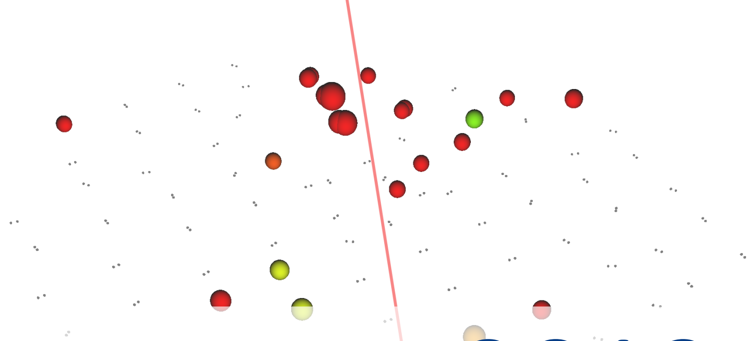
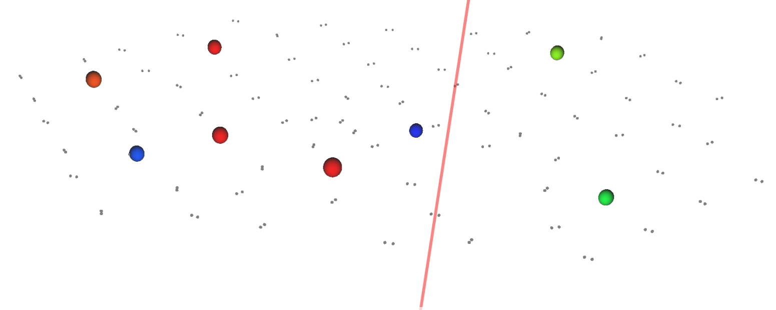
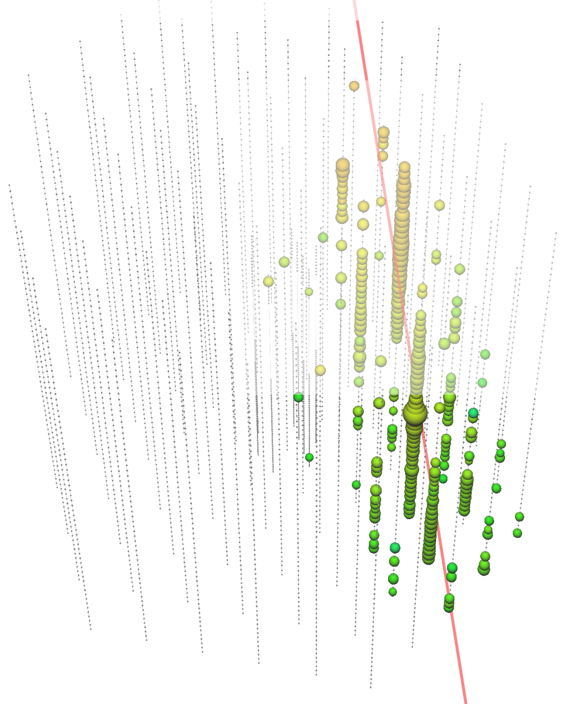




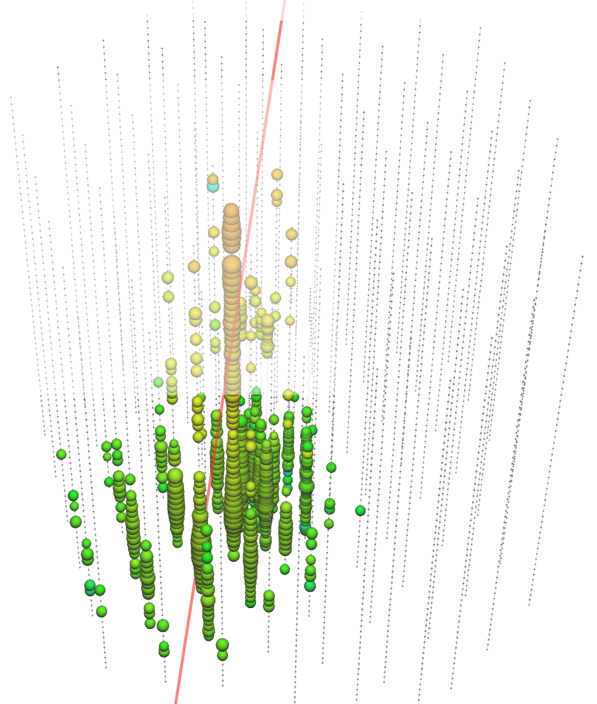
2012-2016 Unblinding Results: Performance of IceTop as Background Veto for Down-going Neutrino Events



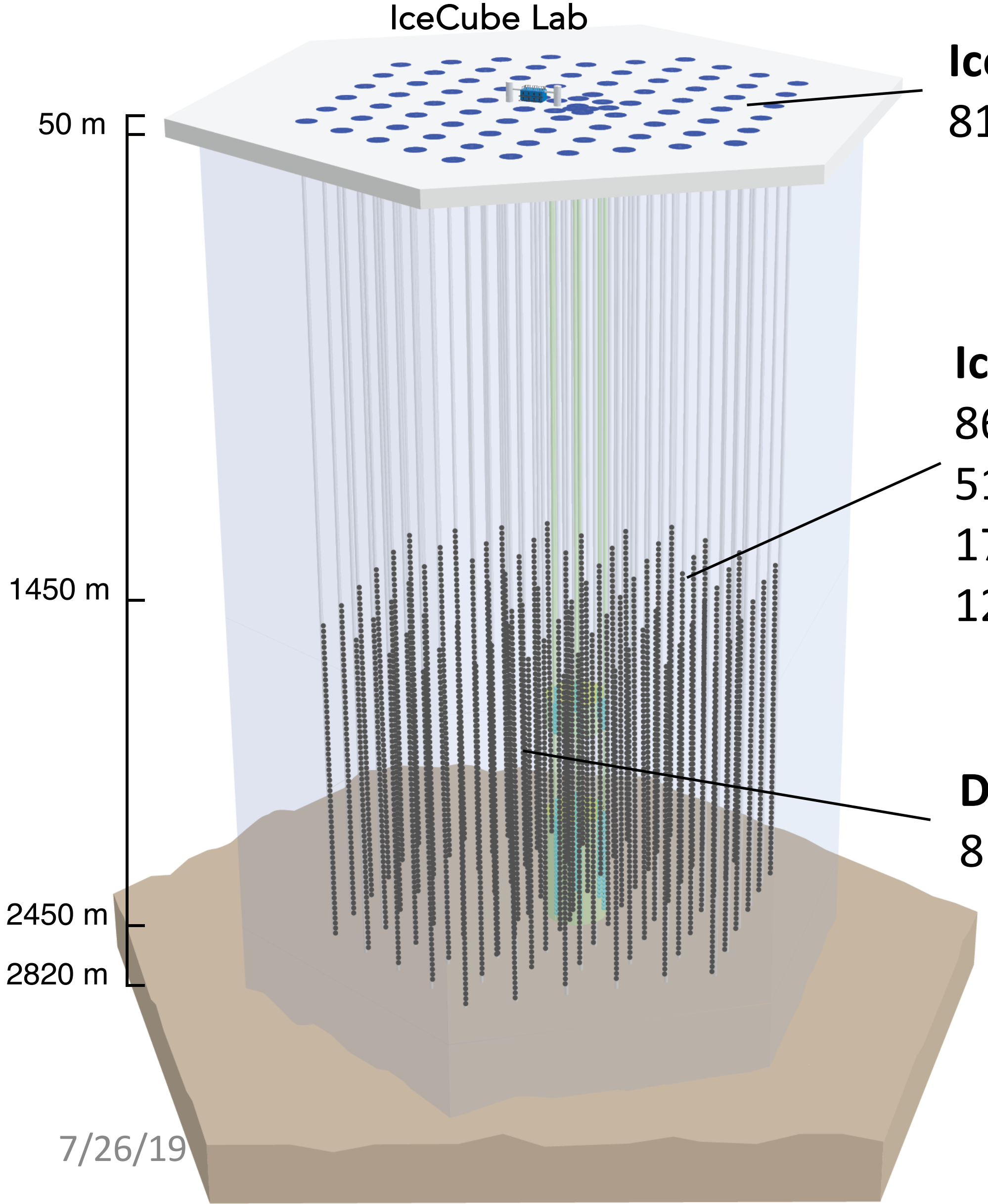
Delia Tosi[1] and Hershal Pandya[2]
for the IceCube Collaboration

36th International Cosmic Ray Conference
Madison, WI, USA, July 24th – August 1st 2019

1 WISCONSIN UNIVERSITY OF WISCONSIN–MADISON
2 UNIVERSITY OF DELAWARE



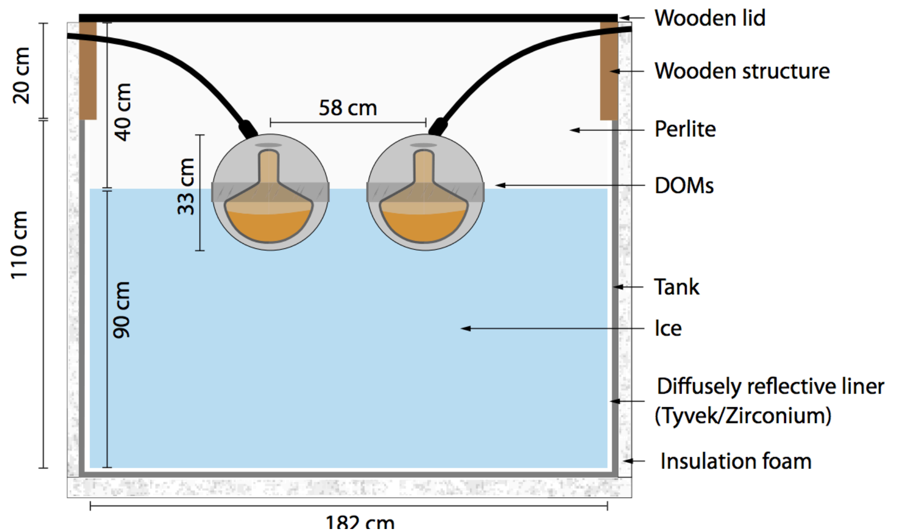
The IceCube Neutrino Observatory

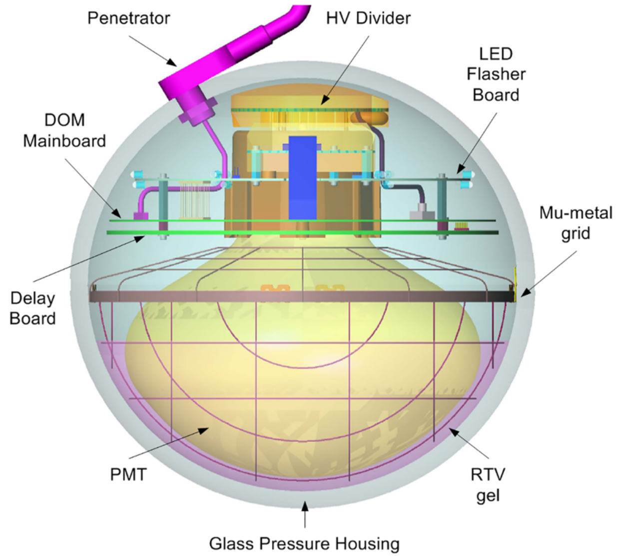


IceTop (CR physics)
81x2 tanks, 324 optical sensors

IceCube (completed in 2011)
86 strings (including DeepCore)
5160 optical sensors over 1 km^3
17 m vertical spacing
125 m horizontal spacing

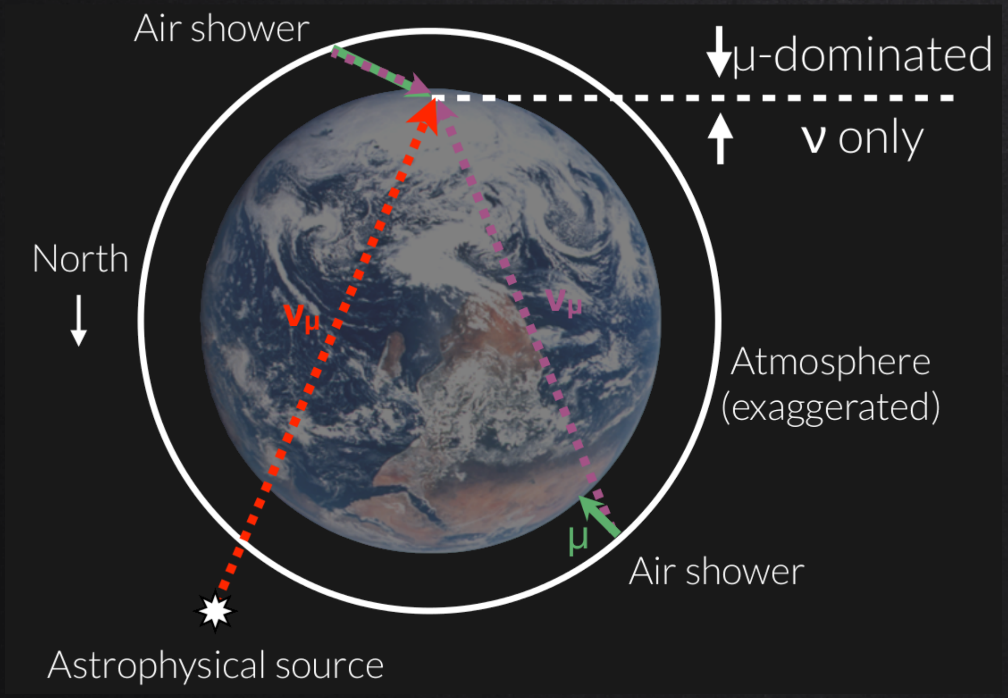
DeepCore (low energy)
8 strings, 480 optical sensors





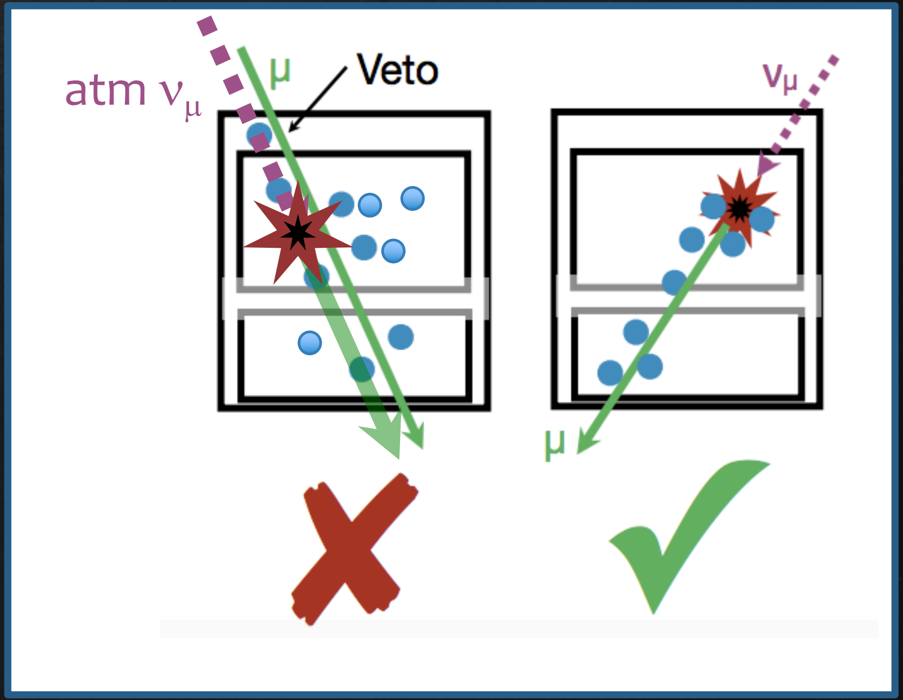
Astrophysical flux detection with IceCube

✓ Northern hemisphere
✓ Neutrino events above 100 TeV μ energy:
- Astrophysical: ~10 events/yr
- Atmospheric: ~10 events/yr



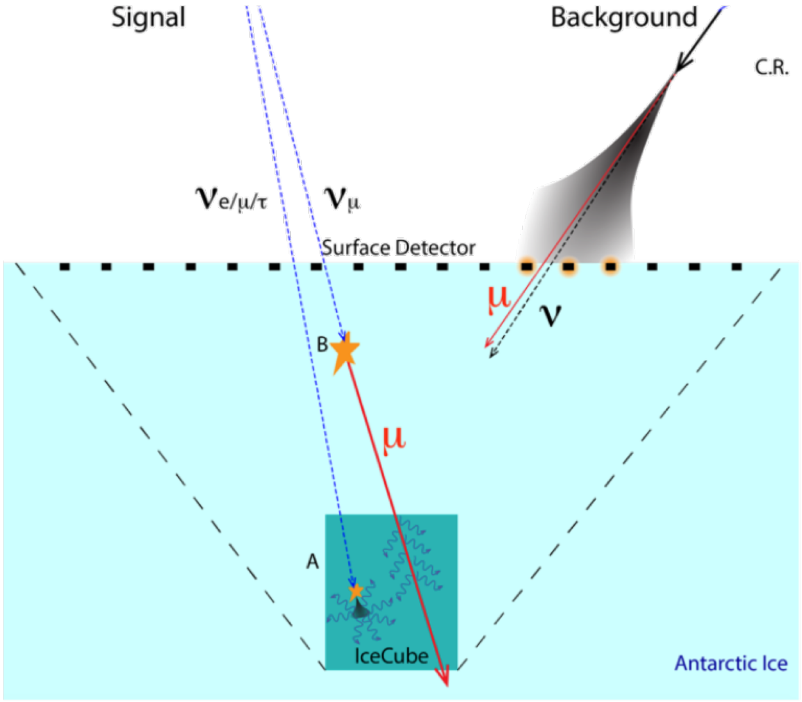
✓ Mostly Southern hemisphere
✓ Neutrino events above 60 TeV:
- Astrophysical: ~8/yr
- Atmospheric: ~5/yr

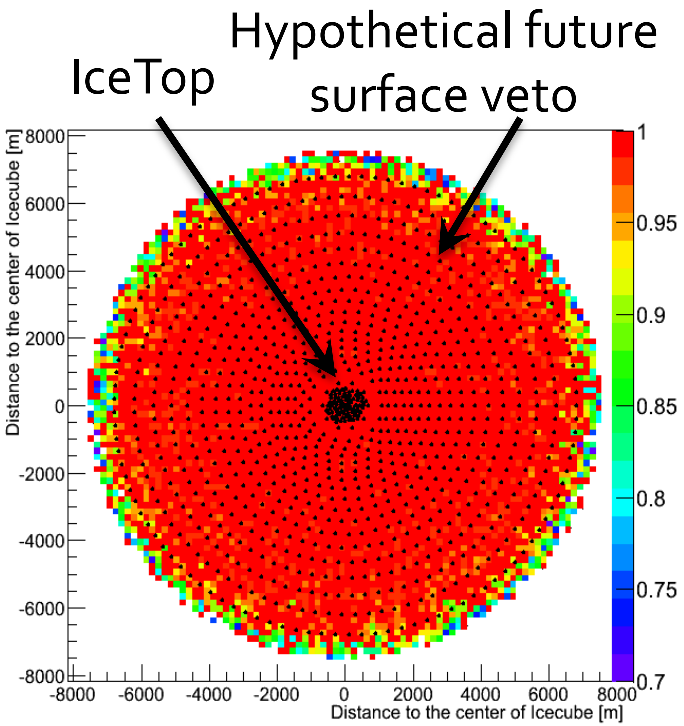
- Interactions inside the detector are more likely to be due to neutrinos, as opposed to penetrating muons
- Effective selection of all flavors neutrinos above 60 TeV

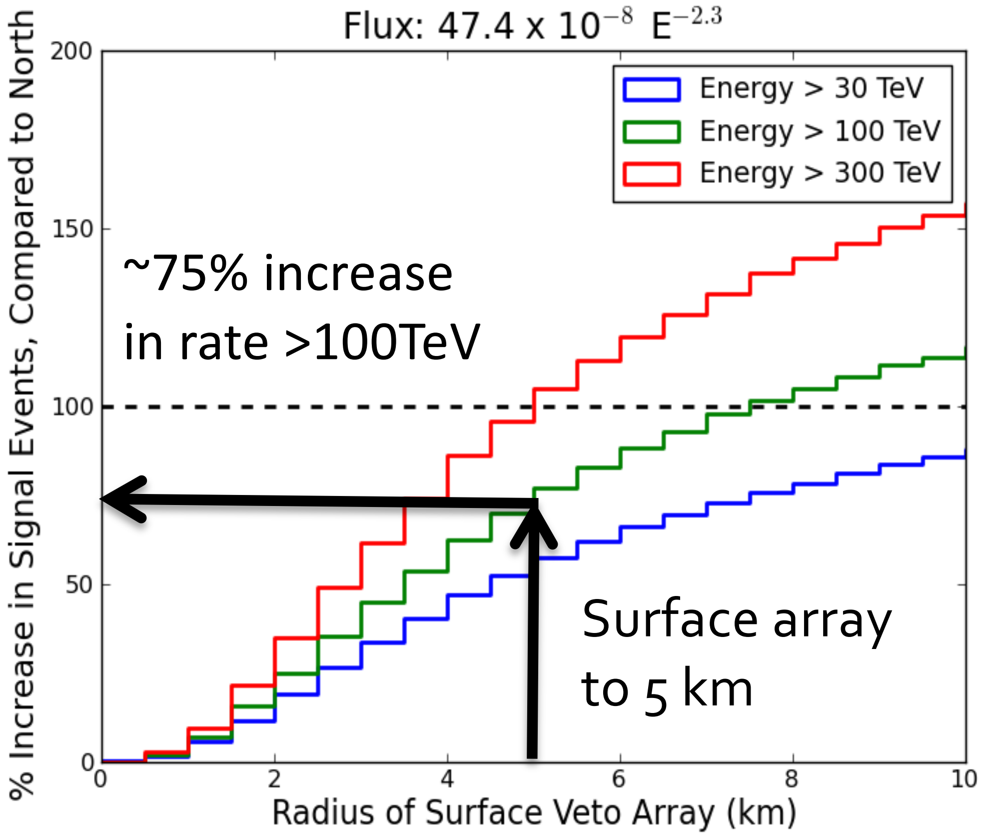


Surface veto motivations

"Catch" more astrophysical neutrinos from the Southern Hemisphere



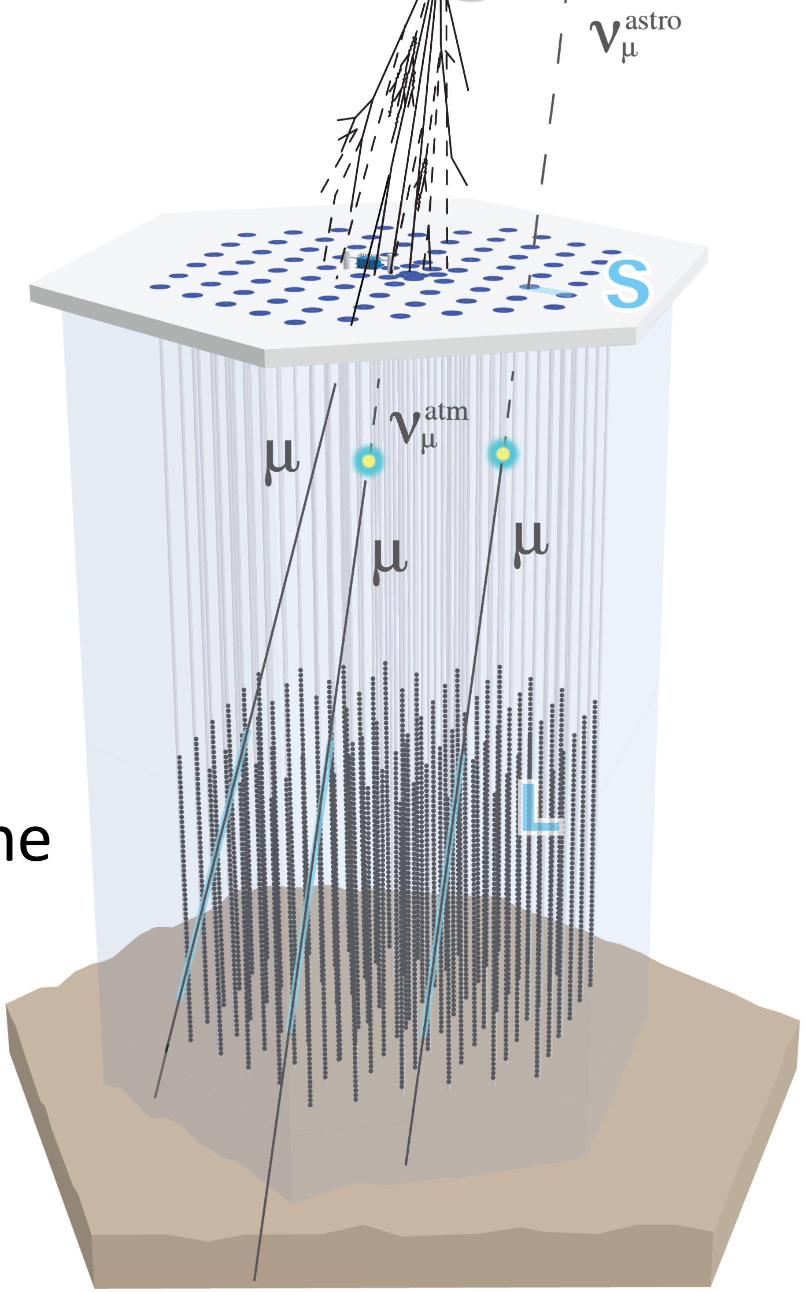




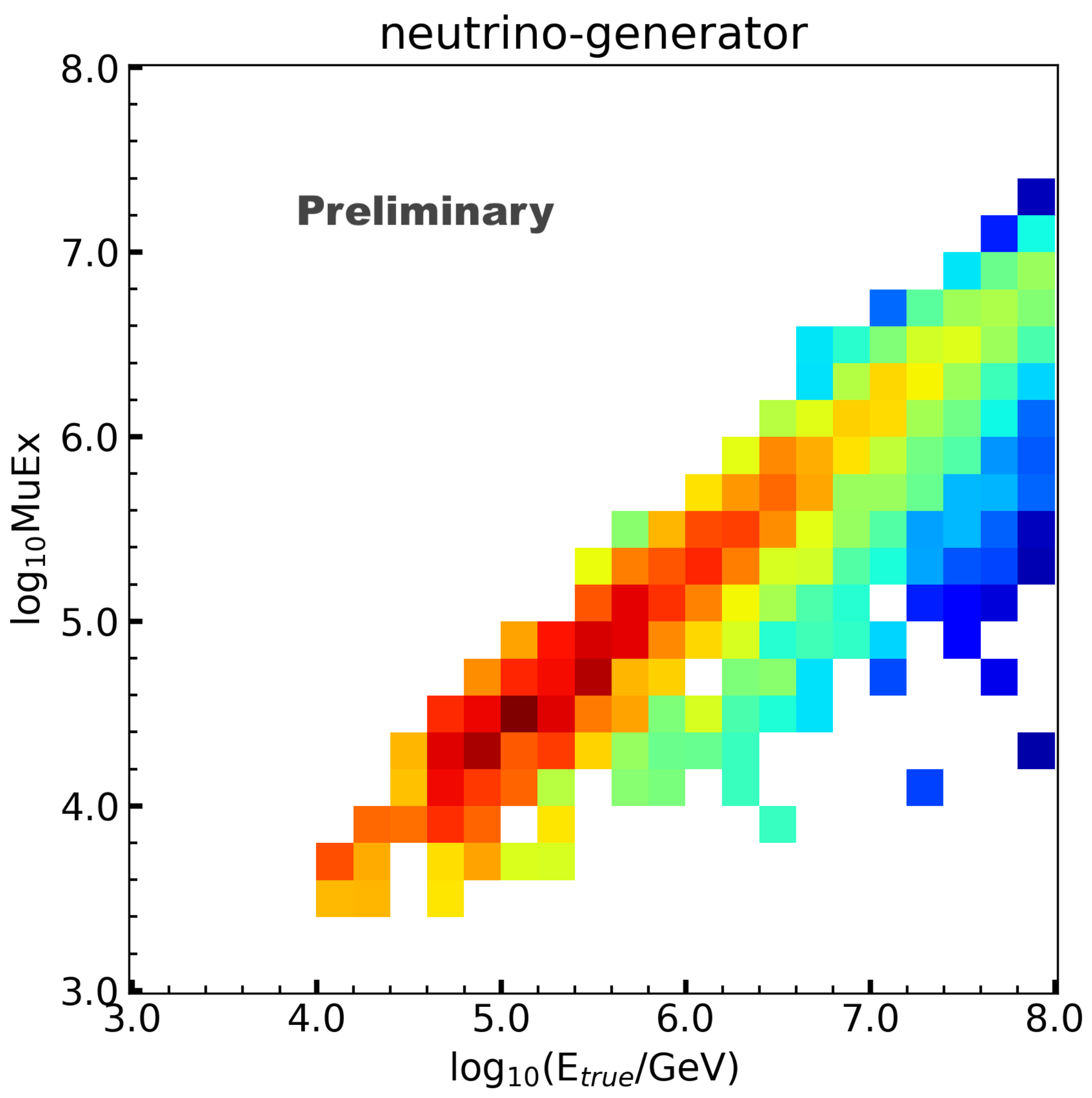
- Small solid angle subtended by IceTop from IceCube prospective, low number of events expected
- Analysis is a proof of concept to evaluate IceTop veto capabilities and to inform a large surface array

Analysis basic principle

- Look for IceTop hits correlated to the reconstructed muon track
- A first guess method is to count IceTop hits in a time window
- This method uses a likelihood ratio test that utilizes all the information available from IceTop:
  - charge recorded by each IceTop DOM
  - distance of each IceTop DOM (with or without a recorded hit) from shower axis
  - time of IceTop DOM hit with respect to the shower time
- Data selection: bright, well reconstructed muon tracks (L> 800m) that are well contained in IceTop (S>60 m or more from the edge)



Energy proxy



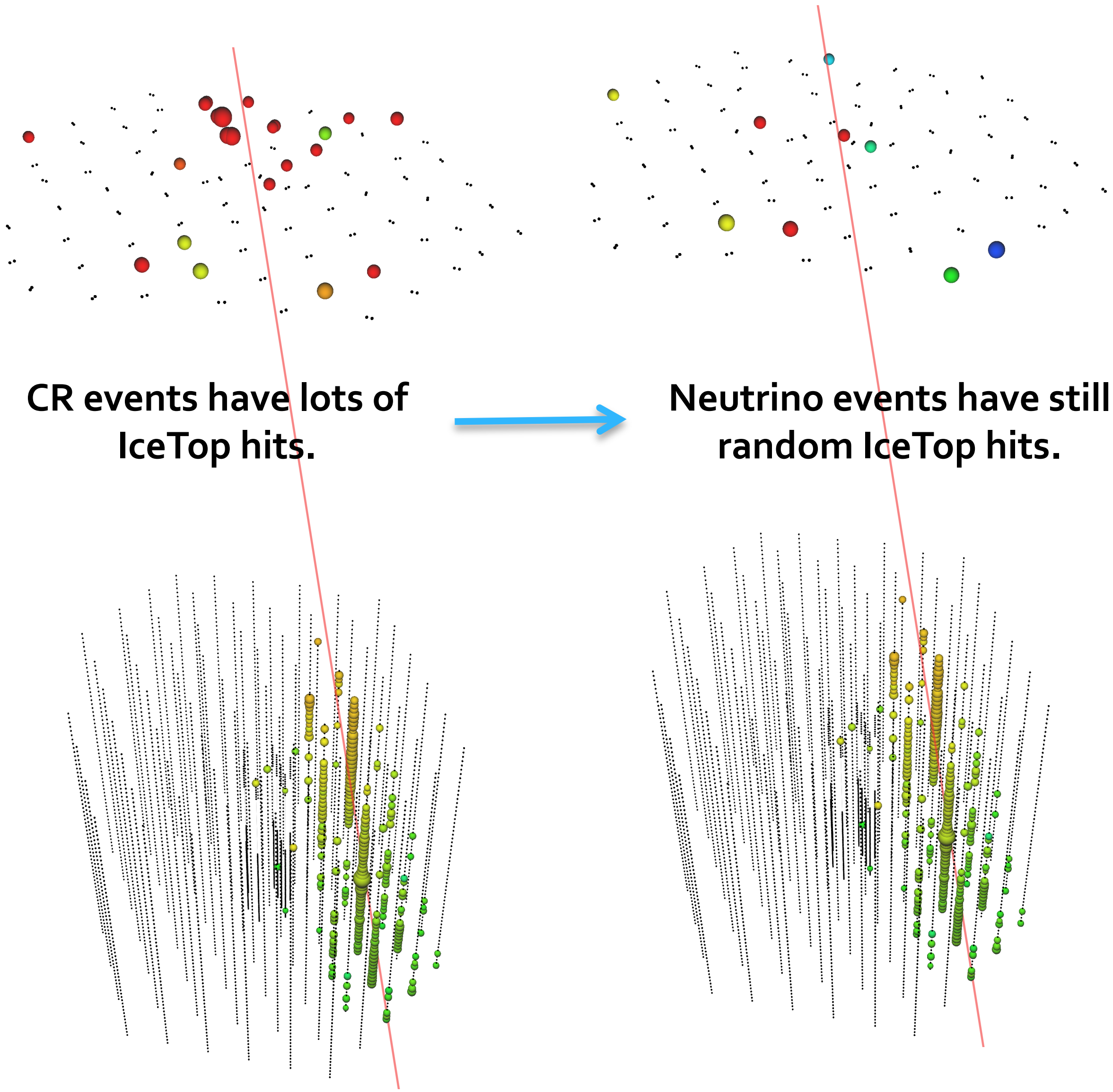
- Analysis based on energy proxy called "MuEx"
- the expected number of photons is fit via an analytic template which scales with the energy of the muon
- accounts for energy losses outside the detector
- more accurate than a simple sum of the DOM charges
- Mapping to neutrino energy depends on analysis cuts

IceTop Neutrino "simulation"

- Fixed Rate Triggers (FRT) contain the ideal random hits events
  - Excluding IceTop Triggers

- To create "neutrino-like" events we take a regular CR muon track, and replace IceTop hits with a FRT "snapshot"

- Snapshots from FRT taken from the same run as muon track
  - Reproduces atmospheric , snow and detector effects



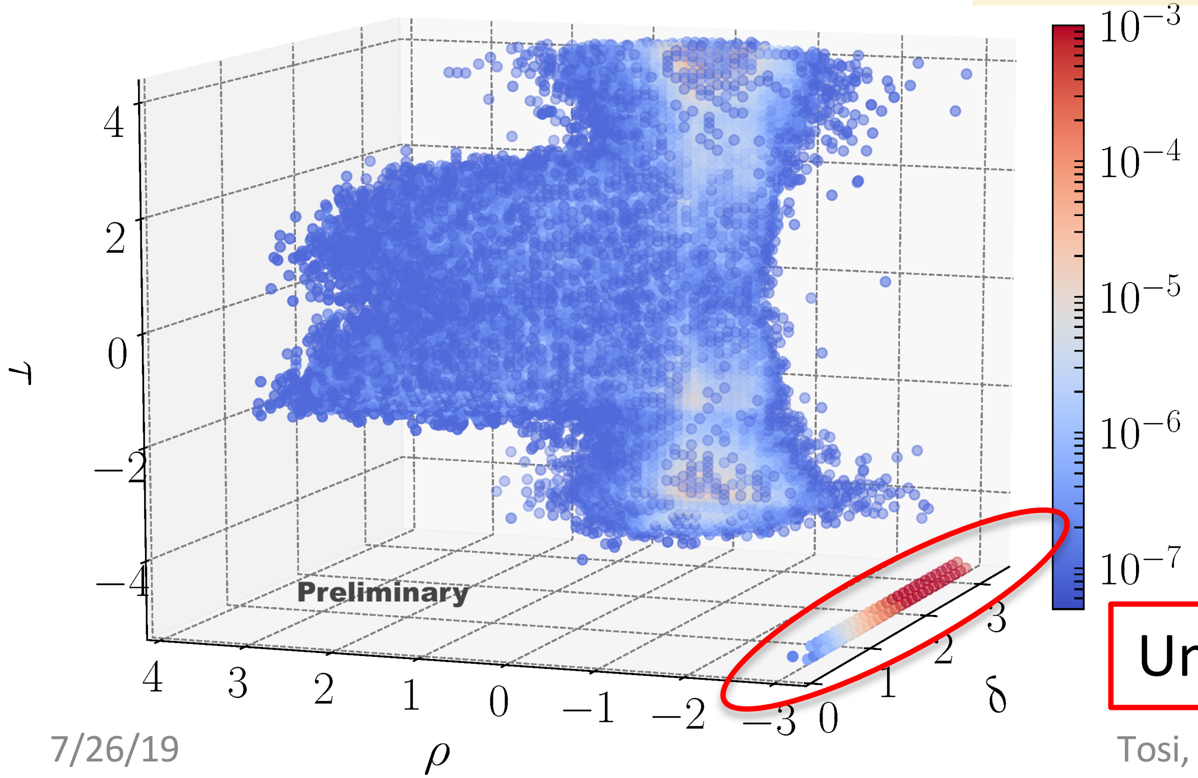
Neutrino and CR Hypotheses

Three variables define the 3-D PDFs

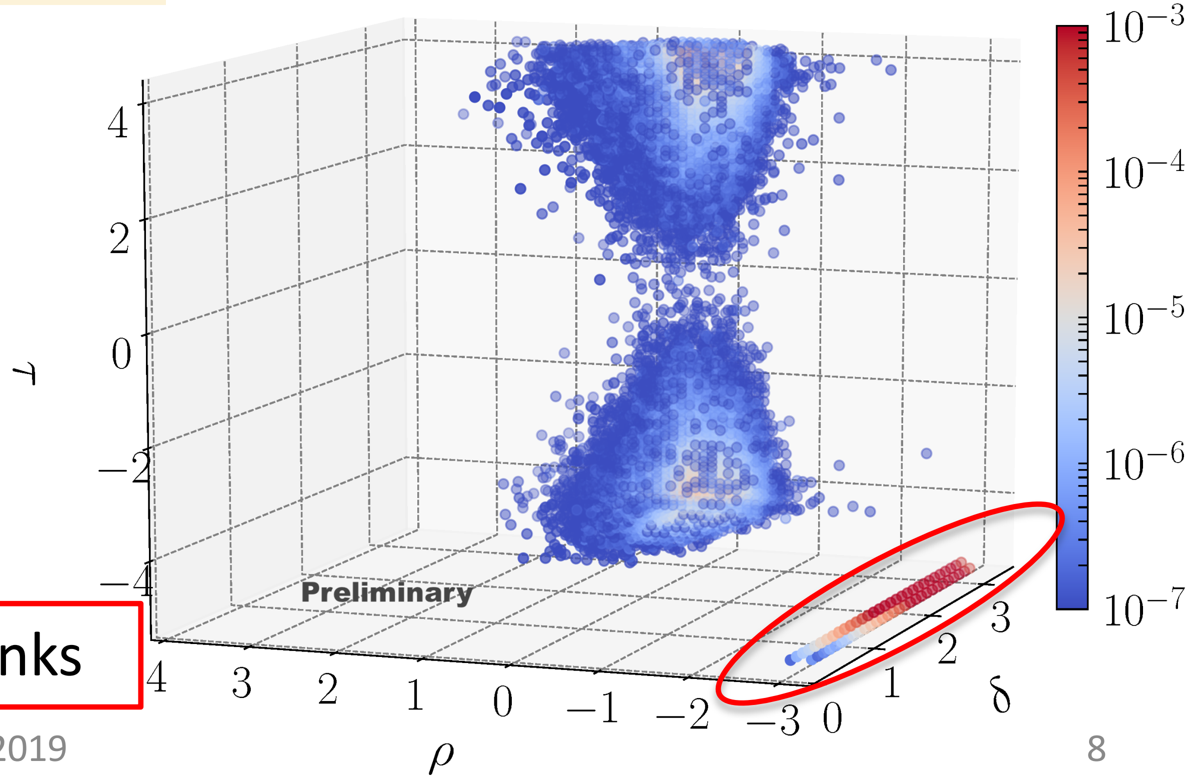
- Dim1: $\rho = \log_{10}$(Tank Charge / VEM)
- Dim2: $\delta = \log_{10}$(Lateral Distance+1 /m)
- Dim3: τ=sign(dt) $\log_{10}$(|dt|/ns +1)
  dt=Time offset w.r.t. shower-front

$4.2 \leq \log_{10}(\text{MuEx}) < 4.6$
$0.96 \leq \cos(\theta) < 0.98$

Cosmic Ray PDF



Neutrino-like PDF

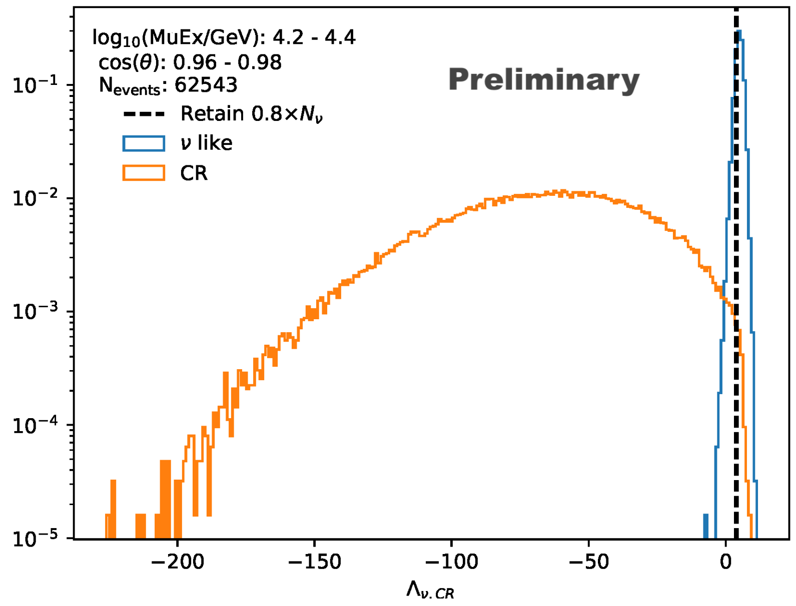


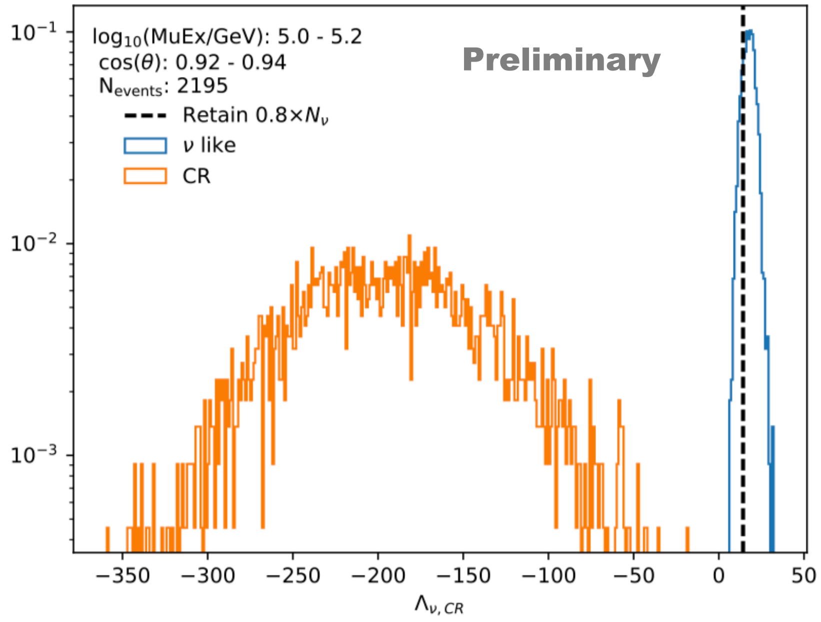
UnHit tanks

IceTop Log-likelihood Ratio

$$LLHR = Log_{10}\left(\frac{\prod_{i=1}^{162} P(Q_i, T_i, R_i \mid H_\nu)}{\prod_{i=1}^{162} P(Q_i, T_i, R_i \mid H_{CR})}\right)$$

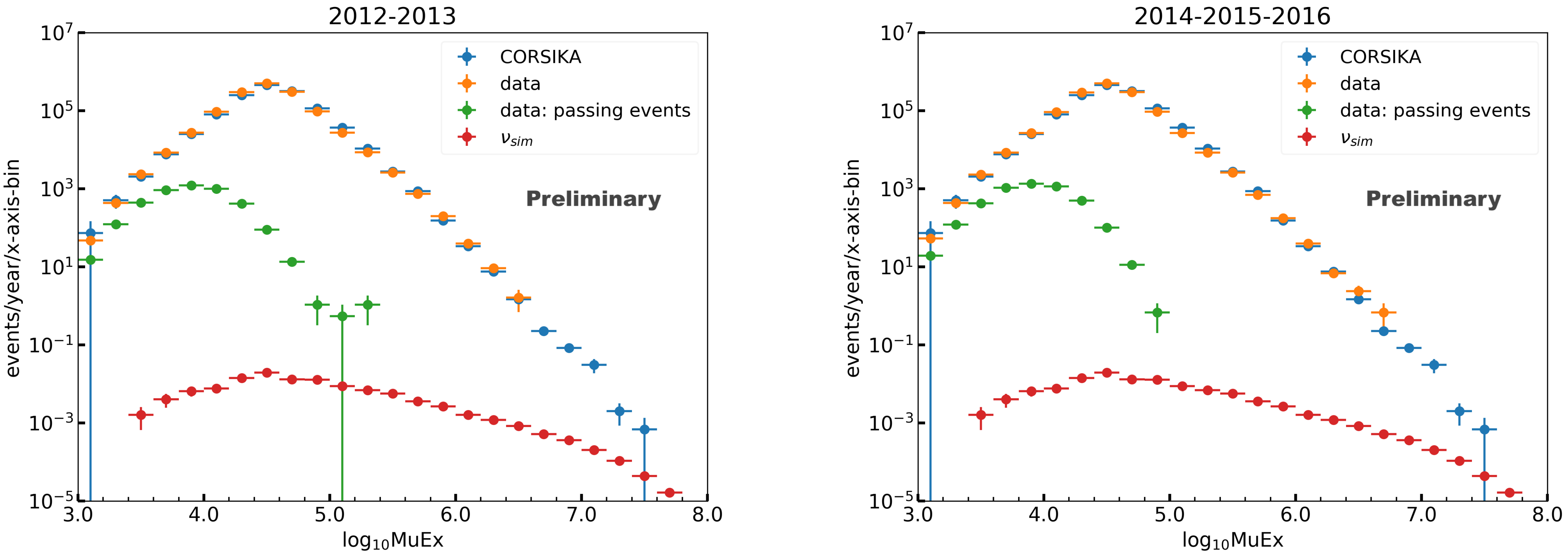
- Hit, Unhit and Excluded tanks contribute to the likelihood
- Shower properties vary with energy/zenith
  - H_ν , H_{CR} are constructed for each log(MuEx) and Cos(Zen) bin
    - $\log_{10}$(MuEx) : 3.0 to 7.0 in bins of 0.2
    - Cos(Zen): 1.0 to 0.86 in bins of 0.02
- Cut fixed using Nu-like LLHR distribution
  - 80% Nu-like retention for log(MuEx)< 5.2
  - 99.9% Nu-like retention for log(MuEx) ≥ 5.2





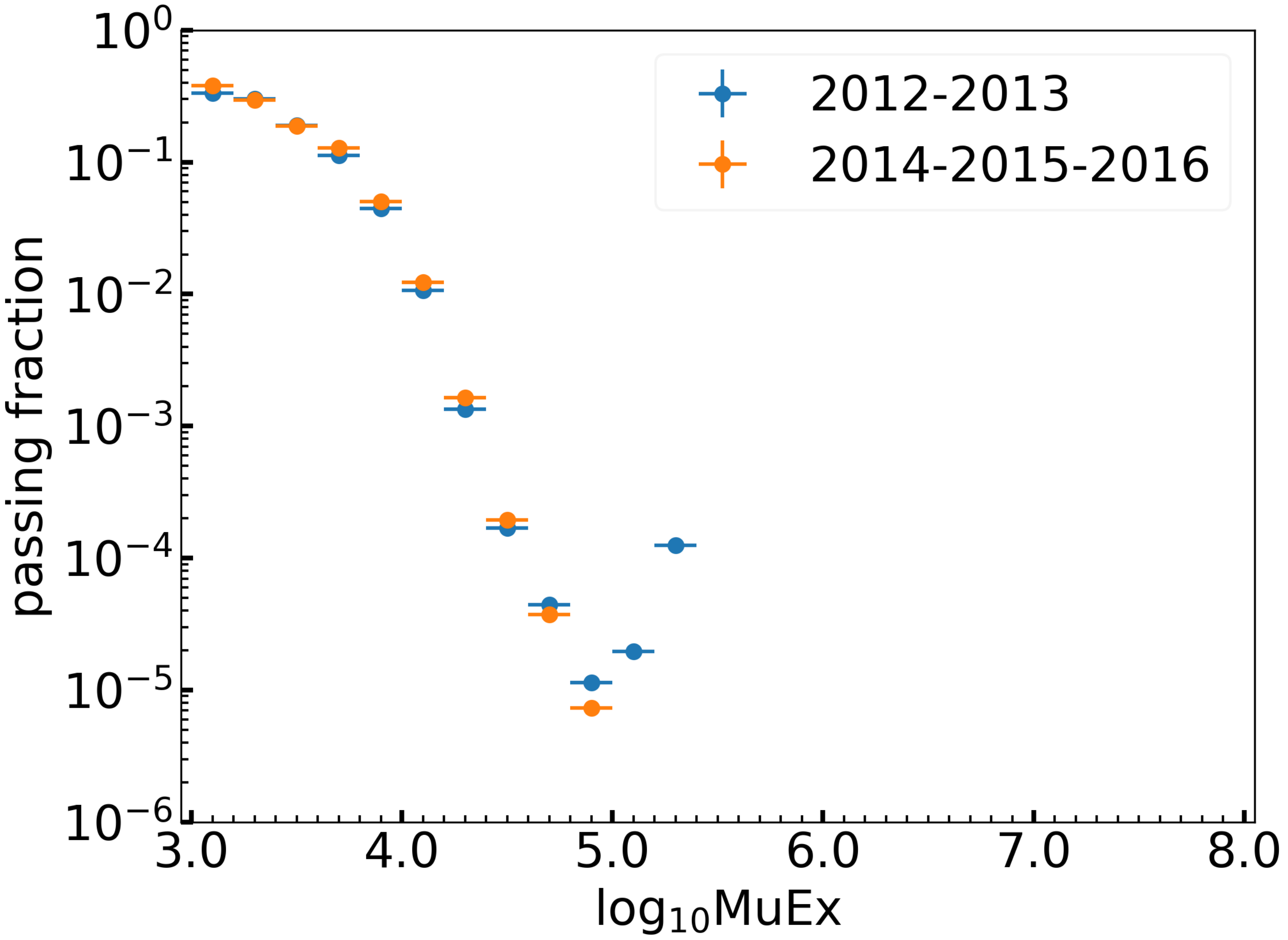
Results: counts/year vs muon energy proxy

Analysis done on each year, presented here as 2012-2013 and 2014-2015-2016 (detector compatibility and similar passing rates)



muon energy proxy

Cosmic rays passing fraction



CR passing fraction calculated as

$$passing\ fraction = \frac{\#\ passing\ events}{\#\ total\ events}$$

assuming that all the passing events are cosmic rays sneaking through the veto

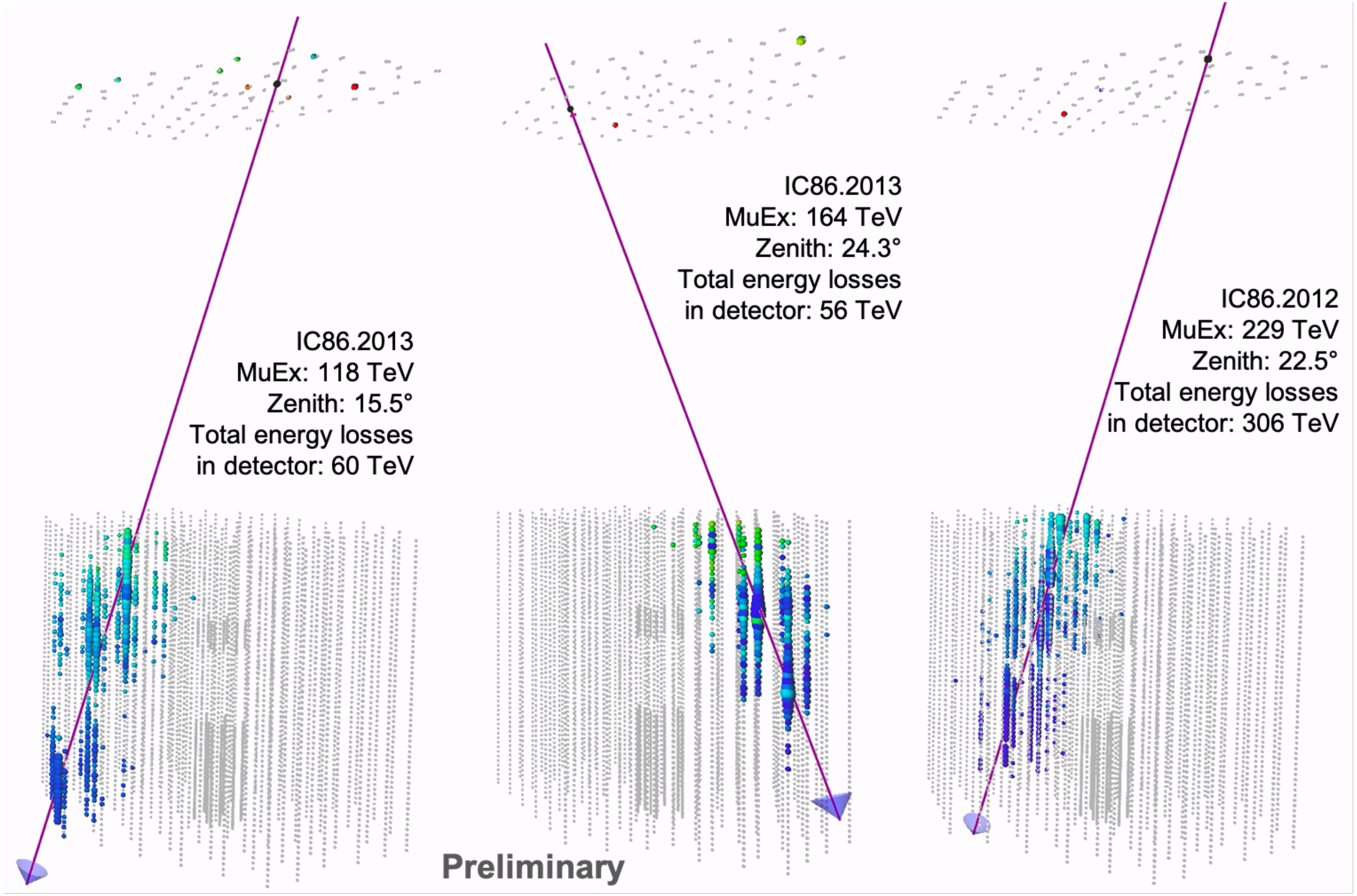
At $\log_{10}$(MuEx)≥4.8 reaches values of:

- 2e-5 (2012/2013)
- 5.2e-6 (2014/15/16)

Veto Efficiency = 1 - passing fraction

5.2e-6 passing rate is equivalent to 99.999% efficiency (1 event / ~190k)

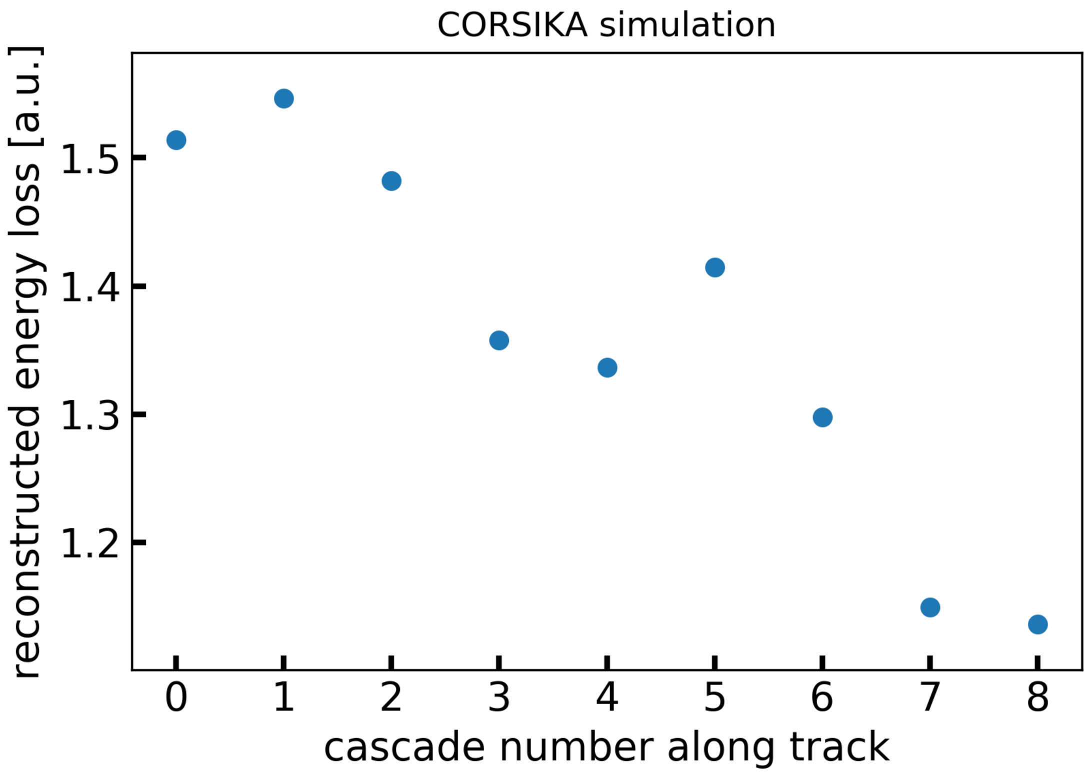
Three highest energy passing events

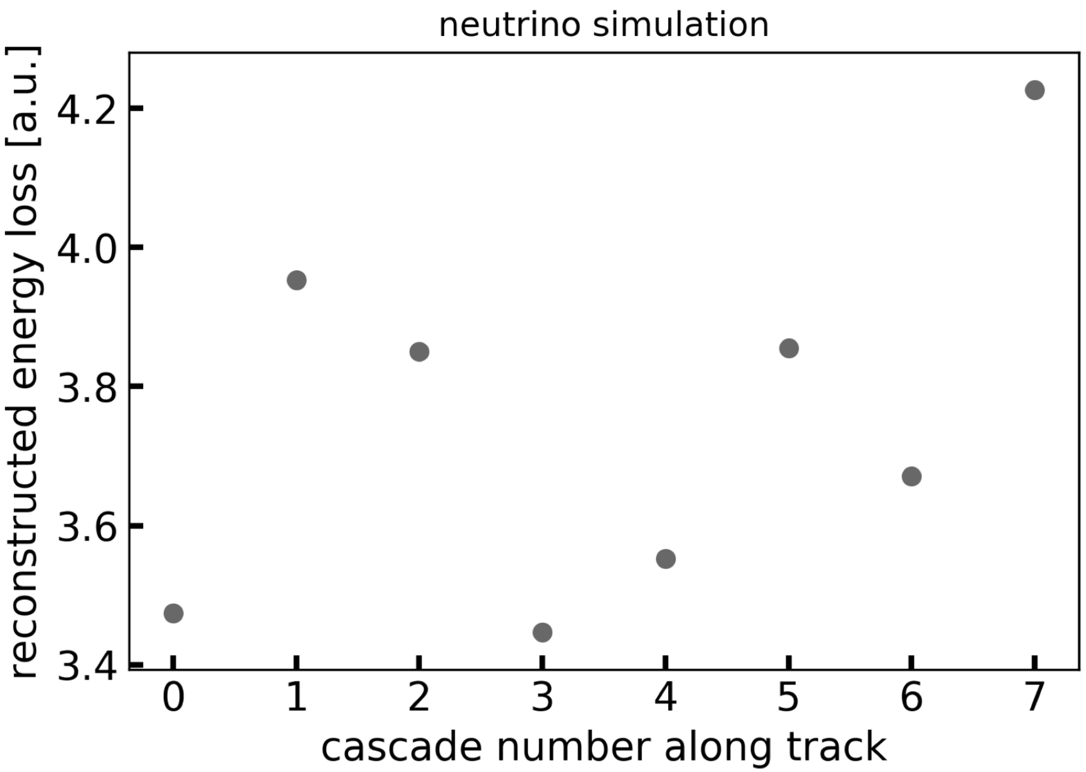


Stochasticity

Single muons exhibit more stochastic energy losses than muon bundles

Examples of energy losses along track from simulation for two similar energy events



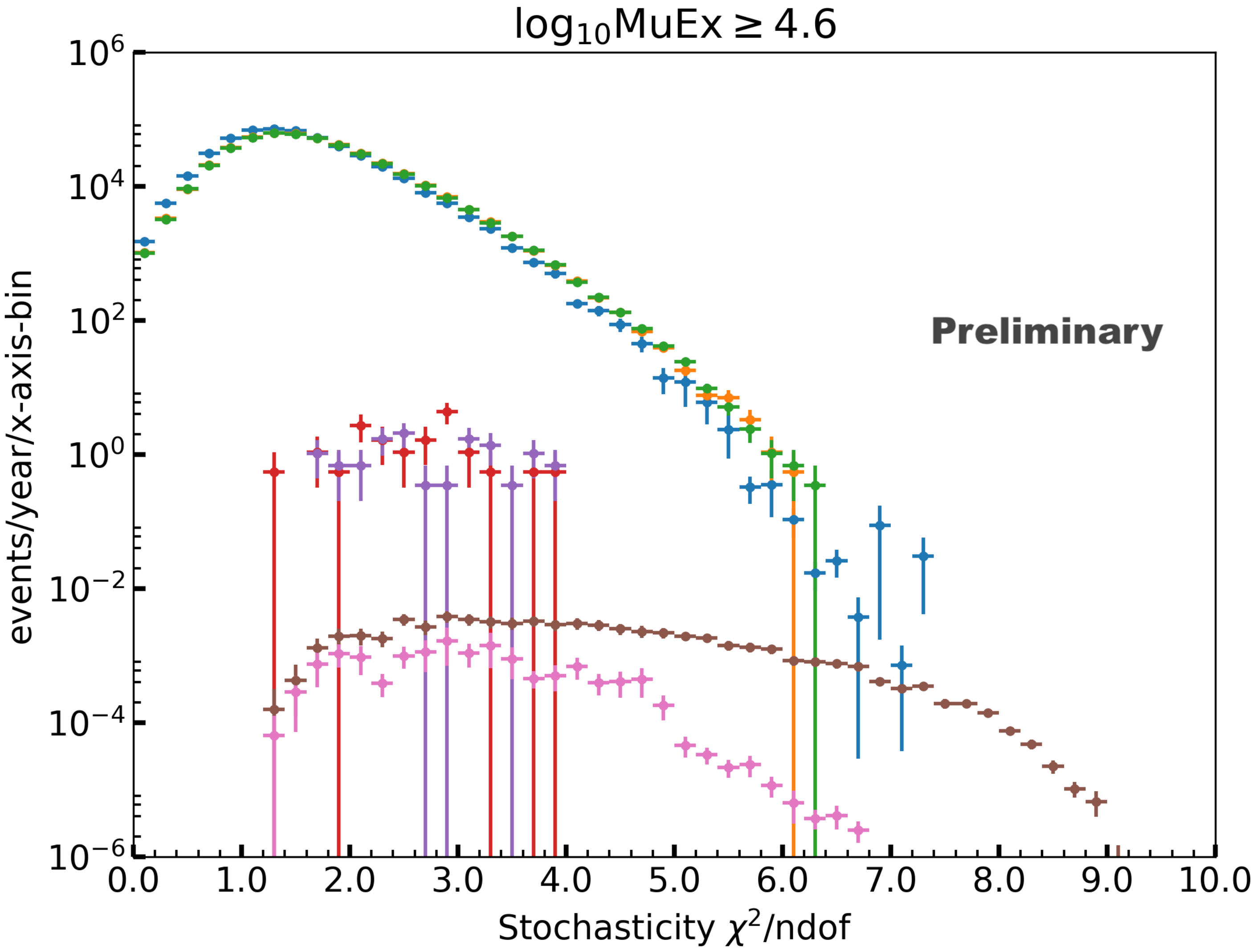


Fitting with a linear function: $\frac{dE_\mu}{dx} = A + BE_\mu$ will yield:

Low chi square

High chi square

Stochasticity



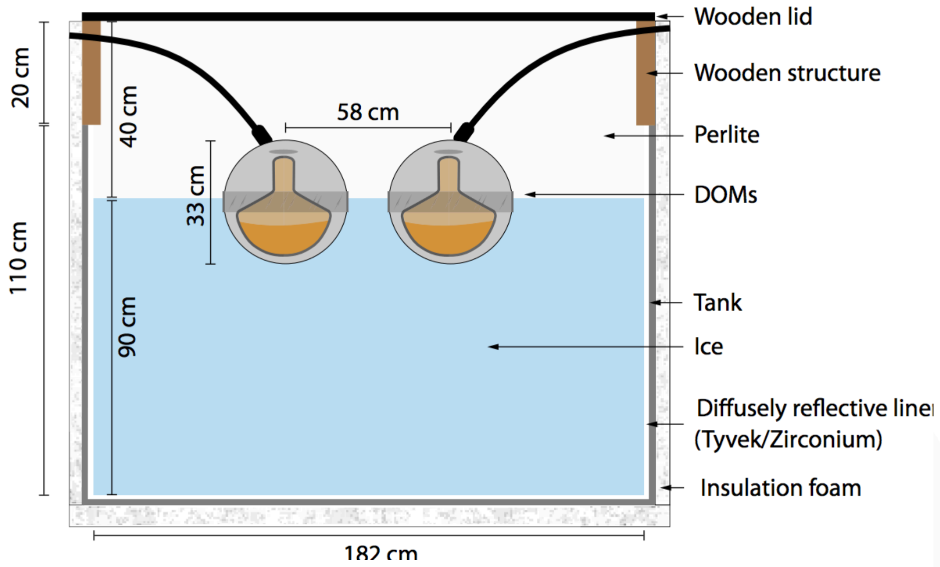
Passing events from center of both distributions

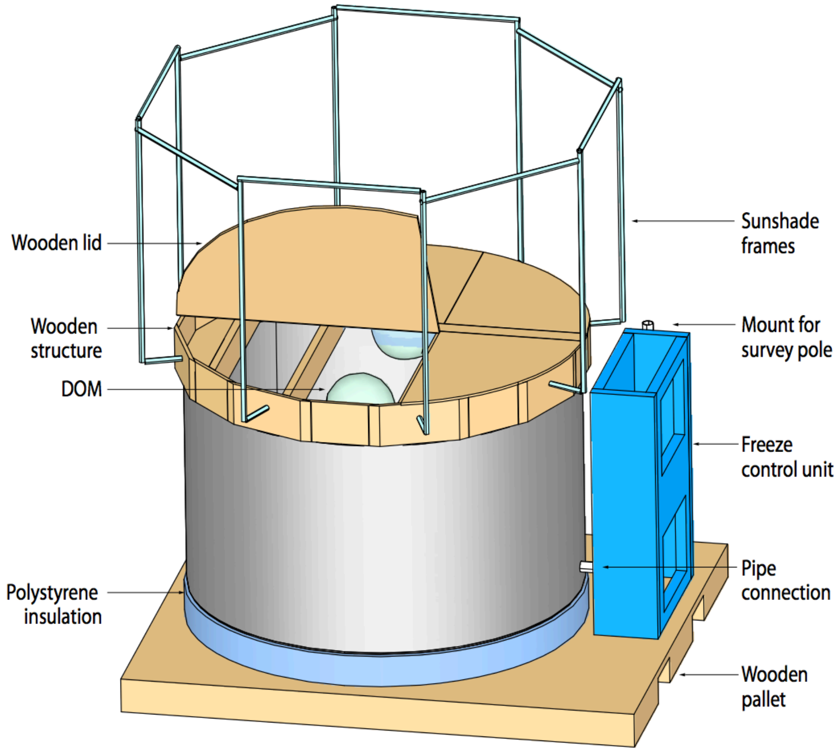
Conclusions

- Method rejects muons as produced by showers which are not immediately recognizable as such by IceTop standard reconstruction methods
- Efficiency depends on energy, reaches values of 2e-5 and 5.2e-6 above muon energies of 60 TeV (neutrino energies of ~ 100TeV – with quite large uncertainty)
- A few astrophysical neutrino candidates have been found and a targeted simulation is necessary to calculate the random occurrence of such events
- Selection criteria can be tuned for real-time alerts to desired number of candidates/year

Backup

IceTop: the current surface array





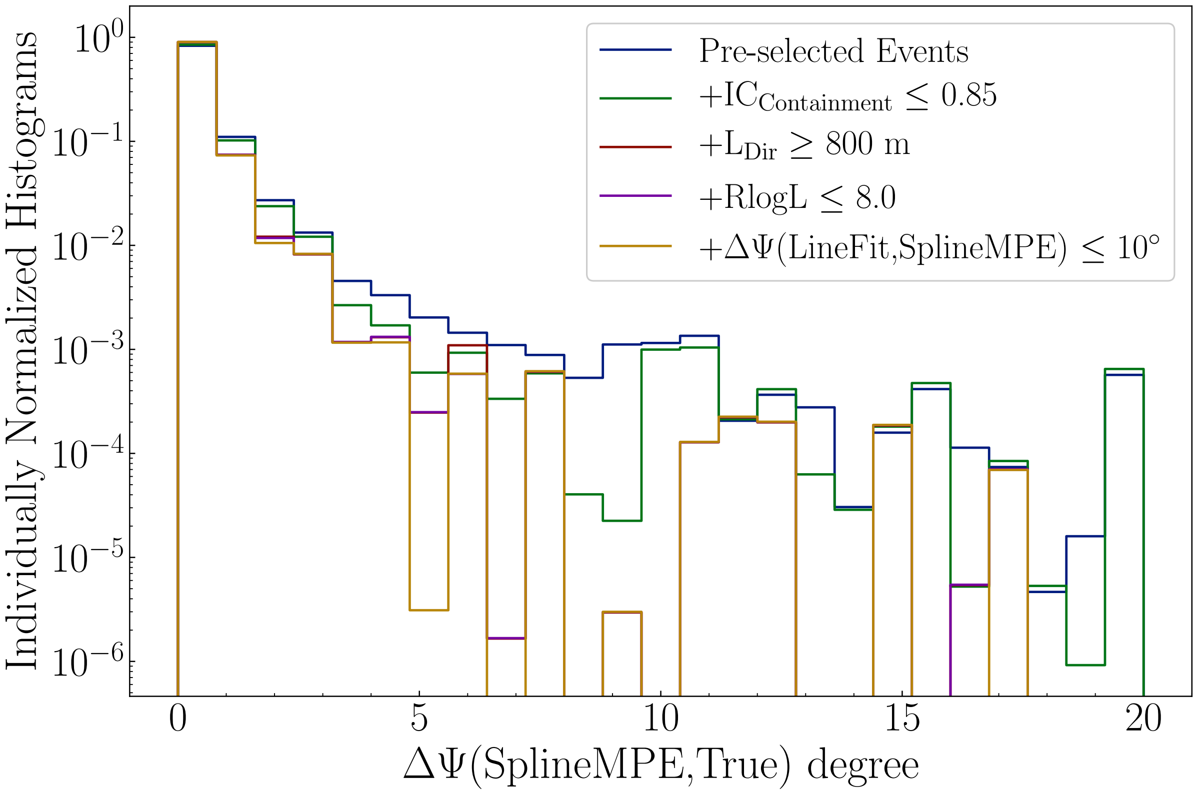
- 162 frozen water tanks, with two digital optical modules each
- 2 tanks in proximity of each string
- Slow, controlled refreezing process to guarantee clear ice
- primary goal: cosmic ray physics

Event Selection and Processing

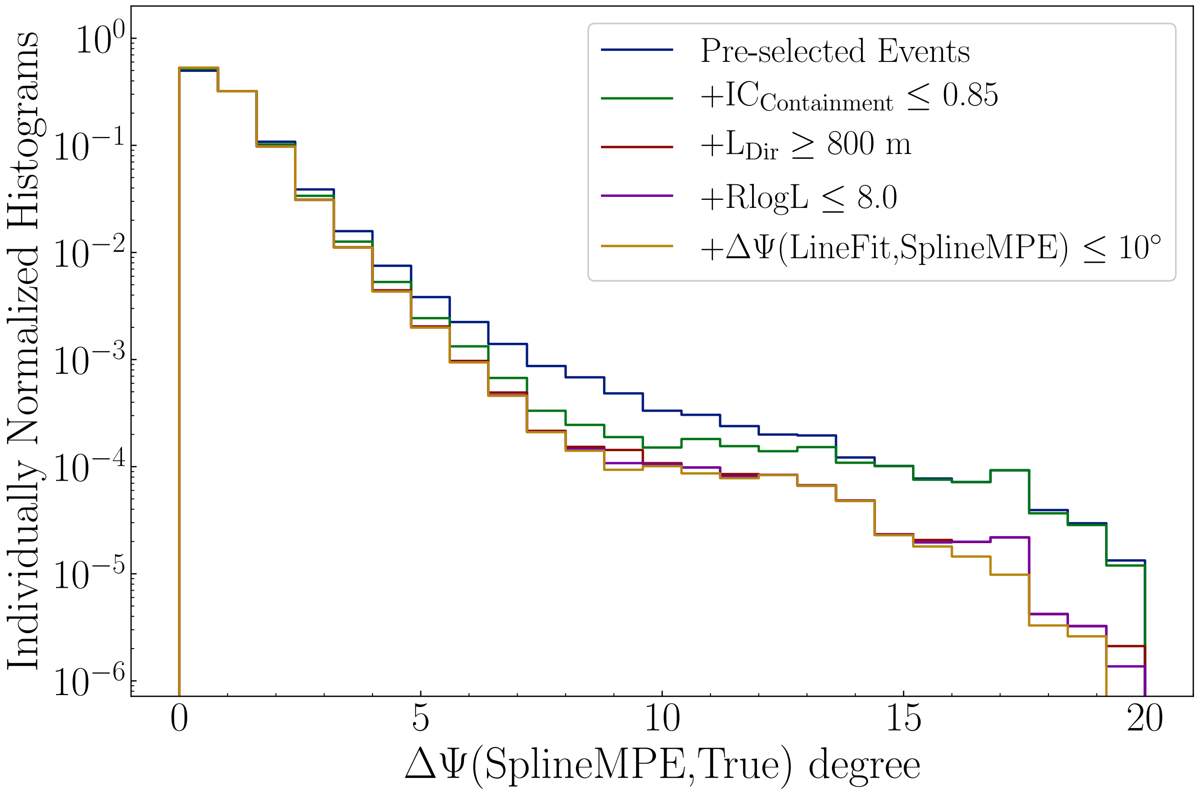
- Select well reconstructed down-going tracks intersecting the area defined by the IceTop perimeter:
  - In-Ice triggers
  - Homogenized Charge ≥ 1000 P.E.
  - Down-going reconstructed track
  - Track intersects IceTop at least 60 m inside from the edge
  - The point on the track, nearest to the center of the in-ice detector, must be located within the inner 85% volume of the detector.
  - Track length needs to be ≥ 800m
  - Events with ambiguous reconstructions are thrown away
- Cuts checked against CORSIKA and NuGen

Quality Cuts: angular resolution

NuGen Weighted To $E^{-2.13}$

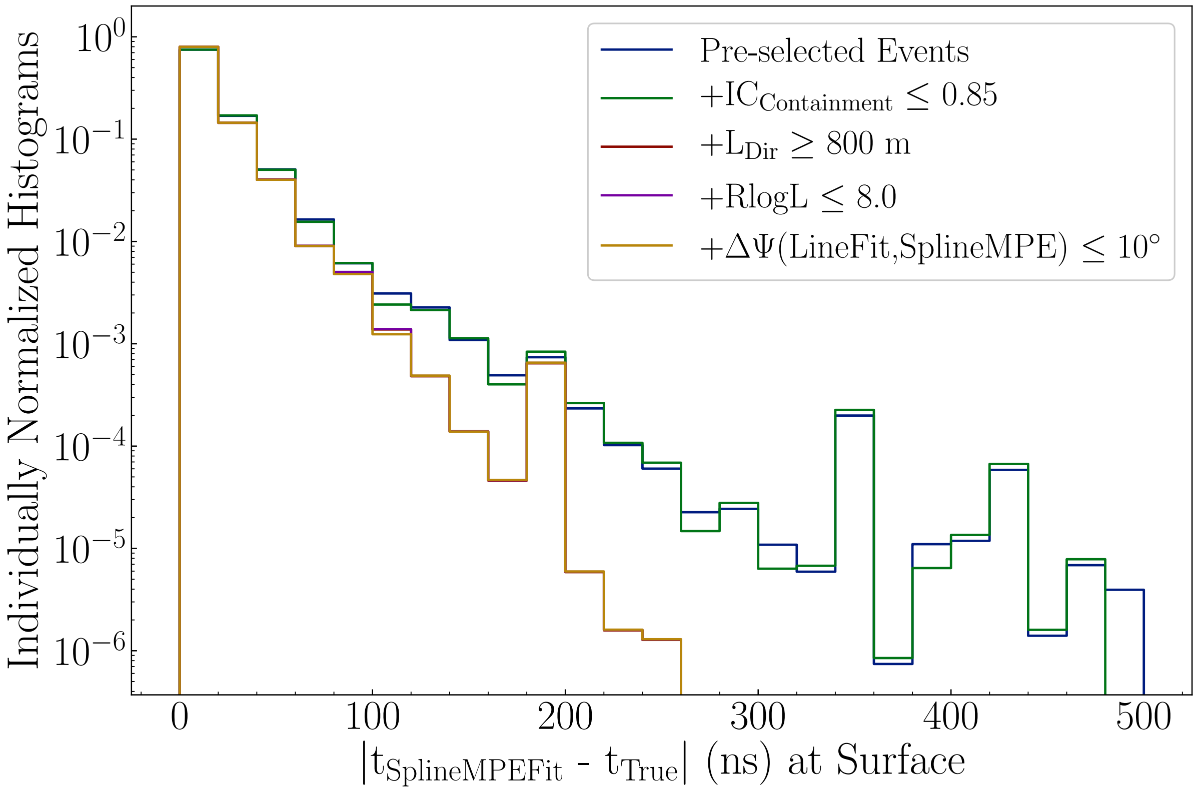


CORSIKA Weighted to H3a

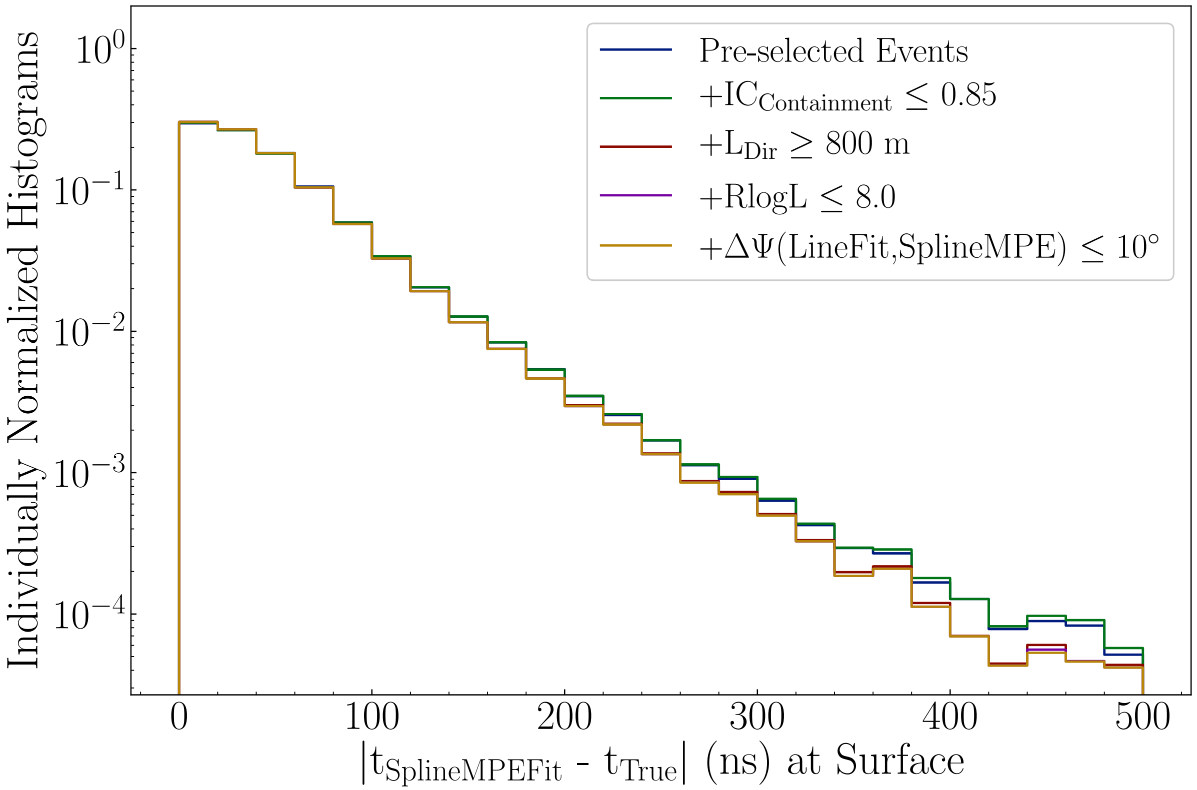


Quality Cuts: time at surface

NuGen Weighted To E$^{-2.13}$



CORSIKA Weighted to H3a



Passing & total events in each sample

Counts in sample	$4.0 \le \log_{10}(MuEx) < 4.6$	$4.6 \le \log_{10}(MuEx) < 4.8$	$4.8 \le \log_{10}(MuEx) < 5.0$	$\log_{10}(MuEx) \ge 5.0$
2012-2013	2741 (1654859)	25 (563658)	2 (176028)	3 (73666)
Passing / Total	0.001656334	4.43531E-05	1.13618E-05	4.07244E-05
2014-2015-2016	5001(2584062)	33(881362)	2(273419)	0(114157)
Passing / Total	0.00193533	3.7442E-05	7.3148E-06	0

Cumulative	$\log_{10}(MuEx) \ge 4.0$	$\log_{10}(MuEx) \ge 4.6$	$\log_{10}(MuEx) \ge 4.8$	$\log_{10}(MuEx) \ge 5.0$
2012-2013	2771 (2468211)	30 (813352)	5 (249694)	3 (73666)
Passing / Total	0.00112268	3.6884E-05	2.0025E-05	4.0724E-05
2014-2015-2016	5036(3853000)	35(1268938)	2(387576)	0(114157)
Passing / Total	0.00130703	2.7582E-05	5.1603E-06	0

Results: counts/year vs zenith angle