Long Baseline: LBNF Events in THEIA

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Contents

- Predicted event numbers from long baseline running. Dependent on:
  - Different beam modes.
  - True cp-phase.
  - Neutrino mass hierarchy.
- Event display.
  - Producing event displays within the rat-pac framework, using GENIE simulated events.
- Reconstruction.
  - Separation of Cherenkov and scintillation light.
  - Cherenkov ring reconstruction.
- Light yield device.

Predicted Events

Predicted Events - Considerations

- In order to calculate the number and composition of events we must consider:
  - Oscillation probabilities.
  - Neutrino beam flux.
  - Cross-section measurements.
  - Detector size.
  - Detector composition.
  - Baseline.
  - Run period.

Oscillation Probabilities

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- To calculate the oscillation probabilities we must consider matter effects and the cp phase:

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) = \; & 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2\Phi_{31}\left(1 + \frac{2a}{\Delta m_{31}^2}(1 - 2S_{13}^2)\right) \\
& + 8C_{13}^2 S_{12} S_{13} S_{23}(C_{12}C_{23}\cos\delta_{CP} - S_{12}S_{13}S_{23})\cos\Phi_{32}\sin\Phi_{31}\sin\Phi_{21} \\
& - 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23}\sin\delta_{CP}\sin\Phi_{32}\sin\Phi_{31}\sin\Phi_{21} \\
& + 4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta_{CP})\sin^2\Phi_{21} \\
& - 8C_{13}^2 S_{13}^2 S_{23}^2 (1 - 2S_{13}^2)\frac{aL}{4E_\nu}\cos\Phi_{32}\sin\Phi_{31},
\end{aligned}
$$

- Where:

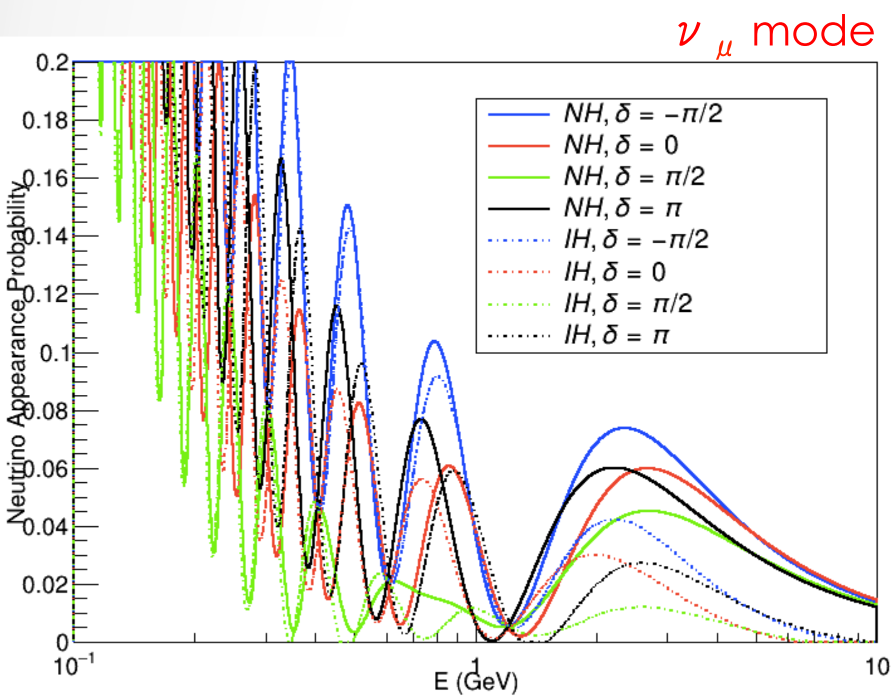
$$\phi_{ji} = \Delta m_{ji}^2 L / 4E_\nu$$

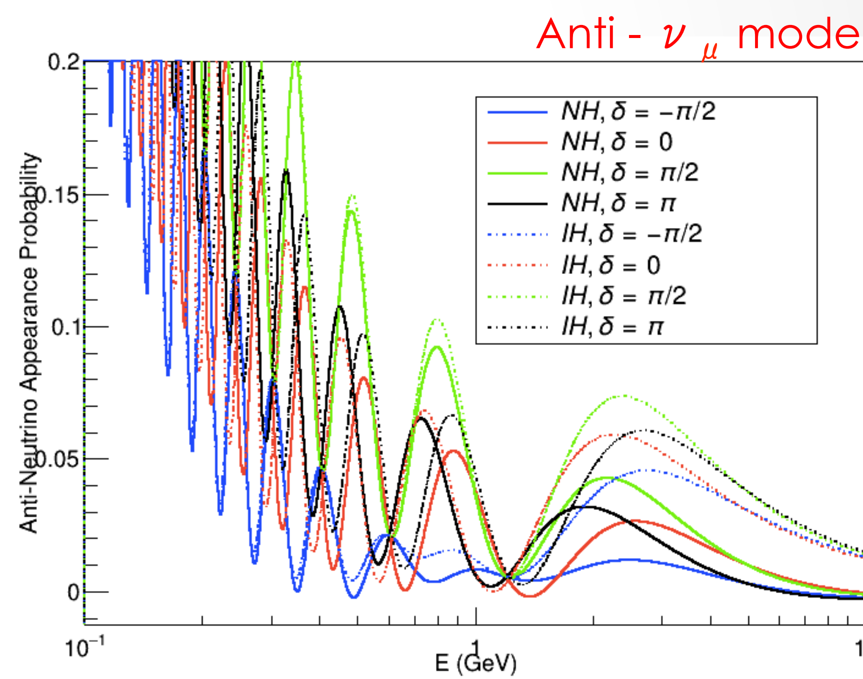
$$a \equiv 2\sqrt{2} G_F n_e E_\nu = 7.56 \times 10^{-5}[eV^2]\left(\frac{\rho}{[g/cm^3]}\right)\left(\frac{E_\nu}{[GeV]}\right)$$

- Assumed a baseline of 1300 km.
- Constant crust density of 2.6 gcm^{-3}.
- Used PDG 2016 values.

Oscillation Probabilities

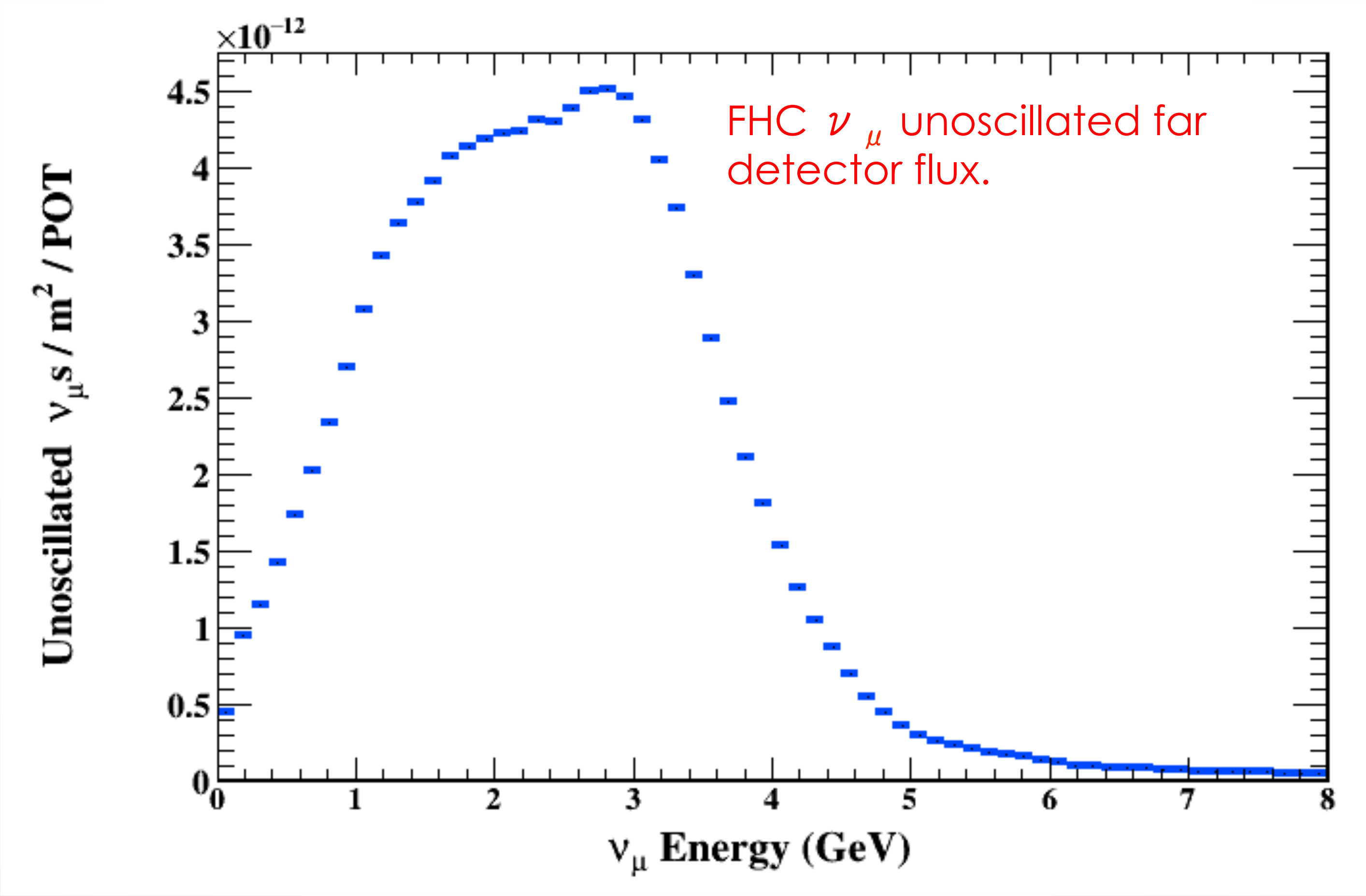
- Deduce the oscillation probabilities for different combinations of true cp phase, mass hierarchy structure and neutrino mode.
- Of particular interest for long-baseline studies is the 1 – 10 GeV range.





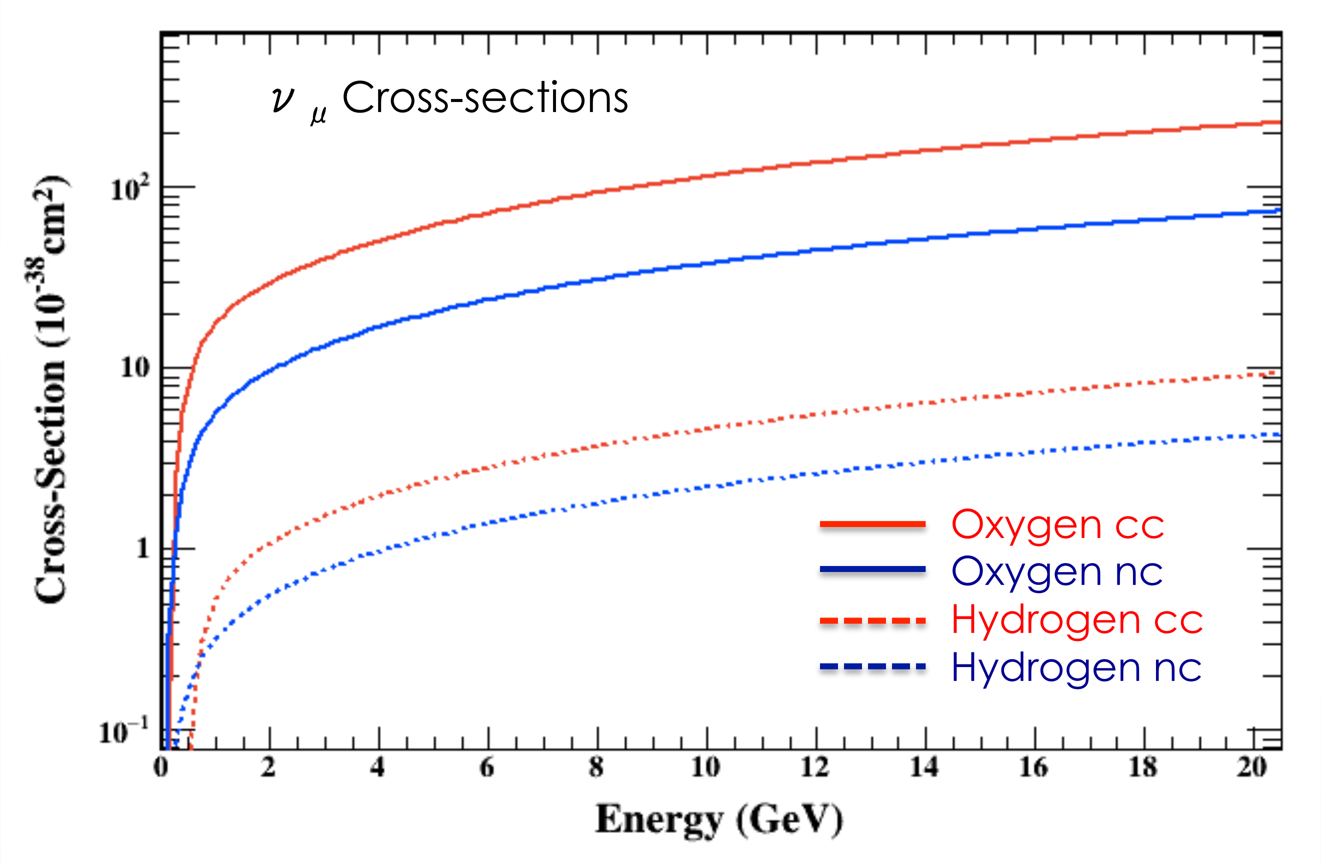
Neutrino Flux

- Used the LBNE optimised neutrino flux files.
  - Gives increased sensitivity to cp violation and mass hierarchy determination measurements.
  - Full details of the configuration can be found in arXiv.1512.06148.



Cross-Sections

- Using GENIE cross-sections.
- Considered interactions on H and O only.



Number of Events - Calculation

- In the example given, the following parameters were used:
  - A 40kT FV.
  - 3.5 years FHC neutrino mode run.
  - $\delta_{cp} = 0$.
  - Normal mass hierarchy.
  - Not included intrinsic ν_e background in the beam.
  - Only considered cross-sections of water and hydrogen (no carbon).
- 20 GENIE simulations.
- Average gives the expected value and the RMS of this gives the uncertainty.

Event Breakdown

- Simulation of the following number of events…

Neutrino Flavour	Number of Events
Anti - ν_μ	898
Anti - ν_e	13
ν_μ	12545
ν_e	1544

- Leading to the following breakdown…

Interaction Type	Number of Events
Anti – ν_μ CC	650.2 ± 12.5
Anti – ν_μ NC	247.8 ± 12.5
Anti – ν_e CC	9.1 ± 1.4
Anti – ν_e NC	3.9 ± 1.4
ν_μ CC	9255.7 ± 35.7
ν_μ NC	3289.3 ± 35.7
ν_e CC	1138.9 ± 17.4
ν_e NC	404.4 ± 17.4

Event Breakdown

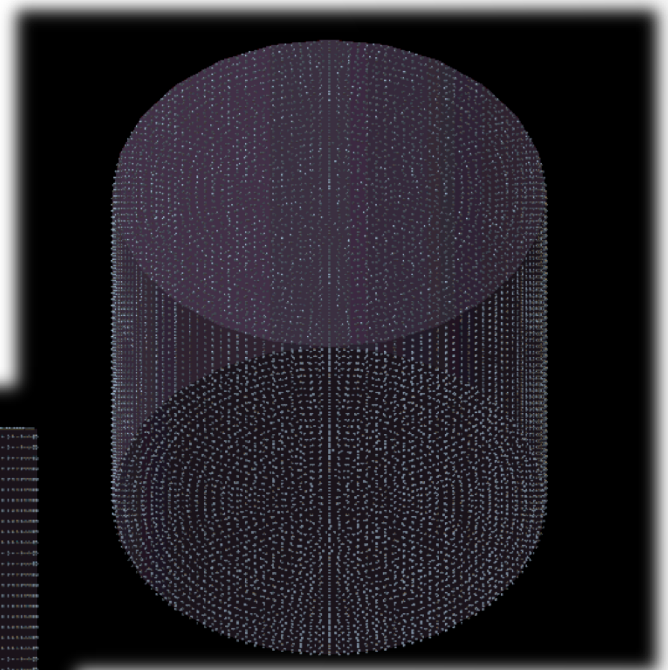
- Which can be further subdivided into…

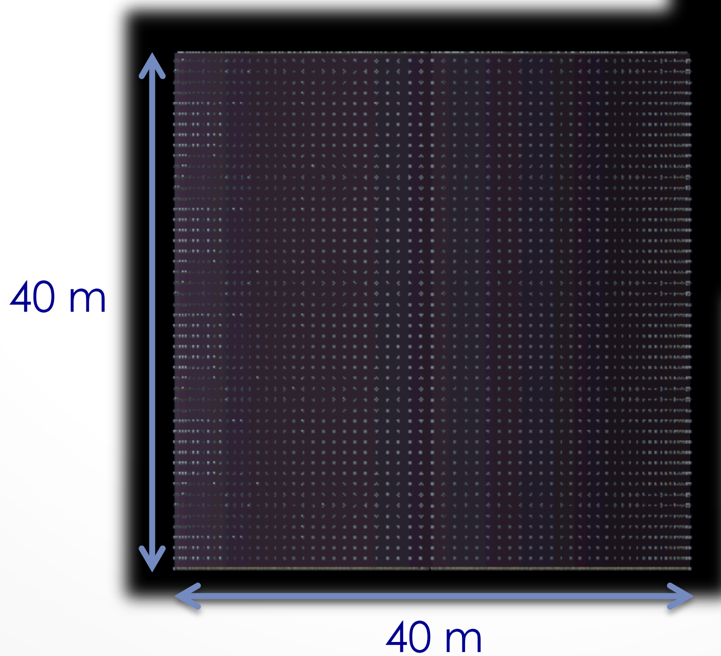
Interaction Type	Number of Events
(Anti –) ν_μ CC QEL	1857.2 ± 40.1 (109.6 ± 9.9)
(Anti –) ν_μ CC RES	2770.9 ± 45.2 (140.9 ± 8.6)
(Anti –) ν_μ CC DIS	4560.2 ± 45.1 (390.9 ± 17.3)
(Anti –) ν_μ CC Other	67.3 ± 11.0 (8.7 ± 3.5)
(Anti –) ν_μ NC QEL	738.3 ± 18.6 (41.0 ± 5.4)
(Anti –) ν_μ NC RES	965.7 ± 20.6 (57.8 ± 7.8)
(Anti –) ν_μ NC DIS	1546.8 ± 35.9 (144.3 ± 9.2)
(Anti –) ν_μ NC Other	38.6 ± 4.4 (4.8 ± 2.1)
(Anti –) ν_e CC QEL	224.9 ± 10.3 (3.5 ± 1.6)
(Anti –) ν_e CC RES	405.9 ± 12.8 (2.6 ± 1.6)
(Anti –) ν_e CC DIS	497.6 ± 21.6 (2.7 ± 1.6)
(Anti –) ν_e CC Other	10.5 ± 3.4 (0.3 ± 0.4)
(Anti –) ν_e NC QEL	86.7 ± 9.2 (1.3 ± 1.1)
(Anti –) ν_e NC RES	144.2 ± 13.0 (1.5 ± 0.8)
(Anti –) ν_e NC DIS	168.7 ± 8.5 (1.1 ± 1.0)
(Anti –) ν_e NC Other	4.8 ± 2.5 (0.0 ± 0.0)

Event Display and Reconstruction

THEIA Simulations

- Able to simulate GENIE events in THEIA using rat-pac.
  - Version issues. Currently using Geant4 Version 10.01.p02.
  - When simulating Cherenkov events the simulation is slower than expected.
- Current setup:
  - 11471 R7081_hqe inner facing PMTS.
  - 26.9 % PMT coverage.
  - Depending on final PMT choice, configuration etc, this can be increased.
  - WbLS 5%.
  - 40 kT volume.



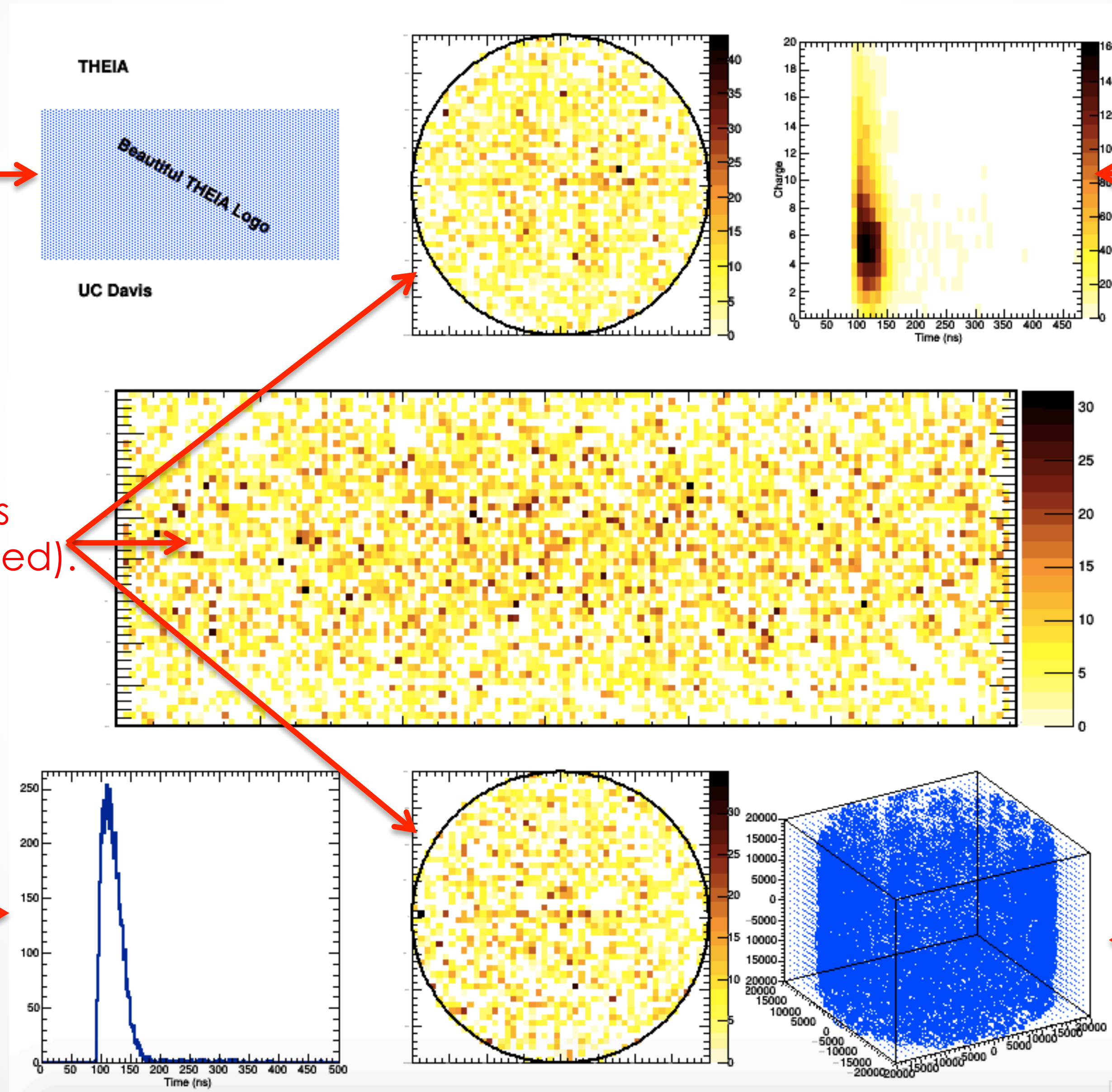


Event Display – Scintillation Only

- Simulation of a ν_μ CC Quasi-Elastic Event.

We need a logo!!!!

Charge vs time distribution.



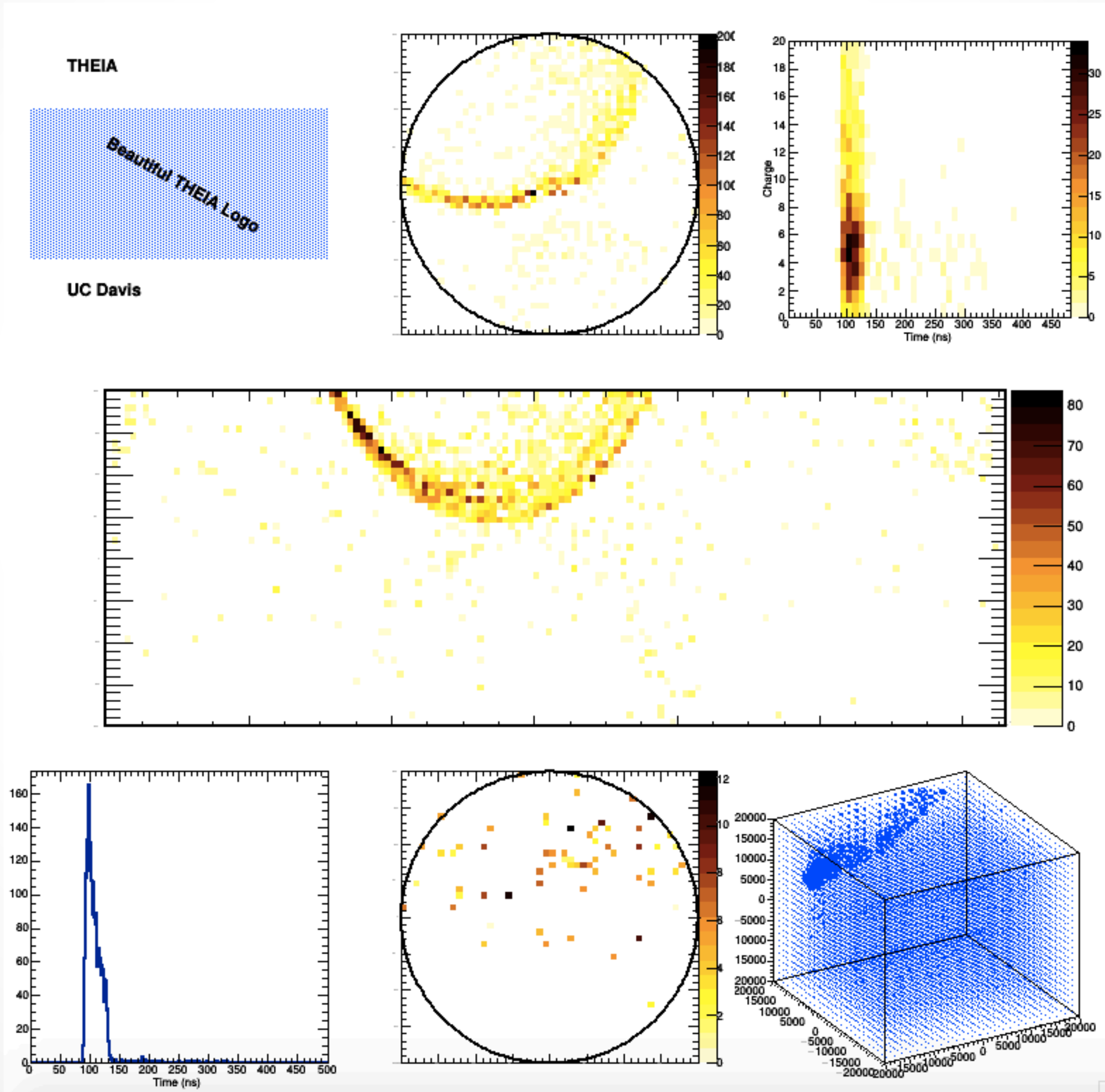
PMT hit positions (charge weighted).

PMT hit times.

PMT hit positions.

Event Display – Cherenkov Only

- Simulation of the same ν_μ CC Quasi-Elastic Event.



Event Display – Both

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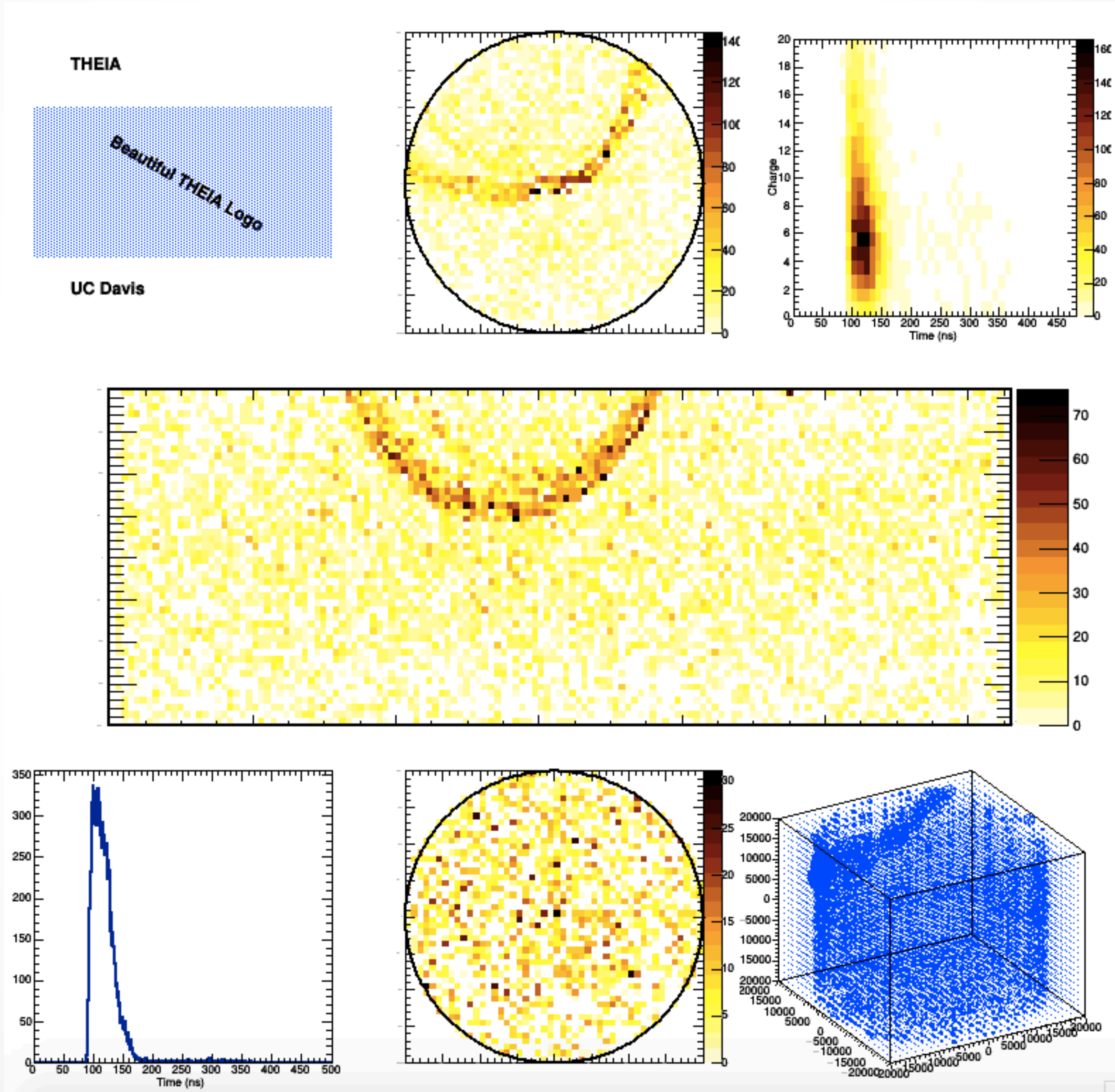
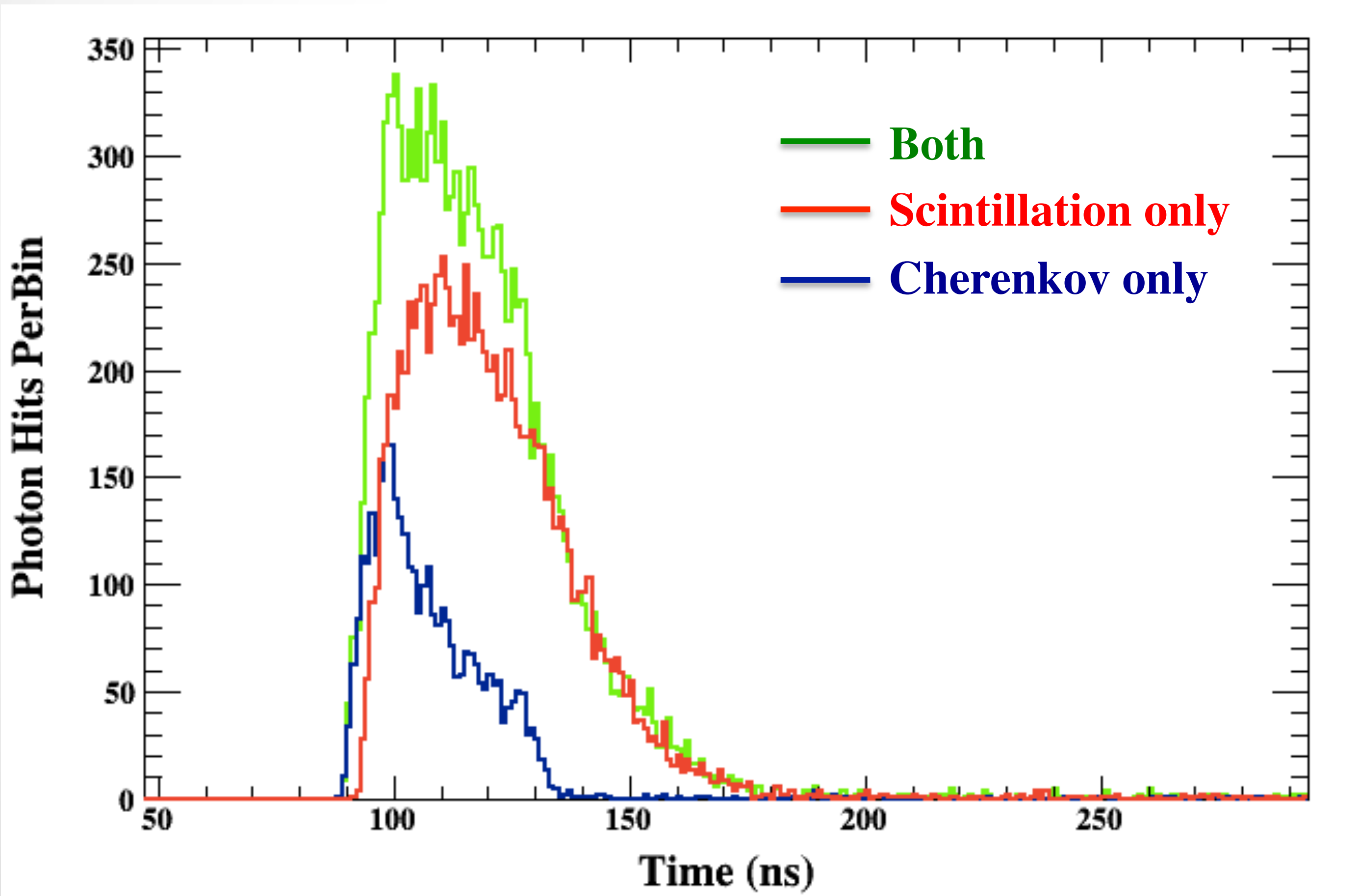
- Simulation of the same ν_{μ} CC Quasi-Elastic Event.



PMT Hit Times

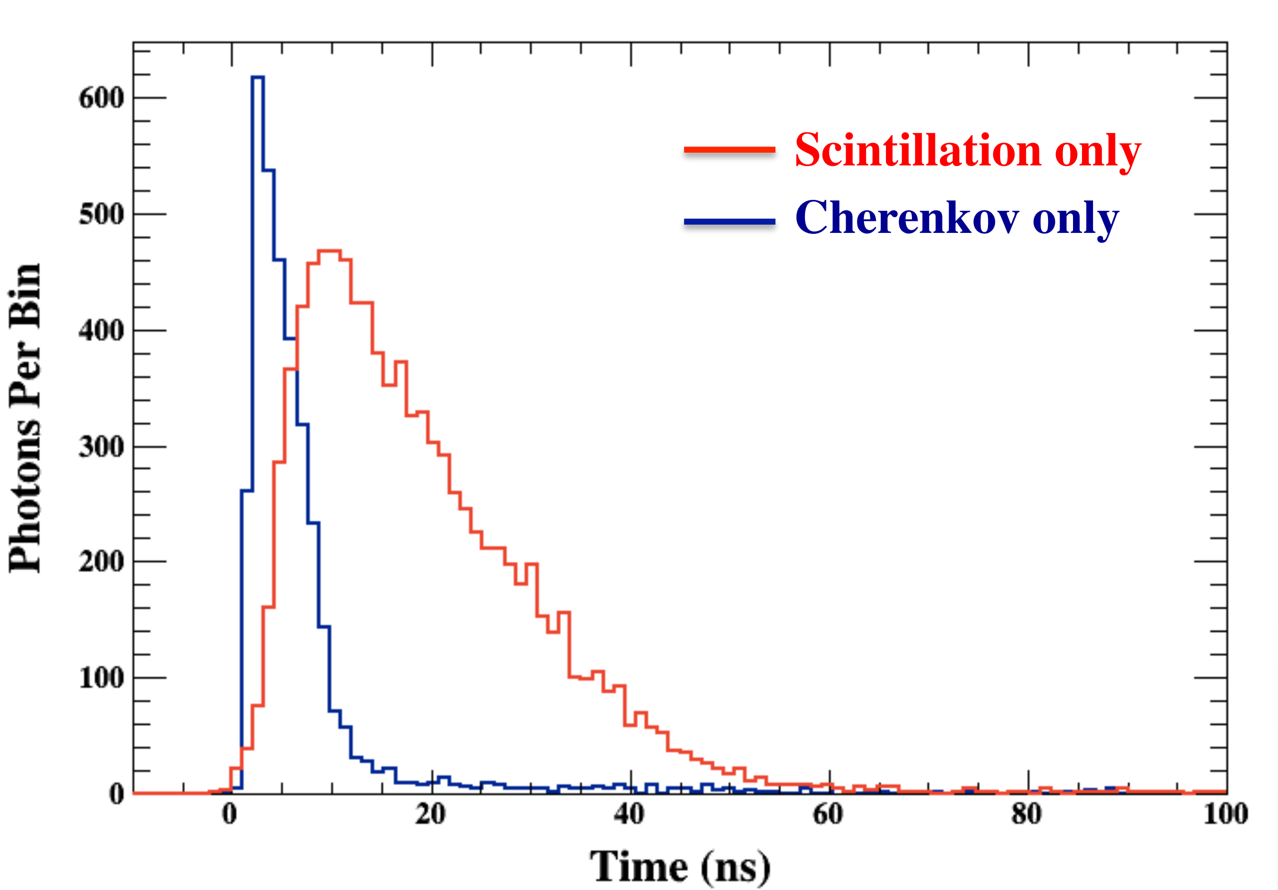
- PMT hit times of photons from Cherenkov emission, scintillation and both.



Although Cherenkov arrives sooner, there is still much overlap with the scintillation light. However, if we consider the time residuals…

Residual Timing

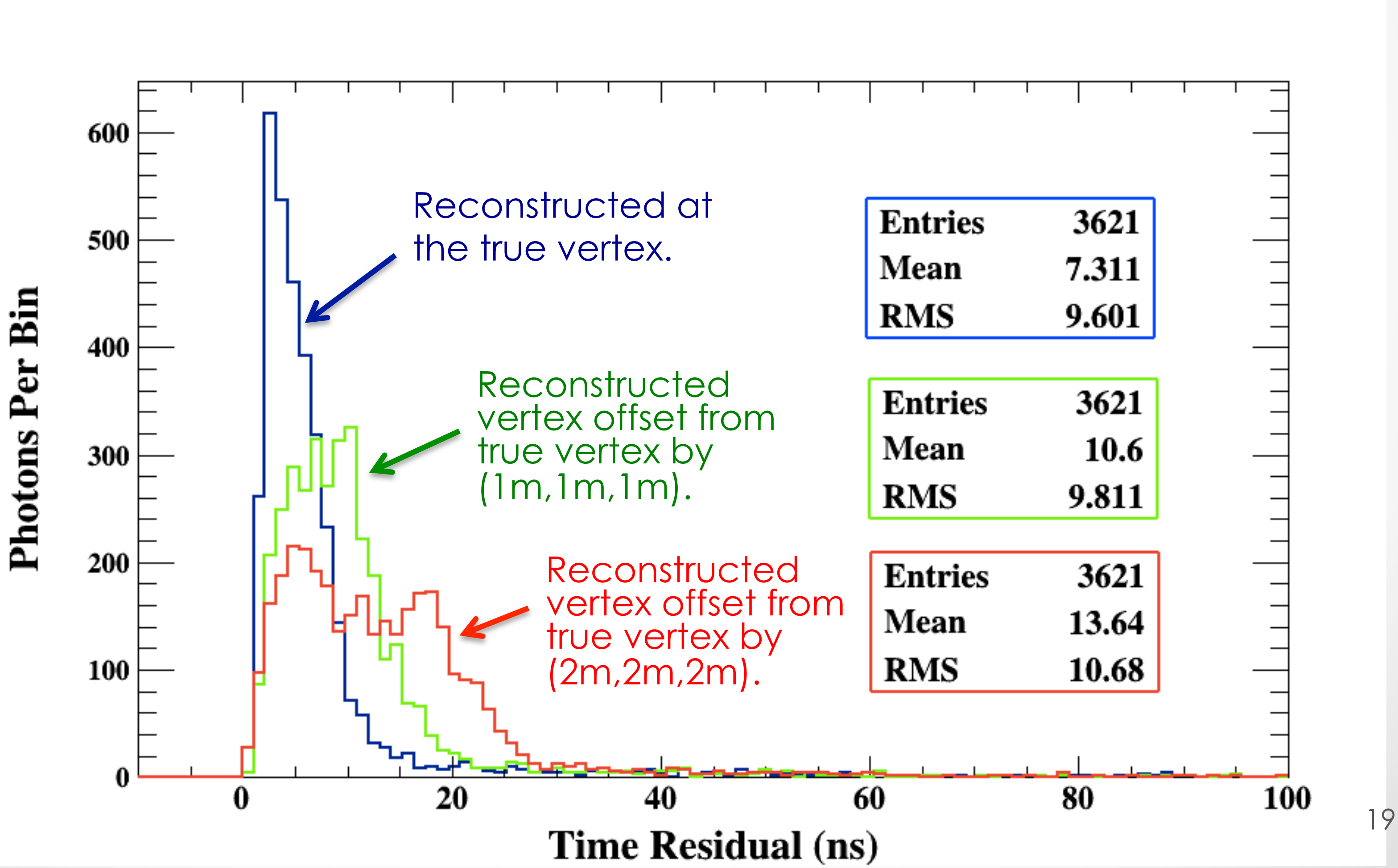
- Using muon truth information and knowledge of the vertex position, the following residuals are produced for Cherenkov and scintillation photons.
- This information can be used to locate the vertex.



Greater separation of Cherenkov and scintillation light compared to the PMT hit timing presented on the previous slide.

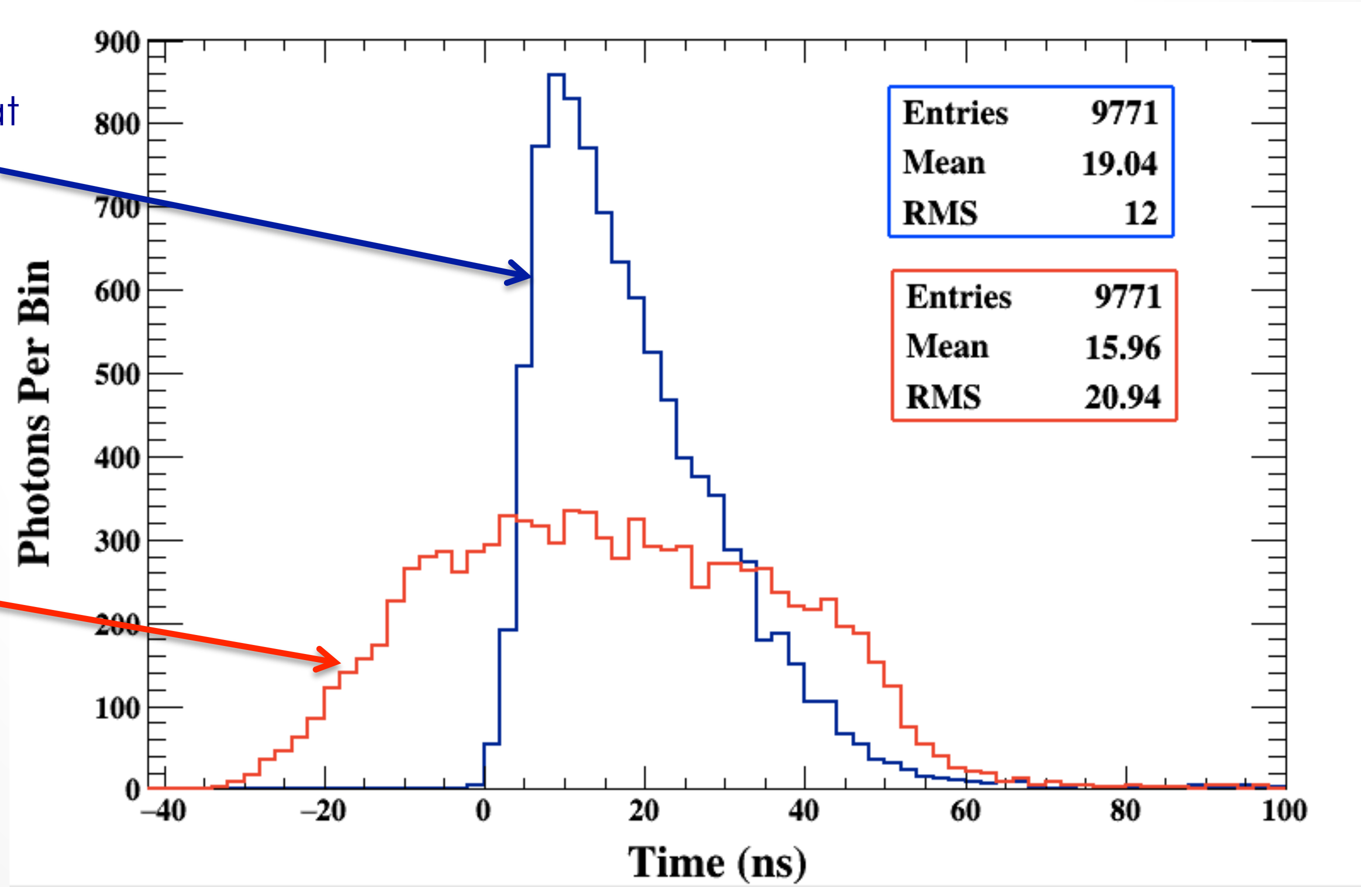
Vertex Reconstruction – Cherenkov Light

- For an accurately reconstructed vertex, we would expect to see a narrower, more peaked, timing residual.
- For the Cherenkov radiation below, we see this is the case.



Vertex Reconstruction – Scintillation Light

- For an accurately reconstructed vertex, we would expect to see a narrower, more peaked, timing residual.
- As with Cherenkov radiation, for scintillation light this is also the case.



Reconstructed at the true vertex.

Reconstructed vertex offset from true vertex by (5m,5m,5m).

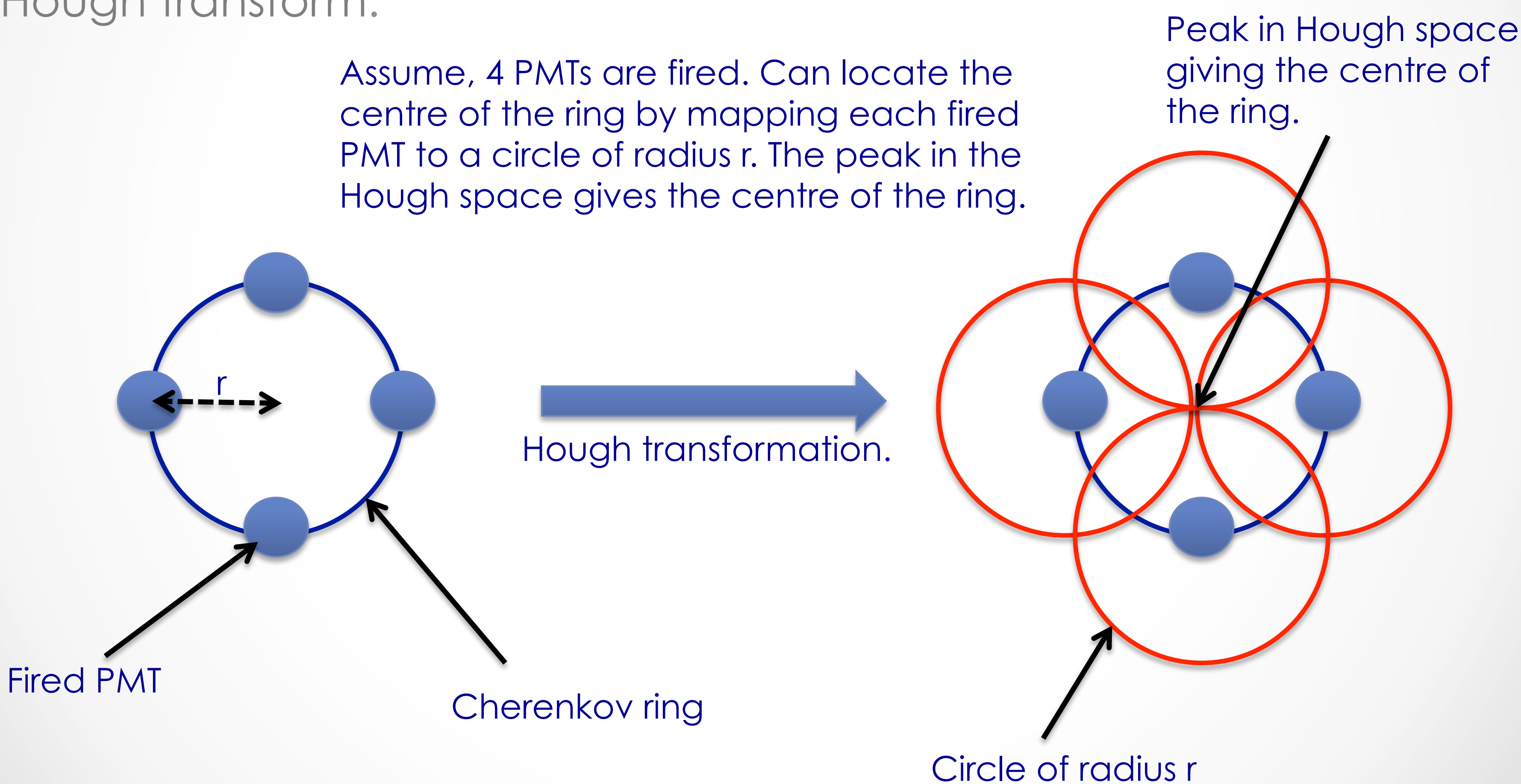
Near Future Reconstruction Work - Separation

- Originally, for Super-Kamiokande the first stage of reconstruction was fitting the vertex.
- As light is produced predominantly by Cherenkov radiation, the residual method is simple to use.
- However, we cannot calculate the time residuals in THEIA without knowing if the light is from scintillation or Cherenkov radiation.
- Perhaps make a PMT hit time cut in an attempt to isolate only scintillation?
- Perhaps search for Cherenkov rings first?

Near Future Reconstruction Work – Ring Fitting

- An easy to implement method for locating ring candidates is to use a Hough transform.

Assume, 4 PMTs are fired. Can locate the centre of the ring by mapping each fired PMT to a circle of radius r. The peak in the Hough space gives the centre of the ring.



Light Yield Device

Nanofiltration

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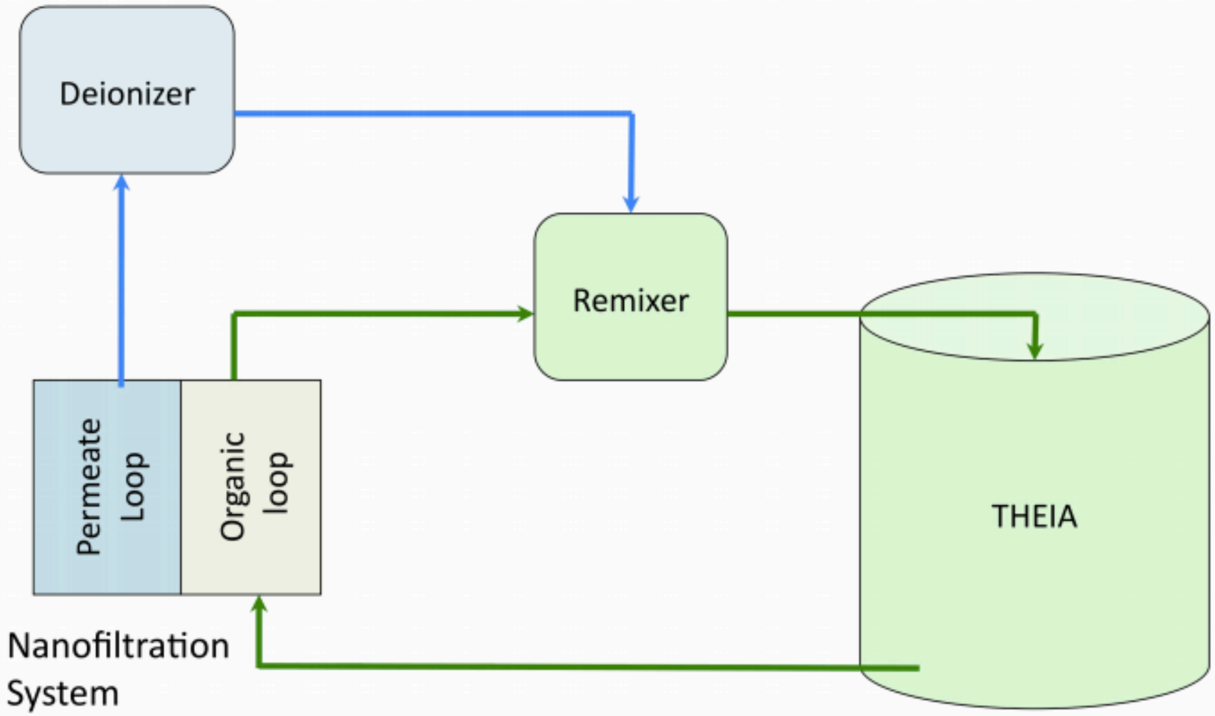
- Testing a nanofiltration system at UC Davis, which will hopefully be scalable to use for THEIA.
- For an in-depth explanation see Prof. Svoboda's Frost Topical Workshop talk.[2]

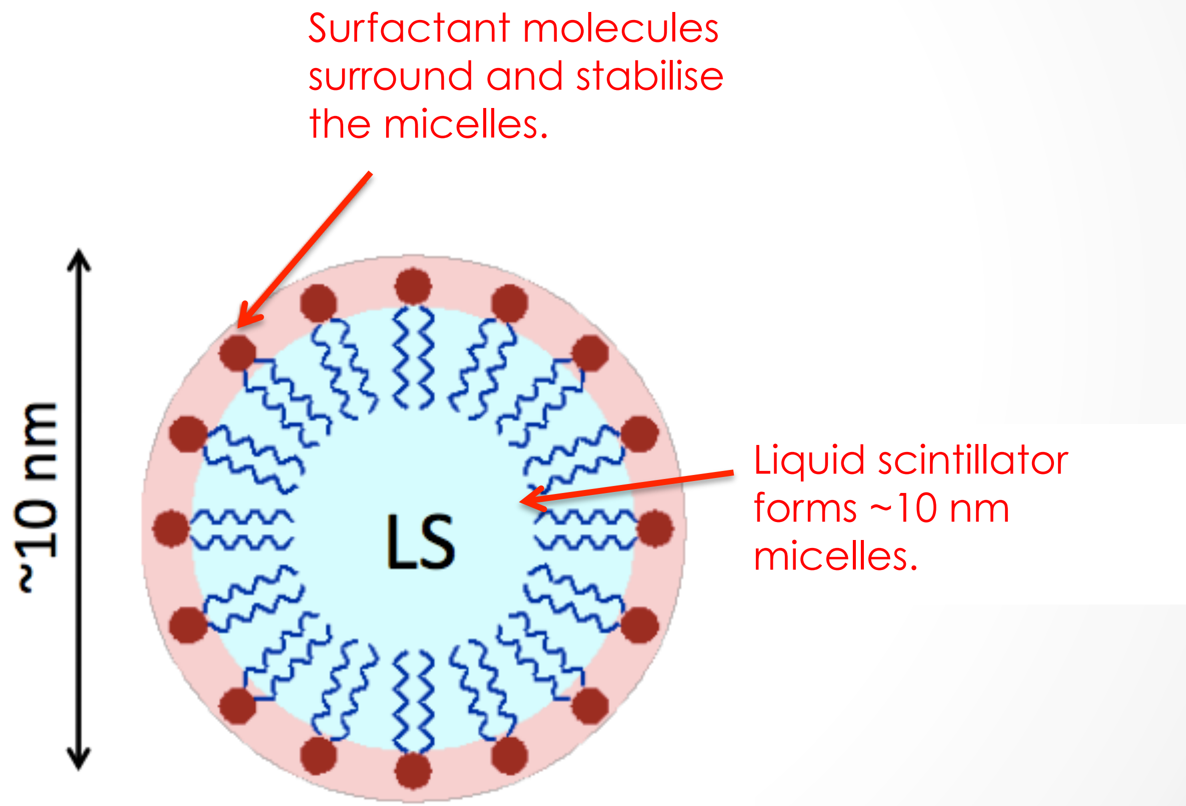


THEIA recirculation concept

2. https://indico.mitp.uni-mainz.de/event/83/session/2/contribution/29/material/slides/0.pdf

Why Do We Need A Light Yield Device?

- One potential problem with nanofiltration, is that it might damage the micelles – affecting light yield.

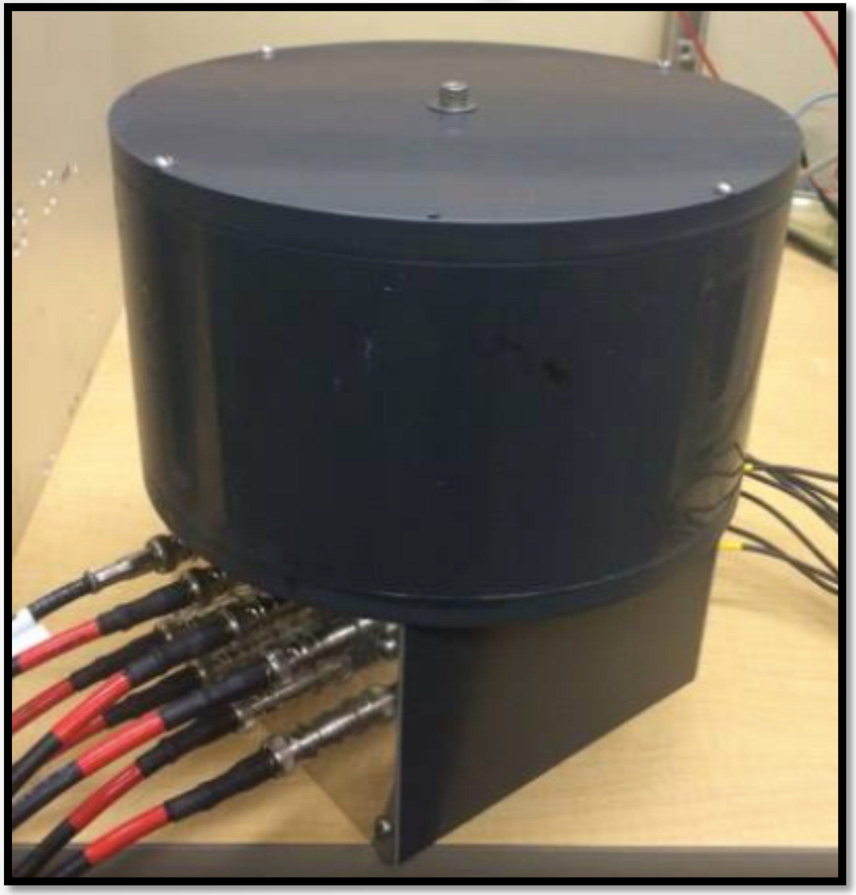


Light Yield Device - Setup

- Designed and built a light yield device that can hold a cuvette (dimensions: 45.2 x 12.5 x 12.5 mm) of WbLS.
- This is surrounded by 8 R928 Hamamatsu PMTs.
- Can measure the light yield when exposed to radiation from a ^{90}Sr source.
- ^{90}Sr undergoes β^- decay into ^{90}Y with a decay energy of 0.546 MeV.
- Source is placed above the cuvette, such that the emitted electron will be fully absorbed by the WbLS.
- Testing is underway and expect to take data soon…

Light yield device setup

Light Yield Device



Summary

- Infrastructure in place to predicted event numbers from long baseline running. Tunable depending on:
  - Different beam modes.
  - True cp-phase.
  - Neutrino mass hierarchy.
- Event display produced.
  - Producing event displays within the rat-pac framework.
- Early stages of reconstruction have begun.
  - Separation of Cherenkov and scintillation light.
  - Cherenkov ring reconstruction.
- Light yield device.
  - Built and ready to begin taking data.