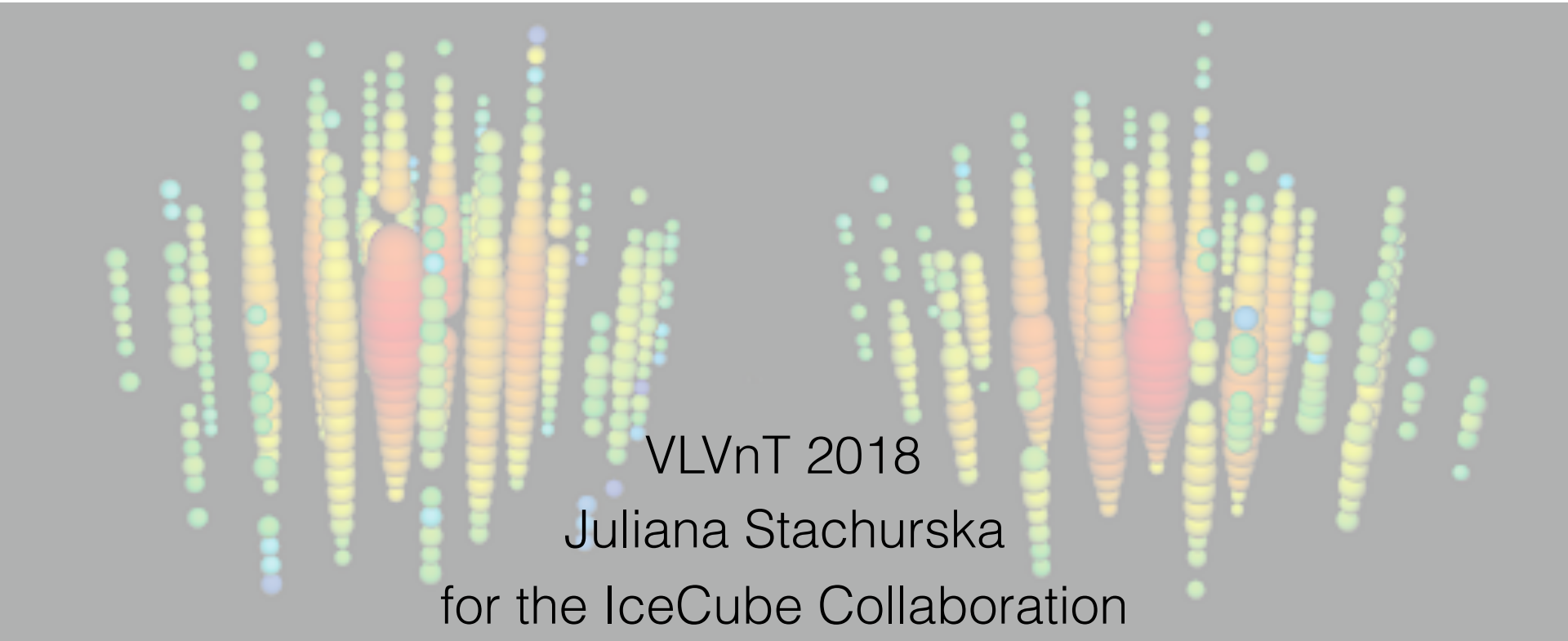
IceCube High Energy Starting Events at 7.5 Years - New Measurements of Flux and Flavor



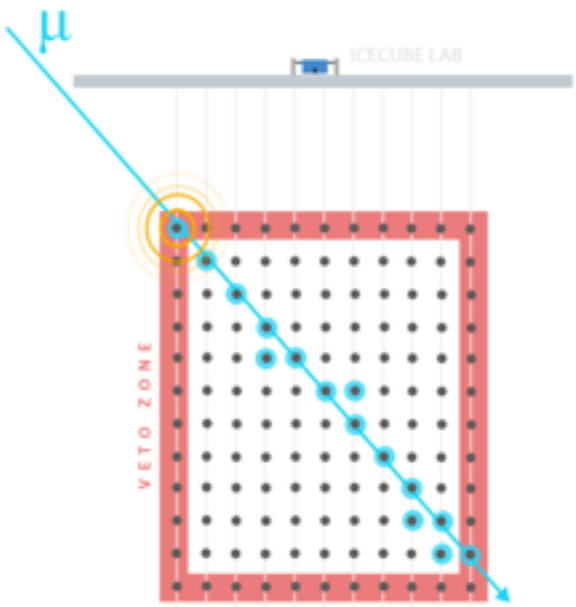
VLVnT 2018
Juliana Stachurska
for the IceCube Collaboration

Motivation

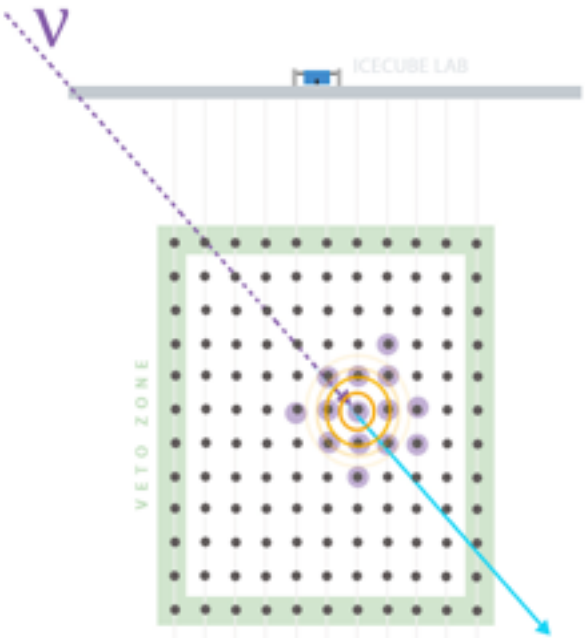
- IceCube observed astrophysical neutrinos
- Improved understanding of detector, systematics, and atmospheric background
- Redo High-Energy Starting Event (HESE) analyses with 7.5 years and improved techniques to:
  - Obtain precise diffuse flux characterization
  - Obtain robust particle physics measurements
  - Measure flavor composition → learn about environment at production sites
  - Obtain strong DM & BSM limits

Starting Events — Veto

Veto region rejects atmospheric muons and neutrinos

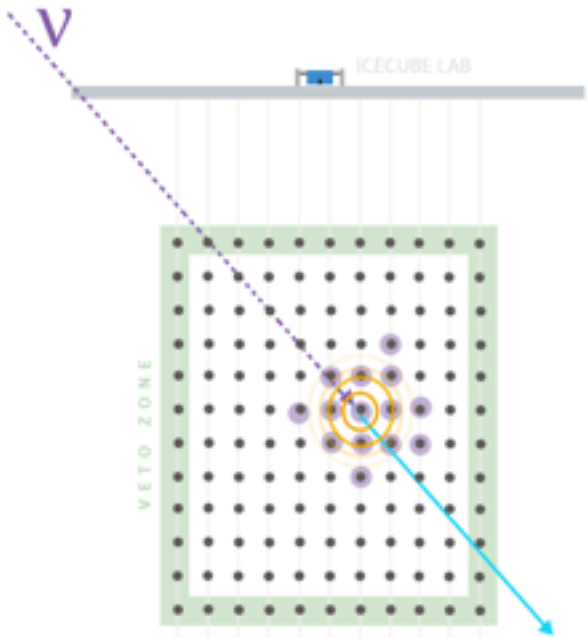


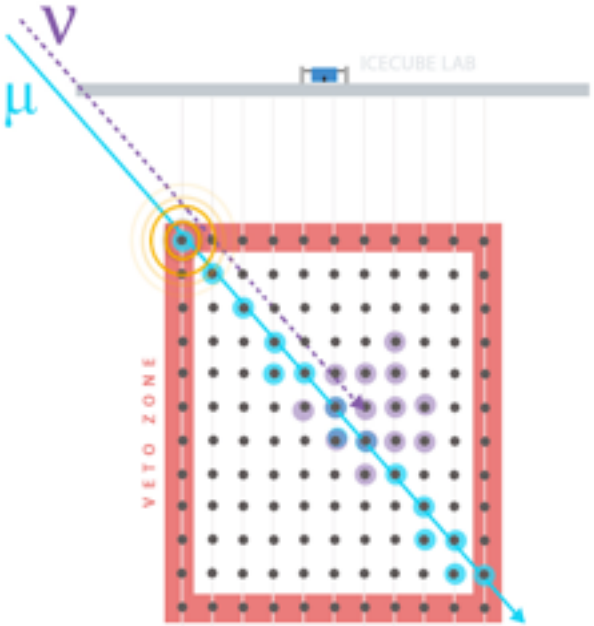
High neutrino signal purity at high energy



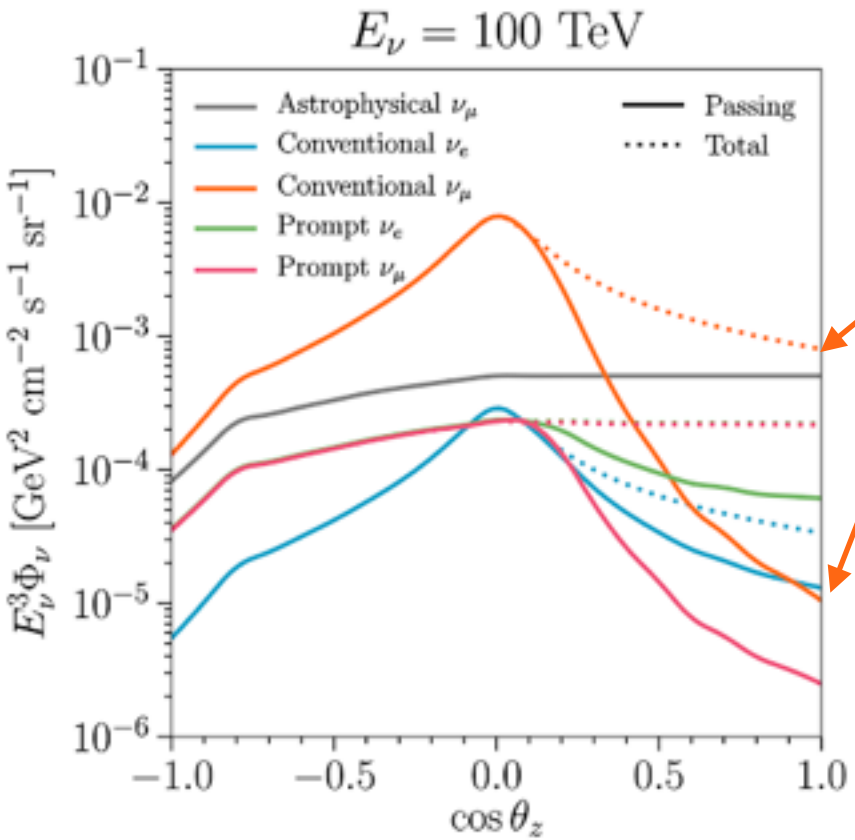
Atmospheric Neutrino Self Veto

A fraction of atmospheric neutrinos is vetoed by accompanying muons





Atmospheric Passing Fraction



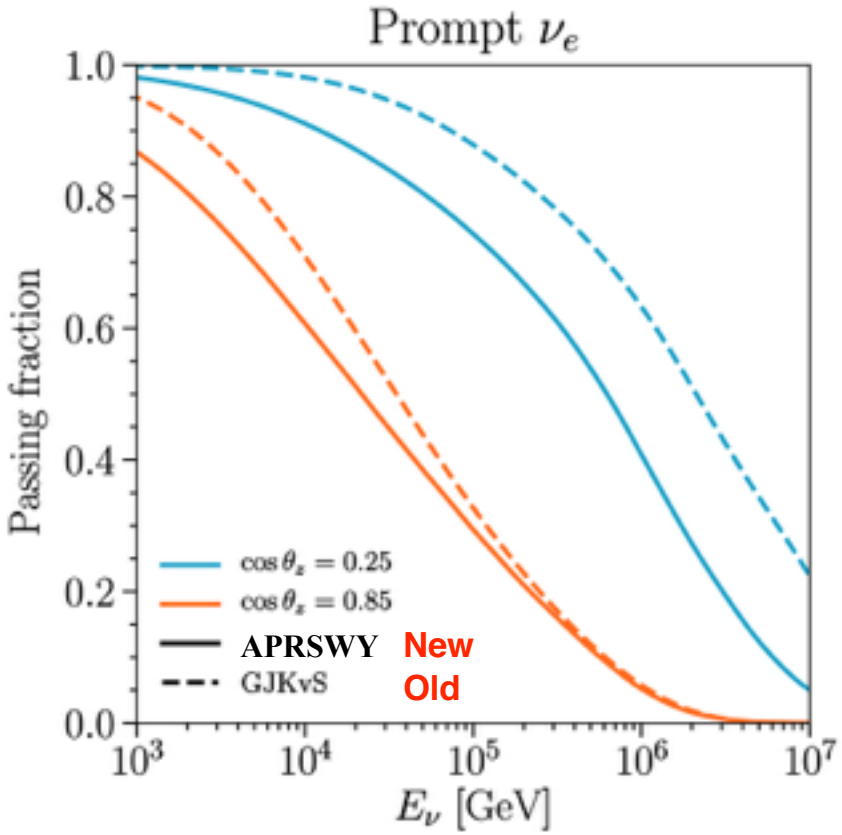
Suppression of downgoing atmospheric neutrinos

Key to measuring astrophysical component

Schönert, Gaisser, Resconi, Schulz
Phys. Rev. D 79; 043009(2009)
Gaisser, Jero, Karle, van Santen
Phys. Rev. D 90; 023009(2014)
Argüelles, Palomares-Ruiz, Schneider, Wille, Yuan
JCAP 1807 (2018) no.07, 047

Atmospheric Passing Fraction

Passing Fraction =
Cosmic Ray Flux ✖
Shower Development ✖
Muon Energy Loss ✖
Detector Response



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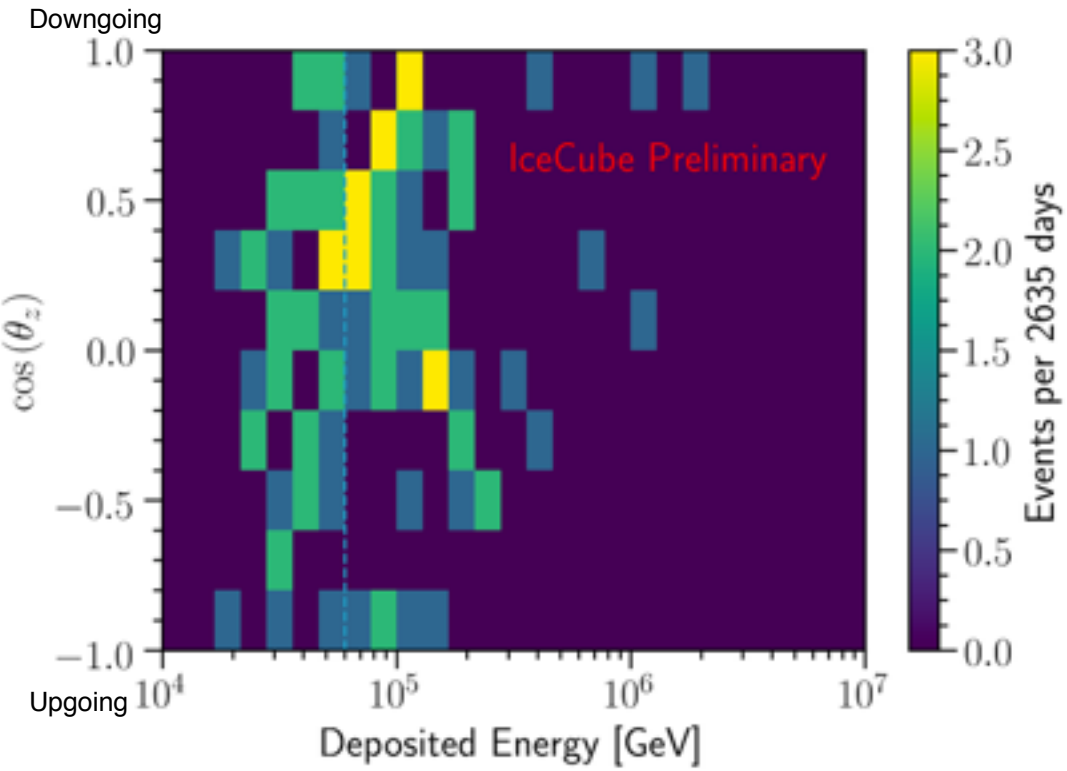
7.5 Years of Starting Events

- 1.5 Additional years of data added
- Detector calibration
- Ternary topology ID added
  - Cascades
  - Tracks
  - Double Cascades
- Dedicated algorithm for topology ID



Above 60TeV: 60 events

12 new events in 2016 season

5 new events in 2017 season

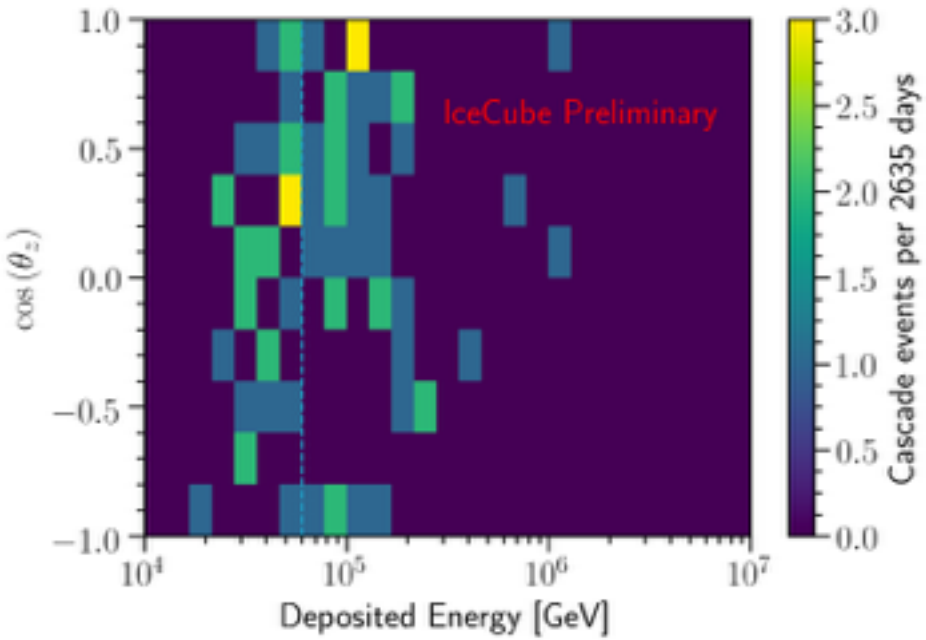
All energies: 102 events

22 new events in 2016 season

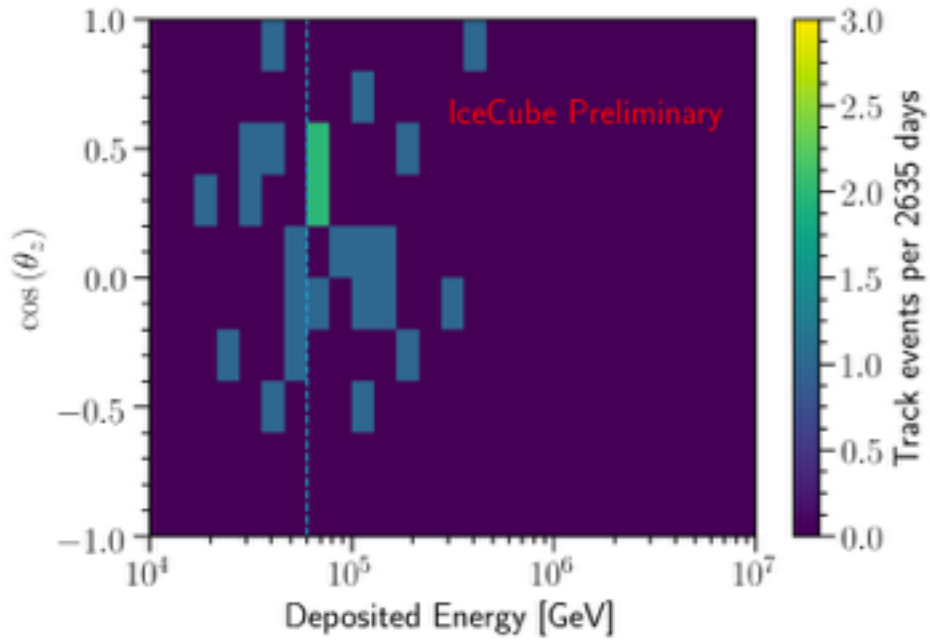
9 new events in 2017 season

7.5 Years of Starting Events

7.5 Years of Cascades



7.5 Years of Tracks

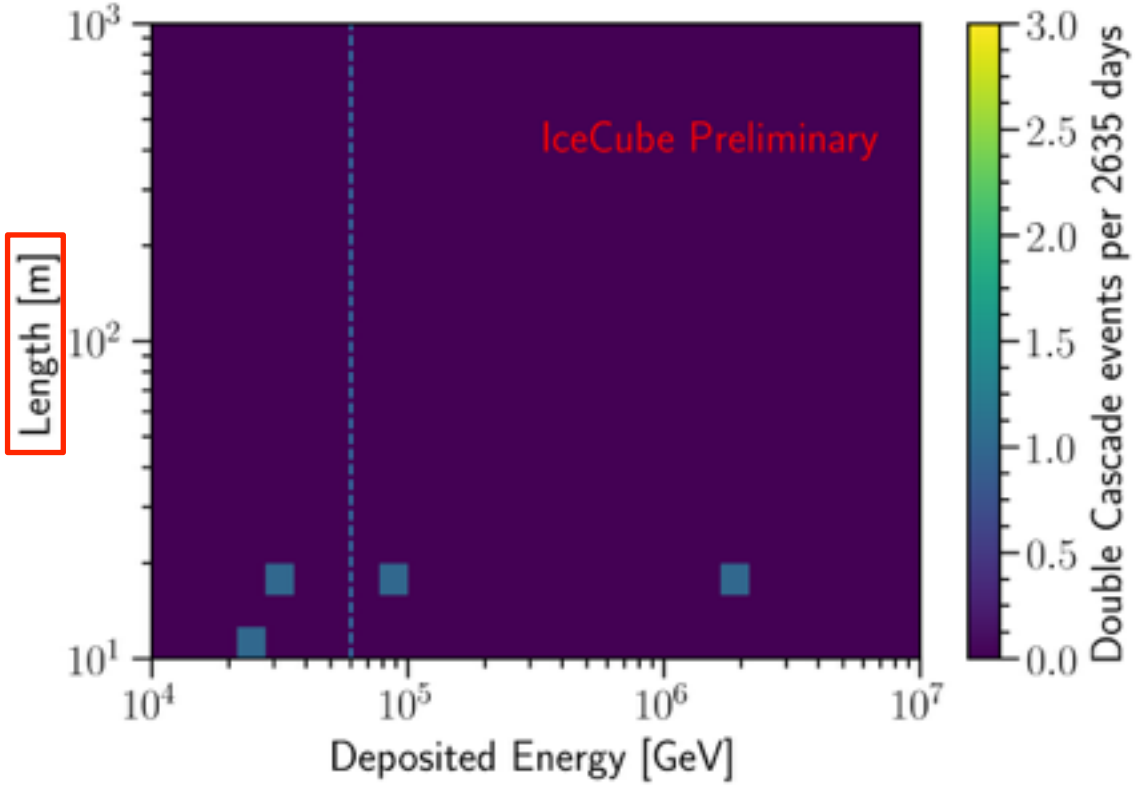


Classic signature of ν_e CC and all flavor NC interactions

Classic signature of ν_μ CC interactions

7.5 Years of Starting Events

7.5 Years of Double Cascades

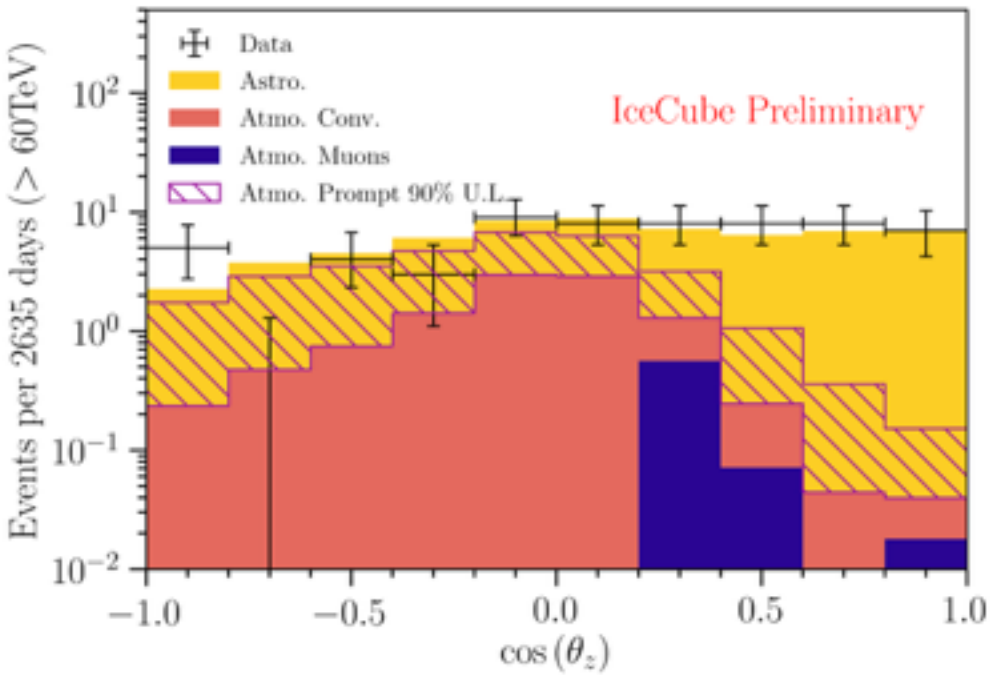


Classic signature of ν_τ CC interactions

Diffuse Astrophysical Neutrino Flux

- Best fit single powerlaw $2.19^{+1.10}_{-0.55} \times E^{-2.91(+0.33,-0.22)}$
- Prompt 90% upper limit 12.3×BERSS model
- Fit performed for events above 60TeV
- Compatible with results from 6 year analysis

$E^2\ \Phi = 2.19 * 10^{-18} (E/100\text{TeV})^{-0.91}$ [GeV cm^{-2} s^{-1} sr^{-1}]



Honda, Kasahara, Midorikawa, Sanuki
Phys.Rev. D75 (2007) 043006
Bhattacharya, Enberg, Reno, Sarcevic, Stasto
JHEP 1506 (2015) 110

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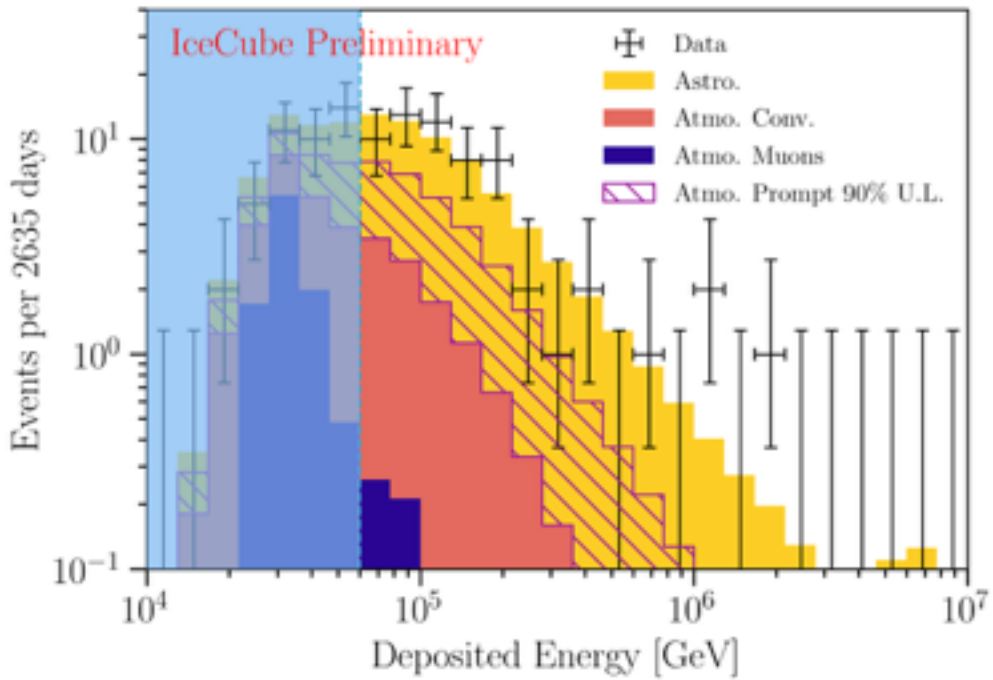

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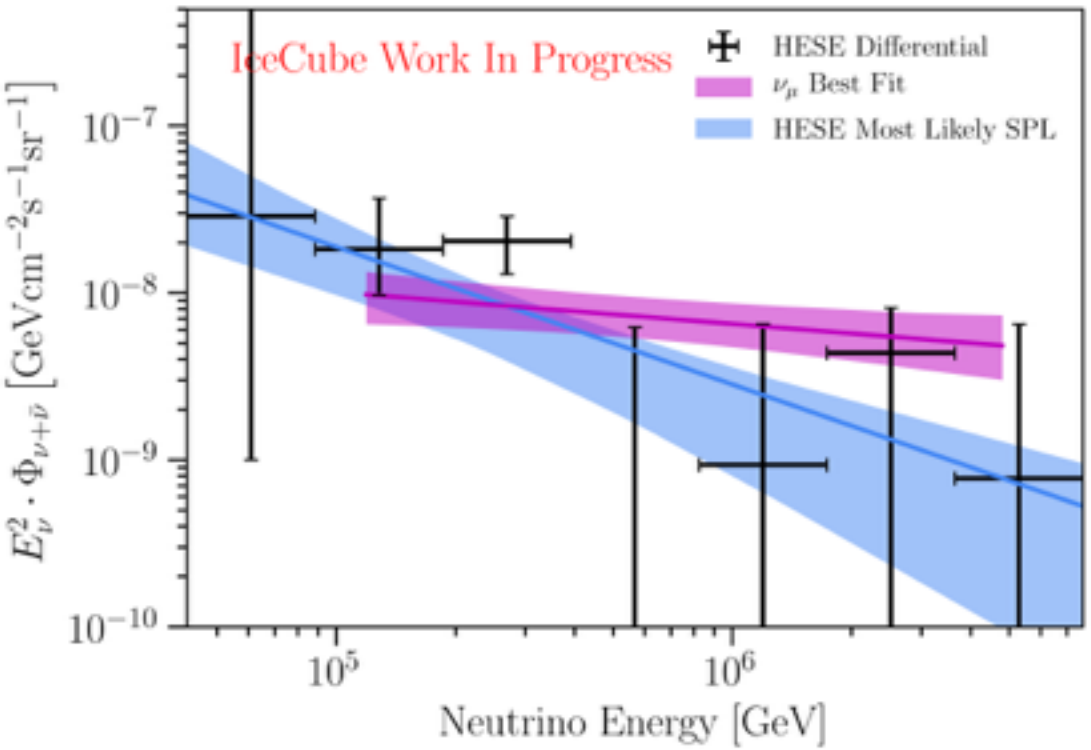
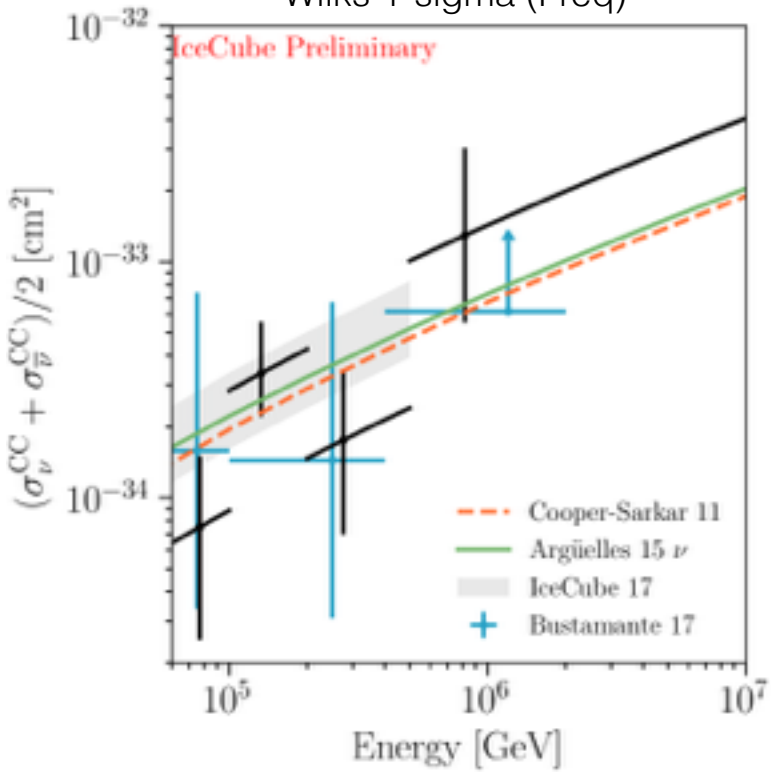


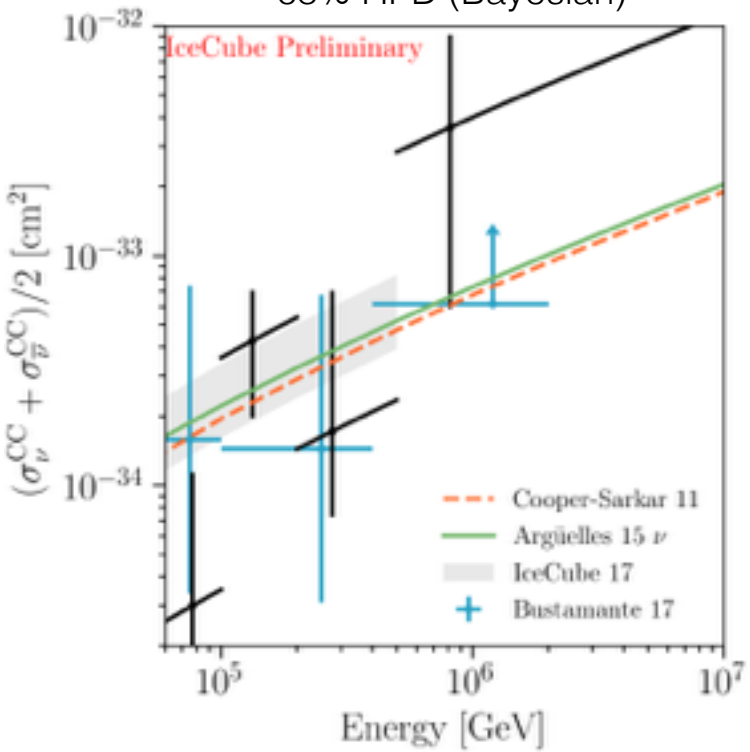
Honda, Kasahara, Midorikawa, Sanuki
Phys.Rev. D75 (2007) 043006
Bhattacharya, Enberg, Reno, Sarcevic, Stasto
JHEP 1506 (2015) 110

Cross-section Measurement

Wilks 1-sigma (Freq)



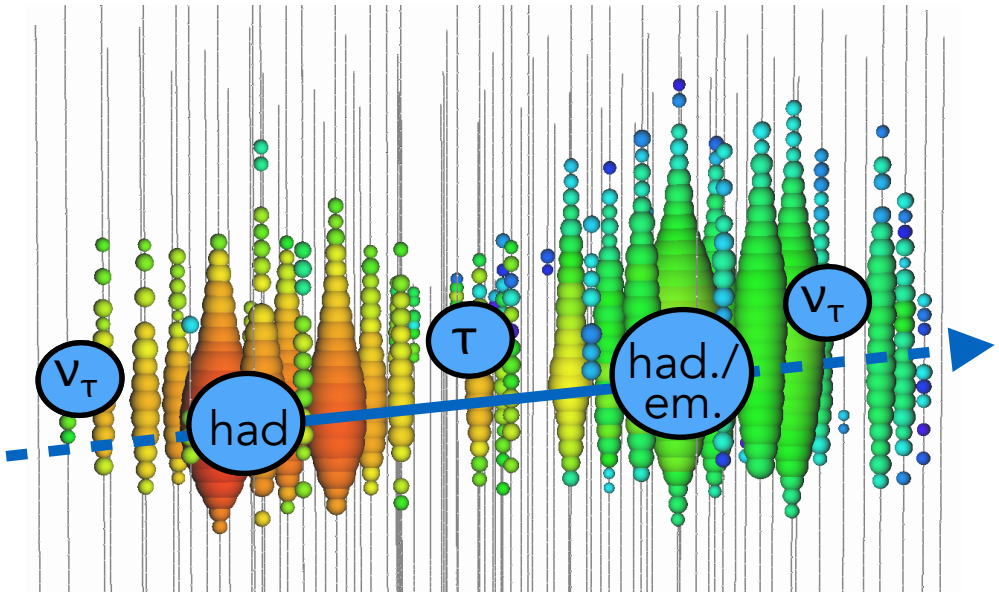
68% HPD (Bayesian)



Results are consistent between statistical methods.
Measurement is also consistent with TGM observation.

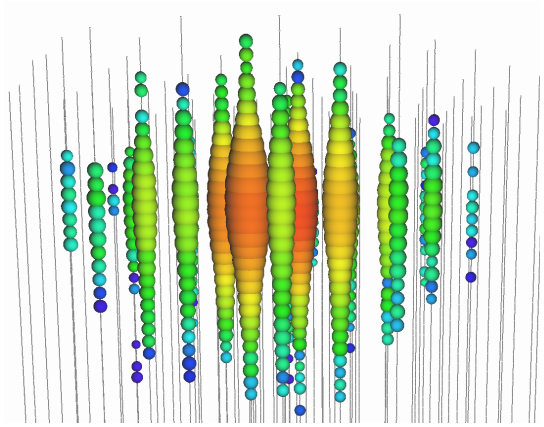
Double Cascade Signal

- ν_τ interaction
- Charged current (71%)
- Tau decays into hadrons / electrons (83%)
- Mean length: 50m x energy/1PeV

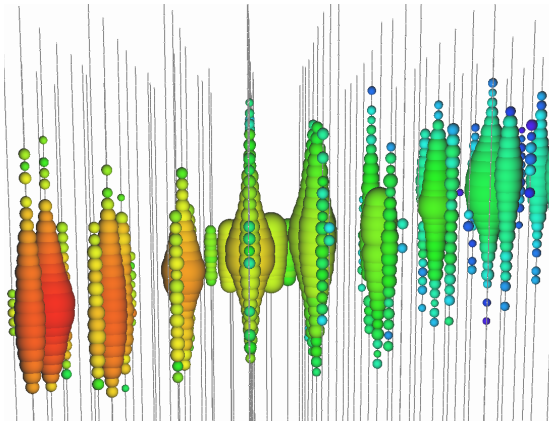


simulated 10PeV Double Cascade event

Background



Cascades:
All NC interactions
ν_e CC interactions
ν_τ CC interactions with unresolvable lengths



Tracks:
ν_μ CC interactions
Atmospheric muons
ν_τ CC interactions with muonic tau decay

Flavor Analysis Overview

All HESE events in 7.5 years of data above 60 TeV

Flavor Analysis Overview

All HESE events in 7.5 years of data above 60 TeV

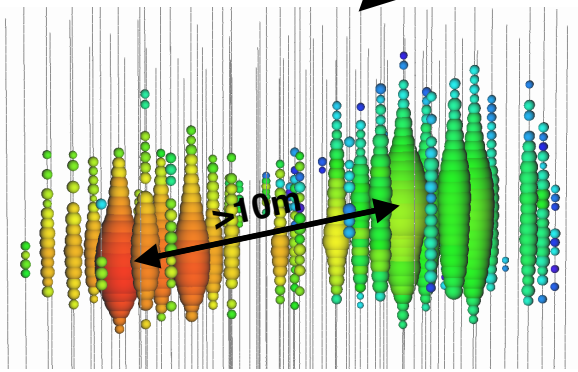
↓

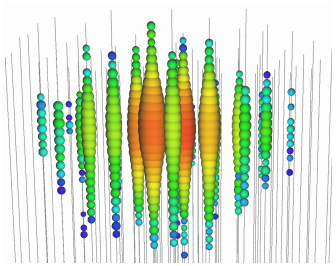
Observables from direct double-cascade reconstruction

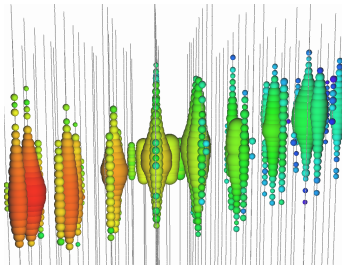
Flavor Analysis Overview

All HESE events in 7.5 years of data above 60 TeV

Observables from direct double-cascade reconstruction







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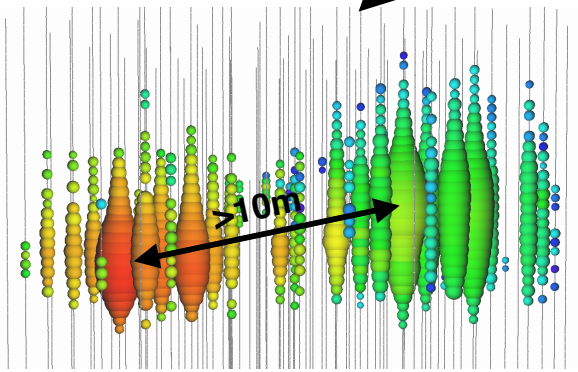
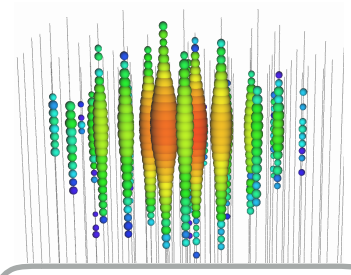
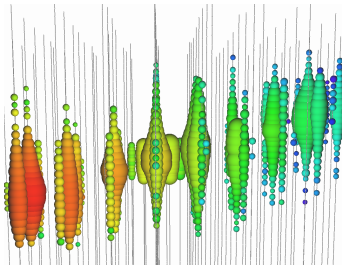
Observables from direct double-cascade reconstruction



Double cascade sample:
$\nu_\tau + N \rightarrow \tau + \text{hadrons} \xrightarrow{>10m}$
hadrons / electrons



Single cascade sample with not well-reconstructable ν_τ – cc interactions, all other cascades



Track sample with ν_τ – cc interactions creating μ, ν_μ – and atm. μ – tracks

Flavor Analysis Overview

All HESE events in 7.5 years of data above 60 TeV

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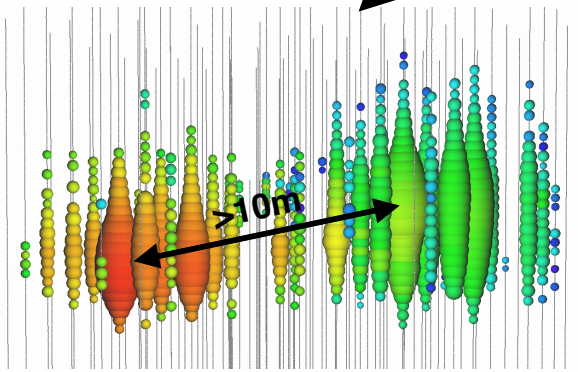

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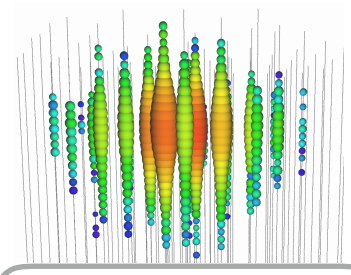
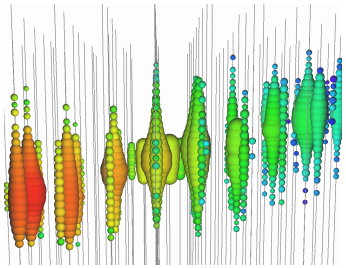


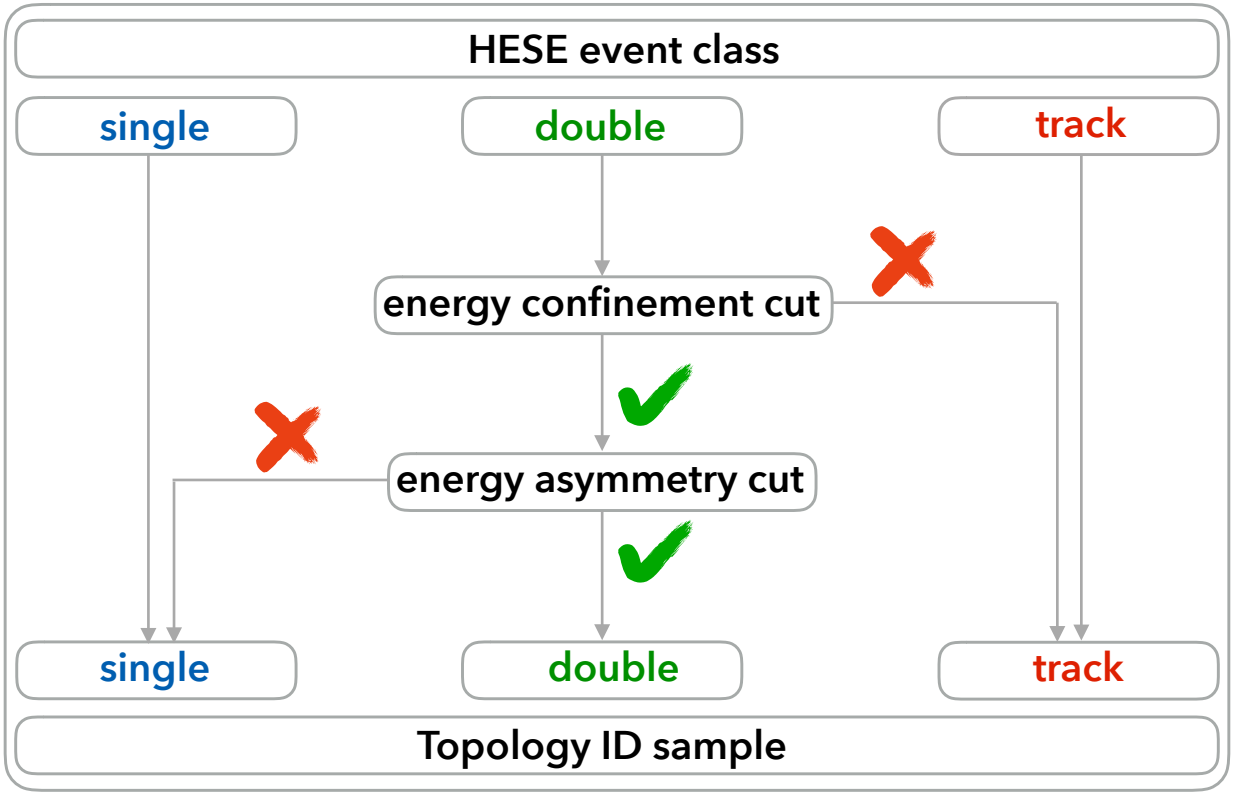
Single cascade sample with not well-reconstructable ν_τ – cc interactions, all other cascades

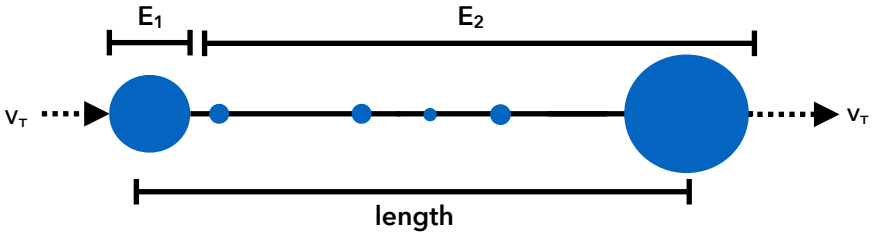


Track sample with ν_τ – cc interactions creating μ, ν_μ – and atm. μ – tracks

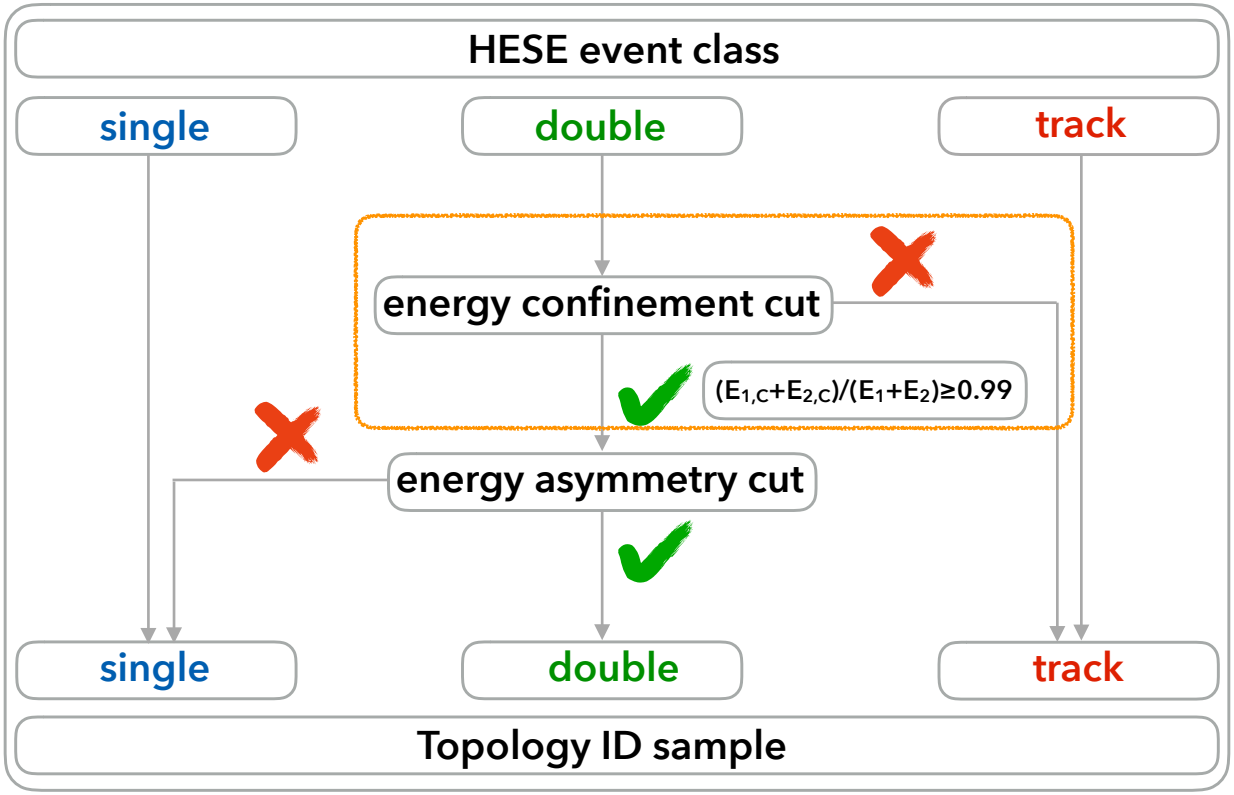
Flavor composition

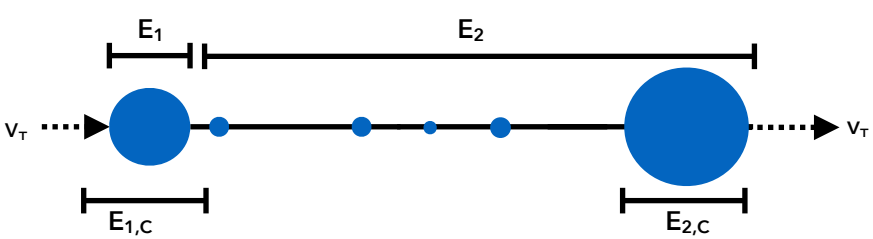
Selection

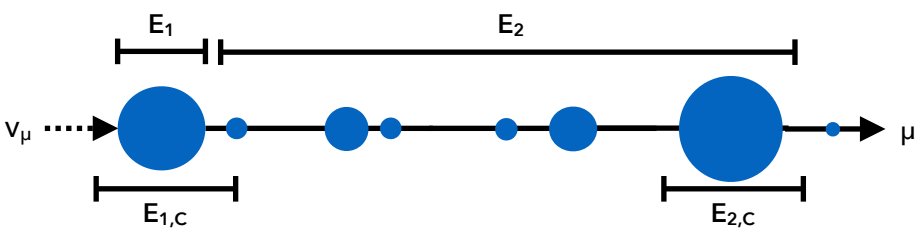

HESE event class
single
double
track
energy confinement cut
energy asymmetry cut
single
double
track
Topology ID sample


E1
E2
νT
νT
length

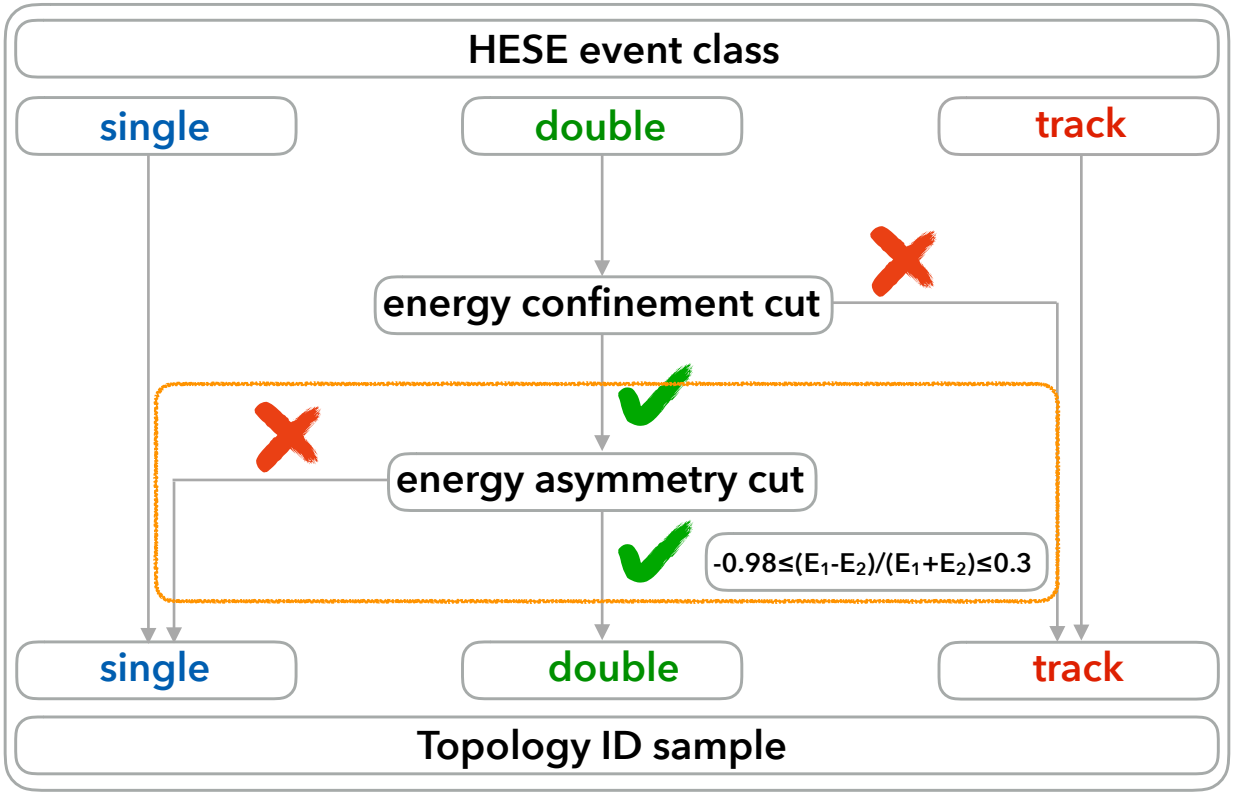
Selection

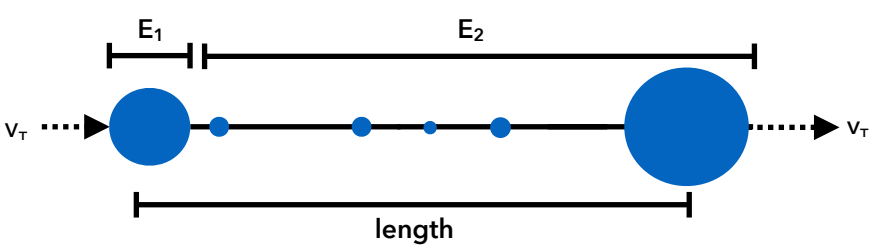

HESE event class
single
double
track
energy confinement cut
$(E_{1,C}+E_{2,C})/(E_1+E_2)\geq 0.99$
energy asymmetry cut
single
double
track
Topology ID sample

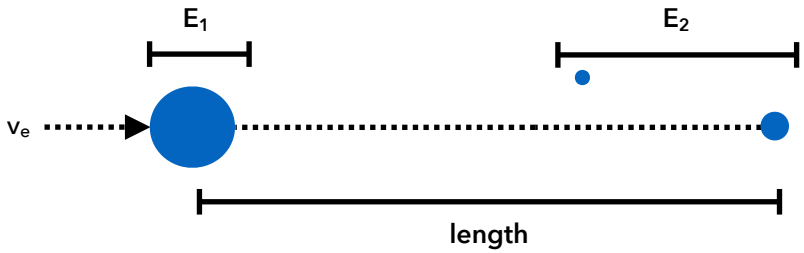

E_1
E_2
ν_τ
ν_τ
$E_{1,C}$
$E_{2,C}$


E_1
E_2
ν_μ
μ
$E_{1,C}$
$E_{2,C}$

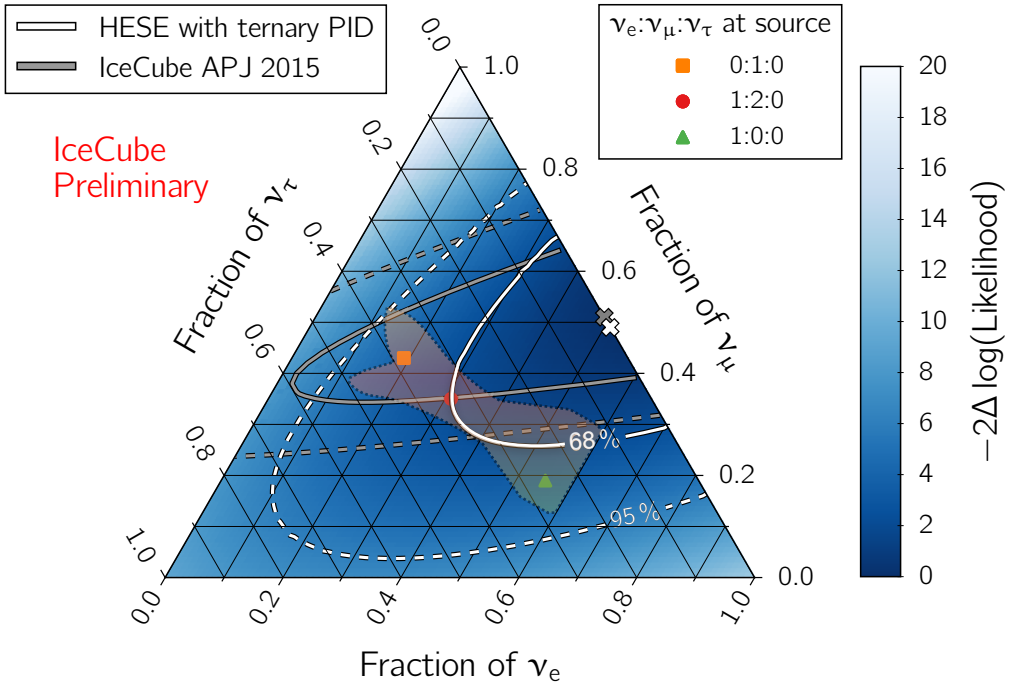
Selection


HESE event class
single
double
track
energy confinement cut
energy asymmetry cut
-0.98≤(E1-E2)/(E1+E2)≤0.3
single
double
track
Topology ID sample


E1
E2
ντ
ντ
length


E1
E2
νe
length

Previous Results



M. Usner, PoS(ICRC2017)974

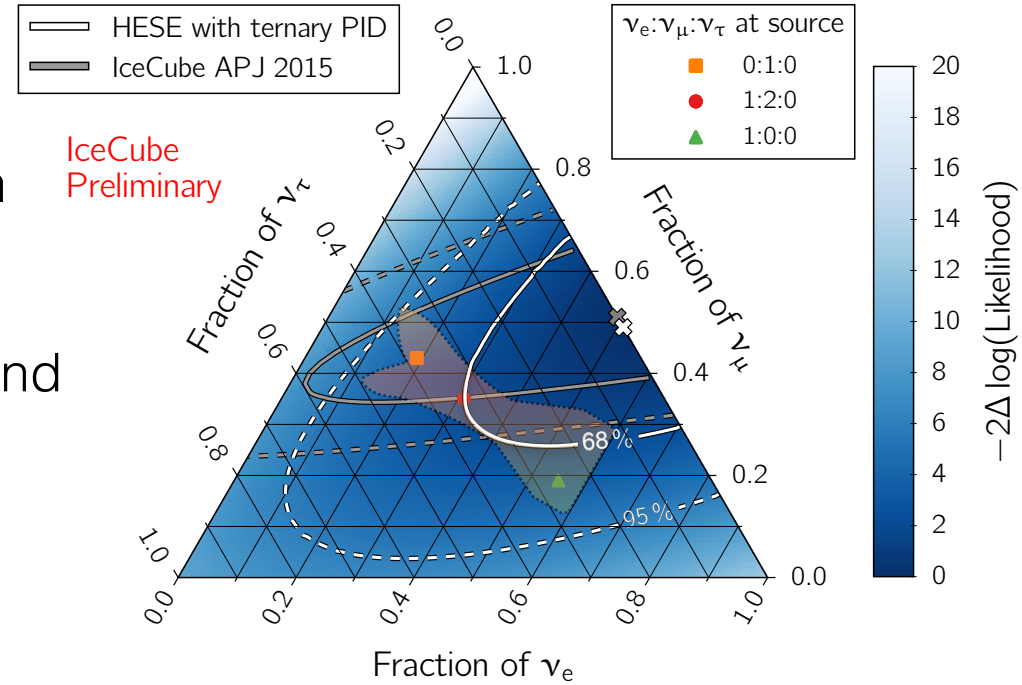
Previous Results

- Flavor composition measurement in global fit measurement:
  - only Cascade and Track topologies
  - large combined data sample
  - Best-Fit:

    $\nu_e:\nu_\mu:\nu_\tau = 0.49:0.51:0.0$

- First flavor measurement with ternary topology in 6 years of HESE data:
  - no Double Cascades found
  - Best-Fit:

    $\nu_e:\nu_\mu:\nu_\tau = 0.51:0.49:0.0$



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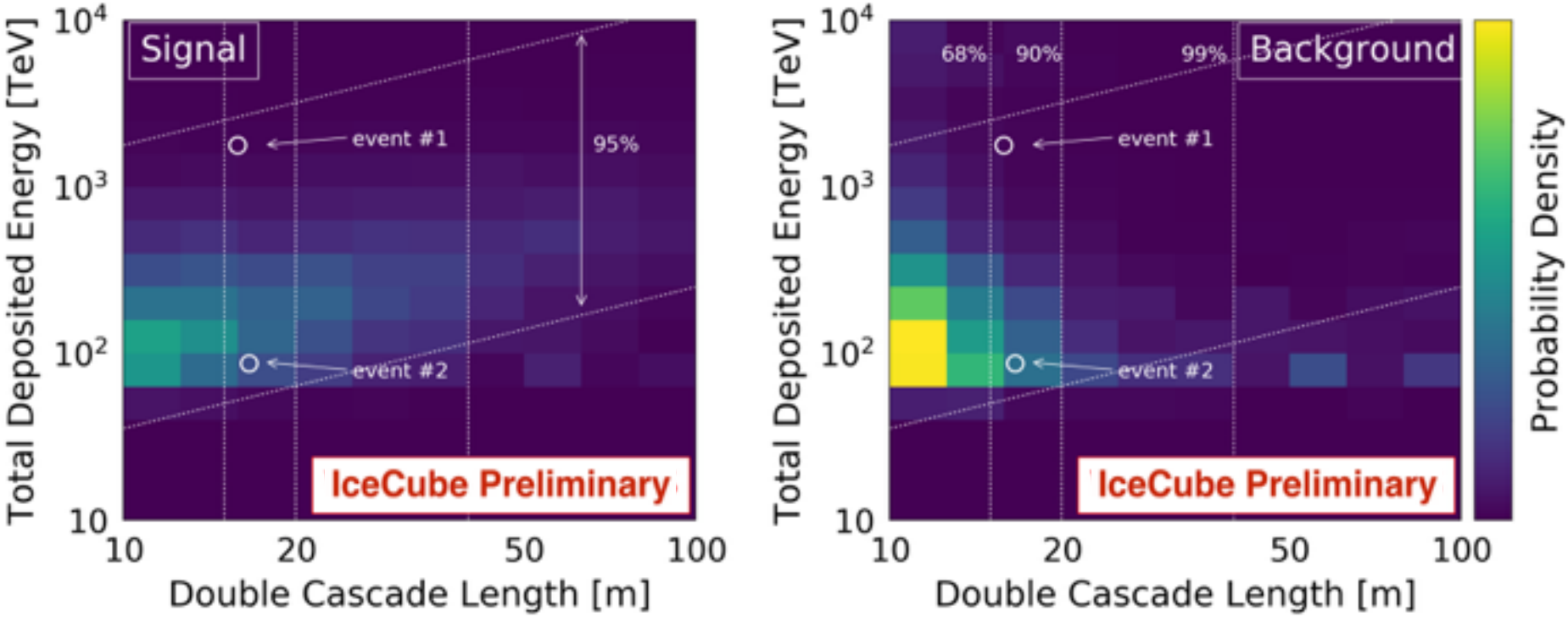
Results

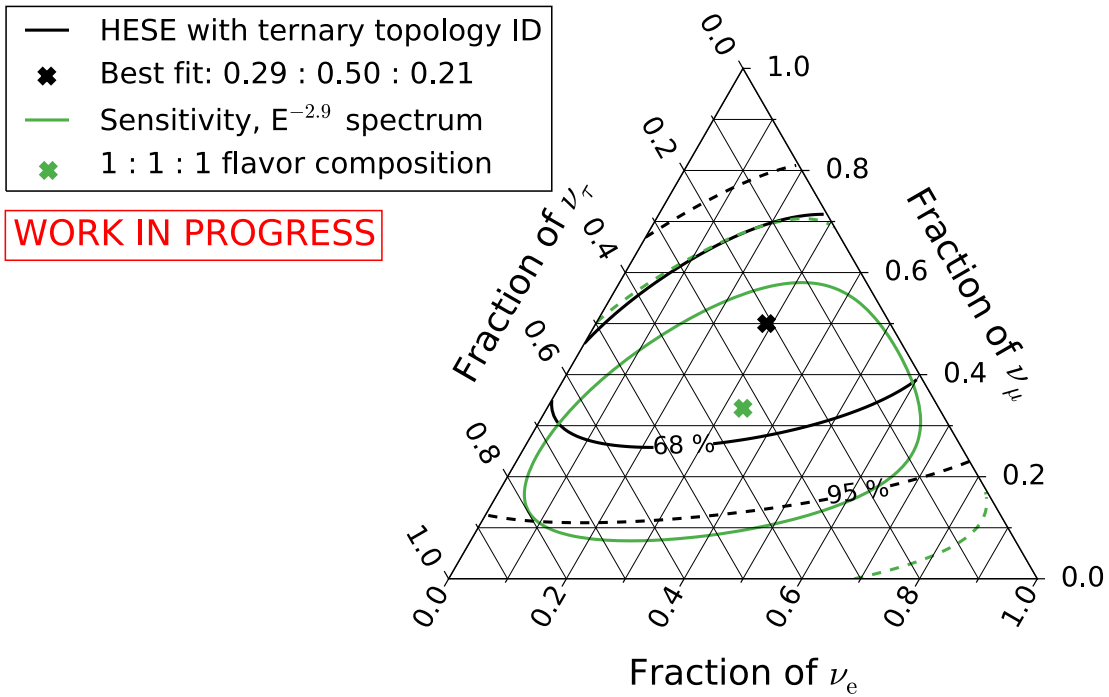


- 2 events in Double Cascade bin
- Soft spectral index: 2.9 → expect ~2.1 events (~1.4 signal + ~0.7 background)

Results

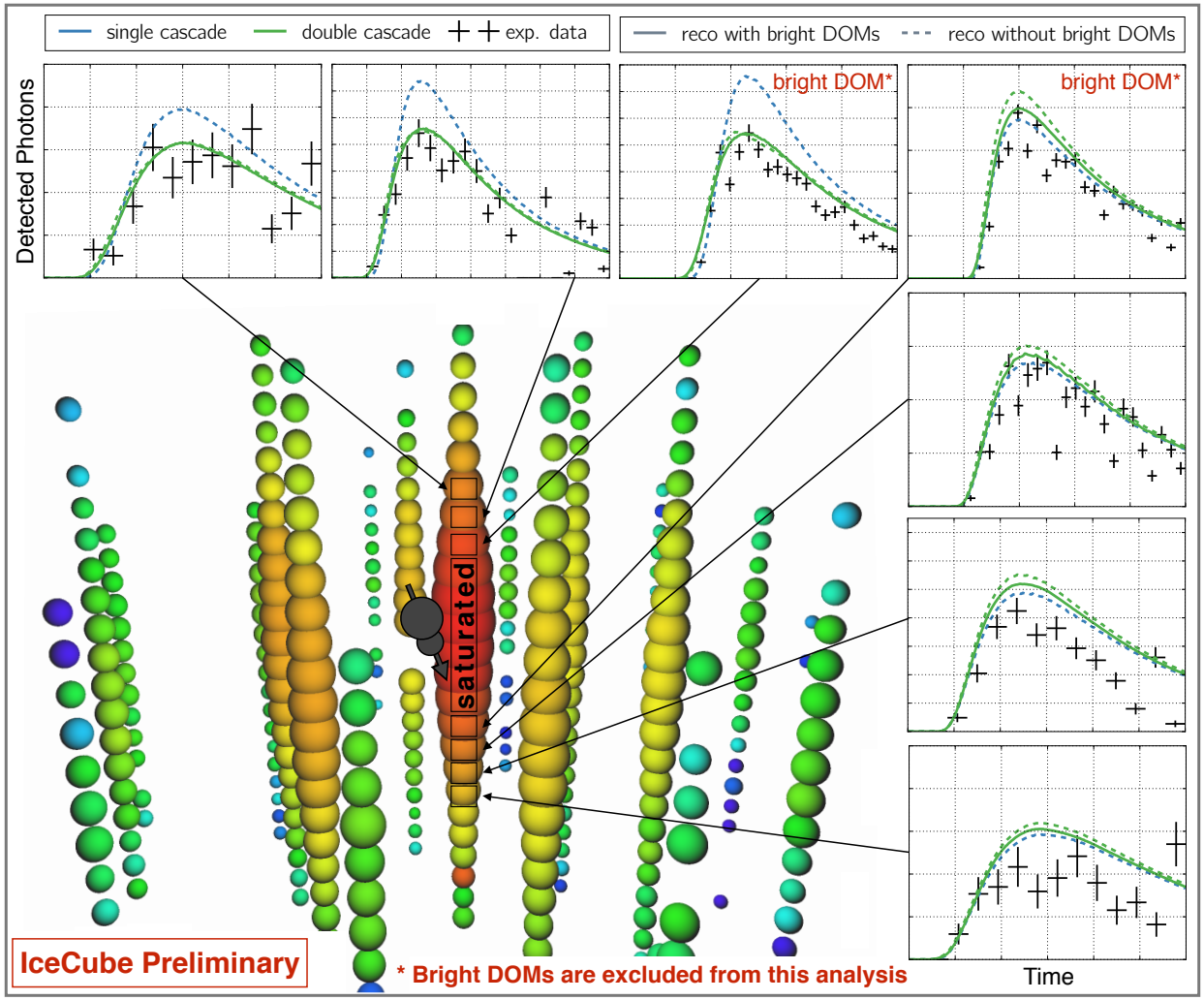
Maximum likelihood flavor composition fit based on 2D histograms:

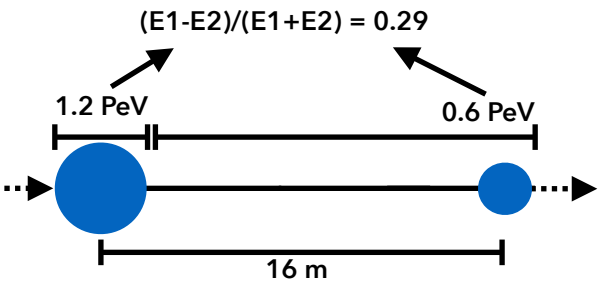
- Zenith & energy for single cascades, tracks
- Length & energy for double cascades



- Best-fit $\nu_e:\nu_\mu:\nu_\tau$ = 0.29:0.50:0.21
- Consistent with previous measurements and expectation of ~1:1:1 for astrophysical neutrinos
- Zero ν_τ flux cannot be excluded
- Systematic errors not included

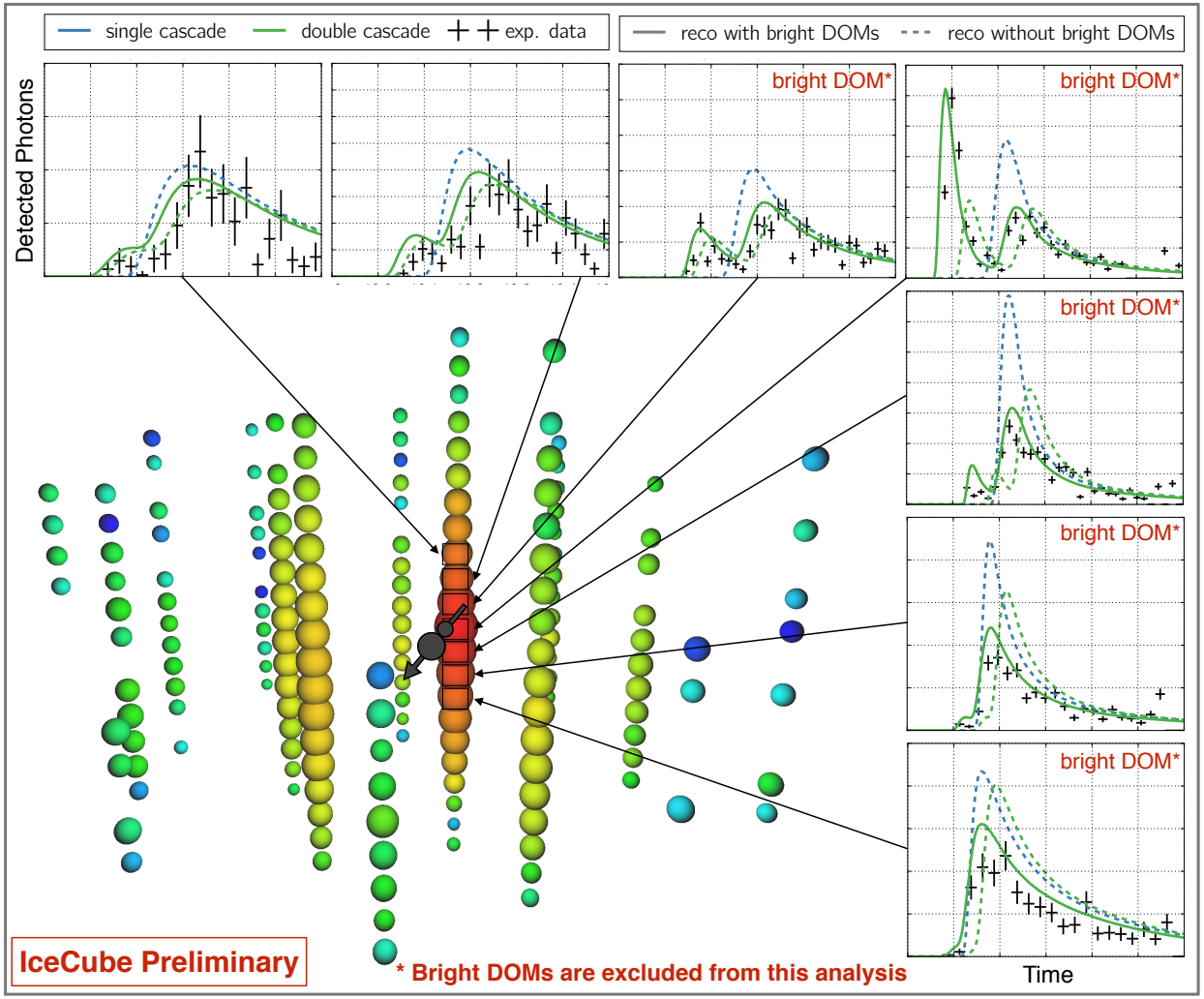
Event #1 (Big Bird)

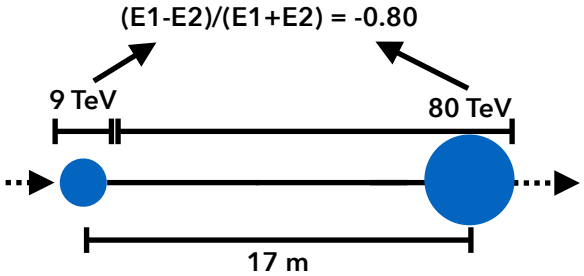




- Observed 2012
- Shows no clear preference between a single cascade and double cascade hypothesis

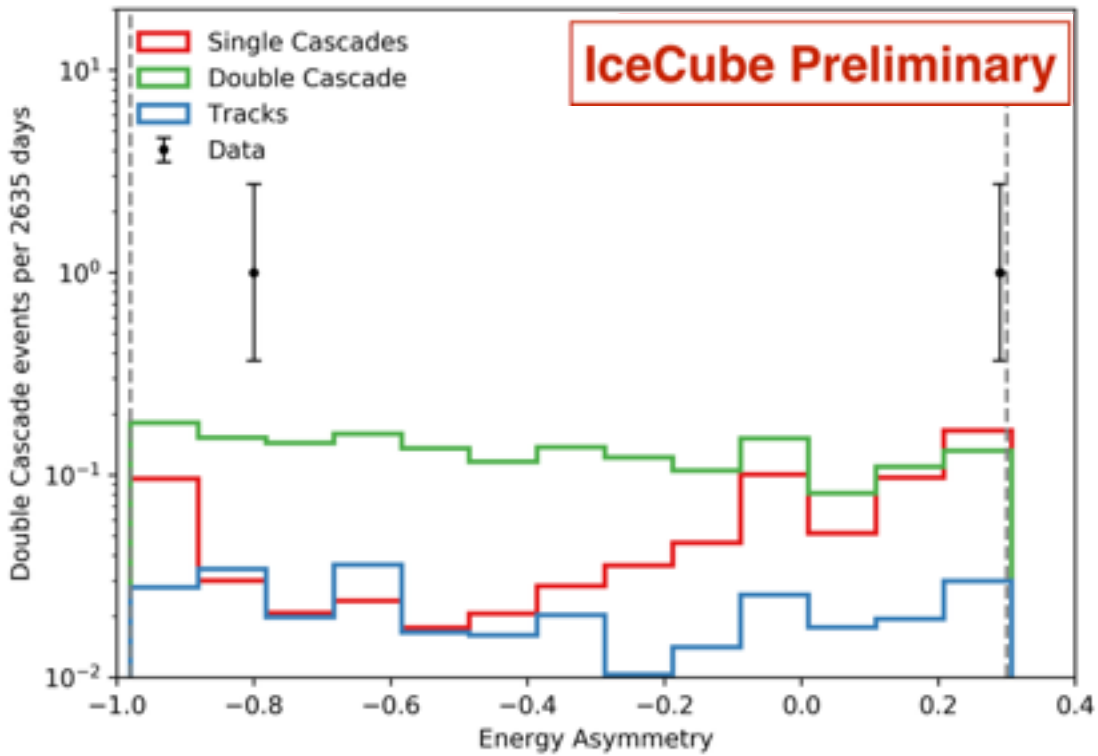
Event #2 (Double Double)





- Observed 2014
- Observed light arrival pattern clearly favors double cascade hypothesis

Energy Asymmetry



Energy asymmetry for best-fit spectrum, and a $\nu_e:\nu_\mu:\nu_\tau$ = 1:1:1 composition

- Only a straight cut was used
- Afterwards all events in Double Cascade bin treated the same regardless of energy asymmetry value
- Mainly due to computational issues
- Plan: incorporate all information into "tauness"

BSM Flavor Overview

New operators can be interpreted in different new physics contexts

- ➔ Lorentz and CPT Violation
- ➔ Noncommutative field theory
- ➔ Dark Energy Interaction
- ➔ Equivalence Principle Violation

Introducing new physics in the **mixing matrix elements**

$$H_d = \frac{1}{2E} U M^2 U^\dagger + \frac{E^{d-3}}{\Lambda_d} \tilde{U}_d O_d \tilde{U}_d^\dagger = V_d(E) \Delta V_d^\dagger(E)$$

Dimension

Standard Mixing

New Physics Terms

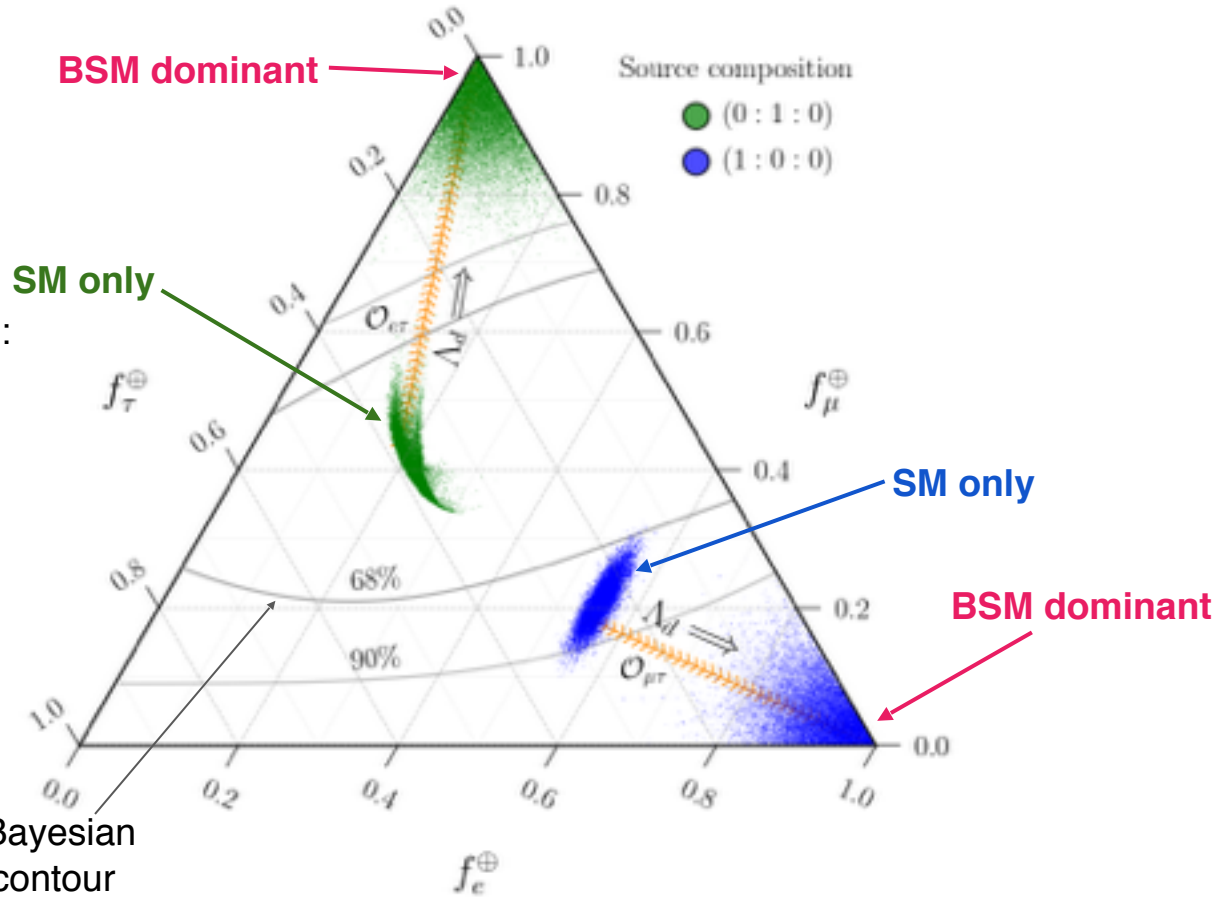
Mixing Matrix with New Physics

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

BSM Flavor Overview

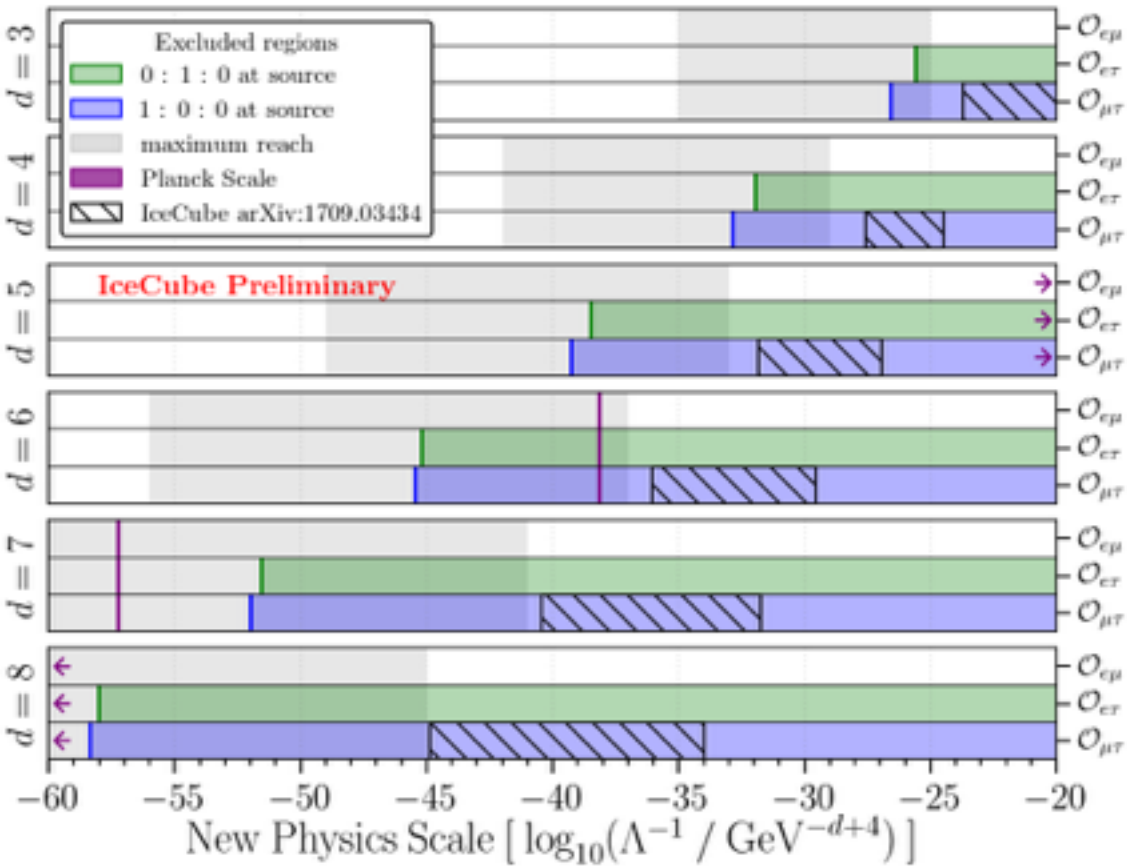
Limits were obtained for 2 scenarios:

- (0 : 1 : 0) for an $\mathcal{O}_{e\tau}$ dominant BSM mixing
- (1 : 0 : 0) for an $\mathcal{O}_{\mu\tau}$ dominant BSM mixing



BSM Flavor Results

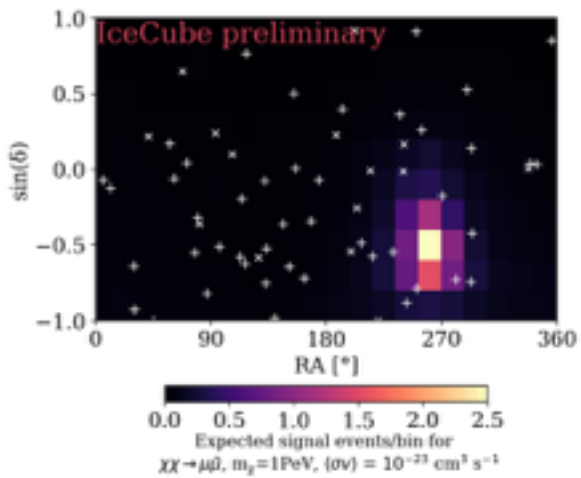
- Limits given per operator dimensionality. Dimension 6 is a Fermi-like interaction between the BSM field and neutrinos.
- Limits given for fixed initial flavor composition and given a BSM operator texture.
- No constraints obtained if the initial flavor composition is pion-based (1:2:0).
- First BSM physics constraints using astrophysical neutrino flavor information.
- Constraints can be reinterpreted in terms of other BSM physics since they have been expressed as effective operators.



Dark Matter Analyses Overview

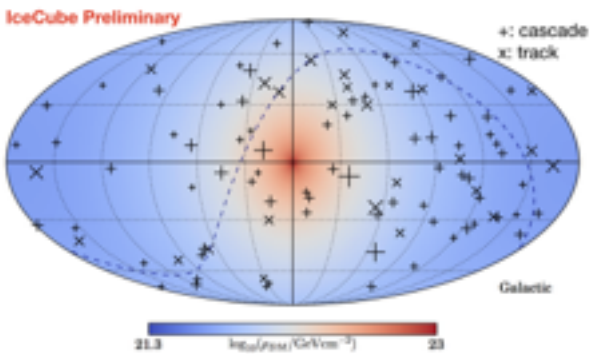
DM annihilation

- Heavy galactic DM self-annihilating into SM particles
- Expected ν excess peaked at the GC →Additional component added to the diffuse fit



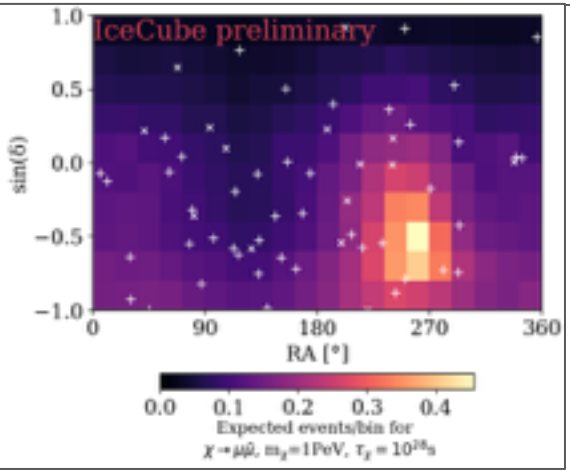
DM scattering

- Astrophysical vs scattering off light galactic DM
- Expected GC ν deficit →Modified the astro. component in the diffuse fit

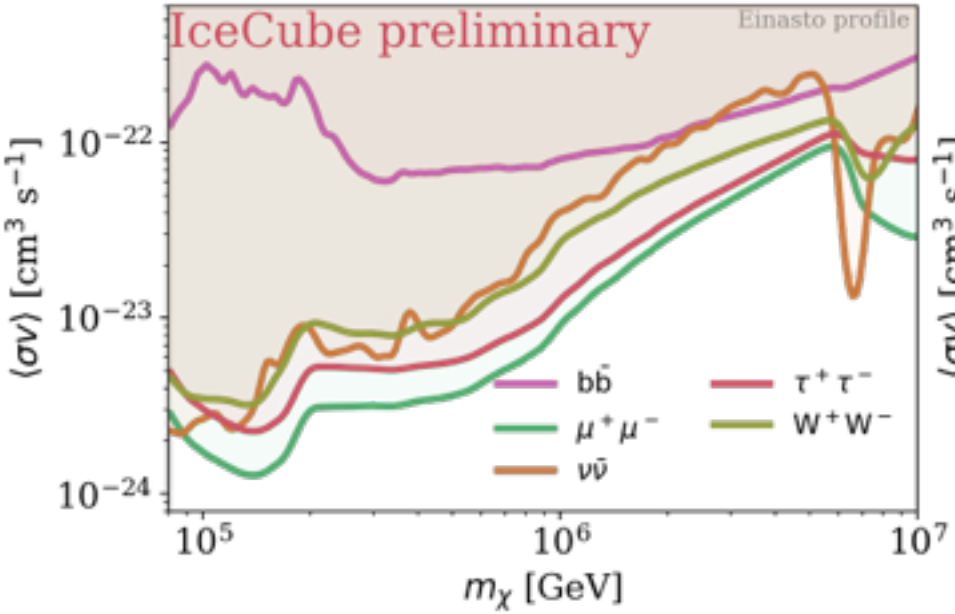


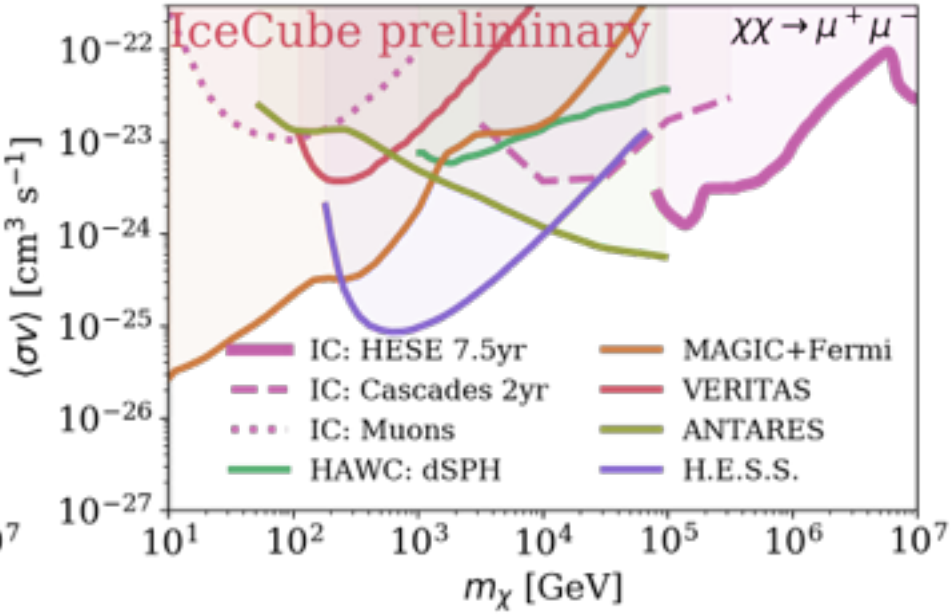
DM decay

- Heavy galactic or extra-galactic DM decaying into SM particles
- Expected anisotropic ν excess →Additional component added to the diffuse fit

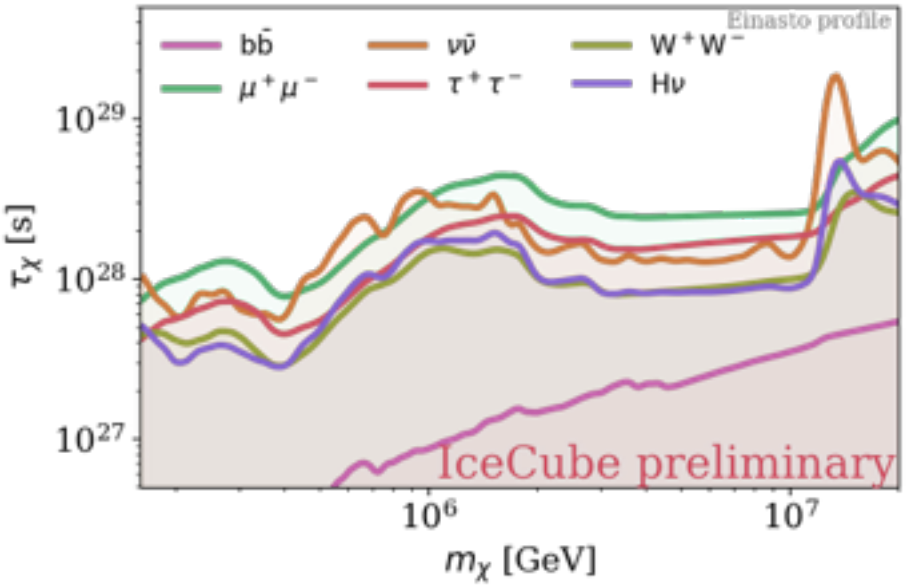


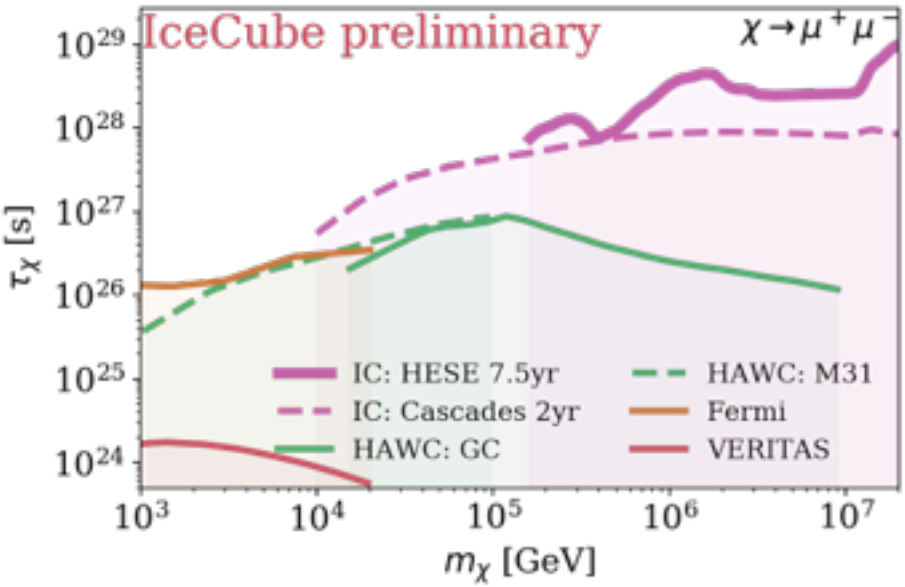
Dark Matter: Annihilation Limits



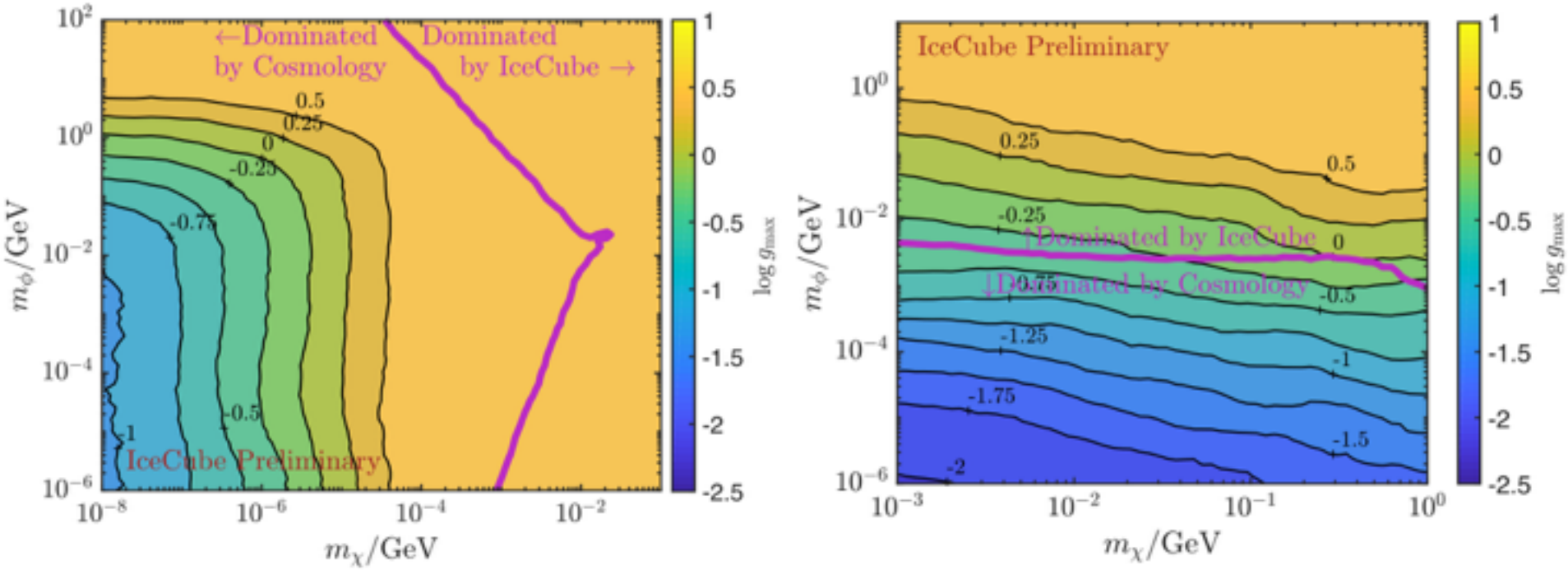


Dark Matter: Decay Limits





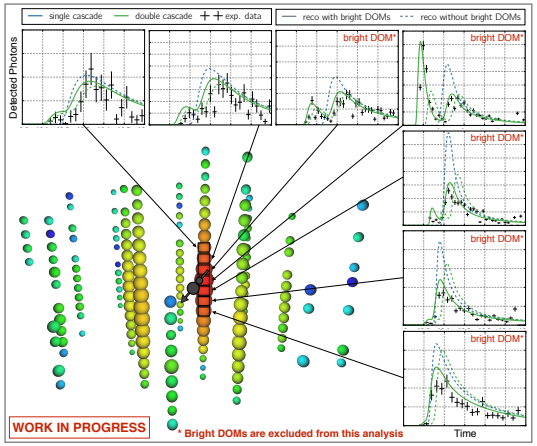
Dark Matter: Scattering Limits



Cosmological constraints from Escudero et al. (2016) using large scale structure.

Summary

- HESE analysis reworked with latest information
- Updated characterization of the astrophysical flux
- Algorithm-based ternary topology ID: Cascades, Tracks, Double Cascades
  - Identified 2 ν_τ candidate events
  - One of which shows obvious signatures of a double cascade
  - A posteriori analysis of the events is ongoing
- New limits on Lorentz violation and DM
- New cross section measurement



=?

- Extension to lower energies for precision measurements!
- MESE! Medium Energy Starting Events >1TeV

Updates & publications coming soon - STAY TUNED

BACKUP

Systematics Treatment

Systematic	HESE 6	HESE 7.5
Passing Fraction	GJKvS	APRSWY + uncertainties
Conventional/ Prompt/Muon Bkg	normalization	normalization
Ice Model	resimulation	model error
CR Spectrum*	n/	spectral index
Hadronic Model*	n/	included
pi/K ratio*	n/	included
Detector energy efficiency*	n/	included

*subleading systematics for astrophysical flux measurement

Plus:

- new fitting tools
- new SAY likelihood taking into account limited MC statistics

Improvements wrt. 6-year analysis

- Data reprocessing after recalibration of the detector:
  - single photon electron (SPE) peak shift → reconstructed energy decreased by ~5% on average
  - “Pass 2”
- Improved software:
  - minimizer tolerance decreased
  - various minor bugfixes
- Improved ice model “Spice3.2”:
  - better constrained bulk ice parameters
  - 25% higher anisotropy
  - holeice modeling
- New “SAY” likelihood:
  - takes into account limited MC statistics
- Now integral part of HESE:
  - events classified using ternary topology ID based on observables