UNIVERSITY OF ALBERTA

Detecting ν_τ in P-ONE

P-ONE Virtual Collaboration meet
December 15 2020
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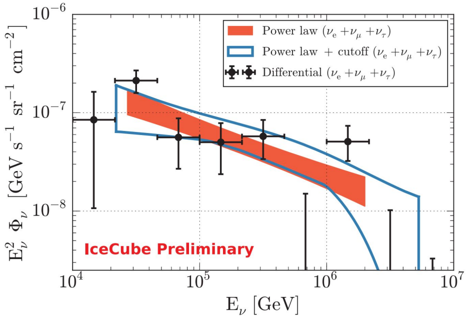
Importance of detecting ν_τ

- ν_τ not usually produced in the atmosphere. They exist only due to oscillations.
- Detecting ν_τ will:
  - **Reaffirm the astrophysical origins of high energy neutrinos.**
  - **Confirm the existing model of neutrino oscillations on cosmological scales.**
- ν_τ detection should be regarded as priority by future detectors.
- 20%-40% of the total astrophysical flux is contributed by ν_τ.
- After 10 years of its construction, IceCube is on the verge of detecting the first ν_τ with 90% C.L. Three potential candidates for ν_τ events discovered so far.
- At high energies IceCube has no problem with detecting ν_τ. At lower energies, due to scattering, hard to separate ν_τ from background

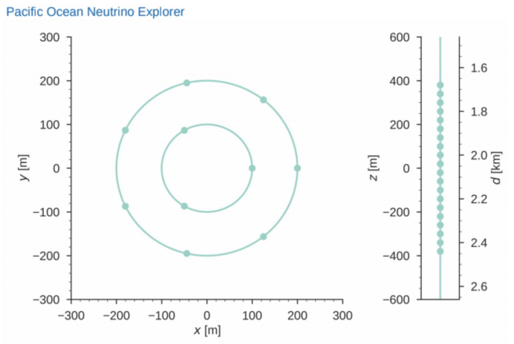


Can P-ONE do better, given that there is less scattering in water?

Simulation

01

The Simulation Chain



- IceCube software for simulations. Uses Ice Tray framework.
- IceTray framework - modules written in C++ accessed by using Python interface
- Geometry of the detector changed to match that of P-ONE phase 1.

Neutrino Generator(NuGen) → **PROPOSAL** → **CLSim** → **PE Hit Generator** → **Noise Generator** → **RecoPulse Generator**

IceCube Modules (yellow)

Modules developed for P-ONE (green)

Simulating mDOM

- Simulating IceCube mDOM, 24 3” PMTs and a flat angular acceptance.
- Angular acceptance of DOM depends on the PMT coverage area.

$$10 \times 3'' PMT\,Area \approx 10'' PMT\,Area$$

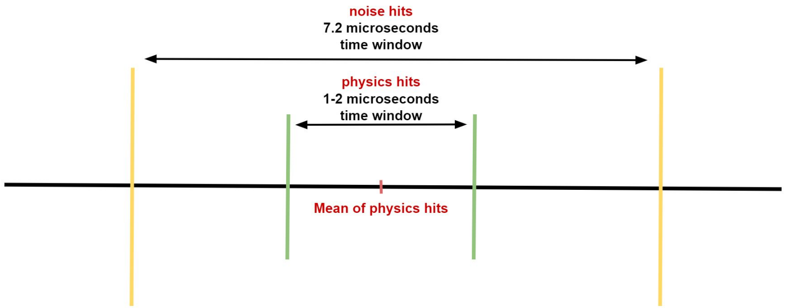
$$\Rightarrow \frac{mDOM area}{IcecubeDOMarea} \approx 2.4$$

$$2.4 \times \sum_{\theta=-1}^{1} f(\theta)_{IceCube\,Angular\,Acceptance} = \sum_{\theta=-1}^{1} mDOM\,Angular\,Acceptance$$

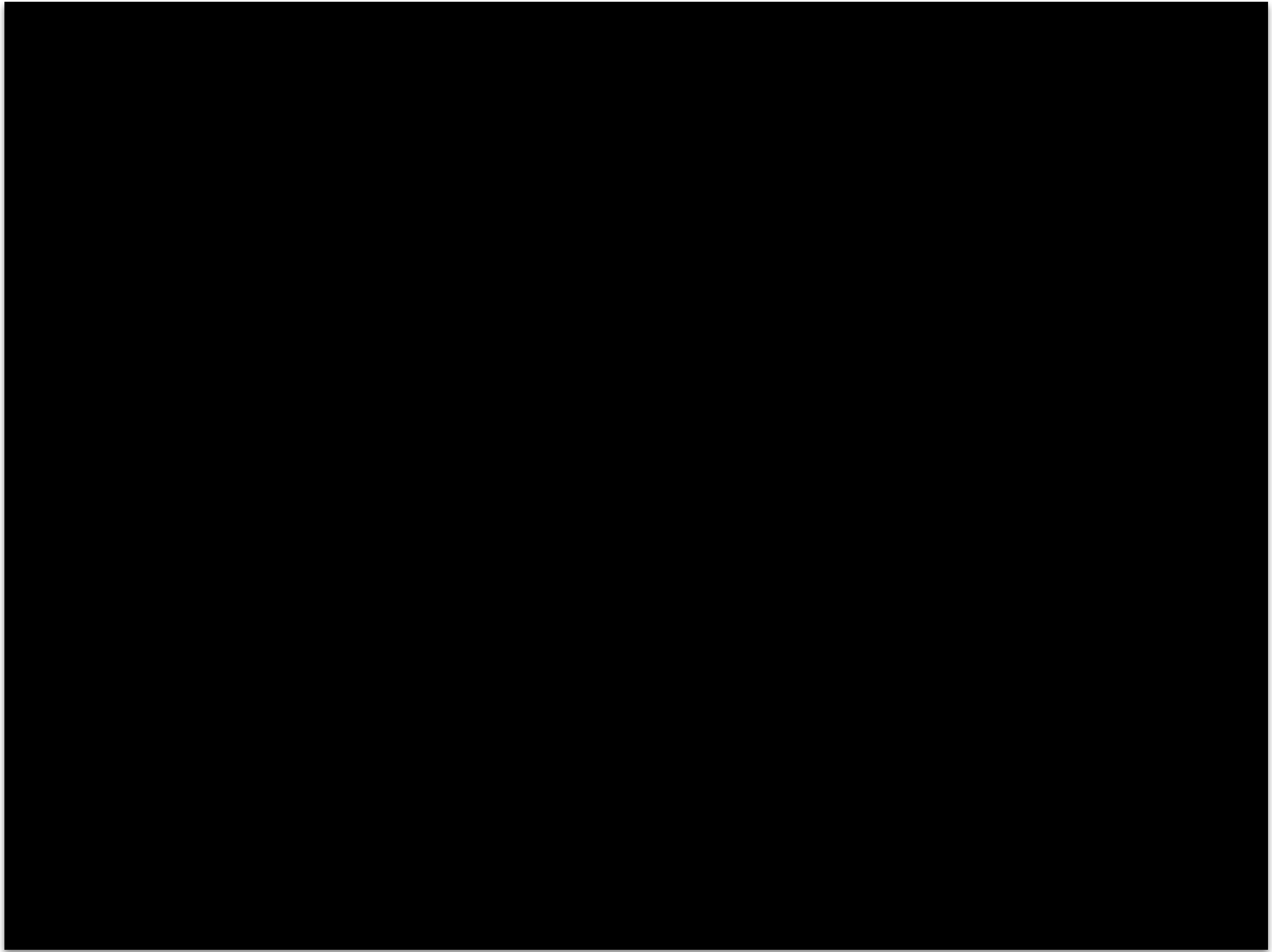
- The angular acceptance is a constant value of 0.811
- The wavelength acceptance is set to be the same as IceCube’s.

MC parameters

- NuGen settings:
  - **Energy: 100TeV to 5PeV**
  - **Azimuth: 0 to 180 degrees**
  - **Zenith: 0 to 180 degrees**
  - **Interaction Cylinder parameters: h=1000m, r=500m**
- Signals assume an mDOM, but no granularity.



- Noise, STRAW data from dark runs, is injected on top of physics hits.
- RecoPulse Generator:
  - The PMT response is simulated here, hits within 3 ns are merged as one, and their charges summed.
  - The width of the pulse is chosen to be a constant, in this case, it is set to 3 ns.
  - 0-1.5 ns smear is added to the timestamps
- 40,000 ν_τ and ν_e events simulated in total

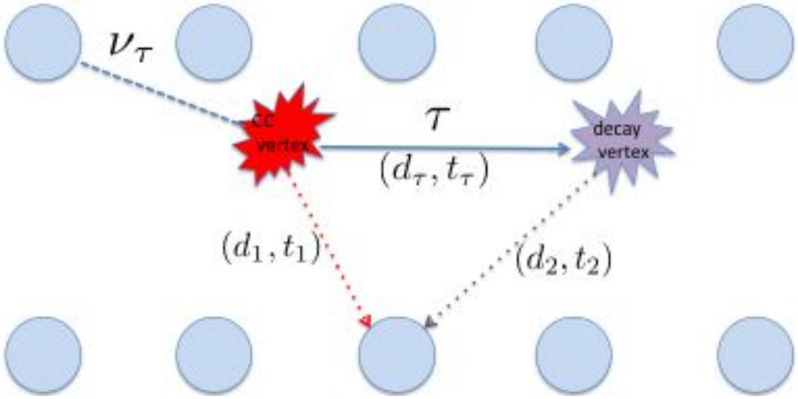


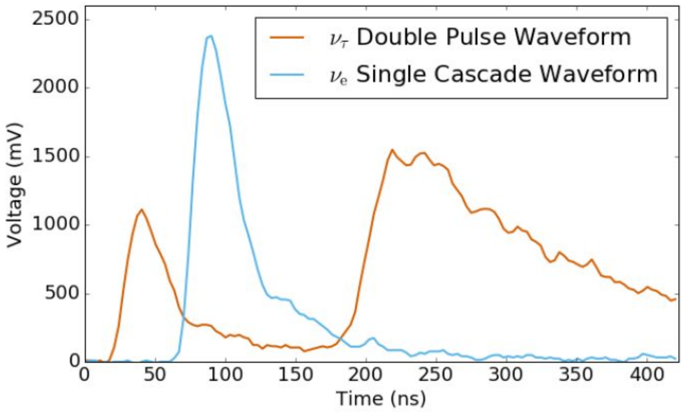
02

Analysis

The Goal of the Analysis

- ν_τ CC interaction produces a characteristic signal called Double Pulse.
- Double Pulse - double cascades - 1) Tau creation 2) Tau Decay
- **Develop an algorithm that identifies tau neutrino signal from the background.**

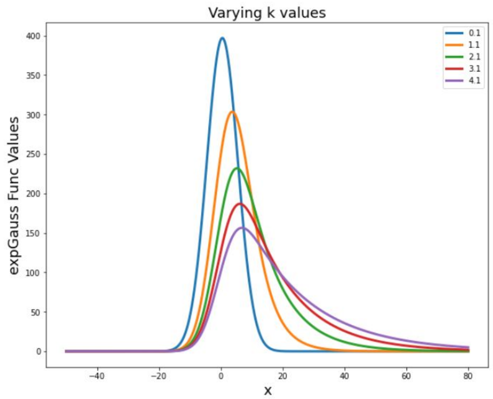




The Method

- The main background while detecting double peak signal is the CC interactions of electron neutrinos, NC interactions of neutrinos of all flavours and atmospheric muon neutrinos
- **The algorithm fits both a single exponential gaussian and double exponential gaussian to every DOM in the event**.
- Four parameters describe a single exponential gaussian - mean, width, amplitude and k(defines how exponential the tail is)
- Parameters of the fit and log likelihood values are used to separate ν_τ and background events.

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



The colours indicate the different k values

The Algorithm

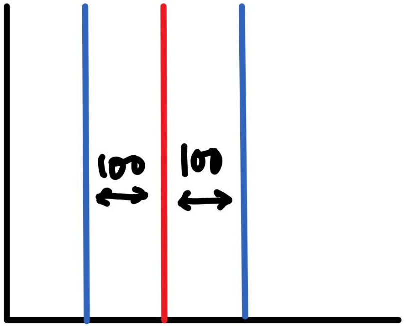
Number of hits in DOMs > 200

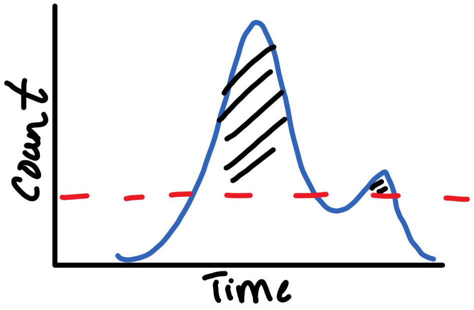
Select hits within 200 nanoseconds

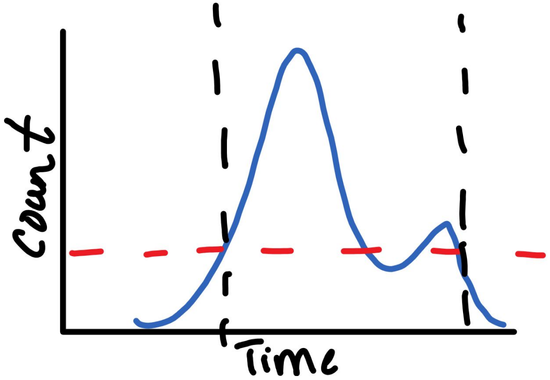
Histogram

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

Number of bins >= 10







The Fit

- Used IMINUIT minimizer.
- The **minimizer minimizes the -log likelihood** value given by:

Ignored: Model independent ←

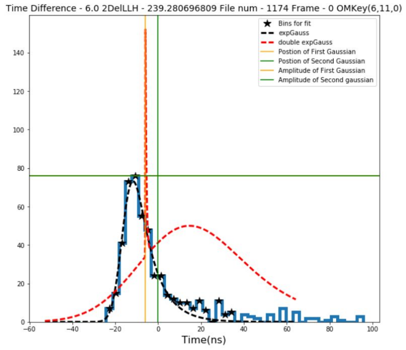
$$\boxed{\sum_i \ln(n_i!)} + \mu_i - n_i \ln \mu_i$$

μ_i = model
n_i = data(Number of hits in a bin)

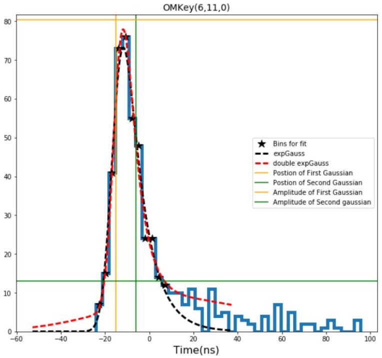
- Bounds and initial values given to the minimizer.

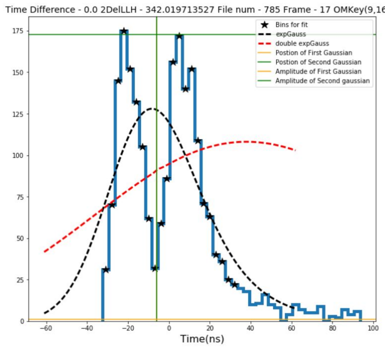
Does the Algorithm work as expected?

- Multiple checks were done to improve the algorithm by changing the bounds and initial values given to minimizer.
- Sensitive to initial values, looping over possible initial values.

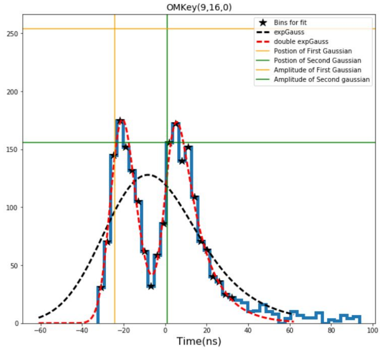


Changing bounds →



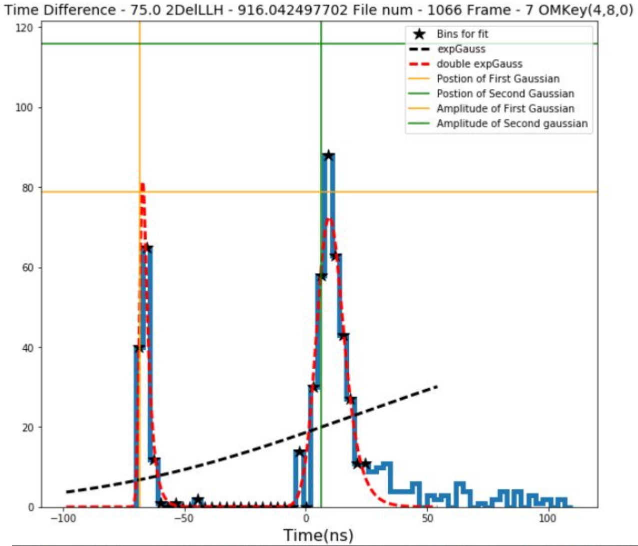


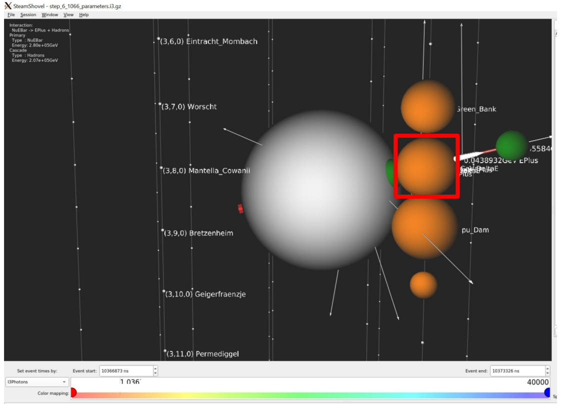
Changing Initial Values →

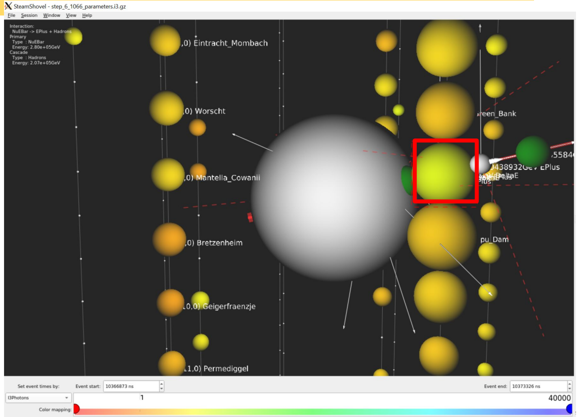


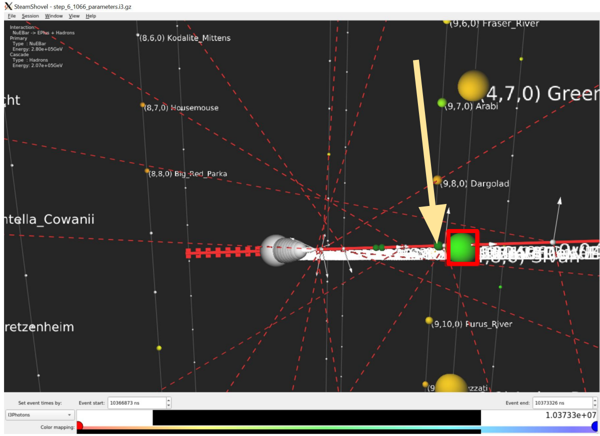
Few examples of changing bounds and initial values to appropriate values to achieve a good fit

Suspicious NuEs and NC events







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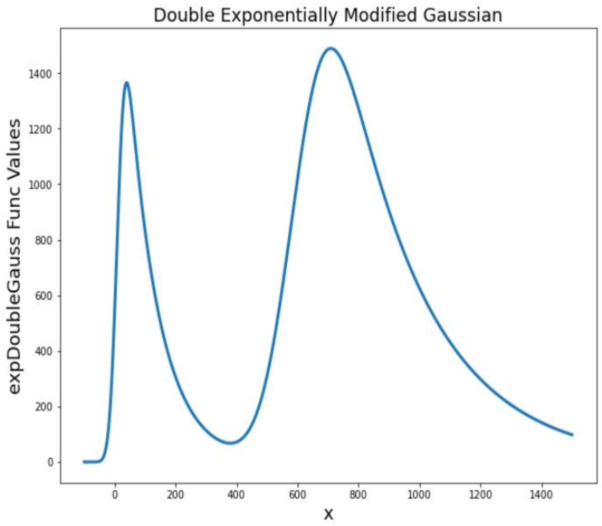
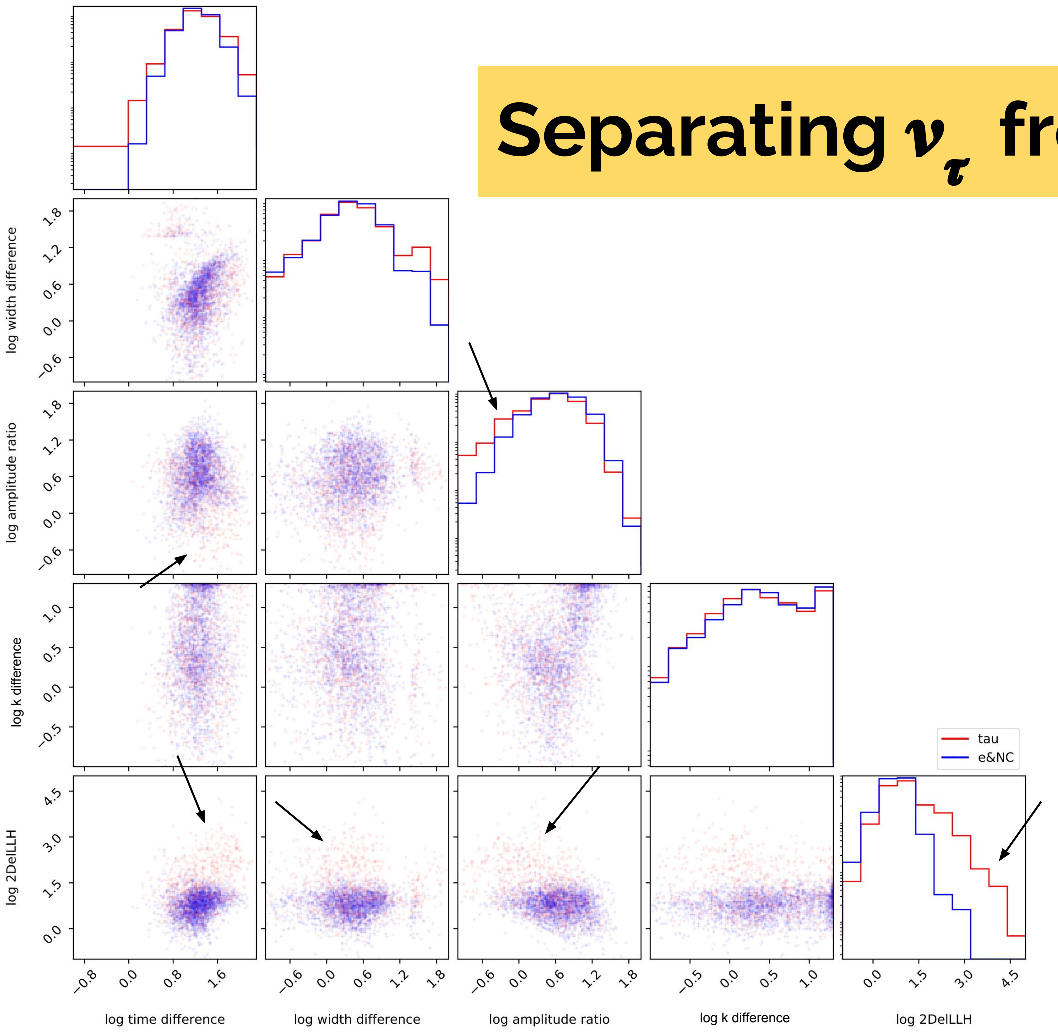
550 Hadrons (-136.427m, -23.7625m, 10.0032m) (104.066deg, 54.4047deg) 1.03671e+07ns 207044GeV 0m
 561 MuPlus (-136.427m, -23.7625m, 10.0032m) (104.066deg, 54.4047deg) 1.03671e+07ns 56.9355GeV 227.179m
  585 MuPlus (-136.427m, -23.7625m, 10.0032m) (104.066deg, 54.4047deg) 1.03671e+07ns 56.9355GeV 51.1243m
  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
```

Parameters for Comparison

- The algorithm returns the mean, width, amplitude and k values of the fits.
- A double exponential gaussian has 8 parameters(double expGauss = expGauss_1 + exp Gauss_2)
- Time Difference = $\text{position}_2 - \text{position}_1$
- Width Difference = $|\text{width}_2 - \text{width}_1|$
- Amplitude Ratio = $\text{amplitude}_1/\text{amplitude}_2$
- k difference = $|k_2 - k_1|$
- LLH difference = $2*(\text{LLH}_{\text{double expGauss}} - \text{LLH}_{\text{expGauss}})$
  - Defines how likely the double expGauss model is the correct fit.



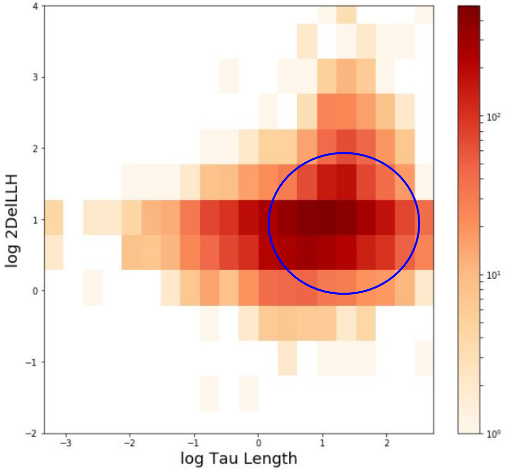
Separating ν_τ from the background

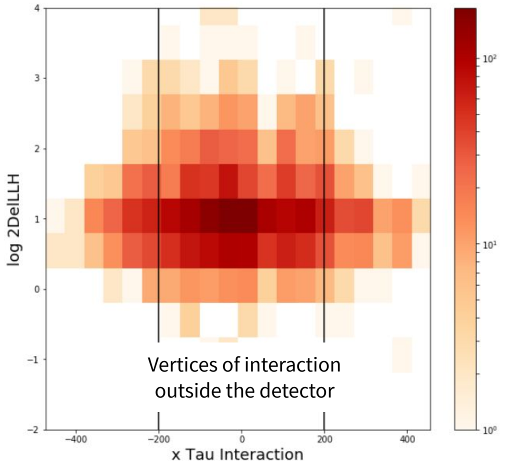


- Some separation in log amplitude ratio.
- Most separation observed in log 2ΔLLH.
- Introducing cuts in the data using log 2ΔLLH(**CUT VARIABLE**) values will be most effective.

Tau length Correlation

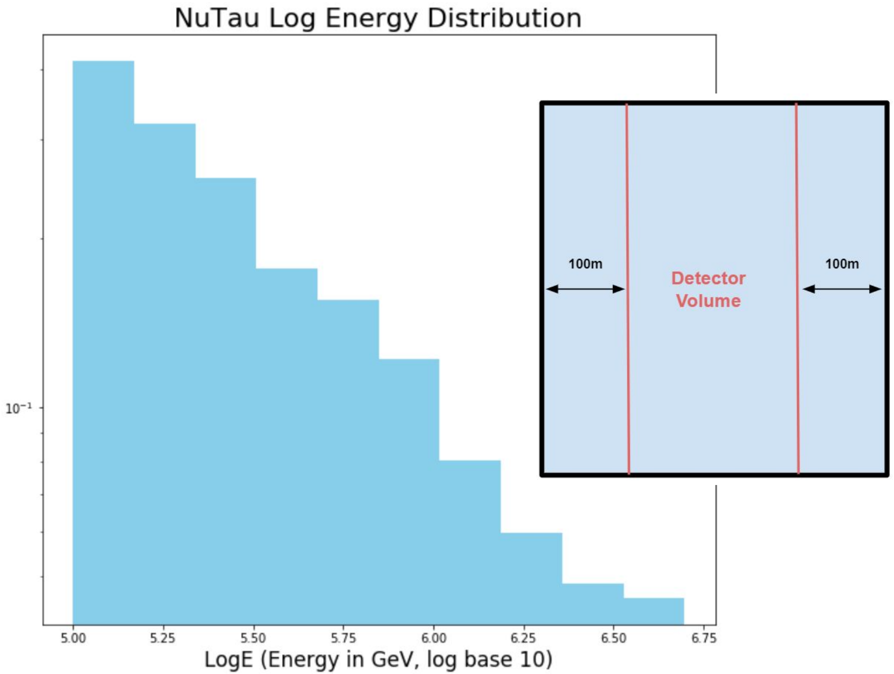
- Ideally large tau length would mean large cut variable value .
- What happens with DOMs with large tau length and small cut variable?
  - Vertices(Tau creation and tau decay) are outside the detector.
  - Tau decays into a muon
  - DOM is not at an ideal distance from the vertices.





Weighting Events

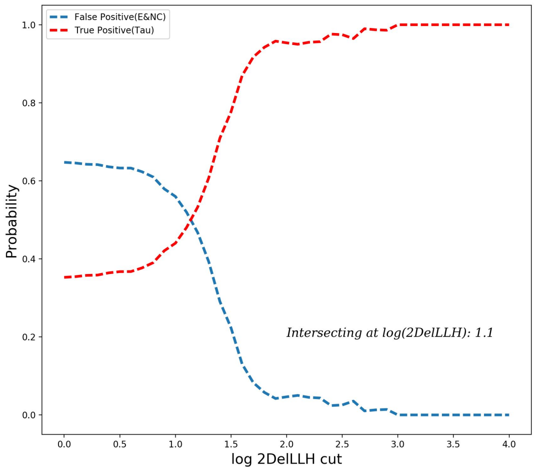
- Each event has a corresponding weight associated with it.
- For the analysis here the events are weighted to include:
  - Signal from astrophysical ν_τ
  - Background from atmospheric muon neutrinos and other flavours of astrophysical neutrinos
- Desired ν_τ events:
  - Charged Current interactions.
  - Interaction vertex should be within 100m around the detector volume in X and Y axis.

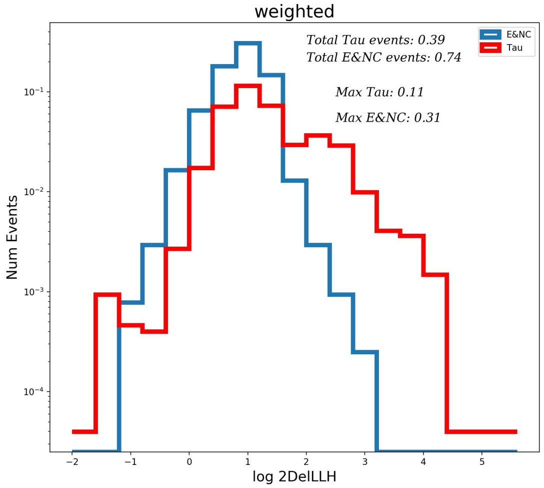


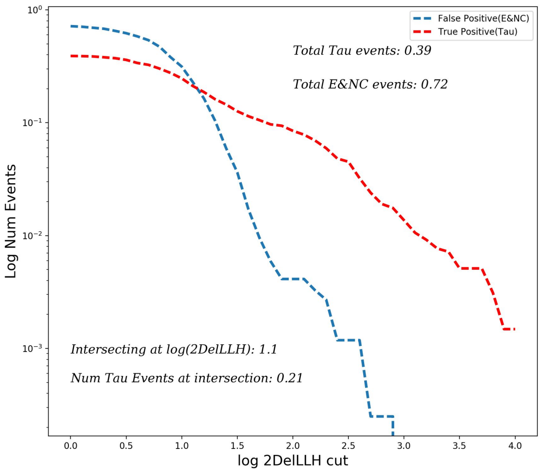
Expected CC ν_τ events per year: 1.68

Separating signal from background

- At cut variable 1.1 there is equal probability of the event being either a $\boldsymbol{\nu_\tau}$ or background event
- Total $\boldsymbol{\nu_\tau}$ events in a year is 0.39. Can this number be improved?

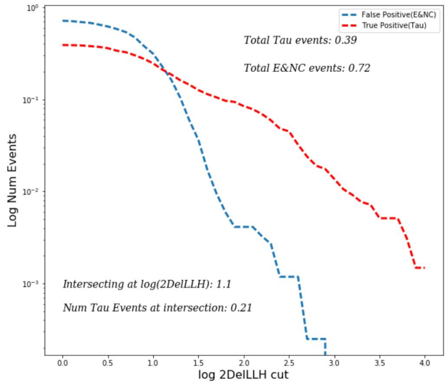


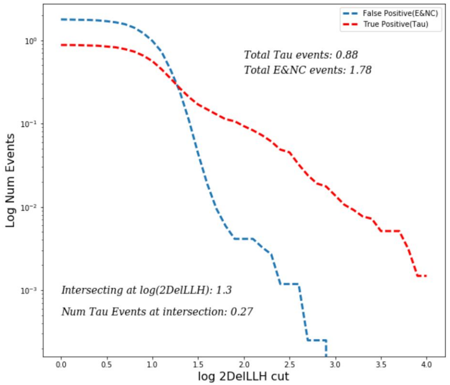


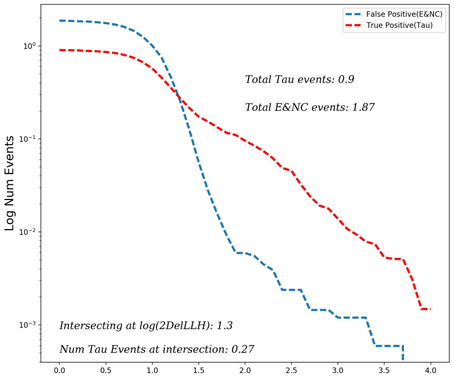


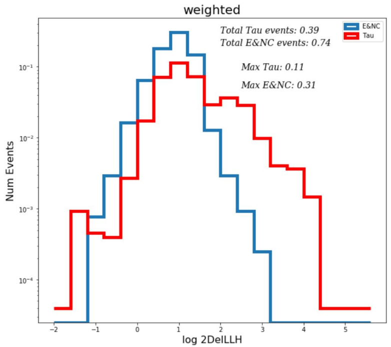
Improving the Number of ν_τ events/year

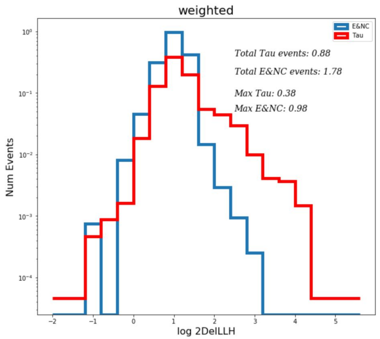
Number of hits in DOMs > **200**	Number of hits in DOMs > **0**	Number of bins >= **9**

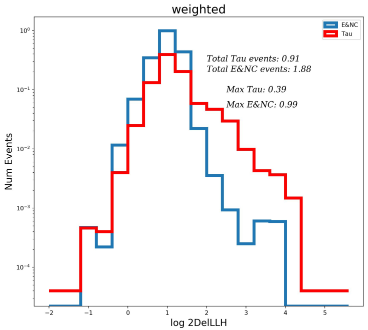












The intersection point moves to the right as the number of events included in the analysis increases.

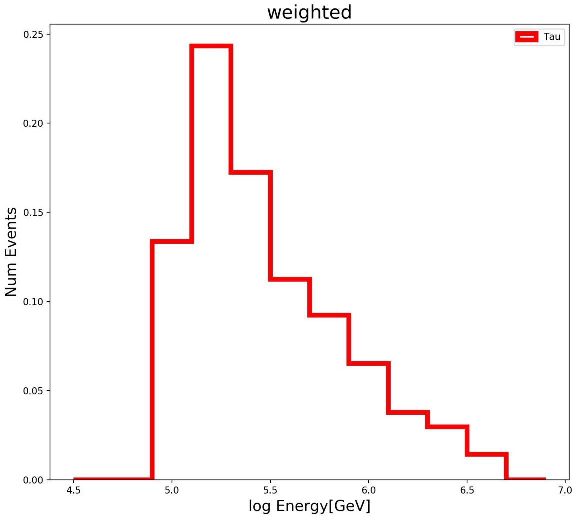
Improving the Number of ν_τ events / year

Conditions Changed	Total NuE&NC 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

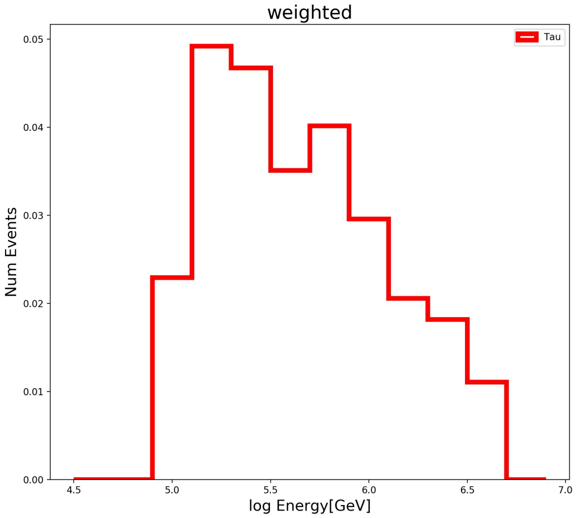
Energy Distributions - Tau neutrino events

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

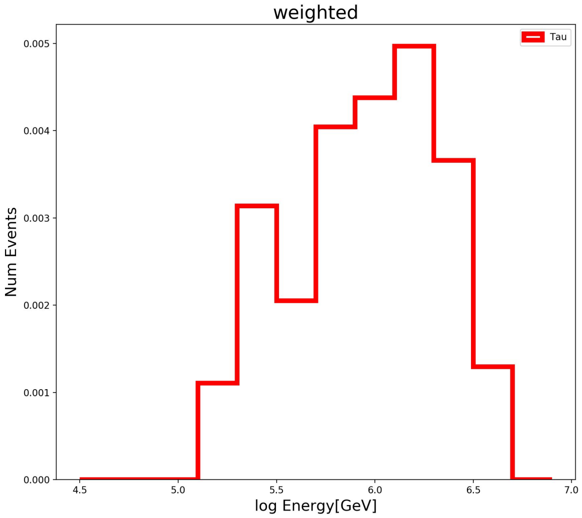
Cut Variable = 0



Cut Variable = 1.3



Cut Variable = 3.0



Energy Distribution - NuE&NC events

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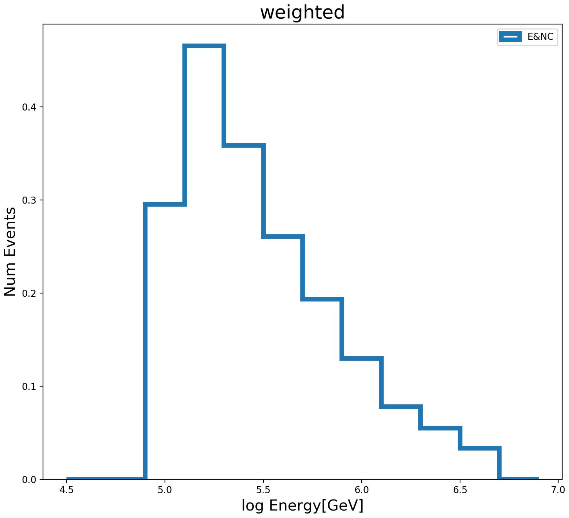
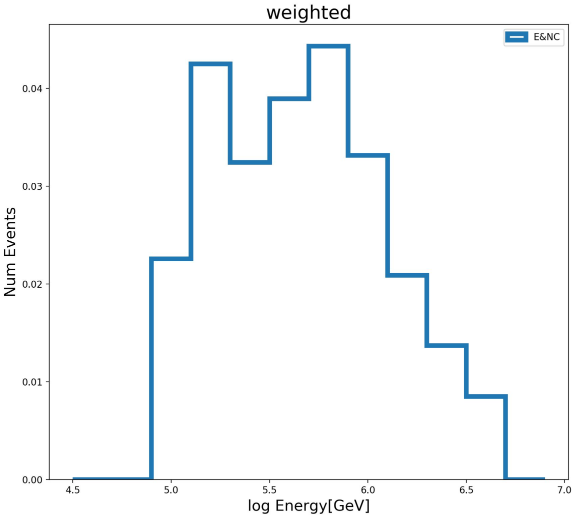
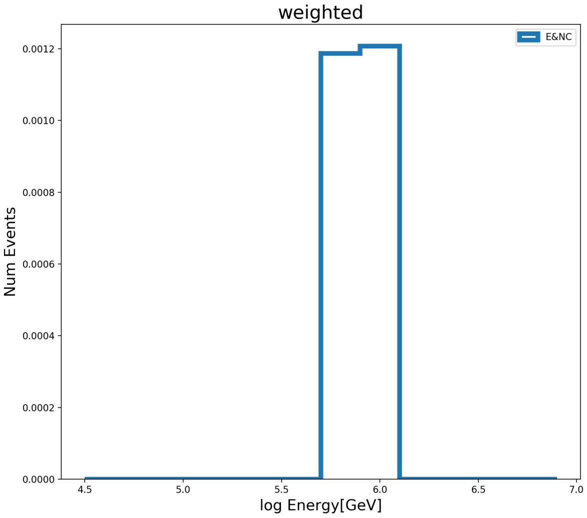


Cut Variable = 1.3



Cut Variable = 3.0



Conclusions and Next Steps

- The algorithm is successful in separating ν_τ 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 ν_τ events expected in a year if the algorithm is capable of identifying all ν_τ from the background.
- ~0.3 tau neutrino events with cut variable > 1.3 are detected in a year in P-ONE.
- The Algorithm can be further improved by having finer binning. The binning currently is motivated by icecube-type time resolution.
- Lower energies can be simulated to increase the number of ν_τ events detected.
- Parameters other than 2ΔLLH can be explored to see more separation.
- DOMs with large number of hits(~ >50,000) can be eliminated from the analysis.
- Machine learning to enhance the separation between tau neutrinos and the background.

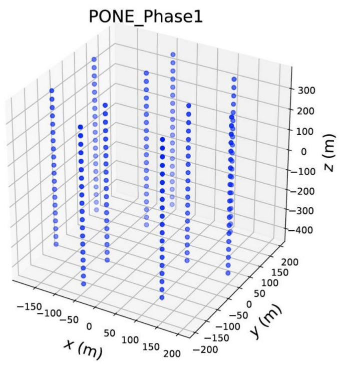
Thank You

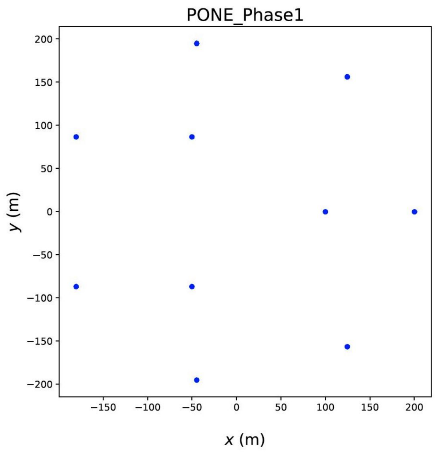
Any Questions?

Backup

GCD File

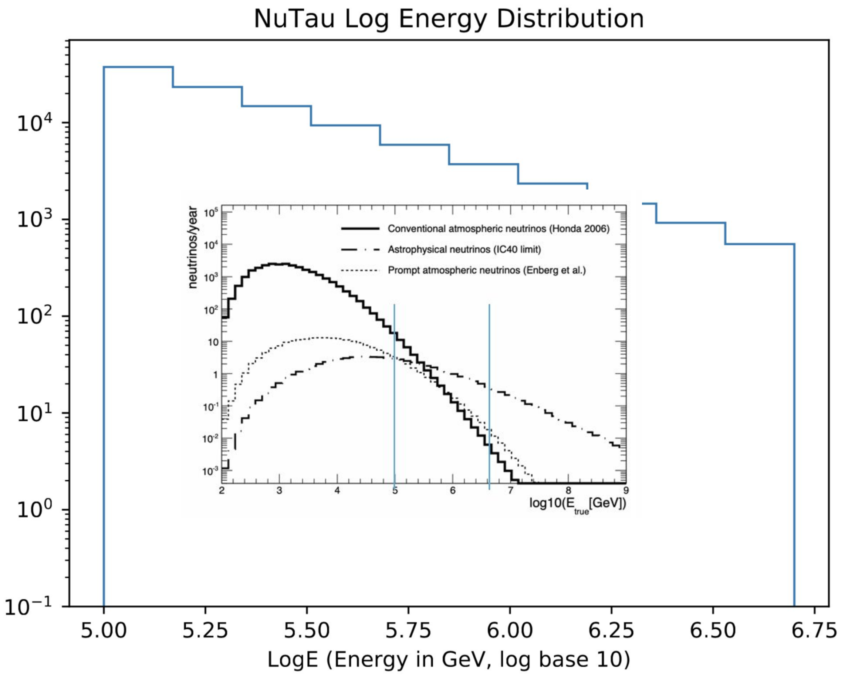
- Before starting the simulation the Geometry(G), Calibration(C) and Detector(D) status information should be updated accordingly to match P-ONE.
- A new GCD file generated.
- Calibration and Detector Status information is irrelevant for P-ONE

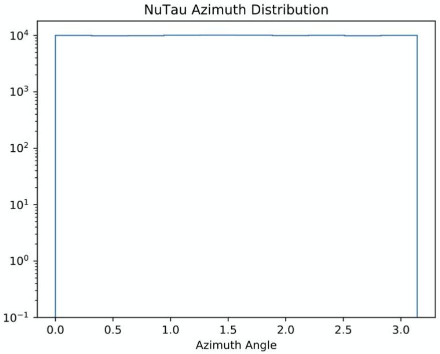


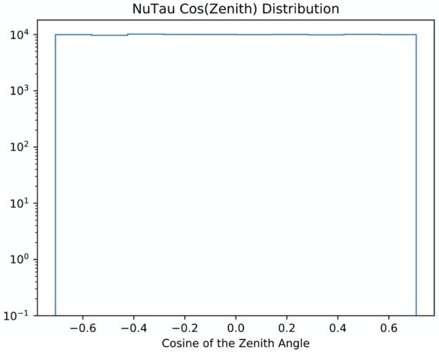


Neutrino Distributions

- 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.

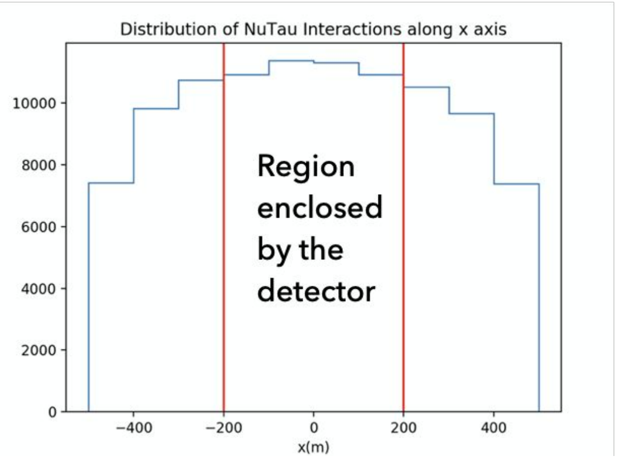


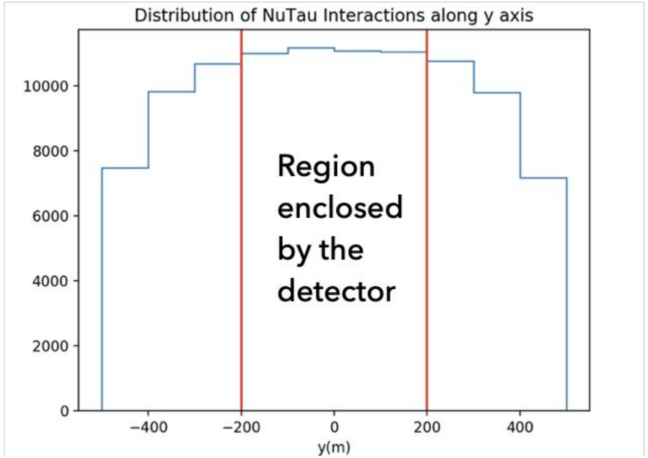


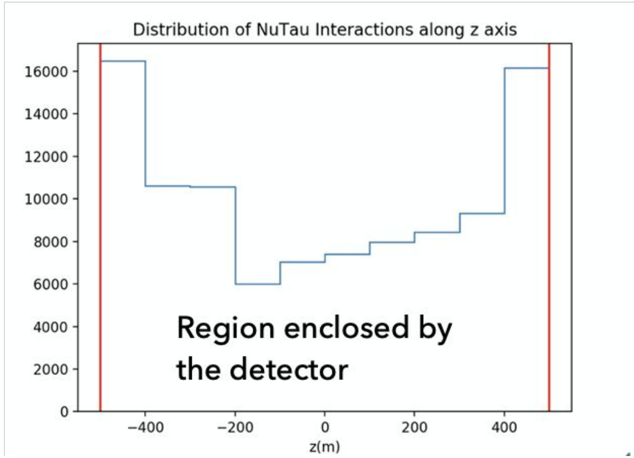


Vertex of Interaction of Neutrinos

Distributions of interactions of neutrinos to produce corresponding lepton



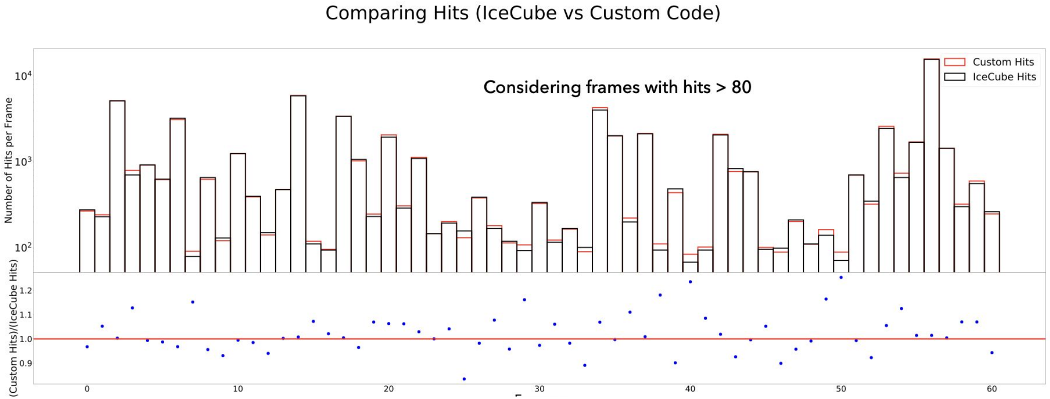


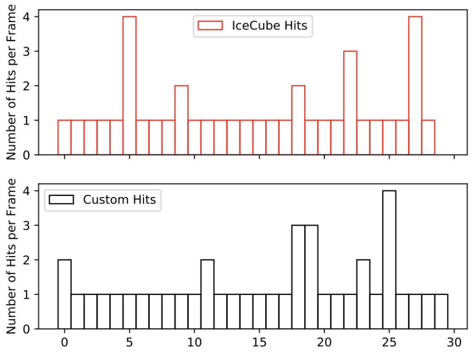


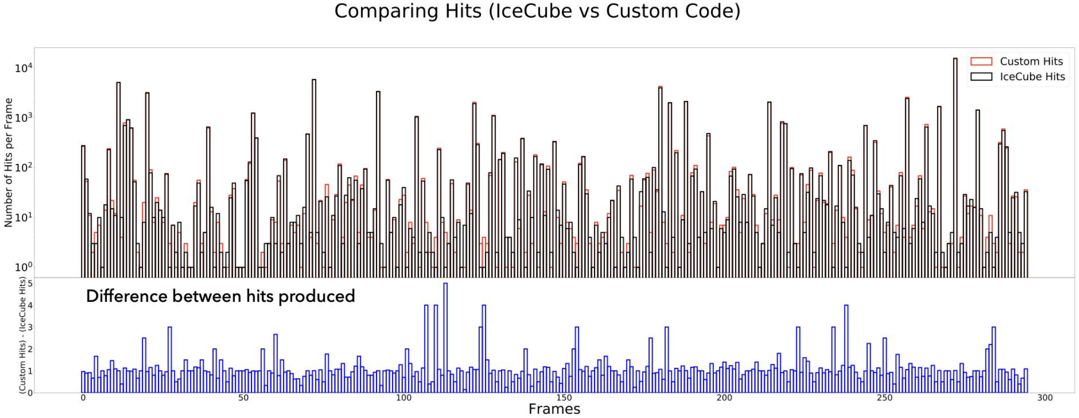
The dimensions of interaction cylinder given - Radius - 500m, height - 1000m, centered at (0, 0, 0)

Comparing Hits

- Frames with hits > 80 are closer to one as expected.
- The frames need enough statistics to get ratio closer to one.
- Number of hits from frames not common to output files from both

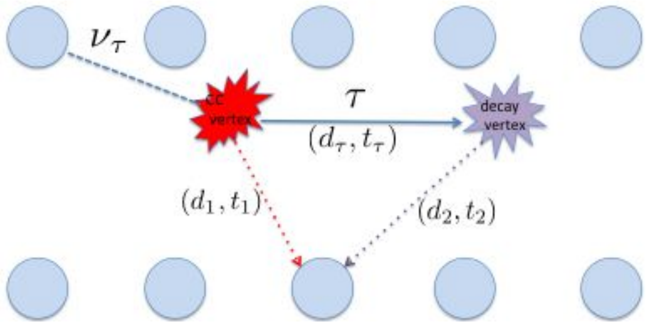




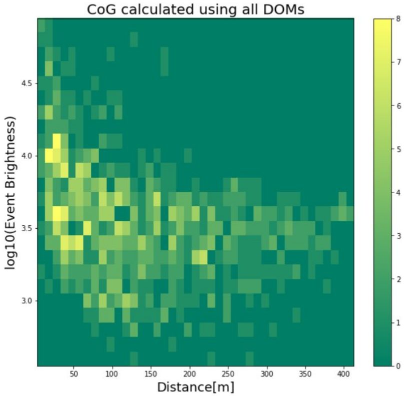


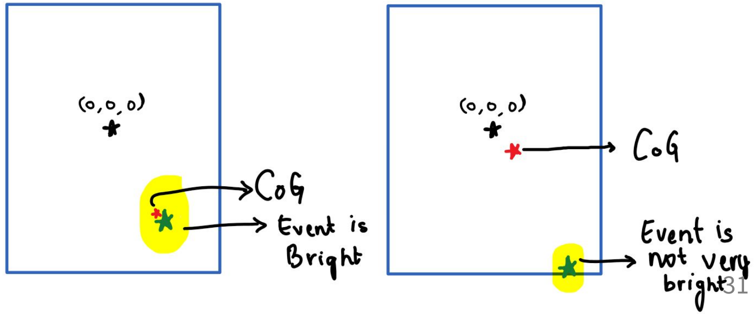
CoG

- Identify DOMs with double pulse signature relative to Centre of Gravity(CoG) of hits?
- Selected DOMs using time difference method. However most doms only have a single peak.
- Minimum distance between DOM and CoG does not show much correlation.



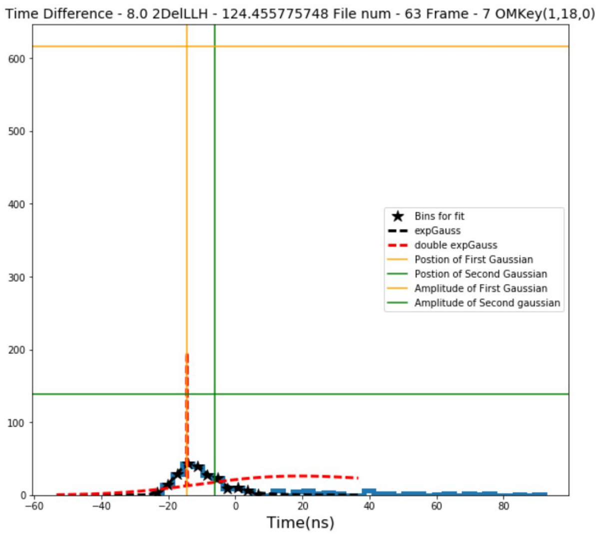
Time Difference = $t_2 - t_1$





Bounds and Initial Values of the Fit

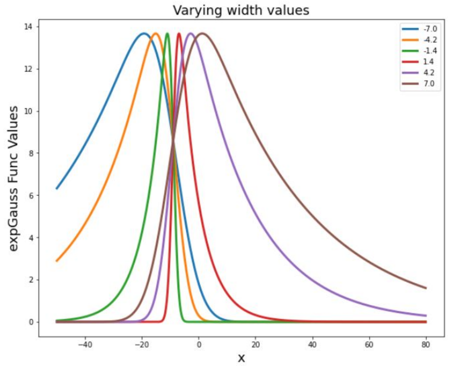
- Width needs to be negative, to change the direction of the exponential tail. However, the caveat here is that the minimizer outputs a NaN once it starts considering width values between (-0.999, 0.999)



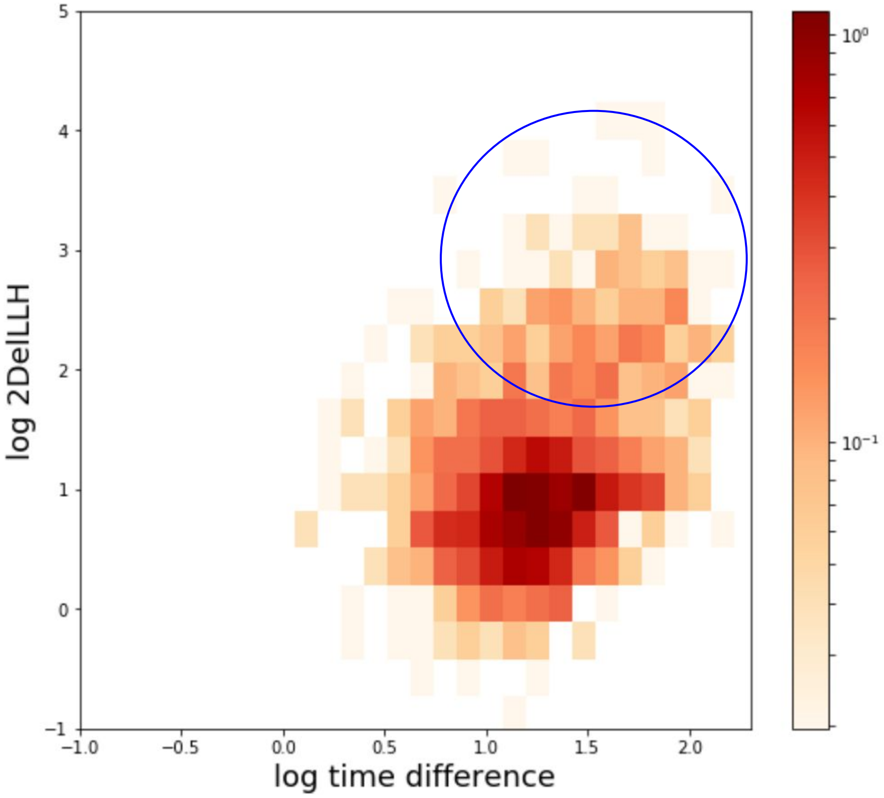
pos1	wid1	k1	amp1	pos2	wid2	k2	amp2	log likelihood
-14.4044	-0.0734752	0.134472	237.057	-5.96877	18.3955	6.09133	248.598	nan

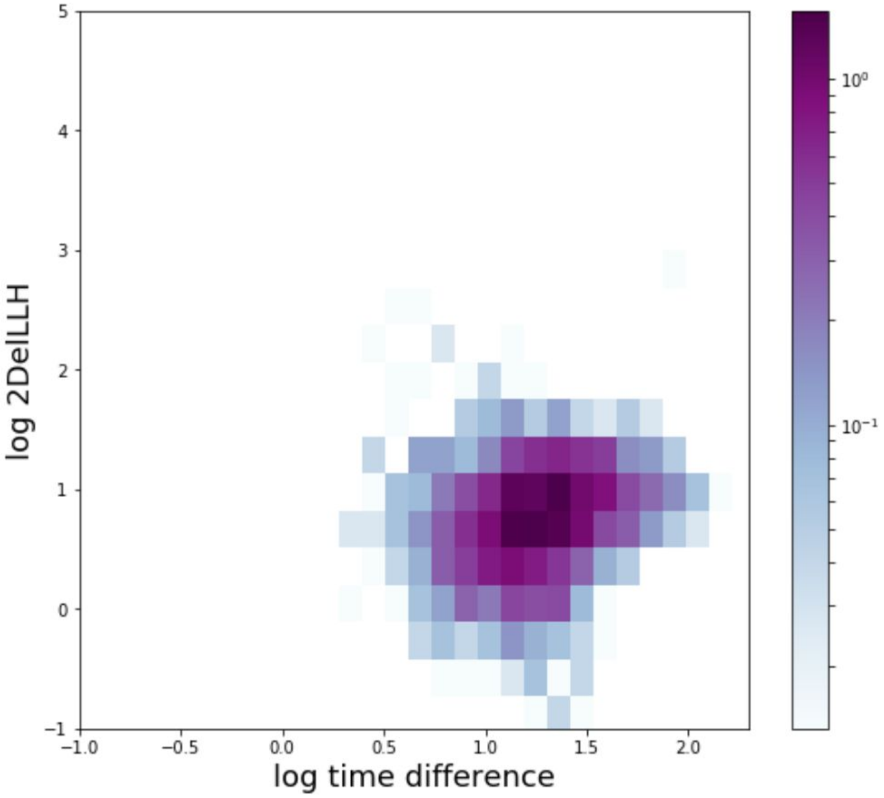
pos1	wid1	k1	amp1	pos2	wid2	k2	amp2	log likelihood
-14.3644	-0.05513	0.427769	638.78	-5.99934	23.245	1.34232	74.7544	nan

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

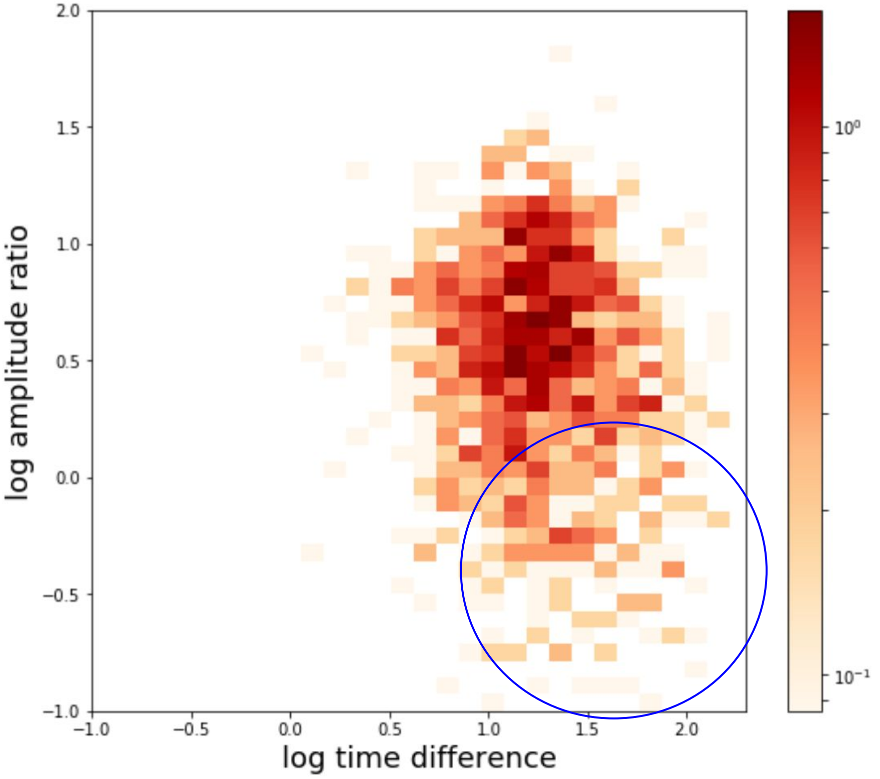


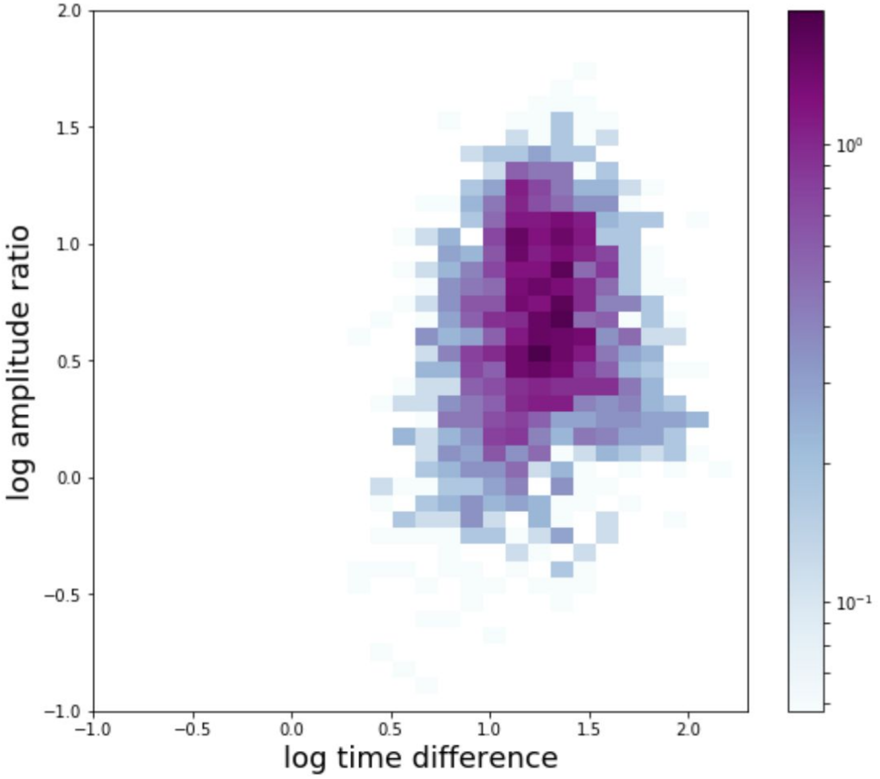
Hist 2Ds for Exponential gaussian fits



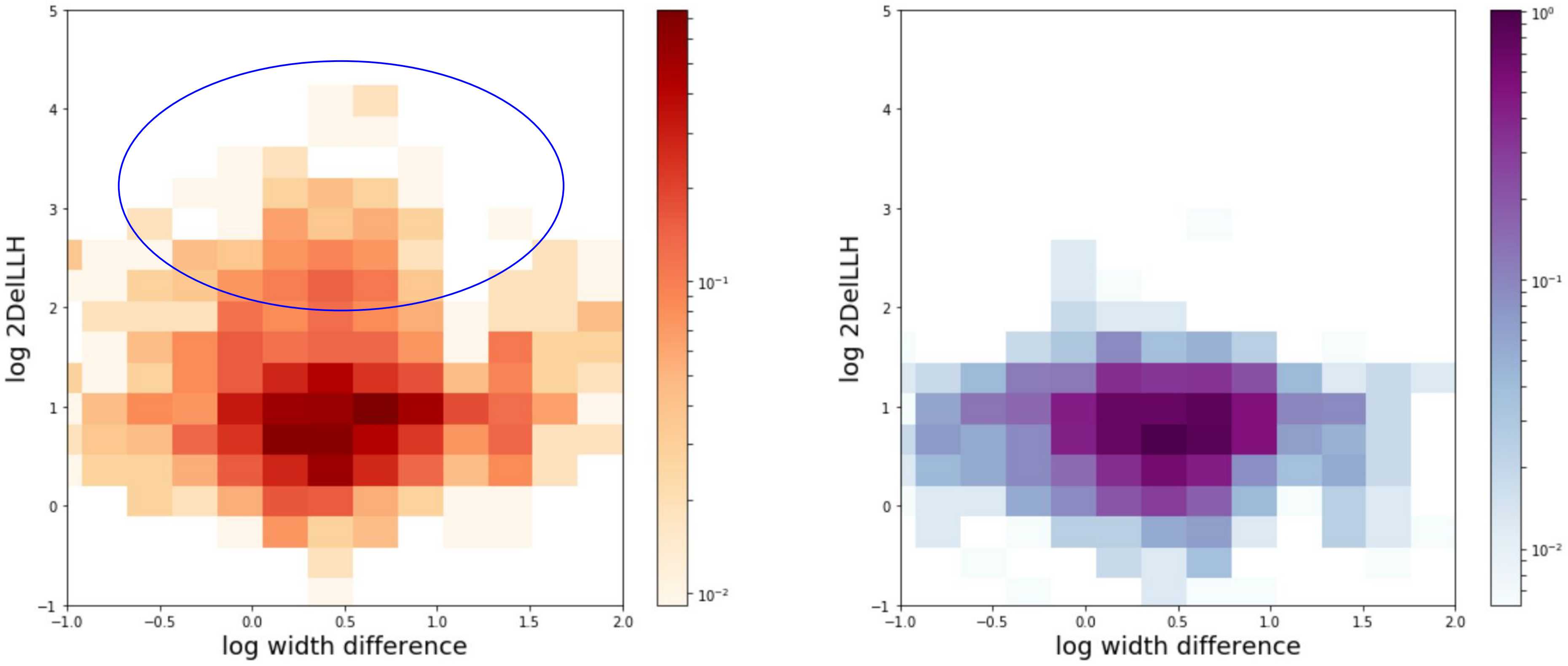


Hist 2Ds for Exponential gaussian fits

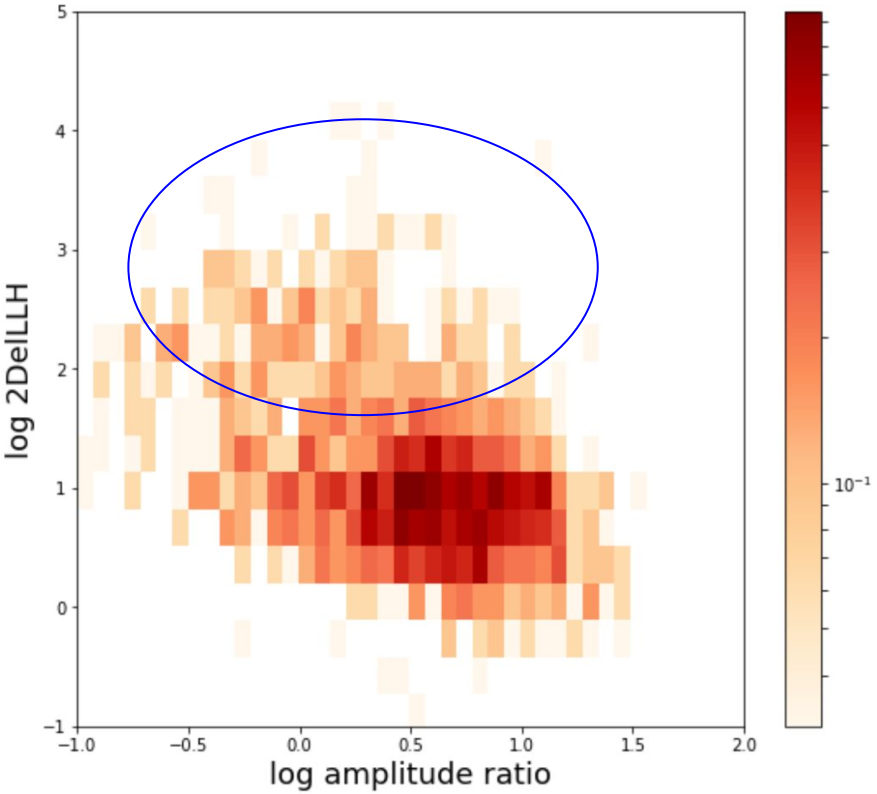


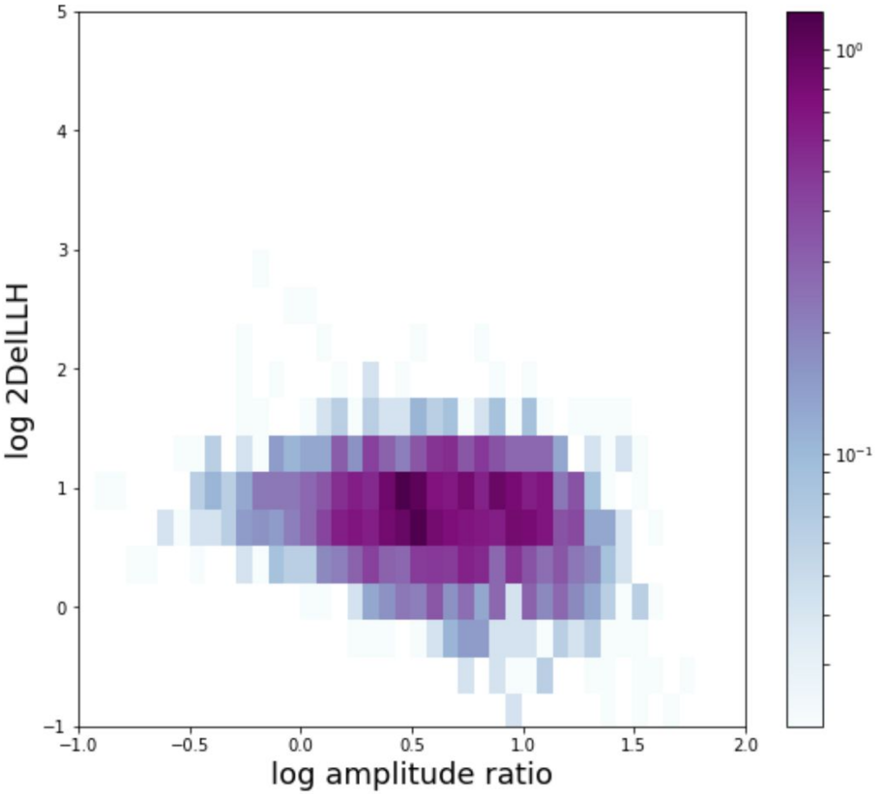


Hist 2Ds for Exponential gaussian fits

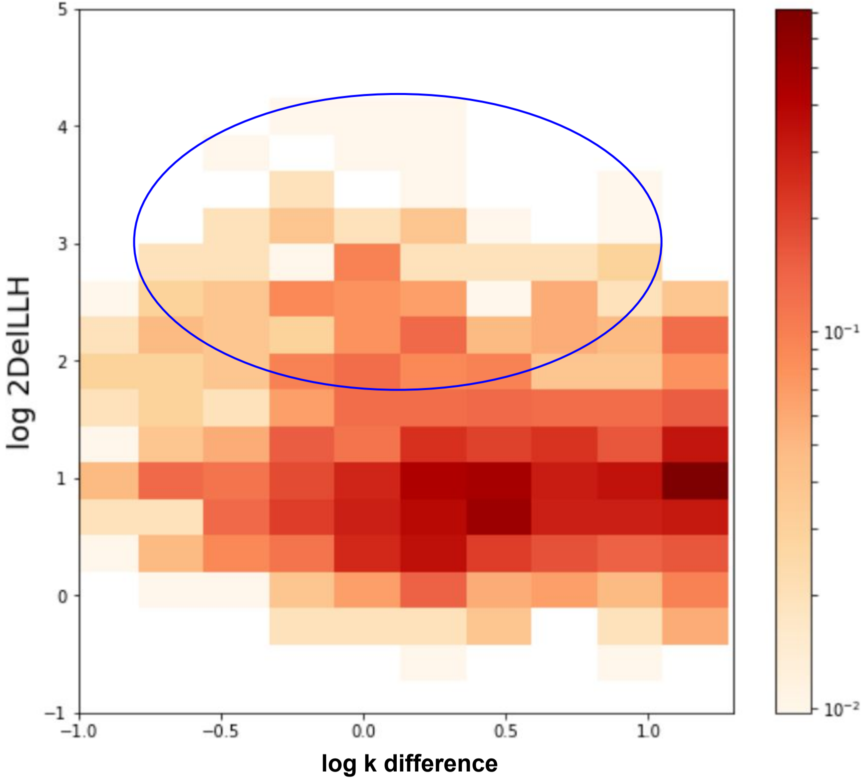


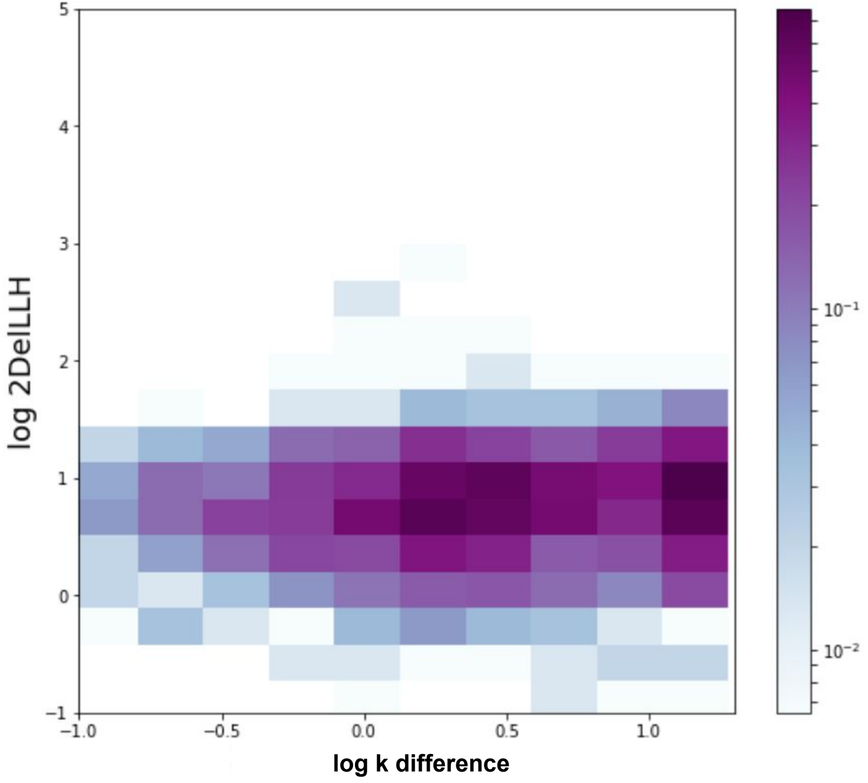
Hist 2Ds for Exponential gaussian fits





Hist 2Ds for Exponential gaussian fits





Weighting Events

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

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

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

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

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

Time Difference