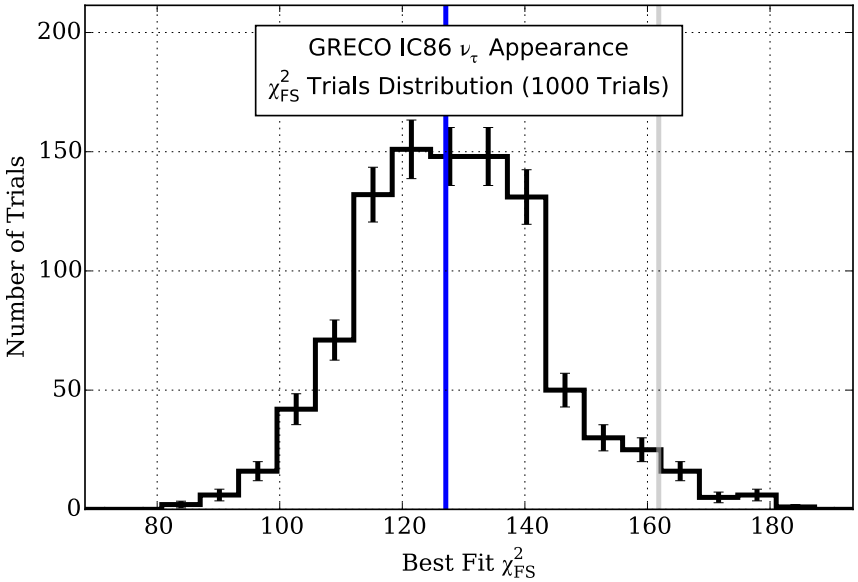


Atm. μ

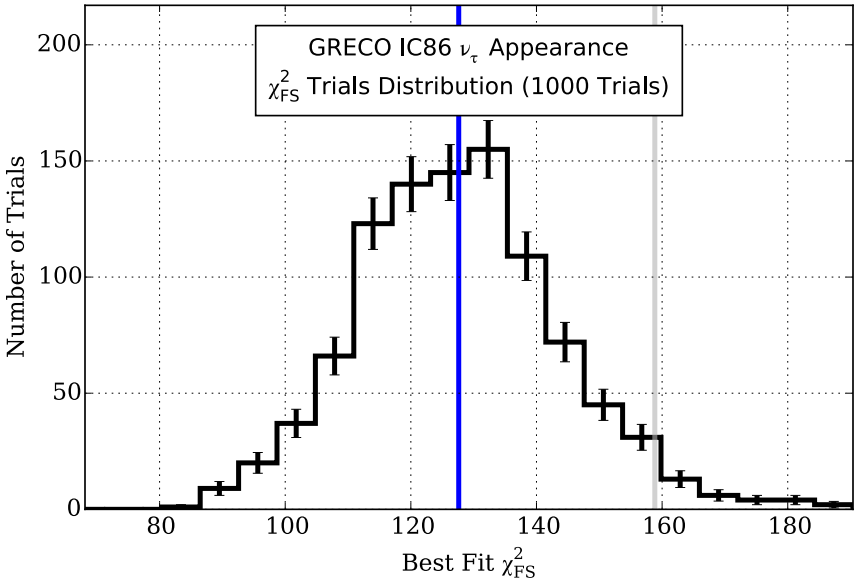
- All events can be broken down into:
  - Hadronic cascade from initial neutrino interaction (DIS)
  - Electromagnetic cascade from resulting free electrons
  - Muon "track" from muon Cherenkov light
- Stochastic losses not important at these energies
- "Pegleg" event reconstruction fits a hadronic cascade + muon track to all events

Goodness-of-fit

CC-Only



NC+CC

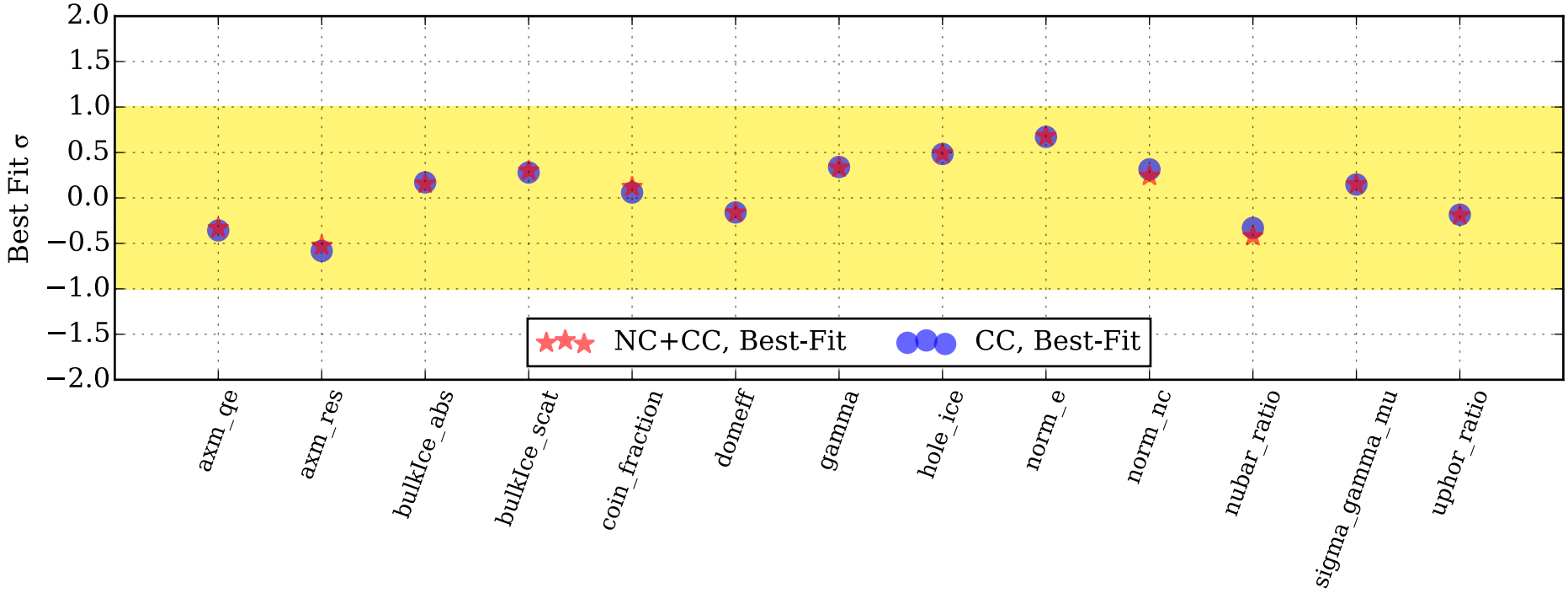


Best Fit

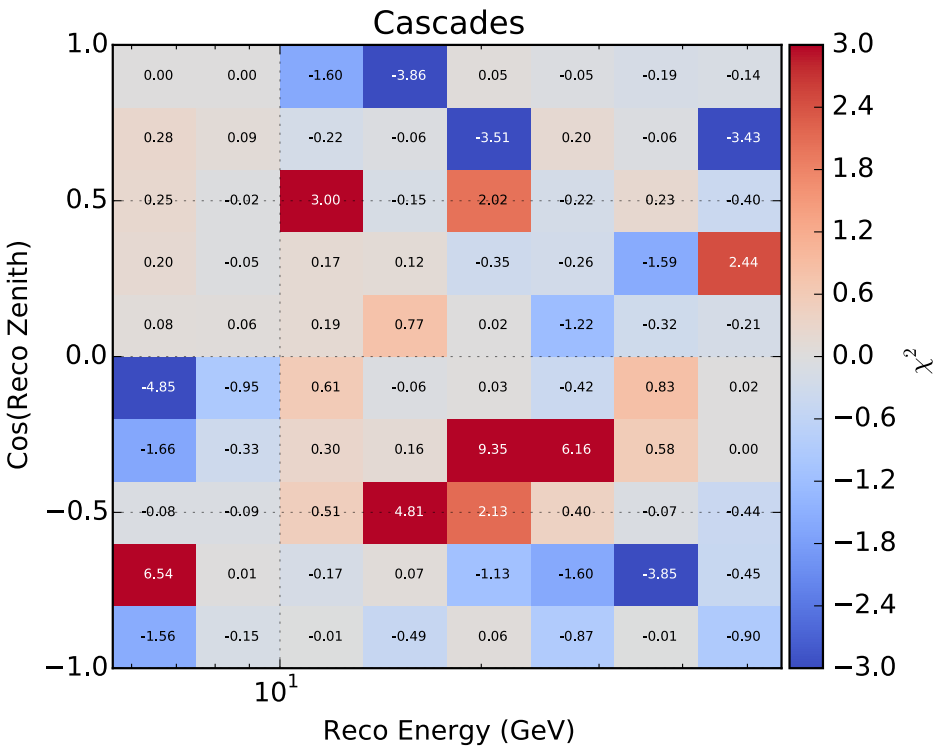
p=5%

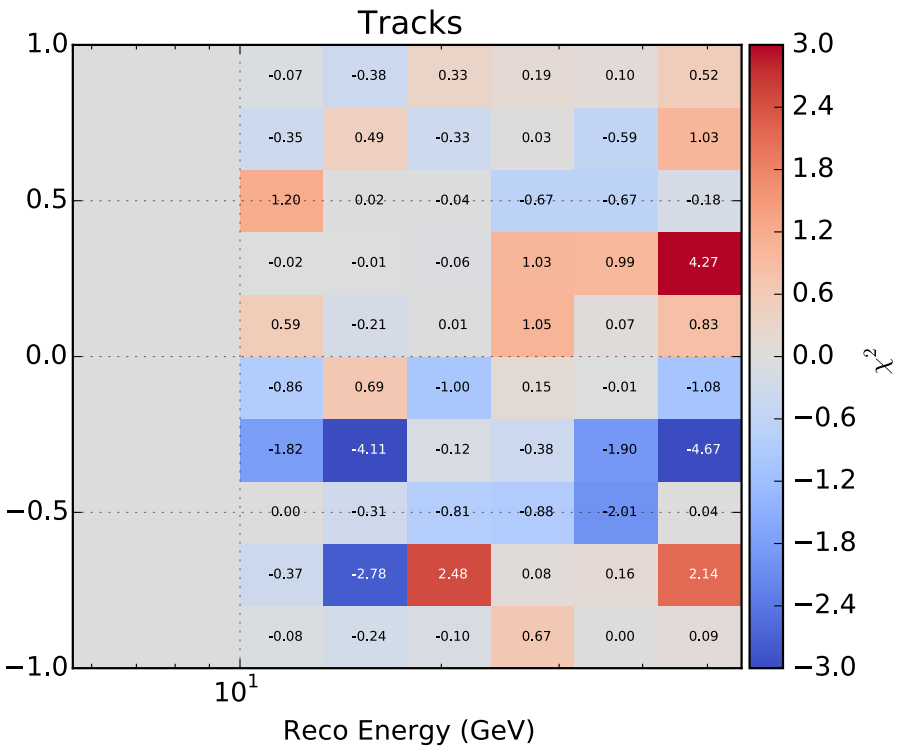
1000 Randomized Trials

Systematics with Priors

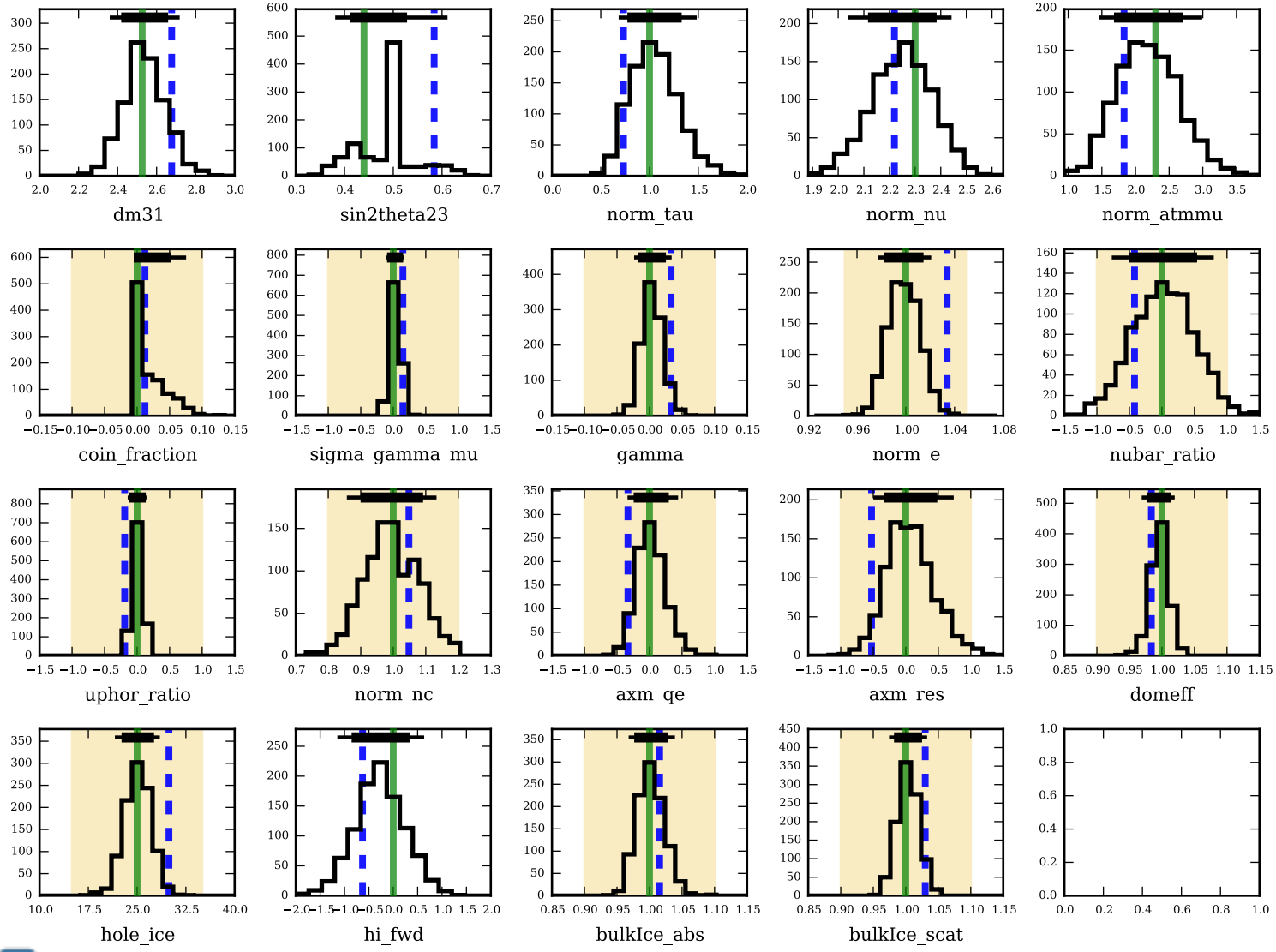


Best-Fit χ2 Maps (NC+CC)

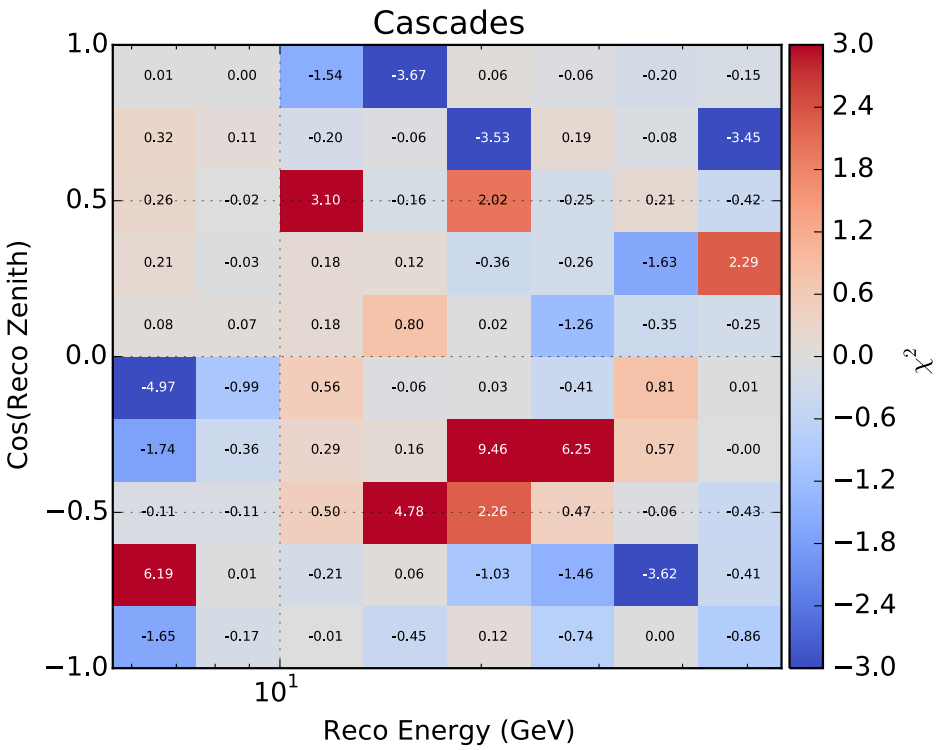


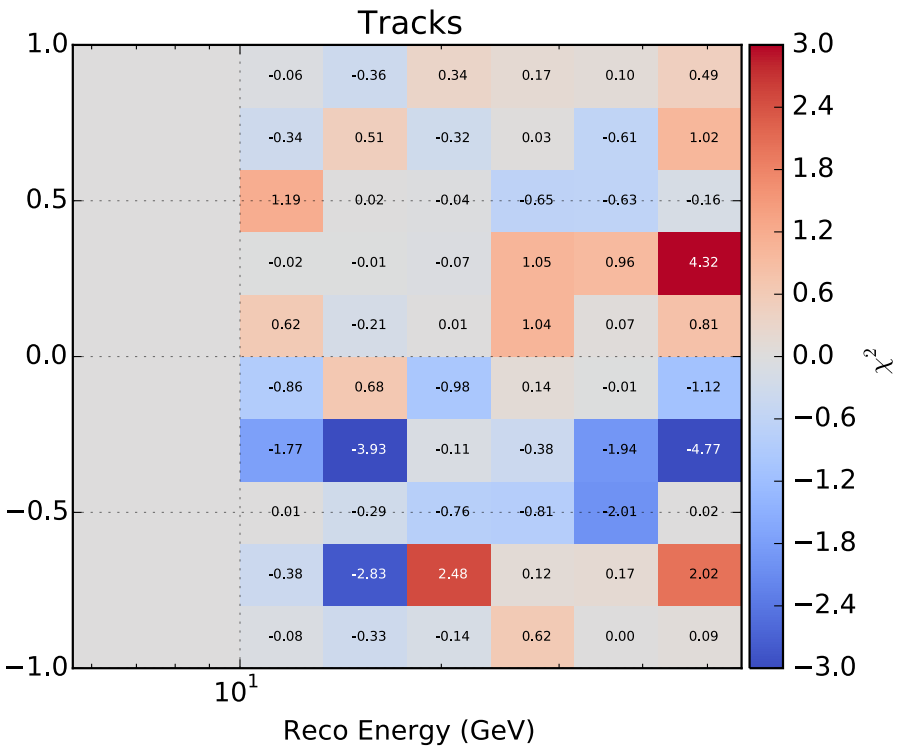


Systematics Values (NC+CC)



Best-Fit χ2 Maps (CC)





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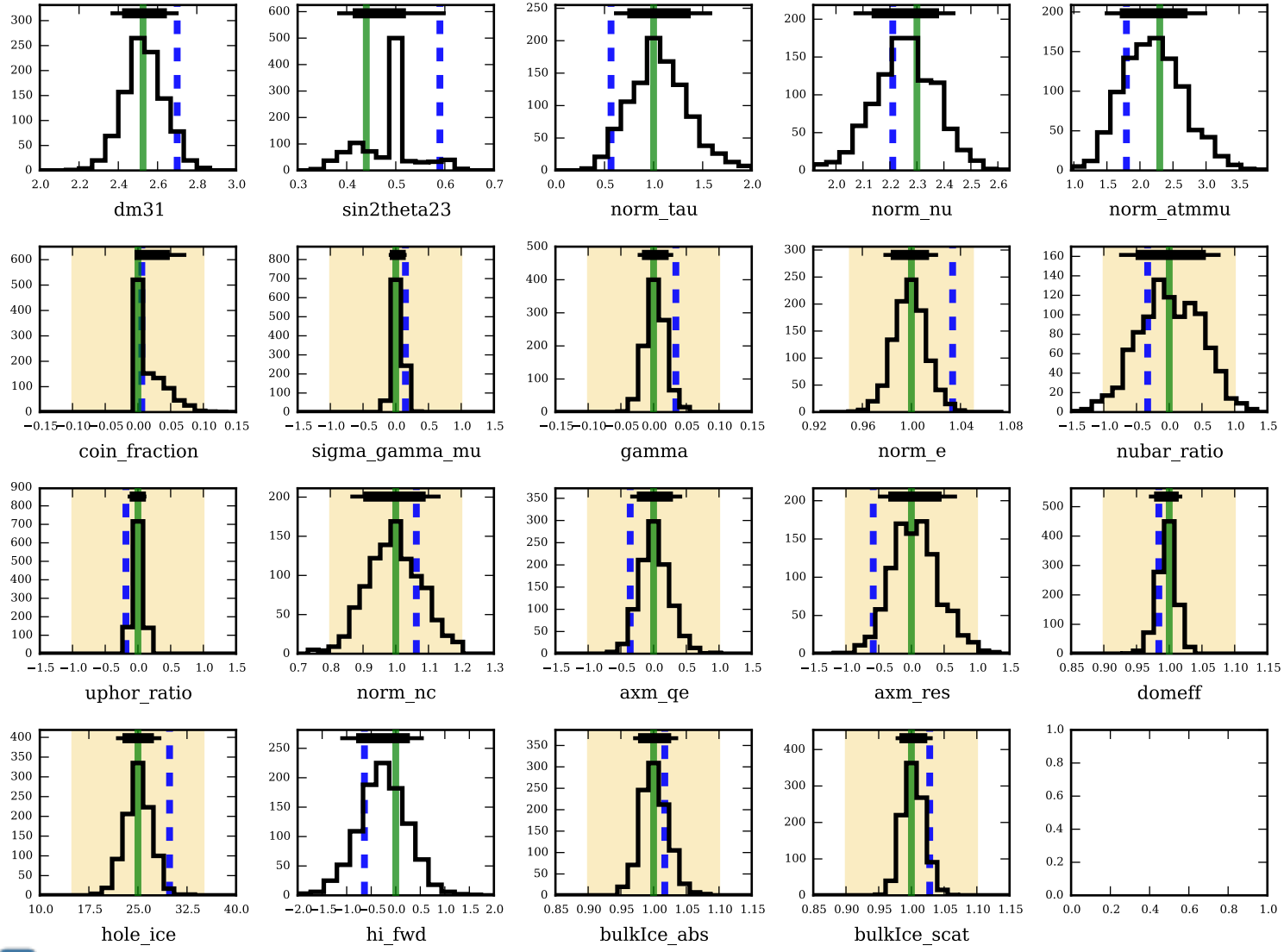
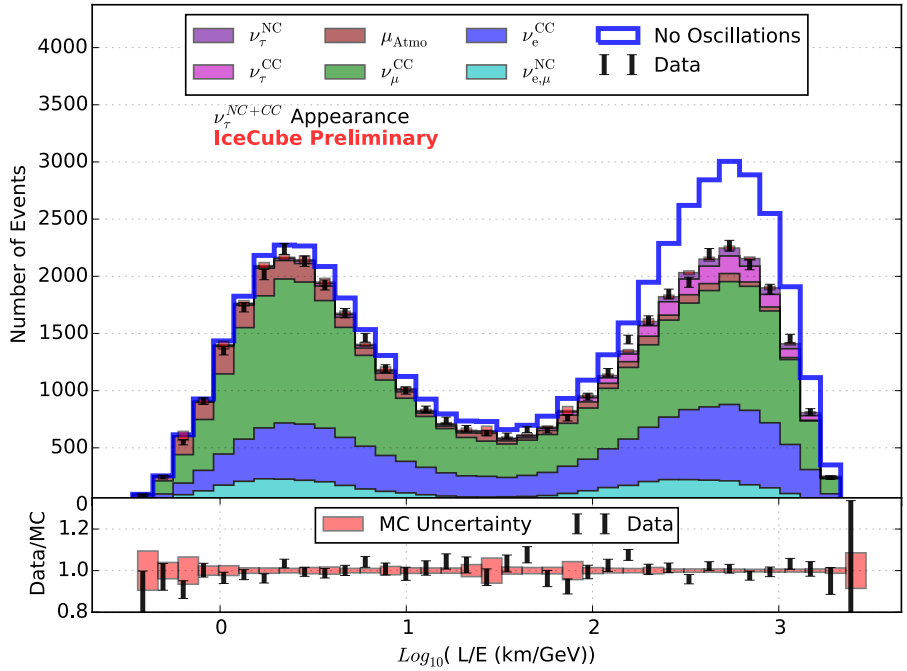
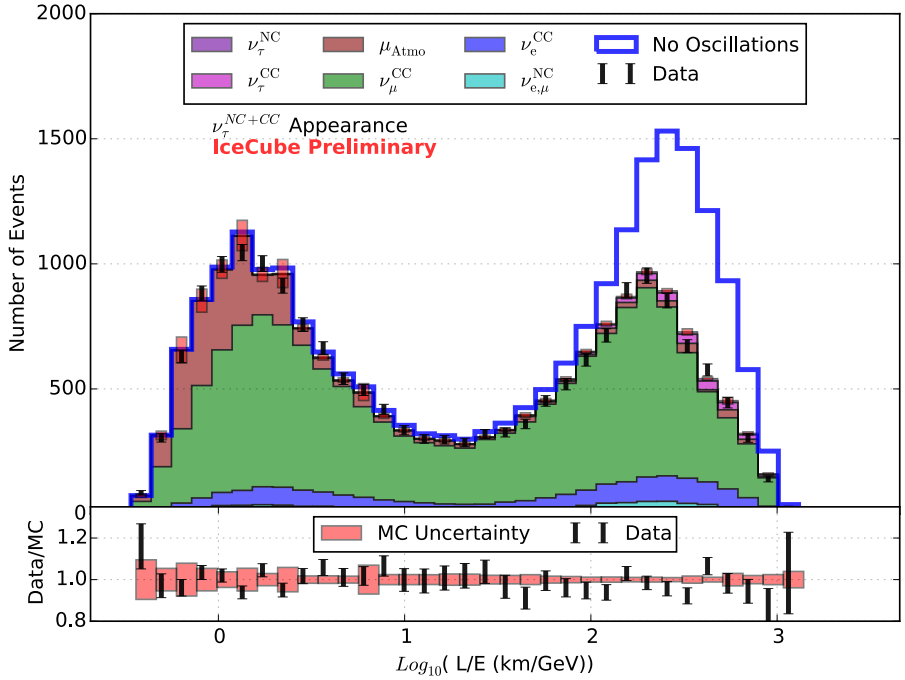


Good Data/MC Agreement

Cascade-like



Track-like



- Good agreement in both cascade-like and track-like events
- Clear appearance effect in cascade-like histogram