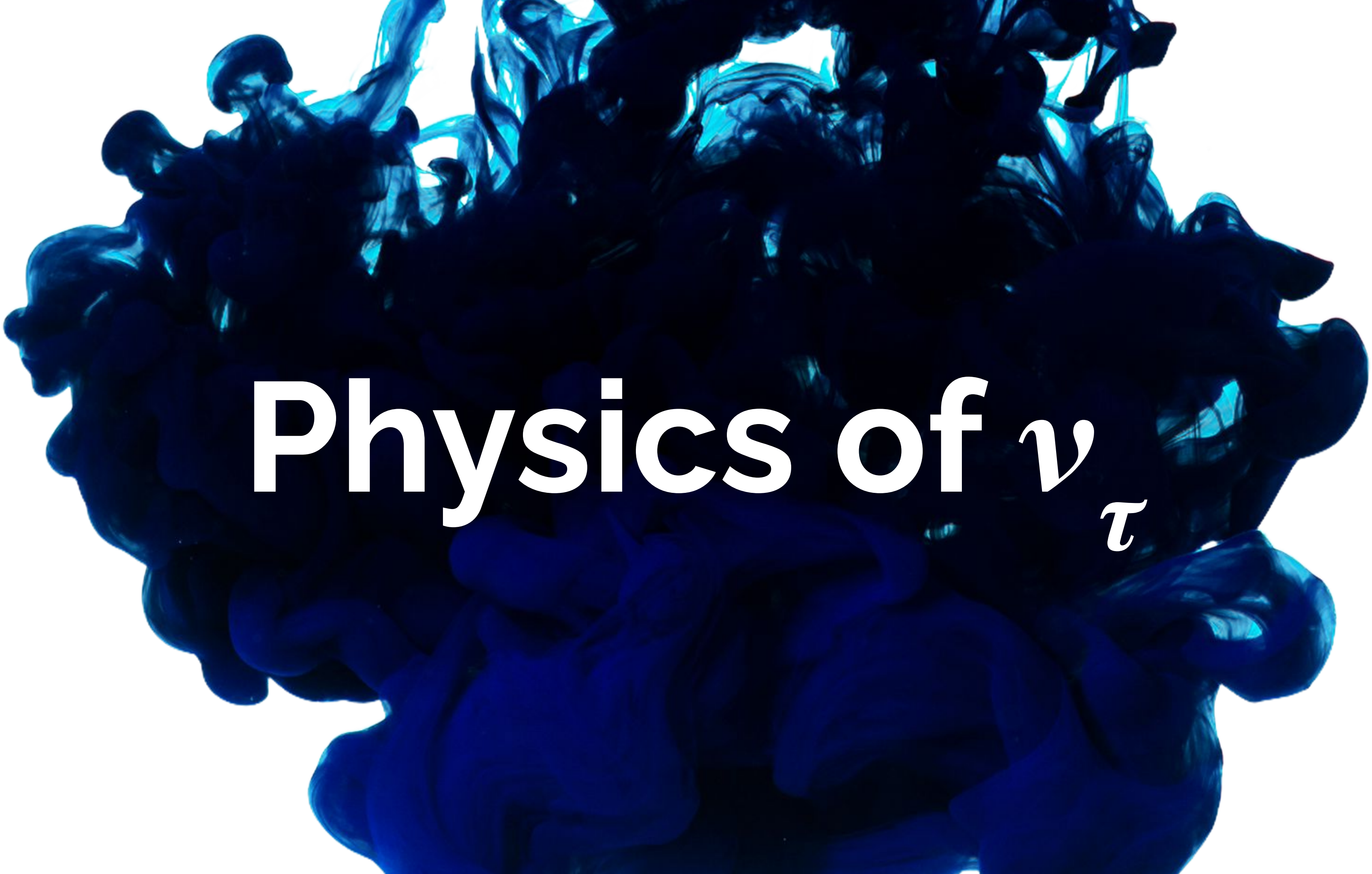
Astrophysical Tau Neutrinos in the Pacific Ocean

Akanksha Katil
Supervisor: Dr. Juan Pablo Yáñez Garza
Feb 10
WNPPC 2021

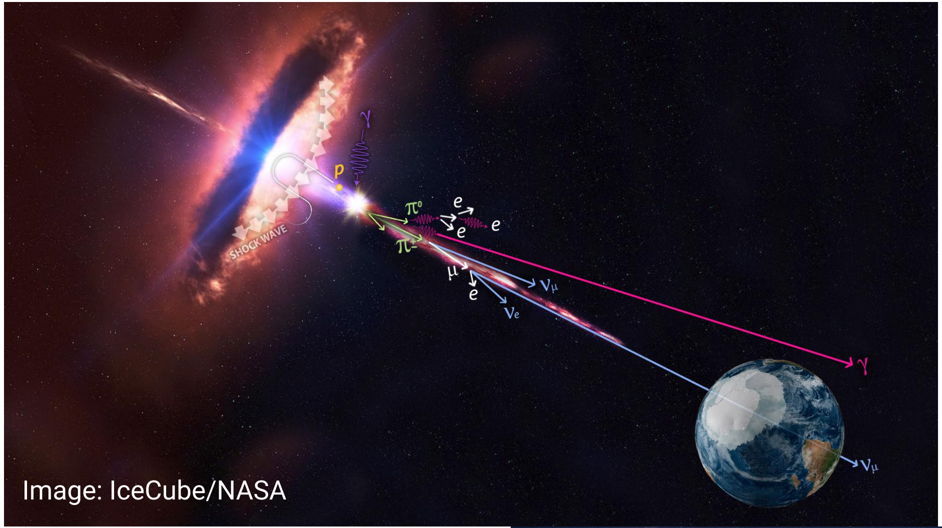
UNIVERSITY OF WATERLOO
UNIVERSITY OF ALBERTA

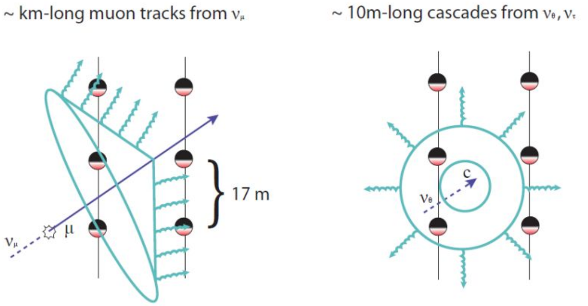
Physics of ν_τ



Astrophysical Neutrinos

- First detected in IceCube.
- Unobstructed view of Universe **above tens of TeV.**
- Energy 1000 times > highest neutrino produced in particle accelerators.
- Study the sources and production mechanisms. 3 flavours - electron, muon, tau.
- Each flavour has a characteristic signals.

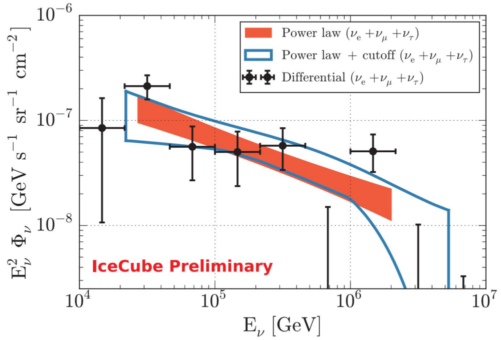


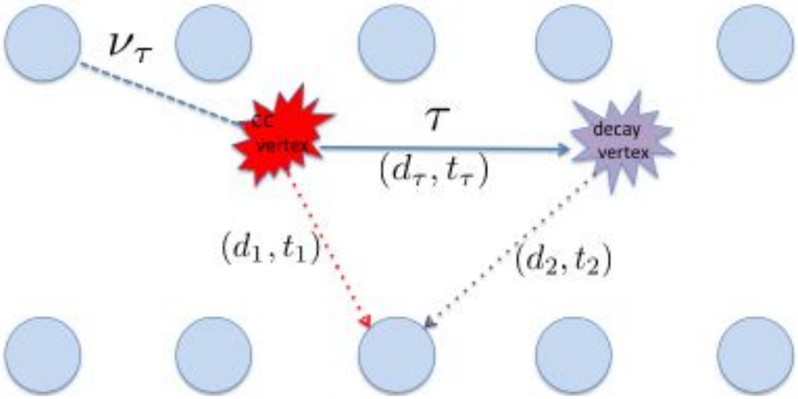


Astrophysical Tau Neutrinos

- Double pulse signature.
- Important implications:
  - **Reaffirm astrophysical origins of neutrinos**
  - **Oscillations on cosmological scales.**
- 20-40% of astrophysical flux, but IceCube on verge of detection first ν_τ only now Why?
  - Scattering in ice
  - Low stats at higher energies

What if a neutrino telescope is deployed in water, where scattering is considerable less?

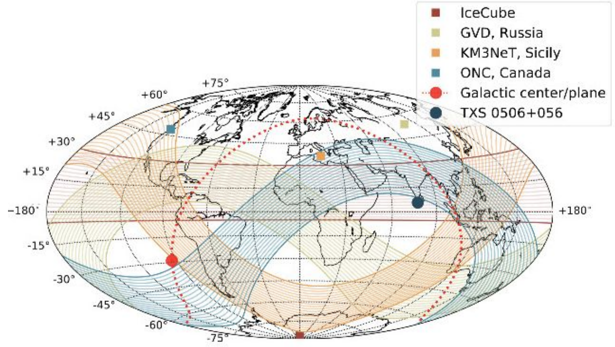




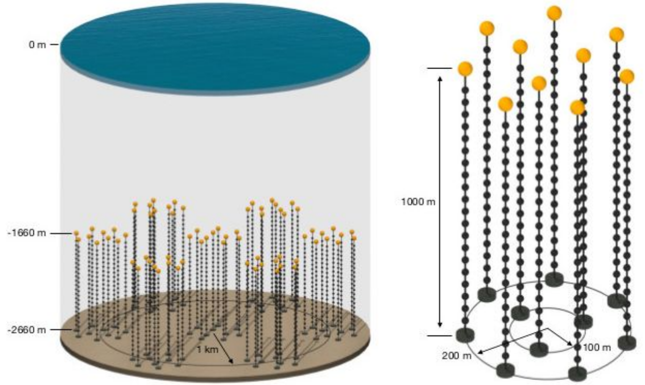

Pacific Ocean
Neutrino Explorer

- [Planned neutrino telescope in the Cascadia Basin near Vancouver Island.](#)
- P-ONE + other neutrino telescopes = an increased sky coverage.
- P-ONE phase 1 - 1 segment, 10 strings and 200 DOMs,
- Long term goal - 7 segments, 70 strings, 1400 DOMs.

Can P-ONE phase 1 contribute in detecting astrophysical ν_τ?



Images taken from https://www.pacific-neutrino.org/



Simulation

Simulation Chain

- **Neutrino Generator**: Inject Interactions at the vicinity of the detector
- **Particle Propagator**: Propagate resulting charged particles through the medium
- **Photon Generator**: Make Cherenkov photons and propagate them through the optical medium
- **PE Hit Generator**: Convert photons into photoelectrons by applying acceptance probabilities for an mDOM
- **Noise Generator**: Injecting Noise from **STR**ings for **A**bsorption Length in **W**ater
- **RecoPulse Generator**: Simulating PMT Response

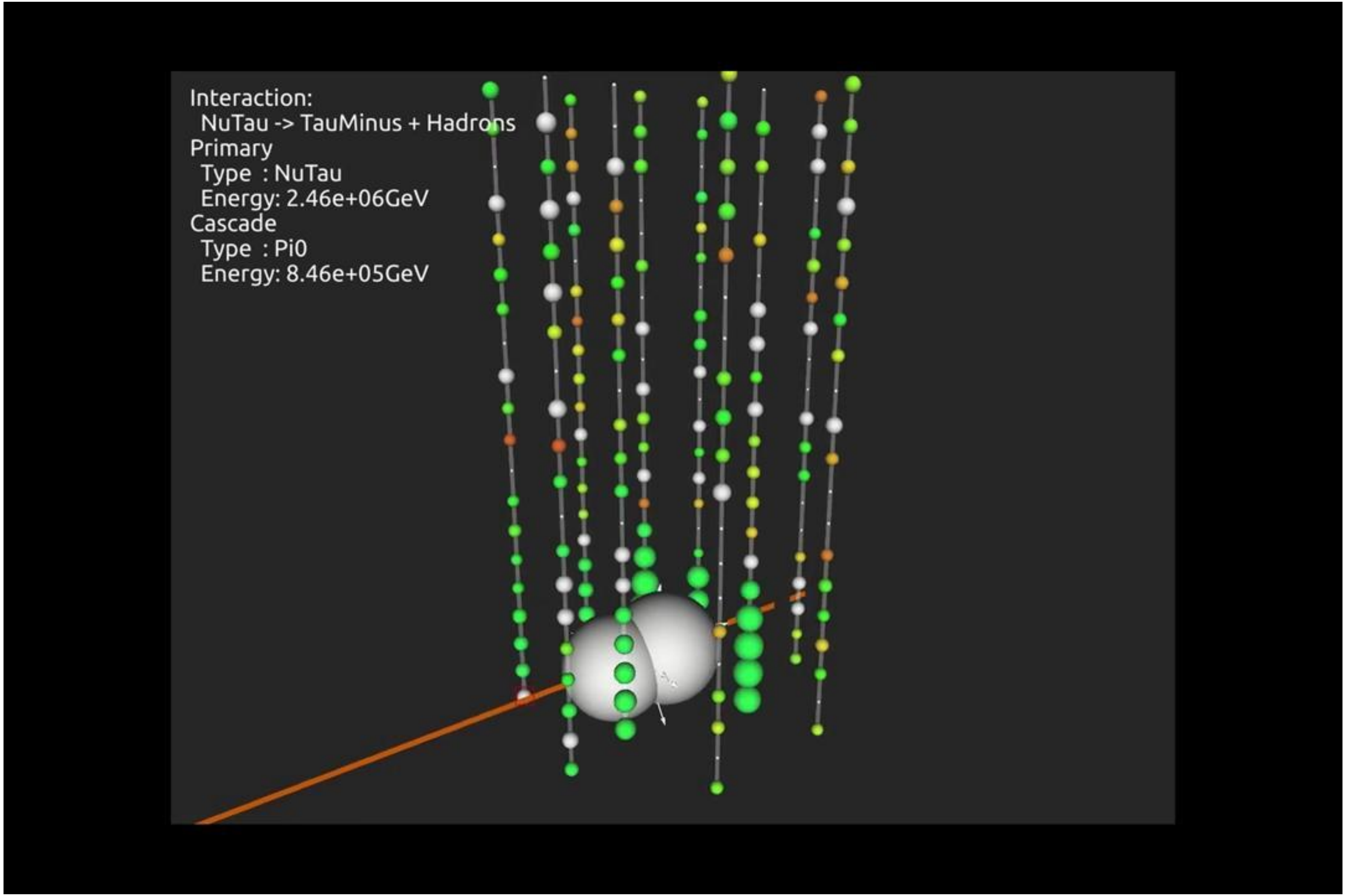
Simulation Parameters

- Absorption and scattering lengths of Cascadia Basin*.
- 24 3” PMTs and a flat angular acceptance of 0.811. The wavelength acceptance = IceCube DOM
- No granularity in hits.
- Hits within 3 ns are merged as on. 0 -1.5 ns smear is added to the timestamps
- **40,000 ν_τ and ν_e events simulated in total between energies 100 TeV to 5PeV.**

IceCube mDOM

Wavelength(nm)	Scattering Length(m)	Effective Scattering Length(m)	Absorption Length(m)
365	32.30	163.16	9.21
405	56.78	286.81	17.56
465	66.87	337.78	31.87

* Taken from Andreas Gaertner’s analysis

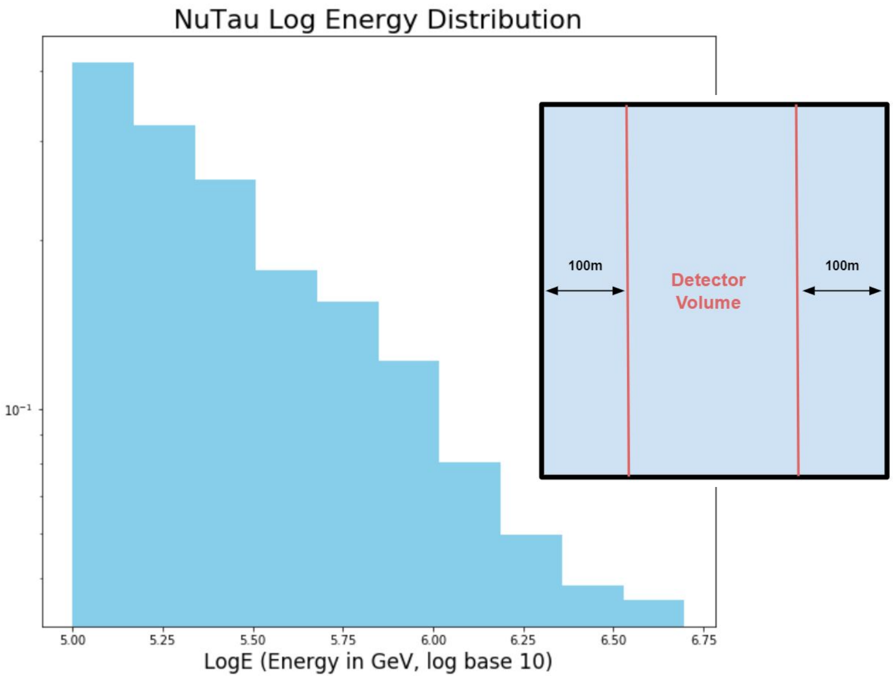

Interaction:
NuTau -> TauMinus + Hadrons
Primary
Type : NuTau
Energy: 2.46e+06GeV
Cascade
Type : Pi0
Energy: 8.46e+05GeV

Analysis

Expected ν_τ In A Year

- Desired ν_τ events:
    - Charged Current interactions.
    - Interaction vertex should be within 100m around the detector volume in X and Y axis.

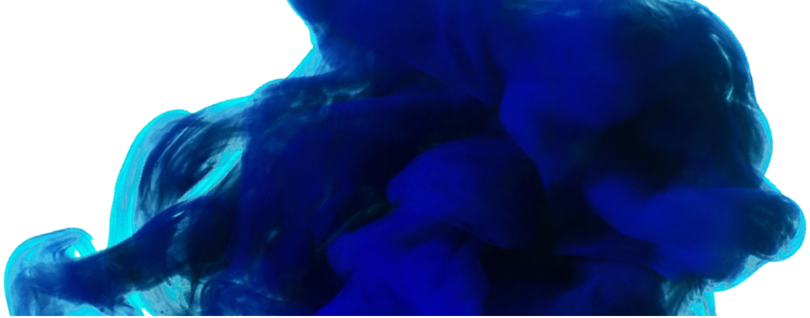
Expected CC ν_τ events per year: 1.68

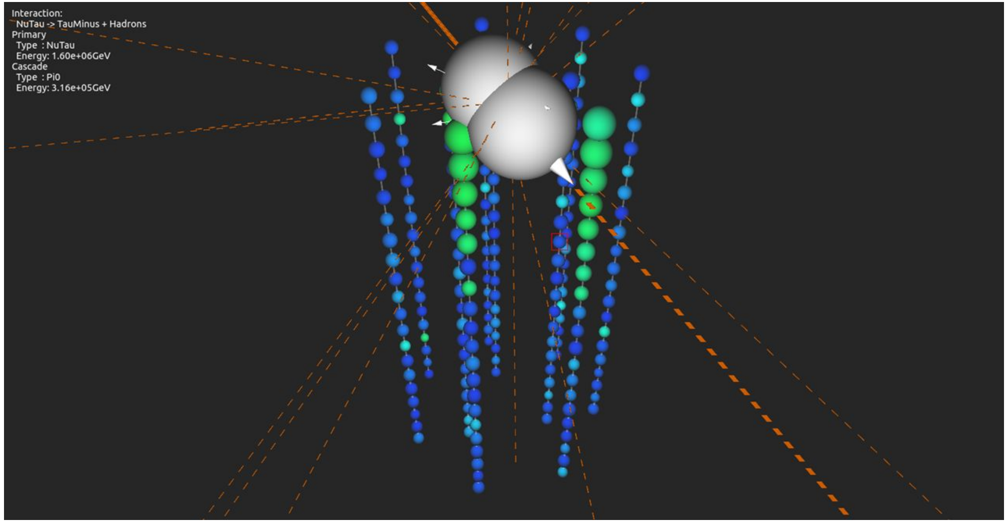


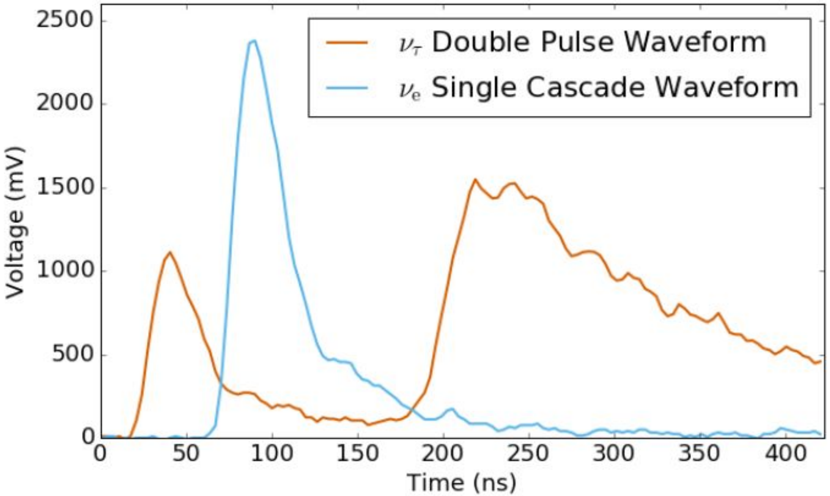
Goal of the Analysis

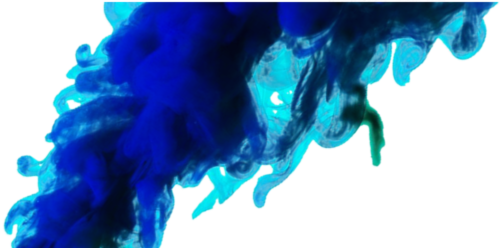
Develop an algorithm that identifies ν_τ from the background

Background from atmospheric muons, CC ν_e and NC interactions from all flavoured neutrinos.





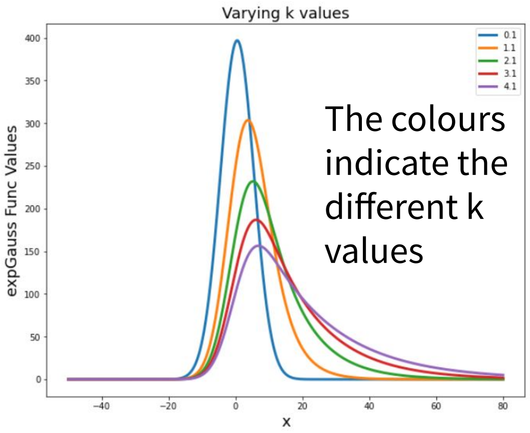


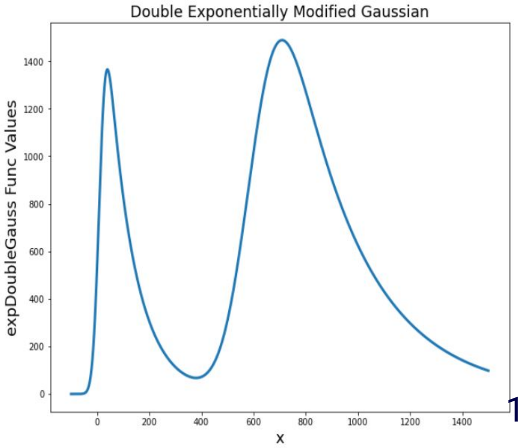


The Method

- **The algorithm fits both a single exponential gaussian and double exponential gaussian to every DOM in the event**.
- Single exponential gaussian(expGauss) - mean, width, amplitude and k(defines how exponential the tail is).
- Double expGauss = $\text{expGauss}_1 + \text{exp Gauss}_2$

$$f(x;\mu,\sigma,\lambda) = \frac{\lambda}{2} e^{\frac{\lambda}{2}(2\mu+\lambda\sigma^2-2x)} \operatorname{erfc}\left(\frac{\mu+\lambda\sigma^2-x}{\sqrt{2}\sigma}\right)$$





The Algorithm

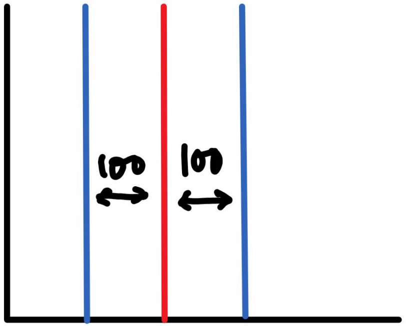
Number of hits in DOMs > 200

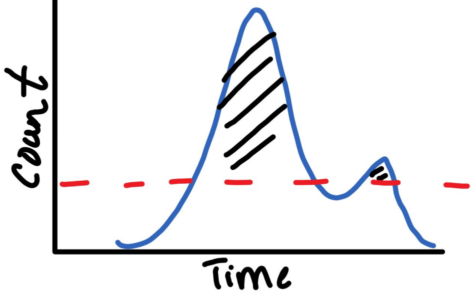
Select hits within 200 nanoseconds

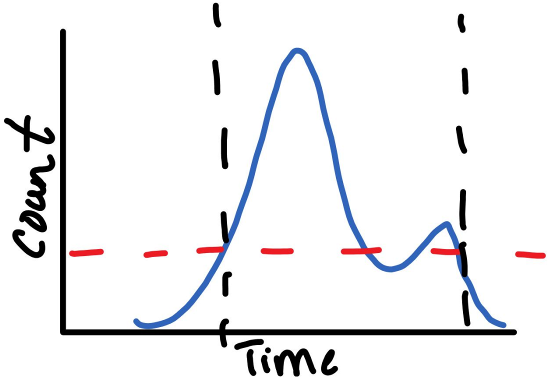
Histogram

Entries ratio = (entries in bins/max bin entry)
Entries Ratio > 0.2
Bins between first-2 and first+2 bins entries ratio

Number of bins >= 10





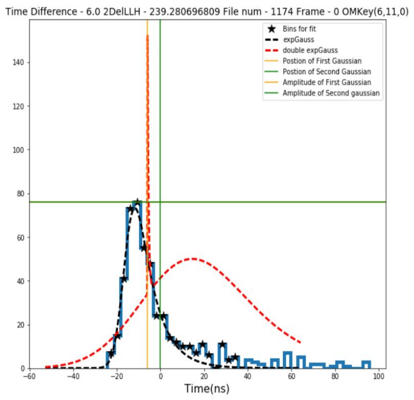


The Fit

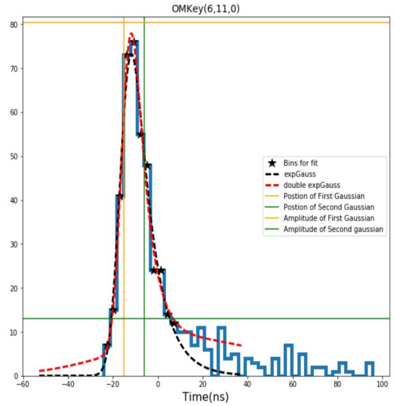
- The minimizer minimizes the -log likelihood value. Takes bounds and initial values

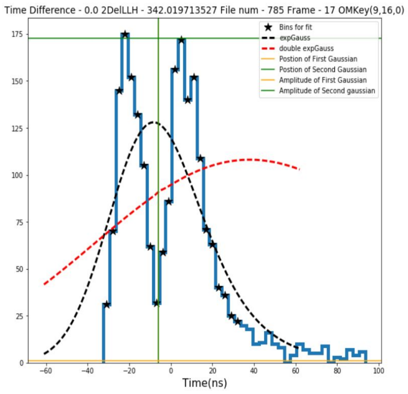
$$-\ln L = \sum_i \ln(n_i!) + \mu_i - n_i \ln \mu_i$$

- Multiple checks done to improve the algorithm.
- Sensitive to initial values - performing a grid search.

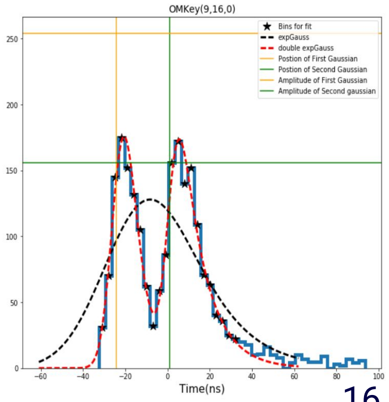


Changing bounds →



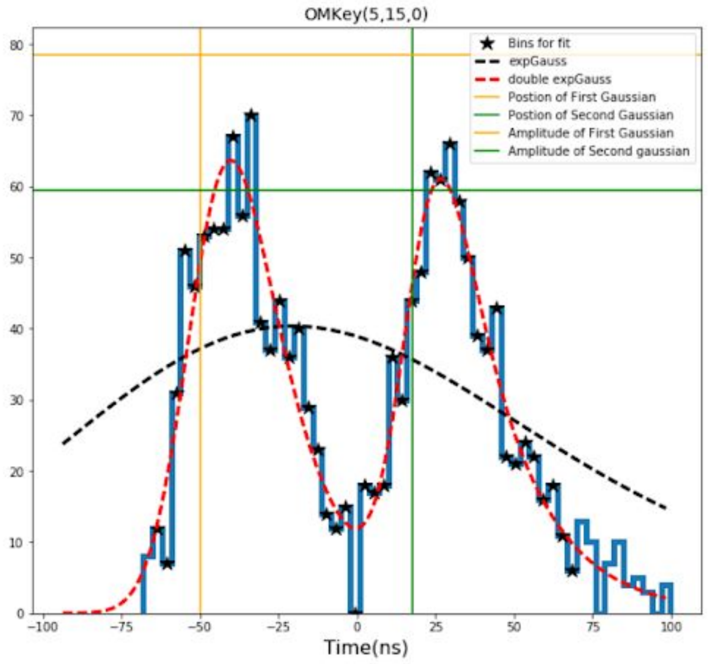


Changing Initial Values →

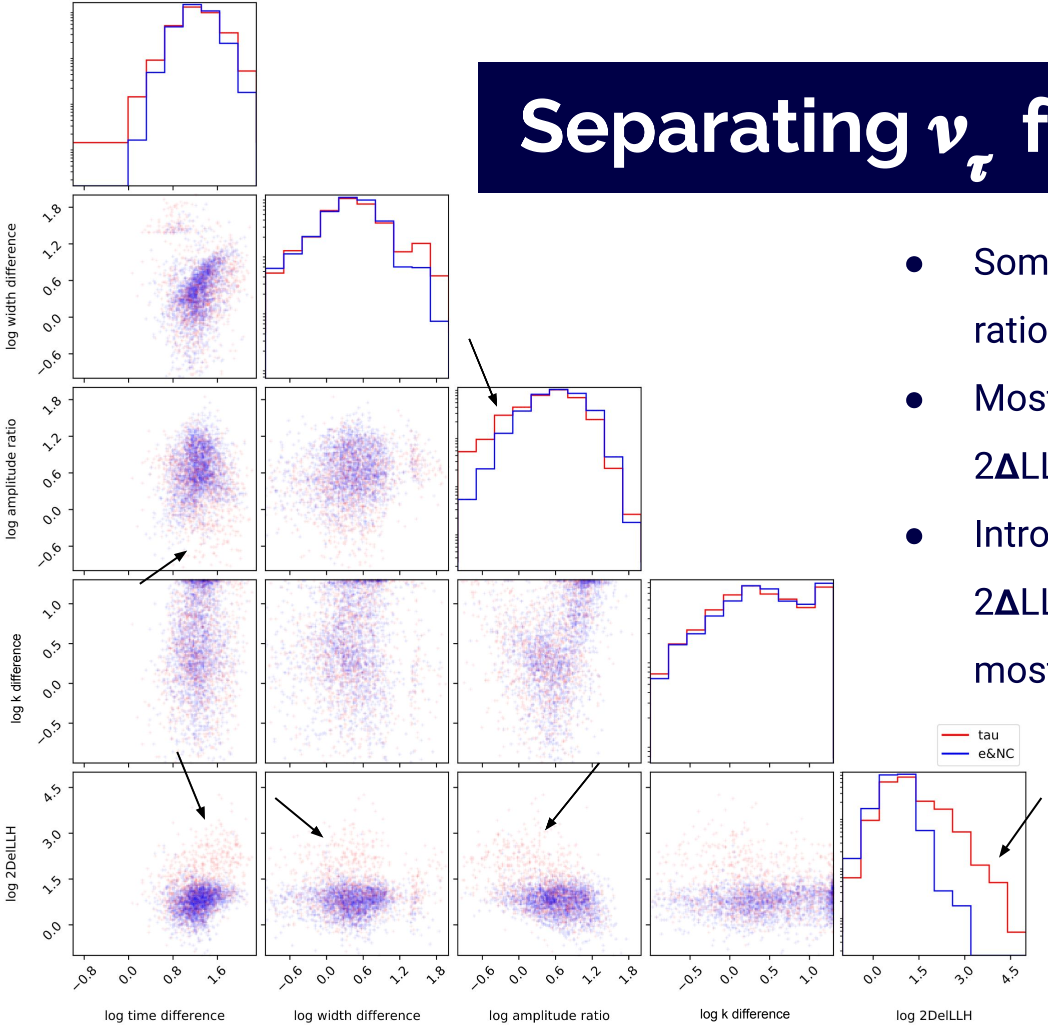


Parameters for Comparison

- Time Difference = $position_2$ - $position_1$
- Width Difference = $|width_2 - width_1|$
- Amplitude Ratio = amp_1/amp_2
- k difference = $|k_2 - k_1|$
- LLH difference = $2*(LLH_{DeG} - LLH_{eG})$



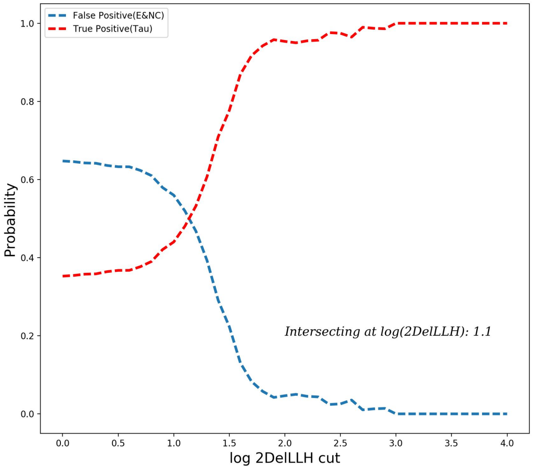
Separating ν_τ from the background

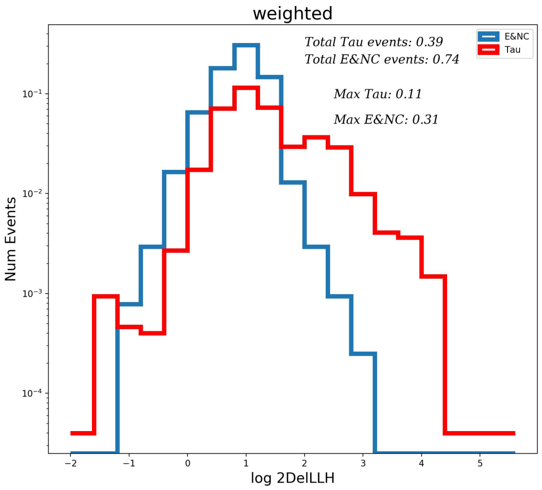


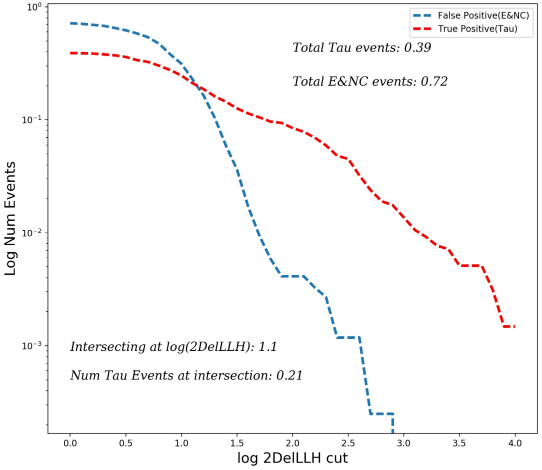
- Some separation in log amplitude ratio.
- Most separation observed in log 2**Δ**LLH.
- Introducing cuts in the data using log 2**Δ**LLH(**CUT VARIABLE**) values will be most effective.

Separating signal from background

- At cut variable 1.1 there is equal probability of the event being either a ν_τ or background event
- Total ν_τ events in a year is 0.39. **Can this number be improved?**







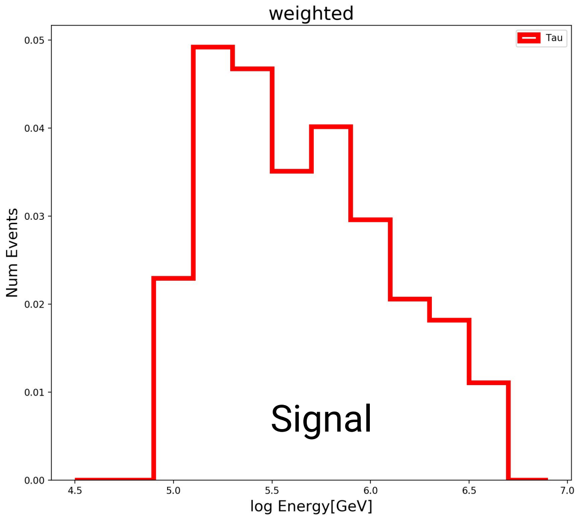
Improving the Number of ν_τ events/year

Conditions Changed	Total Background Events	Total NuTau Events	Intersection Point	Tau Neutrino Events at Intersection Point
Number of hits in DOMs > 200	0.72	0.39	1.1	0.21
Number of hits in DOMs > 100	1.11	0.59	1.3	0.22
Number of hits in DOMs > 0	1.78	0.88	1.3	0.27
Number of bins >= 9	1.87	0.9	1.3	0.27
Entries Ratio > 0.1	2.1	0.97	1.5	0.28

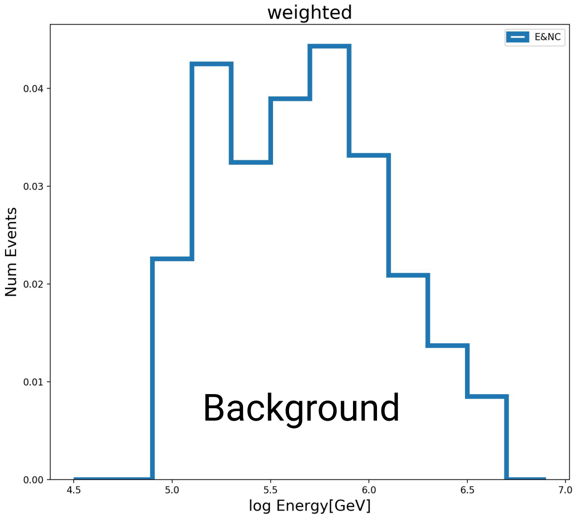
Energy Distributions

Energy distribution of signal and background at intersection point.

Cut Variable = 1.3



Cut Variable = 1.3



Conclusions

- The algorithm is successful in separating $\boldsymbol{\nu_\tau}$ from the background.
- LLH ratio between single/double ExpGauss fits is the most effective parameter that shows a clear separation between tau neutrino and background.
- **~1 $\boldsymbol{\nu_\tau}$ events expected in a year if the algorithm is capable of identifying all $\boldsymbol{\nu_\tau}$ from the background.**
- **~0.3 tau neutrino events with cut variable > 1.3 are detected in a year in P-ONE phase 1.**

THANK YOU!

Any Questions?

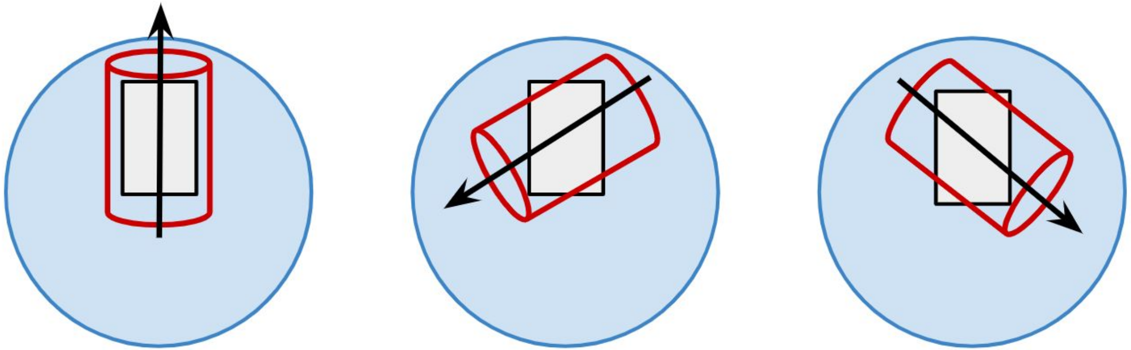
Simulation Steps

More on Analysis

Back Up

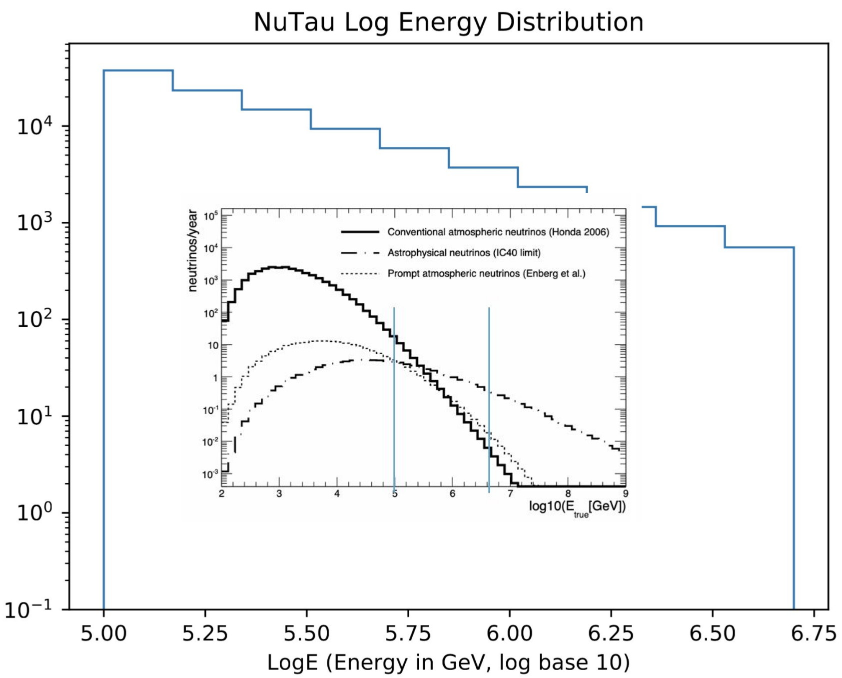
Step 1: Neutrino Generator(NuGen)

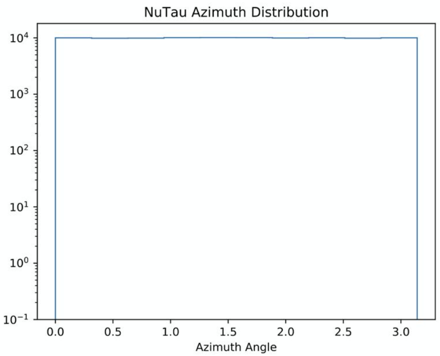
- Injected neutrinos are forced to interact within a given cylinder volume.
- Types of neutrino interactions:
  - CC - Charged Current - Makes charged leptons and hadronic or EM showers
  - NC- Neutral Charged Current - Makes a secondary neutrino and hadronic showers.
- Parameters given to NuGen:
  - Flavour: $\nu_\tau:\bar{\nu}_\tau:\nu_e:\bar{\nu}_e$ = 1:1:1:1
  - Energy: 100TeV to 5PeV
  - Power law index: 2.19
  - Azimuth: 0 to 180 degrees
  - Zenith: 0 to 180 degrees
  - Height of cylinder: 1000m
  - Radius of cylinder: 500m
  - Events per file: 20

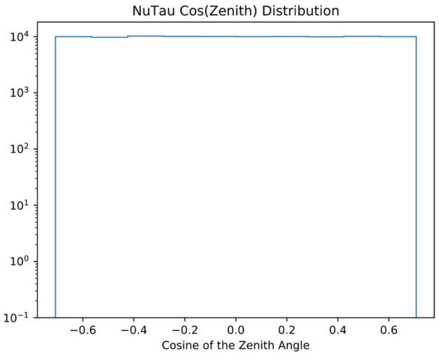


Neutrino Distributions

- Energy range given to the simulation is 100TeV - 5PeV
- Energy distribution looks as expected.
- Simulating events between Zenith(-45, 45) and Azimuth(0, 180), no bias observed.

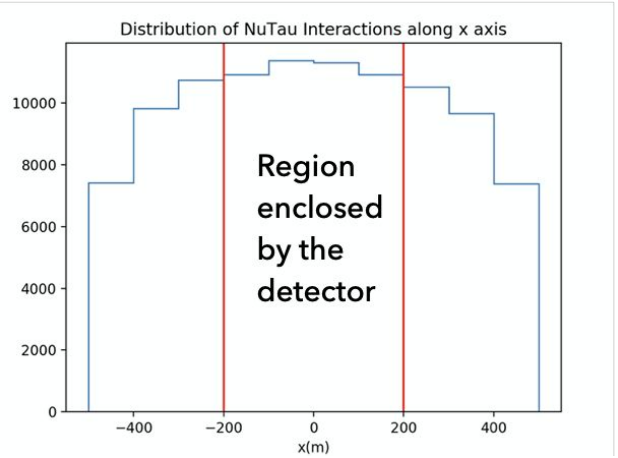


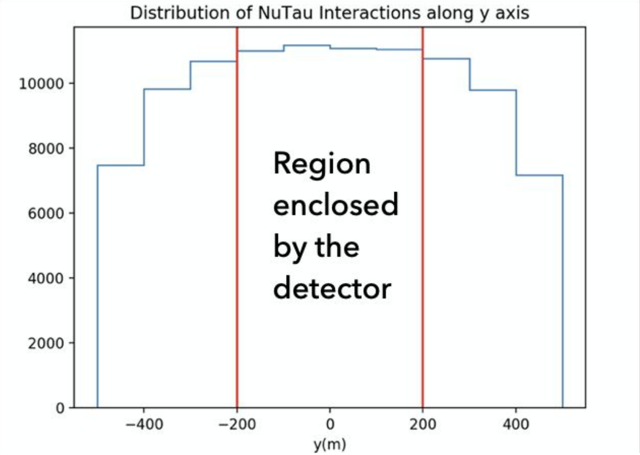


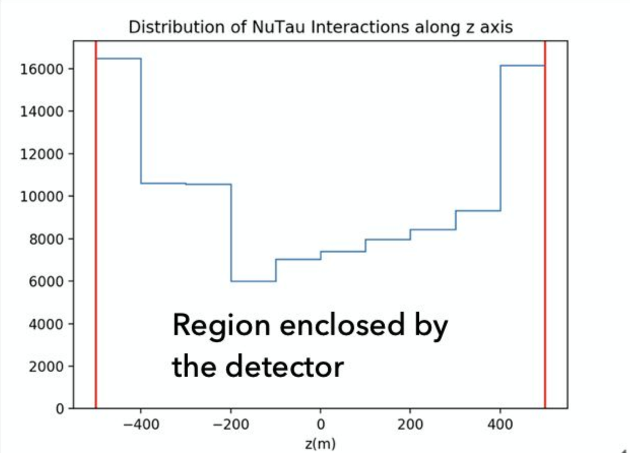


Vertex of Interaction of Neutrinos

Distributions of interactions of neutrinos to produce corresponding lepton







The dimensions of interaction cylinder given - Radius - 500m, height - 1000m, centered at (0, 0, 0)

Step2: PROPOSAL

- Propagates secondary charged particles in ice.
- Medium of propagation not changed to water since the difference is negligible.
- Verifying **τ** propagation:
    - Histogram of tau decay time fit to an exponential curve given by:

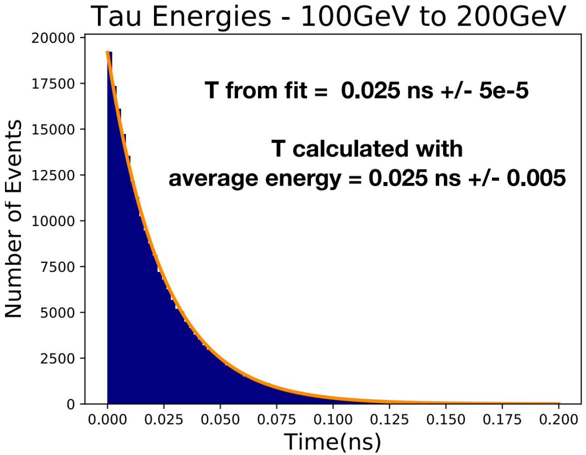
      $$N = N_0 e^{\frac{-t}{T}}$$

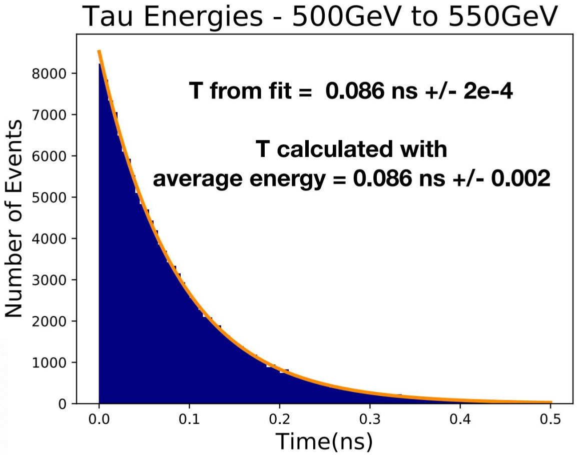
      N_0 = Number of taus produced initially
      T = Life time of tau in rest frame

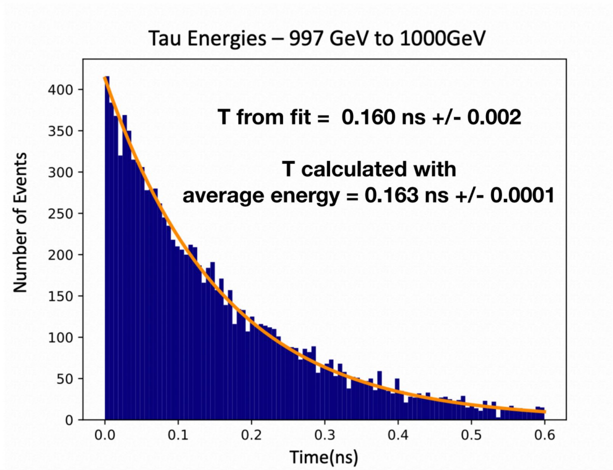
    - The decay time … d a … given by:

      E = Energy of tau
      m = Mass of tau [1776.86 MeV]
      τ = Lifetime of tau [2.9×10^{-4} ns]

Step2: PROPOSAL







Step 3: CLSim - Changing the Medium

- Generate and propagate photons.
- To propagate photons in CLSim, medium should be changed to water.
- The optical properties in IceCube are defined by the following equations

$$b_e = b_{e,400}(\frac{\lambda}{400})^{-\alpha}$$

$$a = a_{dust,400}(\frac{\lambda}{400})^{-\kappa} + \boxed{Ae^{-B/\lambda}(1 + 0.01\Delta T)} \longrightarrow \text{Ignored, need more data}$$

b_e - effective scattering coefficient at a given wavelength λ
$b_{e,400}$ - scattering coefficient at wavelength 400 nm

a - absorption coefficient at a given wavelength λ
$a_{dust,400}$ - absorption coefficient at wavelength 400 nm
Exponential component of wavelength dependence is ignored

Phase Function

- The phase function P(cosθ) is chosen to be a combination of Henyey Greenstein(HG) and simplified Liu(SL)

$$P(\cos\theta) = fsl \cdot \frac{SL(\cos\theta)\sin\theta}{\int_0^\pi SL(\cos\theta)\sin\theta d\theta} + (1 - fsl) \cdot \frac{HG(\cos\theta)\sin\theta}{\int_0^\pi HG(\cos\theta)\sin\theta d\theta}$$

$$HG(\cos\theta) = \frac{1}{2}\frac{1 - g^2}{(1 + g^2 - 2g\cos\theta)^{\frac{3}{2}}}$$

$$SL(\cos\theta) = \frac{1+\zeta}{2}\left(\frac{1+\cos\theta}{2}\right)^{\zeta}, \quad \zeta = \frac{2g}{1-g}$$

- The phase function of water is closer to HG. Therefore, contribution by SL function is neglected by setting ʃsl(Fraction of Simplified Liu) to 0.
- g - average scattering angle given by

$$\langle\cos\theta\rangle = \eta \cdot \langle\cos\theta\rangle_{molecular} + (1 - \eta) \cdot \langle\cos\theta\rangle_{particulate}$$

Effective Scattering Length

- The simulation takes effective scattering length.

$$\lambda_{\text{sct}}^{\text{eff}} \equiv \frac{\lambda_{\text{sct}}}{1 - \langle \cos\theta \rangle}$$

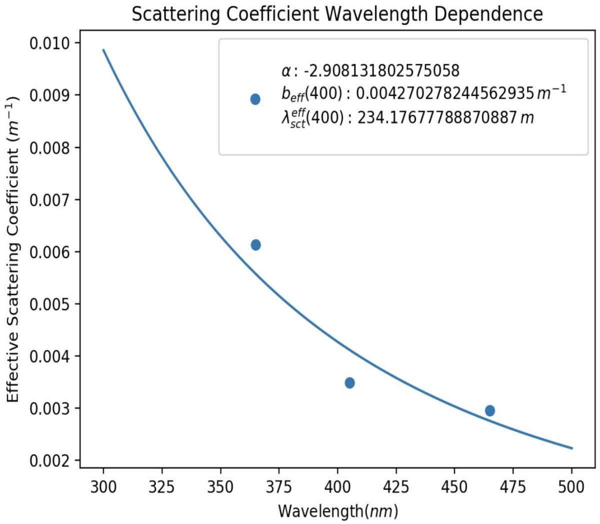
$$\langle \cos\theta \rangle = \eta \cdot \langle \cos\theta \rangle_{molecular} + (1-\eta) \cdot \langle \cos\theta \rangle_{particulate}$$

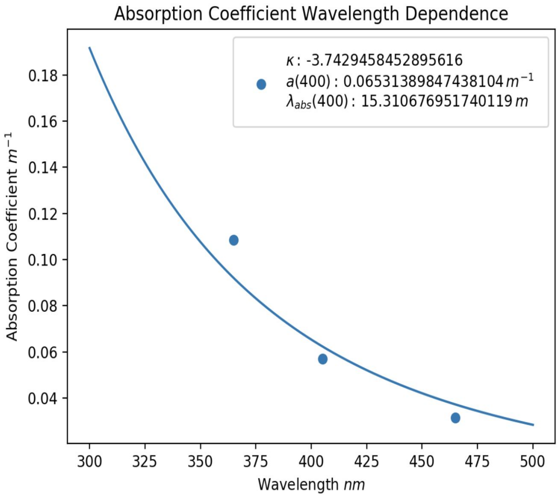
- $\langle \cos\theta \rangle_{\text{molecular}} = 0$
- $\langle \cos\theta \rangle_{\text{particulate}} = 0.924$(from Antares paper)
- η = 0.132(Matthew Man's Analysis)

- Current STRAW analysis considers equal probability for forward and backward scattering.
- For a more correct approach η(fraction of molecular scattering) is included.

Determining Parameters

- The simulation uses scattering coefficient($b_{e,400}$), α , absorption coefficient($a_{e,400}$) and κ obtained from the fit of the data points.

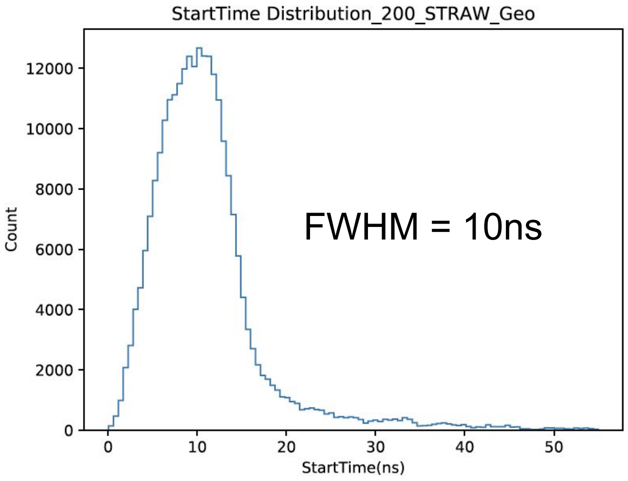


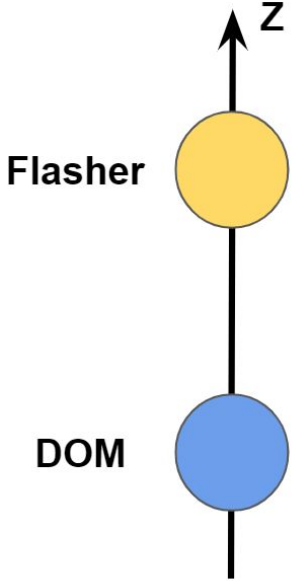


- Phase function in software defined by Simplified Liu(SL) and Henyey Greenstein(HG).
- Phase function of water closer to HG, thus SL ignored by setting ʃsl = 0

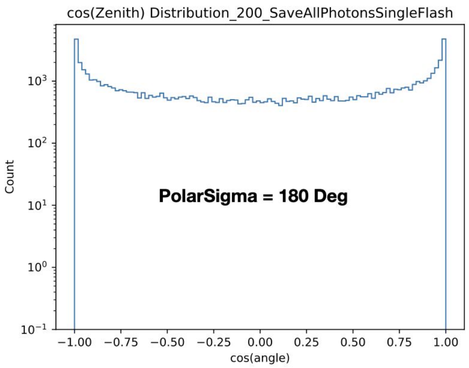
Verification: Simulating Multiple Flashers

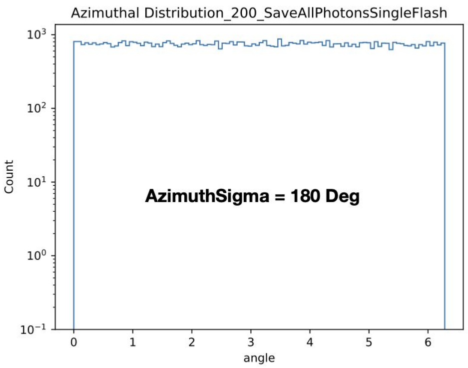
- Simulating multiple flashers, spaced equally in cosine of zenith, for isotropic flashes.
- The pulse shape of multiple flashers is akin to pulse shape of a single flasher.
- DOM position is fixed and flasher position is changed accordin



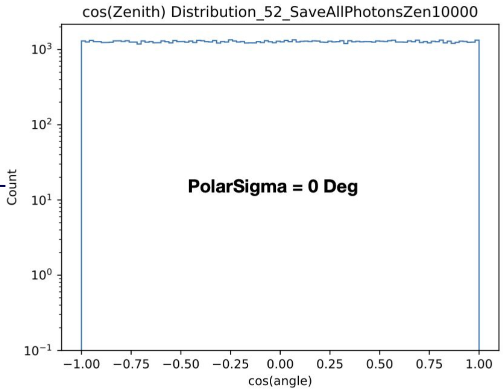


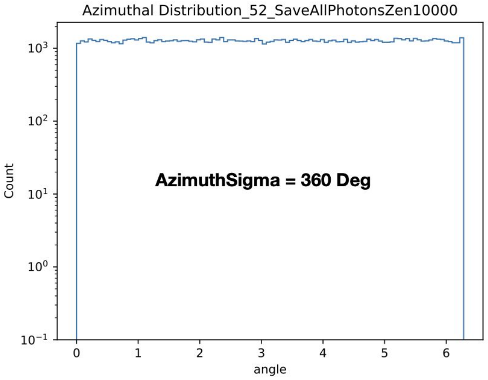
Flasher Isotropy





Single flasher

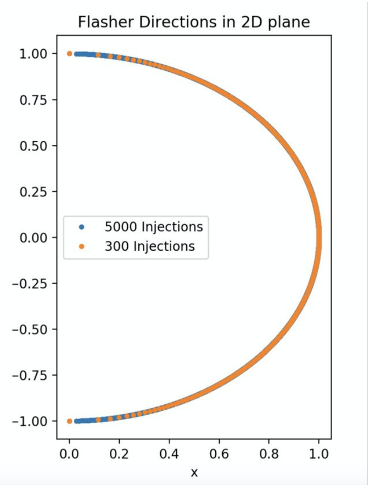


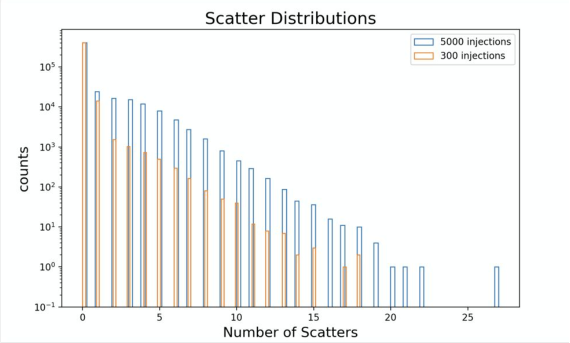


Multiple flasher

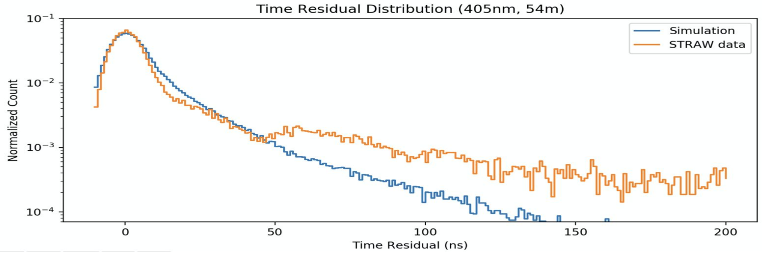
Number of flashers

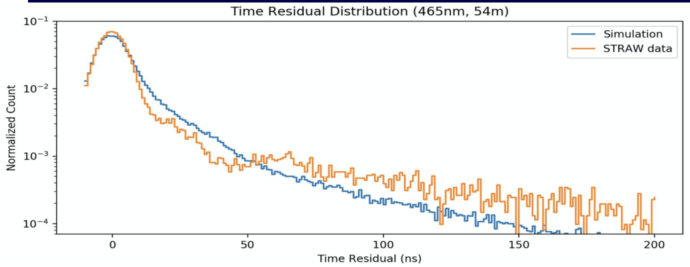
- Number of flashers simulated should be large enough to avoid gaps in cosine zenith.
- Current analysis simulates 200,000 flashers

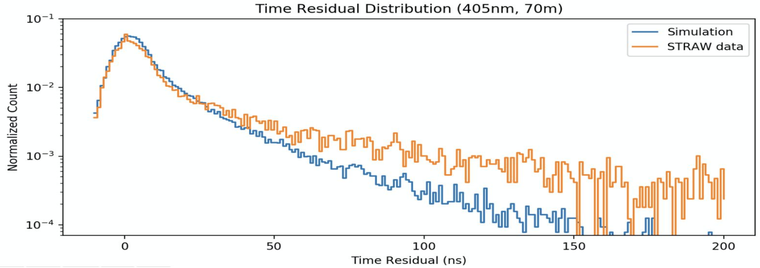


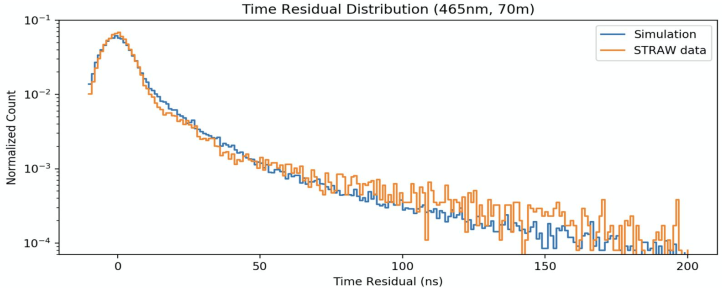


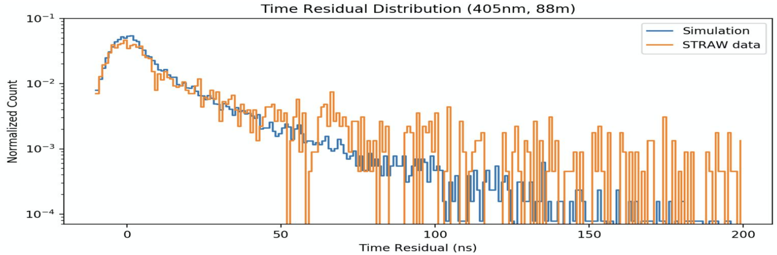
Time Residuals

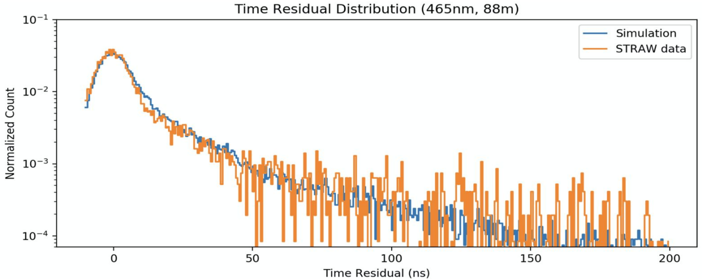


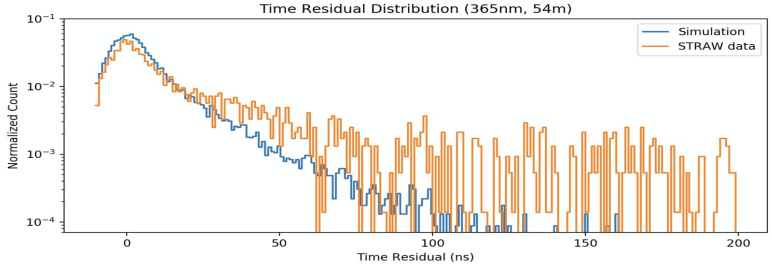












Great tool to test the inputs from STRAW analysis.

Step 4: PE Hit Generator - mDOM

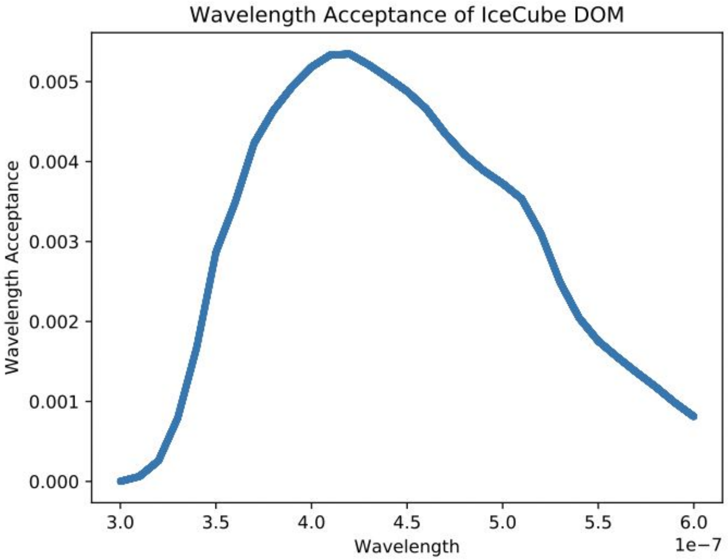
- Once the photons reach a DOM, the probability of a photon generating a photo electron(PE) depends on:
  - Quantum efficiency of PMT
  - Wavelength Acceptance of DOMs(DOM efficiency)
  - Angular Acceptance of DOMs
  - Photon Weight

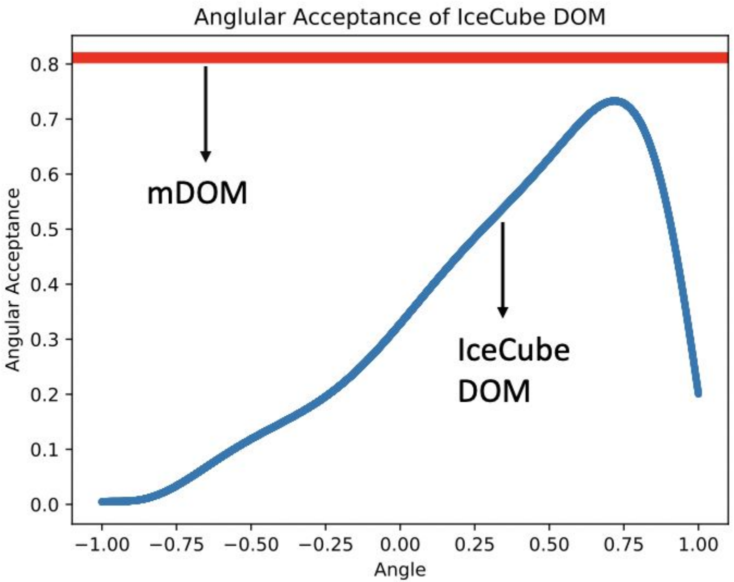
Probability of Hit = relative DOM eff × DOM eff × ang Acc × photon weight

- A simple custom code written to facilitate changes to properties of the DOM.
- Verified the accuracy compared against IceCube code

mDOM Properties

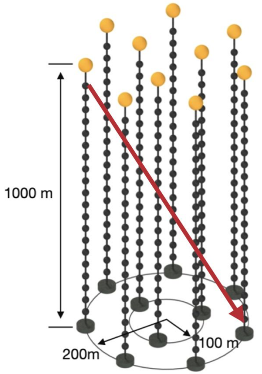
- The wavelength acceptance is set to be the same as IceCube's.
- Angular acceptance of mDOM = 0.811

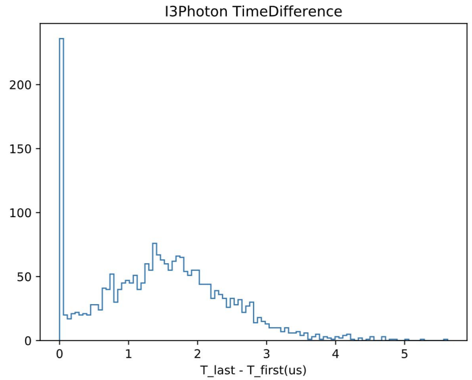


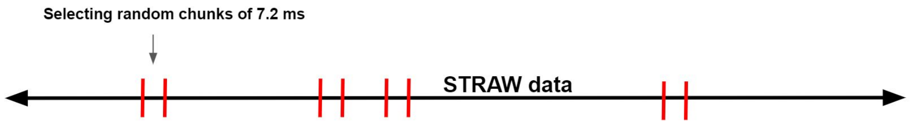


Step 5: Noise Generator

- Time taken for the first and the last photon to hit a DOM in a tau neutrino event is about 1-3 microseconds.
- Considering an event window of about 7.2 microseconds.
- Since noise scales with area, 24 random chunks of 7.2 ms from STRAW data, overlaid on each other, to generate noise in mDOM

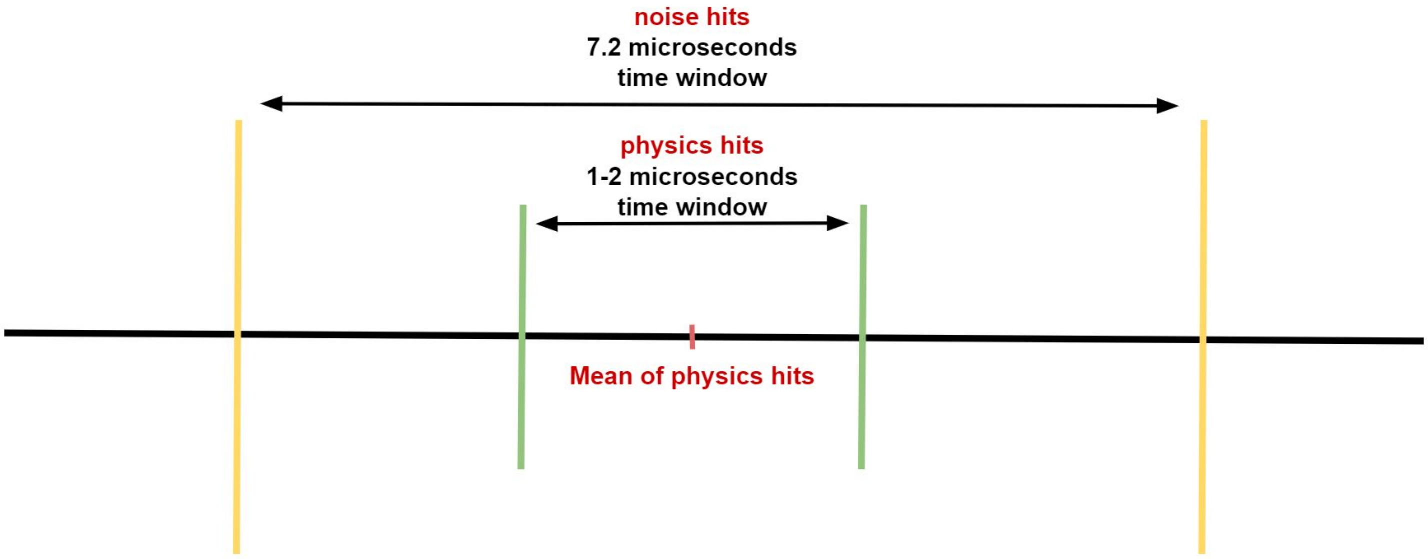


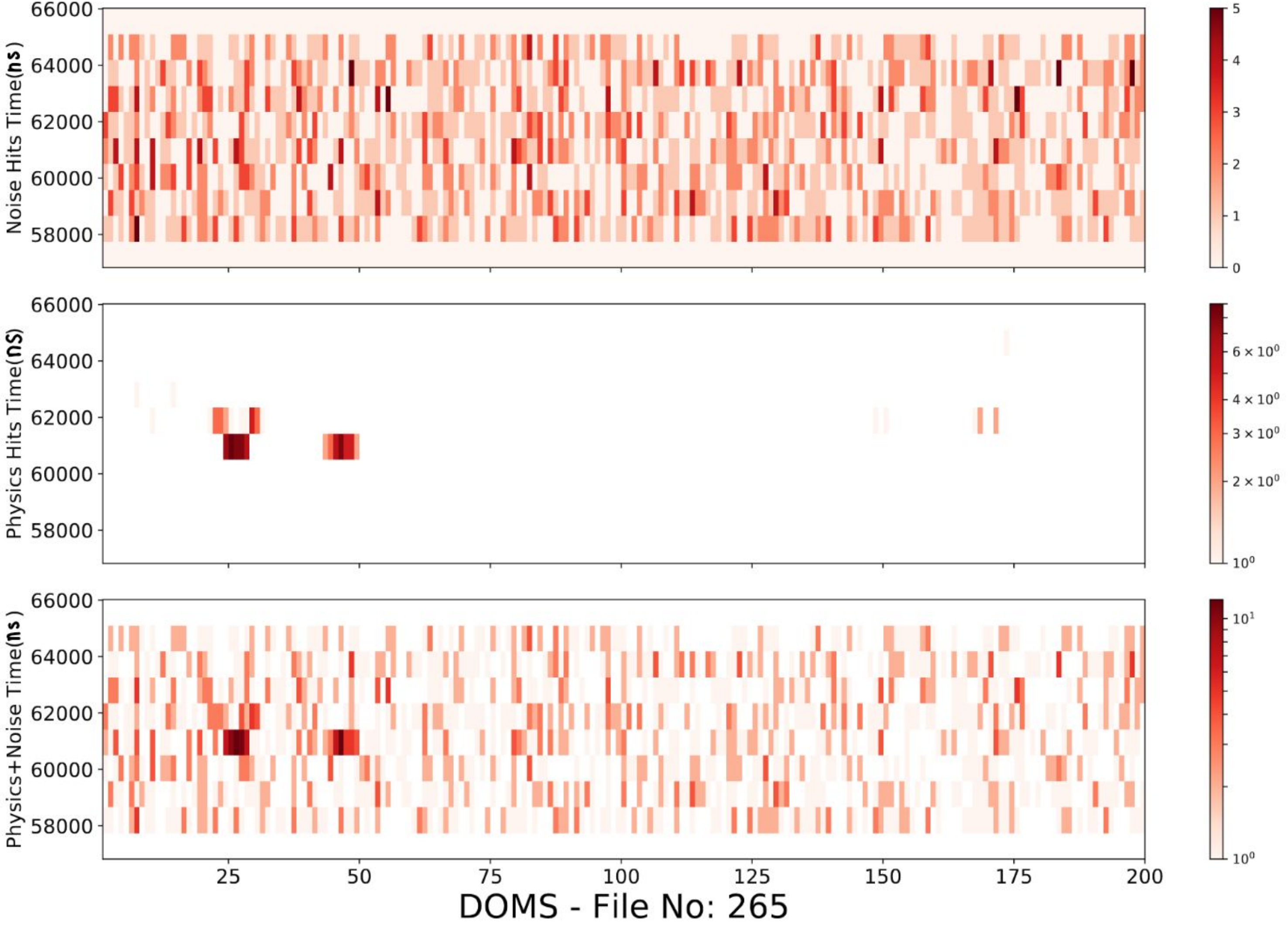




Injecting Noise in mDOMs for a Single Event

- For a single neutrino event the noise hits are chosen to be injected such that they are centered around the mean time of physics hits.





66000
64000
62000
60000
58000
Noise Hits Time(ns)
5
4
3
2
1
0
Physics Hits Time(ns)
6×10^0
4×10^0
3×10^0
2×10^0
10^0
Physics+Noise Time(ns)
10^1
10^0
25
50
75
100
125
150
175
200
DOMS - File No: 265

Weighting Events

$$weight_{CC} = \frac{\phi_{astro} \times OneWeight}{N/4}$$

$$weight_{NC,\nu_\mu} = \frac{(3\phi_{astro} + \phi_{atmo,\nu_\mu}) \times OneWeight}{N/2}$$

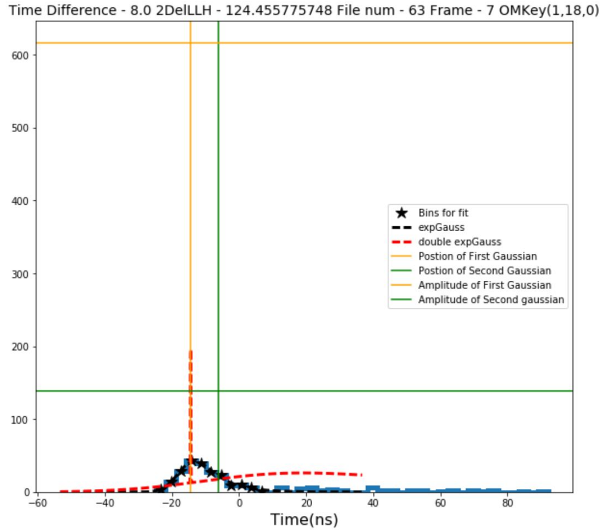
$$weight_{NC,\overline{\nu}_\mu} = \frac{(3\phi_{astro} + \phi_{atmo,\overline{\nu}_\mu}) \times OneWeight}{N/2}$$

$$\begin{aligned} N &= \text{Number of files} \\ OneWeight &= \text{Taken from I3MCWeight} \end{aligned}$$

$$\frac{d\Phi_{\nu+\bar{\nu}}}{dE} = (1.01\pm^{0.26}_{0.23}) \left(\frac{E}{100\,\mathrm{TeV}}\right)^{-2.19\pm0.10} \cdot 10^{-18}\mathrm{GeV}^{-1}cm^{-2}s^{-1}sr^{-1}.$$

Bounds and Initial Values of the Fit

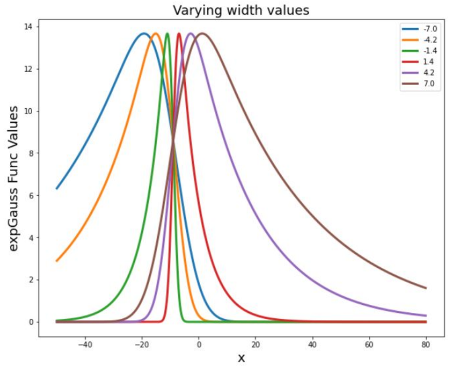
- Width needs to be negative, to change the direction of the exponential tail. However, the caveat here is that the minimizer outputs a NaN once it starts considering width values between (-0.999, 0.999)



pos1	wid1	k1	amp1	pos2	wid2	k2	amp2	log likelihood
-14.4044	-0.0734752	0.134472	237.057	-5.96877	18.3955	6.09133	248.598	nan

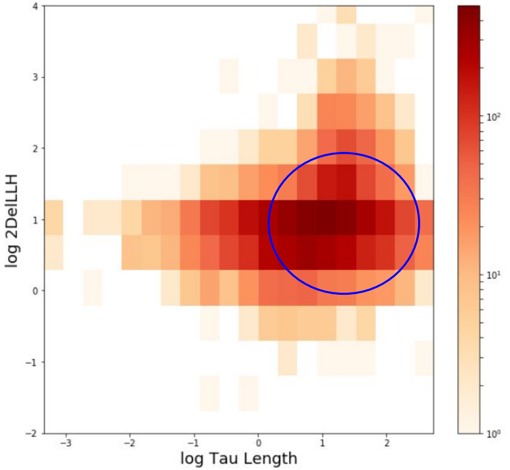
pos1	wid1	k1	amp1	pos2	wid2	k2	amp2	log likelihood
-14.3644	-0.05513	0.427769	638.78	-5.99934	23.245	1.34232	74.7544	nan

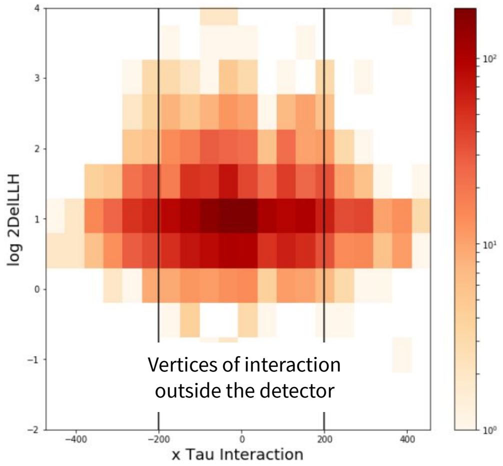
- The same with k, values should be between (0, 0.99).



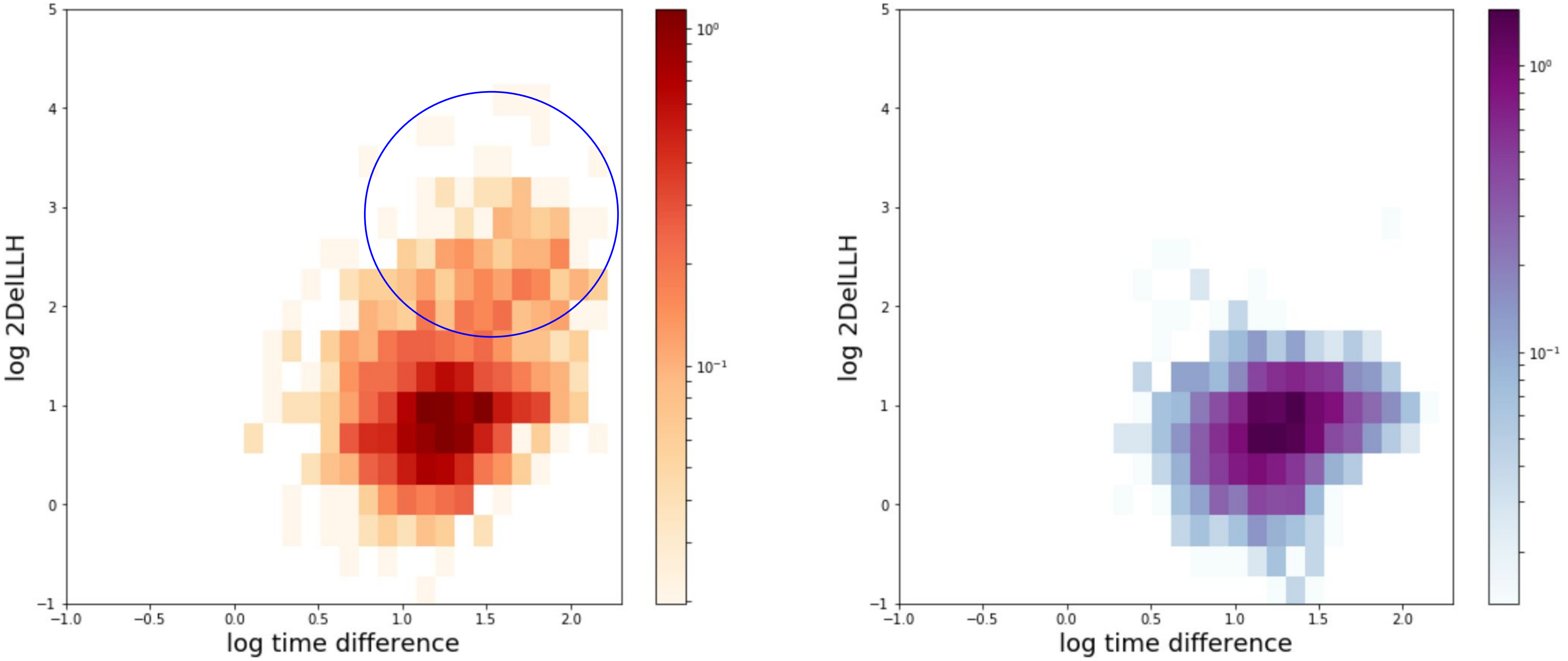
Tau length Correlation

- Ideally large tau length would mean large cut variable value .
- What happens with DOMs with large tau length and small cut variable?
  - Vertices(Tau creation and tau decay) are outside the detector.
  - Tau decays into a muon
  - DOM is not at an ideal distance from the vertices.

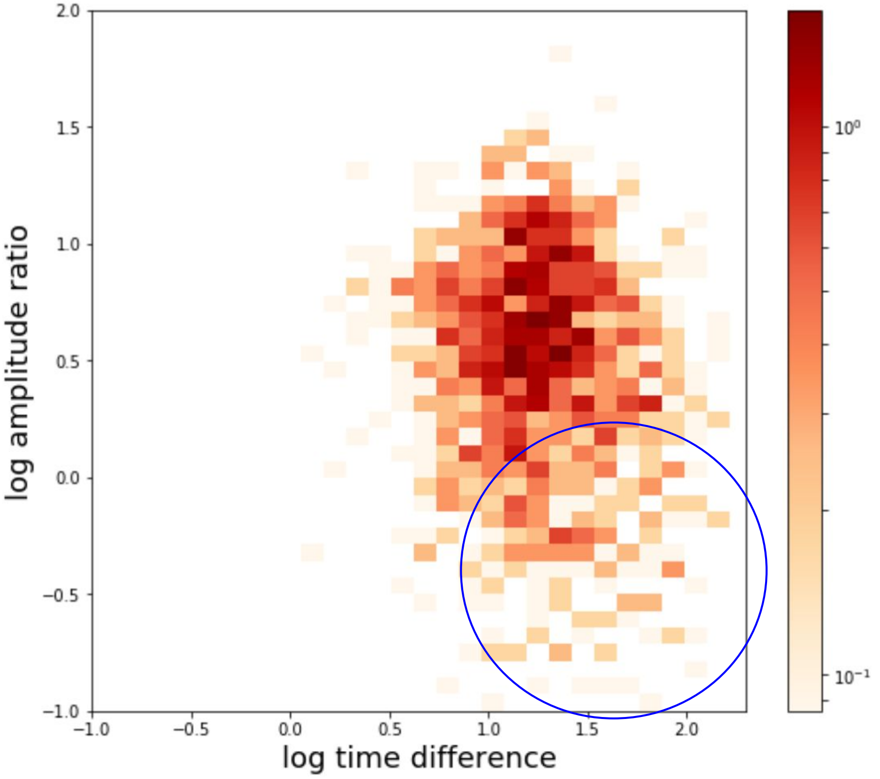


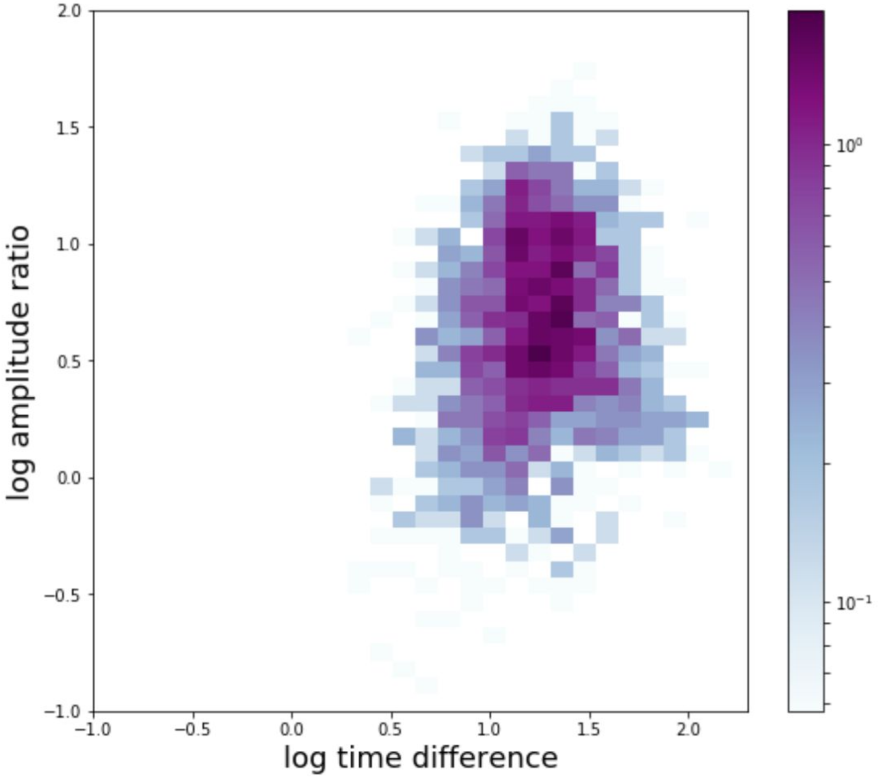


Hist 2Ds for Exponential gaussian fits

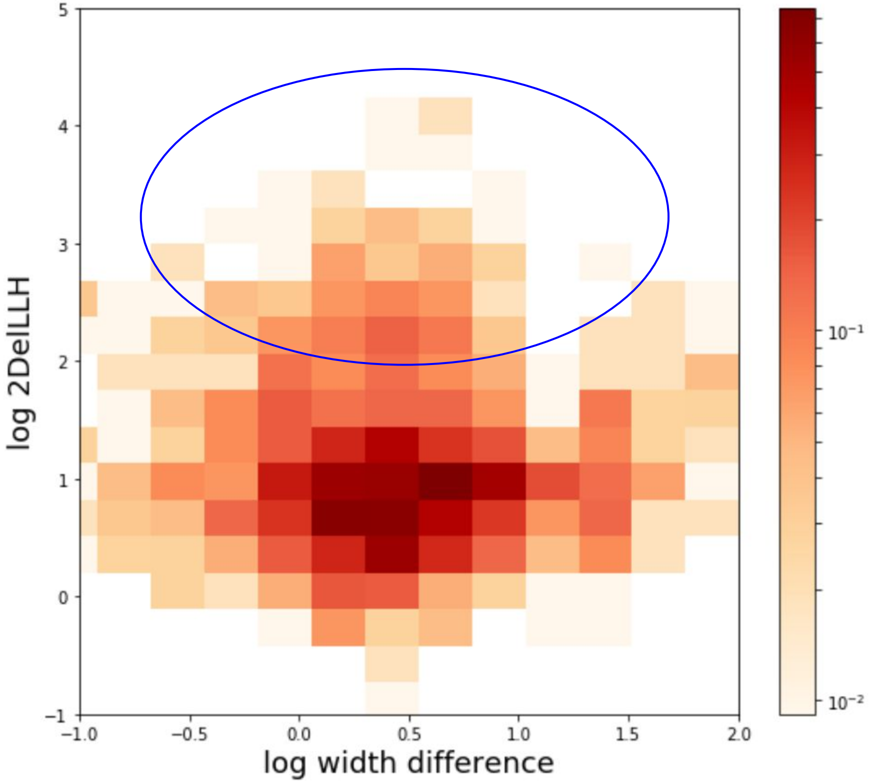


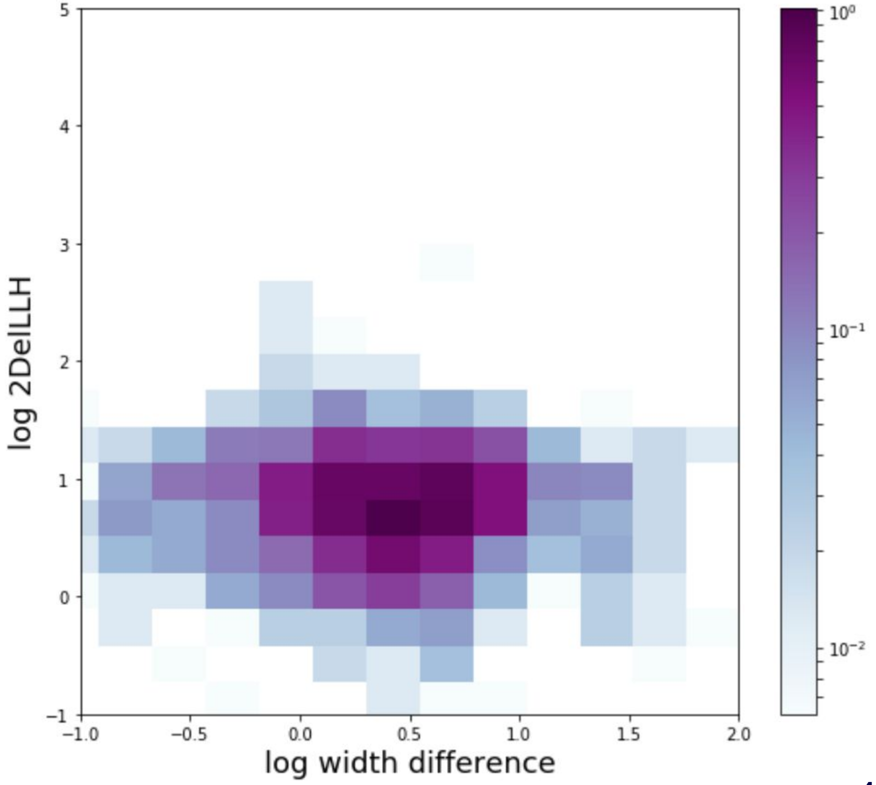
Hist 2Ds for Exponential gaussian fits



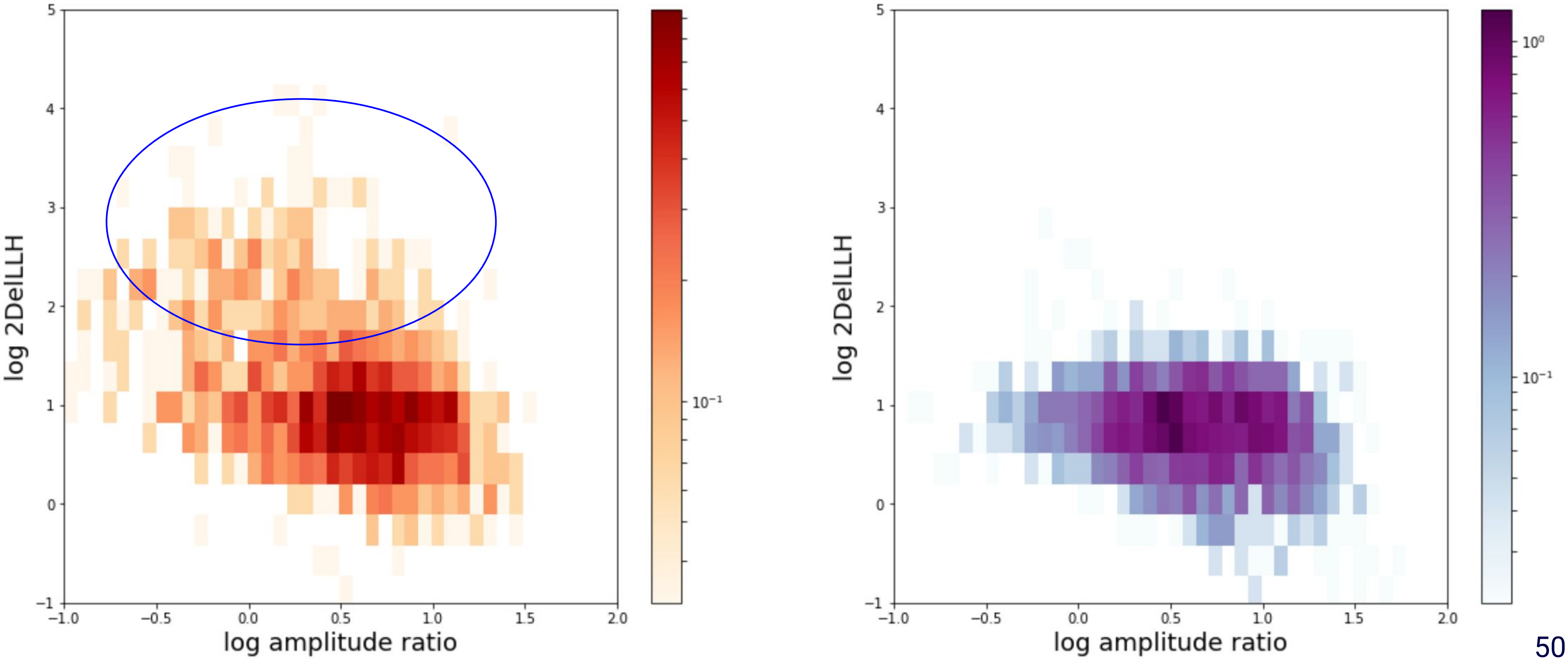


Hist 2Ds for Exponential gaussian fits

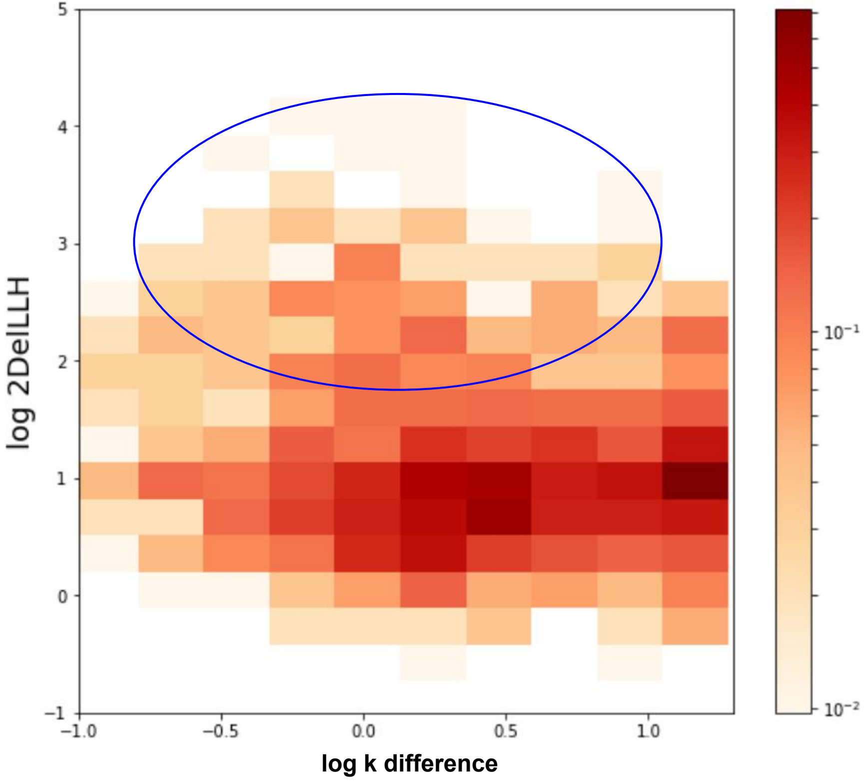


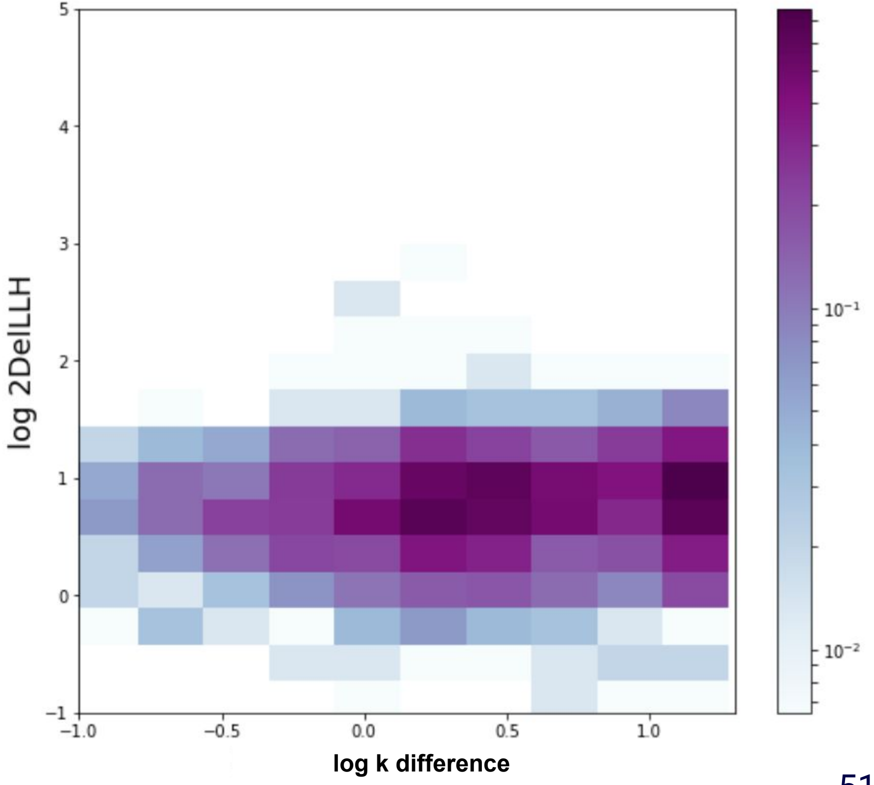


Hist 2Ds for Exponential gaussian fits



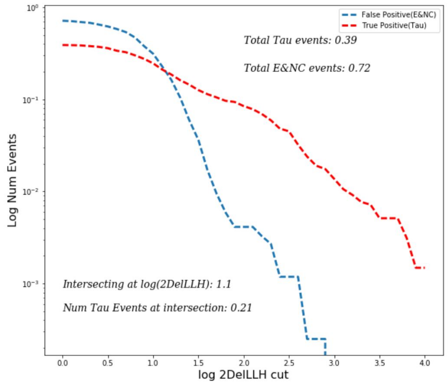
Hist 2Ds for Exponential gaussian fits

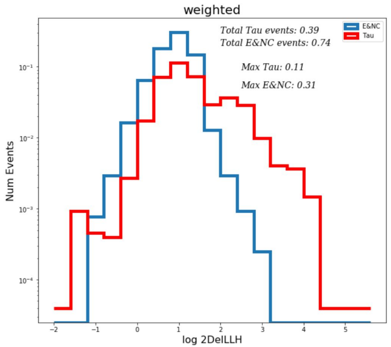




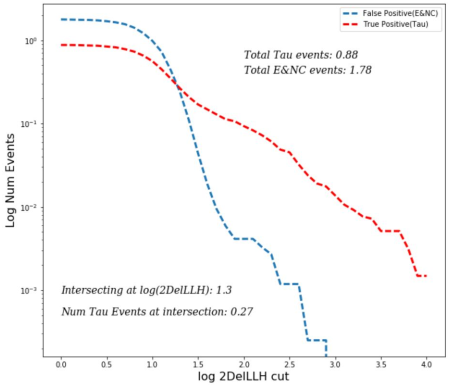
Improving the Number of ν_τ events/year

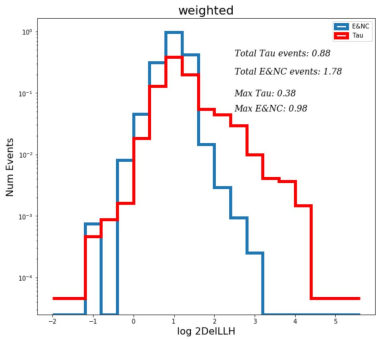
Number of hits in DOMs > 200



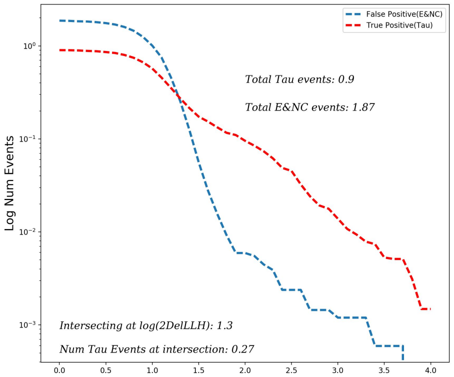


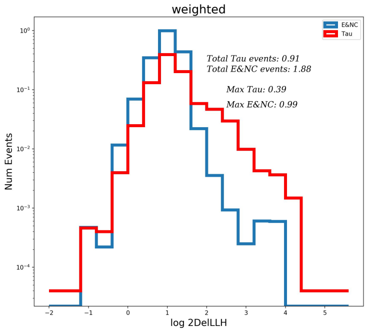
Number of hits in DOMs > 0





Number of bins >= 9



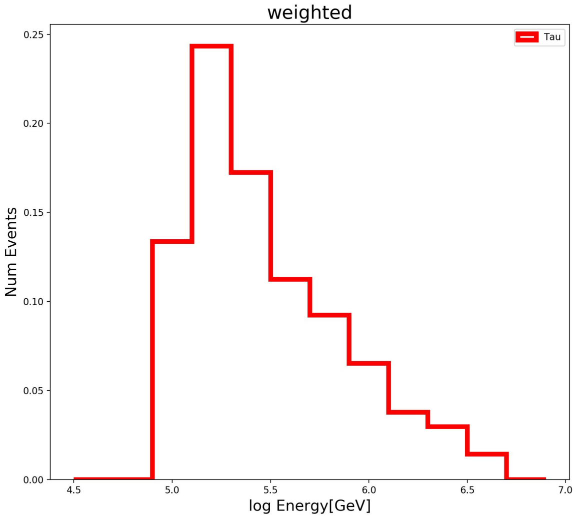


The intersection point moves to the right as the number of events included in the analysis increases.

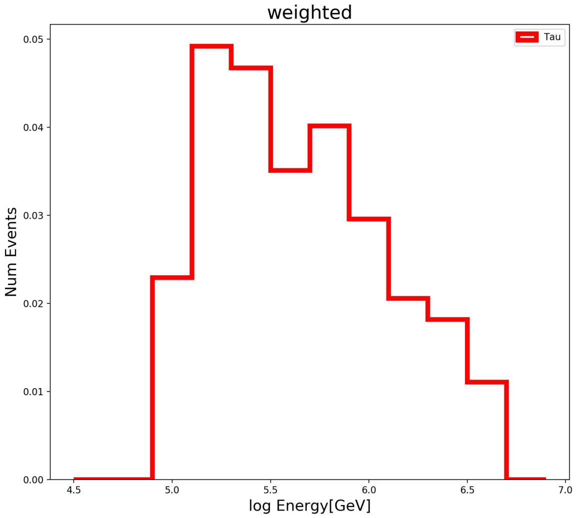
Energy Distributions - Tau neutrino events

- The energy distribution shifts to the right as higher cut variable is imposed.

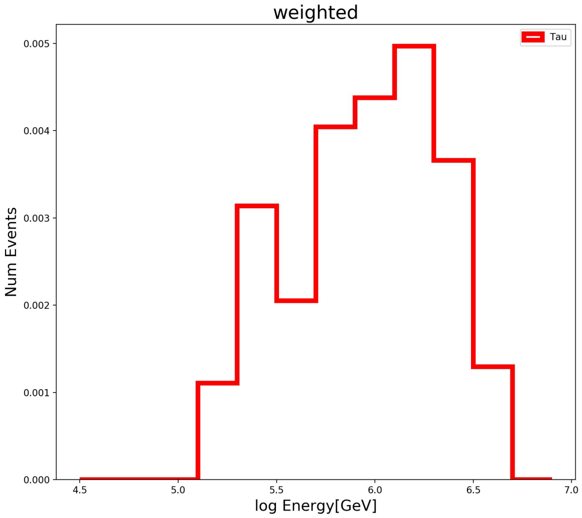
Cut Variable = 0



Cut Variable = 1.3



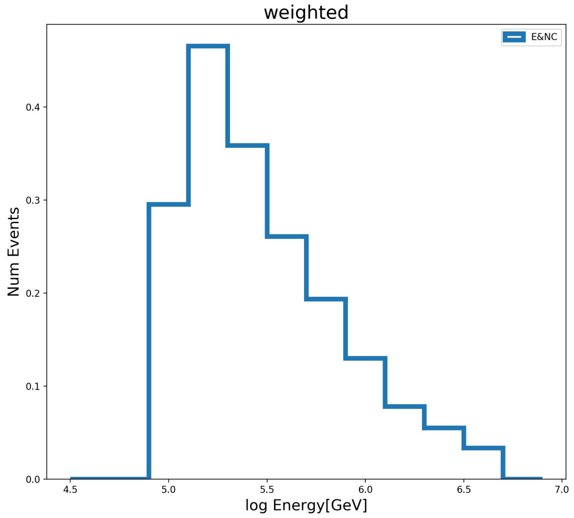
Cut Variable = 3.0



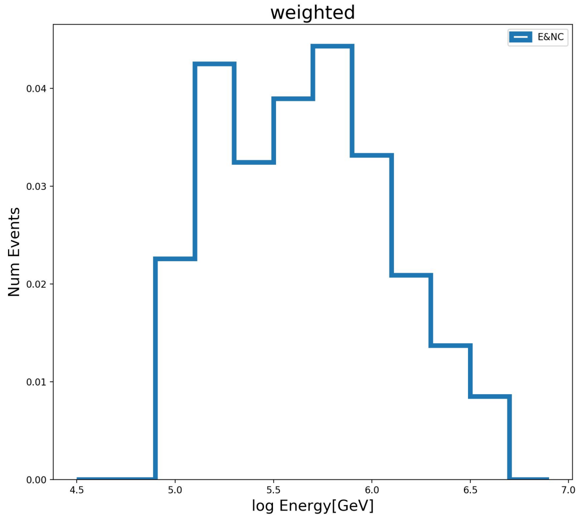
Energy Distribution - NuE&NC events

- The energy distribution shifts to the right as higher cut variable is imposed.

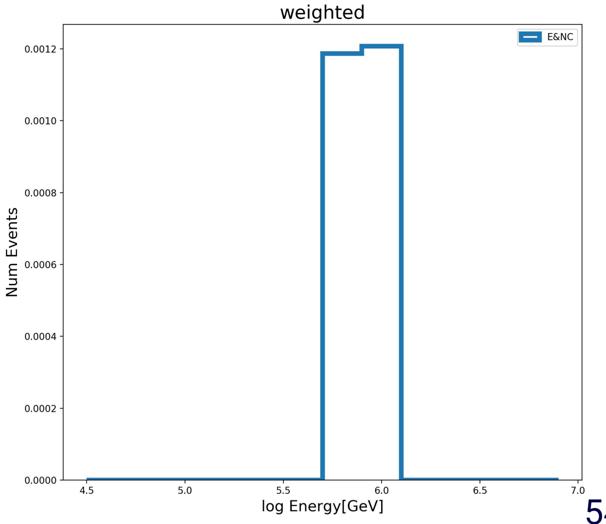
Cut Variable = 0



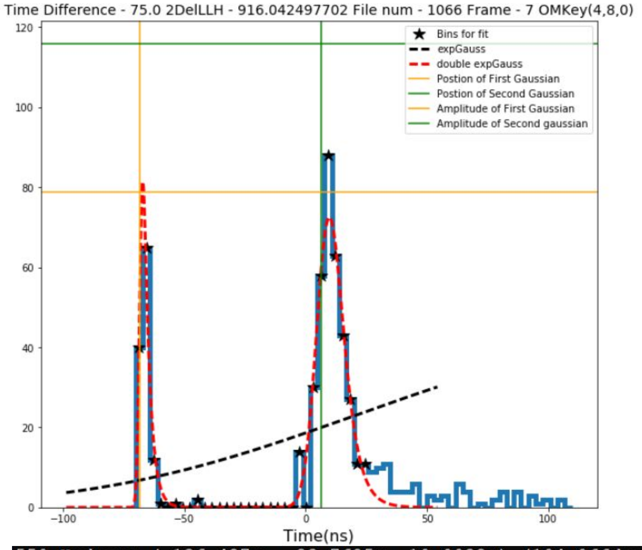
Cut Variable = 1.3

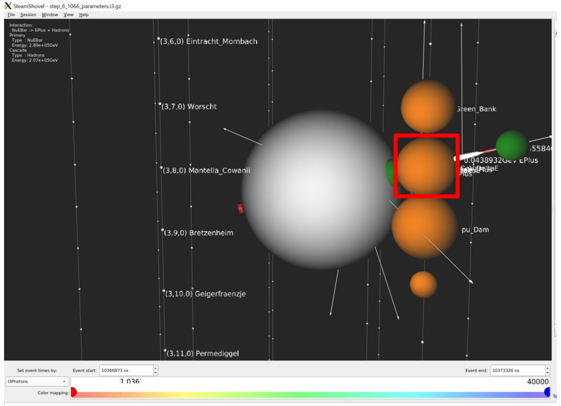


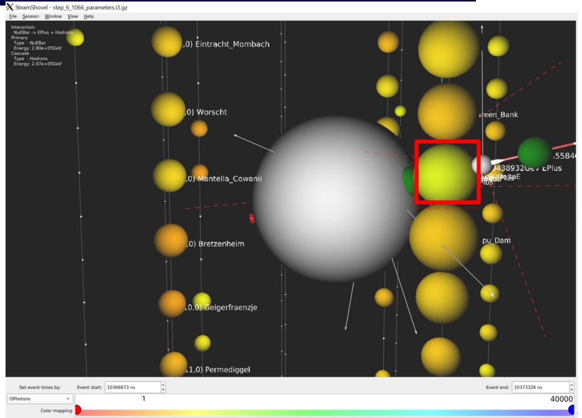
Cut Variable = 3.0

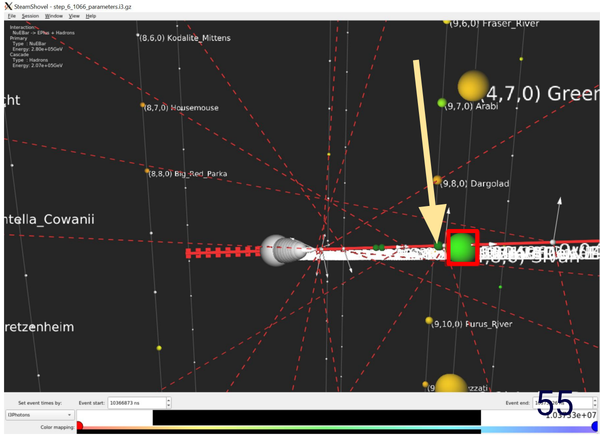


Suspicious NuEs and NC events







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550 Hadrons (-136.427m, -23.7625m, 10.0032m) (104.066deg, 54.4047deg) 1.03671e+07ns 207044GeV 0m
  561 MuPlus (-136.427m, -23.7625m, 10.0032m) (104.066deg, 54.4047deg) 1.03671e+07ns 56.9355GeV 227.179m
    585 MuPlus (-136.427m, -23.7625m, 10.0032m) (104.066deg, 54.4047deg) 1.03671e+07ns 56.9355GeV 51.1243m
    586 DeltaE (-165.292m, -64.0876m, 22.4288m) (104.066deg, 54.4047deg) 1.03673e+07ns 0.890161GeV 0m
    587 MuPlus (-165.292m, -64.0876m, 22.4288m) (104.066deg, 54.4047deg) 1.03673e+07ns 44.5932GeV 21.6877m
    588 DeltaE (-177.537m, -81.1941m, 27.7m) (104.066deg, 54.4047deg) 1.03674e+07ns 4.7113GeV 0m
    589 MuPlus (-177.537m, -81.1941m, 27.7m) (104.066deg, 54.4047deg) 1.03674e+07ns 35.0353GeV 5.9981m
    590 DeltaE (-180.923m, -85.9252m, 29.1578m) (104.066deg, 54.4047deg) 1.03674e+07ns 0.509406GeV 0m
    591 MuPlus (-180.923m, -85.9252m, 29.1578m) (104.066deg, 54.4047deg) 1.03674e+07ns 33.1886GeV 50.916m
    592 DeltaE (-209.671m, -126.086m, 41.5328m) (104.066deg, 54.4047deg) 1.03676e+07ns 0.605584GeV 0m
    593 MuPlus (-209.671m, -126.086m, 41.5328m) (104.066deg, 54.4047deg) 1.03676e+07ns 21.2607GeV 97.4524m
    594 EPlus (-264.693m, -202.953m, 65.2184m) (88.5481deg, 307.068deg) 1.03695e+07ns 0.0203435GeV 0m
    595 NuE (-264.693m, -202.953m, 65.2184m) (17.3608deg, 90.5706deg) 1.03695e+07ns 0.0424134GeV 0m
    596 NuMuBar (-264.693m, -202.953m, 65.2184m) (162.862deg, 163.611deg) 1.03695e+07ns 0.0429015GeV 0m
```

Time Difference