The Search for Tau Neutrinos Using Waveforms

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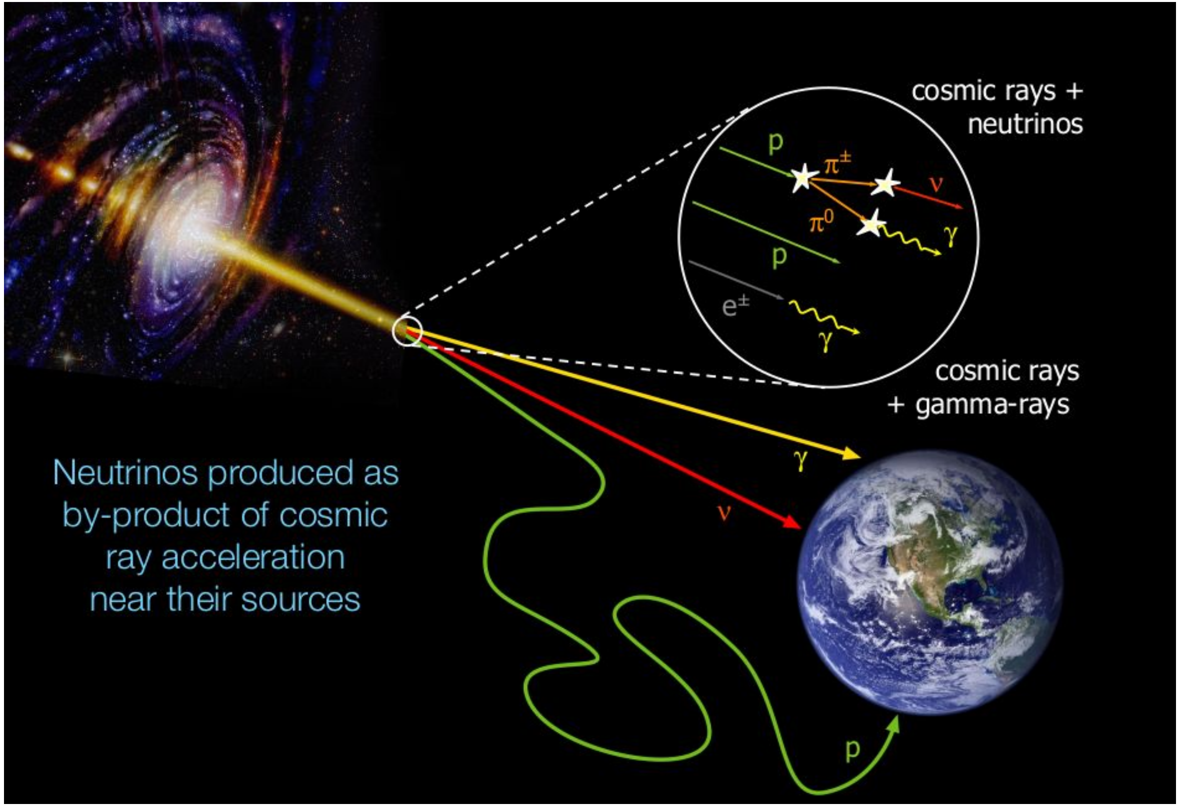
For the IceCube Collaboration
07/31/19

See also:
NU8f and PS1-117

Astrophysical Tau Neutrinos



Tau Neutrinos at Production

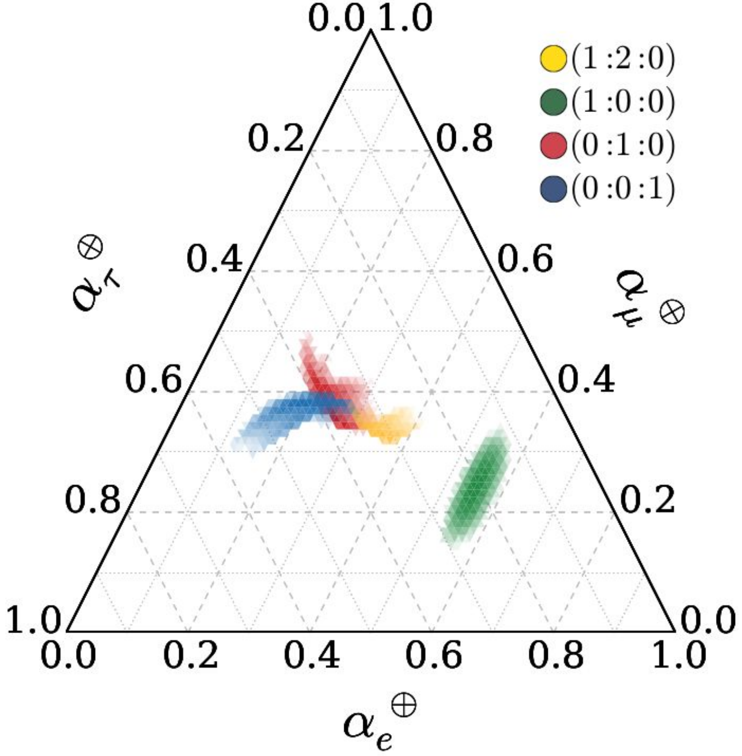
$$p + p \rightarrow \pi^+ + X$$

$$\hookrightarrow \mu^+ + \nu_\mu$$

$$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

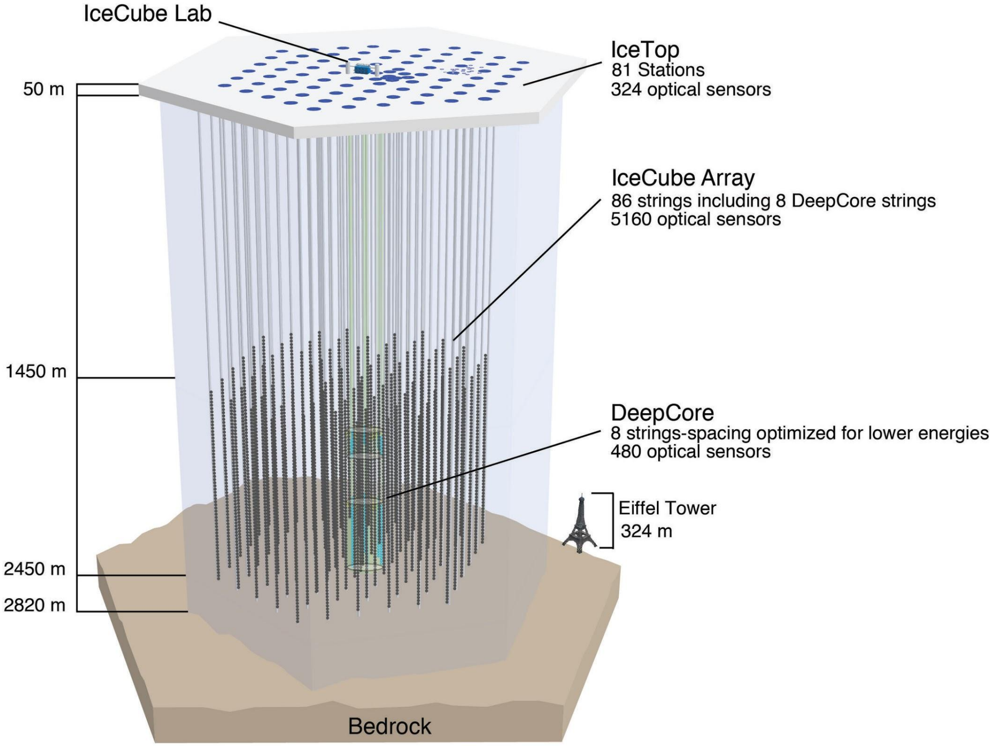
1:2:0

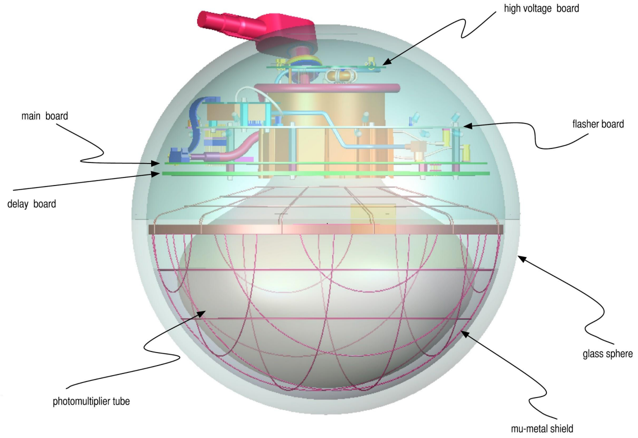
Flavor Ratio



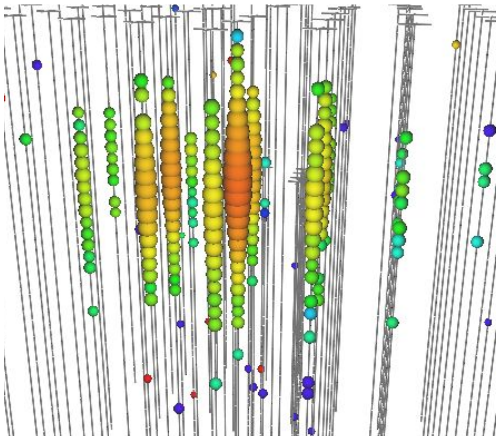
Argüelles et. al. Phys. Rev. Lett., 115:161303

IceCube

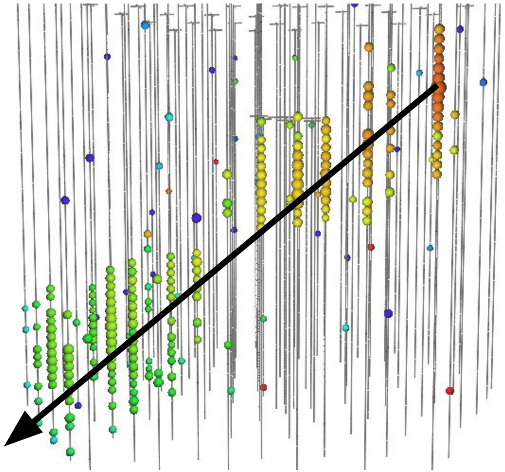

IceCube Lab
50 m
1450 m
2450 m
2820 m
IceTop
81 Stations
324 optical sensors
IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors
DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors
Eiffel Tower
324 m
Bedrock


high voltage board
main board
flasher board
delay board
glass sphere
photomultiplier tube
mu-metal shield

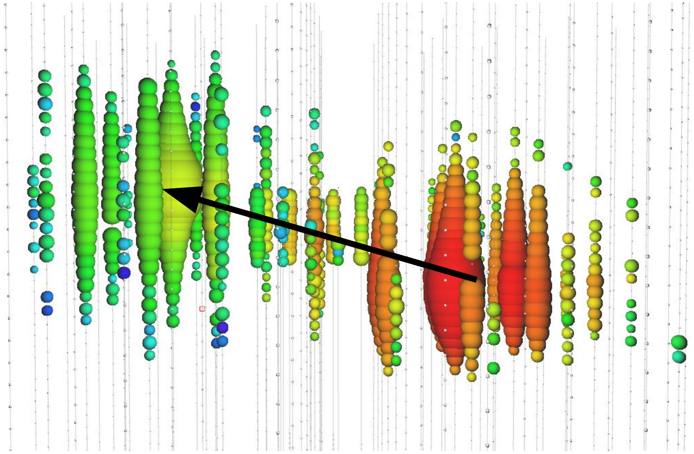
Events in IceCube



Cascade

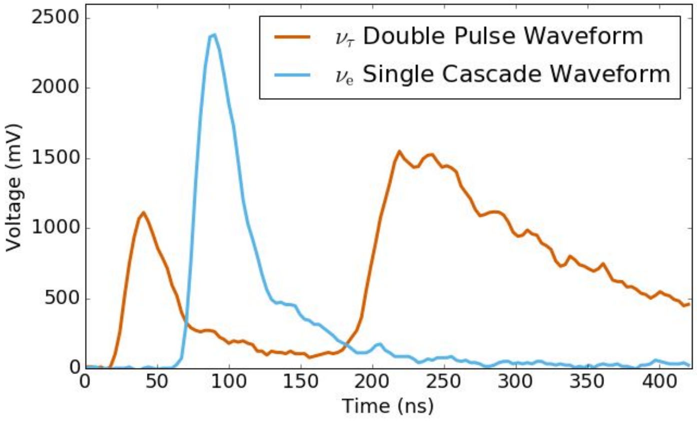


Track

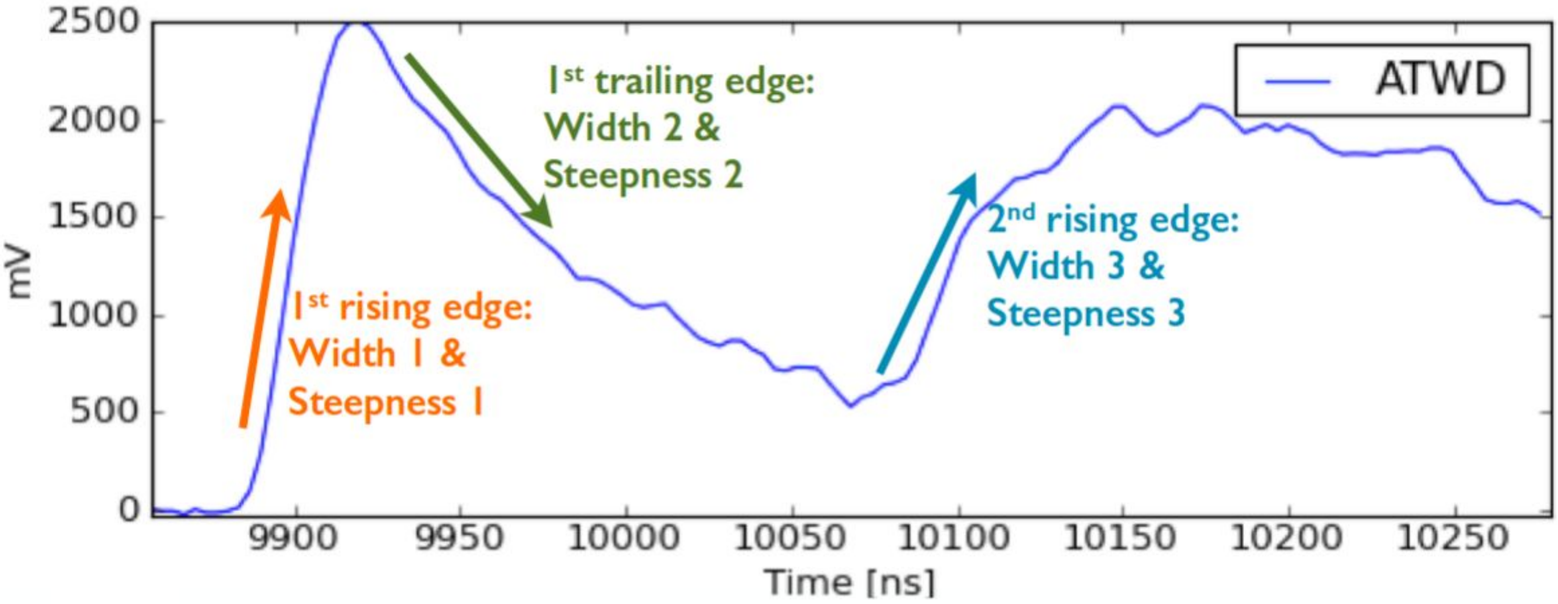


Double Cascade

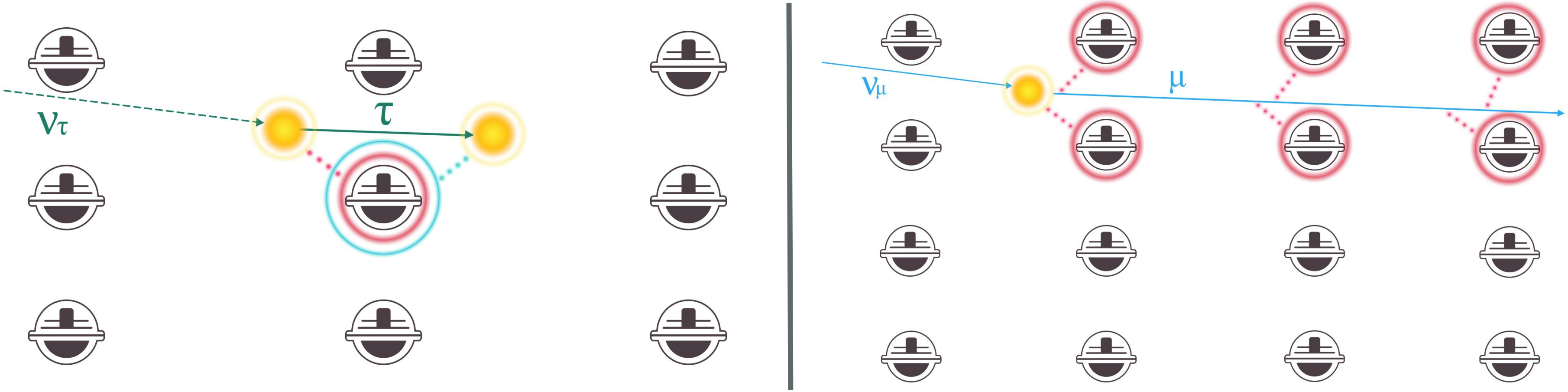
Tau Double Pulse Events



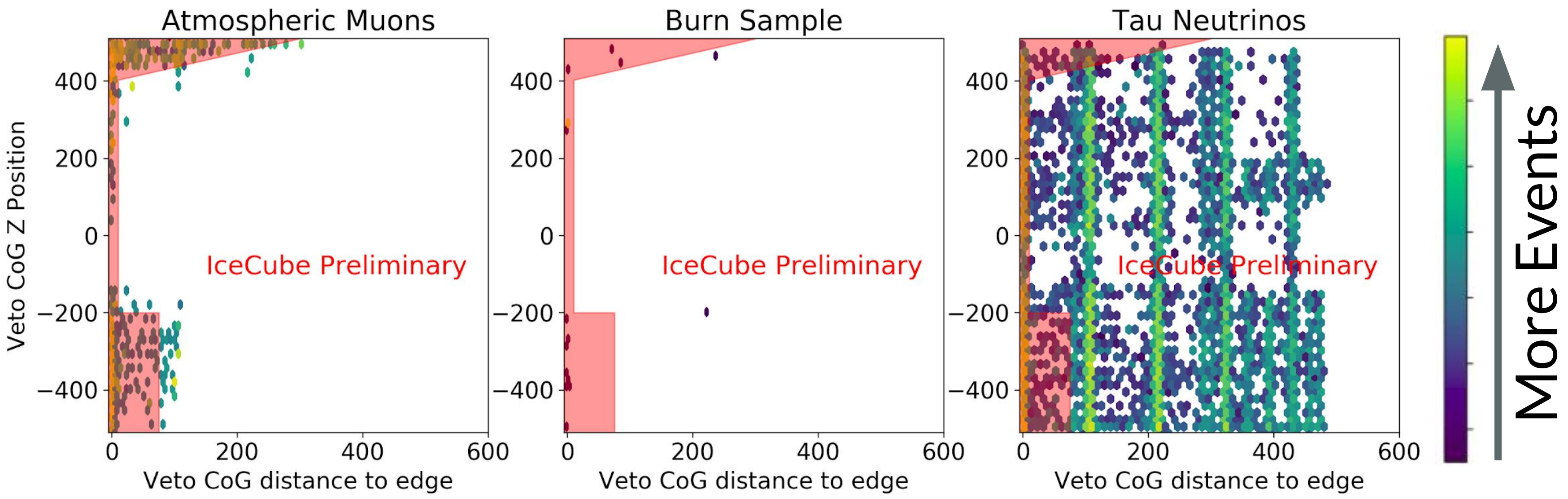
Double Pulse Algorithm (DPA)



Cascade vs Track



Geometric Cut

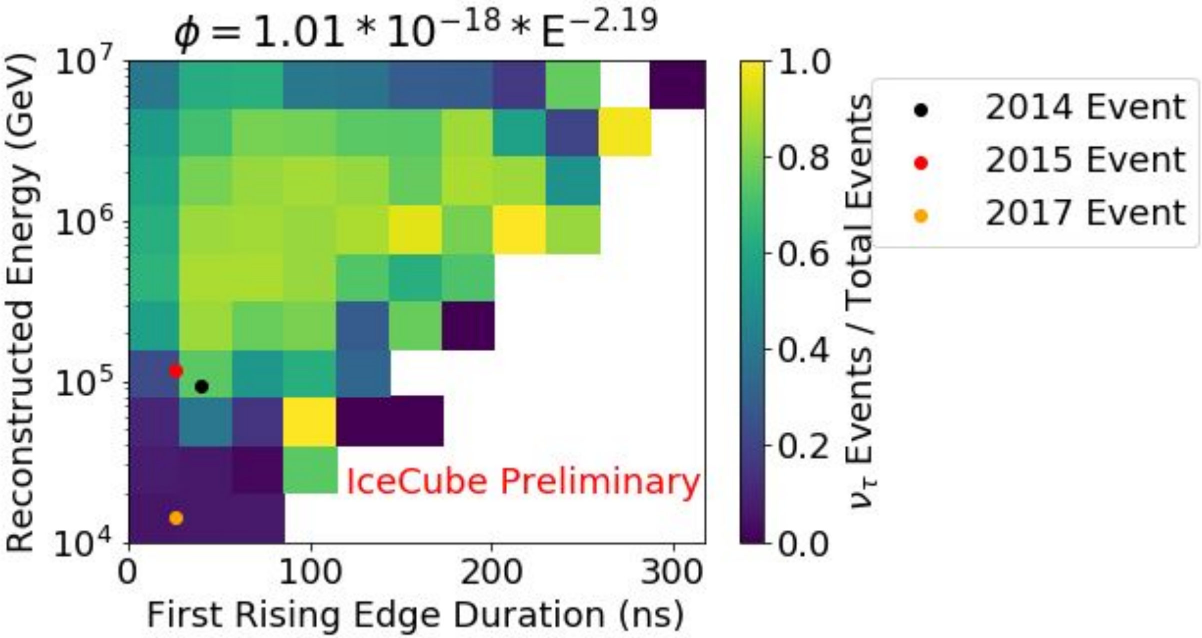


Expected Events and P-value

Rates in 8 Years	Final Sample
NuTau	1.72 +- 0.023
NuMu	0.95 +- 0.05
NuE	0.26 +- 0.01
Muons	0.2 +- 0.14

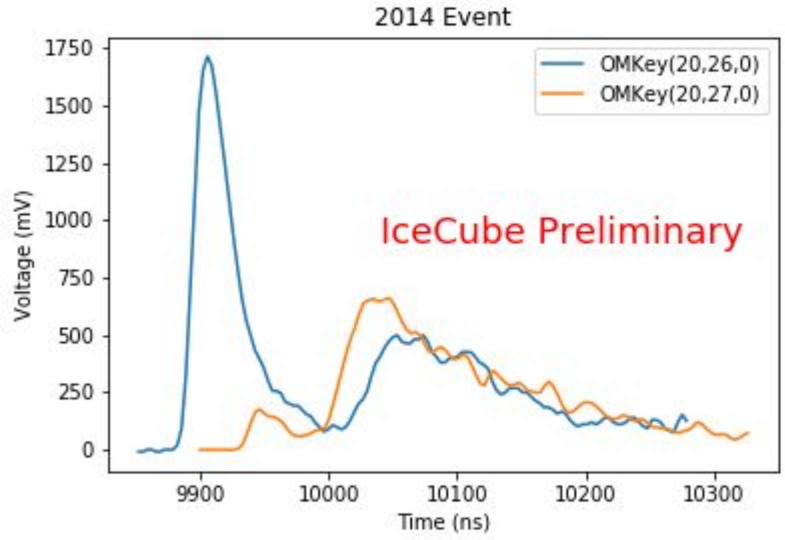
$$TS = Log(L(\lambda) / L(\lambda = 0))$$
$$L(\lambda) = (P_B + P_S \times \lambda)/(1 + \lambda)$$

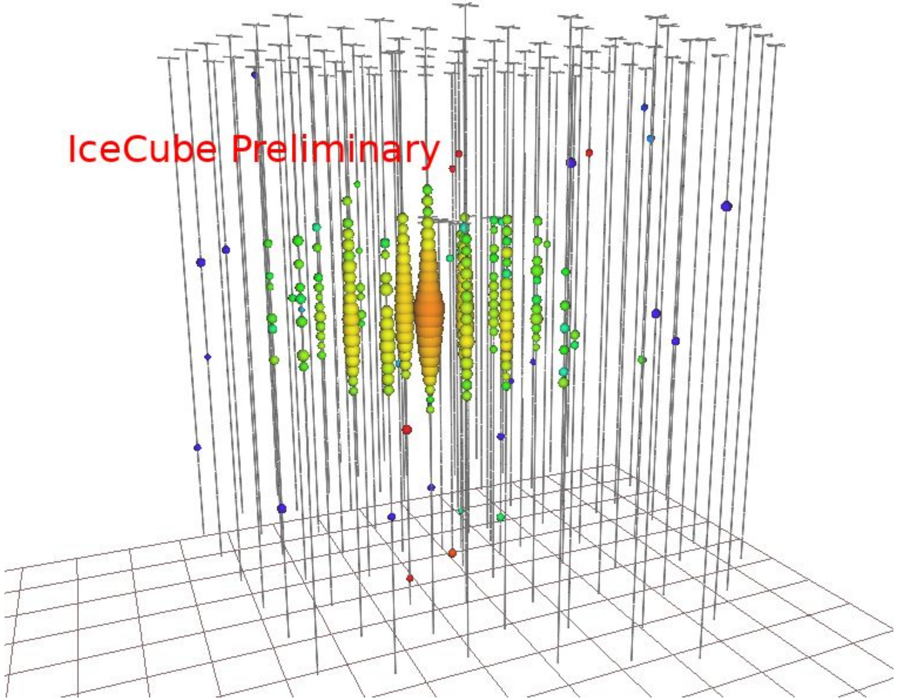
Event Sample



Event #1 (2014)

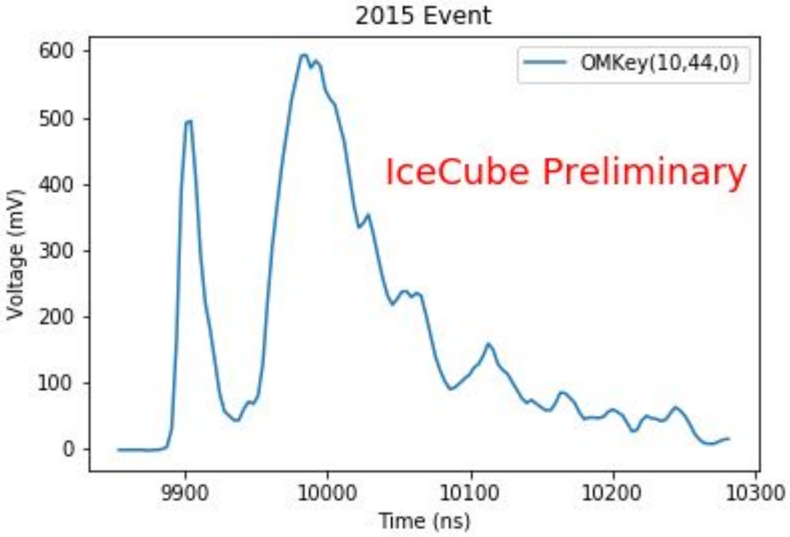
P-value: 0.196

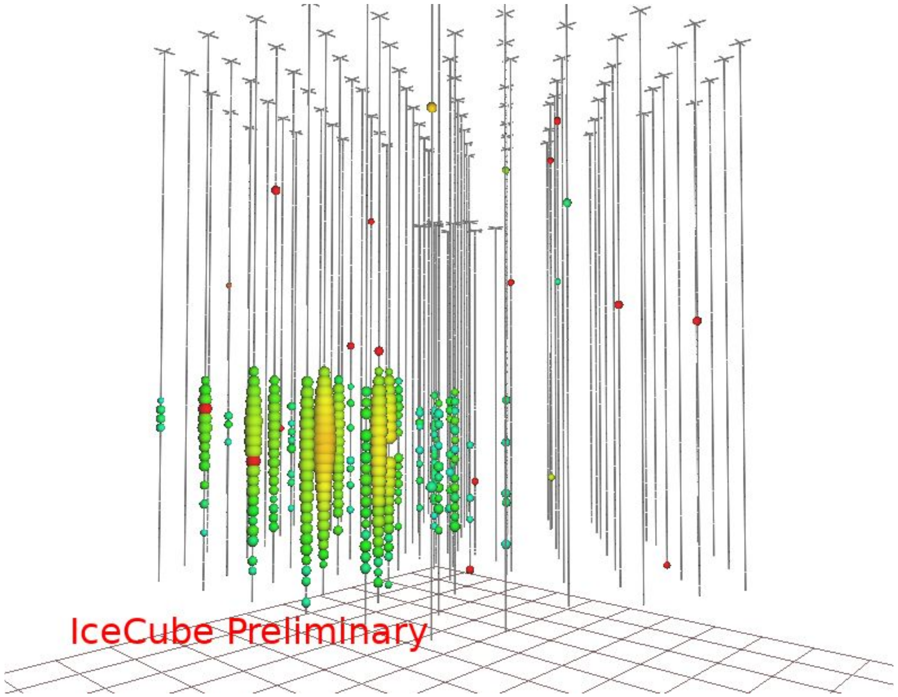




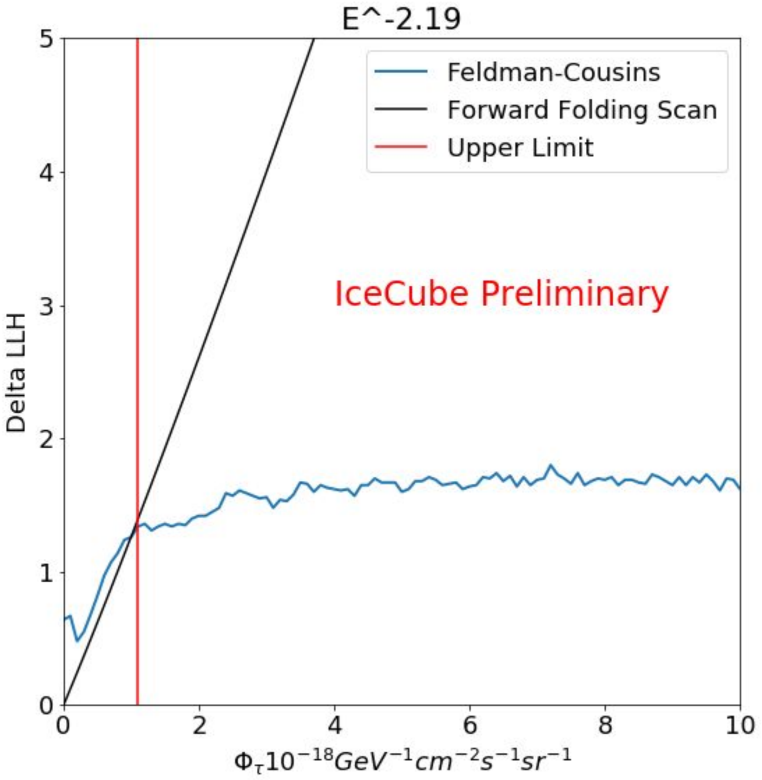
Event #2 (2015)

P-value: 1.0





Forward Folding Results



	90% UL flux
$E^{-2.19}$	**1.11×10^{-18}**
$E^{-2.5}$	**2.5×10^{-18}**
$E^{-2.9}$	**6.0×10^{-18}**

Conclusion

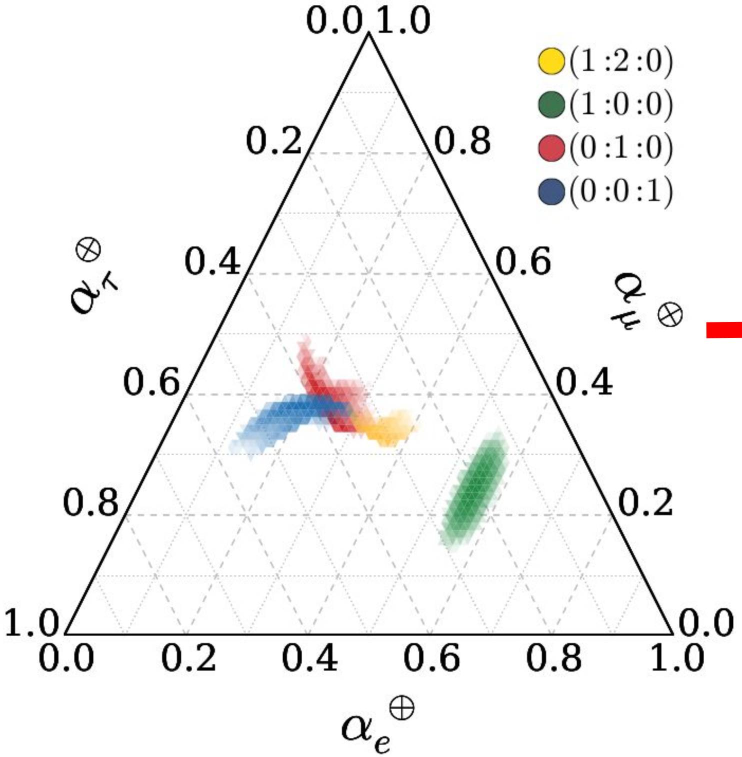
A search was performed on 8 years of data from the IceCube detector to find Tau neutrino events.

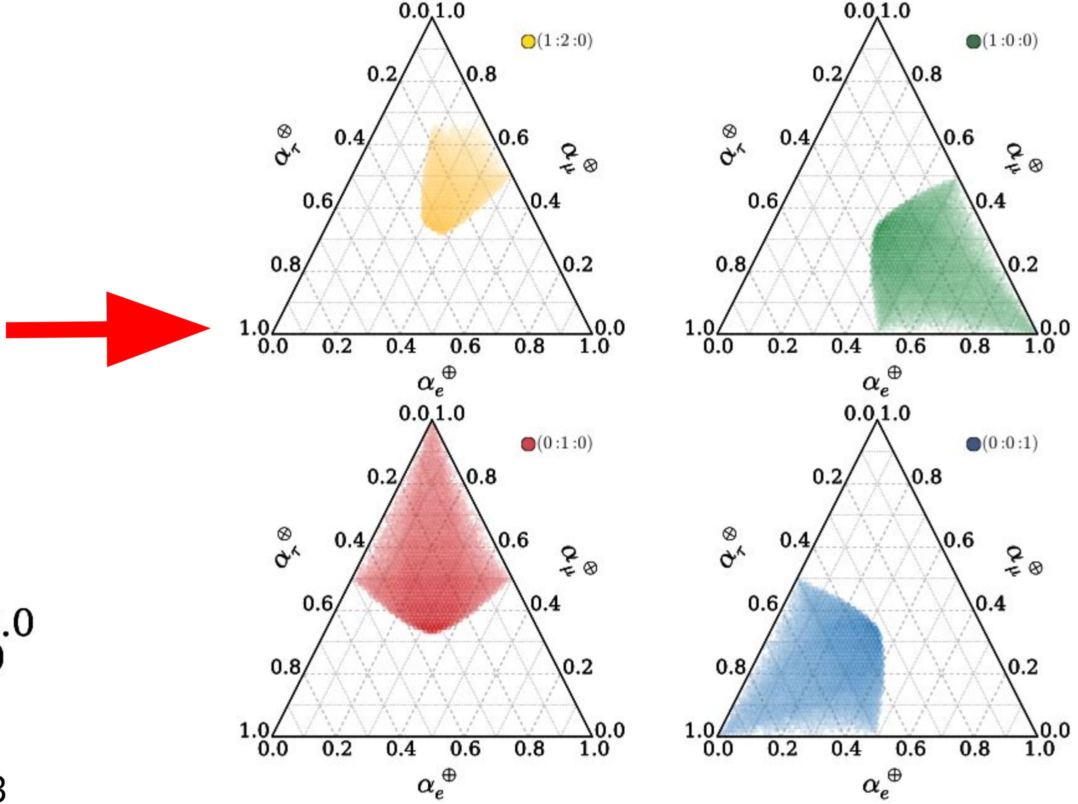
Two Events were observed, both of which appear to be neutrinos. However, neither of the events have significant p-values of being a tau neutrino.

A forward folding was applied to the event sample, a flux of zero tau neutrinos was the best fit. 90% upper limits were found that are not inconsistent with existing neutrino measured astrophysical fluxes.

Backup

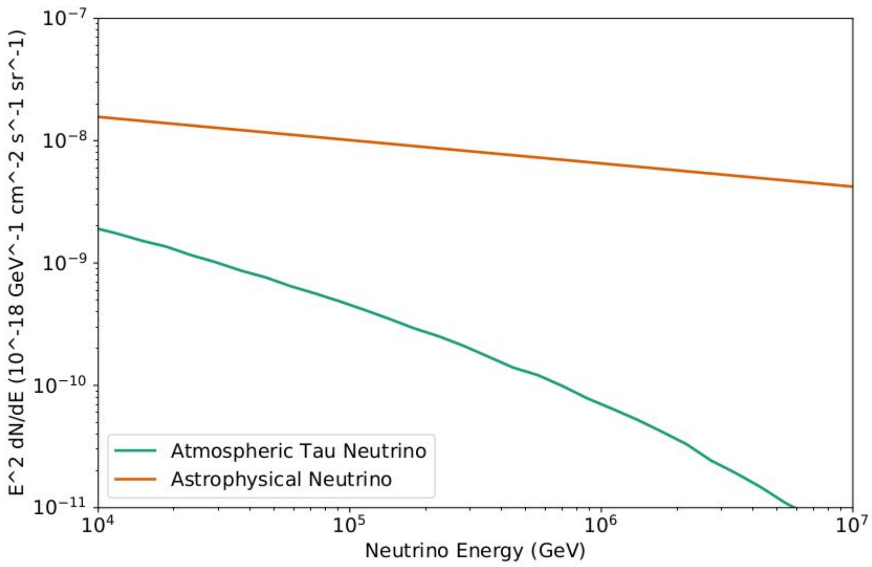
New Physics and the Flavor Ratio



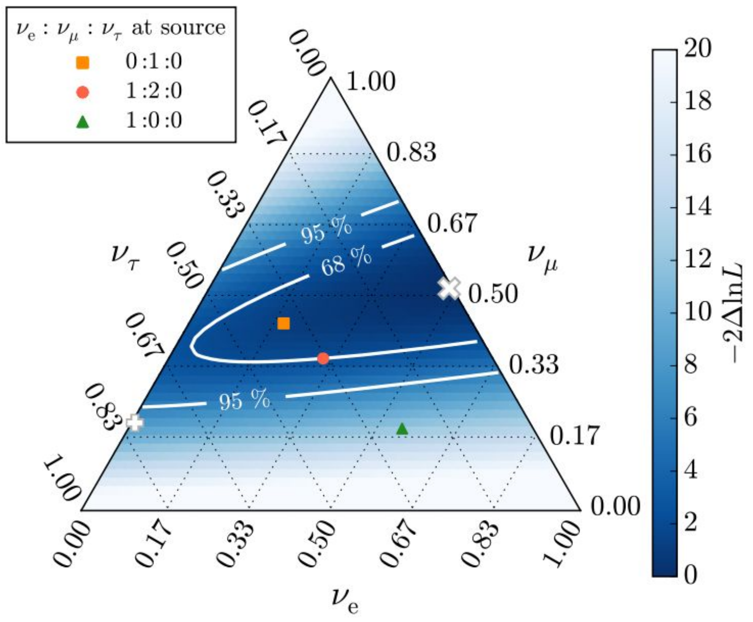


Argüelles et. al. Phys. Rev. Lett., 115:161303

Motivation of Analysis

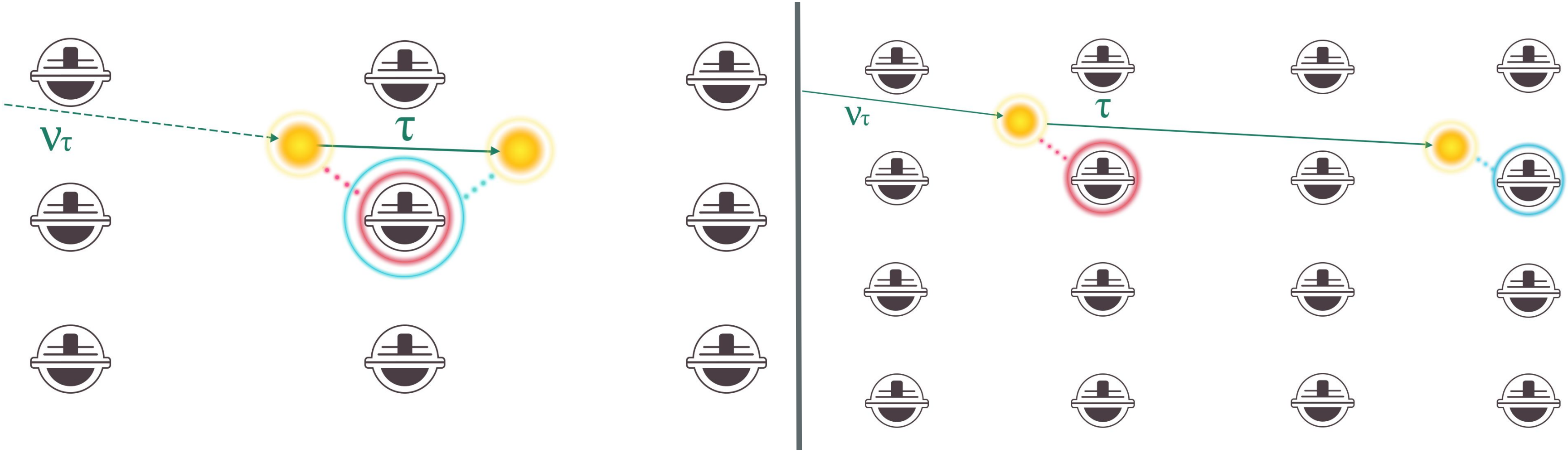


Fedynitch et. al. Arxiv: 1503.00544



IceCube, Phys. Rev. Lett. 114, 171102

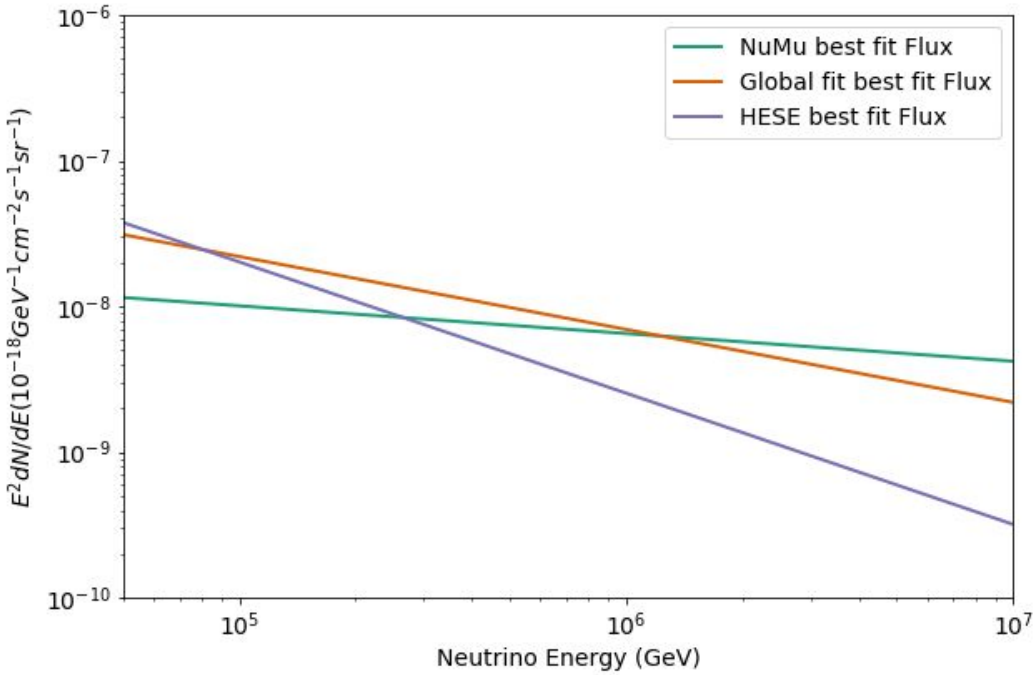
Tau Double Pulse vs. Double Cascade



Local Coincidence DPA

	Local Coincidence (LC)	Single DOM (SD)
1st rising edge dV/dt (mV/ns)	**> 1**	> 10
Trailing edge dV/dt (mV/ns)	**< - 0.5**	< -17
2nd rising edge dV/dt (mV/ns)	**> 12**	> 18
1st rising edge width (13.2 ns bins)	**>= 1**	>= 2
Trailing edge width (13.2 ns bins)	**>= 2**	>= 2
2nd rising edge width (13.2 ns bins)	**>= 3**	>= 3

Spectrums

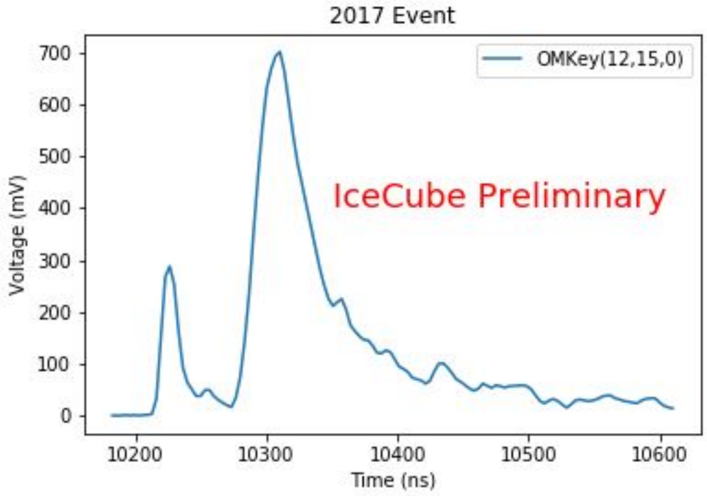


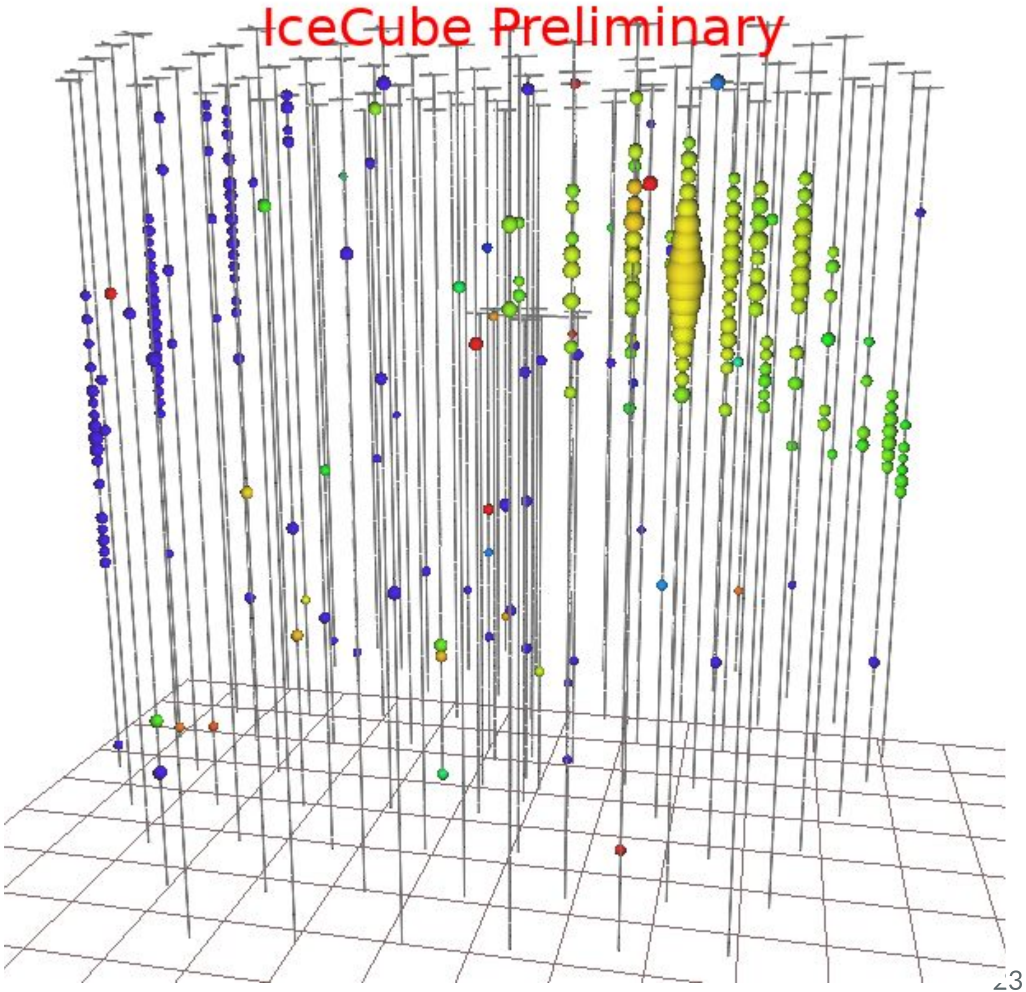
Best fit fluxes:
NuMu : 1.01 x 10^{-18} $E^{-2.19}$
Global: 2.2 x 10^{-18} $E^{-2.5}$
HESE: 2.02 x 10^{-18} $E^{-2.9}$

Total Expected Events: 3.07

Event #3 (2017)

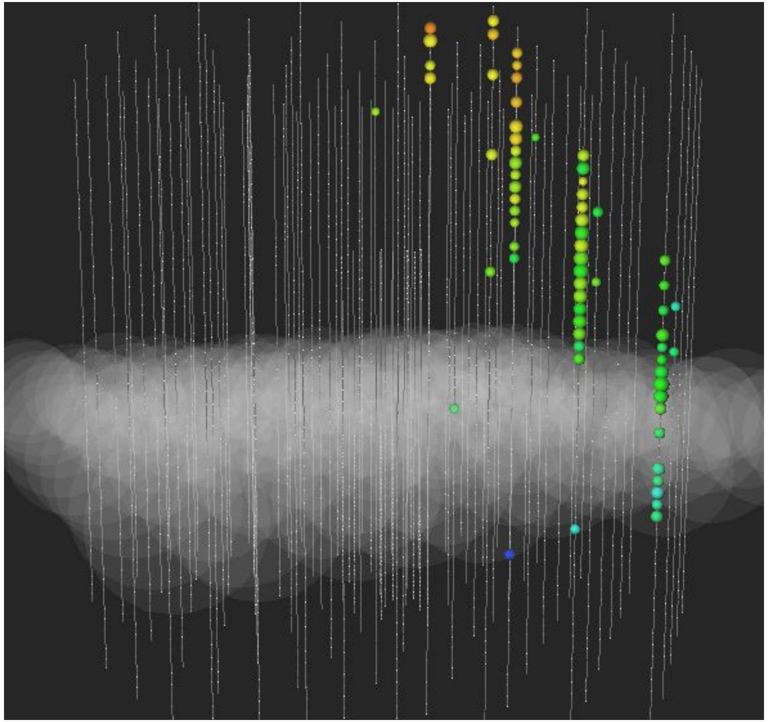
P-value: 1.0



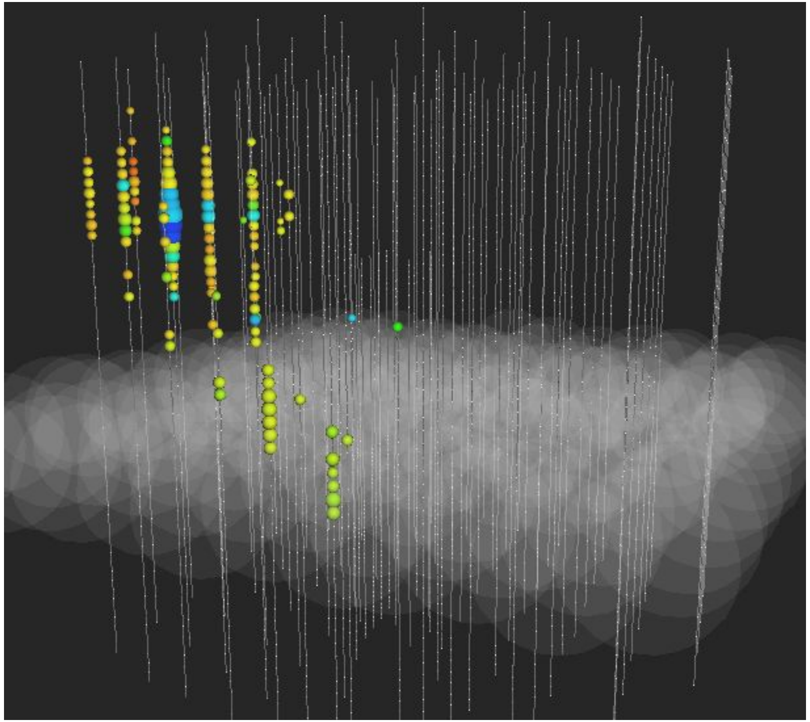


Event #3 Split

QTot: 138 PE



QTot: 1982 PE



Data Selection overview

Precuts:

All filters (IC79 EHEFilter)
2000 PE CasualQTot cut

Level 4:

Double Pulse Algorithm (DPA) - Select events with double pulse waveforms and reject single cascade

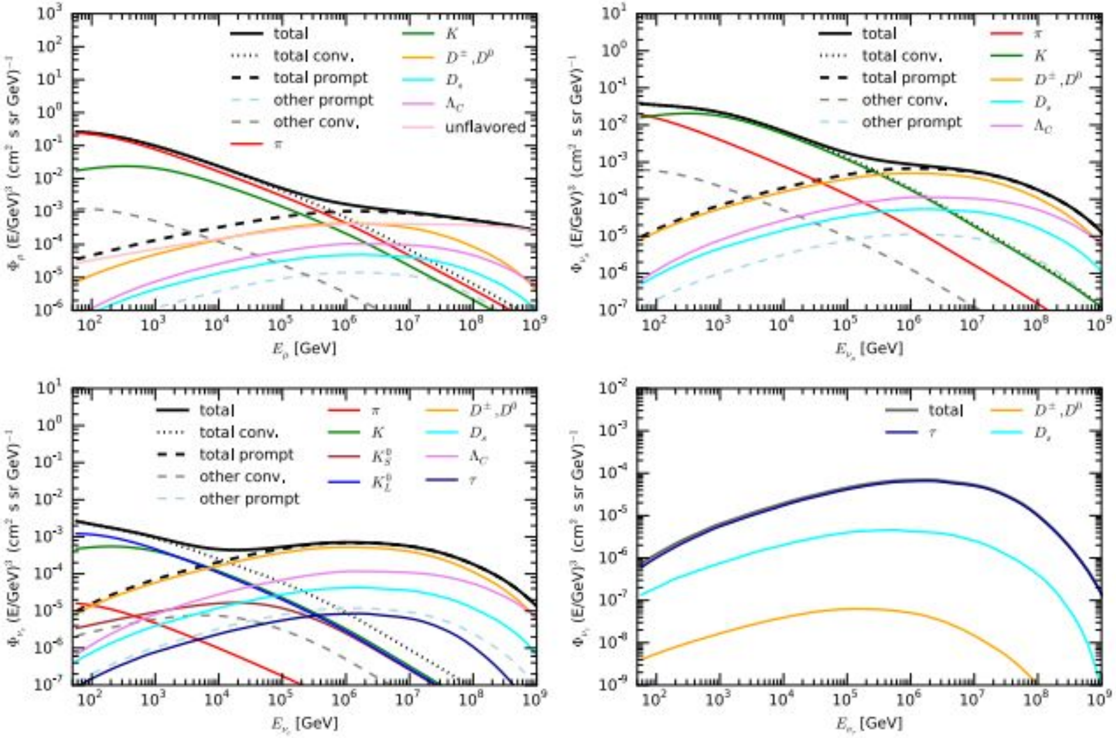
Level 5:

Topology cut - Remove track-like events and retain cascade-like events
First Hitz cut - Remove events starting at top of detector, dominated by muons

Level 6:

Second topology cut - Remove remaining track-like events, harder than Level 5 cut
Containment cut - Remove events starting near

Atmospheric Flux



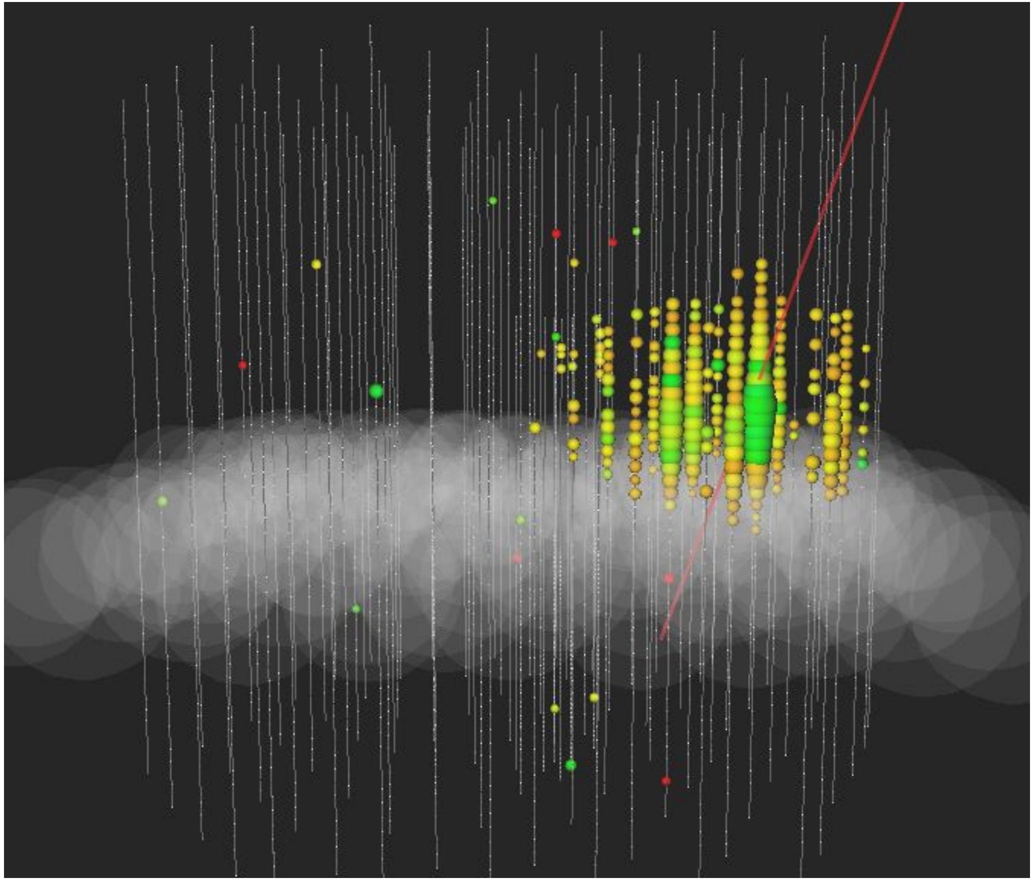
Expected event rates

Rates in 8 Years	E^-2.19	E^-2.5	E^-2.9
NuTau CC	1.72 +- 0.023	1.94 +- 0.029	1.01 +- 0.029
NuTau NC + Muonic CC	0.072 +- .004	0.062 +- 0.006	0.03 +- 0.006
NuMu	0.95 +- 0.048	0.8+- 0.1	0.66+- 0.1
NuE	0.26 +- 0.010	0.31 +- 0.012	0.32 +- 0.01
Muons	0.2 +- 0.14	0.2 +- 0.14	0.2 +- 0.14

Event #1

Taupede reconstruction:

E1=8.4TeV, E2=77.7TeV, L=17.4m



Forward Folding parameters

Astrophysical Normalization - Floating
Astrophysical Flavor Ratio NuE:NuMu:NuTau - Floating
Astrophysical Spectrum - Fixed to -2.19, -2.5, and -2.9

Conventional Neutrino normalization - Floating
Prompt Neutrino normalization - Floating
Atmospheric Muon - Off

DOM Efficiency - Off
Pi/Kaon ratio - Floating
Cosmic ray spectral index modification - Floating

Forward folding: use a binned maximum likelihood method where a sum of Monte Carlos templates is varied until it describes the data best.

For a set of *M* physics parameters $\Theta = \{\Theta_1, \Theta_2, ...\Theta_M\}$

and *K* nuisance parameters $\zeta = \{\zeta_1, \zeta_2, ...\zeta_K\}$

and with *N* observations, the *N* expected values are

$\mu(\Theta, \zeta) = \{\mu_1(\Theta, \zeta), \mu_2(\Theta, \zeta), ..., \mu_N(\Theta, \zeta)\}$

The Poisson probability for bin *i* is: $p(\mu_i(\Theta, \zeta)|n_i) = \frac{(\mu_i(\Theta, \zeta))^{n_i}}{n_i!} \cdot \exp(-\mu_i(\Theta, \zeta))$

The Likelihood can be written as product of the Poisson probabilities and functions of nuisance parameters (usually assumed Gaussian)

$$L(\vec{\mu}(\Theta, \zeta)|\vec{n}) = \prod_{i=1}^{N} p(\mu_i(\Theta, \zeta)|n_i) \prod_{j=1}^{K} f(\zeta_j)$$